ELECTRIC DIPOLE RADIATION FROM SMALL SPINNING DUST GRAINS

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Abstract

The electric dipole radiation from spinning dust grains is a promising candidate for the "anomalous" dust-correlated foreground discovered recently. In this study, the results of the major theoretical papers on the subject, Draine & Lazarian (1998 a and b) (DL98) are confirmed, and coded in a set of IDL routines to be released publicly. Some modifications to DL98 are made to compute the spinning dust emissivity. Updated photoelectric emission rates from Weingartner & Draine (2001) are used to compute the grains charge distribution functions. The full grain angular velocity distribution function is derived to improve the Maxwellian approximation.

The released IDL routines should be a useful tool to model the spectra of Galactic observations as well as for foreground modelling in CMB studies around $10 - 70$ GHz. The emission from spinning dust grains also provides a new window into the complex non-equilibrium physics of the interstellar medium.

1. Introduction

One major concern in CMB analysis is the subtraction of the contaminating foregrounds. These may be unresolved point sources or diffuse galactic emission, which includes synchrotron, free-free, and thermal dust emission. In recent studies of the Galactic emission, Leitch et. al. (1997) and Kogut et. al. (1996) have found a new foreground around $10 - 100$ GHz which is strongly correlated with the far infrared emission from dust. This "anomalous" foreground is not explained by standard emission processes. Draine & Lazarian (1998 a and b) (DL98 hereafter) suggested that it is caused by the electric dipole emission from spinning dust grains.

In this study the results of DL98 have been rederived and refined. In the next section the general ideas of spinning dust physics are given, along with a discussion of the full angular velocity distribution function. In section 3 the rates for rotational damping and excitation of grains are given. They strongly depend on the grain charge distribution function, which is discussed in section 4, and for which updated photoelectric emission rates from Weingartner & Draine 2001 (WD01 hereafter) are used. The spinning dust emissivity is coded in a set of IDL routines, which are made publicly available for further research at Caltech. The results are discussed in sections 5 and 6.

2. Overview of the emissivity of spinning dust grains.

The average power radiated by a grain of dipole moment μ spinning at frequency ω (assuming uncorrelated orientation of the dipole moment and the spin axis) is

$$P = \frac{4}{9}\frac{< \mu^2 >_a \omega^4}{c^3}$$

If one knows the *angular velocity distribution function* of dust grains, for every grain radius a, $f_a(\omega)$, the average dipole moment of the grains as a function of their radius $< \mu^2 >_a$, and the *size distribution* of dust grains $\frac{1}{n_H}\frac{dn}{da}$, one gets the emissivity of spinning dust grains per H atom ($\omega = 2\pi\nu$):

$$\frac{j_\nu}{n_H} = \frac{1}{4\pi}\int da\, \frac{1}{n_H}\frac{dn}{da}\, 2\pi f_a(\omega)\, \frac{4}{9}\frac{< \mu^2 >_a \omega^4}{c^3}$$

- **Grain size distribution function** $\frac{1}{n_H}\frac{dn}{da}$

The grain-size distribution is assumed to be the MRN distribution (Mathis, Rumpl & Nordsieck 1977) for graphitic grains, to which is added a log-normal component normalized so that it contains a fraction f_c (around 5%) of the total carbon abundance. It extends down to $a_{min} = 3.6$ Å:

$$\frac{1}{n_H}\frac{dn}{da} = A_{MRN}a^{-3.5} + Ba^{-1}\exp\left(-\frac{1}{2}(\frac{\ln(a/a_0)}{\sigma})^2\right)$$

The standard parameters are $A_{MRN} = 10^{-25.16}\mathrm{cm}^{2.5}$, $a_0 = 3$ Å and $\sigma = 0.5$. The log-normal component accounts for small carbonaceous grains in the form of Polycyclic Aromatic Hydrocarbons (PAHs).

