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Physics of Grain Alignment

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Abstract. Aligned grains provide one of the easiest ways to study magnetic fields in diffuse gas and molecular clouds. How reliable our conclusions about the inferred magnetic field depends critically on our understanding of the physics of grain alignment. 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 show why mechanisms that were favored for decades do not look so promising right now. I also discuss why the radiative torque mechanism ignored for more than 20 years looks right now the most powerful means of grain alignment.

1. Introduction

Magnetic fields are extremely important for star formation, galactic feedback processes etc. and polarized radiation arising from absorption and emission by aligned grains provides an important means for studying magnetic field topology. However, the interpretation of polarimetry data requires clear understanding of processes of grain alignment and the naive rule of thumb that dust grains are aligned everywhere and with longer axes perpendicular to magnetic field may be misleading (see Goodman et al. 1995, Rao et al. 1998).

Physics of grain alignment is deep and exciting. It is enough to say that its study resulted in a discovery of a few new solid state effects. However, let us start by recalling a few simple facts. The grain alignment in interstellar medium always happens in respect to magnetic field. It is fast Larmor precession of grains that makes magnetic field the reference axis. Note, 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.

The alignment of grain axis is described by the Rayleigh reduction factor:

\[ R \equiv \langle G(\cos^2 \theta)G(\cos^2 \beta) \rangle \]  \hspace{1cm} (1)

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 \( \mathbf{B} \), while \( \beta \) is the angle between the
angular momentum \( J \) and \( B \). One may see (e.g. Hildebrand 1988) that \( R \) is directly related to the degree of polarization. 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 Roberge & Lazarian 1999). This considerably complicates the treatment of grain alignment.

This review attempts to cover the recent advancements of our understanding of grain alignment and places them in the context of the earlier works done by giants of E. Purcell and L. Spitzer caliber. It happened that several times the problem of grain alignment seemed to be solved and theorists got satisfied. However, accumulation of new observational facts and deeper insights into grain physics caused the changes of paradigms. Thus in what follows we describe three periods of grain alignment theory. A more detailed treatment of various aspects of grain alignment the interested reader can find in earlier reviews (e.g. Hildebrand 1988, Roberge 1996, Lazarian, Goodman & Myers 1997).

2. Evolution of Grain Alignment Ideas

Foundations.
The first stage of alignment theory development started directly after the discovery of starlight polarization by Hiltner (1949) and Hall (1949). 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 \( t_{gas} \), the time of randomization through chaotic gaseous bombardment. In practice, the last condition is difficult to satisfy. For \( 10^{-5} \) cm grains in diffuse 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 looked OK initially.

*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\footnote{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.}. 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 align grains over limited
patches of interstellar space only 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 $\mathbf{J}$ using a
Fokker-Planck equation. This approach allowed to account for magnetization
fluctuations within grain material and thus provided a more accurate picture of
$\mathbf{J}$ 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 su-
perparamagnetic, 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 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.

Facing Complexity
Barnett Effect and Fast Larmor Precession
It was realized by Martin (1972) that rotating charged grains will develop mag-
netic moment and the interaction of this moment with the interstellar mag-
netic field will result in grain precession. The characteristic time for the preces-
sion was found to be comparable with $t_{\text{gas}}$. However, soon a process that ren-
ders much larger magnetic moment was discovered (Dolginov & Mytrophanov
1976). This process is the Barnett effect, which is converse of the Einstein-
Haas effect. If in Einstein-Haas effect a paramagnetic body starts rotating
during remagnetizations as its flipping electrons transfer the angular moment-
um (associated with their spins) to the lattice, in the Barnett effect the ro-
tating body shares its angular momentum with the electron subsystem causing
magnetization. The magnetization is directed along the grain angular velocity
and the value of the Barnett-induced magnetic moment is $\mu \approx 10^{-19} \omega_{(5)} \text{ erg}
gauss^{-1}$ (where $\omega_{(5)} \equiv \omega/10^5 \text{s}^{-1}$). Therefore the Larmor precession has a period
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 \( \text{H}_2 \) formation efficiency, and variations of accommodation coefficient over grain surface would result in uncompensated torques acting upon a grain. The \( \text{H}_2 \) formation on the grain surface clearly illustrates the process we talk about: if \( \text{H}_2 \) 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 Brownian and Purcell termed those velocities “suprathermal”. Purcell also noticed that for suprathermally rotating grains internal relaxation will bring \( J \) parallel to the axis of maximal inertia (i.e. \( Q_X = 1 \)). Indeed, for an oblate spheroidal grain with angular momentum \( J \) the energy can be written

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

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. (2) that the energy can be decreased by aligning the axis of maximal inertia along \( J \), 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 \( J \), while angular velocity precesses about \( J \) and in grain body axes. We learned earlier that the Barnett effect results in the magnetization vector parallel to \( \omega \). As a result, the Barnett magnetization will precess in body axes and cause paramagnetic relaxation. The “Barnett equivalent magnetic field”, i.e. the equivalent external magnetic field that would cause the same magnetization of the grain material, is \( H_{BE} = 5.6 \times 10^{-3} \omega (5) \) G, which is much larger than the interstellar magnetic field. Therefore the Barnett relaxation happens on the scale \( t_{Bar} \approx 4 \times 10^7 \omega (5)^{-2}, \) i.e. essentially instantly compared to \( t_{\text{gas}} \) and \( t_{D-G} \).

