What Grain Alignment Can Tell About Circumstellar Discs and Comets

A. Lazarian
Canadian Institute for Theoretical Astrophysics and Department of Astrophysics of University of Toronto, Toronto, Canada, ON M5S 1A1
e-mail: lazarian@cita.utoronto.ca

ABSTRACT

Grain alignment theory suggests that grains should be aligned in circumstellar regions and the observational data available supports this conclusion. We discuss the alignment of grains via (1) magnetic relaxation, (2) mechanical processes, and (3) radiative torques. We show that ferromagnetic relaxation is likely to be more important than superparamagnetic relaxation if the dust in circumstellar regions is similar to species recently captured in Earth atmosphere. Outflows and stellar winds provide grain streaming along magnetic field lines and therefore mechanical alignment competes with the ferromagnetic and radiative alignments. We estimate measures of grain alignment in circumstellar regions, comets and interplanetary space and conclude that in many circumstellar regions and in the interplanetary space radiative torques may constitute the major alignment mechanism which aligns grain longer axes perpendicular to the direction of magnetic field. Observations in submillimeter and microwave ranges are suggested as a means of disentangling effects of multiple scattering from those related to aligned grains.

Subject headings: ISM: Magnetic field, Polarimetry, Comets, Interplanetary Dust, Zodiacal Light

1. Introduction

Recent years have been marked by significant advances in understanding of grain alignment processes (see Roberge 1996, Lazarian, Goodman & Myers 1997). A number of
new alignment mechanisms have been suggested (e.g. Draine & Weingartner 1996, 1997, Lazarian 1995a) and traditional mechanisms underwent serious revision (see Lazarian & Draine 1997). This process was motivated by new interstellar polarization data (e.g. Goodman 1995, 1996) and, unfortunately, has not made the appropriate impact upon the areas beyond the interstellar domain.

At the same time the number of puzzling results is growing in the areas of comet and circumstellar polarimetry, where it is customary to believe that polarization arises from light scattering on randomly oriented dust grains. In this paper we show that some of these puzzles vanish if grain alignment is accounted for.

Although models of circumstellar regions that invoke aligned grains have been occasionally discussed in the literature (see Dolginov & Mytrophanov 1976, Pudritz, 1986, 1988), their applicability was highly questionable in the absence of the reliable grain alignment theory (see Bastien 1988). On the contrary, recent theoretical advances indicate that grain alignment is likely to be ubiquitous and therefore must be accounted for while modeling circumstellar polarization and the polarization from comets.

In what follows we identify mechanisms of alignment that are most efficient in circumstellar regions and in comet atmospheres (section 2), then touch upon the relation between grain alignment and linear and circular polarization (section 3). In section 4 we discuss grain alignment in circumstellar regions, comets and in interplanetary space. Ways of separating the effects of multiple scattering and those of grain alignment are discussed in section 5 and we summarize our results in section 6. Important but more specialized discussion of ferromagnetic versus superparamagnetic relaxation is given in the Appendix.

2. Grain Alignment

Discovered half a century ago (see Hiltner 1949, Hall 1949), grain alignment continues to be a tough problem for theorists. The dynamics of rapidly rotating dust particles is being influenced both by numerous processes that include gaseous and ion bombardment, plasma effects, interactions with starlight etc. (see more detail in Draine & Lazarian 1998a, 1998b). Chemical processes, e.g. H$_2$ formation that take place on grain surfaces also influence grain dynamics (Purcell 1979, Lazarian 1995b). Moreover, observations suggest a strong dependence of the alignment efficiency on grain sizes. Indeed, interstellar observations can
be only explained if grains with sizes $> 10^{-5}$ cm are aligned, while smaller grains are not (Kim & Martin 1995).

In spite of all these difficulties substantial progress has been recently achieved in understanding of grain alignment processes. A list that includes six major mechanisms was presented in Lazarian, Goodman & Myers (1997) and a number of “exotic” mechanisms have been described there as well. Below we discuss only those of the mechanisms that can be relevant for grain alignment in circumstellar regions and in comet atmospheres. We claim that to succeed in these environments the process must be fast. Therefore slow processes that may well work in the interstellar medium are likely to fail in circumstellar regions. For instance, we do not discuss paramagnetic alignment of suprathermal grains (Lazarian & Draine 1997) that slowly but steadily aligns grains over many gaseous damping times.

To characterise the alignment we use the Rayleigh reduction factor (Greenberg 1968)

$$ R = \frac{3}{2} \langle \cos^2 \beta - \frac{1}{3} \rangle , $$

(1)

where $\langle ... \rangle$ denotes the ensemble average, $\beta$ is the angle between grain axis of maximal inertia and the direction of alignment. We show below that often it is magnetic field that defines direction, even for non-magnetic alignment mechanisms.

