Statistics of turbulence via polarimetry: alignment of grains and atoms

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Abstract. Most astrophysical fluids are turbulent and magnetized. Fluctuations of polarization provide a promising way to study astrophysical magnetic turbulence. We discuss polarization that arises from grains and atoms aligned in respect to magnetic field, describe the processes of alignment, explain when the alignment reflects the direction of magnetic field. We show that temporal fluctuations of interplanetary magnetic field can be studied using aligned sodium atoms.

I. WHY DO WE CARE ABOUT ASTROPHYSICAL TURBULENCE?

It is generally accepted that most astrophysical fluids are turbulent with magnetic fields playing important role. In this situation the properties of the fluids depend of the properties of the magnetized turbulence. In most cases astrophysical scales are much larger than the scales determined by the plasma effects and therefore the Magneto-hydrodynamic (MHD) description of astrophysical fluids is adequate.

Scattering and acceleration of cosmic rays (see [56] and references therein), acceleration of charged interstellar dust particles [45, 64], conduction of heat (see [9, 49]) depend intimately on the properties of MHD turbulence. Rates at which the topology of otherwise “frozen in” astrophysical magnetic field changes, i.e. magnetic reconnection rates, according to [43] are controlled by MHD turbulence.\footnote{Note, that magnetic reconnection is essential for a wide variety of astrophysical processes from Solar flares to dynamo generation of magnetic field.}

It happened that for years MHD turbulence was a rather speculative area of research, where many models could coexist without much chance of being tested. An important progress in the field was stimulated by in situ measurements of the statistics of interplanetary turbulence (see [48, 22]). However, these measurements were not sufficiently detailed to get a good insight into the structure of the magnetized eddies.

A study of incompressible MHD turbulence by Goldreich & Sridhar [20] became a milestone for the subject. There a universal scaling was proposed for magnetic eddies in the system of reference related to the local mean magnetic field of the eddy. Considerations applied by Goldreich & Sridhar to pseudo-Alfvén waves have been generalized and extended to slow modes of compressible MHD ([47, 8]). Recent theoretical and numerical work (see [4, 5, 6, 8, 44]) shed light on what is happening with MHD turbulence in partially ionized gas, on turbulence intermittency, on coupling of compressible and...
Alfvénic modes, on rates of turbulence decay etc. In its turn this work stimulated revisions of some earlier paradigms for basic astrophysical processes (see \[63, 64, 9, 65\]).

It is important to stress that for the first time ever the theoretical predictions were tested with direct 3D numerical simulations. Does this mean that we are sure that we know the final truth about the actual astrophysical turbulence? Surely, not. It is well known that flows are similar when their Reynolds numbers, which are the ratio of the advection to dissipation terms in the Navie-Stocks equations are the same. For MHD, magnetic diffusivity is important and therefore magnetic Reynolds numbers should be also the same. As the corresponding numbers for the numerical simulations and astrophysics are different by a factor of $10^6$ and larger, from this point of view, the flows simulated in computers and those in astrophysical fluids are very different.

In other words, while theoretical expectations from elegant, but simplified models exist, their observational testing is essential. Moreover, such observational studies can provide an insight into astrophysically important questions of driving turbulence and the scales of energy injection.

The statistics of density, which is readily available in many cases, is related in a non-trivial way with the magnetic and velocity fluctuations ([47]). Obtaining of the statistics of velocity fluctuations from observations is a problem that has been subjected to scrutiny recently (see [35] and references therein). In what follows we shall discuss the problem of determining the statistics of magnetic fields by observing fluctuation of polarization arising from aligned dust and atoms.

## II. WHAT DOES CAUSE GRAIN ALIGNMENT?

Starlight polarization measurements by Hall and Hiltner [21, 23] revealed that interstellar dust grains are aligned. It did not take long to realize that grains tend in most cases tend to be aligned with their long axes perpendicular to magnetic field. However, progress in theoretical understanding of the alignment has been surprisingly slow in spite of the fact that great minds like L. Spitzer and E. Purcell worked on grain alignment (see [58, 50, 51, 53, 57]). The problem happened to be both very and tough as a lot of relevant physics had to be uncovered.

