Microwave Emission from Galactic Dust Grains

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Abstract. Observations of the cosmic microwave background have revealed a component of 10–60 GHz emission from the Galaxy which correlates with 100–140 µm emission from interstellar dust but has an intensity much greater than expected for the low-frequency tail of the “electric dipole vibrational” emission peaking at ∼130 µm. This “anomalous emission” is more than can be accounted for by dust-correlated free-free emission. The anomalous emission could be due in part to magnetic dipole emission from thermal fluctuations of the magnetization within interstellar dust grains, but only if a substantial fraction of the Fe in interstellar dust resides in magnetic materials such as metallic iron or magnetite. The observed anomalous emission is probably due primarily to electric dipole radiation from spinning ultrasmall interstellar dust grains. This rotational emission is expected to be partially polarized.

1. Introduction

Microwave emission from interstellar dust grains contributes a “galactic foreground” which must be recognized and subtracted from observations of the sky in order to carry out studies of angular structure in the cosmic microwave background radiation (CMBR). This microwave emission also offers us new information on the properties of interstellar dust grains.

In §2 we review the observational evidence for infrared and microwave emission from interstellar dust. There are several sources of “galactic foreground” emission at microwave frequencies: relativistic electrons (synchrotron emission), thermal electrons (free-free emission), and dust grains. Microwave emission from dust grains was discovered by studies of the CMBR, which revealed a surprisingly strong component of the microwave sky brightness which was correlated with interstellar matter, as traced by 100 µm thermal dust emission. Because this dust-correlated signal was much stronger than expected from existing models of interstellar dust, it has been referred to as “anomalous” emission (Leitch et al. 1997; Kogut 1999).

The spectrum of the “anomalous” microwave emission 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 (Kogut et al. 1996a,b; Leitch et al. 1997; de Oliveira-Costa et al. 1997, 1998), so the anomalous emission is evidently not synchrotron radiation from relativistic electrons. In section 3 we conclude that the observed emission significantly exceeds the free-free emission from interstellar plasma. The excess emission must be due to dust.

There are three quite distinct mechanisms whereby dust can radiate at microwave frequencies; they can be classified as (1) “vibrational electric dipole” emission (due to thermal fluctuations in the charge distribution in the grain); (2) “magnetic dipole” emission (due to thermal fluctuations in the magnetization of grain material); and (3) “rotational electric dipole” emission (due to the rotating electric dipole moment of a spinning grain).

Most of the power radiated by interstellar dust is due to “vibrational electric dipole” emission, peaking in the far-infrared at $\sim 100\mu m$. The low-frequency “tail” of this emission can be extrapolated to microwave frequencies, but falls far below the observed 10–60 GHz emission. However, as discussed in §4, if grains contain magnetic materials – such as magnetite or metallic iron – the thermal fluctuations in the magnetization will result in strong magnetic dipole emission.

There is strong independent evidence for a large population of ultrasmall grains. These grains should be spinning rapidly, should have electric dipole moments, and therefore should radiate at microwave frequencies, as discussed in §5. The expected spatial variations of the microwave emission from dust are discussed in §6. The possibility that this radiation can be polarized is discussed in §7, and observational tests are considered in §8. We summarize in §9.

2. Observations

Figure 1 shows the observed emission spectrum of diffuse interstellar dust, based on measurements by the InfraRed Astronomy Satellite (IRAS), the FIRAS spectrometer and the DIRBE photometers on the COSmic Background Explorer (COBE), and the Mid-IR Spectrometer (MIRS) and the Near-IR Spectrometer (NIRS) on the InfraRed Telescope in Space (IRTS).

2.1. Far-Infrared Emission

The emission from interstellar matter between 1 mm (300 GHz) and 100µm (3000 GHz) is due primarily to thermal emission from dust particles heated by diffuse starlight to temperatures $T_d \approx 15 - 25K$, as was expected theoretically (see, e.g., Draine & Lee 1984).

While the observed spectrum between 1 mm and 100µm can be accurately described by multicomponent fits (Wright et al. 1991; Reach et al. 1995; Finkbeiner & Schlegel 1999; Finkbeiner, Schlegel, & Davis 1999) the observed 1 mm – 100µm emission, with $\nu j_{\nu}$ peaking at $\lambda_p \approx 130\mu m$, can be approximated quite well by emission from dust with absorption cross section $\propto \nu^\beta$ and a single temperature $T_d \approx h\nu/(4 + \beta)\lambda_p k$.

