Grain Alignment in Molecular Clouds

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Abstract. Polarimetry is one of the most informative techniques of studying magnetic fields in molecular clouds. How reliable the interpretation of the polarization maps in terms of magnetic fields is the issue that the grain alignment theory addresses. We show that grain alignment involves several processes acting simultaneously, but on different time-scales. We explain that rotating dust grains get substantial magnetic moment that allows them precess fast about magnetic field lines. As the result, grains preserve their orientation to magnetic field when the magnetic field direction fluctuates. We point out to the importance of internal alignment, i.e. the process forces grain axes to be aligned in respect to the grain angular momentum. We show that subtle quantum effects, in particular relaxation related to nuclear magnetic moments of atoms composing the grain, brings to live complex grain motions, e.g. flips. These flips substantially alter the dynamics of grain and limit the applicability of earlier theories that did not account for them. We also briefly review basic physical processes involved in the alignment of grain angular momentum in respect to interstellar magnetic field. We claim that the bulk of existing observational data is consistent with the radiative torque alignment mechanism. In particular, we show that large grains that are known to exist in the cores of molecular clouds may be aligned by the attenuated external interstellar radiation field.

1. Why do we care?

The fact that interstellar grains get aligned has been puzzling researchers for more than half a century. 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 link connecting polarimetry observations with the all-important interstellar magnetic fields\(^1\).

The history of grain alignment ideas is exciting (see review by Lazarian 2003) but we do not have space here to dwell upon it. 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.

Within this short review we discuss the modern understanding of grain alignment processes applicable to molecular clouds. We discuss both internal alignment, i.e. the alignment of grain axes in respect to grain angular momen-

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\(^1\)Additional interest to grain alignment arises from recent attempts to separate the polarized CMB radiation from the polarized foregrounds (see Lazarian & Finkbeiner 2003 for a review).
tum, and the alignment of grain angular momentum in respect to magnetic field. Due to fast grain precession about magnetic field the latter acts as the alignment axis for various alignment mechanisms. We show that at present the radiative torque alignment is the most promising mechanism for explaining the bulk of relevant polarimetry data. However, we show that other mechanisms also have their nishes.

Recent reviews of the grain alignment theory include Roberge (2004), Lazarian (2003). Progress in testing theory is covered in Hildebrand (2000), while unusual and exciting aspects of grain dynamics are discussed in Lazarian & Yan (2004). The interested reader may use the reviews above to guide her in the vast and exciting original literature on grain alignment theory. Polarization from aligned atoms is discussed in a companion paper by Yan & Lazarian (this volume).

2. How does alignment cause polarization?

Aligned grains absorb more light along their longer direction. The situation is reversed if grain emission is considered: more emission emanates in the direction of the longer grain axis.

Consider polarization arising due to selective extinction of grains first. For an ensemble of aligned grains the extinction perpendicular and parallel to the direction of alignment and parallel are different\(^3\). Therefore that is initially unpolarized starlight acquires polarization while passing through a volume with aligned grains. If the extinction in the direction of alignment is \(\tau_\parallel\) and in the perpendicular direction is \(\tau_\perp\) one can write the polarization, \(P_{abs}\), by selective extinction of grains as

\[
P_{abs} = \frac{e^{-\tau_\parallel} - e^{-\tau_\perp}}{e^{-\tau_\parallel} + e^{-\tau_\perp}} \approx -(\tau_\parallel - \tau_\perp)/2 ,
\]

where the latter approximation is valid for \(\tau_\parallel - \tau_\perp \ll 1\). To relate the difference of extinction to the properties of aligned grains one can take into account the fact that the extinction is proportional to the product of the grain density and their cross sections. If a cloud is composed of identical aligned grains \(\tau_\parallel\) and \(\tau_\perp\) are proportional to the number of grains along the light path times the corresponding cross sections, which are, respectively, \(C_\parallel\) and \(C_\perp\).

In reality one has to consider additional complications like incomplete grain alignment, and variations in the direction of the alignment axis along the line of sight. To obtain an adequate description one can (see Roberge & Lazarian 1999) consider an electromagnetic wave propagating along the line of sight \(\hat{z}\).

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\(^2\)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. For these regions aligned grain have great and yet untapped potential for studying magnetic fields. The aforementioned review also deals with circular polarization arising from aligned grains.

