Abstract Observational studies of magnetic fields are crucial. We introduce a process "ground state alignment" as a new way to determine the magnetic field direction in diffuse medium. The alignment is due to anisotropic radiation impinging on the atom/ion. The consequence of the process is the polarization of spectral lines resulting from scattering and absorption from aligned atomic/ionic species with fine or hyperfine structure. The magnetic field induces precession and realign the atom/ion and therefore the polarization of the emitted or absorbed radiation reflects the direction of the magnetic field. The atoms get aligned at their low levels and, as the lifetime of the atoms/ions we deal with is long, the alignment induced by anisotropic radiation is susceptible to extremely weak magnetic fields ($1 \text{G} \gtrsim B \gtrsim 10^{-15} \text{G}$). In fact, the effects of atomic/ionic alignment were studied in the laboratory decades ago, mostly in relation to the maser research. Recently, the atomic effect has been already detected in observations from circumstellar medium and this is a harbinger of future extensive magnetic field studies. A unique feature of the atomic realignment is that they can reveal the 3D orientation of magnetic field. In this article, we shall review the basic physical processes involved in atomic realignment. We shall also discuss its applications to interplanetary, circumstellar and interstellar magnetic fields. In addition, our research reveals that the polarization of the radiation arising from the transitions between fine and hyperfine states of the ground level can provide a unique diagnostics of magnetic fields in the Epoch of Reionization.

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1 Introduction

Astrophysical magnetic fields are ubiquitous and extremely important, especially in diffuse media, where their energy is comparable or exceed the energy of thermal gas. For instance, in diffuse interstellar medium (ISM), magnetic field pressure may exceed the thermal pressure by a factor of ten. In contrast, only a few techniques are available for the studies of magnetic field in diffuse medium and each of them has its own limitation. The Zeeman splitting can sample only relatively strong magnetic fields. In dense and cold clouds (see Crutcher et al. (2010)). In most cases, only line of sight component of the field can be obtained. In some cases, the disentangling of the magnetic field and density fluctuations is nontrivial. For instance, the Faraday rotation is sensitive to the product of the electron density and the line-of-sight magnetic field (see Crutcher & Troland (2008)). Finally, all techniques have their area of applicability, e.g. polarization of the synchrotron emission traces the plane-of-sky magnetic fields of the galactic halo (see Beck (2011)). New promising statistical techniques can measure the average direction of magnetic field using spectral lines fluctuations (Lazarian et al. (2002), Esquivel & Lazarian (2005), Esquivel & Lazarian (2011)) or synchrotron intensity fluctuations Lazarian & Pogosyan (2012).

The closest to the discussed technique of ground state alignment (henceforth GSA) are the techniques based on grain alignment and the Hanle effect. It is well known that the extinction and emission from aligned grains reveal magnetic field direction perpendicular to the line of sight (see Hildebrand (2009) for a review). In spite of the progress in understanding of grain alignment (see Lazarian (2007) for a review), the natural variations in grain shapes and compositions introduce uncertainties in the expected degree of polarization. In contrast, Hanle measurements were proposed for studies of circumstellar magnetic fields and require much higher magnetic fields Landi Degl’Innocenti & Landolfi (2004).

We should mention that all techniques suffer from the line-of-sight integration, which makes the tomography of magnetic fields difficult. As for the relative value, the most reliable is the Zeeman technique, but it is the technique that requires the strongest fields to study. In general, each technique is sensitive to magnetic fields in a particular environment and the synergetic use of the technique is most advantageous. Obviously, the addition of a new techniques is a very unique and valuable development.

Here we discuss a new promising technique to study magnetic fields in diffuse medium. As we discuss below, the physical foundations of these technique can be traced back to the laboratory work on atomic alignment in the middle of the previous century (Kastler (1950); Brossel, Jean et al. (1952); Hawkins & Dicke (1953); Hawkins (1955); Cohen-Tannoudji et al. (1969); see Yan & Lazarian (2012) for details). Later papers Varshalovich (1971) and Landolfi & Landi Degl’Innocenti (1986) considered isolated individual cases of application of the aligned atoms mostly within toy models (see below for a brief review of the earlier development). Yan & Lazarian (Yan & Lazarian (2006), Yan & Lazarian (2007), Yan & Lazarian (2008), Yan & Lazarian (2009)) provided detailed calculations of GSA for a number of atoms and through their study identified GSA as a very unique new technique
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applicable for studying magnetic fields in a variety of environments, from circumstellar regions to the Early Universe. The emission and absorption lines ranging from radio to far UV were discussed. In particular, we identified new ways of study of magnetic fields using absorption lines (see Yan & Lazarian (2006)), radio lines arising from fine and hyperfine splitting (Yan & Lazarian (2008)) and provided extensive calculations of expected polarization degree for a variety of ions and atoms most promising to trace magnetic fields in diffuse interstellar gas, protoplanetary nebula etc.

The GSA technique as it stands now employs spectral-polarimetry and makes use of the ability of atoms and ions to be aligned in their ground state by the external anisotropic radiation. The aligned atoms interact with the astrophysical magnetic fields to get realigned.

It is important to notice that the requirement for the alignment in the ground state is the fine or hyperfine splitting of the ground state. The latter is true for many species present in diffuse astrophysical environments. Henceforth, we shall not distinguish atoms and ions and use word “atoms” dealing with both species. This technique can be used for interstellar and intergalactic studies as well as for studies of magnetic fields in QSOs and other astrophysical objects.

We would like to stress that the effect of ground-state atomic alignment is based on the well known physics. In fact, it has been known that atoms can be aligned through interactions with the anisotropic flux of resonance emission (or optical pumping, see review Happer (1972) and references therein). Alignment is understood here in terms of orientation of the angular momentum vector J, if we use the language of classical mechanics. In quantum terms this means a difference in the population of sublevels corresponding to projections of angular momentum to the quantization axis. There have been a lot of applications since the optical pumping was discovered by Kastler (1950), ranging from atomic clocks, magnetometer, quantum optics and spin-polarized nuclei (see review by Budker & Romalis (2007), book by Cohen-Tannoudji et al. (1969)). We will argue in our review that similar fundamental changes GSA can induce in terms of understanding magnetic fields in diffuse media.

In the review below we discuss three ways of using aligned atoms to trace magnetic field direction: 1) absorption lines 2) emission and fluorescent lines 3) emission and absorption lines related to transitions within splitting of the ground level.

In addition, we shall discuss below how the information from the lines can be used to get the 3D structure of the magnetic fields, and, in particular cases, the intensity of magnetic field.

In terms of terminology, we will use "GSA" in the situations where magnetic field Larmor precession is important and therefore the alignment reveals magnetic fields. Another possible term for the effect is "atomic magnetic re-alignment", which stresses the nature of the effect that we discuss. However, whenever this does not cause a confusion we prefer to use the term "GSA" in the analogy with the dust.

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1 Here interstellar is understood in a general sense, which, for instance, includes reflection nebulae.
alignment which is in most cases caused by radiation and reveals magnetic field due
to dust Larmor precession in external magnetic fields

In what follows, we describe the earlier work on atomic alignment in §2, the basic
idea of GSA in §3. In §4, we expatiate on absorption polarimetry, which is an
exclusive tracer of GSA, we discuss polarimetry of both fine and hyperfine transitions, how to obtain from them 3D magnetic field, different regimes of pumping, circular polarization. Emission polarimetry in presented in §5 and in §6, we discuss
another window of opportunity in IR and submillimetre based on the fine structure transitions within the aligned ground state. In §7, the additional effect of GSA on abundance study is provided. In §8, we put GSA in a context of broad view of radiative alignment processes in Astrophysics. In §9, we focus on observational perspective and show a few synthetic observations with the input data on magnetic field from spacecraft measurements. Summary is provided in §10.