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 \( \text{H}_2 \) formation and create new ones. As the result, \( \text{H}_2 \) 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 \( J \) to deviate from the axis of
maximal inertia. SM79 observed that as the Barnett relaxation couples $J$ with
the axis of maximal inertia it makes randomization of grains during crossover
nearly complete. With the resurfacing time $t_{res}$ estimated by SM79 to be of the
order of $t_{gas}$ 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 SMF inclusions, b. with suprathermal rota-
tion), 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) stressed that the SFM inclusions will have a better
chance to be in larger rather than smaller grains. The success of fitting observ-
ritional data persuaded the researchers that the problem of grain alignment is
solved at last.

New Developments
Optical and near infrared observations by Goodman et al. (1992), 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, their role was un-
clear. 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. The magnitude of torques were found to be sub-
stantial and present for grains of various irregular shape. After that it became
impossible to ignore these torques. Being related to grain shape, rather than
surface these torques are long-lived, i.e. $t_{spin-up} \gg t_{gas}$, 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 alignes 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 1995, Hildebrand et al. 1999).

**New Elements of Crossovers**

Another unexpected development was a substantial change of the picture of crossovers. As we pointed out earlier the 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 \( \exp(-E(\theta)/kT_{\text{grain}}) \), where the energy \( E(\theta) \) is given by Eq. (2). 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 momentum 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 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. \( \text{H}_2 \)) 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 Alfvén waves. Unlike the ambipolar diffusion, this mechanism operates even in ideal MHD and relies only on the difference in inertia of atoms and grains. 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). As it was realized that thermally rotating grains do not $J$ 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 1998) 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

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2A 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.
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. The trouble 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, and therefore the direction of polarization of emitted infrared photons, will be substantially randomized.

3. Summary and Future work

Let us summarize what we learned about the dynamics of grain alignment. For a $10^{-5}$ cm grain in cold diffuse interstellar medium the fastest motion is the grain rotation, which happens on the time scale less than $10^{-4}$ s. The grain tumbling and rotation of angular velocity about $\mathbf{J}$ happens on approximately the same time scale. The alignment of $\mathbf{J}$ with the axis of maximal inertia happens as a matter of hours due to the very efficient nuclear relaxation. On the time scale of days $\mathbf{J}$ rotates about $\mathbf{B}$ due to its magnetic moment (Dolginov & Mytrophanov 1976), while gaseous damping time takes $t_{gas} \sim 10^5$ years. An alignment mechanism is efficient if the alignment time is a fraction of $t_{gas}$ for thermally rotating grains, but it may be many $t_{gas}$ if grains rotate suprathermally. In the latter case the dynamics of crossovers is all-important.

At the moment radiative torques look as the most promising means of aligning dust. Due to thermal trapping the Purcell alignment is suppressed. The superparamagnetic hypothesis looks OK (see Goodman & Whittet 1996), but the mechanism faces the problem with driving grain rotation. The same thermal trapping makes grain alignment less efficient in molecular clouds where grain rotational temperature approaches its body temperature. It is likely that the radiative torques are still required to drive grain rotation.

The most challenging problem right now is to understand the radiative torque mechanism. For this purpose it is necessary to describe crossovers induced by radiative torques and include the recently discovered flipovers into existing codes. It looks necessary to understand why grains align (not always, but very frequently) $\mathbf{J}$ with $\mathbf{B}$ when subjected to anisotropic radiation. My experiments with slightly irregular grains (using the code kindly provided to me by Bruce Draine) interacting with anisotropic monochromatic radiation made me believe that it is possible to get a theoretical insight into the underlying physics. However, whatever theory says, observational tests are necessary. Inversion of the
polarimetric data (see Kim & Martin 1995) allows to find for different environments the critical grain size starting with which grains are aligned. Comparing this size with predictions calculated for radiative torques should enable testing the mechanism.

Whatever the success of the radiative torques, it is necessary to proceed with further development of alternative alignment mechanisms. Some of them, e.g. the mechanism of mechanical alignment is suspected to cause alignment at least in some regions (see Rao et al. 1998). Ward-Thompson et al. (2000) reported 850 µm polarization from dense pre-stellar cores, where radiative torques should be inefficient. Could the grain larger than $a_c$ and aligned via modified Purcell mechanism (LD97) be responsible? Or should we appeal to Alfven waves or ambipolar diffusion? Further research will provide us with the answer. In general, the variety of Astrophysical conditions allows various mechanisms (see Lazarian, Goodman & Myers 1997) to have their niche. Clear understanding of grain alignment will make polarimetry much more informative. Although so far grain alignment theory was applied only to interstellar environments, it is clear that its potential is great for circumstellar and interplanetary studies (see Lazarian 2000).

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