Grain Alignment in Molecular Clouds

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Abstract One of the most informative techniques of studying magnetic fields in molecular clouds is based on the use of starlight polarization and polarized emission arising from aligned dust. How reliable the interpretation of the polarization maps in terms of magnetic fields is the issue that the grain alignment theory addresses. I briefly review basic physical processes involved in grain alignment.

1 Why do we care?

The fact that the grain got aligned has been known for more than half a century. Nevertheless, it has been always a puzzle why grains get aligned in interstellar medium. Very soon after the discovery of grain alignment by Hall (1949) and Hiltner (1949) it became clear that the alignment happens in respect to magnetic field. Since that time grain alignment stopped to be the issue of pure scientific curiosity, but became an important missing link of connecting polarimetry observations with the all-important interstellar magnetic fields\(^1\).

The history of grain alignment ideas is excited (see review by Lazarian 2003) and here we do not have space here to dwell upon it. Within this very short review we will discuss the modern understanding of grain alignment processes applicable to molecular clouds. Last decade has been marked by a substantial progress in understanding new physics associated with grain alignment. The theory has become predictive, which enables researchers to interpret observational data with more confidence.

Recent theory reviews of the grain alignment theory include Roberge (1996), Lazarian (2000, 2003). Progress in testing theory is covered in Hildebrand (2000), while particular aspects of grain dynamics are discussed in

\(^1\) Additional interest to grain alignment arises from recent attempts to separate the polarized CMB radiation from the polarized foregrounds (see Lazarian & Prunet 2002 for a review).
Lazarian & Yan (2003). The presentation in Lazarian (2003) goes beyond molecular cloud environment and deals with the possibility of alignment in circumstellar regions, interplanetary medium, coma of comets etc. The interested reader may use these reviews to guide her in the vast and exciting original literature on grain alignment.

2 How do grains rotate?

Dynamics of grains in molecular clouds is pretty involved (see Fig. 1). First of all, grains rotate. The rotation can arise from chaotic gaseous bombardment of grain surface and be Brownian, or it can arise from systematic torques discovered by Purcell (1975, 1979). The most efficient among those are torques arising from H₂ formation over grain surface. One can visualize those torques imagining a grain with tiny rocket nozzles ejecting nascent high velocity hydrogen molecules (see Fig. 1). Grains are known to enable atoms of hydrogen to form molecules. The reactions are believed to take place over particular catalytic sites on grain surface. Those catalytic sites act as “Purcell rockets”. Even when the surroundings of dust grains is mostly molecular, grains can rotate suprathermally, i.e. with kinetic energies much larger that $kT_{gas}$, due to the variation of the accommodation coefficient. Indeed, if the temperatures of gas and dust are different, those variations allow parts of the grain to bounce back impinging gaseous atoms with different efficiencies. It is easy to understand that this also results in systematic torques. In addition, Purcell (1979) identified electron ejection as yet another process that can drive grain to very large angular velocities.

A very different process of grain spin-up can be found in a very important, but not timely appreciated work by Dolginov & Mytrophanov (1976). These authors considered differential scattering of photons of right and left circular polarization by an irregular dust grain. As the size of the irregularities gets comparable with the wavelength, it is natural that interaction of a grain with photons will depend on the photon polarization. Unpolarized light can be presented as a superposition of equal number of left and right circularly polarized photons. Therefore it is clear that the interaction with photons of a particular polarization would deposit angular momentum to the grain. The authors concluded that for typical diffuse ISM conditions this process should induce grain rotation at suprathermal velocities. However, while Purcell’s torques became a textbook stuff, radiative torques had to wait 20 years before they were reintroduced to the field (Draine 1996, Draine & Weingartner 1996, 1997).