2 History on studies related to atomic alignment

Unlike grain alignment, atomic alignment has been an established physical phe-
nomena which has solid physical foundations and been studied and supported by
numerous experiments (see review by Happer (1972)). The GSA was first proposed
by Kastler (1950), who received Nobel prize in 1966 for pointing out that
absorption and scattering of resonant radiation, which is termed optical pumping,
can induce imbalance on the ground state. Soon after that, the GSA was observed
in experiments (Brossel, Jean et al. (1952); Hawkins & Dicke (1953)). There have
been a lot of applications since the optical pumping was proposed as a way of or-
dering the spin degrees of freedom, ranging from clocks, magnetometer, quantum
optics and spin-polarized nuclei.

It is worth mentioning that atomic realignment in the presence of magnetic
field was also studied in laboratory in relation with early-day maser research (see
Hawkins (1955)). Although our study in YL06 revealed that the mathematical treat-
ment of the effect was not adequate in the original paper, the importance of this
pioneering study should not be underestimated. The astrophysical application of
the GSA was first discussed in the interstellar medium context by Varshalovich
for an atom with a hyperfine splitting. Varshalovich (1971) pointed out
that GSA can enable one to detect the direction of magnetic fields in the interstel-
lar medium, and later in Varshalovich & Chorny (1980) they proposed alignment
of Sodium as a diagnostics of magnetic field in comet’s head though the classical
approach they used to describe the alignment in the presence of magnetic field is
incorrect.

Nearly 20 years after the work by Varshalovich, a case of emission of an idealized
fine structure atom subject to a magnetic field and a beam of pumping radiation

\[ \text{Radiative pumping is much slower than magnetic mixing. Radiation was chosen as the quantiza-
}\] 
\[ \text{tion axis, nevertheless, which inevitably would lead to the nonzero coherence components. They}
\] 
\[ \text{were neglected in Hawkins (1955), however.} \]
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was conducted in Landolfi & Landi Degl’Innocenti (1986). However, in that case, a toy model of a process, namely, an idealized two-level atom was considered. In addition, polarization of emission from this atom was discussed for a very restricted geometry of observations, namely, the magnetic field is along the line of sight and both of these directions are perpendicular to the beam of incident light. This made it rather difficult to use this study as a tool for practical mapping of magnetic fields in various astrophysical environments.

The GSA we deal with in this review should not be confused with the Hanle effect that solar researcher have extensively studied. While both effects are based on similar atomic physics and therefore share some of the quantum electrodynamic machinery for their calculations, the domain of applicability of the effects is very different. In particular, Hanle effect is depolarization and rotation of the polarization vector of the resonance scattered lines in the presence of a magnetic field, which happens when the magnetic splitting becomes comparable to the decay rate of the excited state of an atom. The research into emission line polarimetry resulted in important change of the views on solar chromosphere (see Landi Degl’Innocenti (1983), Landi Degl’Innocenti (1984), Landi Degl’Innocenti (1998), Stenflo & Keller (1997), Trujillo Bueno & Landi Degl’Innocenti (1997), Trujillo Bueno et al. (2002)). However, these studies correspond to a setting different from the one we consider in the case of GSA. The latter is the weak field regime, for which the Hanle effect is negligible. As we mentioned earlier, in the GSA regime the atoms/ions at ground level are repopulated due to magnetic precession. While Hanle effect is prominent in the Solar case, it gets too weak for the environments of interstellar media, circumstellar regions and plasmas of Early Universe. These are the areas where the GSA effect is expected to be very important.

The realignment happens if during the lifetime of an atomic state more than one Larmor precession happens. The time scale of atomic precession scales as 

\[ 0.011 \left( \frac{5 \mu G}{B} \right) \text{s} \]

As the life time of the ground state is long typically (determined by absorption rate, see table 1), even extremely weak magnetic fields can be detected this way. On the contrary, the typical application of the Hanle effect includes excited states with typical life-times of \( A^{-1} \gtrsim 10^7 \). Therefore, unlike GSA Hanle effect is used for studies of relatively strong magnetic fields, e.g. magnetic fields of the stars (see Nordsieck & Ignace (2005)).

Full calculations of alignment of atom and ions in their ground or metastable state in the presence of magnetic field were done in Yan & Lazarian (2006), Yan & Lazarian (2007), Yan & Lazarian (2008). This considers polarization of absorbed light arising from aligned atoms with fine structure. Yan & Lazarian (2007) extends the treatment to emission and atoms with hyperfine, as well as, fine and hyperfine structure. Yan & Lazarian (2008) addresses the issues of radio emission arising from the transitions between the sublevels of the ground state and extended the discussions to the domain of both stronger and weaker magnetic field when the Hanle and ground level Hanle effects are present.

The polarization arising from GSA is on its way of becoming an accepted tool for interstellar and circumstellar studies. We see some advances in this direction. For instance, polarization of absorption lines arising from GSA was predicted in YL06

\[ \text{[Landolfi \\& Landi Degl’Innocenti (1986)]} \]

\[ \text{[Landi Degl’Innocenti (1986), Landi Degl’Innocenti (1984), Landi Degl’Innocenti (1998), Stenflo \\& Keller (1997), Trujillo Bueno \\& Landi Degl’Innocenti (1997), Trujillo Bueno et al. (2002).}} \]
and was detected for the polarization of Hα absorption in Kuhn et al. (2007) though they neglected the important realignment effect of magnetic field in their analysis. Focused on atomic fluorescence, Nordsieck (2008) discussed observational perspective using pilot spectroscopic observation of NGC as an example. We are sure that more detection of the predicted polarization will follow soon. Therefore we believe that the time is ripe to discuss the status of the GSA in the review in order to attract more attention of both observers and theorists to this promising effect.

3 Basic physics of GSA

The basic idea of the GSA is very simple. The alignment is caused by the anisotropic deposition of angular momentum from photons of unpolarized radiation. In typical astrophysical situations the radiation flux is anisotropic (see Fig.1 right). As the photon spin is along the direction of its propagation, we expect that atoms scattering the radiation from a light beam can aligned. Such an alignment happens in terms of the projections of angular momentum to the direction of the incoming light. To study weak magnetic fields, one should use atoms that can be aligned in the ground state. For such atoms to be aligned, their ground state should have the non-zero angular momentum. Therefore fine (or hyperfine) structure is necessary for the alignment that we describe in the review.

Let us discuss a toy model that provides an intuitive insight into the physics of GSA. Consider an atom with its ground state corresponding to the total angular momentum \( I = 1 \) and the upper state corresponding to the angular momentum \( I = 0 \) Varshalovich (1971). If the projection of the angular momentum to the direction of the incident resonance photon beam is \( M \), the upper state \( M \) can have values \(-1\), \(0\), and \(1\), while for the upper state \( M=0 \) (see Fig.1 left). The unpolarized beam contains an equal number of left and right circularly polarized photons whose projections on the beam direction are 1 and -1. Thus absorption of the photons will induce transitions from the \( M = -1 \) and \( M = 1 \) sublevels. However, the decay from the upper state populates all the three sublevels on ground state. As the result the atoms accumulate in the \( M = 0 \) ground sublevel from which no excitations are possible. Accordingly, the optical properties of the media (e.g. absorption) would change.

The 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 sublevel of \( M = 0 \). Collisions, however, redistribute atoms to different sublevels. Nevertheless, as the randomization of the ground state requires spin flips, it is less efficient than one might naively imagine Hawkins (1955). For instance, experimental study in Kastler (1957) suggests that more than 10 collisions with electrons are necessary to destroy the aligned state of sodium. The reduced sensitivity of aligned atoms to

\[ \text{Modern theory of dust alignment, which is a very powerful way to study magnetic fields (see Lazarian (2007) and ref. therein) is also appealing to anisotropic radiation as the cause of alignment.} \]
disorienting collisions makes the effect important for various astrophysical environments.

