Magnetic Fields via Polarimetry: Progress of Grain Alignment Theory

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Abstract

Most astrophysical systems, e.g. stellar winds, the diffuse interstellar medium, molecular clouds, are magnetized with magnetic fields that influence almost all of their properties. One of the most informative techniques of magnetic field studies 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. Although grain alignment is a problem of half a century standing, recent progress achieved in the field makes us believe that we are approaching the solution of this mystery. I review basic physical processes involved in grain alignment and discuss the niches for different alignment mechanisms. I show why mechanisms that were favored for decades do not look so promising right now, while the radiative torque mechanism ignored for more than 20 years looks so attractive. I define the observational tests and outline the circumstances when grain alignment theory predicts that new yet untapped information of magnetic field structure is available through polarimetry. In particular, I touch upon mapping magnetic fields in circumstellar regions, interplanetary space and in comet comae.

1 Introduction

Magnetic fields are of utmost importance most astrophysical systems. Conducting matter is entrained on magnetic field lines and magnetic pressure and tension are very important for its dynamics. For instance, galactic magnetic fields play key role in many processes, including star formation, mediating shocks, influencing heat and mass transport, modifying turbulence etc. Aligned dust grains trace the magnetic field and provide a unique source of information about magnetic field structure. How reliable is this source of information? What are the prospects of the polarimetric research? This review addresses those questions while dealing with the problem of grain alignment theory.
Grain alignment of interstellar dust has been discovered more than half a century ago. Hall (1949) and Hiltner (1949) reported polarization that was attributed to the differential extinction of starlight by dust particles with longer axes preferentially aligned. Very soon it was realized that the alignment happens with respect to the interstellar magnetic field. Starting from that moment polarized starlight and later the polarized emission by aligned grains have become the principal technique of studying magnetic field morphology in molecular clouds. As magnetic fields are thought to control star formation (see Savier, McKee & Stahler 1997) the value of the technique is difficult to overestimate. However, to what extent the polarization maps trace magnetic fields is a non-trivial question that the grain alignment theory deals with.

For many years grain alignment theory had a very limited predictive power and was an issue of hot debates. This caused somewhat cynical approach to the theory among some of the polarimetry practitioners who preferred to be guided in their work by the following rules of thumb: All grains are always aligned and the alignment happens with the longer grain axes perpendicular to magnetic field. This simple recipe was shattered, however, by observational data which indicated that

I. Grains of sizes smaller than the critical size are either not aligned or marginally aligned (Mathis 1986, Kim & Martin 1995).

II. Carbonaceous grains are not aligned, but silicate grains are aligned (see Mathis 1986).

III. Substantial part of grains deep within molecular clouds are not aligned (Goodman et al. 1995, Lazarian, Goodman & Myers 1997).

VI. Grains might be aligned with longer axes parallel to magnetic fields (Rao et al 1998).

These facts could persuade even the most stubborn types that the interpretation of interstellar polarimetric data does require an adequate theory. A further boost of the interest to grain alignment came from the search of Cosmic Mi-

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1 The relation between grain alignment direction and that of magnetic field is clear from a comparison of synchrotron polarization maps and those of galactic starlight polarization (see Serkowski, Mathewson & Ford 1975). Recent measurements of polarization in external galaxies (see Jones 2000) makes this relation even more obvious.

2 A simple, but not always clearly understood property of grain alignment in interstellar medium is that it always happens in respect to magnetic field. It can be shown that the fast (compared with other time scales) Larmor precession of grains makes the magnetic field the reference axis. Note, however, that grains may align with their longer axes perpendicular or parallel to magnetic field direction. Similarly, magnetic fields may change their configuration and orientation in space (e.g. due to Alfvén waves), but if the time for such a change is much longer than the Larmor period the alignment of grains in respect to the field lines persists as the consequence of preservation of the adiabatic invariant.
crowave Background (CMB) polarization (see Lazarian & Prunet 2002, for a review). Aligned dust in this case acts as a source of a ubiquitous foreground that is necessary to remove from the data. It is clear that understanding of grain alignment is the key element for such a removal.

With the present level of interest to the CMB polarization we are bound to have a lot of microwave and far infrared polarimetry data. It is important to understand to what extent this data reflects the structure of magnetic field in the Galaxy and whether this data can be used to get insight into the processes of galactic magnetic field generation and into interstellar turbulence.

While the alignment of interstellar dust is a generally accepted fact, the alignment of dust in conditions other than interstellar has not been fully appreciated. The common explanation of light polarization from comets or circumstellar regions is based on light scattering by randomly oriented particles. The low efficiency and slow rates of alignment were quoted to justify such an approach (see Bastien 1988). This point of view is common in spite of the mounting evidence in favor of grain alignment (see Briggs & Aitken 1986, Aitken et al. 1995, Tamura et al. 1995). However, recent advances in understanding of grain alignment show that it is an efficient and rapid process. Therefore, we do expect to have circumstellar, interplanetary and comet dust aligned. This opens new exciting avenues for polarimetry.

Traditionally linear starlight polarimetry was used. These days far infrared polarimetry of dust emission has become the major source of molecular field structure data (see Hildebrand 2000). It is possible that circular polarization may become an important means of probing magnetic fields in circumstellar regions and comets.

In this review I claim that the modern grain alignment theory allows us to solve most of the existing puzzles and can be used successfully to interpret polarimetry in terms of magnetic field. A substantial part of the review is devoted to the physics of grain alignment, which is deep and exciting. It is enough to say that its study resulted in a discovery of a few new solid state effects. The rich physics of grain alignment (see Fig 1a for an illustration of motion complexity) presents a problem, however, for its presentation. Therefore I shall describe first the genesis of ideas that form the basis of the present-day grain alignment theory. The references to the original papers should help the interested reader to get the in-depth coverage of the topic. Earlier reviews on the subject include Hildebrand (1988), Roberge (1996), Lazarian, Goodman

\[^3\] Velocity and magnetic field statistics provide the most clear insight in what is going on with the turbulence. With velocity statistics available through the recently developed Velocity Channel Analysis (VCA) technique (Lazarian & Pogosyan 2000) magnetic fields statistics is the missing element. Polarized starlight and emission from aligned grains provide the easiest way to get such a statistics.
In what follows we show how the properties of polarized radiation is related to the statistics of aligned grains (section 2), analyze the major alignment mechanisms (section 3), discuss observational data that allows to distinguish between different alignment processes (section 4) and outline the prospects of using grain alignment to study circumstellar, interplanetary magnetic fields (section 5). A discussion and summary are provided in sections 6 and 7.