In general, grain alignment is non-equilibrium process. Therefore in dark clouds where “classical” grains are in thermodynamic equilibrium with the ambient gas no alignment is observed (Lazarian, Goodman & Myers 1997). To align grains, i.e. to decrease the entropy of their distribution, the entropy of some other system (systems) must increase.

### 2.1. Paramagnetic alignment

The oldest of the alignment mechanisms is the process of paramagnetic relaxation suggested by Davis & Greenstein (1951) and later modified by Purcell (1979), who observed that grains may rotate much faster that was originally thought. To understand the essence of this mechanism it is sufficient to consider a spherical grain which angular velocity makes angle $\beta$ with magnetic field $\mathbf{B}$. The component of angular velocity perpendicular to $\mathbf{B}$, i.e. $\omega \sin \beta$, will cause oscillating remagnetization of the grain, while $\omega \cos \beta$ will not cause oscillations of magnetization. As oscillating magnetization entails dissipation, the component $\omega \sin \beta$ decreases, while $\omega \cos \beta$ stays the same. As the result, $\beta$ decreases.

---

2This is not an exact statement as a recent study by Lazarian & Draine (1998) suggests that very small grains with $a < 10^{-7}$ cm may well be aligned.
Thus magnetic field causes anisotropy in the distribution of grain angular momenta. As non-spherical grains tend to rotate about their axes of maximal moment of inertia (Purcell 1979) the anisotropy in the distribution of angular momentum is being translated into the anisotropy of the distribution of grain longer axes.

Leaving aside the mathematical theory of alignment (Lazarian 1997, 1998, Roberge & Lazarian 1999), that accounts for grains being non-spherical and internal relaxation being not complete, we may claim that the alignment happens on the time scale of paramagnetic relaxation, which for ordinary paramagnetic grains is rather long, e.g.

\[ t_{\text{al}} = 4 \times 10^{12} K_{-13}^{-1} B_{-3}^{-2} a_{-5}^{2} \text{s}, \]

where the lower indexes used to denote the normalization values. For instance, the $K$ function, which is the ratio of the imaginary part of grain magnetic susceptibility $\chi(\omega)$ to its angular velocity $\omega$, was normalized to $10^{-13}$ s. In other words, $K_{-13} \equiv K/(10^{-13} \text{s})$. Similarly, magnetic field is normalized by $10^{-5}$ G and grain size $a_{-5} \equiv a/(10^{-5} \text{cm}).$

Grain rotation can be randomized by gaseous bombardment on time scales

\[ t_{\text{gas}} = 6 \times 10^{11} n_{10}^{-1} T_{\text{gas,5000}}^{-1/2} a_{-5} \text{s}, \]

where $n_{10} \equiv n/(3 \text{ cm}^{-3})$, $T_{\text{gas,5000}} \equiv T_{\text{gas}}/(5000 \text{ K})$. In the equation above the environmental parameters are taken rather arbitrary and for particular cases the more relevant values should be substituted. Moreover the estimate for $t_{\text{gas}}$ must be reduced nearly an order of magnitude if gas is ionized (see Anderson & Watson 1993, Draine & Lazarian 1998a). The latter effect is the consequence of higher efficiency of plasma interactions with a charged grain compared to gas-grain interactions.

To obtain efficient paramagnetic alignment $t_{\text{al}}$ should be much less than $t_{\text{gas}}$. Therefore grains with superparamagnetic and ferromagnetic inclusions (Jones & Spitzer 1967, Mathis 1986, Martin 1995, Draine 1996, Draine & Lazarian 1998c) are to be considered.

How abundant ferro- and superparamagnetic grains in comet environment and circumstellar regions is not clear. The presence of small $\text{FeNi}$ and $\text{FeNiS}$ inclusions in particles coming from the interplanetary space has been recently reported (Bradley 1994) and this supports the case for “super” grains (Goodman & Whittet 1996). Our analysis of the particle image in figure 1 in Goodman & Whittet (1996) indicates that most of the inclusions are too large to exhibit superparamagnetic response for $\omega > 10^6 \text{s}^{-1}$ (see

\[ \text{In circumstellar regions “classical” grains of 0.1 \mu m size rotate much faster due to the action of radiative torques.} \]
Appendix). However, our calculations in the Appendix prove that the ferromagnetic response of grains with iron inclusions provides enhancement of the paramagnetic relaxation by a factor $10^3 - 10^4$ if the volume filling factor of inclusions is $\sim 0.01$ as we roughly estimated from the figure in Goodman & Whittet (1996). The decrease of paramagnetic alignment time $t_{al}$ by the factor $10^4$ arising from ferromagnetic inclusions makes $t_{al} \sim 4 \times 10^8$ s. This seems sufficient for circumstellar alignment but may be slow for comet grain alignment.