Owing to the precession, the atoms with different projections of angular momentum will be mixed up. Magnetic mixing happens if the angular momentum precession rate is higher than the rate of the excitation from the ground state, which is true for many astrophysical conditions, e.g., interplanetary medium, ISM, intergalactic medium, etc. As a result, angular momentum is redistributed among the atoms, and the alignment is altered according to the angle between the magnetic field and radiation field $\theta_r$ (see Fig. 1(right)). This is the classical picture.

In quantum picture, if magnetic precession is dominant, then the natural quantization axis will be the magnetic field, which in general is different from the symmetry axis of the radiation. The radiative pumping is to be seen coming from different directions according to the angle between the magnetic field and radiation field $\theta_r$, which results in different alignment.

The classical theory can give a qualitative interpretation which shall be utilized in this paper to provide an intuitive picture. Particularly for emission lines, both atoms and the radiation have to be described by the density matrices in order to obtain quantitative results. This is because there is coherence among different magnetic sublevels on the upper state.$^4$

Our simple considerations above indicate that, in order to be aligned, first, atoms should have enough degrees of freedom: namely, the quantum angular momentum number must be $\geq 1$. Second, the incident flux must be anisotropic. Moreover, the

$^4$ In quantum physics, quantum coherence means that subatomic particles are able to cooperate. These subatomic waves or particles not only know about each other, but are also highly interlinked by bands of shared electromagnetic fields so that they can communicate with each other.
\[ \nu_L (s^{-1}) \quad \text{Larmor precession frequency} \]
\[ \tau_R^{-1} (s^{-1}) \quad \text{radiative pumping rate} \]
\[ \tau_T^{-1} (s^{-1}) \quad \text{emission rate within ground state} \]
\[ \tau_c^{-1} (s^{-1}) \quad \text{collisional transition rate} \]

Table 1 Relevant rates for GSA. \( A_m \) is the magnetic dipole emission rate for transitions among \( J \) levels of the ground state of an atom. \( f_{kj} \) is the inelastic collisional transition rates within ground state due to collisions with electrons or hydrogens, and \( f_{sp} \) is the spin flip rate due to Van der Waals collisions. In the last row, example values for C II are given. \( \tau_R^{-1} \) is calculated for an O type star, where \( R_* \) is the radius of the star radius and \( r \) is the distance to the star. (From Yan & Lazarian (2006))

\[ \nu_L \gg \tau_R^{-1} > \tau_c^{-1} > \tau_T^{-1} \]
Other relations are possible, however. If \( \tau_T^{-1} > \tau_R^{-1} \), the transitions within the sublevels of ground state need to be taken into account and relative distribution among them will be modified (see YL06,c). Since emission is spherically symmetric, the angular momentum in the atomic system is preserved and thus alignment persists in this case. In the case \( \nu_L < \tau_R^{-1} \), the magnetic field does not affect the atomic occupations and atoms are aligned with respect to the direction of radiation. From the expressions in Table 1, we see, for instance, that magnetic field can realign CII only at a distance \( r \gtrsim 7.7 \text{AU} \) from an O star if the magnetic field strength \( \sim 5 \mu \text{G} \).

If the Larmor precession rate \( \nu_L \) is comparable to any of the other rates, the atomic line polarization becomes sensitive to the strength of the magnetic field. In these situations, it is possible to get information about the magnitude of magnetic field.

Fig 2 illustrates the regime of magnetic field strength where atomic realignment applies. Atoms are aligned by the anisotropic radiation at a rate of \( \tau_R^{-1} \). Magnetic precession will realign the atoms in their ground state if the Larmor precession rate \( \nu_L > \tau_R^{-1} \). In contrast, if the magnetic field gets stronger so that Larmor frequency becomes comparable to the line-width of the upper level, the upper level occupation, especially coherence is modified directly by magnetic field, this is the domain of Hanle effect, which has been extensively discussed for studies of solar magnetic...
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Fig. 2 Different regimes divided according to the strength of magnetic field and the Doppler line width. Atomic realignment is applicable to weak field ($< 1G$) in diffuse medium. Level interferences are negligible unless the medium is substantially turbulent ($\delta v \gtrsim 100\text{km/s}$) and the corresponding Doppler line width becomes comparable to the fine level splitting $\nu_{\Delta J}$. For strong magnetic field, Zeeman effect dominates. When magnetic splitting becomes comparable to the Doppler width, $\sigma$ and $\pi$ components (note: we remind the reader that $\sigma$ is the circular polarization and $\pi$ represents the linear polarization.) can still distinguish themselves through polarization, this is the magnetograph regime; Hanle effect is dominant if Larmor period is comparable to the lifetime of excited level $\nu_{\perp}^{-1} \sim A^{-1}$; similarly, for ground Hanle effect, it requires Larmor splitting to be of the order of photon pumping rate; for weak magnetic field ($< 1G$) in diffuse medium, however, GSA is the main effect provided that $\nu_{L} = 17.6(B/\mu G)\text{s}^{-1} > \nu_{R}^{-1}$. (From Yan & Lazarian (2006)).

Long-lived alignable metastable states that are present for some atomic species between upper and lower states may act as proxies of ground states. Absorptions from these metastable levels can also be used as diagnostics for magnetic field therefore.

The variety of species that are subject to the ground state or metastable state alignment render the GSA technique with really unique capabilities. Different species are expected to be aligned when the conditions for their existence and their alignment are satisfied. This allows to study the 3D distribution of magnetic fields,
rather than line-average magnetic fields, which are available through most of the alternative techniques.

Most atoms have sublevels on the ground state, among which there are magnetic dipole transitions. Although its transition probability is very low, it can be comparable to the optical pumping rate in regions far from any radiation source. Depending on how far away the radiation source is, there can be two regimes divided by the boundary where the magnetic dipole radiation rate $A_m$ is equal to the pumping rate $\tau_{\text{ref}}^{-1}$. Inside the boundary, the optical pumping rate is much larger than the M1 transition rate $A_m$ so that we can ignore the magnetic dipole radiation as a first order approximation. Further out, the magnetic dipole emission is faster than optical pumping so that it can be assumed that most atoms reside in the lowest energy level of the ground state and alignment can only be accommodated on this level. The two regimes are demarcated at $r_1$ (see Fig. 3), where

$$\tau_{\text{ref}}^{-1} = B_{J_1J_0}I_{BB}(R_r/r_1)^2 = A_m,$$

and $I_{BB}, R_r$ are the intensity and radius of the pumping source. For different radiation sources, the distance to the boundary differs. For an O type star, the distance would be $\sim 0.1$ pc for species like C II, Si II, while for a shell star ($T_{\text{eff}} = 15,000$ K), it is as close as to $\sim 0.003 - 0.01$ pc. For the species like, C II, Si II the lowest level is not alignable with $J_l = 1/2$, and thus the alignment is absent outside the radius $r_1$, which ensures that observations constrain the magnetic field topology within this radius.

4 Polarization of absorption lines

The use of absorption lines to study magnetic fields with aligned atoms was first suggested by Yan & Lazarian (2006) Yan & Lazarian (2006). Below we briefly outline the main ideas of the proposed techniques.

When atomic species are aligned on their ground state, the corresponding absorption from the state will be polarized as a result of the differential absorption parallel and perpendicular to the direction of alignment. The general expression for finite optical depth would be

$$I = (I_0 + Q_0)e^{-\tau(1+\eta_1/\eta_0)} + (I_0 - Q_0)e^{-\tau(1-\eta_1/\eta_0)},$$

$$Q = (I_0 + Q_0)e^{-\tau(1+\eta_1/\eta_0)} - (I_0 - Q_0)e^{-\tau(1-\eta_1/\eta_0)},$$

$$U = U_0e^{-\tau}, V = V_0e^{-\tau},$$

where $I_0, Q_0, U_0$ are the Stokes parameters of the background radiation, which can be from a weak background source or the pumping source itself. $d$ refers to the thickness of medium. $\eta_0, \eta_1, \eta_2$ are the corresponding absorption coefficients. In the case of unpolarized background radiation and thin optical depth, the degree of linear polarization is given by
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For multiple lower levels, $\tau_0^{-1}$ is less than collisional rates, alignment is partially destroyed. For atoms with multiple lower levels, depending on the comparison between the pumping rate and the magnetic dipole radiation rate among the lower levels, the atoms are aligned differently. In the strong pumping case, all the alignable lower levels are aligned; on the contrary, only the ground level can be aligned in the case of weak pumping. From [Yan & Lazarian (2006)].

