

Part IV
Interpreting CMB
Observations

Polarized Microwave Radiation from Dust

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Abstract. Observations of cosmic microwave background in the range 10–90 GHz have revealed an anomalous foreground component well correlated with 12 μm , 60 μm and 100 μm emission from interstellar dust. As the recent cross-correlation analysis of WHAM H α maps with the Tenerife 10 and 15 GHz maps supports an earlier conclusion that the emission does not arise from free-free radiation, the interstellar dust origin of it is left as the only suspect. Two competing models of this emission exist. The more favored at the moment is the spinning dust model, the other is the model that uses grains with strong magnetic response. In the spinning dust model the emission arises from rapid rotation of ultrasmall grains that have dipole moments, while in the other model magnetic grains emit due to thermal vibrations of magnetic dipoles. Both models predict the emission to be partially polarized and this emission can seriously interfere with the CMB polarization measurements. We discuss observational signatures that can be used to distinguish and eventually filter out the polarized component of the microwave dust radiation.

1. Introduction

Diffuse Galactic microwave emission carries important information on the fundamental properties of interstellar medium, but it also interferes with the Cosmic Microwave Background (CMB) experiments (see Tegmark et al. 1999 and references therein). Polarization of the CMB provides information about the Universe that is not contained in the temperature data (see Prunet & Lazarian 1999, Davis & Wilkinson 1999) and a number of groups around the world (see Table 1 in Staggs et al. 1999) work hard to determine the CMB polarization. In view of this work, the issue of determining the degree of Galactic foreground polarization becomes vital.

Microwave emission from Galactic dust has been recently identified as an important component of Galactic microwave foreground (see Draine & Lazarian 1999) and this poses a question of the degree of its polarization. Even moderate polarization can substantially interfere with the ongoing CMB polarization measurements.

In this review, we summarize the properties of the recently discovered anomalous emission (see Kogut 1999) and discuss why it is inconsistent with free-free or synchrotron explanations and present two competing explanations of this emission, namely, the spinning grain model and the magneto-dipole model (section 2). Polarization of microwave foreground due to alignment of ultrasmall grains is covered in section 3, where we show that a new solid state effect termed “resonance paramagnetic relaxation” can produce the alignment. Polarization

of magneto-dipole emission and its characteristic signatures are discussed in section 4.

2. Anomalous Microwave Emission

Until very recently it has been thought that there are three major components of the diffuse Galactic foreground: synchrotron emission, free-free radiation from plasma (thermal bremsstrahlung) and thermal emission from dust. In the microwave range of 10-90 GHz the latter is definitely subdominant, leaving essentially two components. However, it is exactly in this range that an anomalous emission was reported (Kogut et al. 1996a, 1996b). In the recent paper by de Oliveira-Costa et al. (2000) this emission was nicknamed “Foreground X”, which properly reflects its mysterious nature. This component is spatially correlated with 100 μm thermal dust emission, but its intensity is much higher than one can expect by directly extrapolating thermal dust emission spectrum to the microwave range.

Since its discovery the Foreground X has been detected in the data sets from Saskatoon (de Oliveira-Costa et al. 1997), OVRO (Leitch et al. 1997), the 19 GHz survey (de Oliveira-Costa et al. 1998), and Tenerife (de Oliveira-Costa et al. 1999, Mukherjee et al. 2000). Present in the range of 10-90 GHz the Foreground X is particularly disturbing as many CMB experiments are performed or planned for this frequency range. Thus it is not surprising that the nature and properties of the Foreground X have been of considerable interest.

