A Study of the Galactic Dusts for the Improvement of the CMB Components Separation

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ABSTRACT

We have been working on construction of the physically motivated Galactic dust emission SED models both for intensity and polarization in order to improve the detection limit of the cosmic microwave background (CMB) B-mode polarization imprinted by primordial gravitational waves. A full treatment of photon absorption processes due to quantum mechanical transitions between two-level systems (TLS) caused by deformation of lattice structure is developed to model absorption coefficients of interstellar dust grains in mm, submm and FIR wavebands. We showed that there are 8 free parameters which control shape and amplitude of emission spectrum of amorphous dust grains. Since interstellar dust consists of two main species, that is carbon and silicate, totally 16 free parameters must be defined to model interstellar dust SED at least. To construct polarization emission model from dust grains, dust grain shapes are modeled by ellipsoids. Continuous distribution of ellipsoids (CDE) is adopted as distributions of ratios of major to minor axes and major to semi-minor axes. We also showed that the degree of polarization of ellipsoidal dust depends only on the real part of the permittivity in the mm wavelength range. On the other hand, the emissivity depends on both real and imaginary parts. Therefore, the complex permittivity of interstellar dust grains is able to be constrained by measuring the frequency dependence of both degree of polarization and intensity. It provides an important clue to clarify physical nature and origin of interstellar dust grains. Our amorphous dust grain models predict that the degree of polarization of the ellipsoidal dust is monotonically decreasing function of the frequency.

Keywords: ISM: amorphous dust grains: Cosmic microwave background: Polarization emission

1. INTRODUCTION

Although the standard big bang model has achieved great success to describe the evolution of the universe, it does not provide why it banged, why our universe is so big and where origins of structures emerged in the current universe came from. Inflation theory provides answers to these fundamental questions. It postulates that size of the universe is more than 10^{30} times expanded during just 10^{-34} s at the very early stage of the universe due to the vacuum energy. Since the expansion rate of the universe is drastic, this period is named as inflation period. One of the significant predictions of the inflation theory is that universe is filled with background gravitational waves generated by quantum fluctuation of space time during inflation period. Although technologies required for the direct detection of these primordial gravitational waves are not yet ready, it has been known that the existence of the primordial gravitational waves imprints B-mode polarization on the cosmic microwave background (CMB). Many activities are now on going aiming to get honor of the first detection of the CMB B-mode polarization imprinted by the primordial gravitational waves (e.g., Oguri et al. 2014; Matsumura et al. 2014). Not only the further improvement of accuracy of dust removal from the data but also the construction of theoretical framework on what we can extract on physics of the Galactic dust from high precision and wide field mm wavelength polarization observations, are mandatory to maximize outcomes of future CMB B-mode polarization experiments.

A lesson of the BICEP2 failure is that accuracy of removal of the Galactic dust emission contribution from the data is crucial for the secure detection and the improvement of the detection limit of the wanted signal (BICEP2 and Keck

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collaborations 2015; BICEP2/Keck and Planck collaborations 2015). Except the dense molecular cloud regions, the Galactic interstellar dust is optically thin against electromagnetic waves with the wavelength longer than FIR. Therefore, the emission spectrum from the Galactic dust with a temperature of T is well described by

$$I_\nu^{\mathrm{dust}}(T) = \tau_\nu B_\nu(T), \tag{1}$$

where $B_\nu(T)$ is the Planck function, ν is the frequency and τ_ν is optical depth at frequency ν. When all dust particles have a crystal structure, the optical depth is described by $\tau_\nu = \tau_0(\nu/\nu_0)^2$ where ν_0 is a reference frequency and τ_0 is an optical depth at ν_0. However, observations show that the frequency dependence of the Galactic dust SED is flatter than the expectation of the crystal model. By adopting a simple power law as dependence on frequency for dust optical depth, Planck Collaboration (2014) showed that the spectrum indexes of the Galactic dust SED stay around 1.5. These results show that the Galactic dust grains are not crystal but are composed of amorphous solids. Further, dust size dependence of equilibrium temperature and non-thermal equilibrium nature of small grains (Draine and Anderson 1985) must be taken into account to construct realistic SED models. The polarization intensity from the Galactic dust is related to the emission intensity through the polarization degree Π_ν^{dust} as

$$P_\nu^{\mathrm{dust}} = \Pi_\nu^{\mathrm{dust}} I_\nu^{\mathrm{dust}}. \tag{2}$$