### 2.2. Mechanical Alignment

Another mechanism of grain alignment stems from mechanical interaction of grains with streaming gas. Suggested initially by Gold (1952) for grains rotating with thermal velocities, the mechanical alignment has been recently proved to be efficient for grains rotating with much higher velocities (Lazarian 1994a, Lazarian 1995a, Lazarian & Efroimsky 1996, Lazarian, Efroimsky & Ozik 1996). Such high (suprathermal) velocities arise from uncompensated quasi-regular torques, e.g. from torques arising from H$_2$ formation over catalytic sites on grain surface (Purcell 1975, 1979). These sites act as rocket engines and their action spins up the grain. The number of sites over grain opposing surfaces, in general, is different and this causes a regular spin-up.

The original Gold’s idea is based on the observation that when a flow of gas interacts with an elongated grain the angular momentum deposited with the grain tends to be directed perpendicular to the flow. Accounting for suprathermal rotation and the presence of magnetic field makes the process of alignment a bit more involved (see Lazarian 1995a).

The necessary condition for the mechanical alignment is the supersonic relative motion of grains and gas. If this condition is not satisfied isotropic gaseous bombardment randomizes grains (see eq. (25) in Lazarian 1997a). The rule of thumb for mechanical alignment is that the process tends to minimize gas-grain cross section of interaction$^4$.

It is easy to see that, unlike paramagnetic alignment, the mechanical one is not directly connected with the action of the ambient magnetic field. However, in many cases mechanical processes align grains either parallel or perpendicular to the direction of magnetic field. This is the consequence of grain rapid precession about magnetic field. Indeed, a rotating grain acquires a magnetic moment via the Barnett effect (Dolginov & Mytrophanov 1976, Purcell 1979) and this magnetic moment precesses in the external magnetic field with the

---

$^4$This is not true, however, for the process of alignment through friction described in Lazarian (1995a). A detailed discussion of the joint action of various alignment processes will be given elsewhere.
period
\[ t_L = 2 \times 10^5 B_{-5}^{-1} a_{-5}^2 \text{ s} \quad . \tag{4} \]

If \( t_L \) is much shorter than the time of mechanical alignment \( t_{\text{mech}} \), external magnetic field defines the axis of alignment.

\( t_{\text{mech}} \) is different for thermally and suprathermally (much faster than thermally) rotating grains. In the former case \( t_{\text{mech}} \) can be defined as a time during which the angular momentum of a grain changes by the value of its thermal angular momentum \( J_{\text{th}} = (kT_{\text{gas}}/I)^{1/2} \), where \( I \) is the grain moment of inertia. In the case of suprathermally rotating grains \( t_{\text{mech}} \) is the time between crossovers, i.e. moments when grain angular velocity approaches zero and the grain flips over (see Lazarian & Draine 1997).\(^5\) The time between crossovers is approximately the sum of the gaseous damping time \( t_{\text{gas}} \) and a rather uncertain time of grain resurfacing (see Spitzer & McGlynn 1979, Lazarian 1995a). When \( t_{\text{mech}} \ll t_L \) the alignment happens in respect to the direction of gas-grain relative motion. One could expect that in circumstellar regions both situations \( t_{\text{mech}} > t_L \) and \( t_{\text{mech}} < t_L \) may be present. However, in many cases violent outflows of plasma are likely to deform magnetic field lines and therefore the correlation of the magnetic field and the direction of alignment is expected even for \( t_{\text{mech}} \ll t_L \). Also note that grains carry electric charge (Martin 1972) and therefore tend to follow magnetic field lines.

A number of processes can cause the relative grains-gas drift. Stellar winds, outflows are examples of processes that would tend to align grains with long axis along magnetic field lines. Ambipolar diffusion in Roberge & Hanany (1990) and Alfvén waves in Lazarian (1994a) were suggested as the processes that can mechanically align grains perpendicular to magnetic field lines. In circumstellar regions and comet atmospheres we expect mechanical alignment to happen mostly along magnetic field lines.

2.3. Radiative Torques

The third mechanism that is likely to be dominant in circumstellar regions is based on the action of radiative torques. Although mentioned first in Dolginov (1972) and Dolginov & Mytrophanov (1976) this process has not been considered seriously until very recently. Draine & Weigartner (1996, 1997) rediscovered the mechanism and proved using the DDA code that radiative torques (1) can be the dominant source of grain suprathermal rotation.