2 Aligned Grains & Polarized Radiation

2.1 Linear Polarized Starlight from Aligned Grains

For an ensemble of aligned grains the extinction perpendicular and parallel to the direction of alignment and parallel are different. 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, $P_{\text{abs}}$, by selective extinction of grains as

$$P_{\text{abs}} = \frac{e^{-\tau_\parallel} - e^{-\tau_\perp}}{e^{-\tau_\parallel} + e^{-\tau_\perp}} \approx -\frac{\tau_\parallel - \tau_\perp}{2} ,$$

where the latter approximation is valid for $\tau_\parallel - \tau_\perp \ll 1$. To relate the difference of extinctions 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 (in most cases the latter is the direction of magnetic field, as discussed above) 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 $\hat{z}^o$ axis. The transfer equations for the Stokes parameters depend on the cross sections, $C_{x_0}$ and $C_{y_0}$, for linearly polarized waves with the electric vector, $E$, along the $\hat{x}^o$ and $\hat{y}^o$ directions that are in the plane perpendicular to $\hat{z}^o$ (see Lee & Draine 1985).

\footnote{According to Hildebrand & Dragovan (1995) the best fit of the grain properties corresponds to oblate grains with the ratio of axis about 2/3.}
To calculate $C_{xo}$ and $C_{yo}$, one transforms the components of $E$ to a frame aligned with the principal axes of the grain and takes the appropriately-weighted sum of the cross sections, $C_\parallel$ and $C_\perp$ for $E$ polarized along the grain axes (Fig 1b illustrates the geometry of observations). 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

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

(2)

$$C_{yo} = C_{avg} + \frac{1}{3} R \left( C_\perp - C_\parallel \right),$$  

(3)

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

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

(4)

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) and the magnetic field $B$, while $\beta$ is the angle between the angular momentum $J$ and $B$. To characterize $J$ 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 $Q_J Q_X$ (see Lazarian 1998, Roberge & Lazarian 1999). This considerably complicates the treatment of grain alignment.

2.2 Polarized Emission from Aligned Grains

The difference in $\tau_\parallel$ and $\tau_\perp$ results in emission of aligned grains being polarized:

$$P_{em} = \frac{(1 - e^{-\tau_\parallel}) - (1 - e^{-\tau_\perp})}{(1 - e^{-\tau_\parallel}) + (1 - e^{-\tau_\perp})} \approx \frac{\tau_\parallel - \tau_\perp}{\tau_\parallel + \tau_\perp},$$  

(5)

where both the optical depths $\tau_\parallel$ 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.(1) and (6), one gets for $\tau = (\tau_\parallel + \tau_\perp)/2$

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

(6)
which establishes the relation between polarization in emission and absorption. The minus sign in eq (6) reflects the fact that emission and absorption polarization are orthogonal. As \( P_{\text{abs}} \) depends on \( R \), \( P_{\text{em}} \) also depends on the Rayleigh reduction factor.

2.3 Circular Polarization from Aligned Grains

A way of obtaining circular polarization is to have a magnetic field that varies along the line of sight (Martin 1972). Passing through one cloud with aligned dust the light becomes partially linearly polarized. On passing the second cloud with dust aligned in a different direction the light gets circular polarization. Literature study shows that this effect that is well remembered (see Menard et al 1988), while the other process that also creates circular polarization is frequently forgotten. We mean the process of single scattering of light on aligned particles. Electromagnetic wave interacting with a single grain coherently excites dipoles parallel and perpendicular to the grain long axis. In the presence of adsorption these dipoles get phase shift giving rise to circular polarization. This polarization can be observed from the ensemble of grains if the grains are aligned. The intensity of circularly polarized component of radiation emerging via scattering of radiation with \( k \) wavenumber on small \((a \ll \lambda)\) spheroidal particles is (Schmidt 1972)

\[
V(e, e_0, e_1) = \frac{I_0 k^4}{2 r^2} i (\alpha_\parallel \alpha_\perp^* - \alpha_\parallel^* \alpha_\perp) ([e_0 \times e_1]e) (e_0 e),
\]

where \( e_0 \) and \( e_1 \) are the unit vectors in the directions of incident and scattered radiation, \( e \) is the direction along aligned axes of spheroids; \( \alpha_\parallel \) and \( \alpha_\perp \) are particle polarizabilities along \( e \) and perpendicular to it.

The intensity of the circulary polarized radiation scattered in the volume \( \Delta \Gamma(d, r) \) at \( |d| \) from the star and distances \( |r| \) from the observer is (Dolginov & Mytrophanov 1978)

\[
\Delta V(d, r) = \frac{L_\star n_{\text{dust}} \sigma_V}{6\pi |d|^2 |r| |d - r|^2} R (|d \times r|h) (dr) \Delta \Gamma(d, r),
\]

where \( L_\star \) is the stellar luminosity, \( n_{\text{dust}} \) is number density of dust grains and \( \sigma_V \) is the cross section for producing circular polarization, which is for small grains is \( \sigma_V = i/(2k^4)(\alpha_\parallel \alpha_\perp^* - \alpha_\parallel^* \alpha_\perp) \). According to Dolginov & Mytrophanov (1978) circular polarization arising from single scattering on aligned grains can be as high as several percent for metallic or graphite particles, which is much more than one may expect from varying magnetic field direction along the line of sight (Martin 1972). In the latter case linear polarization produced
by one layer of aligned grains passes through another layer where alignment direction is different. If passing through a single layer the linear polarization degree is $p$, passing through two layers produces circular polarization that does not exceed $p^2$.

### 3 Grain Alignment Theory: New and Old Ideas

We have seen in the previous sections that both linear and circular polarizations depend on the degree of grain alignment given by $R$-factor (4). Therefore it is the goal of grain alignment theory to determine this factor. The complexity of the grain alignment is illustrated in Fig 1, which shows that grain alignment is indeed a multi-stage process.

A number of different mechanisms that produce grain alignment has been developed by now (see table 1 in Lazarian, Goodman & Myers 1997). Dealing with a particular situation one has to identify the dominant alignment process. Therefore it is essential to understand different mechanisms. By now the theory of grain alignment is rather complex. This makes it advantageous to follow the evolution of grain alignment ideas. It is instructive to see the major role that observations played in shaping up of the theory.

#### 3.1 Foundations of the Theory

The first stage of alignment theory development started directly after the discovery of starlight polarization. Nearly simultaneously Davis & Greenstein (1950) and Gold (1951) proposed their scenarios of alignment.