In most of the previous studies, the polarization degree was treated as a constant number and the frequency dependence of $\Pi_\nu^{\mathrm{dust}}$was neglected without any physical reasoning.

Construction of the physically motivated Galactic dust emission SED models both for intensity and polarization should be now progressed. Although several works touched the dust SED modeling based on physics of amorphous dust grains, studies were still incomplete (e.g., Meny et al. 2007). Moreover, although there are studies on modeling of the dust shape effect (e.g., Min et al. 2008), most of them did not consider dust polarization emission. Therefore, we develop a full treatment of photon absorption processes due to quantum mechanical transitions between two-level systems (TLS) caused by deformation of a lattice structure. Further, polarization emission models are constructed self-consistently with adopted shape models of the dust grains.

2. THERMAL EMISSION FROM AMORPHOUS DUST

It is familiar that amorphous solids exhibit the thermal properties which are different from crystal solids at low temperature. In the Debye model, the heat capacity is proportional to a cubic of temperature and the thermal conductivity has dependence of the cubic of the temperature. However, amorphous solids show that the former is proportional to the temperature and the latter has dependence of the square of the temperature. Since these characteristics appear universally for all amorphous solids, it has been believed that these are originated from universal underlying physics of amorphous solids. The TLS model has been accepted as the standard model to explain these universal features of amorphous solids (Anderson, Halperin, and Varma 1972; Phillips 1972). In low temperature, the transition between the TLS dominates over lattice vibration to absorb heat energy (Figures 1 and 2). As a result, the degree of freedom absorbing heat energy becomes one and heat capacity proportional to temperature appears.

Meny et al. (2007) applied the TLS model to the Galactic dust SED in mm, submm and FIR wavebands at the first time. However, their treatments were still insufficient; for example, they did not take into account the frequency dependence of the real part of the permittivity and the SED of the polarization emission. Therefore, we calculated the frequency dependence of the complex permittivity of amorphous dust self-consistently in mm, submm and FIR wavebands based on the TLS model. As a result, we found that there are 8 free model parameters for each amorphous component to define the shape of the SED. In this work, we focus on 4 parameters from among them, dust temperature T, relaxation time for resonance τ_+, the maximum of the energy difference between TLS $E_m = hc/\lambda_m$, and the ratio of TLS density f_{TLS}.

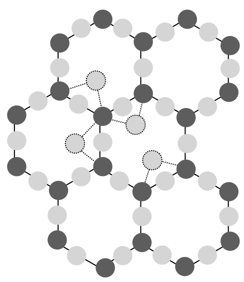

Figure 1. Schematic picture of an amorphous solid. In the case of a crystal, each particle is placed regularly and the position is fixed. On the other hand, each particle composed amorphous solid has two steady positions.

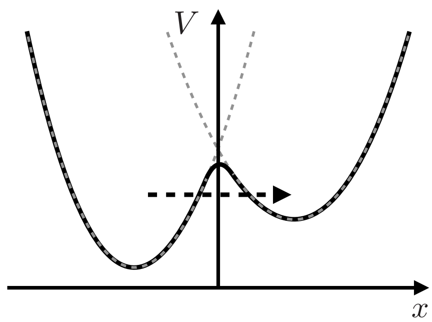

Figure 2. Schematic picture of the potential energy for each particle in amorphous solids. Since each particle has two steady positions, the shape of potential is like a double-well. The tunneling through this potential barrier happens.