The polarization in this case has a simple relation given by

$$P = \frac{Q}{I} \approx \frac{-\eta_1}{\eta_0} \approx -\tau \frac{\eta_1}{\eta_0}$$

with the alignment parameter $\sigma_0^2 \equiv \frac{\rho_{12}^2}{\rho_{00}^2}$, the normalized dipole component of density matrix of ground state, which quantifies the degree of alignment. For instance, for a state of angular momentum 1, the definition of $\rho_{12}^2 = [\rho(1, 1) - 2\rho(1, 0) + \rho(1, -1)]$. The generic definition can be found in ??.

$$\frac{P}{\tau} = \frac{Q}{I\eta_0d} \approx \frac{-\eta_1}{\eta_0} = \frac{1.5\sigma_0^2(J, \theta_r) \sin^2 \theta w^2_{JL_JL}}{\sqrt{2 + \sigma_0^2(J, \theta_r)(1 - 1.5 \sin^2 \theta)w^2_{JL_JL}}}.$$  

with $\theta$ is the angle between the line...
of sight and magnetic field. $w^2_{J,J_\alpha}$ defined below, is a parameter determined by the atomic structure

$$w^K_{J,J_\alpha} \equiv \left\{ \begin{array}{l} 1 1 K \\ J_l \ J_l \ J \alpha \end{array} \right\} / \left\{ \begin{array}{l} 1 1 0 \\ J_l \ J_l \ J \alpha \end{array} \right\}. \quad (5)$$

The values of $w^2_{J,J'}$ for different pairs of $J, J'$ are listed in Table 2. We see that it totally depends on the sign of $w^2_{J,J'}$, whether the alignment and polarization are either parallel or orthogonal. Once we detect the direction of polarization of some absorption line, we immediately know the direction of alignment. The alignment is either parallel or perpendicular to the direction of symmetry axis of pumping radiation in the absence of magnetic field. Real astrophysical fluid though is magnetized, and the Larmor precession period is usually larger than the radiative pumping rate unless it is very close to the radiation source as we pointed out earlier. In this case, realignment happens and atomic species can be aligned either parallel or perpendicular to the local magnetic field. The switch between the two cases is always at the Van Vleck angle $\theta_r = 54.7^\circ, 180^\circ - 54.7^\circ$, where $\theta_r$ is the angle between the magnetic field and radiation. As the result the polarization of the absorption line also changes according to Eq.(4). This turnover at the Van Vleck angle is a generic feature regardless of the specific atomic species as long as the background source is unpolarized and it is in the atomic realignment regime. In practice, this means that once we detect any polarization in absorption line, we get immediate information of the direction of magnetic field in the plane of sky within 90 degree degeneracy. If we have two measurable, then according to eq.(4) both $\theta_r, \theta$ can be determined. With $\theta_r$ known, the 90 degree degeneracy in the pictorial plane can be removed and we can get 3D information of magnetic field.

Fig[4] shows the dependence of polarization of S II absorption on $\theta_r, \theta$, which is representative for all polarization of absorption lines. From these plots, a few general features can be identified. At $\theta = 90^\circ$, the observed polarization reaches a maximum for the same $\theta_r$ and alignment, which is also expected from Eq.(4). This shows that atoms are indeed realigned with respect to magnetic field so that the intensity difference is maximized parallel and perpendicular to the field (Fig[4]right). At $\theta = 0^\circ, 180^\circ$, the absorption polarization is zero according to Eq.(4). Physically
| Species | Ground state | excited state | Wavelength(Å) | \( P_{\text{max}} \) |
|---------|--------------|---------------|---------------|------------------|
| S II    | 4S^{7/2}_3/2 | 4P^{1/2,3/2,5/2}_1/2 | 1250-1260     | 12%(3/2 → 1/2)  |
| Cr I    | a3F^5/2      | 7P^5/2_3,4    | 3580-3606     | 5%(3 → 2)       |
| C II    | 2P^1/2,3/2   | 2S^1/2,2P^1/2,3/2,2D^3/2,5/2 | 1036.3-1335.7 | 15%(3/2 → 1/2)  |
| Si II   |              |               | 989.9-1533.4  | 7%(3/2 → 1/2)   |
| O I     | 3P^{2,1,0}   | 3S^1, 3D^1,2,3 | 911-1302.2    | 29%(2 → 2)      |
| S I     | 3S^1,3P^0,1,2, 3D^1,2,3 | 1205-1826     | 22%(1 → 0)    |
| C I     | 3P^{0,1,2}   | 3P^0,1,2,3D^0,2 | 1115-1657    | 18%(1 → 0)      |
| Si I    |              |               | 1695-2529     | 20%(2 → 1)      |
| S III   |              |               | 1012-1202     | 24.5%(2 → 1)    |
| Ti II   | a4F^4/2      | z4G^5/2       | 3384.74       | -0.7%           |
|         |              | z4F^0,5/2     | 3230.13       | -0.7%           |
|         |              | z4F^0,3/2     | 3242.93       | 2.9%            |
|         |              | z4F^0,5/2     | 3067.25       | 2.9%            |
|         |              | z4F^0,3/2     | 3073.88       | 7.3%            |

Table 3 Absorption lines of selected alignable atomic species and corresponding transitions. Note only lines above 912 Å are listed. Data are taken from the Atomic Line List [http://www.pa.uky.edu/~peter/atomic/](http://www.pa.uky.edu/~peter/atomic/) and the NIST Atomic Spectra Database. The last column gives the maximum polarizations and its corresponding transitions. For those species with multiple lower levels, the polarizations are calculated for shell star (\( T_{\text{eff}} = 15,000 \)K) in the strong pumping regime; in the weak pumping regime, the maximum polarizations are 19% for OI transition (2 → 2), and 9% for SI transition (2 → 2).

Fig. 4 *left*: Degree of polarization of S II absorption lines vs. \( \theta_r \), the angle between magnetic field and direction of pumping source \( \theta \), the angle between magnetic field and line of sight. *right*: The contour graphs of S II polarization. It is determined by the dipole component of density matrix \( \sigma_0 (\theta_r) \) and the direction of observation \( \theta \) (Eq. (4)). From Yan & Lazarian (2006).
this is because the precession around the magnetic field makes no difference in the \( x, y \) direction when the magnetic field is along the line of sight (Fig.1 right).

We consider a general case where the pumping source does not coincide with the object whose absorption is measured. If the radiation that we measure is also the radiation that aligns the atoms, the direction of pumping source coincides with line of sight, \( i.e., \theta = \theta_r \) (Fig.1 right).

### 4.1 Is there any circular polarization?

Note that if the incident light is polarized in a different direction with alignment, circular polarization can arise due to de-phasing though it is a 2nd order effect. Consider a background source with a nonzero Stokes parameter \( U_0 \) shining upon atoms aligned in \( Q \) direction\(^5\). The polarization will be precessing around the direction of alignment and generate a \( V \) component representing a circular polarization

\[
\frac{V}{I} \approx \frac{\kappa Q}{\eta_l I_0} \frac{U_0}{\xi_v \eta_l I_0} \approx \frac{\psi \eta Q}{\xi_v \eta_l I_0} \tag{6}
\]

where \( \kappa \) is the dispersion coefficient, associated with the real part of the refractory index, whose imaginary part corresponds to the absorption coefficient \( \eta \). \( \psi \) is the dispersion profile and \( \xi \) is the absorption profile.