**Paramagnetic Alignment: Davis-Greenstein Process**

Davis-Greenstein 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 $B$. 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 $\omega$ is parallel to $B$, the grain magnetization does not change with time and therefore no dissipation takes place. Thus the paramagnetic dissipation acts to decrease the component of $\omega$ perpendicular to $B$ and one may expect that eventually grains will tend to rotate with $\omega \parallel B$ 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 $7 \times 10^{13} a_{(-5)}^2 B_{(5)}^{-2} s$, while $t_{gas}$ 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, in view of uncertainties in interstellar parameters the D-G theory initially looked plausible.

Mechanical Alignment: Gold Process
Gold 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 $\delta J = m_{atom} r \times v_{atom}$ with the grain, which is directed perpendicular to both the needle axis $r$ and the velocity of atoms $v_{atom}$. 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. 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.

Quantitative Treatment and Enhanced Magnetism
The first detailed analytical treatment of the problem of D-G alignment was given by Jones & Spitzer (1967) who described the alignment of $J$ 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 $J$ alignment. $Q_X$ was assumed to follow the Maxwellian distribution, although the authors noted that this might not be correct. 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 (1969) noticed that if interstellar grains contain superparamagnetic, ferro- or ferrimagnetic (henceforth SFM) inclusions, 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 Spitzer & Turkey 1950, Martin 1995) and therefore the idea was widely accepted. Indeed, with enhanced magnetic susceptibility the D-G mechanism was able to solve all the contemporary problems of alignment. The conclusive at this stage was the paper by Purcell & Spitzer (1971) where all various models of grain alignment, including, for instance, the model of cosmic ray alignment by Salpeter & Wickramasinha (1969) and

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5 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.

6 The evidence for such inclusions was found much later through the study of interstellar dust particles captured in the atmosphere (Bradley 1994).
photon alignment by Harwit (1970) were quantitatively discussed and the D-G model with enhanced magnetism was endorsed. It is this stage of development that is widely reflected in many textbooks.

3.2 Additional Essential Physics

Barnett Effect and Fast Larmor Precession
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 & 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

$$\mu \approx 10^{-10} \omega_{(5)} \text{erg gauss}^{-1} \quad \text{(where } \omega_{(5)} \equiv \omega/10^5 \text{s}^{-1}).$$

Therefore the Larmor precession has a period $t_{\text{Lar}} \approx 3 \times 10^6 B_{(5)}^{-1} \text{s}$ and the magnetic field defines the axis of alignment as we explained in section 1.

Suprathermal Paramagnetic Alignment: Purcell Mechanism
The next step was done by Purcell(1975, 1979), who discovered that grains can rotate much faster than were previously thought. He noted that variations of photoelectric yield, the H$_2$ formation efficiency, and variations of accommodation coefficient over grain surface would result in uncompensated torques acting upon a grain. The H$_2$ formation on the grain surface clearly illustrates the process we talk about: if H$_2$ formation takes place only over particular catalytic sites, these sites act as miniature rocket engines spinning up the grain. Under such uncompensated torques the grain will spin-up to velocities much higher than thermal (Brownian) and Purcell termed those velocities “suprathermal”. Purcell also noticed that for suprathermally rotating grains internal relaxation will bring $\mathbf{J}$ parallel to the axis of maximal inertia (i.e. $Q_X = 1$). Indeed, for an oblate spheroidal grain with angular momentum $\mathbf{J}$ the energy can be written

$$E(\theta) = \frac{J^2}{I_{\text{max}}} \left(1 + \sin^2 \theta (h - 1)\right) \quad \text{(9)}$$

where $h = I_{\text{max}}/I_\perp$ is the ratio of the maximal to minimal moments of inertia. Internal forces cannot change the angular momentum, but it is evident from
Eq. (9) that the energy can be decreased by aligning the axis of maximal inertia along $\mathbf{J}$, i.e. decreasing $\theta$. Purcell (1979) discusses two possible causes of internal dissipation, the first one related to the well known inelastic relaxation, the second is due to the mechanism that he discovered and 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 $\mathbf{ω}$. 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 $H_{BE} = 5.6 \times 10^{-3} \omega(3)^{-1} \text{G}$, which is much larger than the interstellar magnetic field. Therefore the Barnett relaxation happens on the scale $t_{\text{Bar}} \approx 4 \times 10^7 \omega(3)^{-2} \text{sec}$, i.e. essentially instantly compared to $t_{\text{gas}}$ and $t_{\text{D~G}}$.

**Theory of Crossovers**

If $Q_X = 1$ and the suprathermally rotating grains are immune to randomization by gaseous bombardment, will paramagnetic grains be perfectly aligned with $R = 1$? This question was addressed by Spitzer & McGlynn (1979) (henceforth SM79) who observed that adsorption of heavy elements on a grain should result in the resurfacing phenomenon that, e.g. should remove early sites of H$_2$ formation and create new ones. As the result, H$_2$ torques will occasionally change their direction and spin the grain down. SM79 showed that in the absence of random torques the spinning down grain will flip over preserving the direction of its original angular momentum. However, in the presence of random torques this direction will be altered with the maximal deviation inflicted over a short period of time just before and after the flip, i.e. during the time when the value of grain angular momentum is minimal. The actual value of angular momentum during this critical period depends on the ability of $\mathbf{J}$ to deviate from the axis of maximal inertia. SM79 observed that as the Barnett relaxation couples $\mathbf{J}$ with the axis of maximal inertia it makes randomization of grains during crossover nearly complete. With the resurfacing time $t_{\text{res}}$ estimated by SM79 to be of the order of $t_{\text{gas}}$, the gain of the alignment efficiency was insufficient to reconcile the theory and observations unless the grains had SFM inclusions.

**Radiative Torques**

If the introduction of the concept of suprathermality by Purcell changed the way researchers thought of grain dynamics, the introduction of radiative torques passed essentially unnoticed. Dolginov (1972) argued that quartz grains may be spun up due to their specific rotation of polarization while later Dolginov & Mytrophanov (1976) discovered that irregular grain shape may allow grains scatter left and right hand polarized light differentially, thus
spinning up helical grains through scattering of photons. They stressed that the most efficient spin-up is expected when grains size is comparable with the wavelength and estimated the torque efficiency for particular helical grain shapes, but failed to provide estimates of the relative efficiency of the mechanism in the standard interstellar conditions. In any case, this ingenious idea had not been appreciated for another 20 years.