Currently, grain alignment theory is an exciting branch of research where a lot of insight has been obtained lately (see reviews [34, 36]). We shall refer the reader to these reviews which contain dozens of references to the original important work, while here we present a few facts about dust alignment that are needed to understand how well the alignment represents magnetic field direction.

Originally it was widely believed that interstellar grains can be well aligned by a paramagnetic or Davis-Greenstein mechanism [11]. This mechanism based on the direct interaction of rotating grains with the interstellar magnetic field required magnetic fields that are stronger than those obtained by other techniques. Later, a pioneering work by Purcell [53] showed a way how to make grain alignment more efficient. Purcell introduced several processes that are bound to make grains very fast rotators and noticed that grains rotating at high rates are not so susceptible to the randomization induced by gaseous collisions. For decades this became a standard explanation for grain alignment,
even though it could not explain several observational facts, e.g. why small grains are less aligned than the large ones (28).

New physics of grain internal motion uncovered recently explains inefficiency of alignment of small grains by Purcell’s mechanism. Lazarian & Draine [37] found that small grains flip frequently due to the coupling of rotational and vibrational degrees of freedom of a grain. As the result regular torques, e.g. torques due to ejection of H$_2$ molecules, get averaged out and grains rotate at thermal velocities. The paramagnetic alignment of thermally rotating grains as we mentioned earlier is inefficient (see [55]). Interestingly enough, Lazarian & Draine [38] found that coupling of rotational and vibrational degrees of freedom happens most efficiently through a process the origin of which is related to nuclear spins! This relaxation makes grains of size $10^{-5}$ cm $< a < 10^{-4}$ cm rotate thermally, which makes the Purcell mechanism inefficient for most of dust in diffuse interstellar medium.

A group of alternative mechanisms of alignment related to the relative gas-grain motion have their particular niches. The first mechanical alignment mechanism was pioneered by Gold [18]. Later work included driving grains by ambipolar diffusion [54] and Alfvén waves [30, 32, 64]. Although new efficient processes of mechanical alignment [31, 39], this did not make the mechanical alignment universally applicable.

Quite recently, radiative torque (henceforth RT) have been accepted as the most promising mechanism for explaining grain alignment over vast expanses of interstellar space. Introduced first by Dolginov [12] and Dolginov & Mytrophanov [13], the RT were mostly forgotten till a more recent study by Draine & Weingartner [14], where their efficiency was demonstrated using numerical simulations (see also [15, 62, 7]).

The RT make use of interaction of radiation with a grain to spin the grain up. Unpolarized light can be presented as a superposition of photons with left and right circular polarization. In general, the cross-sections of interaction of such photons with an irregular grain are different. As the result of preferential extinction of photons with a particular polarization the grain experiences regular torques and gets spun up.

The predictions of RT mechanism are roughly consistent with the molecular cloud extinction and emission polarimetry [41] and the polarization spectrum measured [26]. RT have been demonstrated to be efficient in a laboratory setup [1]. Evidence in favor of RT alignment was found for the data obtained at the interface of the dense and diffuse gas (see [34]).

While it was originally believed that RT cannot align grains at optical depths larger than $A_v \approx 2$, Cho & Lazarian [7] demonstrated that the efficiency of RT increases sharply with the grain size and therefore bigger grains that exist within molecular clouds can be aligned for $A_v$ more$^2$ than 10. Large grains may constitute an appreciable part of the total mass of dust within a cloud, while still be marginal in terms of light extinction. Therefore a non-detectable polarization in optical and near infrared does not preclude substantial polarization to be present in submillimeter. This makes submillimeter polarimetry the preferred tool for studies magnetic fields and magnetic turbulence in molecular clouds.