\(^5\)Crossovers happen due to the occasional change of the direction of quasi-regular torques. As this direction changes a grain first spins down then flips over and spins up.
and that (2) these torques can align grains with the longer directions perpendicular to magnetic field. The origin of the latter fact is not clear and this tendency contradicts to the conclusions in Dolginov & Mytrophanov (1976). Nevertheless, treating the properties of radiative torques as established experimentally we have to conclude that this alignment mechanism should be very important in circumstellar regions where the radiation flux is orders of magnitude higher than that in the interstellar environment. Note, that even in the interstellar medium radiative torques constitute a major mechanism of rotation for sufficiently large, e.g. $a > 10^{-5}$ cm, grains. Within circumstellar regions with enhanced UV flux smaller grains can 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) that has been interpreted as the 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 in their circumstellar regions, this may explain why no similar effect is observed along other lines of sight.

Radiative torques work in unison with paramagnetic relaxation. The situation is less clear when mechanical alignment tends to align grains along magnetic field lines, while radiative torques act to align grains perpendicular to magnetic field lines. It takes radiative torques at least a few gaseous damping times to align grains while mechanical alignment can happen in one crossover time. For particular angles between the direction of the incoming radiation and magnetic field the grains perform numerous crossovers. This means that in these situations the mechanical alignment should dominate. The theory of crossovers in the presence of radiative torques is being developed (Draine & Lazarian, work in progress) and we hope to learn soon at what conditions the mechanical alignment can win.

3. Polarization

Grain alignment theory can supply $R$. The observations can get Stocks parameters. To compare observations and the theory one should related $R$ to polarization. Because different definitions of $R$ have appeared in the literature and confusing statements have been made in relation to circular polarization of circumstellar origin, we find a brief discussion of this subject appropriate.

---

6Analytical results in Dolginov & Mytrophanov (1976) do not explain grain spin-up when the radiation is isotropically distributed. This fact was noted to me by Lyman Spitzer, Jr.

7A peculiarity of the radiative torque mechanism is that the gas acts as a cooling reservoir.
3.1. Linear Polarization from Aligned Grains

For an ensemble of aligned grains the extinction perpendicular the direction of alignment and parallel to it will be different. Therefore the electromagnetic wave that initially was not polarized acquires polarization.

To characterize the process quantitatively one can 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 $C_x^o$ and $C_y^o$ 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 Martin 1974, Lee & Draine 1985).

To calculate $C_x^o$ and $C_y^o$ 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. When the transformation is carried out and the resulting expressions are averaged over precession angles, one finds that the mean cross sections are

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

where $\zeta$ is the angle between the polarization axis and the $\hat{x}^o \hat{y}^o$ plane,

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

where $C_{\text{avg}} \equiv \left( 2C_\perp + C_\parallel \right) / 3$ is the effective cross section for randomly-oriented grains.

3.2. Circular Polarization from Aligned Grains

One of the ways of obtaining circular polarization is to have 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 polarized. 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 rize 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)

\[
V(e, e_0, e_1) = \frac{I_0 k^4}{2 r^2} i(\alpha_{||}^* - \alpha_{\perp}^*) (\hat{e}_0 \times \hat{e}_1) (\hat{e}_0 \hat{e}_1),
\]

(7)

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; \( \alpha_{\perp} \) and \( \alpha_{||} \) are particle polarizabilities along \( e \) and perpendicular to it.

The intensity of the circular 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)

\[
\Delta V(d, r) = \frac{L_\star n_{dust} \sigma_V}{6 \pi |d|^4 |r|^2} R (\hat{d} \times \hat{r}/h) (\hat{d} \Delta \Gamma(d, r) \hat{r}^2),
\]

(8)

where \( L_\star \) is the stellar luminosity, \( n_{dust} \) is number density of dust grains and \( \sigma_V \) is the cross section for producing circular polarization, which is for small grains is

\[
\sigma_V = i/(2k^4)(\alpha_{||}^* - \alpha_{\perp}^*),
\]

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 expects from the process of varying magnetic field direction along the line of sight.

4. Particular cases

4.1. Circumstellar Regions

Multiple scattering has been used to explain polarization arising from circumstellar regions (see Bastien 1988, 1996). At the same time it is obvious that in the presence of radiation and magnetic field, grains in circumstellar envelops must be aligned perpendicular to magnetic field. For the stars that exhibit outflows and intensive stellar winds, numerical models (see Netzer & Elitzur 1994) predict a supersonic relative drift of grain and gas and this should result in mechanical alignment. In circumstellar environments the grain rotation temperature is likely to be much higher than its body temperature. Therefore results for mechanical obtained in Lazarian (1994a) and Lazarian (1995a) are applicable. This entails \( R \sim -0.3 \) for both prolate and oblate grains with grain long axis along the outflow direction. The uncertainty involved, as we have mentioned earlier, is related to the absence of the theory of radiative crossovers. We may claim that our estimate of \( R \) is valid for sufficiently small (e.g. \( a < 5 \times 10^{-6} \) cm) grains, while for larger grains the situation is unclear as yet.