**Observational tests: Serkowski Law**

All in all, by the end of seventies the the following alignment mechanisms were known: 1. paramagnetic (a. with SFM inclusions, b. with suprathermal rotation), 2. mechanical, 3. radiative torques. The third was ignored, the second was believed to be suppressed for suprathermally rotating grains, which left the two modifications of the paramagnetic mechanism as competing alternatives. Mathis (1986) noticed that the interstellar polarization-wavelength dependence known as the Serkowski law (Serkowski et al. 1975) can be explained if grains larger that \( \sim 10^{-5} \) cm are aligned, while smaller grains are not. To account for this behavior Mathis (1986) noticed that the SFM inclusions will have a better chance to be in larger rather than smaller grains. The success of fitting observational data persuaded the researchers that the problem of grain alignment is solved at last.

### 3.3 Present Stage of Grain Alignment Theory

Optical and near infrared observations by Goodman et al. (1995) showed that polarization efficiency may drop within dark clouds while far infrared observations by Hildebrand et al. (1984), Hildebrand et al. (1990) revealing aligned grains within star-forming dark clouds. This renewed interest to grain alignment problem.

**New Life of Radiative Torques**

Probably the most dramatic change of the picture was the unexpected advent of radiative torques. Before Bruce Draine realized that the torques can be treated with the versatile discrete dipole approximation (DDA) code (Draine & Flatau 1994), their role was unclear. 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 revolu-

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7 The principal difference between radiative torque mechanism and the radiative emission/absorption mechanism proposed by Harwit (1970) is that the radiative torques are regular and therefore increase the grain velocity in proportion to time. Harwit’s mechanism, on the other hand, is based on stochastic spin-up and therefore is subdominant. We also note that the emission of photons is insensitive to grain helicity as the emitted photons have wavelengths much larger than the grain size.
tionized 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. Being related to grain shape, rather than surface these torques are long-lived\(^8\), i.e. \(t_{\text{spin-up}} \gg t_{\text{gas}}\), which allowed Draine & Weingartner (1996) to conclude that in the presence of isotropic radiation the radiative torques can support fast grain rotation long enough in order for paramagnetic torques to align grains (and without any SFM inclusions). However, the important question was what would happen in the presence of anisotropic radiation. Indeed, in the presence of such 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 \(\mathbf{J}\) along magnetic field. The reason for that is yet unclear and some caution is needed as the existing treatment ignores the dynamics of crossovers which is very important for the alignment of suprathermally rotating grains. Nevertheless, radiative torques are extremely appealing as their predictions are consistent with observational data (see Lazarian, Goodman & Myers 1997, Hildebrand et al. 1999, see section 4 as well).

\textit{New Elements of Crossovers}

Another unexpected development was a substantial change of the picture of crossovers. As we pointed out earlier, Purcell’s discovery of fast internal dissipation resulted in a notion that \(\mathbf{J}\) should always stay along the axis of maximal inertia as long as \(t_{\text{dis}} \ll t_{\text{gas}}\). Calculations in SM79 were based on this notion. However, this perfect coupling was questioned in Lazarian (1994) (henceforth L94), where it was shown that thermal fluctuations within grain material partially randomize the distribution of grain axes in respect to \(\mathbf{J}\). The process was quantified in Lazarian & Roberge (1997) (henceforth LR97), where the distribution of \(\theta\) for a freely rotating grain was defined through the Boltzmann distribution \(\exp\left(-\frac{E(\theta)}{kT_{\text{grain}}}\right)\), where the energy \(E(\theta)\) is given by Eq. (9). This finding changed the understanding of crossovers a lot. First of all, Lazarian & Draine (1997)(henceforth LD97) observed that thermal fluctuations partially decouple \(\mathbf{J}\) and the axis of maximal inertia and therefore the value of angular moment at the moment of a flip is substantially larger than SM79 assumed. Thus the randomization during a crossover is reduced and LD97 obtained a nearly perfect alignment for interstellar grains rotating suprathermally, provided that the grains were larger than a certain critical size \(a_c\). The latter size was found by equating the time of the crossover and

\(^8\) In the case of the Purcell’s rockets the duration of torque action is limited by the time of resurfacing, while in the case of radiative torques it is the time scale on which the grain is either destroyed via collisions, coagulates with another grain or gets a different shape in the process of growth.
the time of the internal dissipation $t_{\text{dis}}$. For $a < a_c$ Lazarian & Draine (1999a) found new physical effects, which they termed “thermal flipping” and “thermal trapping”. The thermal flipping takes place as the time of the crossover becomes larger than $t_{\text{dis}}$. In this situation thermal fluctuations will enable flipovers. However, being random, thermal fluctuations are likely to produce not a single flipover, but multiple ones. As the grain flips back and forth the regular (e.g. $H_2$) torques average out and the grain can spend a lot of time rotating with thermal velocity, i.e. being “thermally trapped”. The paramagnetic alignment of grains rotating with thermal velocities is small (see above) and therefore grains with $a < a_c$ are expected to be marginally aligned. The picture of preferential alignment of large grains, as we know, corresponds to the Serkowski law and therefore the real issue is to find the value of $a_c$. The Barnett relaxation provides a comforting value of $a_c \sim 10^{-5}$ cm. However, in a recent paper Lazarian & Draine (1999b) reported a new solid state effect that they termed “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 (1999) concluded that the nuclear relaxation can be a million times faster than the Barnett relaxation. If this is true $a_c$ becomes of the order $10^{-4}$ cm, which means that the majority of interstellar grains undergo constant flipping and rotate essentially thermally in spite of the presence of uncompensated Purcell torques. The radiative torques are not fixed in body coordinates and it is likely that they can provide a means for suprathermal rotation for grains that are larger than the wavelength of the incoming radiation. Naturally, it is of utmost importance to incorporate the theory of crossovers into the existing codes, and this work is under way.

New Ideas and Quantitative Theories

An interest to grain alignment resulted in search of new mechanisms. For instance, Sorrell (1995a,b) proposed a mechanism of grain spin-up due to interaction with cosmic rays that locally heat grains and provide evaporation of adsorbed $H_2$ molecules. However, detailed calculations in Lazarian & Roberge (1997b) showed that the efficiency of the torques was overestimated; the observations (Chrysostomou et al. 1996) did not confirm Sorrell’s predictions either. A more promising idea that ambipolar diffusion can align interstellar grains was put forward in Roberge & Hanany (1990)(calculations are done in Roberge et al. 1995). Within this mechanism ambipolar drift provides the supersonic velocities necessary for mechanical alignment. Independently L94 proposed a mechanism of mechanical grain alignment using Alfven waves. Un-