Away from molecular regions, the 100µm emission correlates very well with 21 cm emission (Boulanger & Pérault 1988), allowing us to infer the average
Figure 1. Infrared emissivity per H, based on data from IRAS (crosses; Boulanger & Perault 1988), COBE-FIRAS (Wright et al. 1991); COBE-DIRBE (diamonds: Arendt et al. 1998); and IRTS (heavy curve: Onaka et al. 1996, Tanaka et al. 1996). An assumed stellar continuum has been subtracted from the IRTS spectra. The dotted line is to guide the eye. The IRTS spectra show emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 µm.
emissivity per H nucleon (Draine 1999):

$$\nu j_\nu = \lambda j_\lambda \approx 2.3 \times 10^{-25} \left( \frac{130 \mu m}{\lambda} \right)^{4+\beta} \left[ \frac{\exp(4+\beta) - 1}{\exp(h\nu/kT_d) - 1} \right] \text{erg s}^{-1}\text{sr}^{-1}\text{H}^{-1}$$  \hspace{1cm} (1)

where a good fit is obtained for $T_d = 19.5K$ and $\beta = 1.7$. This choice of $\beta$ and $T_d$ corresponds to an absorption cross section per H nucleon

$$\frac{\tau_\nu}{N_H} = 2.5 \times 10^{-25} \left( \frac{100 \mu m}{\lambda} \right)^{1.7} \text{cm}^2\text{H}^{-1}.$$  \hspace{1cm} (2)

Figure 1 shows this and other single-temperature fits together with observational determinations of the dust emission spectrum.

### 2.2. Mid-IR Emission

A striking feature of Figure 1 is the strong emission at $\lambda < 50 \mu m$ observed by IRAS, COBE-DIRBE, and IRTS. This emission, accounting for $\sim 35\%$ of the total power radiated by dust, is far in excess of what would be expected from dust grains at $T \approx 20K$. The only natural explanation for this is to attribute it to dust grains which are so small that absorption of a single starlight photon heats them to temperatures high enough for thermal emission to produce the observed radiation (Draine & Anderson 1985). Grain temperatures as high as $\sim 200K$ are required to account for the emission observed in the 12$\mu$m band, so the grains must be very small: if the specific heat is characterized by a Debye temperature $\Theta = 420K$ (the value for graphite; Furukawa et al. 1972), then a 6 eV starlight photon could heat a grain with $N \approx 280$ atoms to $T = 200K$.

Even smaller particles are required by the strong emission observed at shorter wavelengths (see Figure 1). The population of small particles must be very large, since they must account for $\sim 35\%$ of the total absorption of energy from starlight!

### 2.3. Extrapolation to Lower Frequencies

Since eq. (1) fits the 1 mm – 100$\mu$m emission so well, it is natural to extrapolate it to lower frequencies. A good single-temperature fit is for $\beta \approx 1.7$, close to the value $\beta = 2$ predicted by simple models for the response of dielectrics at frequencies below all the optically-active resonances as well as simple models of conductive materials (Draine & Lee 1984).

In Figure 2 we show the prediction for $\beta = 1.7$ and three other values of $\beta$. Note that the $\beta = 1$ extrapolation overestimates the emission for 2000 $>$ $\lambda$ $>$ 300$\mu$m (see Fig. 1), and is included in Figure 2 only as an extreme example.

Figure 2 also shows the observed dust-correlated emissivity $j_\nu$ per H nucleon deduced for diffuse interstellar matter by cross-correlating the measured microwave sky brightness $I_\nu$ with an FIR sky map (either DIRBE 140$\mu$m or IRAS 100$\mu$m). The best-fit slope $\Delta I_\nu/\Delta I_\nu$(FIR) reported by different experiments is then converted to an emissivity per H nucleon using the 140$\mu$m or 100$\mu$m emissivity from eq. (1).