If grains have superparamagnetic or ferromagnetic inclusions and for radiative torques the alignment tends to be nearly perfect (i.e. \( R \sim 1 \)) with the logner grain dimensions
perpendicular to magnetic field lines. If, however, a grain with ferromagnetic inclusions (e.g. “Goodman-Whittet grain” discussed above) is subjected to streaming along field lines, it will be aligned perpendicular to magnetic field lines as the magnetic relaxation time is typically shorter than that for mechanical alignment. We tend to believe that grain alignment with grain longer axes perpendicular to magnetic field and $R \sim 1$ can be a rule for circumstellar regions. Future research should test this conjecture.

The examples above indicate that future modeling of circumstellar regions should include aligned grains. Whether multiple scattering or dichroic adsorption is dominant should be decided by quantitative comparison of the simulations that include both effects and observations. Submillimeter polarimetry will be helpful for establishing grain alignment in circumstellar regions (see below).

4.2. Comets

Polarization from comets has been long known to exhibit anomalies (see Martel 1960) that motivated a conjecture that grains may be aligned in the comet atmospheres (see Dolginov & Mytrophanov 1976). Later studies of linear and circular polarization from Halley and Hale-Bopp comet (Beskrovnaja et al 1987, Ganesh et al 1998) seem to support this conclusion.

The alignment mechanism operating in comet heads should be really fast. Indeed, dust particles spend only $\sim 10^5$ s crossing a comet head. Unless magnetic field in the comet head is extremely high (e.g. $> 10^{-2}$ G) the ferromagnetic relaxation fails to provide the alignment. In comet heads grains are likely to disaggregate and change their shape rather rapidly. This should mitigate the importance of radiative torques that will change their direction with the change of grain shape. At the same time, dramatic changes of grain shapes on the timescale $t_{\text{mech}}$ wash out the distinction between prolate and oblate grains and hinder the mechanical alignment as well.

We believe that outflowing gases can be important for grain alignment at the comet head. Calculations in Probstein (1969) indicate that the relative velocities of dust and gas are supersonic. We expect the alignment for thermally rotating grains to be small (e.g. $R \sim -0.1$) and to happen in respect to the outflow direction. Higher degrees of alignment are possible (e.g. $R \sim -0.3$) if grains rotate suprathermally. Indeed, both radiative torques and asymmetry in the gas evaporation from grain surface may contribute to suprathermal rotation. Very large dust particles (e.g. $a > 10^4$ cm) may be aligned by a weathercock mechanism discussed in Lazarian (1994b).
Later, in the outer parts of comet coma and in its tail the alignment via radiative torques and interaction with solar wind should be important. $R$ approaching unity is attainable in the former case. Quantitative modeling of the grain alignment in comets is under way (Bastien & Lazarian, work in progress).

### 4.3. Zodiacal Light

Zodiacal Light, i.e. solar light reflected from the interplanetary dust particles, is partially polarized. Greenberg (1970) suggested that interplanetary grains could be aligned. Later on similar ideas were discussed by e.g. Wolstencroft & Kemp (1972) and Dolginov & Mytrophanov (1978).

Greenberg (1970) worried that interplanetary particles can be sputtered quicker than be aligned by solar wind. However, his arguments ignore important plasma interactions and ion focusing effect (see Draine & Lazarian 1998b) that make transfer of angular momentum from solar wind to grains much more efficient. Thus mechanical alignment is concivable ($R \sim -0.3$) with grain long axis along magnetic field lines.

The alignment by radiative torques and via ferromagnetic relaxation are possible as well. If large silicate grains that produce most of the linear polarization are aligned along magnetic field lines, while a possible population of absorptive iron grains that would account for most of the circular polarization are aligned perpendicular to interplanetary magnetic field, quite complex picture of polarization may arise. However, it is likely that mechanical alignment is most important for small ($a < 5 \times 10^{-6}$ cm) grains, while larger grains are being aligned by radiative torques. Then both small iron grains and large silicate ones are being aligned with long axes perpendicular to the direction of the interplanetary magnetic field. Potentially, studies of Zodiacal Light can bring a lot of information about magnetic field structure and its variability in the Solar neighborhood.

The interplanetary magnetic field, as well as those of circumstellar regions and comets, is not stationary. In fact it undergoes 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 time variations of the Zodiacal Light can provide important information on the magnetic variability up to the scale $t_L$. 
5. Future Work

It is often difficult to separate the effects of multiple scattering from the effects of grain alignment. One of the alluring possibilities is to observe at longer wavelengths, where the effects of multiple scattering are negligible. Polarimetry at submillimeter and longer wavelengths should help constructing adequate models of polarized light transfer in circumstellar regions and comets and unravel magnetic field structure in these regions.