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9 A study by Lazarian & Efroimsky (1999) corrected the earlier estimate by Purcell (1979), but left the conclusion about the Barnett relaxation dominance, and therefore the value of $a_c$, intact. For larger objects, e.g. for asteroids, comets, the inelastic relation is dominant (Efroimsky & Lazarian 2000, Efroimsky 2001).
like the ambipolar diffusion, this mechanism operates even in ideal MHD and relies only on the difference in inertia of atoms and grains and on the direct interaction of grains with fluctuating magnetic field (Lazarian & Yan 2002, Yan & Lazarian 2002). An additional boost to interest to mechanical processes was gained when it was shown that suprathermally rotating grains can be aligned mechanically (Lazarian 1995, Lazarian & Efroimsky 1996, Lazarian, Efroimsky & Ozik 1996, Efroimsky 2002). As it was realized that thermally rotating grains do not \( \mathbf{J} \) tightly coupled with the axis of maximal inertia (L94) and the effect was quantified (LR97), it got possible to formulate quantitative theories of Gold (Lazarian 1997a) and Davis-Greenstein (Lazarian 1997b, Roberge & Lazarian 1999) alignments. Together with a better understanding of grain superparamagnetism (Draine & Lazarian 1998a), damping of grain rotation (Draine & Lazarian 1998b) and resurfacing of grains (Lazarian 1995c), these developments increased the predictive power of the grain alignment theory.

**Alignment of PAH**

All the studies above dealt with classical “large” grains. What about very small (e.g. \( a < 10^{-7} \) cm) grains? Can they be aligned? The answer to this question became acute after Draine & Lazarian (1998) explained the anomalous galactic emission in the range 10 – 100 GHz as arising from rapidly (but thermally!) spinning tiny grains. This rotational dipole emission will be polarized if grains are aligned. Lazarian & Draine (2000) (henceforth LD00) found that the generally accepted picture of the D-G relaxation is incorrect when applied to such rapidly rotating (\( \omega > 10^8 \) s\(^{-1}\)) particles. Indeed, the D-G mechanism assumes that the relaxation rate is the same whether grain rotates in stationary magnetic field or magnetic field rotates around a stationary grain. However, as grain rotates, we know that it gets magnetized via Barnett effect and it is known that the relaxation rate within a magnetized body differs from that in unmagnetized body. A non-trivial finding in LD00 was that the Barnett magnetization provides the optimal conditions for the paramagnetic relaxation which enables grain alignment at frequencies for which the D-G process is quenched (see Draine 1996). LD00 termed the process “resonance relaxation” to distinguish from the D-G process and calculated the expected alignment values for grains of different sizes. Will this alignment be seen through infrared emission of small transiently heated small grains (e.g. PAH)? The answer is probably negative\(^{10}\). The reason for the such an answer is that internal alignment of \( \mathbf{J} \) and the axis of maximal inertia is being essentially destroyed if a grain is heated up to high temperatures (LR97). Therefore even if \( \mathbf{J} \) vectors are well aligned, grain axes will wobble with large amplitude about \( \mathbf{B} \). The expected alignment in terms of \( R \) and therefore the polarization of emitted infrared photons, will be marginal in agreement with observations (Sellgren, 1990). Earlier calculations by Rouan et al (1992) of the problem were done at a time when much of the relevant physics, e.g. resonance relaxation, thermal flipping, incomplete internal relaxation were not known.
Rouan & Leger 1988).

4 Observational Tests of Interstellar Alignment

As the reader may see from the previous discussion that that several times the problem of grain alignment seemed to be solved. However, the accumulation of new observational facts and deeper insights into grain physics caused the changes of paradigms. The problem was attacked again and again at a higher level of understanding. Three important questions arise:
I. Do we need to keep in mind different mechanisms while dealing with data?
II. Which mechanism dominates in which environment?
III. Are we still missing essential physics?

The answer to the first question is positive. As pointed out by Hildebrand (1988) astrophysical environments present such a variety of conditions that it is likely that every mechanism has its own niche. How wide is this niche depends on the special conditions required for the mechanism operation as well as its efficiency. This brings us to the second and third questions. As we shall see below, the present day theory provides quantitative predictions that can be tested. So far this tests are consistent with the theoretical predictions. More studies, both observational and theoretical, are necessary, however.

4.1 Testing Alignment in Molecular Clouds

The data on grain alignment in molecular clouds looked at some point very confusing. On one hand, optical and near-infrared polarimetry of background stars did not show an increase of polarization degree with the optical depth (Goodman et al. 1995). This increase would be expected if absorbing grains were aligned by magnetic field within molecular clouds. On the other hand, far-infrared measurements (see Hildebrand 2000, henceforth H00) showed strong polarization that is consistent with emission from aligned grains. A quite general explanation to those facts was given in Lazarian, Goodman & Myers (1997, henceforth LGM), where it was argued that all the suspected alignment mechanisms are based on non-equilibrium processes that require free energy to operate. Within the bulk of molecular clouds the conditions are close to equilibrium, e.g. the temperature difference of dust and gas drops, the content of atomic hydrogen is substantially reduced, and the starlight is substantially attenuated. As the result the major mechanisms fail in the bulk part of molecular clouds apart from regions close to the newly formed stars as well as the cloud exteriors.
The alternative explanations look less appealing. For instance, Wiebe & Watson (2001) speculated that small scale turbulence in molecular clouds can reduce considerably the polarization even if grain alignment stays efficient. This, however, seems inconsistent with the results of far-infrared polarimetry (see H00) that reveals quite regular pattern of magnetic field in molecular clouds.

An extremely important study of alignment efficiency has been undertaken by Hildebrand and his coworkers (Hildebrand et al. 1999, H00). They started by noticing that for a uniform sample of aligned grains made of dielectric material consistent with the rest of observational data $P(\lambda)$ should stay constant if $\lambda$ belongs to the far-infrared range. The data at 60 $\mu$m, 100 $\mu$m from Stockes on the Kuiper Airborne Observatory, 350 $\mu$m from Hertz on Caltech Submillimeter Observatory, and 850 $\mu$m from SCUBA on the JCMT revealed a very different picture. This was explained (see Hildebrand 2002) as the evidence for the existence of populations of dust grains with different temperature and different degree of alignment. The data is consistent with cold (T=10 K) and hot (T=40 K) dust being aligned, while warm (T=20 K) grains being randomly oriented (H00).