The minimal rotational velocity of grain is the velocity of their Brownian motion. This can be characterized by a temperature that is somewhere between that of the gas and the dust. In the case of PAHs or very small grains emitting copious microwave radiation as they rotate (Draine & Lazarian 1998) the effective rotational microwave temperature may be subthermal (see discussion in Lazarian & Yan 2003).
Fig. 1. Grain alignment implies several alignment processes acting simultaneously and spanning many time scales (shown for $10^{-5}$ cm grain in cold interstellar gas). The rotational dynamics of a grain is rather complex. The internal alignment introduced by Purcell (1979) was thought to be slower than precession until Lazarian & Draine (1999b, henceforth LD99b) showed that it happens $10^6$ times faster when relaxation through induced by nuclear spins is accounted for (approximately $10^4$ s for the $10^{-5}$ cm grains).

It was realized by Martin (1971) that rotating charged grains will develop magnetic moment and the interaction of this moment with the interstellar magnetic field will result in grain precession. The characteristic time for the precession was found to be comparable with $t_{\text{gas}}$. However, soon a process that renders much larger magnetic moment was discovered (Dolginov & Myrophanov 1976). This process is the Barnett effect, which is converse of the Einstein-de Haas effect. If in Einstein-de Haas effect a paramagnetic body starts rotating during remagnetizations as its flipping electrons transfer the angular momentum (associated with their spins) to the lattice, in the Barnett effect the rotating body shares its angular momentum with the electron subsystem causing magnetization. The magnetization is directed along the grain angular velocity and the value of the Barnett-induced magnetic moment is $\mu \approx 10^{-19} \omega(5)$ erg gauss$^{-1}$ (where $\omega(5) \equiv \omega/10^5$s$^{-1}$). Therefore the Larmor precession has a period $t_{\text{Lar}} \approx 3 \times 10^6 B_{(5)}^{-1}$ s.

Nevertheless, suprathermal, thermal and subthermal grain rotation are just components of complex grain dynamics. As any solid body, interstellar grains can rotate about 3 different body axes. As the result they tumble while rotating. This effect was attracting attention of the early researchers (see Jones & Spitzer 1967) till Purcell (1979) identified internal relaxation within grains as the process that can suppress grain rotation about all axes, but the axis corresponding to the grain maximal moment of inertial (henceforth axis of maxi-
mal inertia). Indeed, consider a spheroidal grain, which kinetic energy can be presented as (see Lazarian & Roberge 1997) $E(\theta) = \frac{\mu^2}{I_{\text{max}}} (1 + \sin^2 \theta (h - 1))$, where $\theta$ is the angle between the axis of major inertia and grain angular momentum. In the absence of external torques grain angular momentum is preserved. The minimum of grain energy corresponds therefore to $\theta = 0$, or grain rotating exactly about the axis of maximal inertia. As internal dissipation decreases kinetic energy, it sounds natural that $\theta = 0$ is the expected state of grain subjected to fast internal dissipation.

Purcell (1979) introduced a new process of internal dissipation which he termed ”Barnett relaxation”. This process may be easily understood. We know that a freely rotating grain preserves the direction of $\mathbf{J}$, while angular velocity precesses about $\mathbf{J}$ and in grain body axes. We learned earlier that the Barnett effect results in the magnetization vector parallel to $\Omega$. As a result, the Barnett magnetization will precess in body axes and cause paramagnetic relaxation. The “Barnett equivalent magnetic field”, i.e. the equivalent external magnetic field that would cause the same magnetization of the grain material, is $H_{BE} = 5.6 \times 10^{-3} \omega_{(5)}$ G, which is much larger than the interstellar magnetic field. Therefore the Barnett relaxation happens on the scale $t_{\text{Bar}} \approx 4 \times 10^7 \omega_{(5)}^{-2}$ sec, i.e. essentially instantly compared to the time that it takes to damp grain rotation for typical molecular cloud conditions.

Even stronger relaxation process has been identified recently by Lazarian & Draine (1999a). They termed it “nuclear relaxation”. This is an analog of Barnett relaxation effect that deals with nuclei. Similarly to unpaired electrons nuclei tend to get oriented in a rotating body. However the nuclear analog of “Barnett equivalent” magnetic field is much larger and Lazarian & Draine (1999a) concluded that the nuclear relaxation can be a million times faster than the Barnett relaxation.