Equation (1) is appropriate only for dust in diffuse regions. The procedure used here will tend to overestimate the emissivity $j_\nu = I_\nu/N_H$ when the
Figure 2. Emissivity per H at $\nu < 200\text{GHz}$, together with prediction of eq. (1) for various choices of $\beta$. "Observed" emissivities shown here and in following figures are based on observations of microwave emission correlated with 100–140$\mu$m emission. In regions with cooler dust, the emissivity shown here will overestimate the actual emissivity (see text); this might explain the relatively high emissivities obtained from the observations of Leitch et al. and Lim et al. The dust-correlated H$\alpha$ emission (see §3.) has been used to estimate the dust-correlated free-free emission; the shaded region corresponds to the uncertainties given in eq. (3). The observed emission at $\nu < 60\text{ GHz}$ substantially exceeds both the dust-correlated free-free emission and the predicted thermal emission from dust with $\beta \approx 1.7$. 

$\nu$: Frequency (GHz)
observations include regions (e.g., non-star-forming molecular clouds) where the
dust is somewhat cooler than in diffuse HI clouds. The cooler dust will have a
lower FIR emissivity, and hence $N_H$ will actually be larger than deduced from
$L_v$(FIR) using eq. (1). This might explain the relatively high emissivities shown
in Fig. 1 obtained from the observations of Leitch et al. (1997), as the fields
observed by these experiments could contain significant amounts of molecular
gas (Finkbeiner, private communication).

The much larger fields observed by Kogut et al. (1996b) and de Oliveira-
Costa et al. (1997,1998) are expected to be dominated by diffuse atomic gas,
so the emissivities deduced from these experiments are probably more accurate.
Better estimates of emissivities $j_\nu = I_\nu/N_H$ could be obtained if the H col-
umn density $N_H$ is estimated using the maps of dust optical depth produced by
Schlegel et al. (1998), who used the DIRBE 100 and 240\(\mu\)m maps to allow for
dust temperature variations.

The observed dust-correlated microwave emissivities at $\nu < 60$ GHz tend to
be well above the extrapolation to low frequencies with the “best fit” $\beta \approx 1.7$.
For this reason the dust-correlated microwave emission has been referred to as
“anomalous” (Leitch et al. 1997).

3. Free-Free Emission?

Since the observed dust-correlated emission at $\nu < 60$GHz is so much greater
than expected from simple extrapolation of the dust spectrum from far-infrared
and sub-mm wavelengths, we must consider what other mechanisms could be
responsible. Kogut et al. (1996a) suggested that the observed 30–50 GHz excess
was due to free-free emission from ionized gas which was correlated with dust.
However, Leitch et al. (1997) measured the dust-correlated 14.5 and 32 GHz
emission from 36 fields around the North Celestial Pole, and showed that for
these fields the “anomalous emission” could not be free-free emission from gas
at $T_{\text{gas}} \leq 10^4$K, as the recombination radiation which must accompany free-free
emission is not present on H\(\alpha\) maps (Gaustad et al. 1996).

Leitch et al. noted that if the anomalous emission in this region were in-
stead free-free radiation from plasma with $T_{\text{gas}} > 10^6$K, the predicted H\(\alpha\) would
be consistent with existing limits. However, Finkbeiner & Schlegel (1999) have
recently reported a negative correlation between the Leitch et al. 14.5 GHz mea-
surements and emission in the ROSAT X-ray C Band, so it is not clear that hot
gas can explain the anomalous emission in the Leitch et al. fields.

McCullough et al. (1999) review H\(\alpha\) observations and the contribution of
free-free emission to the Galactic microwave foreground. Observing programs
now underway will soon provide a much better knowledge of the H\(\alpha\) sky, but
existing studies of the correlation between H\(\alpha\) emission and dust 100\(\mu\)m emission
(McCullough 1997; Kogut 1997) over limited regions find a dust-correlated H\(\alpha\)
component with

$$\frac{I(\text{H}\alpha)}{I_{100}} \approx (0.65 \pm 0.30) \frac{\text{Rayleigh MJy sr}^{-1}}{\text{MJy sr}^{-1}}.$$  \hfill (3)

This correlation is found when averaging on angular scales of a few degrees
(McCullough et al. 1999). The dust-correlated H\(\alpha\) presumably originates mainly
from photoionized cloud rims, but approximately 25% of the high latitude H\(\alpha\)
is estimated to be scattered light (Jura 1979; McCullough 1997). Thus we take
the Hα emission correlated with dust to be 75% of eq. (3):

\[ \frac{I(\text{H}\alpha \text{em})}{I_{100}} \approx (0.49 \pm 0.23) \text{Rayleigh MJy sr}^{-1}. \]  (4)

In Figure 2 we show the dust-correlated free-free emissivity which would accompany the dust-correlated Hα emission from eq. (4), assuming \( T_{\text{gas}} \approx 8000\text{K}. \) Figure 2 shows that the observed dust-correlated 10-60 GHz emission is systematically well above the level expected for free-free emission from \( \sim 10^4\text{K} \) gas. An additional source of emission is required.