If cold grains are identified with the outer regions of molecular clouds, hot grains with regions near the stars and warm with the grains in the bulk of molecular clouds the picture gets similar to that in LGM. A quantitative theoretical study is absolutely necessary, nevertheless. In LGM it was stated that within molecular clouds both paramagnetic alignment aided by $\text{H}_2$ formation torques and radiative torque alignment may be equally important. However, it was later claimed in Lazarian & Draine (1999) that the frequent flipping of grains should make grain rotation essentially thermal (“thermal trapping”). Recently calculated degrees of paramagnetic alignment for thermally rotating grains (Lazarian 1998, Roberge & Lazarian 1999) that accounts for the complex grain dynamics are pretty low to explain the observed degrees of polarization, however. This leaves the radiative torque mechanism as the most probable candidate for alignment of dust within molecular clouds. The quantitative testing of the mechanism requires simulating radiative transfer within a molecular cloud supplemented by a quantitative recipe for the alignment efficiency dependence on the attenuated radiation spectrum. The latter element should become available soon.

4.2 Testing Alignment at the Diffuse/Dense Cloud Interface

Grain alignment can be directly tested at the cloud interface. As we mentioned earlier, Mathis (1986) explained the dependence of the polarization degree
versus wavelength, namely the Serkowski law (Serkowski 1973)

\[ P(\lambda)/P_{\text{max}} = \exp\left(-K\ln^2(\frac{\lambda_{\text{max}}}{\lambda})\right), \tag{10} \]

(where \(\lambda_{\text{max}}\) corresponds to the peak percentage polarization \(P_{\text{max}}\) and \(K\) is a free parameter), assuming that it is only the grains larger than the critical size that are aligned. Those grains were identified in Mathis (1986) as having superparamagnetic inclusions and therefore subjected to more efficient paramagnetic dissipation. The ratio of the total to selective extinction \(R_v \equiv A_v/E_{B-V}\) reflects the mean size of grains present in the studied volume. It spans from \(\sim 3.0\) in diffuse ISM to \(\sim 5.5\) in dark clouds (see Whittet 1992 and references therein) as the mean size of grain increases due to coagulation or/and mantle growth. Earlier studies were consistent with the assumption that the growth of \(R_v\) is accompanied by the corresponding growth of \(\lambda_{\text{max}}\) (see Whittet & van Brenda 1978). The standard interpretation for this fact was that as grains get bigger, the larger is the critical size starting with which grains get aligned. This interpretation was in good agreement with Mathis’ (1986) hypothesis.

However, a recent study by Whittet et al. (2001) showed that grains at the interface of the Taurus dark cloud do not exhibit the correlation of \(R_v\) and \(\lambda_{\text{max}}\). This surprising behavior was interpreted in Whittet et al (2001) as the result of size-dependent variations in grain alignment with small grains losing their alignment first as deeper layers of the cloud are sampled. Whittet et al (2001) do not specify the alignment mechanism, but their results pose big problems to the superparamagnetic mechanism. Indeed, the data is suggestive that \(R_v\) and therefore the mean grain size may not grow with extinction while the critical size for grain alignment grows. The suprathermal torques due to \(H_2\) formation on grain surfaces (see Lazarian & Draine 1997) do not look promising either, even if thermal trapping (Lazarian & Draine 1999a,b) is disregarded. At the same time the observed behavior is exactly what is expected from radiative torques! Although the quantitative comparison of the observations and the theoretical predictions is still due to come, the results by Whittet et al. are very suggestive that the radiative torques may be the dominant mechanism to align dust in ISM.

### 4.3 Testing Alignment for Small Grains

Maximum entropy inversion technique in Kim & Martin (1995) indicate that grains larger than a particular critical size are aligned. This is consistent with our earlier discussion. However, an interesting feature of the inversion is that it is suggestive of smaller grains being partially aligned. Initially this effect was attributed to the problems with the assumed dielectric constants employed during the inversion, but a further analysis that we undertook with
Peter Martin indicated that the alignment of small grains is real. Indeed, paramagnetic (DG) alignment must act on the small grains\textsuperscript{11}. An important consequence of this is that the alignment is proportional to the magnetic field strength. This opens an avenue for a new technique of probing magnetic field using UV polarimetry\textsuperscript{12}.

5 Testing Alignment in New Environments

\textit{Indications of Alignment}

While interstellar grain alignment is an accepted process, alignment of grains in other environments, e.g. comets, circumstellar disks, interplanetary medium, remains a controversial subject. Recent advances in the alignment theory make us believe that grains are well aligned there. This is the point of view that was shared by a number of earlier researchers. For instance, Greenberg (1970) claimed that interplanetary dust should be mechanically aligned. Dolginov & Mytrophanov (1978) conjectured that comet dust and dust in circumstellar regions was aligned. However, both the problems in understanding of grain alignment and the inadequacy of polarimetric data did not allow those views to become prevalent (although see Wolstencroft 1985, Briggs & Aitken 1986 where alignment was supported).

As the situation with observations was gradually improving, the alignment of grains became difficult to disregard. It has been known for decades that various stars, both young and evolved, exhibit linear polarization (see a list of polarization maps in Bastien & Menard 1988). While multiple scattering was usually quoted as the cause of the polarization, recent observations indicate the existence of aligned dust around eta Carinae (Aitken et al. 1995), evolved stars (Kahane et al. 1997) and T Tauri stars (Tamura et al. 1999). This is suggestive that for other stars grains should be aligned. New observations (Chrisostomou et al 2000) support this. In fact, some of the arguments that were used against aligned grains are favor them. For instance, Bastien & Menard (1988) point out that if polarization measurements of young stellar object are interpreted in terms of grain alignment with longer grain axes perpendicular to magnetic field, the magnetic field of accretion disks around stars should preferentially

\textsuperscript{11}To avoid a confusion we should specify that we are talking about grains of $10^{-6}$ cm. For those grains the results of DG relaxation coincide with those through resonance relation in Lazarian & Draine (2000). It is for grains of the size less than $10^{-7}$ cm that the resonance relaxation is dominant.

\textsuperscript{12}UV polarimetry is sensitive to aligned small grains. As we discussed earlier, the tiny PAH grains emit in microwave range, and their alignment also depends on the magnetic field strength. Thus both microwave and UV polarimetry may be useful in estimating the values of magnetic field.
be in the disk plane. This is exactly what the present day models of accretion disks suggest.

Similarly, “anomalies” of polarization from comets see Martel 1960, Beskrovnaja et al 1987, Ganesh et al 1998) as well as circular polarization from comets (Metz 1972, Metz & Haefner 1987, Dollfus & Suchail 1987, Morozhenko et al 1987) are indicative of grain alignment. However, conclusive measurements of grain alignment have been done only recently for the Levi (1990 20) comet through direct measurements of starlight polarization as the starlight was passing through comet coma (Rosenbush et al 1994). The data proved the existence of aligned grains, which corresponds to theoretical expectations that we discuss below.