Why would the actual relaxation rate matter? The rate of internal relaxation couples grain rotational and vibrational degrees of freedom. LD99b showed that this will result in grain “thermal flipping”. Such a flipping would average out Purcell’s torques and result in grain being “thermally trapped” in spite of the presence of uncompensated torques. Whether grain gets “thermally trapped” depends on its size (with the grains less than a critical size $a_c$ rotating thermally). While Barnett and inelastic relaxation (see also Lazarian & Efroimsky 1999) results in $a_c$ equal or less than $10^{-5}$ cm, the nuclear internal relaxation provides $a_c \sim 10^{-4}$ cm. This means that most grains rotate thermally in the presence of Purcell’s torques. The exception to this thermalization are radiative torques that are not fixed in grain coordinates. Such torques can spin-up dust in spite of thermal flipping.

3 What does align grains?

Paramagnetic Alignment
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Davis-Greenstein (1951) mechanism (henceforth D-G mechanism) is based on the paramagnetic dissipation that is experienced by a rotating grain. Paramagnetic materials contain unpaired electrons which get oriented by the interstellar magnetic field $\mathbf{B}$. The orientation of spins causes grain magnetization and the latter varies as the vector of magnetization rotates in grain body coordinates. This causes paramagnetic loses at the expense of grain rotation energy. Note, that if the grain rotational velocity $\mathbf{\Omega}$ is parallel to $\mathbf{B}$, the grain magnetization does not change with time and therefore no dissipation takes place. Thus the paramagnetic dissipation acts to decrease the component of $\mathbf{\Omega}$ perpendicular to $\mathbf{B}$ and one may expect that eventually grains will tend to rotate with $\mathbf{\Omega} \parallel \mathbf{B}$ provided that the time of relaxation $t_{D-G}$ is much shorter than $t_{\text{gas}}$, the time of randomization through chaotic gaseous bombardment. In practice, the last condition is difficult to satisfy. For $10^{-5}$ cm grains in the diffuse interstellar medium $t_{D-G}$ is of the order of $7 \times 10^{13} a_{(-5)}^2 B_{(-5)}^{2/3}$ s, while $t_{\text{gas}}$ is $3 \times 10^{12} n_{(20)} T_{(2)}^{-1/2} a_{(-5)}^{-6}$ s (see table 2 in Lazarian & Draine 1997) if magnetic field is $5 \times 10^{-6}$ G and temperature and density of gas are 100 K and 20 cm$^{-3}$, respectively. However, at the time when it was introduced, in view of uncertainties in interstellar parameters, the D-G mechanism looked plausible.

The first detailed analytical treatment of the problem of D-G alignment was given by Jones & Spitzer (1967) who described the alignment of $\mathbf{J}$ using a Fokker-Planck equation. This approach allowed them to account for magnetization fluctuations within grain material and thus provided a more accurate picture of $\mathbf{J}$ alignment. The first numerical treatment of D-G alignment was presented by Purcell (1969). By that time it became clear that the D-G mechanism is too weak to explain the observed grain alignment. However, Jones & Spitzer (1967) noticed that if interstellar grains contain superparamagnetic, ferro- or ferrimagnetic (henceforth SFM) inclusions\(^2\), the $t_{D-G}$ may be reduced by orders of magnitude. Since 10\% of atoms in interstellar dust are iron the formation of magnetic clusters in grains was not far fetched (see Martin 1995). However, detailed calculations in Lazarian (1997), Roberge & Lazarian (1999) showed that the alignment achievable cannot account for observed polarization coming from molecular clouds provided that dust grains rotate thermally. This is the consequence of thermal fluctuations within grain material. These internal magnetic fluctuations randomize grains orientation in respect to magnetic field if grain body temperature is close to the rotational temperature.

Purcell (1979) pointed out that fast rotating grains are immune to both gaseous and internal magnetic randomization. Thermal trapping limits the range of grain sizes for which Purcell’s torques can be efficient (Lazarian & Draine 1999ab). Grains with the sizes larger than the wavelength size can be spun up by the incoming starlight, however (see Draine & Weingartner 1996).