Hot gas cannot explain the emission observed over large fields by Kogut et al. (1996) and de Oliveira-Costa et al. (1997, 1998), since the resulting X-ray power would exceed the estimated rate of energy input from supernovae by a factor \( \sim 10^2 \) (Draine & Lazarian 1998a, hereafter DL98a).

Since synchrotron radiation has been ruled out, dust appears to be the only possible source of the excess emission. Since the predicted “vibrational electric dipole” emission has been seen above to be insufficient, one or more additional dust emission mechanisms must be important at microwave frequencies.

4. Magnetic Dipole Emission? Possibly.

Magnetic dipole emission is marginal at optical and infrared frequencies (\( \nu > 10^{12} \text{Hz} \)) but gets quite appreciable as the frequency of oscillating magnetic field approaches the precession frequency of an electron spin in the magnetic field of its neighbors, which is \( \sim 10^{10} \text{Hz} \). The magneto-dipole microwave emissivity is enhanced if the grain material is strongly magnetic, e.g. ferro- or ferrimagnetic.

Iron is the fifth most abundant element by mass (after H, He, O, and C), and it is well known from absorption line studies that interstellar gas-phase Fe is heavily “depleted”, with most of the Fe locked up in dust grains (see the review by Savage & Sembach 1996). If \( \sim 30\% \) of the grain mass is carbonaceous, Fe and Ni contribute \( \sim 30\% \) of the mass of the remaining grain material.

The chemical form in which the solid-phase Fe resides is not yet known, but some fraction might be in strongly magnetic materials, such as metallic Fe or magnetite (Fe₃O₄). Draine & Lazarian (1999, hereafter DL99) discuss emission and absorption of radiation by grains containing magnetic materials, and show that magnetic dipole emission due to thermal fluctuations in the magnetization can dominate the thermal emission at microwave frequencies.

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1McCullough et al. argue that the observational uncertainties are still large enough that one cannot conclusively reject the hypothesis that the observed microwave excess is due to free-free emission from \( \sim 10^4\text{K} \) gas, but we feel that the evidence for an additional source of dust-correlated microwave emission – as seen in Fig. 2 – is very strong. See also Kogut (1999).

2Another way to see that the magnetic response of ferromagnetic materials will dominate in the microwave range is through the Kramers-Kronig relations. If the zero frequency magnetic and electric susceptibilities of a material are comparable while the high frequency magnetic response is negligible, the Kramers-Kronig relations require that the magneto-dipole adsorption should dominate at low frequencies (see DL99).
“Ordinary” paramagnetism will result in more emission at $\nu < 35\,\text{GHz}$ than predicted by eq. (1), but still far less than observed. In order for magnetic dipole emission to reach intensities comparable to those observed, it is necessary for a substantial fraction of interstellar Fe to be in ferromagnetic (e.g., metallic Fe) or ferrimagnetic (e.g., magnetite Fe$_3$O$_4$) materials. Figure 3 shows that if 100% of the Fe is in magnetite, the magnetic dipole emission would approach that observed; if as little as 5% of the Fe is in pure metallic form – either as bare single-domain particles, or single-domain inclusions within larger paramagnetic grains), the magnetic dipole emission will peak at $\sim 90\,\text{GHz}$, as the result of a magnetic dipole “Föhrlich resonance” (DL99). Existing observations show no evidence for such an emission feature, so DL99 conclude that not more than $\sim 5\%$ of the interstellar Fe can be in (pure) metallic iron.
Figure 4. Thermal magnetic dipole emission from hypothetical magnetic grain material.