\[^2\] Our studies reveal that for fractal molecular clouds the alignment can be present for cores with $A_v$ of 30. In addition, as large grains do not flip frequently the Purcell alignment gets efficient as well.
To align grains with RT mechanism requires grains to be comparable to the wavelength they interact with. Therefore grains smaller than $\sim 5 \times 10^{-6}$ cm are not aligned by RT in typical interstellar conditions. These grains flip frequently and therefore they cannot be aligned by the process according to [37]. However, these grains can be aligned by the original Davis-Greenstein process (see detailed calculations in [32, 55]). The degree of the expected alignment for typical interstellar conditions does not exceed several percent, but this alignment is sensitive to the magnitude of magnetic field. The data in [28] is consistent with the existence of a population of small aligned grains. Such aligned grains may be revealed with UV polarimetry.

III. WHAT DOES ALIGNED DUST REVEAL?

Most of the processes produce grain alignment in respect to magnetic field, even if the alignment mechanism is of non-magnetic nature. This is true due to the rapid precession of grains about magnetic field. This precession stems from the substantial magnetic moment that grains get due to their rotation [13]. The corresponding period of grain precession $\tau_L$ is $\sim 10^5 B_3^{-1} a^{-5} \text{s}$, where the external magnetic field is normalized over its typical interstellar value of $3 \times 10^{-6}$ G and grain size is chosen to be $a = 10^{-5}$ cm. This means that for turbulent motions on time scales longer than $\tau_L$ grain alignment in respect to magnetic field lines does not change as the consequence of the adiabatic invariant conservation (see more discussion in [34]).

If the alignment happens on the time scales shorter than $\tau_L$ the dust orientation may not reflect the magnetic field. For the RT such a fast alignment will happen with longer grain axes perpendicular to the direction of radiation, while the fast mechanical alignment will happen with longer axes parallel to the flow. The mechanical and RT alignment takes place on the time scale of approximately gaseous damping time, which is for interstellar medium $\sim 10^{11} T_{100}^{-1/2} n_{-20}^{-1} a_{-5}^{-5} \text{s}$, where typical temperatures and densities of cold interstellar medium, which are respectively 100K and 20 cm$^{-3}$, were used for the normalization. Note, that magnetic alignment takes place over even longer time scales, namely, $\sim 10^{13} B_3 a_{-5}^{-2} \text{s}$. Therefore in most cases the magnetic field indeed acts as the alignment axis.

It is worth noting that the turbulent fluctuations with periods longer than $\tau_L$ do not suppress alignment. The rapidly precessing grains preserve their orientation to the local direction of magnetic field and undergo the alignment even when this local direction is changing in space. In this respect grain alignment is a local process that can reflect local direction of magnetic field for magnetic ripples larger than $\tau_L V_A$, where $V_A$ is Alfvén speed. Whatever is the process of alignment, if it aligns grains over timescale larger than

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3 Such grains can still be aligned by strong UV flux near some stars.
4 The rule of thumb for mechanical alignment is that it tends to minimize the grain cross section for the grain-flow interaction, while for RT is that the grain precession is minimized.
5 The mechanical alignment happens faster due to the fact that the flows are supersonic. This is an important difference to be considered for transient alignment, but such an alignment is not typical for ISM.
the alignment is perpendicular or parallel to magnetic field.

The issues of the mechanism and the efficiency of alignment is essential when averaging along the line of sight is involved. For instance, if we study turbulence in a molecular cloud we would like to know whether the polarization signal that we measure is coming from a thin skin layer of the cloud or from the whole cloud volume. We also would like to know whether the direction of alignment changes along the line of sight.

It follows from the discussion above that in most cases the assumption that grains are aligned with long axes perpendicular to magnetic fields is a valid one. The fact, that RT have been identified as a dominant alignment mechanism plus that this process seems to be efficient even at substantial optical depths simplifies the interpretation of the polarization fluctuations in terms of magnetic field fluctuations.