The incident light can be polarized in the source, \( e.g., \) synchrotron emission from pulsars, or polarized through the propagation in the interstellar medium, \( e.g., \) as a result of selective extinction from the aligned dust grains (see Lazarian (2007)). In the latter case, the polarization of the impinging light is usually low and the intensity of circular polarization is expected to be low as well. This should not preclude the detection of the effect as the instrumentation improves.

### 5 IR/submilimetre transitions within ground state

The alignment on the ground state affects not only the optical (or UV) transitions to the excited state, but also the magnetic dipole transitions within the ground state. Similar to HI, other species that has a structure within the ground state is also influenced by the optical pumping\(^6\) through the Wouthuysen-Field effect (Wouthuysen (1952); Field (1958)). After absorption of a Ly\( \alpha \), the hydrogen atom can relax to either of the two hyperfine levels of the ground state, which can induce a HI 21cm.

\(^5\) To remind our readers, The Stokes parameters \( Q \) represents the linear polarization along \( e_1 \) minus the linear polarization along \( e_2 \); \( U \) refers to the polarization along \( (e_1 + e_2)/\sqrt{2} \) minus the linear polarization along \( (e_1 - e_2)/\sqrt{2} \) (see Fig.1 right).

\(^6\) To clarify, we do not distinguish between pumping by optical lines or UV lines, and name them simply "optical pumping".
emission if the atom falls onto the ground triplet state (see also Furlanetto et al. (2006) for a review). Recently, the oxygen pumping has been proposed as a probe for the intergalactic metals at the epoch of reionization Hernández-Monteagudo et al. (2007).

However, in all these studies, the pumping light is assumed to be isotropic. This is problematic, particularly for the metal lines whose optical depth is small. During the early epoch of reionization, for instance, the ionization sources are localized, which can introduce substantial anisotropy. The GSA introduced by the anisotropy of the radiation field can play an important role in many circumstances. The earlier oversimplified approach can lead to a substantial error to the predictions. The emissivity and absorption coefficients for the Stokes parameters are modified due to the alignment effect. The ratio of corresponding optical depth to that without alignment is

\[ \tilde{\tau} = \frac{\tau}{\tau_0} = \frac{\tilde{\eta}_l,\text{exp}(-T_s/T_s)}{1 - \exp(-T_s/T_s)}, \]

where \( T_s \) is the equivalent temperature of the energy separation of the metastable and ground level, \( T_s \) is the spin temperature.

\[ \tilde{\eta}_l = \eta_l/\eta_l^0 = 1 + w_0\sigma_0^2(J_l^0)\mathcal{J}_0^2(i,\Omega), \]

\[ \tilde{\eta}_{l,i} = \tilde{\varepsilon}_i = \varepsilon_i/\varepsilon_i^0 = 1 + w_0\sigma_0^2(J_l)\mathcal{J}_0^2(i,\Omega) \]

are the ratios of absorption and stimulated emission coefficients with and without alignment, where \( \mathcal{J}_0^2(i,\Omega) \) are the irreducible tensors for Stokes parameters (see, e.g. Yan & Lazarian 2006). Since both the upper (metastable) level and the lower level are long lived and can be realigned by the weak magnetic field in diffuse medium, the polarization of both emission and absorption between them is polarized either parallel or perpendicular to the magnetic field like the case of all the absorptions from the ground state, and can be described by Eq. (4). In the case of emission, the dipole component of the density matrix in Eq. (4) should be replaced by that of the metastable level. In fig. 11 we show an example of our calculation of the polarization of [CI] 610\( \mu \)m, which can be detected in places like PDRs.

We discussed pumping of hyperfine lines [H I] 21 \( \text{cm} \) and [N V] 70.7 \( \text{mm} \) in Yan & Lazarian (2007) and fine line [O I] 63.2\( \mu \)m here. Certainly this effect widely exists in all atoms with some structure on ground state, e.g., Na I, K I, fine structure lines, [C I], [C II], [Si II], [N II], [N III], [O II], [O III],[S II], [S III], [S IV], [Fe II], etc (see Table 4.1 in Lequeux (2005)). The example lines we have calculated are listed in Table 4. Many atomic radio lines are affected in the same way and they can be utilized to study the physical conditions, especially in the early universe: abundances, the extent of reionization through the anisotropy (or localization) of the optical pumping sources, and magnetic fields, etc.
6 Atoms with hyperfine structure

Although the energy of hyperfine interaction is negligible, the hyperfine interaction should be accounted for atoms with nuclear spins. This is because angular momentum instead of energy is the determinative factor. Hyperfine coupling increases the total angular momentum and the effects are two-sided. For species with fine structure \((J > 1/2)\), the hyperfine interaction reduces the degree of alignment since in general the more complex the structure is, the less alignment is. This is understandable. As polarized radiation is mostly from the sublevels with largest axial angular momentum, which constitutes less percentage in atoms with more sublevels. For species without fine structure \((J < 1/2)\) like alkali, the hyperfine interaction enables alignment by inducing more sublevels \(^7\) (see Fig. 5).

Note that the alignment mechanism of alkali is different from that illustrated in the cartoon (depopulation pumping) since the excitation rates from different sublevels on the ground state are equal. In other words, atoms from all the sublevels have equal probabilities to absorb photons. For the same reason, the absorption from alkali is not polarized \(^8\). The actual alignment is due to another mechanism, repopulation pumping. The alkali atoms are repopulated as a result of spontaneous decay from a polarized upper level (see Happer (1972)). Upper level becomes polarized because of differential absorption rates to the levels.

7 Polarization of resonance and fluorescence lines

When the magnetic precession rate becomes less than the emission rate of the upper level, the direct effect of magnetic field on the upper level is negligible. The only influence of magnetic field is on the ground state through the alignment of atoms. This is the effect that was the focus of our studies in Yan & Lazarian \(2006, 2007, 2008\). The atoms are aligned either parallel or perpendicular to the magnetic field as we discussed before.

---

\(^7\) There are no energy splittings among them, the effect is only to provide more projections of angular momentum (see Yan & Lazarian (2007)).

\(^8\) Only if hyperfine structure can be resolved, polarization can occur.
Fig. 5 The occupation in ground sublevels for Na. It is modulated by the angle between magnetic field and the radiation field $\theta_r$.

The differential occupation on the ground state (see Fig 5) can be transferred to the upper level of an atom by excitation. Emission from such a differentially populated state is polarized, the corresponding emission coefficients of the Stokes parameters are given in Landi Degl’Innocenti (1984); Yan & Lazarian (2008) for fine structure transitions and Yan & Lazarian (2007) for transitions involving hyperfine structures. Indeed emission line can be polarized without GSA. This corresponds the textbook description of polarization of scattered lines. It can be shown that if the dipole and other higher order components of the ground state density matrix $\rho^g_{ij}$ are zeros, we recover the classical result in the optically thin case

$$e_2 = e_3 = 0, \quad P = \frac{e_1}{e_0} = \frac{3E_1 \sin^2 \alpha}{4 - E_1 + 3E_1 \cos^2 \alpha}$$

(10)

where $\alpha$ is the scattering angle. The polarizability is actually given by

$$E_1 = \frac{w_{\mu,\nu}^2 r_{20}}{\rho_0}$$

(11)

for transitions in fine structure. If we account for the alignment by radiation, but ignore magnetic field, i.e., $\theta_r = 0$, then

$$E_1 = \frac{w_{\mu,\nu}^2 \left[ r_{20} + r_{22} \sigma_0^2 (J_l) + \sqrt{2} \rho_2 \sigma_0^2 (J_l) \right]}{\sqrt{2} \rho_0 + r_{02} \sigma_0^2}$$

(12)

9 Since there is no alignment on the ground state and we can choose the direction of radiation as the quantization axis, $\alpha = \theta$. 