Initially, the anomalous emission was identified as thermal bremsstrahlung from ionized gas correlated with dust (Kogut et al. 1996a) and presumably produced by photoionized cloud rims (McCullough et al. 1999). This idea was subjected to scrutiny in Draine & Lazarian (1997) and criticized on energetic grounds. Additional arguments against the free-free hypothesis became available through correlating anomalous emission with ROSAT X-ray C Band (Finkbeiner & Schlegel 1999) and $\text{H}\alpha$ with 100 μm emission (McCullough et al. 1999). They are summarized in Draine & Lazarian (1999). In a recent preprint de Oliveira-Costa et al. (2000) used Wisconsin H-Alpha Mapper (WHAM) survey data and established that the free-free emission “is about an order of magnitude below Foreground X over the entire range of frequencies and latitudes where is detected”. The authors conclude that the Foreground X cannot be explained as free-free emission.

The spectrum of the Foreground X is not consistent with synchrotron emission, and maps at 408 MHz (Haslam 1981) and 1.42 GHz (Reich & Reich 1988) do not correlate with the observed 15-100 GHz intensity, so the anomalous emission is evidently not synchrotron radiation from relativistic electrons.

2.1. Microwave Emission from Spinning Dust

The surprisingly strong correlation of the Foreground X with 100 μm emission from dust induced Draine & Lazarian (1998a, henceforth DL98a) to conjecture that this radiation can be related to a particular component of dust, namely, ultrasmall grains. The existence of such grains follows from observations by IRAS, COBE-DIRBE and IRTS at wavelength less than 50 μm . For instance, emission from diffuse clouds at 12 and 25 μm (Boulanger & Perault 1988) is

believed to be thermal emission from grains so small that absorption of a single photon can raise the grain temperature to ~ 150 K for the $25 \mu\text{m}$ emission and to ~ 300 K for the $12 \mu\text{m}$ emission. Such grains contain $10^2 - 10^3$ atoms and must be sufficiently numerous to account for $\sim 35\%$ of total absorption of energy from starlight. These grains are usually assumed to be primarily carbonaceous with $\sim 5\% - 10\%$ of the carbon in the interstellar medium (in the model by Desert, Boulanger & Puget 1990 polycyclic aromatic hydrocarbon molecules, PAH, contain 9% of carbon). Li and Draine (2001) show that the observed IR emission can be reproduced by a grain model with $\sim 10\%$ of the carbon in grains with less than 500 c atoms.

How can these ultrasmall grains be responsible for the microwave emissivity? DL98a appealed to rotational emission that must emerge when a grain with a dipole moment μ rotates with angular velocity ω . The corresponding dipole emission is proportional to $\mu^2\omega^4/c^3$ times the number of emitting grains n_g along the line of sight. Thus to estimate emissivity Draine & Lazarian (1997) had to calculate n_g , ω and μ . An important finding of DL98a and Draine & Lazarian (1998b, henceforth DL98b) was that for reasonable parameter values the rotational radiation from ultrasmall grains can account for the observed anomalous emission.

The DL98a model of anomalous emission is often referred to as “emission of spinning charged grains”, which misrepresents the process. In general, centroid of grain charge and centroid of grain inertia do not coincide and indeed, this results in dipole moment μ_{charge} appearance. However, more significant for grains is the intrinsic electric dipole moment μ_{int} . The latter originates naturally as the tiny grains we deal with are essentially large molecules and many of molecules are known to exhibit polarization of atomic bonds and therefore intrinsic dipole moments. Of course, highly symmetric molecules are not expected to have dipole moment. However, under interstellar conditions we do not expect the carbon skeleton for very small grains to be fully hydrogenated (Omont 1986). Detachment of hydrogen atoms under UV flux is expected to render dipole moment to symmetric species, i.e. $\text{C}_{24}\text{H}_{12}$ (coronene).