\(^3\)According to Hildebrand & Dragovan (1995) the best fit of the grain properties corresponds to oblate grains with the ratio of axis about 2/3.
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axis. The transfer equations for the Stokes parameters depend on the cross sections, \(C_{xo}\) and \(C_{yo}\), for linearly polarized waves with the electric vector, \(\mathbf{E}\), along the \(\hat{x}^0\) and \(\hat{y}^0\) directions that are in the plane perpendicular to \(\hat{z}^0\) (see Lee & Draine 1985).

To calculate \(C_{xo}\) and \(C_{yo}\), one transforms the components of \(\mathbf{E}\) to a frame aligned with the principal axes of the grain and takes the appropriately-weighted sum of the cross sections, \(C_{||}\) and \(C_{\perp}\) for \(\mathbf{E}\) polarized along the grain axes. When the transformation is carried out and the resulting expressions are averaged over precession angles, one finds (see transformations in Lee & Draine 1985 for spheroidal grains and in Efroimsky 2002 for a general case) that the mean cross sections are

\[
C_{xo} = C_{avg} + \frac{1}{3} R \left( C_{\perp} - C_{||} \right) \left( 1 - 3 \cos^2 \zeta \right),
\]

(2)

\[
C_{yo} = C_{avg} + \frac{1}{3} R \left( C_{\perp} - C_{||} \right),
\]

(3)

where \(\zeta\) is the angle between the polarization axis and the \(\hat{x}^0\) \(\hat{y}^0\) plane; \(C_{avg} \equiv \left( 2C_{\perp} + C_{||} \right) / 3\) is the effective cross section for randomly-oriented grains. To characterize the alignment we used in eq. (3) the Rayleigh reduction factor (Greenberg 1968)

\[
R \equiv \langle G(\cos^2 \theta)G(\cos^2 \beta) \rangle
\]

, where angular brackets denote ensemble averaging, \(G(x) \equiv 3/2(x - 1/3)\), \(\theta\) is the angle between the axis of the largest moment of inertia (henceforth the axis of maximal inertia, see Fig 1) and the magnetic field \(\mathbf{B}\), while \(\theta\) is the angle between the angular momentum \(\mathbf{J}\) and \(\mathbf{B}\). To characterize \(\mathbf{J}\) alignment in grain axes and in respect to magnetic field, the measures \(Q_X \equiv \langle G(\theta) \rangle\) and \(Q_J \equiv \langle G(\beta) \rangle\) are used. Unfortunately, these statistics are not independent and therefore \(R\) is not equal to \(Q_JQ_X\) (see Roberge & Lazarian 1999). This considerably complicates the treatment of grain alignment.

Polarization arising from emitting grains can be calculated as follows:

\[
P_{em} = \frac{(1 - e^{-\tau_{||}}) - (1 - e^{-\tau_{\perp}})}{(1 - e^{-\tau_{||}}) + (1 - e^{-\tau_{\perp}})} \approx \frac{\tau_{||} - \tau_{\perp}}{\tau_{||} + \tau_{\perp}},
\]

(4)

where both the optical depths \(\tau_{||}\) are \(\tau_{\perp}\) were assumed to be small. Taking into account that both \(P_{em}\) and \(P_{abs}\) are functions of wavelength \(\lambda\) and combining eqs. (4) and (5), one gets for \(\tau = (\tau_{||} + \tau_{\perp})/2\)

\[
P_{em}(\lambda) \approx -P_{abs}(\lambda)/\tau(\lambda),
\]

(5)

which establishes the relation between polarization in emission and absorption. The minus sign in eq (5) reflects the fact that emission and absorption polarization are orthogonal. As \(P_{abs}\) depends on \(R\), \(P_{em}\) also depends on \(R\).

3. How complex is grain motion?

Dynamics of grains in molecular clouds is pretty involved (see Fig. 1). Grain rotation can arise from chaotic gaseous bombardment of grain surface and be
Simplified Model of Alignment

Notation of $\mathbf{B}$ around $\mathbf{T}$
$\tau_B < 10^{-5}$ s

Alignment of $\mathbf{J}$ and $\mathbf{B}$
Internal alignment

Precession of $\mathbf{J}$ around $\mathbf{B}$
$\tau_P \sim 10^9$ s

Gradual alignment of $\mathbf{J}$
$\tau_d \sim 10^{11}$ s

Precession of $\mathbf{J}$ is rapid $\Rightarrow$ magnetic field
is the axis of alignment
$\parallel$ and $\perp$ are possible

Figure 1. Left panel– 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).