If we limit ourselves to discussing grains aligned by RT, the grains in diffuse interstellar medium can be considered perfectly aligned with longer axes perpendicular to magnetic field. Optical and near infrared emission from stars will be polarized via the differential extinction by the aligned grains so that the direction of linear polarization will be parallel to the local interstellar magnetic field. The variations of magnetic field directions along the line of sight from the star to the observer will influence the resulting degree of polarization $p$ as well as the positional angle of the polarization vector $\delta \phi$. These observational parameters can be used to obtain the polarization statistics.

The geometry of lines of sight is also important for the interpretation of interstellar polarization statistics. It can be easily shown (see [42], [3]) that when a signal is collected along the converging lines of sight (see Fig. 1), the turbulence provides a universal $\theta^{-1}$ spectrum of fluctuations when the correlated lines of sight are separated by an angle larger than the ratio of the injection scale of turbulence and the distance to the stars, i.e. $L/d_{max}$.

The variations of $p$ were studied in [16] for a sample of polarization measurement available in Heiles catalog. They provided a spectrum $\theta^{-1.5}$ that was interpreted by

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$^6$ Mechanical alignment by plasma streaming as well as Davis-Greenstein alignment when grains are warmer than the ambient gas present exceptions from this rule.
as the result of the superposition of the contributions from distant and nearby stars in the presence of MHD turbulence in the interstellar dusty gas (see Fig. 1). A more systematic study of polarization using only close and only distant stars could test the predictions in [3]. It shall also be able to establish the correlation scale of galactic turbulence \( L \). Interestingly enough, confirming that the polarization fluctuations in Milky Way arise from MHD turbulence is important from the point of view of CMB studies. Aligned dust provides an important contribution to polarized microwave foreground (see [40] and references therein). This foreground must be removed to reveal the polarized emission originated in the Early Universe. MHD turbulence has a well defined statistics and therefore this open ways for more reliable ways of weeding out such a foreground.

**IV. WHAT IS ATOMIC ALIGNMENT?**

As we discussed above, polarimetry of aligned dust provides one of the ways of studying MHD turbulence. Polarimetry of some molecular lines using Goldreich-Kylafis effect [19] have been shown recently to be a good tool for magnetic field studies in molecular clouds ([17]). Here we discuss yet another promising technique to study magnetic fields that employs optical and UV polarimetry. This technique can be used for interstellar\(^7\) and circumstellar studies as well as for studies of magnetic fields in QSOs and other exotic objects. The technique is based on the ability of atoms to be aligned by external radiation in their ground state and be realigned through precession in magnetic field.

It has been known that atoms can be aligned through the interactions with the anisotropic flux of resonance emission (see review [24]). Alignment is understood here in terms of orientation of vector angular momentum \( \mathbf{J} \), if we use the language of classical mechanics. In quantum terms this means a difference in the population of sublevels corresponding to the projections of angular momentum to the quantization axis. We will call atomic alignment as the alignment of \( \mathbf{J} \) in the ground state. This state is long lived and therefore is being affected by weak magnetic field.

Atomic alignment has been studied in laboratory in relation with early day maser research ([25]). Alignment of atoms in ground state can change the optical properties of the medium. This effect was noticed and made use of for the interstellar case by [60] in case of hyperfine structure of the ground state, for fine structure of the ground state by, e.g. [46]. Here we shall be concerned with the variations of degree of polarization \( p \) and the positional angle \( \delta \phi \) that is caused by atomic alignment.

A possibility of using atomic alignment to study weak magnetic field in diffuse media was first discussed in [29] for ideal two-level atoms with fine structures and polarization of emissions from these atoms were considered for a very restricted geometry of observations, namely, when magnetic field is aligned with line of sight and perpendicular to the incident light. A discussion of alignment of various atoms and ions for arbitrary orientations of magnetic fields towards the line of sight and the direction to the illumination source is given in [60].

