SUBSONIC MECHANICAL ALIGNMENT OF IRREGULAR GRAINS

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ABSTRACT

We show that grains can be efficiently aligned by interacting with a subsonic gaseous flow. The alignment arises from grains having irregularities that scatter atoms with different efficiency in the right and left directions. The grains tend to align with long axes perpendicular to magnetic field, which corresponds to Davis-Greenstein predictions, but does not involve paramagnetic dissipation. Choosing conservative estimates of the scattering efficiency of impinging atoms and a conservative “degree of helicity” of grains, the alignment of helical grains is much more efficient than the Gold-type alignment processes.

Subject headings: dust, extinction — ISM: magnetic fields — polarization

Online material: color figure

1. INTRODUCTION

One of the most convenient ways to trace magnetic field is related to emission and absorption of polarized radiation by aligned dust. Therefore aligned dust is widely used for this purpose, both in diffuse interstellar medium and molecular gas. Moreover, there is evidence of aligned dust around young stellar objects and evolved stars, as well as in other astrophysical environments. At the same time, the processes that aligned dust and their relation to magnetic field are still the subject of debates and require further studies (see Lazarian 2007 for a review). While radiative torques (Dolginov & Myrophanov 1976; Draine & Weingartner 1996, 1997; Weingartner & Draine 2003; Cho & Lazarian 2005; Lazarian & Hoang 2007; Hoang & Lazarian 2007) are currently seen as the most promising candidate mechanism, the variety of astrophysical conditions may enable other mechanisms to dominate in particular environments.

Mechanical alignment was pioneered by Gold (1952a, 1952b) and then quantified and elaborated by other researchers (e.g., Purcell 1969; Purcell & Spitzer 1971; Dolginov & Myrophanov 1976; Lazarian 1994, 1997; Roberge et al. 1995). While the original mechanism could deal with thermally rotating grains only, two modifications of the mechanism introduced in Lazarian (1995) and elaborated later in Lazarian & Efroimsky (1996) and Lazarian et al. (1996) enabled the alignment of grains rotating at much higher rates, i.e., at suprathermal rates. The latter were introduced to the field by Purcell (1979) (see also Lazarian & Draine 1999a, 1999b, where the limitations on the size for suprathermally rotating grains are discussed).

The main shortcoming of the mechanical alignment processes was that they required supersonic gas-dust drift to get any appreciable degree of alignment (see Purcell 1969). Although later studies indicated that such drifts can be produced by ambipolar diffusion (Roberge & Hanany 1990; Roberge et al. 1995) or interactions of charged grains with MHD turbulence (Lazarian 1994; Lazarian & Yan 2002; Yan & Lazarian 2003; Yan et al. 2004), the degree of alignment that is achievable for the Mach number drifts of order unity is insufficient to explain observations (see estimates in Lazarian 1997).

The possibility of subsonic flows mechanically aligning grains was mentioned in passing in Lazarian (2007) and Lazarian & Hoang (2007, hereafter LH07), but no relevant calculations were provided there. This possibility is related to irregular grains demonstrating helicity, i.e., the ability of spin up in a regular way while interacting with a flow of particles.

2. TOY MODEL OF A HELICAL GRAIN

In LH07 radiative torques that arise from the interaction of photons with a grain were considered. Similar torques, however, should emerge when atoms bombard the surface of an irregular grain.

In Figure 1 we provide a simple model1 of a helical grain. The grain consists of an oblate spheroid or an ellipsoid with a mirror attached to it at an angle $\pi/4$. This renders the grain with helicity, as explained in § 3.3 in LH07. The difference with LH07 is that we assume that the mirror is reflective to atoms rather than photons.

For our purposes in this Letter, the actual properties of a spheroid or an ellipsoid do not matter. Those geometric shapes are too symmetric and do not produce torques that can spin up a grain in a regular way, i.e., with angular velocity growing in proportion to time. The stochastic, i.e., with angular velocity growing as a square root of the time, spin up is the essence of the Gold-type alignment processes and is ignored here, where we deal with subsonic flows. For the sake of simplicity, we assume that the Larmor precession of the grain in the external magnetic field is much faster than precession arising from the interaction of the ellipsoidal body with the gaseous flow. As a result, following arguments similar to those in LH07, one can disregard the effects of the gaseous flow on the ellipsoidal body altogether. Thus, the only torques to consider are those arising from the mirror. As in LH07, the major role of the ellipsoidal body is to provide steady rotation about its axis corresponding to the maximal moment of inertia.

The difference between the calculations in LH07 and those in the current Letter stems from the fact that, while in LH07 the photons are coming as a beam from a single direction, for the subsonic flow that we deal with, atoms hit the mirror from all directions characterized by the flux of atoms given by equation (2). This induces averaging of the torques that we implement below.