On the other hand, the Fe could be in some impure metallic form which is more strongly magnetic than magnetite, but less magnetic than pure Fe metal. If we allow ourselves the freedom to “tune” the frequency-dependent magnetic susceptibility, DL99 show that there are parameter combinations which come close to reproducing the observed emission; an example of such a “designer” material is shown in Figure 4. The magneto-dipole contribution to the “anomalous” emission can be established via observations (see §8).

5. Emission from Spinning Ultrasmall Dust Grains? Yes!

The possibility of rotational emission from dust grains was apparently first discussed by Erickson (1957). However, as the rotational emission is proportional to the fourth power of the angular velocity, only extremely small grains rotate
sufficiently rapidly to produce appreciable emission. As the evidence for such grains did not exist at the time, the idea was not pursued. More recently, after the discovery of the population of ultrasmall grains, Ferrara & Dettmar (1994) noted that the rotational emission from these grains could be observable, and DL98a proposed that the observed “anomalous” emission was just the expected rotational emission from the population of ultrasmall grains.

The rotational dynamics of dust grains, and resulting rotational emission, are discussed by Draine & Lazarian (1998b; herafter DL98b). To predict expected levels of microwave emissivity DL98b had to estimate the distribution of ultrasmall grains, their rates of rotation and their dipole moment. An important finding of DL98b is that for reasonable parameter values the rotational radiation from ultrasmall grains can account for the observed anomalous emission.
For a population of small grains containing 5% of the cosmic carbon abundance (with 3% of the cosmic carbon abundance in grains with radii \( a < 6 \text{Å}, \) or \( N < 120 \text{C atoms} \)), the predicted microwave emissivity of dust in HI clouds \((n_H = 30 \text{cm}^{-3}, T_{\text{gas}} = 100\text{K})\) is shown in Figure 5. We see that this rotational emission appears to be quite capable of explaining the observed \( \nu < 50\text{GHz} \) “anomalous” emission.

A number of different processes (including collisions with ions, collisions with neutrals, “plasma drag”, emission of infrared photons, and electric dipole radiation) play a role in the excitation and damping of grain rotation. Quite unexpectedly, DL98b found that collisions with ions and plasma interactions are extremely important for the dynamics of ultrasmall grains even in mostly neutral media. Because the interstellar medium is far from thermodynamic equilibrium, the mean rotational kinetic energy can be larger or smaller than the \( 1.5kT_{\text{gas}} \) which would apply if the system were in LTE. For example, \( a = 6 \text{Å} \) grains in HI clouds are estimated to have an rms rotation rate of 20 GHz, corresponding to a mean rotational kinetic energy of only \( 1.1kT_{\text{gas}} \) (DL98b). The subthermal rotation is the result of the strong damping due to electric dipole radiation. For ultrasmall grains quantum effects become important. DL98b found that they limit the “rotational drag” on ultrasmall grains due to the plasma.

The spectrum shown in Figure 5 is only approximate. DL98a,b considered a number of models corresponding to various different assumptions regarding electric dipole moments, grain geometry, and numbers of small grains. The resulting emissivities vary by a factor of several. Figure 5 corresponds to the most likely choice of the parameters.

The calculations in DL98b assumed a Maxwellian form for the distribution of rotational velocities. For very small grains, the actual distribution of rotational velocities is expected to be highly non-Maxwellian, particularly because the rotational excitation is dominated by collisions with ions, which deliver angular impulses which can be large compared to the rms angular momentum of the grain (DL98b). A more detailed study of the rotational distribution function for ultrasmall grains, and the resulting rotational emission spectrum, is in progress (Draine & Li 1999).

6. Emissivity Variations

For microwave background experiments it is important to measure the signal as a function of the angular scale. Variations of microwave emission from dust on scales of a few degrees will interfere with measurements of the cosmic background radiation on these scales.