\(^{7}\) Here interstellar is understood in a general sense, which, for instance includes reflection nebulae.
TABLE 1. Note: only polarizable and alignable components are listed. "M" stands for marginal polarization. From [66]

| Atom  | Nuclear spin | Lower state | Upper state | Wavel(Å) | Pol(emi) | Pol(abs) |
|-------|--------------|-------------|-------------|---------|----------|----------|
| Na I  | 3/2          | 1S_{1/2}    | 2P_{3/2}    | 5891.6  | Y        | Y        |
|       |              |             | 2P_{1/2}    | 5897.6  |          |          |
| N V   | 1            | 1S_{1/2}    | 2P_{3/2}    | 1238.8  | Y        | Y        |
|       |              |             | 2P_{1/2}    | 1242.8  |          |          |
| Al III| 5/2          | 1S_{1/2}    | 2P_{3/2}    | 1854.7  | M        | M        |
|       |              |             | 2P_{1/2}    | 1862.7  |          |          |
| H I   | 1/2          | 1S_{1/2}    | 2P_{1/2,3/2}| 912-1216| Y        | N        |
| N I   | 1            | 4S'_{5/2}   | 4P'_{1/2,3/2,5/2}| 865 – 1201 | Y    | Y        |
| O II  | 0            | 6S_{5/2}    | 6P'_{3/2,5/2,7/2}| 2056, 2062, 2066 | Y    | Y        |
| Cr II | 0            | 6S_{5/2}    | 6P'_{3/2,5/2,7/2}| 2056, 2062, 2066 | Y    | Y        |
| C II  | 0            | 2P'_{3/2}   | 2P_{3/2}    | 904.1   | Y        | Y        |
|       |              |             | 2D_{3/2,5/2}| 1335.7  |          |          |
| O IV  | 0            | 2P'_{3/2}   | 2P_{3/2}    | 554.5   | Y        | Y        |
|       |              |             | 2D_{3/2,5/2}| 239, 790 |          |          |
| C I   | 0            | 3P_{1,2}    | 3P'_{0,1,2} | 1118-1657| Y    | Y        |
|       |              |             | 3D'_{1,2,3} | 1115-1561|          |          |
| O III | 0            | 3P_{0,1,2}  | 3P'_{0,1,2} | 304, 374, 703| Y    | Y        |
|       |              |             | 3D'_{1,2,3} | 267, 306, 834|          |          |

Similar to the case of interstellar dust, the rapid precession of atoms in magnetic field makes the direction of polarization sensitive to the direction of underlying magnetic field. As the precession of magnetic moments of atoms is much faster than the precession of magnetic moments of grains atoms can reflect much more rapid variations of magnetic field. More importantly, alignable atoms and ions (see Table 1) can reflect magnetic fields in the environments where either properties of dust change or the dust cannot survive. This opens wide avenues for the magnetic field research in circumstellar regions, interstellar medium, interplanetary medium, intracluster medium and quasars etc. In addition, the degree of alignment \( p \) can help in determining the angle between the direction towards the illumination source and the direction of magnetic field. This information is not available by any other technique.

V. HOW DO ATOMS GET ALIGNED?

The basic idea of the atomic alignment is simple. The alignment is caused by the anisotropic deposition of angular momentum from photons. In typical astrophysical situations the radiation flux is anisotropic. As the photon spin is along the direction of its propagation, we expect that atoms that scattered the radiation can be aligned in
terms of their angular momentum. Such an alignment happens in terms of the projection of angular momentum to the direction of the incoming light. It is clear that to have the alignment of the ground state, the atom should have non-zero angular momentum in its ground state. Therefore fine or hyperfine structure of the ground state is necessary to enable various projection of angular momentum to exist in the ground state. Whether polarization arising from aligned atoms is parallel or perpendicular to magnetic field depends on the angle that the anisotropic radiation makes with the magnetic field.