1 Historically, simple models played an important role in developing models of mechanical alignment (see Gold 1952a, 1952b).
3. TORQUES ON A HELICAL GRAIN

Consider a helical grain (see Fig. 1) drifting across a gas chamber with a velocity \( \mathbf{v} \) along the \( \mathbf{e}_1 \) axis. The velocity of an atom with respect to the grain is \( \mathbf{v} - \mathbf{v}_t \), where \( \mathbf{v}_t \) is the thermal velocity of the atom. The torque arising from the perfect reflecting of atoms from a surface area \( A \) of the mirror is given by

\[
d\mathbf{T} = (r \times \Delta P)A\mathbf{f}(s - s_d)ds,
\]

where \( s = \mathbf{v}/v_{th} \), \( ds \equiv ds_1ds_2ds_3 \), \( v_{th} = (kT_{gas}/2m_0)^{1/2} \), \( r = l_1\hat{r} \) is the radius vector directed from the spheroid to the mirror, \( s_d = \mathbf{v}/v_{th} \), \( A \) is the surface area of the mirror, and

\[
f(s - s_d) = m v_{th} (s - s_d) \cdot N e^{-\gamma s^2} \quad \text{for} \quad (s - s_d) \cdot N < 0 \tag{2}
\]

is the flux per unit area of incoming atoms. Here \( N \) is the normal vector, which is a function of angles \( \alpha, \beta \) describing the orientation of the grain in the lab system defined by \( \hat{e}_1, \hat{e}_2, \) and \( \hat{e}_3 \) (see Fig. 1), as given in LH07.\(^2\) Angular momentum element \( \Delta P \) is antiparallel to the normal vector and is given by

\[
\Delta P = -2m v_{th} N|\mathbf{v} - \mathbf{v}_t| \cos \gamma, \tag{3}
\]

where \( \cos \gamma = -(\mathbf{v} - \mathbf{v}_t) \cdot N/|\mathbf{v} - \mathbf{v}_t| \). Substituting equations (2) and (3) into equation (1), we get

\[
d\mathbf{T} = 2nm v_{th}^2 (r \times N)[(s - s_d) \cdot N]A e^{-\gamma s^2}ds. \tag{4}
\]

Taking into account the contribution from the reflection on the other surface, total torque becomes then

\[
d\mathbf{T} = 2nm v_{th}^2 (r \times N) \int_{(s - s_d) \cdot N < 0} [(s - s_d) \cdot N]^2A e^{-\gamma s^2}ds
\]

\[
-2nm v_{th}^2 (r \times N) \int_{(s - s_d) \cdot N > 0} [(s - s_d) \cdot N]^2A e^{-\gamma s^2}ds. \tag{5}
\]

\(^2\) \( N \) is given by eq. (B6) in LH07, where \( n_\alpha = -\sin \alpha \) and \( n_\gamma = \cos \alpha \) are components of \( N \) in the grain coordinate system.

4. GRAIN ALIGNMENT WITH RESPECT TO MAGNETIC FIELD \( B \)

When the Larmor precession of a grain is larger than the precession induced by the mechanical torques (see § 11.6 in LH07) the alignment happens with respect to magnetic field.
is efficient or not. The maximal rotational velocity of grains
convenient to have a simple criterion of whether the alignment
However, rather than tracing phase trajectories, it is practically
anism of paramagnetic relaxation predicts, but the process we
(see Yan & Lazarian 2003), the angular momentum $J$ can be further decreased by a factor 100. The horizontal line corresponds to $J_{\text{max}} = 3J_{\text{therm,gas}}$ which presents the threshold for grain alignment obtained in Hoang & Lazarian (2007).

induced by torques can be used for this purpose. A study in Hoang & Lazarian (2007), which solves the Laggevin equation in order to account for randomizing gaseous bombardment, shows that this velocity, which is a function of $\psi$, should be approximately 3 times larger than the thermal rotational velocity of the grain.

For practical calculations of the rotational velocity we assume that 10% of the atoms impinging on the grain mirror are reflected. Figure 4 shows the angular velocity of a grain as a function of the Mach number of the flow. The horizontal line corresponds to $J_{\text{max}}(\psi) = 3J_{\text{therm,gas}}$ for $\psi = 0^\circ$.

It is clear from looking at Figure 4 that for our model, helical grains get aligned for relatively low velocities of gas-grain drift. All the earlier mechanisms of mechanical alignment are inefficient for such low subsonic velocities. Indeed, drifting velocities of the order of 0.1 of sound speed should be quite common in the ISM (see Yan et al. 2004), so potentially the mechanism is widely applicable. However, it requires further studies.

One may wonder whether the condition of perfect reflection is absolutely necessary. It can be shown that the torques are changed by a factor of unity if impinging atoms are absorbed on the grain surface, thermalized there, and then emitted from the same points where they hit the surface. Moreover, in fact, it is sufficient to have a correlation of the place that the atom impinges on the grain surface and is evaporated from it. It is only when there is no correlation at all that our model grain does not experience regular torques. Therefore we believe that we may not overestimate the torques with our assumption of 10% reflection. In general, to characterize the interaction of grain surface with the gaseous flow, one can introduce a "reflection efficiency factor" $E$.