[1] Landi Degl’Innocenti (1984)
[2] Yan & Lazarian (2008)
[3] Yan & Lazarian (2007)
For optically thin case, the linear polarization degree \( p = \sqrt{Q^2 + U^2} / I = \sqrt{\epsilon_2^2 + \epsilon_1^2} / \epsilon_0 \),
the positional angle \( \chi = \frac{1}{2} \tan^{-1}(U/Q) = \frac{1}{2} \tan^{-1}(\epsilon_2/\epsilon_1) \).

Since the weak magnetic field does not have direct influence on the upper level,
there is no general simple geometrical correspondence between the polarization and magnetic field as in the case of absorption except the special case where the scattering angle is small (see [8] and Shangguan & Yan [2012] for details). In fact, from the discussions above (eq.10), we see that polarization is either parallel or perpendicular to the radiation field in the absence of GSA. The effect of GSA is to introduce coherence on the upper level through the radiative excitation, which is then transferred to emission. To obtain the direction of magnetic field, one needs quantitative measurements of at least two lines. The lines for which we have calculated the polarizations are listed in Table 5.

| Species | Lower state | Upper state | Wavelength(Å) | \( P_{\text{max}} \) |
|---------|-------------|-------------|---------------|-----------------|
| S II    | 4S\( \frac{1}{2} \) | 4P\( \frac{3}{2} \) | 1253.81       | 30.6%           |
|         |             | 4P\( \frac{1}{2} \) | 1259.52       | 31.4%           |
|         | 3P\( \frac{1}{2} \) | 3S\( \frac{1}{2} \) | 1306          | 16%             |
| O I     | 3P\( \frac{1}{2} \) | 3S\( \frac{1}{2} \) | 1304          | 8.5%            |
|         | 3P\( \frac{1}{2} \) | 3S\( \frac{1}{2} \) | 1302          | 1.7%            |
|         | 3P\( \frac{1}{2} \) | 3P\( \frac{1}{2} \) | 5555,6046,7254 | 2.3%            |
| H I     | 1S\( \frac{1}{2} \) | 2P\( \frac{3}{2} \) | 912-1216      | 26%             |
| Na I    | 1S\( \frac{1}{2} \) | 2P\( \frac{3}{2} \) | 5891.6        | 20%             |
| K I     | 1S\( \frac{1}{2} \) | 2P\( \frac{3}{2} \) | 7667,4045.3   | 21%             |
| N V     | 1S\( \frac{1}{2} \) | 2P\( \frac{3}{2} \) | 1238.8        | 22%             |
| P V     | 1S\( \frac{1}{2} \) | 2P\( \frac{3}{2} \) | 1117.977      | 27%             |
| N I     | 4S\( \frac{1}{2} \) | 4P\( \frac{1}{2} \) | 1200          | 5.5%            |
| Al II   | 1S\( \frac{1}{2} \) | 1P\( \frac{1}{2} \) | 8643A         | 20%             |

Table 5: The maximum polarizations expected for a few example of emission lines and their corresponding transitions.

In the case that the direction of optical pumping is known, e.g., in planetary system and circumstellar regions, magnetic realignment can be identified if the polarization is neither perpendicular or parallel to the incident radiation (see eqs.10,12). As an example, we show here polarization map from a spherical system with poloidal magnetic field [Yan & Lazarian (2009), eg., a circumstellar envelope, the polarization is supposed to be spherically symmetric without accounting for the effect of the magnetic field. With magnetic realignment though, the pattern of the polarization map is totally different, see fig.9. In practice, one can remove the uncertainty by measuring polarization from both alignable and non-alignable species, which does not trace the magnetic field.
8 Influence of Magnetic Field on Polarization and line intensity

The influence of magnetic field on the polarization of scattered lines can be illustrated by contour maps of position angle as a function of magnetic field direction for fixed scattering angle. The geometry of the maps is defined in Fig. 6 left.

When scattering angle is relatively large ($\theta_0 \gtrsim 20^\circ$), quasi-symmetry is maintained and $\phi_B$ corresponding to the symmetric axes equals to the scattering angle (or to $\theta_0 + 180^\circ$) (see dash lines in Fig. 7 right). $\chi$ on the quasi-symmetric axes are zero. This means that when the projection of magnetic field on the scattering plane is parallel to the line of sight, the vector of polarization also lies in the same plane. In general, the position angle reduces with the decrease of the scattering angle. When the scattering angle is small, the direction of polarization generally traces directly the magnetic field direction in the pictorial plane. (see Fig. 7 left) In addition, the polarizations are the same for $\theta_0$ and $(180^\circ - \theta_0)$ because of the symmetry.

Magnetic field alters not only the direction of polarization of scattered lines, but also the degree of polarization (see Fig. 6 right). Due to an average caused by magnetic mixing the magnetic field decreases the polarization degree at large scattering angle and increases the polarization at small scattering angle. In the classical description, there is some similarity to the Hanle process as discussed in ?? The difference is that magnetic coherence is transferred to the upper state indirectly from the ground state through absorption (see details in Shangguan & Yan [2012]).
Fig. 7 The contour map of position angle, $\chi$, as a function of the direction of magnetic field. The scattering angles are set to be 5° (left) and 60° (right). In the right panel, the dashed lines are two quasi-symmetry axes corresponding to $\phi_B = 60°$ and 240°, respectively. $\theta_B$ and $\phi_B$ are defined in Fig. 6. From Shangguan & Yan (2012).

9 Observational Perspective

9.1 Interstellar absorption and 3D magnetic field measurement

Different from the case of emission, GSA is a unique mechanism to polarize absorption lines, which was first proposed by Yan & Lazarian (2006). As illustrated above, 2D magnetic field in the plane of sky can be easily obtained by the direction of polarization. If we have quantitative measurement, we can get 3D magnetic field.

The resonance absorption lines in the Table 2 appropriate for studying magnetic fields in diffuse, low column density ($A_V \sim$ few tenths) neutral clouds in the interstellar medium are NI, OI, SII, MnII, and FeII. These are all in the ultraviolet.

At higher column densities, the above lines become optically thick, and lines of lower abundance, as well as excited states of the above lines become available. Significantly, some of these (TiII, FeI) are in the visible. An interesting region where the degenerate case (pumping along the line of sight) should hold is the "Orion Veil" [Abel et al. 2006], a neutral cloud with $A_V \sim 1.5$, and $N_s \sim 1000$, which is 1-2 parsec in the foreground of the Orion Nebula. The Orion Veil should be pumped by the Trapezium. This region is of particular interest for magnetic field studies, since it is one of the only places where maps exist of the HI 21 cm Zeeman Effect. This gives the sign and magnitude of the magnetic field along the line of sight. The magnetic realignment diagnostic, on the other hand, gives the orientation of the magnetic field lines in 3D, which is exactly complimentary information: combination of the two yields a complete 3D magnetic field map.

The TiII lines provide a fairly accessible test of the magnetic alignment diagnostic, although there are not enough strongly polarized lines in the visible to be useful
by themselves: observation of an effect at TiII with moderate resolution would motivate a serious study of the pumping of the much more numerous FeI lines, and the construction of more advanced instrumentation. Table 3 shows the five strongest TiII lines, all from the J = 3/2 ground state of the ion (see also Fig.8). The polarization depends only on the J of the upper state, regardless of the other quantum numbers. We have assumed “weak pumping” for this calculation, so that the rate of decay from the excited states of the ground term exceeds the pumping rate. The most strongly polarized line, 3074, is unfortunately difficult from the ground, and the strongest line, 3384, is only weakly polarized. The 3243 line is the most favorable. It is estimated that for a line with \( \tau \sim 1 \) and a width of 20 km/sec, this effect would be detectable at 10\( \sigma \) for all stars brighter than \( V=8 \) with the spectropolarimeter at SALT with resolution \( R = 6000 \) (Nordsieck, private communications).