Let us discuss a toy model that provides an intuitive insight into the physics of atomic alignment. First of all, consider a toy model of an atom with lower state corresponding to the total angular momentum $I = 1$ and the upper state corresponding to angular momentum $I = 0$. If the projection of the angular momentum to the direction of the incident resonance photon beam is $M$, for the lower state $M$ can be $-1$, $0$, and $1$, while for the upper state $M = 0$ (see Fig. 2left). The unpolarized beam contains an equal number of left and right circularly polarized photons which projection on the beam direction are $1$ and $-1$. Thus absorption of the photons will induce transitions from $M = -1$ and $M = 1$ states. However, the decay of the upper state happens to all three levels. As a result the atoms get accumulated at the $M = 0$ ground state from which no excitations are possible. As a result of that the optical properties of the media (e.g. absorption) would change.

This above toy model can also exemplify the role of collisions and magnetic field. Without collisions one may expect that all atoms reside eventually at the state of $M = 0$. Collisions, however, redistribute atoms with different states. However, as disalignment of the ground state requires spin flips, it is less efficient than one can naively imagine. Calculations by [25] show that to disalign sodium one requires more than 10 collisions with paramagnetic atoms and experimental data by [27] support this. This reduced sensitivity of aligned atoms to disorienting collisions makes the effect important for various astrophysical environments.

Magnetic field would also mixes up different $M$ states. However, it is clear that the randomization in this situation will not be complete and the residual alignment would reflect the magnetic field direction in respect to the observer. Magnetic mixing happens if the angular momentum precession rate is higher than the rate of the excitation of atoms from the ground state, which is true for many astrophysical conditions.

Note that in order to be aligned, first the atoms should have enough degree of freedom, namely, the quantum number of angular momentum must be $\geq 1$. Second, incident flux must be anisotropic. Moreover, the collisional rate should not be too high. While the latter requires special laboratory conditions, it is the case for many astrophysical environments such as the outer layers of stellar atmosphere, interplanetary, interstellar, and intergalactic media, etc.

As long as these conditions are satisfied, atoms can be aligned within either fine or hyperfine structure. For light elements, the hyperfine splitting is very small and the line

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8 Not every type of alignment affects the polarization of the scattered of absorbed radiation. Interestingly enough, alignment that we discuss within the toy model does not affect polarization of resonant light. To have emission polarized, the alignment on the ground state should be transfered to the excited level. Therefore atoms with more complex structure of the excited levels should be considered.
components overlap to a large extent. However, for resonant lines, the hyperfine interactions cause substantial precession of electron angular momentum $J$ about the total angular momentum $F$ before spontaneous emission. Therefore total angular momentum should be considered and the $FM_F$ basis must be adopted ([61]). For alkali-like atoms, hyperfine structure should be invoked to allow enough degrees of freedom to harbor the alignment and to induce the corresponding polarizations.

In terms of time scales, we have a number of those, which makes the problem interesting and allows getting additional information about environments. The corresponding rates are 1) the rate of the precession $\tau_L^{-1}$, 2) the rate of the photon arrival $\tau_A^{-1}$, 3) the rate of collisional randomization $\tau_R^{-1}$, 4) the rate of the transition within fine or hyperfine structure $\tau_T^{-1}$. In many case $\tau_L^{-1} > \tau_A^{-1} > \tau_R^{-1} > \tau_T^{-1}$. Other relations are possible, however. If the Larmor precession gets comparable with any of the other rates, it is possible to get information about the magnitude of magnetic field. Another limitation of our approach is that we consider that $\tau_L^{-1}$ is much smaller that the rate of the decay of the excited state, which means that we disregard the Hanle effect.