3. POLARIZATION EMISSION FROM ELLIPSOIDAL DUST

To construct polarization emission model from dust grains, dust grain shapes are modeled by ellipsoids. Continuous distribution of ellipsoids (CDE) is adopted as distributions of ratios of major to minor axes and major to semi-minor axes. Uniform distribution of permittivity is assumed for the inside of the ellipsoid. Since the inter distance between each dust grain is much larger than the dust size, the outside of dust grain is able to treat as the vacuum. For simplicity, we assume that a minor axis becomes parallel to the Galactic magnetic field lines. Relative directions of the Galactic magnetic field lines across the line of sight may significantly vary. Since this does not affect the frequency dependence of the polarization degree, we assume that there is no variation of magnetic field direction across the line of sight and the magnetic field direction is always perpendicular to the line of sight. Since the typical large grain size is 0.1 μm and much smaller than the wavelength of FIR to mm wavebands, the electric dipole approximation is enough to evaluate the response of ellipsoid dust to light. According to our amorphous dust models, the imaginary part of permittivity is much smaller than the real part of permittivity in the wavelength range longer than FIR. Under these conditions, we calculate the imaginary part of electric susceptibilities for each dust axis (x, y and z-axes correspond to major, semi-minor and minor axes),

$$\chi''_{0x} = \frac{3}{2\pi}\frac{\varepsilon''}{(\varepsilon'-1)^2}\left[\varepsilon' - 1 - 3\ln\left(\frac{\varepsilon'+2}{3}\right)\right], \tag{3}$$

$$\chi''_{0y} = \frac{3}{2\pi}\frac{\varepsilon''}{(\varepsilon'-1)^2}\left[6\ln\left(\frac{\varepsilon'+2}{3}\right) - 4\ln\left(\frac{\varepsilon'+1}{2}\right)\right], \tag{4}$$

$$\chi''_{0z} = \frac{3}{2\pi}\frac{\varepsilon''}{(\varepsilon'-1)^2}\left[-\ln\varepsilon' + 4\ln\left(\frac{\varepsilon'+1}{2}\right) - 3\ln\left(\frac{\varepsilon'+2}{3}\right)\right], \tag{5}$$

where $\varepsilon = \varepsilon' + i\varepsilon''$ is the complex dielectric constant. In addition, the degree of polarization can be calculated as

$$\Pi^{\rm dust}_\nu = \frac{\epsilon^x_\nu + \epsilon^y_\nu - 2\epsilon^z_\nu}{\epsilon^x_\nu + \epsilon^y_\nu + 2\epsilon^z_\nu}, \tag{6}$$

where ϵ^x_ν, ϵ^y_ν and ϵ^z_ν are the emissivities for each axis. Since an absorption cross section of a dust grain is proportional to the imaginary part of the electric susceptibility under the electric dipole approximation, the optical depth is also proportional to that. Equations (3)-(6) indicate that the degree of polarization for the ellipsoidal dust depends only on the real part of the permittivity in the long wavelength range as the imaginary part of that is canceled. Figure 3 shows how the polarization degrees of amorphous dust grain respond to physical parameters of amorphous dust grains. For each panel variable