As a first step, with low resolution measurement, 2D magnetic field in the pictorial plane can be easily obtained from the direction of polarization with a 90 degree degeneracy, similar to the case of grain alignment and Goldreich-Kylafs effect. Different from the case of emission, any polarization, if detected, in absorption lines, would be an exclusive indicator of alignment, and it traces magnetic field since no other mechanisms can induce polarization in absorption lines. The polarization in H\( \alpha \) absorption that Kuhn et al. (2007) reported in fact was due to the GSA as predicted in Yan & Lazarian (2006) for general absorptions.

If we have two measurable, we can solve Eq.4 and obtain \( \theta_r, \theta \). With \( \theta_r \) known, the 90 degree degeneracy can be removed since we can decide whether the polarization is parallel or perpendicular to the magnetic field in the plane of sky. Combined with \( \theta \), the angle between magnetic field and line of sight, we get 3D direction of magnetic field.
9.2 Circumstellar Absorption

The Be star ζ Tau illustrates one application of the diagnostic in circumstellar matter. A number of absorption lines from SiII metastable level \(2P_{3/2}\) are seen, along with the OI and SII lines already discussed. This provides for a large number of different species. In this case the absorption is likely being formed in a disk atmosphere, absorbing light from the disk and pumped by light from the star. The net polarization signal is integrated across the disk, and depends just on the magnetic field geometry and the inclination of the disk. In this case, the inclination is known from continuum polarization studies to be 79° Carciofi et al. (2005). The FUSP sounding rocket should be sensitive to these effects: ζ Tau is one of the brightest UV sources in the sky.

A second interesting circumstellar matter case is for planetary disks around pre-main sequence stars. In this case, pumping conditions are similar to those for comets in the Solar System: pumping rates on the order of 0.1 – 1 Hz, and realignment for fields greater than 10 – 100 mGauss. Conditions here are apparently conducive to substantial populations in CNO metastable levels above the ground term: Roberge, et al (2002) find strong absorption in the FUV lines (1000 - 1500 Ang) of OI (1D) and NI and SII (2D), apparently due to dissociation of common ice molecules in these disks (these are also common in comet comae). Since these all have \(J_i > 1\), they should be pumped, and realigned. This presents the exciting possibility of detecting the magnetic geometry in planetary disks and monitoring them with time. Since these are substantially fainter sources, this will require a satellite facility.

9.3 Fluorescence from reflection nebulae

The magnetic realignment diagnostic can also be used in fluorescent scattering lines. This is because the alignment of the ground state is partially transferred to the upper state in the absorption process. There are a number of fluorescent lines in emission nebulae that are potential candidates (see Nordsieck (2008)). Although such lines have been seen in the visible in HII regions Grandi(1975b,a) and planetary nebulae Sharpee et al. (2004), we suggest that reflection nebulae would be a better place to test the diagnostic, since the lack of ionizing flux limits the number of levels being pumped, and especially since common fluorescent ions like NI and OI would not be ionized, eliminating confusing recombination radiation. Realignment should make itself evident in a line polarization whose position angle is not perpendicular to the direction to the central star. This deviation depends on the magnetic geometry and the scattering angle. The degree of polarization also depends on these two things. It will be necessary to compare the polarization of several species with different dependence on these factors to separate the effects. This situation is an excellent motivation for a pilot observation project.
9.4 Magnetic field in PDR regions

Most fine structure FIR lines arise from photon dominated (PDR) region, a transition region between fully ionized and molecular clouds illuminated by a stellar source of UV radiation. The line ratio of the brightest ones, e.g., [C II] 158μm, [O I] 63, 145μm, are used to infer physical parameters, including density and UV intensity based on the assumption that they are collisionally populated. Recent observations of UV absorption by Sterling et al. [Sterling et al. (2005)], however, find that the population ratio of 3P_{1,0}, the originating levels of [O I] 63, 145μm is about twice the LTE value in the planetary nebula (PN) SwSt 1, and fluorescence excitation by stellar continuum is concluded to be the dominant excitation mechanism. In this case, the alignment is bound to happen on the two excited levels 3P_{1,0} because of the anisotropy of the pumping radiation field, resulting polarizations in the [O I] 63, 145μm lines.

The high spatial resolution of SOFIA, for instance, is advantageous in zooming into PDRs and resolving the lines. Moreover, in highly turbulent environment, we expect that the magnetic field is entangled. The higher resolution means less averaging in the signals from atoms aligned with the magnetic field. The high sensitivity of the upgraded HAWC++ also provides us a possibility of doing precise quantitative measurement of the spectral polarizations, which can resolve the ambiguity of the 90 degree degeneracy and enables a 3D topology of magnetic field, which cannot be obtained from any other present magnetic diagnostics.
10 Observational testings

Here we demonstrate a synthetic observation of polarization of the sodium D lines can reveal the magnetic fields of Jupiter and the solar wind that interacts with the comet via magnetic alignment. The advantage of direct studies of magnetic perturbations by spacecrafts has been explored through many important missions. However, the spacecraft measurement are rather expensive. Are there any other cost-effective ways to study magnetic turbulence in interplanetary medium?

Comets are known to have sodium tails and sodium is an atom that can be aligned by radiation and realigned by solar wind magnetic fields. This opens an opportunity of studying magnetic fields in the solar wind from the ground, by tracing the polarization of the Sodium line. We simulated the the degree of polarization and its variations arising from resonant scattering from Na line in a magnetized comet wake Yan & Lazarian (2007); Shangguan & Yan (2012). The study has been extended for comet Halley and Jupiter’s Io based on the magnetic field data from Vega1&2 during the encounter with comet Halley in 1986 and the Galileo’s mission to Jupiter, respectively (see details in Shangguan & Yan (2012)).

Though the abundance of sodium in comets is very low, its high efficiency in scattering sunlight makes it a good tracer Thomas (1992). As discussed in Yan & Lazarian (2007), the gaseous sodium atoms in the comet’s tail acquire angular momentum from the solar radiation, i.e. they are aligned. Resonant scattering from these aligned atoms is polarized. Collision rates in the coma of comets are very low, less than once/day beyond a few 1000 km from the nucleus, so that fluorescent alignment should be rapidly established in the outflowing sodium from the comet ?.

As shown in Fig. 10, the geometry of the scattering is well defined, i.e., the scattering angle $\theta_0$ is known. The alignment is modulated by the local magnetic field. The polarization of the sodium emission thus provides exclusive information on the magnetic field in the interplanetary medium. Depending on its direction, the embedded magnetic field alters the degree of alignment and therefore the polarization of the light scattered by the aligned atoms. Fig 10 illustrates the trajectory of a comet along which the magnetic field varies and the polarization of Sodium D2 emission changes accordingly. By comparing observations with them, we can cross-check our model and determine the structure of magnetic field in the heliosphere with similar observations. One can investigate not only spatial, but also temporal variations of magnetic fields. Since alignment happens at a time scale $\tau_R$, magnetic field variations on this time scale will be reflected. This can allow for a cost-effective way of studying interplanetary magnetic turbulence at different scales.

GSA provides us a unique opportunity to detect the magnetic field that is beyond the reach of space probes. The polarization direction traces directly the orientation of magnetic field, especially, when the scattering angle is small. We can acquire the entire accurate information of the magnetic field with two or more lines from alignable species. Since alignment happens on a very short timescale (inverse of photo-excitation rate), instantaneous tomography of the magnetic field can be realized through GSA.
11 GSA and Cosmological studies

11.1 Magnetic field in the epoch of reionization?

The issue of magnetic field at the epoch of reionization is a subject of controversies. The fact that the levels of O I ground state can be aligned through anisotropic pumping suggest us a possibility of using GSA to diagnose whether magnetic field exists at that early epoch.