Our discussion above was centered on the issue what “classical” or sufficiently large grains can tell us. It looks, however, that very small grains can make a valuable input as well. Recent experiments to map cosmic microwave background, e.g. Kogut et al (1996), Oliveira-Costa et al (1997) and Leitch et al (1997), have revealed a new component of galactic microwave emission at 14 - 90 GHz. This component was identified by Draine & Lazarian (1998a) with the dipole emission from small ($a < 10^{-7}$ cm) rotating grains. Lazarian & Draine (1998) predicted that such grains can be aligned and that this should result in anomalous emission being partially polarized. This opens a new valuable window for interstellar and circumstellar studies. An important feature of the relaxation mechanism suggested is that it stays efficient even when “classical” grains are in thermodynamic equilibrium with the ambient gas and are randomly oriented. Thus the progress in grain alignment theory presents new tools for observers.

6. Conclusions

The principal results of this paper are as follows:

The application of the results obtained in grain alignment theory to comets and circumstellar regions suggest that the dust should be aligned there. Three most important alignment mechanisms are (1) radiative torques, (2) mechanical alignment, (3) ferromagnetic and superparamagnetic relaxation. Observational data supports the conjecture that the dust is aligned in circumstellar regions and comets. Therefore numerical codes that describe radiation transfer in young stellar objects and evolved stars should be modified to account for dust alignment.

The analysis of the images of the dust particles coming from the interplanetary space testify that the ferromagnetic relaxation, rather that superparamagnetic relaxation is likely. The calculated enhancement of the relaxation (compared to that in paramagnetic grains) is $\sim 10^4$ and is sufficiently large to enable the efficient alignment of circumstellar dust with ferromagnetic inclusions.
Mechanical alignment and radiative torques compete in aligning grains, (along and perpendicular magnetic field lines, respectively) in the regions of outflows. When streaming velocities are supersonic small grains ($a < 5 \times 10^{-6} \text{ cm}$) without ferromagnetic inclusions are to be aligned with long axes parallel to magnetic field lines, while those with ferromagnetic inclusions are to be aligned with long axes perpendicular to the field lines. The situation is still unclear with large ($a > 10^{-5} \text{ cm}$) grains, but we conjecture that at least in circumstellar regions and interplanetary space grains are aligned with long axes perpendicular to magnetic field.

Both linear and circular polarization provide a valuable input on magnetic fields in circumstellar regions, comet atmospheres and in the Solar neighborhood. Measurements at submillimeter wavelengths can disentangle effects of multiple scattering from those of grain alignment. In particular cases when large grains are not aligned it is advisable to use microwave polarimetry that is sensitive to the alignment of tiny ($a < 10^{-7} \text{ cm}$) grains.

Acknowledgements

I am grateful to Pierre Bastien, Bruce Draine, Alyssa Goodman and Peter Martin for helpful discussions and happy to acknowledge the support of NASA grant NAG5 2858 and CITA Senior Research Fellowship.

A. Ferromagnetic and Superparamagnetic Susceptibilities

How superior can be “supergrains” in terms of paramagnetic relaxation? To answer this question we consider iron inclusions. It is well known that small iron particles are superparamagnetic (Morrish 1980). If iron forms clusters containing $N$ atoms the zero-frequency magnetic susceptibility of a grain increases $N$ times compared with a grain where the same amount of iron is uniformly distributed within a diamagnetic lattice (Draine 1996):

$$\chi(0)_{\text{super}} \approx N\chi_{\text{param}} \quad , \quad (A1)$$

where

$$\chi_{\text{param}} \approx 0.04 f_p \left( \frac{n_{\text{tot}}}{10^{23} \text{ cm}^{-3}} \right) \left( \frac{p}{5.5} \right)^2 \left( \frac{15 \text{ K}}{T_{\text{grain}}} \right) \quad . \quad (A2)$$

Above $p\mu_B$ is the magnetic moment of a paramagnetic ion, $\mu_B = e\hbar/2m_e c$ is the Bohr magneton and $n_p = f_p n_{\text{tot}}$ is the number of paramagnetic ions in a grain with density $n_{\text{tot}}$. Within interstellar grains $f_p$ is of the order of 0.1. We use this value as a rough estimate for the circumstellar and cometary dust.
How large can be a particle to exhibit superparamagnetic response in oscillating magnetic field with frequency $\omega$ depends on the thermally activated relaxation rate

$$\tau_{\text{activ}} \approx \nu_0 \exp[-NT_{\text{activ}}/T_{\text{grain}}]$$  \hspace{1cm} (A3)

where $T_{\text{activ}} \approx 0.011$ K and $\nu_0 \approx 10^9$ s for Fe particles (Bean & Livingston 1959).