How many small grains do we expect to observe along a line of sight? While the size distribution of tiny grains is still undetermined, it is quite clear that the number of such grains exceeds the value that one can obtain by extrapolating the power law distribution obtained for much larger grains (see Weingartner & Draine 2000). DL98a considered a lognormal distribution of tiny grains to estimate n_g and by making use of the observed correlation of $100 \mu\text{m}$ emission with 21 cm emission, $I_\nu(100 \mu\text{m}) \approx 0.85 \text{ MJy sr}^{-1} (N_H/10^{20} \text{ cm}^{-2})$ (Boulanger & Perault 1988) inferred the excess microwave emission per H atom for a number of models. Those differed in cosmic carbon abundance in lognormal component, grain shape and intrinsic dipole moment. For the model with the most likely set of parameters, DL98a obtained a reasonable fit with observations available at that time. It is extremely important that new data points obtained later (de Oliveira-Costa et al. 1998, de Oliveira-Costa et al. 1999) correspond to the already published model. The observed flattening of the spectrum and its turnover around 20 GHz agreed well with the spinning dust predictions.

How else can DL98a,b theory be verified? DL98a predicted correlations of Foreground X and diffuse $12 \mu\text{m}$ emission, while in DL98b expected microwave

emissivities for various regions, including reflection nebulae, photodissociation regions and dark clouds, were calculated. Finkbeiner et al. (2000) used the Green Bank 140' telescope to measure 10 GHz emission from IRAS dust filaments. Their results provided only upper limits, while DL98b model predicts 8σ detection. This stimulated de Oliveira-Costa et al. (2000) to infer that the correlation of ultrasmall and large ("classical") dust grain components may not be good at small scales. The authors refer to possible grain separation processes (see Weingartner & Draine 2000) that are likely to act over small scales. We note here that grain coagulation is another process that is likely to be important on small scales within dense clouds and this process can substantially deplete the small grain population. de Oliveira-Costa et al. (2000) tested correlations of Foreground X with 60 μm map and obtained a marginally better correlation than with 100 μm map, which is consistent with DL98a predictions. The authors correctly point out that the crucial test of the spinning dust model will come when higher resolution microwave maps, i.e. those by NASA MAP satellite, become available. It also seems that the Weingartner & Draine (2000) starlight segregation process can be tested by studying correlation of 100 μm emission and Foreground X along and perpendicular to magnetic field lines, which may be determined via optical and infrared polarimetry. Indeed, the starlight segregation of small and large grains should happen along magnetic field lines, while grain electric charge will substantially impede segregation perpendicular to field lines.

The expected relative contribution of various foregrounds on 1 degree scale for intermediate galactic latitudes is shown in Fig. 1. It is easy to see that the foreground signal is minimal at 60-120 GHz.

2.2. Microwave Emission from Magnetic Grains

While the spinning grain hypothesis got recognition in the community, the magnetic dipole emission model suggested by Draine & Lazarian (1999, henceforth DL99) was left essentially unnoticed. This is unfortunate, as magnetic dipole emission provides a possible alternative explanation to the Foreground X. Magnetic dipole emission is negligible at optical and infrared frequencies. However, when the frequency of the oscillating magnetic field approaches the precession frequency of electron spin in the field of its neighbors, i.e. 10 GHz, the magneto dipole emissivity becomes substantial.

How likely is that grains are strongly magnetic? Iron is the fifth most abundant element by mass and it is well known that it resides in dust grains (see Savage & Sembach 1996). If 30% of grain mass is carbonaceous, Fe and Ni contribute approximately 30% of the remaining grain mass. Magnetic inclusions are widely discussed in grain alignment literature (Jones & Spitzer 1967, Mathis 1986, Martin 1995, Goodman & Whittet 1996). If a substantial part of this material is ferromagnetic or ferrimagnetic, the magneto-dipole emission can be comparable to that of spinning grains. Indeed, calculations in DL99 showed that less than 5% of interstellar Fe in the form of metallic grains or inclusions is necessary to account for the Foreground X at 90 GHz, while magnetite, i.e. Fe_3O_4 , can account for a considerable part of the anomalous emissivity over the whole range of frequencies from 10 to 90 GHz. Adjusting the magnetic response of the material, i.e. making it more strongly magnetic than magnetite, but less