Conditions for Alignment

Expected measures of alignment and the necessary conditions for the alignment to take place are listed in Table 1. Both mechanical and radiative alignment in comets and circumstellar regions can be transient, i.e. happen on the time scales less than the Larmor precession time. My radiative torque simulations with the code kindly supplied to me by Bruce Draine show that when the magnetic field is not important (i.e. \( \tau_L \gg \) time of alignment), the alignment tends to happen with grain angular momentum along the radiation flow. The rough estimate for the transient alignment time is the time at which the angular momentum supplied either by radiative torques or gaseous bombardment becomes comparable with the initial grain angular momentum. The stationary alignment requires a time larger than the gaseous damping time. For instance, for rapid Larmor precession the radiative torque alignment on the time scales much shorter than the gaseous damping time is marginal. It can be seen from Table 1 that transient mechanical alignment and that via radiative torques may act in opposite directions. If, as in the case of comets, the radiation direction and the streaming direction coincide, mechanical torques would tend to align grains parallel to the flow, while radiative torques will align grain perpendicular to the flow. Accurate measurements of polarization direction may determine the prevalence of one or the other mechanism. In the generally accepted picture of mechanical alignment, the increase of angular momentum

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13 When light is scattered by the randomly oriented particles with sizes much less than the wavelength, the scattered light is polarized perpendicular to the scattering plane, which is the plane passing through the Sun, the comet and the observer. Linear polarization from comets has been long known to exhibit polarization that is not perpendicular to the scattering plane.

14 The subject was controversial for a while. Observations of both left and right handed polarization in different parts of coma with the average over whole coma close to zero probably explains why earlier researchers were unsuccessful using large apertures. Recent measurements by Rosenbush et al. (1999), Manset et al. (2000) of circular polarization from Hale-Bopp Comet support the notion that circular polarization is a rule rather than an exception.
$J$ through collisions is proportional to $\sim t^{1/2}$, while radiative torques act to increase $J$ in proportion to time. Thus even if mechanical alignment dominates initially, for grains with $a \sim \lambda$ the radiative torques eventually dominate. The mechanical alignment will still dominate for $a \ll \lambda$.

For mechanical alignment the existence of supersonic relative grain-gas motions is essential. The joint action of radiative and mechanical torques has not been studied yet, but we may suspect that the alignment may be caused by the difference in frictional damping parallel and perpendicular to the flow (see Lazarian 1995). Models of stellar winds (see Netzer & Elitzur 1994) and comet outflows predict supersonic relative velocities and thus mechanical alignment. High resolution polarimetry and modeling of the outflows are required.

High intensities of radiation flow make radiative torques the most natural means of aligning grains in circumstellar envelopes. However, one should remember that radiative torques are most efficient when grain sizes are comparable with wavelengths. For particles much less than the wavelength their efficiency drops as $(a/\lambda)^4$. This provides an interesting possibility that large particles can be aligned via radiative torques, while small ones may be aligned via other mechanisms. This effect may be revealed via spectropolarimetry of linear and circularly polarized light. Note, that even in the interstellar medium, radiative torques are a major mechanism of rotation for sufficiently large, e.g. $a > 10^{-5}$ cm, grains. Within circumstellar regions, where UV flux is enhanced smaller grains can also be aligned radiatively. This could present a possible solution for the recently discovered anomalies of polarization in the 2175 Å extinction feature (see Anderson et al 1996) which have been interpreted as evidence of graphite grain alignment (Wolff et al 1997). If this alignment happens in the vicinity of particular stars with enhanced UV flux and having graphite grains present in their circumstellar regions, this may explain why no similar effect is observed along other lines of sight.

We can see from Table 1 that if we assume a model for Zodiacal dust particles that includes large silicate grains and small (less than the typical wavelength) iron grains, both species will be aligned with longer axes perpendicular to magnetic field direction, although in the case of iron grains, the cause would be paramagnetic relaxation, while in the case of silicate grains the alignment would be due to radiative torques.

Potentially, studies of Zodiacal Light might give a lot of information about magnetic field structure and its variability in the Solar neighborhood, information that could be compared with direct, in situ, measurements of the field. For instance, the interplanetary magnetic field and fields in circumstellar regions comet tails, are not stationary. In fact they undergo variations on a whole range of time scales. If the variations are long compared to the Larmor period $t_L$ they are adiabatic in the sense that the angle between grain angular
momentum and $\mathbf{B}$ is preserved. Therefore measuring variations of the Zodiacal Light polarization in a particular direction can provide information on the magnetic variability down to the scale $t_L$.

6 Discussion

I anticipate a number of questions that can worry the reader. For instance:

- Does the review cover all the astrophysically important situations when grain alignment is important? It has become clear recently that grain alignment should happen in various astrophysical conditions. Polarized radiation from neighboring galaxies (Jones 2000), galactic nuclei (see Tadhunter et al 2001), AGNs, Seyfet galaxies (see Lumsden et al 2001), accretion discs (see Aitken et al 2002) can be partially due to aligned particles. Revealing this contribution would allow to study magnetic fields in those and other interesting objects.

- To what degree do aligned grains reveal magnetic field geometry/topology during star formation? It is generally accepted that star formation starts with the accumulation of interstellar gas that is caused by turbulence and gravity. Aligned grains allow to trace magnetic fields during this preliminary stage. At some point of evolution the conditions within molecular clouds approach equilibrium with the alignment being shut down (see LGM). Finding out exactly when this happens is extremely important and this requires the quantitative description of grain alignment processes. Consider, for instance, radiative torques. Realistic clumpy, fractal-type structure of molecular clouds allows photons to penetrate much deeper into clouds compared with the idealized uniform structure frequently assumed in theoretical modeling. Therefore we expect grains within skin layers of the clumps to be aligned and to reveal magnetic field up to a substantial optical depth. Simulations in (Padoan et al. 2001) support this argument. As protostars are formed in molecular clouds their light induces grain alignment in their neighborhood. The size of this neighborhood also depends on the cloud inhomogeneity in the protostar vicinity as well as on the radiative torque efficiency as a function of wavelength. The fact that grains in molecular clouds are larger than their counterparts in diffuse media allows for a more efficient alignment by starlight reddened by dust extinction; this increases the neighborhood volume. Therefore we expect to be able to trace magnetic evolution via polarimetry through important stages of star formation. Additional information can be available through microwave emission of the aligned PAH-type tiny grains, which rotate non-thermally due to their collisions with ions (see Draine & Lazarian 1998b). The abundance of such grains in molecular clouds is poorly known, however.

