Resonance Paramagnetic Relaxation and Alignment of Ultrasmall Grains

A. Lazarian

Princeton University Observatory, Princeton, NJ 08544

Abstract.

A mechanism of enhanced paramagnetic relaxation for rapidly rotating interstellar grains is presented. We show that the Barnett magnetization that arises from grain rotation ensures that paramagnetic absorption happens at its maximum efficiency, i.e. the conditions for paramagnetic resonance are automatically fulfilled. The differences between the predictions of classical Davis-Greenstein relaxation and the process which we refer to as “resonance relaxation” are most pronounced for grains rotating faster than 10 GHz. Microwave polarization is likely to be an impediment for cosmic microwave background studies, but can provide a good tool for studying galactic magnetic field.

1. Introduction

In my other paper in this volume (Lazarian 1999) I discuss the “anomalous” emissivity and the two alternative explanations that this emission was given in Draine & Lazarian (1998a,b; 1999). Here I discuss polarization that can arise from small rotating grains, as I believe that this mechanism provides a more natural explanation for the observed emissivity. The polarization of emission arising from large magnetic grains is discussed in Draine & Lazarian (1999).

While paramagnetic alignment was one of the first mechanisms of grain alignment to be discussed in the literature (Davis & Greenstein 1951), it has been believed that ultrasmall grains rotate too fast to be subjected to paramagnetic relaxation. Indeed, it is easy to show that paramagnetic response of candidate materials to oscillating magnetic field is suppressed at $10^{10} - 10^{11}$ Hz, which are typical frequencies of ultrasmall grain rotation. As from the very beginning of the paramagnetic research it has been taken for granted that paramagnetic relaxation does not depend on whether a grain is rotating in magnetic field or magnetic field is rotating about the grain the conclusion about marginal alignment of rapidly rotating grains seemed self-evident. We show that this assumption is incorrect as it disregards an important effect, namely, the Barnett magnetization. We prove that, if this magnetization is accounted for, paramagnetic relaxation is dramatically enhanced at high frequencies.

1 Present address: CIT, Univ. of Toronto, e-mail: lazarian@cita.utoronto.ca
We call this effect "resonance paramagnetic relaxation" and discuss its implications for the alignment of small carbonaceous and silicate grains. The results that this paper deals with were first announced in Lazarian & Draine (1998) and will be discussed in detail in our forthcoming paper (Lazarian & Draine 1999).

In what follows I compare Davis-Greenstein and resonance relaxation processes (section 2) and discuss microwave polarization that is expected from various ISM phases (section 3).

2. Davis-Greenstein and Resonance Relaxation

One of the mechanisms that can provide alignment is the paramagnetic dissipation mechanism suggested by Davis and Greenstein half a century ago as a means of explaining the polarization of starlight (Davis & Greenstein 1951). Its main idea is straightforward: for a spinning paramagnetic 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. As the the axis of maximal inertia of the rotating grain is aligned with the angular momentum (see Purcell 1979) the anisotropy in grain rotation causes alignment with the long axis grain perpendicular to the interstellar magnetic field.

Grain should have unpaired electrons to be susceptible to paramagnetic relaxation. Fortunately, even very small grains are likely to contain paramagnetic species. Even in the absence of paramagnetic ions, UV radiation, X-, γ-, and cosmic rays create the whole gamut of different free radicals that are known to have paramagnetic properties.

However, it is known that the paramagnetic response drops if the oscillating magnetic field has frequency $\omega > 1/\tau_2$, where $\tau_2$ is spin-spin relaxation time, which is essentially the Larmor precession period of a spin in the field of its neighbors. We expect $\tau_2^{-1} > 10$ GHz. Does this mean that the alignment is not efficient for higher frequencies of grain rotation?

We claim that the traditional picture of paramagnetic relaxation is incomplete (Lazarian & Draine 1999). It disregards magnetization that develops due to grain rotation and becomes increasingly important at high angular velocities.

It is well known that a paramagnetic body rotating in field-free space develops a magnetic moment due to the Barnett effect (Landau & Lifshitz 1960), which can be understood in terms of body sharing part of its angular momentum with the spin system. Therefore the implicit assumption in Davis & Greenstein (1951) that the dissipation within a grain rotating in a stationary magnetic field is equivalent to the dissipation within a stationary grain in a rotating magnetic field is clearly not exact.

Paramagnetic dissipation in a grain depends upon the imaginary part of the magnetic susceptibility $\chi''$, which characterizes the phase delay between grain magnetization and the rotating magnetic field.