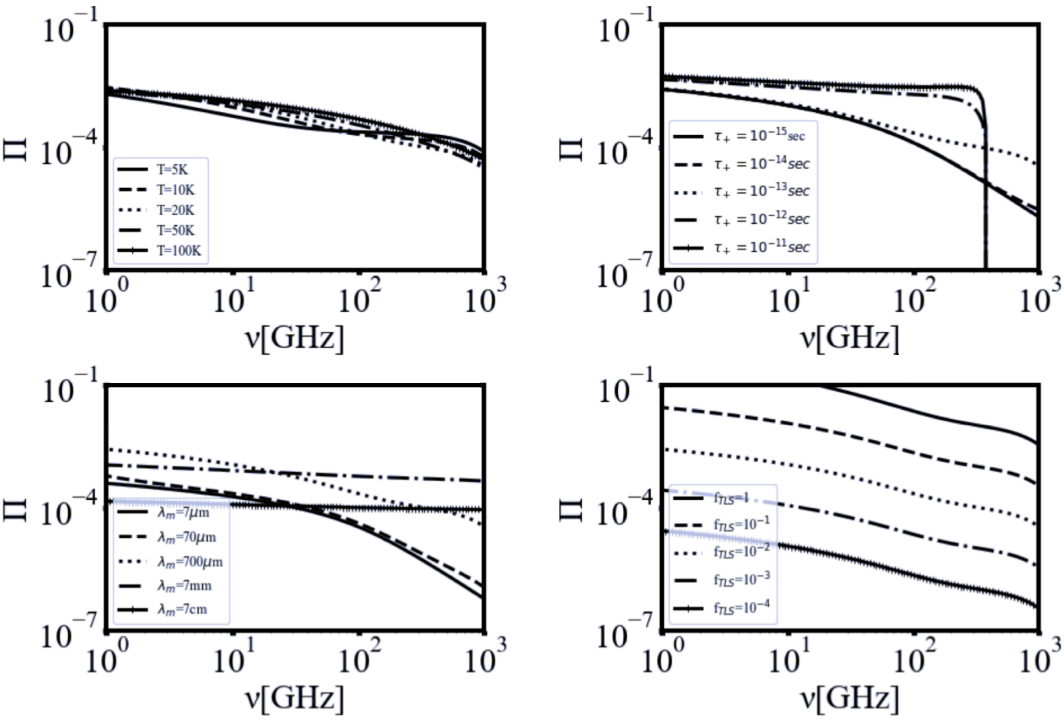

Figure 3. Calculation results of the frequency dependence of the degree of polarization. We calculated for several variable parameters, temperature(top left panel), relaxation time for resonance(top right panel), the maximum of the energy difference between TLS(bottom left panel) and the ratio of TLS density(bottom right panel).

parameters are T (top left panel), τ_+ (top right panel), λ_m (bottom left panel) and $f_{\rm TLS}$ (bottom right panel). The values of the remaining parameters are fixed at $T = 20$ K, $\tau_+ = 10^{-13}$ s, $\lambda_m = 700$ μm, and $f_{\rm TLS} = 10^{-2}$; that is, each dotted line agrees with all other ones. Figure 3 shows that the frequency dependence of the degree of polarization of amorphous dust grains has complex shapes and depends significantly on the choice of parameters.

4. DISCUSSIONS

We showed that the degree of polarization of ellipsoidal dust depends only on the real part of the permittivity in the mm wavelength range. On the other hand, the emissivity depends on both real and imaginary parts. Therefore, the complex permittivity of interstellar dust grains is able to be constrained by measuring the frequency dependence of both degree of polarization and intensity. It provides an important clue to clarify physical nature and origin of interstellar dust grains. As far as the standard models of the distribution of parameters of amorphous dust are adopted, the degree of polarization of the ellipsoidal dust is monotonically decreasing function of the frequency (Figure 3). It provides an important test to check the standard amorphous models. The variation of the Galactic magnetic field directions across the line of sight and the imperfectness of the dust alignment along magnetic field lines simply reduce the polarization degree and do not affect the frequency dependence of the polarization degree.

We are already ready to construct the Galactic dust SED models based on our own dust models outlined in this paper. The Monte Carlo simulation code which follows the thermal history of each dust grain heated stochastically by absorption of interstellar radiation field photon is completed. In this code, by taking time average of the emission spectrum from a single dust grain, ensemble average of the emission spectrum from a fixed size dust grains is calculated. We are going to make an all-sky dust map fitting *AKARI*-FIS data (Doi et al. 2015; Takita et al. 2015) by our own SED models.

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