Right panel– Grain rotation arising from systematic torques arising from $\text{H}_2$ formation (P79). In the presence of efficient internal relaxation the angle $\beta$ between the axis of maximal moment of inertia and $\mathbf{J}$ is small is grain is rotating at suprathermal rates ($E_{\text{kinetic}} \gg kT_{\text{grain}}$).

Brownian, or it can arise from systematic torques discovered by Purcell (1975, 1979). The most efficient among those are torques arising from $\text{H}_2$ 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). Indeed, $\text{H}_2$ formation is believed to take place over particular catalytic sites on grain surface. These catalytic sites ejecting molecules are frequently called "Purcell rockets". Even when the surroundings of dust grains is mostly molecular, according to Purcell (1979) grains can rotate suprathermally, i.e. with kinetic energies much larger that $kT_{\text{gas}}$, due to the variation of the accommodation coefficient. Indeed, if the temperatures of gas and dust are different, the variations of the sticking probabilities allow parts of the grain to bounce back impinging gaseous atoms with different efficiencies. In addition, Purcell (1979) identified electron ejection as yet another process that can drive grain to large angular velocities. All these three processes are so natural that until very recently it was generally accepted that all interstellar grains in diffuse interstellar gas must rotate suprathermally.

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 pre-
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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).

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. However, soon a process that renders much larger magnetic moment was discovered (Dolginov & Mytrophanov 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 \( \mu \approx 10^{-19} \omega(5) \text{ erg gauss}^{-1} \) (where \( \omega(5) \equiv \omega/10^5 \text{s}^{-1} \)). Therefore the Larmor precession has a period \( t_{\text{Lar}} \approx 3 \times 10^6 B(5)^{-1} \text{s} \). If magnetic field direction changes over timescales much larger than \( t_{\text{Lar}} \), the orientation of grain angular momentum and magnetic field is preserved. Thus MHD turbulence in molecular clouds (see Lazarian & Cho 2004) does not destroy grain alignment. This fast Larmor precession makes magnetic field in most cases the axis of alignment.

Being solid bodies, interstellar grains can rotate about 3 different principal axes of grain inertia. 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 inertia (henceforth axis of maximal inertia). Indeed, consider a spheroidal grain, which kinetic energy can be presented as (see Lazarian & Roberge 1997)

\[
E(\theta) = \frac{J^2}{I_{\text{max}}} \left( 1 + \sin^2 \beta (h - 1) \right),
\]

where \( \beta \) is the angle between the axis of major inertia and grain angular momentum (see Fig. 1). In the absence of external torques grain angular momentum is preserved. The minimum of grain energy corresponds therefore to \( \beta = 0 \), or grain rotating exactly about the axis of maximal inertia. As internal dissipation decreases kinetic energy, it sounds natural that \( \beta = 0 \) is the expected state of grain subjected to fast internal dissipation.

4. What is the physics of internal alignment?

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 \( \mathbf{J} \). We learned earlier that the Barnett effect results in the magnetization vector parallel to \( \vec{\Omega} \). As a result, the Barnett magnetization will precess in body axes and cause paramagnetic dissipation. 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 \( t_{Bar} \approx 4 \times 10^7 \omega^{-2}(5) \) 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 a 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.

5. What does align angular momentum of grains?

While a number of processes can result in grain angular momentum alignment (see Lazarian 2003), we shall briefly discuss only 3 of them.

**Paramagnetic Alignment.** — 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 \( \vec{\Omega} \) 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 \( \vec{\Omega} \) perpendicular to \( \mathbf{B} \) and one may expect that eventually grains will tend to rotate with \( \vec{\Omega} \parallel \mathbf{B} \) provided that the time of relaxation \( t_{D-G} \) is much shorter than \( t_{gas} \), 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 \( 7 \times 10^{13} a_c^2(5) B^{-2}(5) s \).
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, while \( t_{\text{gas}} \) is \( 3 \times 10^{12} n_{(20)} T_{(2)}^{-1/2} a_{(-5)} \) 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 \( \vec{J} \) 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 \( \vec{J} \) 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\(^4\), the \( t_{\text{D-G}} \) 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). For grains that are less than the critical size, which can be \( 10^{-4} \) cm and larger, rotation is essentially thermal. Alignment of such grains is expected in accordance with the DG mechanism predictions (see Roberge & Lazarian 1999) and seem to be able to explain the residual alignment of small grains that is seen in the Kim & Martin (1995) inversion. An important feature of this weak alignment is that it is proportional to the energy density of magnetic field. This potentially opens a way for a new type of magnetic field diagnostics.