A different issue is the degree of helicity of an irregular grain. Naturally, most of the grains do not have clear-cut facets, but have numerous irregularities. An idealized grain, for which the damping arising from its ellipsoidal body tends to zero, has the maximal possible value of the torques $Q_{\text{opt}}(a, M)$ with its "helicity reduction factor" $D = 1$. This factor, in a general case, can be characterized by $D = Q(a, M)/Q_{\text{opt}}(a, M)$. Further numerical studies should clarify the value of $D$ for actual irregular grains. In Figure 4 we show results for different $ED$ factors.
5. DISCUSSION AND SUMMARY

In our Letter we use the same toy model of a helical grain as in LH07. In LH07 we proved the validity of the toy model (which uses a geometric optics approximation) comparing the functional dependencies of the model torques and those numerically calculated for the actual irregular grains (which is a different regime of scattering). In comparison, the justification of the model for the gaseous bombardment is self-evident. However, the combination $ED$ presents a combined uncertainty factor, which characterizes both the uncertainties in grain-gas interactions and grain shape. Testing of the former requires laboratory studies, while the latter can be established via numerical research.

What is the relative role of traditional mechanisms of mechanical alignment? Those mechanisms require supersonic motions to be efficient. It is only mechanical alignment of helical grains that allows alignment for the subsonic motions. Thus we may claim that mechanical alignment of helical grains constitutes a new class of mechanical alignment processes. In fact, the difference between the mechanical alignment of helical grains and the Gold process is similar to the difference between the radiative torque alignment and the Harwit (1970) process. The latter appeals to stochastic torques arising from absorption of photons from a light beam and was shown by Purcell & Spitzer (1971) to be inefficient for most interstellar situations.

Similarly, as the radiative torque alignment is more efficient than the Harwit (1970) alignment, we believe that the mechanical alignment of helical grains is more efficient than the Gold process even if the drift is supersonic. Therefore, at supersonic velocities we expect the mechanical alignment of the actual irregular grains to be governed by their helicity, rather than the degree of their oblateness or prolateness, which is the case for the Gold mechanisms. The consequence of this is that the mechanical alignment of grains will happen with long grain axes perpendicular to magnetic field irrespective of the gas-grain velocities. This is in contrast to the Gold alignment, for which the change of alignment happens at the Van Vleck angle $\alpha = 54.7^\circ$.

In Hoang & Lazarian (2007), the effects of gaseous bombardment and uncompensated Purcell torques (Purcell 1979), e.g., $H_2$ torques, was studied in connection with the alignment of helical grains subjected to radiative torques. That study shows that, in the case when both high-$J$ and low-$J$ attractor points coexist, gaseous bombardment transfers grains from low-$J$ to high-$J$, thus resulting in better alignment. This is surely true only if $J_{\text{max}}(\psi)$ is sufficiently high, e.g., higher than $3J_{\text{ }}/\omega_{\text{helm,gas}}$. The Purcell torques do not change $J$ in the low-$J$ attractor points because grains flip fast at those points, causing thermal trapping, as discussed in Lazarian & Draine (1999a). They, however, can increase the values of $J$ at high-$J$ attractor point. For most situations, this does not affect the degree of alignment.

Our considerations above deal with ordinary paramagnetic grains. For those, the influence of paramagnetic torques is mostly negligible for typical ISM conditions. The situation changes if grains are superparamagnetic (see Jones & Spitzer 1967). In this situation one can expect always to have alignment with high-$J$ attractor points, thus having degrees of alignment close to 100%. The assumption of the presence of superparamagnetic inclusions is an extra assumption, however.

As we have stressed above, the mechanical alignment we discuss here and the radiative torque alignment are different incarnations of the alignment of helical grains. While the radiative torques have attracted a lot of attention recently, the mechanical alignment of helical grains has only been mentioned in a couple of publications (Lazarian 1995, 2007; Lazarian et al. 1996; LH07). The relative roles of the mechanisms depends on the yet uncertain factor $ED$ for the mechanical processes. The observations tends to be in agreement with the radiative torque predictions (see Lazarian 2007 and references therein). It is encouraging that both mechanisms predict the alignment with long grain axes perpendicular to magnetic field. Therefore one may hope that the subsonic alignment of helical grains can reveal via polarimetry the magnetic fields in the situations when the radiative torques fail. The variety of astrophysical circumstances ensures that there are situations when grains are aligned by mechanical subsonic flows. Note that aligned grains were reported not only for the ISM, but also for comets and circumstellar regions. They are also likely to be present in the disks around evolved and young stars.

The goal of this Letter is to attract the attention of the community to the possibility of mechanical alignment of helical dust grains. While further studies of the process are necessary, the following points can be made at this moment:

1. We conjecture that irregular grains, in general, exhibit helicity when they interact with gaseous flows.
2. The mechanical alignment of helical grains is efficient even when the flow of gas is subsonic. This alignment is likely to dominate Gold-type processes.
3. The mechanical alignment of helical grains aligns grains with long axes perpendicular to magnetic field, thus increasing the chances of magnetic field tracing when other alignment mechanisms fail.

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