• **Dipole moment** $<\mu^2>_a$

The grains are assumed to have an intrinsic dipole moment $\mu_i = N_a^{1/2}\beta$, where N_a is the number of atoms in the grain In addition, charged grains may have an additional dipole moment due to the displacement of the charge centroid relative to the mass centroid, assumed to be ϵa. The mean square dipole moment per grain will be

$$<\mu^2>_a = N_a\beta^2 + \epsilon^2 a^2 <Z^2> e^2$$

It is assumed that 25% of the grains have $\beta = 0.5\beta_0$, 50% have $\beta = \beta_0$ and 25% have $\beta = 2\beta_0$, where $\beta_0 = 0.4$ debye. For computed grain charges, it appears that the intrinsic dipole moment dominates.

• **Angular velocity distribution function** $f_a(\omega)$

This section has been inspired by Chris Hirata. The probability distribution function of grain angular velocities $P(\vec{\omega}, t)$ evolves because of damping mechanisms and random fluctuations according to the Fokker-Planck equation :

$$\frac{\partial P(\vec{\omega})}{\partial t} = \vec{\nabla}.(\vec{D}(\vec{\omega})P(\vec{\omega})) + \frac{1}{2}\frac{\partial^2}{\partial\omega_i\partial\omega_j}(E_{ij}(\vec{\omega})P(\vec{\omega}))$$

$$\delta\vec{\omega}|_{damping} = -\vec{D}(\vec{\omega})\delta t$$

$$(\delta\omega_i\delta\omega_j)|_{excitation} = E_{ij}(\vec{\omega})\delta t$$

We specify to the case where all damping processes merely decrease the magnitude of $\vec{\omega}$ but do not change its direction, and are isotropic, $\vec{D}(\vec{\omega}) = d(\omega)\vec{\omega}$. We further assume that the components of ω are excited in an uncorrelated manner, i.e. $\delta\omega_i\delta\omega_j = E_{ij}\delta t = 0$ for $i \neq j$, and that the fluctuations are isotropic, i.e. $E_{xx} = E_{yy} = E_{zz} \equiv 1/3E(\omega) = 1/3(\delta\omega)^2/\delta t$. Both $d(\omega)$ and $E(\omega)$ will be *even functions* as they depend only on ω^2. We develop $d(\omega)$ and $E(\omega)$ in Taylor series in $\omega = 0$.

DL98 implicitly assume that one can truncate the damping rate at the second order, $d(\omega) = \alpha + \beta\omega^2$ and keep only the zero order term in the fluctuation rate, $E(\omega) = E(0) \equiv E$

Assuming a steady state, we are left with an easily solvable first order differential equation :

$$(\alpha\omega + \beta\omega^3)P + \frac{1}{6}E\frac{dP}{d\omega} = 0$$

$$\text{i.e.}\quad P(\omega) = P_0\exp\left(-\frac{3\alpha}{E}\omega^2 - \frac{3\beta}{2E}\omega^4\right)$$

Note that this is a Maxwellian distribution only if β vanishes. Note also that, using previous section notation, $f_a(\omega) = 4\pi\omega^2P(\omega)$.

3. Rotational damping and excitation of grains

We need to compute the damping and excitation rates as functions of the medium conditions. The angular momentum of a grain of radius a and moment of inertia I might change due to collisions with neutrals or ions, plasma drag (interaction of the grain dipole moment with the electric field of passing ions), infrared emission, and electric dipole emission. Both damping and excitation processes are normalized to the values they would have for a pure neutral, non polarizable Hydrogen gas. The resulting coefficients take the following form :

$$\alpha = \frac{F}{\tau_H} \quad , \quad \beta = \frac{I}{3\ k\ T\tau_{ed}} = \frac{4\mu^2}{9Ic^3} \quad , \quad E = \frac{6kT}{I\tau_H}G$$

$$\text{where}\quad \tau_H^{-1} = n_H\left(\frac{8kT}{\pi m_H}\right)^{1/2}\frac{2\pi a^4 m_H}{3I}$$

is the rotational damping rate for pure H collisions, and

$$\tau_{ed} = \frac{3I^2c^3}{4<\mu^2>kT}$$

$$F = F_n + F_i + F_p + F_{IR}$$

$$G = G_n + G_i + G_p + G_{IR}$$

The various F_j and G_j are complicated functions that are derived in DL98, and which depend on the neutrals and ions number density, mass, charge, polarizability, on the ambient starlight intensity and spectrum (taken to be a multiple χ of the Average Interstellar Radiation Field as given by Mezger, Mathis & Panagia (1982)), on the grain and gas temperature, and on the **grain charge distribution function**, which we discuss in the next section.