Lazarian & Draine (2000) predicted that PAH-type particles can be aligned paramagnetically due to the relaxation that is faster than the DG process. In fact, they showed that the DG alignment is not applicable to very fast rotating particles, for which Barnett magnetic field gets comparable with magnetic fields of the atom neighbors.

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 \( \delta \vec{J} = n_{\text{atom}} \vec{r} \times \vec{v}_{\text{atom}} \) with the grain, which is directed perpendicular to both the needle axis \( \vec{r} \) and the velocity of atoms \( \vec{v}_{\text{atom}} \). 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

\(^4\)The evidence for such inclusions was found much later through the study of interstellar dust particles captured in the atmosphere (Bradley 1994).
to see that this type of alignment will be efficient only if the flow is supersonic. 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, it has been 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) has shown 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 while 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 definitely 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 (1995). 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 radiative torque alignment.

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 angular momentum which is likely to overwhelm rather weak paramagnetic torques. These sort of questions were addressed by Draine & Weingartner (1997) and it was found that for most of the tried grain shapes the torques tend to align J along magnetic field. The reason for that is yet unclear and more work is clearly necessary before we can treat radiative alignment as a theory rather than an empirical fact. One of the authors of the review (AL) recalls that this was also the opinion of Lyman Spitzer who got interested in the action of radiative torques and was encouraging the author to do analytical work and simple testing to clarify the essence of the radiative torque alignment. One of the missing pieces of physics, namely the dynamics of radiative torques, has been dealt with recently by Weingartner & Draine (2003), who treated flipping of grains in the presence of monochromatic radiation.

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5Otherwise 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.
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Quantitative description. — As we discussed above, to relate the polarization to magnetic field, the Rayleigh reduction factor $R$ should be calculated. This factor was calculated for DG alignment (see Roberge & Lazarian 1999), for Purcell alignment (see Lazarian & Draine 1997), mechanical alignment of thermally (see Lazarian 1997a) and suprathermally rotating grains (see Lazarian 1995, Lazarian & Efroimsky 1996, Efroimsky 2002). For radiative torques no quantitative theory exists. An educated guess may be that for grains larger than the critical size $R = 1$, i.e. the grains are perfectly aligned. The calculations of the critical grain size can be done by comparing the radiative torques calculated with the DDA software and the damping of grain rotation via gas-grain, ion-grain collisions, plasma drag etc. (see Draine & Lazarian 1999 for a description of various damping mechanisms).

6. What can align grains deep in molecular clouds?

We believe that a substantial degree of understanding of grain alignment has been achieved recently. For the first time ever the available observational data look consistent with the theoretical expectations.

Both the dependences 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, henceforth LGM97). According to Lazarian (2003) the study of grain alignment at the diffuse/dense cloud interface by Whittet et al. (2001) is suggestive that grains are aligned by radiative torques. Indeed, the latter study finds that the properties of grains stay the same, while the minimal size of the aligned grains is increasing with the increase of extinction. This behavior is inconsistent with superparamagnetic grains discussed in Mathis (1986). For those grains the size of aligned grains is determined by the presence of superparamagnetic inclusion and does not change unless the grain size distribution changes. On the contrary, radiative torque efficiency decreases for smaller grains as the shorter wavelength radiation field gets preferentially attenuated by extinction.

An earlier review of observational molecular cloud data was given in LGM97. It broadly reconciled the near-infrared data that was suggestive of the suppression of grain alignment at high extinction and the far-infrared data suggestive of grain alignment in the vicinity of stars deep embedded into molecular cloud. LGM97 showed that within molecular clouds far from embedded stars all the grain alignment mechanisms fail, while near the stars a few of them, particular radiative torques looked promising.

Data summarized in Hildebrand (2003) suggest that either hot grains in the vicinity of stars or cold grains at the cloud boundary are well aligned, while the warm grain at the bulk of the cloud are marginally aligned. This data are consistent with the LGM97 expectations. However, the data obtained for pre-stellar cores in Ward-Thompson et al. (2000) at the first glance seem to be at odds with the LGM97 predictions. Indeed, the properties of these cores summarized in Ward-Thompson et al. (2002) and Crutcher et al. (2004) fit into the category of zones that must be dead for grain alignment according to LGM97.
Figure 2. Radiative torque at high extinction by Cho & Lazarian (2004).
(a) Different curves represent radiative torque by an anisotropic part of radiation field. The degree of anisotropy of 10% was assumed for ISRF. The visual extinction $A_V$ is for a giant molecular cloud located at 5kpc from the Galactic center. Although the UV smoothed refractive index of silicon is used for small grains, our results are consistent with torques published in Draine & Weingartner (1996). (b) Aligned grain size vs. visual extinction $A_V$. For the threshold suprathermal angular velocity 5 times larger than the thermal angular velocity was chosen. It is clear that increase of grain size can compensate for the extinction of light in cloud cores. Solid line: $n_H = 10^4 \text{cm}^{-3}$; Dotted line: $n_H = 10^5 \text{cm}^{-3}$ in the cloud.