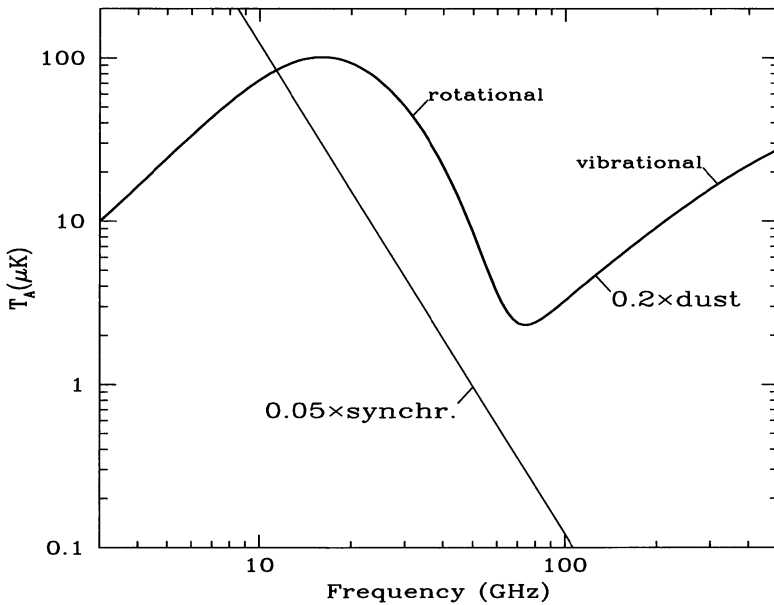


Figure 1. Estimate of rms variations from Galactic foregrounds including rotating grains near North Celestial Pole (from DL98a.). If magneto-dipole emission is responsible for the Foreground X, the plot may be also used to get a crude idea of how much of such emission is expected. Details of magneto-dipole emission are less well constrained due to uncertainties related to magnetic properties of grain material.

magnetic than pure metallic Fe, it is possible to get a good fit for the Foreground X (DL99).

How can magneto-dipole emission be distinguished from that from spinning grains? The most straightforward way is to study microwave emission from regions of different density. The population of small grains is depleted in dark clouds (Leger and Puget 1984) and this should result in a decrease of contribution from spinning grains. Obviously the corresponding measurements are highly desirable. As for now, magnetic grains remain a strong candidate process for producing part or even all of Foreground X.

3. Polarization of Spinning Grain Emission

Microwave emission from spinning grains is expected to be polarized if grains are aligned. Alignment of ultrasmall grains which are essentially large molecules is likely to be different from alignment of large (i.e. $a > 10^{-6}$ cm) grains for which the theory of grain alignment (see review by Lazarian 2000) has been developed.

One of the mechanisms that might produce alignment of the ultrasmall grains is the paramagnetic dissipation mechanism suggested half a century ago by Davis and Greenstein (1951) as a means of explaining the polarization of starlight. The Davis-Greenstein alignment mechanism is straightforward: for a spinning grain the component of interstellar magnetic field perpendicular to the grain angular velocity varies in grain coordinates, resulting in time-dependent magnetization, associated energy dissipation, and a torque acting on the grain. As a result grains tend to rotate with angular momenta parallel to the interstellar magnetic field.

Are the ultrasmall grains paramagnetic? The answer to this question is positive owing to the presence of free radicals, paramagnetic carbon rings (see Alshuler & Kozyrev 1964) and captured ions. For paramagnetic grains, the alignment time-scale $\tau \approx 10^4$ yr $(a/10^{-6} \text{ cm})^2 (10^{-13} \text{ s/K})$ with $K(\omega) \equiv \text{Im}(\chi)/\omega$, where ω is the angular rotational velocity and $\chi(\omega)$ is the magnetic susceptibility. The characteristic time of grain magnetic response is the electron precession time in the field of its neighbors, which is also called spin-spin relaxation time and is denoted τ_2 . If $\omega \leq \tau_2^{-1} \sim 10^8 \text{ s}^{-1}$, normal materials at $T \approx 20$ K have $K \approx 10^{-13} \text{ s}$. For higher frequencies, however, $K(\omega)$ begins to decrease rapidly (DL99). As discussed earlier spinning grains must rotate much faster to account for the Foreground X, thus apparently calling into question the efficacy of alignment by paramagnetic dissipation.