\(^2\) The evidence for such inclusions was found much later through the study of interstellar dust particles captured in the atmosphere (Bradley 1994).
Mechanical Alignment

Gold (1951) mechanism is a process of mechanical alignment of grains. Consider a needle-like grain interacting with a stream of atoms. Assuming that collisions are inelastic, it is easy to see that every bombarding atom deposits angular momentum $\delta J = m_{\text{atom}} \mathbf{r} \times \mathbf{v}_{\text{atom}}$ with the grain, which is directed perpendicular to both the needle axis $\mathbf{r}$ and the velocity of atoms $\mathbf{v}_{\text{atom}}$. It is obvious that the resulting grain angular momenta will be in the plane perpendicular to the direction of the stream. It is also easy to see that this type of alignment will be efficient only if the flow is supersonic\(^3\). Thus the main issue with the Gold mechanism is to provide supersonic drift of gas and grains. Gold originally proposed collisions between clouds as the means of enabling this drift, but later papers (Davis 1955) showed that the process could only align grains over limited patches of interstellar space, and thus the process cannot account for the ubiquitous grain alignment in diffuse medium.

Suprathermal rotation introduced in Purcell (1979) persuaded researchers that mechanical alignment is marginal. Indeed, fast rotation makes it difficult for gaseous bombardment to align grains. However, two new developments must be kept in mind. First of all, a number of papers proved that mechanical alignment of suprathermally rotating grains is possible (Lazarian 1995, Lazarian & Efroimsky 1996, Efroimsky 2002). Moreover, recent work on grain dynamics (Lazarian & Yan 2002, Yan & Lazarian 2003) proved that MHD turbulence can render grains with supersonic velocities. While we do not believe that mechanical alignment is the dominant process, it should be kept in mind in analyzing observations (see Rao et al. 1998).

Alignment via Radiative Torques

Anisotropic starlight radiation can both spin the grains and align them. This was first realized by Dolginov & Mytrophanov (1976), but this work came before its time. The researchers did not have reliable means to study dynamics of grains and the impact of their work was marginal. Before Bruce Draine realized that the torques can be treated with the versatile discrete dipole approximation (DDA) code (Draine & Flatau 1994) the radiative torque alignment was very speculative. For instance, earlier on difficulties associated with the analytical approach to the problem were discussed in Lazarian (1995a). However, very soon after that Draine (1996) modified the DDA code to calculate the torques acting on grains of arbitrary shape. His work revolutionized the field! The magnitude of torques were found to be substantial and present for grains of various irregular shape (Draine 1996, Draine & Weingartner 1996). After that it became impossible to ignore these torques.

One of the problem of the earlier treatment was that in the presence of anisotropic radiation the torques will change as the grain aligns and this may result in a spin-down. Moreover, anisotropic flux of radiation will deposit\(^3\) Otherwise grains will see atoms coming not from one direction, but from a wide cone of directions (see Lazarian 1997a) and the efficiency of alignment will decrease.
angular momentum which is likely to overwhelm rather weak paramagnetic
fluxes. These sort of questions were addressed by Draine & Weingartner
(1997) and it was found that for most of the tried grain shapes the fluxes tend
to align along magnetic field. The reason for that is yet unclear and some
cautions are needed as the existing treatment ignores the dynamics of crossovers
which is very important for the alignment of suprathermally rotating grains.
A recent work by Weingartner & Draine (2003) treats flipping of grains in the
presence of monochromatic radiation.

3.1 What is Future Work?

Observational testing of alignment is extremely important. Both the depend-
ences of the polarization degree versus wavelength that follow Serkowski
law (Serkowski 1973) and studies of changes of polarization degree with the
wavelength done in Far Infrared (see Hildebrand 2000) are consistent with
theoretical predictions (see discussion in Lazarian, Goodman & Myers 1997).
According to Lazarian (2003) the study of grain alignment at the diffuse/dense
cloud interface by Whittet et al. (2001) is suggestive that grains there are be-
ing aligned by radiative torques.

Radiative torques look as the most attractive mechanism to align grains
in molecular clouds. However more theoretical work is required to understand
why grains subjected to anisotropic radiation get preferentially aligned with
their long axes perpendicular to magnetic field.

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