The spatial structure of the 100\(\mu\text{m} \) cirrus has been studied by Gautier et al. (1992), and Herbstmeier et al. (1998). For measurements made with a telescope beam of angular resolution \( \theta \), the rms variations in beam-averaged surface brightness are empirically given by

\[
\frac{\langle (\Delta I_\nu)^2 \rangle^{1/2}}{\langle I_\nu \rangle} \approx 0.08 \left( \frac{\theta}{\text{deg}} \right)^{0.5} \left( \frac{I_{100}}{\text{MJy sr}^{-1}} \right)^{0.5} .
\]  

(5)
Figure 6. Estimated rms variations on angular scales of \(\sim 1^\circ\) at intermediate galactic latitudes, \(b \approx 30^\circ\). The foreground signal is minimized in the 60–120 GHz region, indicated in the figure. After Draine & Lazarian (1999a).

where \(\langle I_{100}\rangle\) is the 100\(\mu\)m surface brightness in that region of the sky. For the “north polar cloud” near the North Celestial Pole studied by Gautier et al., \(\langle I_{100}\rangle = 4.7\text{MJy sr}^{-1}\), and \(\langle (\Delta I_{\nu})^2 \rangle^{1/2}/\langle I_{\nu}\rangle \approx 0.17(\theta/\text{deg})^{0.5}\).

Figure 6 illustrates the relative importance of the emission from dust for intermediate Galactic latitudes, with \(I_{100} \approx 5\text{MJy sr}^{-1}\). The rms variations of dust column density are taken to be 20% on \(\sim 1^\circ\) scales, of the order expected from eq. (5). The fluctuations in the \(\text{H}\alpha\) emission on \(\sim 1^\circ\) scales are taken to be 1 Rayleigh, and the accompanying free-free emission is shown for \(T_{\text{gas}} \approx 8000\text{K}\). The synchrotron background is smoother than dust and the corresponding fluctuations are taken to be 5% on the same angular scale. From the standpoint of minimizing confusion with non-CBR foregrounds, 60-120 GHz appears to be the optimal frequency window.
Substantial variations of microwave emissivity are expected when the line of sight crosses particular regions. Calculations in DL98b were done for emission from spinning dust grains in from dark clouds, reflection nebulae, photodissociation regions etc. These variations can be used to test the spinning dust model.

7. Polarization

Polarization of cosmic microwave background can provide valuable insight to the physics of early Universe (Zaldarriaga 1997, Seljak & Zaldarriaga 1997) and therefore is the subject of intensive theoretical studies (see Kamionkowski & Kosowsky 1998). To study polarization of cosmological origin one has to separate it from foreground polarization caused by dust.

The far-infrared and sub-mm thermal "electric dipole vibrational" emission is expected to be linearly polarized with electric vector \( \mathbf{E} \perp \mathbf{B}_0 \), where \( \mathbf{B}_0 \) is the local interstellar magnetic field. The degree of polarization depends on the degree of alignment of the \( a > 0.1\mu m \) grains which dominate both the far-infrared thermal emission and the polarization of starlight. Polarizations of \( \sim 5\% \) are expected (Prunet et al. 1997) at frequencies \( \nu > 100\text{GHz} \) where the "electric dipole vibrational" emission dominates (see more in Prunet & Lazarian 1999).

7.1. Spinning Grains

At frequencies \( \nu < 100 \text{ GHz} \), however, we expect the spinning grains to dominate the emission. For perfectly aligned rotating grains the degree of polarization would approach 100\%. Such polarized emission could completely mask the polarization of cosmological origin.

Finding the actual degree of alignment for ultrasmall grains is a challenging theoretical problem. The existing theories of alignment (see list of the processes in Lazarian, Goodman & Myers 1997) deal with \( a > 0.1\mu m \) grains, while processes that can align ultrasmall grains have not been studied until very recently.

Lazarian & Draine (1997, 1999, henceforth LD99) concluded that paramagnetic dissipation is the most promising process that can align ultrasmall grains over substantial ISM regions. Paramagnetic dissipation is the most natural mechanism to consider as even ultrasmall grains almost certainly contain atoms and ions with unpaired electrons, and they will be rotating in the galactic magnetic field.

The effect of the galactic magnetic field \( \mathbf{B}_0 \) is to damp the component of angular momentum perpendicular to the field, thereby bringing about partial alignment of the angular momentum \( \mathbf{J} \) with \( \mathbf{B}_0 \). As a result, the electric dipole radiation from the spinning grains will be partially linearly polarized with the electric vector \( \mathbf{E} \perp \mathbf{B}_0 \).