Lazarian & Draine (2000, henceforth LD00) found that the traditional picture of paramagnetic relaxation is incomplete, since it disregards the splitting of energy levels within a rotating body. Unpaired electrons spin parallel and antiparallel to the grain angular velocity have different energies causing the so-called ‘‘Barnett magnetization’’ (Landau & Lifshitz 1960). The Barnett effect, the inverse of the Einstein-De Haas effect, consists of the spontaneous magnetization of a paramagnetic body rotating in field-free space. This effect can be understood in terms of the lattice sharing part of its angular momentum with the spin system. Therefore the implicit assumption in Davis & Greenstein (1951)–that the magnetization within a *rotating grain* in a *static* magnetic field is equiv-

alent to the magnetization within a *stationary grain* in a *rotating* magnetic field – is clearly not exact.

If electrons within a rotating grain are treated as nearly free, the magnetization of the grain is the same for a stationary grain in a “Barnett- equivalent” magnetic field directed along the grain angular velocity ω and having an amplitude $H_{BE} = \hbar\omega/(g\mu_B)$, where g is the electron gyromagnetic ratio ≈ 2 and μ_B is the Bohr magneton. In these conditions the component of magnetic field perpendicular to ω causes electron spin resonance (see Athertson 1973).

LD00 called the process of paramagnetic relaxation within a rotating body “resonance relaxation” as opposed to Davis-Greenstein relaxation that disregards the spontaneous magnetization of a rotating body. Solving the Bloch equations (Bloch 1946) LD00 obtained the following expression for the imaginary part of the grain paramagnetic susceptibility (the part responsible for dissipation and therefore alignment):

$$Im(\chi) = \chi_0 \frac{\omega\tau_2}{1 + \gamma^2 g^2 \tau_1 \tau_2 H_1^2} \quad , \quad (1)$$

where $\gamma \equiv e/2m_e c = 8.8 \times 10^6 \text{ s}^{-1} \text{ G}^{-1}$, τ_1 is the spin-lattice relaxation time, and H_1 is interstellar magnetic field intensity. Unlike the corresponding expression in Davis-Greenstein theory, eq. (1) does not vanish for ω much larger than the spin-spin relaxation time τ_2 . The saturation, however, depends on the value of H_1 and τ_1 . The latter parameter was calculated in LD00 using Raman scattering of phonons, but the calculations are based on the so-called Waller theory, which is known to overestimate τ_1 considerably. Thus laboratory measurements of relaxation within isolated grains are required.

Fig. 2 shows the predictions of the resonance relaxation mechanism for cold interstellar gas assuming that the spin-lattice relaxation is fast. The discontinuity at ~ 20 GHz is due to the assumption that smaller grains are planar, and larger grains are spherical. The microwave emission will be polarized in the plane perpendicular to magnetic field. The dipole rotational emission predicted in DL98a,b is sufficiently strong that polarization of a few percent may interfere with efforts to measure the polarization of the CMB.

Can we check the alignment of ultrasmall grains via infrared polarimetry? The answer to this question is “probably not”. Indeed, as discussed earlier, infrared emission from ultrasmall grains, e.g. $12 \mu\text{m}$ emission, takes place as grains absorb UV photons. These photons raise grain temperature, randomizing grain axes in relation to its angular momentum (see Lazarian & Roberge 1997). Taking values for Barnett relaxation from Lazarian & Draine (1999), we get the randomization time of the 10^{-7} cm grain to be 2×10^{-6} s, which is less than grain cooling time. As the result, the emanating infrared radiation will be polarized very marginally. If, however, Barnett relaxation is suppressed, the randomization time is determined by inelastic relaxation (Lazarian & Efroimsky 1999) and is ~ 0.1 s, which would entail a partial polarization of infrared emission.