VI. HOW TO STUDY INTERPLANETARY TURBULENCE WITHOUT SPACE MISSIONS?

As an illustration, we discuss here a synthetic observation of a comet wake. Though the abundance of sodium in comets is very low, its high efficiency of scattering Sun light makes it a good tracer ([59, 10]). The sodium atoms ejected from the comets are aligned by the solar radiation. Distant from comets, the Sun can be considered a point source. As shown in Fig. 2 Middle, the geometry of the scattering is well defined, i.e., the scattering angle $\alpha$ is known. The polarization of the sodium emission thus provides an exclusive information of the magnetic field in the comet wake. Embedded in Solar wind, the magnetic field is turbulent in a comet wake. We take a data cube directly from MHD simulations of a comet wake. Depending on its direction, the embedded magnetic field alter the degree of alignment and therefore polarization of the light scattered by the
aligned atoms. Therefore, fluctuations in the linear polarization are expected from such a turbulent field (see Fig. 2right). For interplanetary studies, one can investigate not only spatial, but also temporal variations of magnetic fields. This can allow cost effective way of studying interplanetary magnetic turbulence at different scales.

VII. WHAT CAN WE LEARN ABOUT MHD TURBULENCE?

Astrophysical environments provide unique opportunities for studying MHD turbulence at Reynolds and magnetic Reynolds numbers that are not available through either numerical simulations or laboratory experiments. This allows to test our theoretical constructions to see whether numerics is adequate.

It is difficult to overestimate the importance of understanding better astrophysical turbulence including its spectra, injection and dissipation scales. Magnetic field statistics is complementary to the velocity statistics that can be studied using Doppler shifted spectral lines (see [30]).

Aligned dust and aligned atoms provide a unique way of studying magnetic turbulence in various astrophysical environments from molecular clouds to quasars. Recent progress in theories of atomic and grain alignment gives us confidence in interpreting polarization in terms of underlying magnetic fields.

Aligned atoms provide a possibility of studying temporal variations arising from interplanetary turbulence. Techniques that use aligned atoms and aligned grains are synergetic for studies of magnetic turbulence.