What could be wrong with LGM97 arguments? The latter paper treats grains of $10^{-5}$ cm size. Such grains are typical for diffuse ISM, while grains in prestellar cores can be substantially larger. Grain alignment is a function of size. Therefore the estimates in LGM97 should be reevaluated.

Cho & Lazarian (2004, preprint, henceforth CL04) revealed a steep dependence of radiative torque efficiency on grain size. While an earlier study by Draine & Weingartner (1996) was limited by grains with size $a \leq 0.2 \times 10^{-4}$ cm, CL04 studied grains up to $3 \times 10^{-4}$ cm size subjected to the attenuated radiative field calculated in accordance with the prescriptions in Mathis, Mezger & Panagia (1983). Figure 3 shows that large grains can be efficiently span up by radiative torques even at the extinction of $A_v$ of 10 and higher. Real molecular clouds are likely to be inhomogeneous. As the result, the radiation has more chances to penetrate deep within molecular clouds$^6$.

In general, alignment of large grains by other mechanisms can also be more efficient. Such grains are not subjected to thermal trapping (see Lazarian & Draine 1999ab) and therefore can be aligned by Purcell’s mechanism (see Lazarian & Draine 1997 calculations that take into account crossover dynamics). Larger grains also get larger velocities due to turbulent motions (see Yan & Lazarian 2003) and therefore are more likely to be aligned mechanically. This gives further hope that using Far Infrared polarimetry it is possible to trace magnetic fields deep in molecular clouds.

$^6$Even larger grains are known to be present in the accretion discs around young stars. Grain alignment may be efficient for such grains revealing the structure of the all-important magnetic fields. However, this issue is beyond the scope of this review.
7. Summary

1. Aligned grains provide a unique way to study magnetic field. As we better understand grain alignment the interpretation of emission and absorption polarization data in terms of underlying magnetic field gets more reliable.

2. Grain alignment is a complex process that includes precession and gradual alignment of angular momentum in respect to magnetic field and the alignment of grain axes in respect to angular momentum. The latter alignment influences the former one. Rapid precession of grain angular momentum about magnetic field makes magnetic field the axis alignment even if the alignment mechanism is not of magnetic nature.

3. Internal relaxation is the process that minimizes grain kinetic energy for a fixed angular momentum. As the result of the process grain rotates about its axis of maximal inertia. Relaxation related to the nuclear moments within a grain have been recently identified as the major mechanism of internal relaxation.

4. Internal relaxation couples rotational and vibrational degrees of freedom. As the result, thermal fluctuations in grain material prevent perfect alignment of grain axes in respect to angular momentum. Moreover, thermal fluctuations cause rapid flipping and "thermal trapping" of sufficiently small grains, i.e. they prevent the grains from spinning rapidly (suprathermally) even in the presence of uncompensated Purcell's torques.

5. Paramagnetic alignment is definitely present for small thermally trapped grains. However, quantitative theories predict that the degree of expected alignment is rather marginal and depends on the magnetic field intensity. Purcell's paramagnetic alignment of suprathermally rotating grains is applicable only to sufficiently large $>10^{-4}$ cm grains, i.e. to the grains that are not thermally trapped. The mechanical alignment should not be disregarded as grains can be driven by turbulence to supersonic velocities.

6. Radiative torques mechanism is the most promising mechanism for alignment of grain angular momentum. The efficiency of radiative torques depends on grain size and properties of ambient radiation field. This allows to explain why some interstellar grains are aligned, while others are not aligned.

7. Alignment of large dust grains is possible within cores of molecular clouds. Radiative torques efficiency increases substantially for larger grains. As the result, even substantially attenuated interstellar radiation field can provide good alignment. This makes Far Infrared Polarimetry an essential tool for getting insight into the magnetic fields in hotbeds of star formation.

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