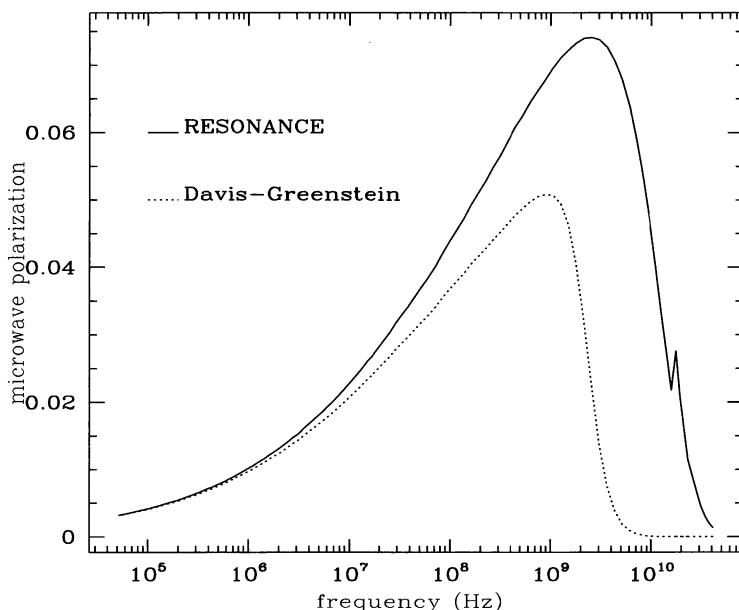


Figure 2. Measure of grain alignment for both resonance relaxation and Davis-Greenstein relaxation for grains in the cold interstellar medium as a function of frequency (from LD00). For resonance relaxation the saturation effects (see eq. (1)) are neglected, which means that the upper curves correspond to the *maximal* values allowed by the paramagnetic mechanism.

4. Polarization of Magneto-Dipole Emission

The mechanisms of producing polarized magneto-dipole emission is similar to that producing polarization of electro-dipole thermal emission emitted from aligned non-spherical grains (see Hildebrand 1988). There are two significant differences, however. First, strongly magnetic grains can contain just a single magnetic domain. Further magnetization along the axis of this domain is not possible and therefore the magnetic permeability of the grains gets anisotropic: $\mu = 1$ along the domain axis, and $\mu = \mu_{\perp}$ for a perpendicular direction. Second, even if a grain contains tiny magnetic inclusions and can be characterized by isotropic permeability, polarization that it produces is orthogonal to the electro-dipole radiation emanating through electro-dipole vibrational emission. In case of the electro-dipole emission, the longer grain axis defines the vector of the electric field, while it defines the vector of the magnetic field in case of magneto-dipole emission.

The results of calculations for single domain iron particle (longer axis coincides with the domain axis) and a grain with metallic Fe inclusions are shown in Fig. 3. Grains are approximated by ellipsoids $a_1 < a_2 < a_3$ with \mathbf{a}_1 perfectly aligned parallel to the interstellar magnetic field \mathbf{B} . The polarization is taken to be positive when the electric vector of emitted radiation is perpendicular to \mathbf{B} ; the latter is the case for electro-dipole radiation of aligned grains. This is also true (see Fig. 3) for high frequency radiation from single dipole grains. It is easy to see why this happens. For high frequencies $|\mu_{\perp} - 1|^2 \ll 1$ and grain