For $\tau_{\text{activ}} \omega \ll 1$ $K(\omega)$ super that is equal to the imaginary part of $\chi(\omega)_{\text{super}} / \omega$ is approximately $\chi_{\text{super}} \tau_{\text{activ}}$ (Spitzer 1978). When $\tau_{\text{activ}} \omega > 1$ $K(\omega)$ super rapidly decreases with $\omega$ (Jones & Spitzer 1968, Draine & Lazarian 1998c). It is easy to show that the number of iron atoms should not exceed $3 \times 10^3$ to enable efficient paramagnetic relaxation of grains rotating faster than $10^5$ s$^{-1}$. Therefore the maximal value of $K_{\text{super}}$ is approximately $3 \times 10^3 \chi_{\text{param}} \tau_{\text{activ}} \approx 3 \times 10^{-6} \chi_{\text{param}}$. This value should be compared to $K_{\text{param}}$ which is approximately $3 \times 10^{-11} \chi_{\text{param}}$ (see Draine 1996). All in all, the maximal increase of relaxation due to superparamagnetism is given by a factor $10^5$.

The latter factor of the relaxation enhancement is frequently quoted in the literature without mentioning that, first of all, this is an upper limit for superparamagnetic relaxation enhancement and, even more important, that inclusions of larger size do not exhibit superparamagnetic response for $\omega > 10^5$ s$^{-1}$. The minimal number of paramagnetic atoms that make up a superparamagnetic inclusion is uncertain. We know that inclusions with more than 20 atoms do exhibit superparamagnetism (Billas, Chatelain & de Heer 1994). For 30 atom inclusions the superparamagnetic relaxation is $10^3$ times enhanced. Inclusions with more than 3000 atoms will exhibit ferromagnetic properties.

The magnetic susceptibility of large particles follows from the solution of the Bloch equations (see Pake 1962)

$$\chi(\omega) \approx \chi_{Fe}(0) \frac{\omega}{1 - (\omega/\omega_0)^2 - i\omega\tau}$$  \hspace{1cm} (A4)

where $\chi(0)$ is the zero frequency magnetic susceptibility and $\omega_0$ and $\tau$ are two parameters that have the meaning of the characteristic frequency and time. To approximate experimental results available (see Epstein 1954) one can assume that $\chi_{Fe} \approx 10$, $\tau \approx 10^{-9}$ s and $\omega_0 \approx 10^{10}$ s$^{-1}$ (Draine & Lazarian 1998c). The susceptibility of a grain with large inclusions may be estimated using effective medium theory (Bohren & Huffman 1984). For a small volume filling factor $\phi \ll 1$

$$\chi_{\text{eff}} \approx \frac{\phi \chi(\omega)}{1 + 2\pi \chi(\omega)}$$  \hspace{1cm} (A5)

where $\chi(\omega)$ is given by Eq. (A4). Therefore for the volume filling factor of 0.01 the efficiency of relaxation for grains with ferromagnetic inclusions is approximately $10^4$ times that of
a paramagnetic grain. More elaborate calculations show that grains with single domain
inclusions exhibit susceptibilities which are a factor 5 smaller than those found above for
the multidomain $Fe$ inclusions (Draine & Lazarian 1998c).

REFERENCES

Anderson, N. & Watson, W.D. 1993, A& A, 270, 477

Bastien, P. 1988, in “Polarized Radiation of Circumstellar Origin”, eds. G.V. Coyne, A.M.
Magalhaes, A.F.J. Moffat, R.E. Schulte-Ladbeck, S. Tapia, D.T. Wickramasinghe,
Vatican Observatory, p. 541

Bastien, P. 1996, in Polarimetry of the Interstellar Medium, eds Roberge W.G. and Whittet,
D.C.B. p. 297

Bean, C.P., & Livingston, J.D., 1959, J. Appl. Phys., 30, Suppl. 120S

Beskrovnaja, N.G., Silantev N.A., Kiselev, N.N., & Chrenova, G.P., 1987, in “Diversity and
Similarity of Comets, Burssels, ESA SP-278, p. 681

Billas, I.M., Chatelain, A., & de Heer, W.A. 1994, Science, 265, 1682

Bradley, J.P. 1994, Science, 265, 925

Bohren, C.F., & Huffman, D.R. 1983, Absorption and Scattering of Light by Small Particles,
NY: Wiley

Davis, J., & Greenstein, J.L. 1951, ApJ, 114, 206

de Oliveira-Costa, A., Kogut, A., Devlin, M.J., Netterfield, C.B., Page, L.A., & Wollack,
E.J. 1997, ApJ, 482, L17

Dolginov, A.Z. 1972, Ap&SS, 16, 337

Dolginov, A.Z. & Mytrophanov, I.G. 1976, ApSS, 43, 257

Dolginov, A.Z. & Mytrophanov, I.G. 1978, A&A, 69, 421

Draine, B.T. 1996, in Polarimetry of the Interstellar Medium, eds Roberge W.G. and
Whittet, D.C.B., p.16