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REFERENCES

1. Abbas, M., Craven, P., Spann, J., Tankosic, D., LeClair,A., Gallagher, D., West, E., Weingartner, J., Witherow, W., & Tielens, A. 2004, ApJ, 614, 781
2. Cho, J. & Lazarian, A. 2002, Phy. Rev. Lett., 88, 245001
3. Cho, J. & Lazarian, A. 2002, ApJL, 575, L63
4. Cho, J. & Lazarian, A., 2003, MNRAS, 345, 325
5. Cho, J. & Lazarian, A. 2004, in Proc. of the Summer Program 2004, Stanford Univ., p. 75
6. Cho, J. & Lazarian, A. 2005, Theoret. Comput. Fluid Dynamics, in press
7. Cho, J. & Lazarian, A. 2005, ApJ, submitted
8. Cho, J., Lazarian, A., Vishniac, E. T. 2003 ApJ, 595, 812
9. Cho, J., Lazarian, A., Honein, Al., Knaepen, B., Kassinos, S., Moin, P. 2003, ApJ, 589, 77L
10. Cremonese et al. 1997, ApJL, 490, L199
11. Davis, J., & Greenstein, J.L. 1951, ApJ, 114, 206
12. Dolginov, A. Z. 1972,ApSS, 16, 337
13. Dolginov A.Z. & Mytrophanov, I.G. 1976, Ap&SS, 43, 291
14. Draine, B.T., & Weingartner, J.C. 1996, ApJ 470, 551 (DW96)
15. Draine, B. & Weingartner, J. 1997, ApJ, 480, 633
16. Fosalba, P., Lazarian, A., Prunet, S., & Tauber, J. 2003, ApJ, 564, 762
17. Girart, J. M.; Crutcher, R. M., & Rao, R. 1999, ApJ, 525L, 109
18. Gold, T. 1951, Nature, 169, 322
19. Goldreich, P. & Kylafis, N. D. 1982, ApJ, 253, 606
20. Goldreich, P. & Sridhar, H. 1995, ApJ, 438, 763
21. Hall, J.S. 1949, Science, 109, 166
22. Higdon, J.C. 1984, ApJ, 285, 109
23. Hiltner, W.A. 1949, ApJ, 109, 471
24. Happer, W. 1972 Rev. Modern Phys., 44, 2
25. Hawkins, W. B.1955, Phys. Rev. 98, 478
26. Hildebrand, R. H., Davidson, J. A., Dotson, J. L., Dowell, C. D., Novak, G., & Vailancourt, J. E. 2000, ASP, 112, 1215
27. Kastler, A. 1956, J. Optical Soc. America, 47, 460
28. Kim, S.-H. & Martin, P. 1995, ApJ, 444, 293
29. Landolfi, M. & Landi Degl'Innocenti E. 1986, A&A, 167, 200
30. Lazarian, A. 1994, MNRAS, 268, 713
31. Lazarian, A. 1995, ApJ, 451, 660
32. Lazarian, A. 1997, MNRAS, 288, 609
33. Lazarian, A. 1997, ApJ, 483, 296
34. Lazarian, A. 2003, Journal of Quant. Spect. and Radiative Transfer, 79, 881
35. Lazarian, A. 2004, JKAAS, 37, 563
36. Lazarian, A. & Cho, J. 2005, in Astrophysical Polarimetry 2004, Hawaii, in press, astro-ph/0408174
37. Lazarian, A., & Draine, B.T. 1999a, ApJL, 516, L37
38. Lazarian, A., & Draine, B.T. 1999b, ApJL, 520, L67
39. Lazarian, A., Efroimsky, M., & Ozik, J. 1996, ApJ, 472, 240
40. Lazarian, A., & Finkbeiner 2003, New Astronomy Reviews, 47, v-viii, p.1107
41. Lazarian, A., Goodman, A.A., & Myers, P.C. 1997, ApJ, 490, 273
42. Lazarian, A. & Shutenkov, V. 1990, Pis'ma v Astronom. Zhurnal, 16, 690
43. Lazarin, A. & Vishniac, E. 1999, ApJ, 517, 700L
44. Lazarin, A., Vishniac, E. T., & Cho, J. 2004 ApJ, 603, 180L
45. Lazarian A., & Yan, H. 2002 ApJL, 566, L105
46. Lee, H.-W., Blandford, R. D., & Western, L., 1994, MNRAS, 267, 303
47. Lithwick, Y. and Goldreich, P. 2001, ApJ, 562, 279
48. Montgomery, D. & Turner, L. 1981, Phys. Fluids, 24, 825
49. Narayan, R. & Medvedev, M., ApJ, 562, 129L
50. Purcell, E.M. 1969, Physica, 41, 100
51. Purcell, E.M. 1975, in The Dusty Universe, eds G.B. Field & A.G.W. Cameron, New York, Neal Watson, p. 155.
52. Roberge, W. & Hanany, S. 1990, B.A.A.S., 22, 862
53. Purcell, E.M. 1979, ApJ, 231, 404
54. Roberge, W. & Hanany, S. 1990, B.A.A.S., 22, 862
55. Roberge, W.G., & Lazarian, A. 1999, MNRAS, 305, 615
56. Schlickeiser, R. 2002, Cosmic Ray Astrophysics, Springer-Verlag, Berlin Heidelberg
57. Spitzer, L., & McGlynn, T.A. 1979, ApJ, 231, 417
58. Spitzer, L., Jr.; Tukey, J. 1951 ApJ, 114, 187
59. Thomas, N. 1992, Suvey Geophys., 13, 91
60. Varshalovich, D. A. 1968, Astrofizika, 4, 519
61. Walkup, R., Migdall, A. L., & Pritchard, D. E. 1982, Phys. Rev. A, 25, 3114
62. Weingartner, J. & Draine, B. 2003, ApJ, 589, 289
63. Yan, H. & Lazarian, A. 2002, Phys. Rev. Lett., 89, 281102
64. Yan, H., & Lazarian, A. 2003, ApJL, 592, L33
65. Yan, H. & Lazarian, A. 2004, ApJ, 614, 757
66. Yan, H. & Lazarian, A. 2005, ApJ, submitted