The time of paramagnetic relaxation is inversely proportional to $K = \chi''/\omega$ (see Davis & Greenstein 1951). For a stationary grain its magnetic response to
the oscillation field can be approximated (Draine & Lazarian 1999):

\[ K(\omega) \approx \frac{\chi_0}{(1 + (\omega \tau)^2)^2} \]  

(1)

Calculations in Lazarian & Draine (1999) provide a different expression for \( K(\omega) \), if the grain is rotating in a stationary magnetic field and \( \omega \gg \tau_2 \):

\[ K(\omega) \approx 0.5 \chi_0 \tau_2 \left( \frac{1}{1 + \gamma^2 g_s^2 \tau_1 \tau_2 B^2} \right) \]  

(2)

where \( g_s \) is the gyromagnetic ratio \( \approx 2 \), \( \gamma \equiv e/(2mc) \approx 1.76 \times 10^6 \text{ s}^{-1} \text{ gauss}^{-1} \), \( B \) is the magnetic field intensity, \( \tau_1 \) and \( \tau_2 \) are spin-spin and spin-lattice relaxation times. The latter time is essentially the time over which the spin system can transfer its energy to the lattice. Estimates in Lazarian & Draine (1999) have shown that, for typical interstellar magnetic field, the factor \( \gamma^2 g_s^2 \tau_1 \tau_2 B^2 < 1 \) and therefore \( K(\omega) \approx 0.5 \chi_0 \tau_2 \).

As the magnetic alignment time \( t_m \) is inversely proportional to \( K(\omega) \) it is evident that for \( \omega \gg \tau_2 \) magnetic alignment time predicted by DG theory, is much higher than that for resonance relaxation. Grain alignment depends on the ratio \( \delta \equiv t_d/t_m \), where \( t_d \) is the time scale of rotational damping; large \( \delta \) correspond to good alignment. Therefore it is evident that DG mechanism underestimates the alignment of very rapidly rotating grains.

It is instructive to consider why paramagnetic dissipation may proceed effectively in a very rapidly rotating body while it may be “saturated” if the body is stationary and the magnetic field rotates about it. A quantum picture may be useful for the purpose: paramagnetic absorption happens when the energy of the electromagnetic quantum is equal to the difference between energy levels within the spin system. In the Davis-Greenstein picture the energy levels arise from the interactions of adjacent spins and for a particular electron the energy difference depends on whether its spin is directed along or against the magnetic field in its vicinity. This field intensity is determined by the spin concentration and therefore for sufficiently high frequencies the density of appropriate levels drops and so does paramagnetic absorption. Barnett magnetization alters the picture as the energy of an individual the spin becomes different when the spin is directed parallel or anti-parallel to the angular velocity; the higher the rotational velocity, the greater the splitting. Therefore absorption of electromagnetic quanta proceeds efficiently for high frequencies.

3. Microwave Polarization from ISM Phases

Emission from a rotating dipole is highly polarized. Therefore if small grains are aligned, we expect to see polarization of the microwave emission.

Alignment of tiny rotating grains depends on \( \delta \) and consequently on the damping time \( t_d \). This time varies for various ISM phases (Draine & Lazarian 1998b). Calculations in Lazarian & Draine (1999) show that the polarization of microwave emission from small grains in cold ISM can reach 6% in the range 10 – 30 GHz. This may potentially present a problem for cosmic microwave background experiments. In molecular clouds the polarization can be as high
as 10% for the same frequency range and may trace magnetic field deep inside dark clouds where large grains are not aligned (Lazarian, Goodman & Myers 1997) and polarimetry at other wavelength fail. In hot and warm ISM phases grain coupling with plasma is large and $t_d$ is reduced. As a result, microwave polarization of a fraction percent is achievable.

CMB measurements are intended at high galactic latitudes. For those directions microwave foreground polarization mostly originates in cold phase of the ISM. Overall polarization of the order of 3% is expected.

4. Summary

1. The efficiency of paramagnetic relaxation depends on whether a grain rotates in a stationary magnetic field or magnetic field rotates about a stationary grain. This difference arises from the Barnett magnetization of a rotating grain. The original Davis-Greenstein theory disregarding this magnetization is incomplete, though sufficiently accurate for slowly rotating grains. Grains rotating faster than $\sim 10$ GHz experience resonance relaxation that enables alignment of very small grains (e.g. $a < 10^{-7}$ cm).

2. Alignment of small grains varies from one ISM phase to another and so does the polarization of microwave emission. The expected degree of polarization is of the order of a few percent in the range $10 - 30$ GHz.

3. Polarization of microwave emission can become an important tool for studies of magnetic field structure in molecular clouds.

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References

Davis, L., & Greenstein, J. 1951, ApJ, 114, 206
Draine, B.T., & Lazarian, A. 1998a, ApJL, 494, L19
Draine, B.T., & Lazarian, A. 1998b, ApJ, 508, 000
Draine, B.T., & Lazarian, A. 1999, ApJ, in press (also astro-ph/9807009)
Landau, LD., & Lifshitz, E.M. 1960, Electodynamics of Continuous Media, New York, Pergamon
Lazarian, A. 1999, contribution to this volume
Lazarian, A., Goodman, A.A., & Myers, P.C. 1997, ApJ, 490, 273
Lazarian, A., Draine, B.T. 1998, BAAS, Vol. 29, No. 5, 1299, 51.20
Lazarian, A., Draine, B.T. 1999, ApJ, in preparation
Purcell, E.M. 1979, ApJ, 231, 404

The issue of $K(\omega)$ saturation for high values of magnetic field $B$ is unclear at the moment. It can be resolved on the basis of laboratory measurements of $\tau_1$ for small grains.