Draine, B.T., & Weingartner J.C. 1996, ApJ, 470, 551.
Draine, B.T., & Weingartner J.C. 1997, ApJ, 480, 633
Draine, B.T., & Lazarian A. 1998a, ApJ, 494, L19
Draine, B.T., & Lazarian A. 1998b, ApJ, accepted
Draine, B.T., & Lazarian A. 1998c, astro-ph 9807009
Epstein, D.J. 1954, in “Dielectric Materials and Applications”, ed. A. von Hippel, New York: Wiley, 122
Ganesh, S. et al. 1998, A & A Suppl. 129, 489
Gold, T. 1951, Nature, 169, 322
Goodman, A.A. 1996, in Polarimetry of the Interstellar Medium, eds Roberge W.G. and Whittet, D.C.B. p. 325
Goodman, A.A. & Whittet, D.C.B. 1995, ApJ, 455, L181
Greenberg J.M. 1968, in Nebulae and Interstellar Matter, eds B.M. Middlehurst and L.H. Aller, University of Chicago Press, Chicago, p. 221.
Greenberg, J.M. 1970, Space Research X, p. 225
Hall, J.S. 1949, Science, 109, 166
Hiltner, W.A. 1949, ApJ, 109, 471
Jones, R.V., & Spitzer, L.,Jr 1967, ApJ, 147, 943
Kim, S.-H., & Martin, P., G. 1995, ApJ, 444, 293
Kogut, A., Banday, A.J., Bennett, C.L., Gorski, K.M., Hinshaw, G., & Reach, W.T. 1996, ApJ, 460, 1
Lazarian, A. 1994a, MNRAS, 268, 713
Lazarian, A. 1994b, Ap&SS, 216, 235
Lazarian, A. 1995a, ApJ, 451, 660
Lazarian, A. 1995b, MNRAS, 274, 679
Lazarian, A. 1997a, ApJ, 483, 296
Lazarian, A. 1997b, MNRAS, 288, 609
Lazarian, A., & Draine, B.T. 1997, ApJ, 487, 248
Lazarian, A., & Draine, B.T. 1998, BAAS, 28, No.4, 1294
Lazarian, A., & Efroimsky, M. 1996, ApJ, 466, 274
Lazarian, A., Efroimsky, M. & Ozik J. 1996 ApJ, 472, 240
Lazarian, A., Roberge, W.G. 1997 ApJ, 484, 230
Lee, H.-M., & Draine, B.T. 1985, ApJ, 290, 211
Leitch, E.M., Readhead, A.C.S., Pearson, T.J., & Myers, S.T. 1997, ApJ, 486, L23
Martin, P.G. 1971, MNRAS, 153, 279
Martin, P.G. 1972, MNRAS, 155, 283
Martin, P.G. 1974, ApJ, 187, 461
Martin, P.G. 1978, Cosmic Dust, Oxford: Clarendon
Martin, P.G. 1995, ApJ, 445, L63
Mathis, J.S. 1986, ApJ, 308, 281
Menard, F., Bastien P. & Robert, C 1988, ApJ, 335, 290
Morrish, A.H. 1980, The Physical Principles of Magnetism, NY: R.E. Krieger
Netzer, N., & Elitzur, M. 1993, ApJ, 410, 701
Pake, G.E. 1962, Paramagnetic Resonance, NY, W.A. Benjamin
Probstein, R.F. 1969, in “Problems of Hydrodynamics and Continuum Mechanics”, ed. M.A. Lavrentev, Philadelphia, p. 568
Pudritz, R.E. 1986, Pub. Ast. Soc. Pacific, 98, 709
Pudritz, R.E. 1988, in Galactic and Extragalactic Star Formation, eds. R. Pudritz and M. Fish, Dordrecht, Reidel, p. 135
Purcell E.M. 1975, in The Dusty Universe, eds G.B. Field & A.G.W. Cameron, New York, Neal Watson, p. 155.
Purcell E.M. 1979, ApJ, 231, 404.

Roberge, W.G. 1996 in Polarimetry of the Interstellar Medium, eds Roberge W.G. and Whittet, D.C.B. p. 401

Roberge, W.G., & Hanany, S. 1990, B.A.A.S., 22, 862

Roberge, W.G., Hanany, S., Messinger, D.W. 1995, ApJ, 453, 238

Roberge, W.G., DeGraff, T.A. & Flaherty, J. 1993, ApJ, 418, 287

Roberge, W.G., & Lazarian, A.L. 1999, MNRAS, submitted

Schmidt, Th. 1972, IAU Symp. 52, Albany, NY, p.

Spitzer, L., Jr 1978, Physical Processes in the Interstellar Medium, NY: Wiley

Spitzer, L., Jr, & McGlynn, T.A. 1979, ApJ, 231, 417.

Wolstencroft, R.D., Kemp, J.C. 1972, ApJ, 147, 271