The resulting angular momentum distribution function is :

$$f_a(\omega) \propto \omega^2 \exp\big[-\frac{F}{G}\frac{I\omega^2}{2kT} - \frac{\tau_H}{3G\tau_{ed}}\big(\frac{I\omega^2}{2kT}\big)^2\big]$$

This is a Maxwellian only if $\tau_{ed} = \infty$, i.e. in the case where electric dipole damping is negligible. As one can see in Fig.1, the distribution departs quite significantly from a Maxwellian at small grain radii. Moreover, the grains *do not rotate thermally*, as in general $F \neq G$. This is due to the the non-equilibrium state of the ISM.

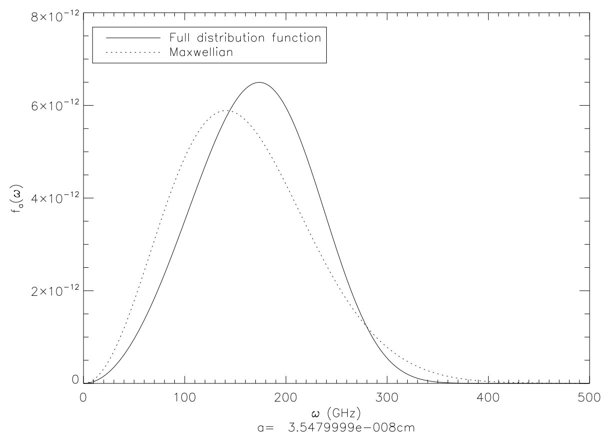

Fig. 1.— Angular velocity distribution function for Cold Neutral Medium conditions, radius $a = 3.5$ Å

4. Grain charge distribution function

Grain charging occurs through three main processes: sticking collisions with electrons, with rate $J_e(Z)$, collisions with positive ions (as we assume the colliding species always leave the grain surface as neutrals), with rate $J_i(Z)$ and photoelectric emission of electrons, which rate $J_{pe}(Z)$ is highly uncertain. We used WD01 model for the later, which gives us noticeable differences in the charge distribution functions with the ones computed in DL98. The collisional charging rates we use are those of Draine & Sutin (1987), with sticking coefficients for electrons of WD01. From these rates, the charge distribution function is computed recursively from the steady-state condition (note that it has to be computed *for each grain radius*):

$$\big[J_i(Z) + J_{pe}(Z)\big] f(Z) = J_e(Z+1) f(Z+1)$$

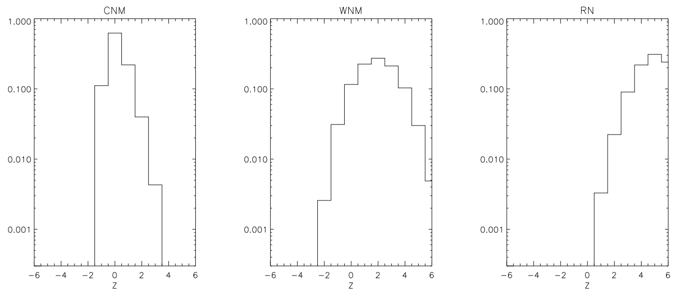

Fig. 2.— Charge distribution functions for Cold Neutral Medium, Warm Neutral Medium, and Reflection Nebula conditions, radius $a = 20$ Å

5. Resulting emissivities and observation project

The described model was coded in IDL and used to compute the electric dipole radiation in several environments, some of which are shown in Table 1. The resulting emissivity for Cold Neutral Medium conditions is shown in Fig. 3. Even when using the Maxwellian approximation for angular velocity distribution, there is a noticeable difference at high frequencies from the results of DL98. This is very likely due to a difference in the computed charge distribution functions, as the model used by these authors for the photoemission rate is an older, unpublished version that the one used in this project (and could unfortunately not be obtained from the authors).