LD99 claim that paramagnetic relaxation for rapidly rotating grains is more efficient than Davis-Greenstein (1951) theory predicts. The latter implicitly assumes that the relaxation does not depend on whether the grain rotates in stationary magnetic field or the magnetic field rotates around a stationary grain. However, a rotating grain gets magnetized via the Barnett effect (Landau & Lifshitz, 1960) as the grain rotation effectively removes the degeneracy between...
“spin-up” and “spin-down” states. This splitting of energy levels also implies that energy dissipation will not be suppressed by very rapid rotation rates since, in effect, the grain rotation frequency is always resonant with the splitting of energy levels. LD99 term this effect “resonance relaxation”.

Work to estimate the frequency-dependent polarization expected for the galactic foreground is in progress but estimates of polarization of the order a few percent were obtained in LD99 for frequencies less than 30 GHz. For frequencies higher than 40 GHz the polarization becomes negligible as the result of efficient radiative damping. We note that the degree of grain alignment depends on the ratio of the rotational damping time to the paramagnetic dissipation time. The rapid increase of rotational damping with frequency causes the decrease of alignment of the most rapidly rotating grains.

7.2. Magnetic Dipole Emission

If magnetic dipole emission from single-domain ferromagnetic grains is present,
it will add a distinct, frequency-dependent, polarization signature, with polarization of the magnetic dipole radiation changing sign close to the frequency where the intensity of the magnetic dipole radiation peaks (DL99).

Even if emission from rotating grains dominates the overall emission, the polarized emission from single-domain ferro- and ferrimagnetic grains could be very important. Constraining the abundance of such grains via observations is a problem for future research.

8. Discussion

Both the magnetic dipole mechanism and the spinning grain mechanism predict that the emissivity $j_\nu$ should show a sharp decrease as the frequency falls below $\sim 15$GHz; future low-frequency CMBR studies should be able to test this prediction. The spectra predicted for magnetic grain materials (Figures 3 and 4) differ from the spectrum predicted for spinning grains in Figure 5, but it must be remembered that these spectra depend on uncertain assumptions: magnetic susceptibilities are required to estimate magnetic dipole radiation; size distributions and electric dipole moments are required to estimate the emission due to spinning grains. The emission spectra in Figures 3–5 are therefore not expected to be accurate in detail.

As pointed out by DL99, one way to distinguish between the spinning grain mechanism and magnetic dipole emission would be to measure the microwave emission from dust in a dense globule. Studies of wavelength-dependent extinction (see the review by Mathis 1990) indicate that small grains are underabundant in dense regions, so the rotational emission per H should be lower in dense clouds. The magnetic dipole emission, on the other hand, is proportional to the total grain volume, but insensitive to the particle size. Hence the coagulation which presumably acts to reduce the population of ultrasmall grains in dark, dense regions will not affect the magnetic dipole emission. Measurement of the microwave emission spectrum from a dark globule can therefore reveal whether the anomalous emission is due to spinning grains or magnetic grains.

9. Summary

The principal points discussed above are as follows:

- There is strong evidence for 10–60 GHz emission correlated with interstellar gas beyond that due to free-free emission.
- The strong emission from interstellar dust at $\lambda < 50$µm (see Figure 1) requires a large population of ultrasmall dust grains.
- These ultrasmall dust grains will rotate rapidly, and will radiate electric dipole radiation at microwave frequencies (see Figure 5) which could explain the observed “anomalous” emission.
- The preferred range of cosmic microwave background observations is from 60 to 120 GHz.
• The small grains will be partially aligned, with their angular momenta tending to be either parallel or antiparallel to the local interstellar magnetic field $B_0$ (Lazarian & Draine 1997). The electric dipole emission will therefore tend to be polarized with $E \perp B_0$.

• Polarization from rotating grains is expected to be negligible for frequencies larger than 40 GHz.

• If grains consist in part of magnetic material, such as metallic Fe or magnetite $Fe_3O_4$, the thermal fluctuations in the magnetization will result in strong magnetic dipole emission. If most of the interstellar Fe resides in a magnetic material such as magnetite, a substantial fraction of the observed “anomalous” emission could be thermal radiation from such magnetic materials.

• If single-domain ferromagnetic grains are present and aligned, the magnetic dipole radiation from them will have an unusual polarization signature.

• Measurement of the emission from dark globules may allow us to decide between spinning grains and magnetic dipole emission as the dominant contribution to the anomalous emission.

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