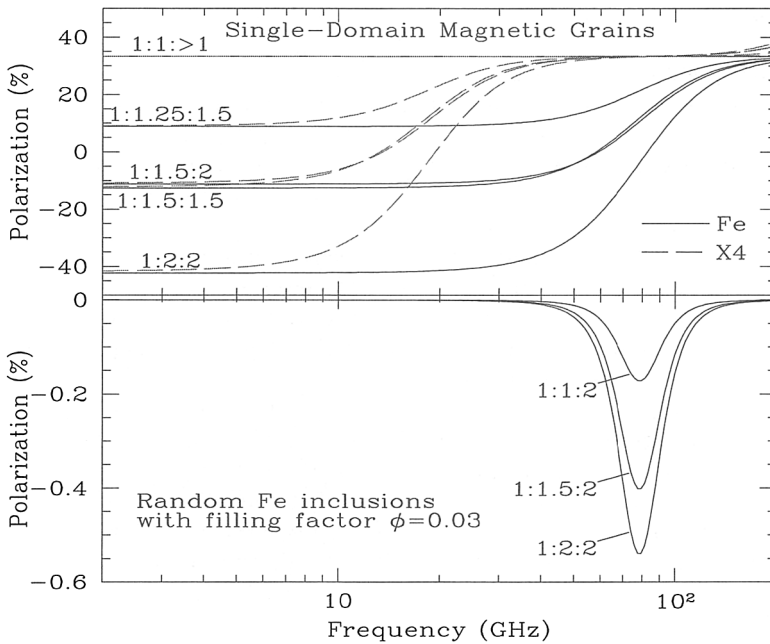


Figure 3. Polarization from magnetic grains (from DL99). Upper panel: Polarization of thermal emission from perfectly aligned single domain grains of metallic Fe (solid lines) or hypothetical magnetic material that can account for the Foreground X (broken lines). Lower panel: Polarization from perfectly aligned grains with Fe inclusions (filling factor is 0.03). Grains are ellipsoidal and the result are shown for various axial ratios.

shape factors are unimportant. The only important thing is that the magnetic fluctuations happen perpendicular to \mathbf{a}_1 . With \mathbf{a}_1 parallel to \mathbf{B} , the electric fluctuations tend to be perpendicular to \mathbf{B} which explains the polarization of single domain grain being positive. For lower frequencies magnetic fluctuations tend to happen parallel to the intermediate size axis \mathbf{a}_2 . As the grain rotates about $\mathbf{a}_1 \parallel \mathbf{B}$, the intensity in a given direction reaches maximum when an observer sees the $\mathbf{a}_1 \mathbf{a}_2$ grain cross section. Applying earlier arguments it is easy to see that magnetic fluctuations are parallel to \mathbf{a}_2 and therefore for sufficiently large a_2/a_1 ratio the polarization is negative. *The variation of the polarization direction with frequency presents the characteristic signature of magneto-dipole emission from aligned single-dipole grains and it can be used to separate this component from the CMB signal.* Note that the degree of polarization is large, and such grains may substantially interfere with the attempts of CMB polarimetry. Even if the intensity of magneto-dipole emission is subdominant to that from rotating grains, it can still be quite important in terms of polarization. A relatively weak polarization response is expected for grains with magnetic inclusions (see Fig. 3). The resulting emission is negative as magnetic fluctuations are stronger along longer grain axes, while the short axis is aligned with \mathbf{B} .

5. Summary

The principal points discussed above are as follows:

Dust emission in the microwave range is stronger than it was thought to be. Ultrasmall grains, whose existence is required to explain $\lambda < 50\mu\text{m}$ emission, should also produce microwave emission as they rotate rapidly. Moreover, magnetic fluctuations within large interstellar grains constitute another important source of microwave dust emissivity.

Both dipole rotational emission from ultrasmall grains and magneto-dipole emission may explain the 10-100 GHz anomalous emission correlated with interstellar dust. At the moment, rotating grains seem to be more favored candidates to account for the anomalous emission, but further tests that include measurements from e.g. dark globules are necessary.

Microwave emission of both origins is expected to be partially polarized. "Resonance paramagnetic relaxation" is the process that can enable alignment and therefore polarization from ultrasmall grains. Although the details of the process still require laboratory testing, it looks that the polarization is marginal beyond 40 GHz. On the contrary, magneto-dipole emission may be substantially polarized for higher frequencies. Thus it can be important in terms of polarization even if it is subdominant in terms of total emissivity.

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