This theoretical project was complemented by three weeks at the *Cosmic Background Imager* (CBI) in Chile. The purpose was to observe unresolved galaxies and planetary nebulae selected

phase	CNM	WNM	WIM	RN
$n_H(cm^{-3})$	30	0.4	0.1	10^3
$T(K)$	100.	6000.	8000.	100.
$T_d(K)$	20.	20.	20.	40.
χ(starlight)	1.	1.	1.	1000.
$x_H \equiv n(H^+)/n_H$	0.0012	0.1	0.99	0.001
$x_M \equiv n(M^+)/n_H$	0.0003	0.0003	0.001	0.0002

Table 1: Some idealized phases for interstellar matter.

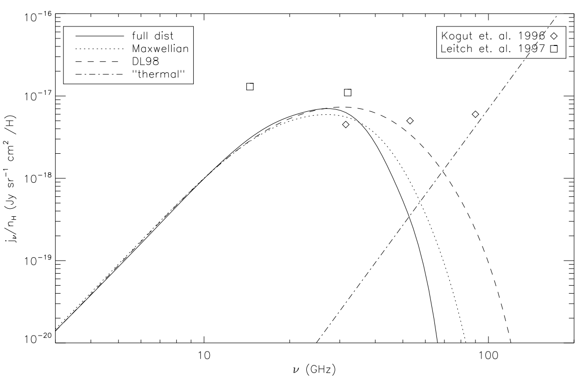

Fig. 3.— Electric dipole emission per H atom from spinning dust, Cold Neutral Medium conditions. "Thermal" emission for grains with $a \gtrsim 100$ Å is included, with absorption cross section $\propto \nu^{1.7}$

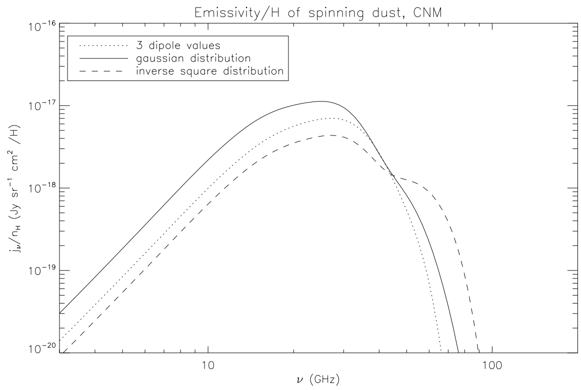

Fig. 4.— Emissivities resulting from peculiar dipole moment distributions.

from the WMAP point source catalog (5 bands at 23, 33, 41, 61 and 94 GHz) for hinting at spinning dust emission. CBI indeed observes at 30 GHz, which corresponds to the peak emissivity of spinning dust. Unfortunately, the instrument suffered motor problems which impeded any observation during this period. But we expect to observe a few promising targets by the end of the year.

6. Review of assumptions and conclusive remarks

The described model comprises a lot of parameters, which make the predicted emissivities quite uncertain, among which :

- The grain charge distribution function is quite uncertain, in particular because of the uncertainty in the photoemission rate.
- The grain size distribution function is poorly known. The abundance of small grains may well vary by a factor as big as 5, which would vary the electric dipole emissivity by the same factor.
- The electric dipole moments of grains are probably more complex than modelled here. A full distribution of dipole moments would be needed to be accurate, which might well broaden, or change significantly the shape of the emissivity. The effect of peculiar dipole distribution functions is shown in Fig. 4. A different size dependence to the one used here ($< \mu^2 > \propto a^3$) is also to be investigated, along with the underlying physics.

Several observations have already confirmed DL98 models, as for example the dark cloud LDN1622 observed by CBI (Casassus et. al. (2006)). Some regions, however, show an excess over free-free emission that is not well fitted by these models (see e.g. Cassassus et. al. (2007)). Tweaking the various parameters with the written IDL routines does not seem to allow for recovering the observed emissivities, unless maybe extreme dipole distributions are used. However, the parameter space is wide and numerical investigation remains to be done.

An important aspect that remains to be investigated further would be the polarization of such an emission, in the case of the presence of a magnetic field that causes the partial alignment of grains rotation axis. However, the observed polarization of this foreground seems to be weak.

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