- What is the advantage of far-infrared polarimetry for studies of magnetic
field in molecular clouds compared to optical and near infrared ones? The trivial answer is that far infrared polarimetry reveals aligned grains near newly born stars unaccessible by optical and near infrared photons. A more subtle but essential effect is that photons, as we discussed earlier, can align grains within skin layers of clumps rather far into molecular clouds. Those aligned grains are only accessible by far infrared polarimetry. This, for instance, makes SOFIA airborn observatory so desirable for studies of magnetic fields in molecular clouds. Additional advantage of far infrared spectropolarimetry stems from the fact that it allows us to separate contributions from different parts of the cloud (see Hildebrand 2000). This enables tomography of magnetic field structure.

- What is the future of optical and near infrared polarimetry? It would be wrong to think that with the advent of far infrared polarimetry there is a bleak future for extinction polarimetry at shorter wavelengths. In fact, its potential for studies of magnetic fields in the Galaxy is enormous (see Fosalba et al. 2002, Cho & Lazarian 2002a). The possibility of using stars at different distances from the observer allows to get an insight into the 3D distribution of magnetic fields. In general, however, it is extremely advantageous to combine optical/near infrared and far infrared polarimetry. For instance, it may be pretty challenging to trace the connection of Giant Molecular Clouds (GMCs) with the ambient interstellar medium using just far-infrared measurement. However, if extinction polarimetry of the nearby stars is included, the task gets feasible. Similarly testing modern concepts of MHD turbulence (Goldreich & Shridhar 1995, Lithwick & Goldreich 2001, Cho & Lazarian 2002b) and turbulent cloud support (see reviews by McKee 1999, and Cho, Lazarian & Vishniac 2002) would require data from both diffuse and dense media.

- What is the advantage of doing polarimetry for different wavelengths? The list of advantages is pretty long. It is clear that aligned grains can be successfully used as pick up devices for various physical and chemical processes, provided that we understand the causes of alignment. Differences in alignment of grains of different chemical composition (see Smith et al. 2000) provides a unique source of the valuable information. Comets present another case in support of simultaneous multifrequency studies. There the properties of dust evolve in a poorly understood fashion and this makes an unambiguous interpretation of optical polarimetry rather difficult. Degrees and directions of dust alignment that can be obtained via far infrared polarimetry can be used to get a self-consistent picture of the dust evolution and grain alignment.

- Do we need grain alignment theory to deal with polarized CMB foregrounds? Polarized emission spectrum arising from aligned dust may be very complex if grains having different temperatures exhibit different degrees of alignment. In this situation the use of the naive power-law templates may result in huge er-
errors unless we understand grain alignment properly. Needless to say that grain alignment theory is necessary to predict the spectrum of polarized emission from PAHs in the range of 10-100 GHz.

• What is the future of grain alignment theory? Although the recent progress in understanding grain alignment is really encouraging, it would be a mistake to think that grain alignment theory does not require intensive work any more. For instance, radiative torques alignment in the presence of starlight anisotropy should be treated as an experimental fact obtained via simulations rather than a theoretically understood effect. Moreover, crossover dynamics must be added to the existing code to get the simulations more realistic and frequency dependence of radiative torques should be quantified. More special cases of alignment should be studied. The simultaneous action of various processes, e.g. grain streaming together with the action of radiative torques must be investigated. Some additional processes, e.g. mechanical alignment of helical grains (see table 1. in LGM) must be quantified. Alignment of tiny PAH grains, in particular, is an essentially unexplored field that requires more studies of relaxation processes in minute quantum mechanical samples as well as plasma and magnetic turbulence interactions with grains. More observational testings are necessary as well. For instance, comets allow to trace grain alignment in time. More systematic studies that include not only linear polarimetry, but circular polarimetry as well, should be made. All in all, grain alignment has become a predictive theory, but there is more work, both observational and theoretical to be done.

7 Summary

The principal points discussed above are as follows:

• Grain alignment results in linear and circular polarimetry. The degree of polarization depends on the degree of grain alignment and the latter is the subject of grain alignment theory.
• Grain alignment theory has at last reached its mature state when predictions are possible. In most cases grain alignment happens in respect to magnetic field, i.e. reveal magnetic field direction, even if the alignment mechanism is not magnetic. However, depending on the mechanism the alignment may happen with grain longer axes parallel or perpendicular to magnetic field.
• Radiative torques, after being ignored for many years, have become the most promising mechanism which expectations agree with interstellar observations. However, astrophysical circumstances exhibit such a variety of conditions that other mechanisms have their own niches.
• Advances in grain alignment theory make it possible to use grains as sensitive pick up devices. For instance, we discussed ways to use polarization as
a direct measure of magnetic field intensity.

- It is clear that the importance of grain alignment is not limited to interstellar medium and molecular clouds. Polarimetry can be used to study magnetic fields in accretion disks, AGN, circumstellar regions, comets etc.

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Fig. 1. a) Left panel. Alignment of grains implies several alignment processes acting simultaneously spanning over many scales. Internal alignment was introduced by Purcell (1979) and was assumed to be a slow process. Lazarian & Draine (1999a) showed that the internal alignment is $10^6$ times faster if nuclear spins are accounted for. The time scale of $\mathbf{J}$ and $\mathbf{B}$ alignment is given for diffuse interstellar medium. It is faster in circumstellar regions and for comet dust. b) Right panel. Geometry of observations (after Roberge & Lazarian 1999).
| Features   | Comets                          | Circumstellar Regions |
|-----------|--------------------------------|-----------------------|
| **Radiative** | **options**: transient and stationary | stationary mostly |
| **Torques** | **conditions**: effective when $a \sim \lambda$ | the same |
|            | **direction**: ⊥ to photon flux for transient ⊥ to magnetic field $\mathbf{B}$ ⊥ to $\mathbf{B}$ for stationary alignment |
|            | **measure**: $R \sim 1$ | $R \sim 1$ |
| **Paramagnetic** | **conditions**: pure iron grains grains with inclusions |
| **Alignment** | **direction**: ⊥ to $\mathbf{B}$ | the same |
|            | **measure**: upto $R \sim 1$ | the same |
| **Mechanical** | **options**: transient and stationary | mostly stationary |
| **Alignment** | **conditions**: supersonic drift | the same |
|            | **direction**: || to gas flow for transient ⊥ or || to $\mathbf{B}$ ⊥ or || to $\mathbf{B}$ for stationary |
|            | **measure**: from $-0.5$ to $0.4$ | the same |

Table 1
Conditions for successful alignment and the expected measures of the Rayleigh reduction factor $R$. For paramagnetic alignment only the stationarity option is available.
For grains with $a \ll \lambda$ the radiative torques are negligible.