The degree of polarization in the optically thin case can be obtained in a similar way as above by replacing $\tilde{\eta}_0, \tilde{\varepsilon}_0$ by $\tilde{\eta}_1, \tilde{\varepsilon}_1$. In the alignment regime, the Stokes parameters, $U=0$, and therefore,

$$P = \frac{Q_v}{B_v(T_{CMB})} = \tau \left\{ \frac{\tilde{\varepsilon}_1 \left[ \exp(T_v/T_{CMB}) - 1 \right]}{\tilde{\eta}_1 \exp(T_v/T_s) - \tilde{\varepsilon}_1 - 1} \right\}$$

$$\approx \tau_0 \left( 1 + y_{\text{iso}}/\tau_0 \right) - \frac{\tilde{\eta}_1 - \tilde{\varepsilon}_1}{1 - \exp(-T_v/T_s)}$$

$$= \tilde{\varepsilon}_1 y_{\text{iso}} - \tau_0 \frac{1.5 \sin^2 \theta [w_{\text{iso}} \sigma_0^2(J_I) - w_{\text{iso}} \sigma_0^2(J_0)] / \sqrt{2}}{1 - \exp(-T_v/T_s)}$$

(13)

In the case of nonzero magnetic field, the density matrices are determined by $\theta_r$, the angle between magnetic field as well as the parameter $\beta$. Similar to $y$, the degree of polarization is also proportional to $\beta$. In Fig[11] we show the dependence of the ratios $y/(\tau \beta), P/(\tau \beta)$ on $\theta_r$ and $\theta$. Since $U=0$, the line is polarized either parallel ($P > 0$) or perpendicular ($P < 0$) to the magnetic field. The switch between the two cases happen at $\theta_r = \theta_V = 54.7^\circ, 180 - 54.7^\circ$, which is a common feature.
of polarization from aligned level (see Yan & Lazarian (2006, 2008) for detailed discussions).

Fig. 11 Left: the the schematics of fluorescence pumping of [O I] line; middle & right: \( \gamma/(\tau\beta) \), \( P/(\tau\beta) \) of [OI] line in early universe. \( \theta_r, \theta \) are respectively the angles of the incident radiation and l.o.s. from the magnetic field. From YL08.

11.2 Influence on abundance studies

The GSA not only induces/influences the polarization of spectral lines, but also modulate the line intensity. This can cause substantial error in the estimates of chemical abundances if this effect is not included. This has been shown in last section on the pumping of [OI] line in early universe. The same also happens with the permitted absorption and emission lines (see Fig. 12).

Fig. 12 The contour map of line ratio, \( I_{D2}/I_{D1} \) as a function of the direction of magnetic field. The scattering angle is also set to be 5\(^\circ\). From Shangguan & Yan (2012).
11.3 Metal detection in early universe

For instance, the distortion of CMB due to the optical pumping calculated accounting for the anisotropy of the optical/UV radiation field for the optically thin case differs from the result without anisotropy included [Yan & Lazarian (2009)]:

\[
y = \frac{\Delta I_\nu}{B_\nu(T_{CMB})} = \tau \left\{ \frac{\tilde{e}_1[\exp(T_s/T_{CMB}) - 1]}{\tilde{\eta} \exp(T_s/T_s) - \tilde{\eta}_s} - 1 \right\}
\]

\[
= \tau_0 \left[ \frac{\tilde{e}_1[\exp(T_s/T_{CMB}) - 1]}{\exp(T_s/T_s) - 1} - \tilde{\tau} \right]
\]

\[
\simeq \tau_0 [\tilde{e}_1(1 + y_{iso}/\tau_0) - \tilde{\tau}]
\]

\[
y = \tilde{e}_1 y_{iso} + \tau_0 \frac{[w_{10} \sigma_0^2(J_l) - w_{10} \sigma_0^2(j_0^0)](1 - 1.5 \sin^2 \theta)/\sqrt{2}}{1 - \exp(-T_s/T_s)}
\]

(14)

where \(y_{iso}\) is the distortion neglecting the anisotropy of the radiation field and GSA (see Hernández-Monteagudo et al. (2007)). Indeed if alignment is not accounted, then

\[
y = y_{iso} = \tau_0 \frac{T_s}{T_s} \frac{\Delta T}{T_{CMB}} = \tau_0 \frac{T_{CMB}}{T_s} \exp \left( \frac{T_s}{T_{CMB}} \right) \left[ 1 - \frac{A(J_l^0)}{\sum_J A(J_l)} \right] \frac{[j_0^0] \beta B_m I_m}{[J_l](A_m + B_m^o I_m)}
\]

(15)

where \(A_m, B_m, B_m^o\) are the Einstein coefficients for the magnetic dipole transitions within the ground state, and \(I_m\) is the corresponding line intensity. \(\beta = B_{1\nu}/B_{m^o I_m}\). Both \(\tilde{\eta}_s\) and \(\tilde{\tau}\) depend on the line of sight and the GSA (Eqs.7, 9), the resulting distortion in radiation is thus determined by the angle \(\theta\) as well as the UV intensity of the OI line \(I_{\nu}\) (or \(\beta\), see Fig.11). Since both of the two terms on the right hand side of Eq.14 are proportional to \(\beta\), the resulting distortion \(y\) is also proportional to \(\beta\).

In some sense, this study is made for the case of weak pumping regimes discussed in [Yan & Lazarian (2006)]. But we take into account in addition the absorption and stimulated emission within the ground state.

12 Feasibility of GSA studies

The GSA is a subtle effect that is described by a complex quantum electrodynamics formalism. Therefore it is important to stress that this does not translates into the effect being difficult to measure. Indeed, as we mentioned earlier, the effect was studied successfully in the laboratory many years ago. The predicted polarization measures, as we shown in the text, can be very substantial. Moreover, different species show different degrees of alignment (including zero alignment) and this al-
allows to separate the GSA-induced polarization from the polarization of instrumental origin.

We have also discussed that the effects related to the GSA, but in a different regime of magnetic saturation have been successfully studied in the solar atmosphere. This vividly supports our claim that the GSA effect is not only measurable in laboratory, but also in not pure astrophysical conditions. In fact, the polarization of Kuhn et al. (2007, [Kuhn et al. (2007)]) circumstellar envelope already indicate the effect of the GSA polarization of absorption lines predicted in Yan & Lazarian (2006, [Yan & Lazarian (2006)]).

In terms of observational studies, one should remember that it usually takes some time for the technique to get accepted. One may recall a long history of attempts of measuring of the Goldreich-Kylafis effect. However, now the technique is routinely used. We feel that a similar process takes place with the practical usage of the GSA effect. We hope that this review can accelerate the observational work towards practical use of the GSA.

13 Summary

GSA is an important effect the potential of which for magnetic field studies has not been yet tapped by the astrophysical community. The alignment itself is an effect studied well in the laboratory; the effects arise due to the ability of atoms/ions with fine and hyperfine structure to get aligned in the ground/metastable states. Due to the long life of the atoms in such states the Larmor precession in the external magnetic field imprints the direction of the field into the polarization of emitting and absorbing species. This provides a unique tool for studies of magnetic fields using polarimetry of UV, optical and radio lines. The range of objects for studies is extremely wide and includes magnetic fields in the early universe, in the interplanetary medium, in the interstellar medium, in circumstellar regions. Apart from this, the consequences of alignment should be taken into account for correct determining the abundances of alignable species.

As astrophysical magnetic fields cover a large range of scales, it is important to have techniques to study magnetic fields at different scales. In this respect atomic realignment fits a unique niche as it reveals small scale structure of magnetic field. For instance, we have discussed the possibility of studying magnetic fields in interplanetary medium. This can be done without conventional expensive probes by studying polarization of spectral lines. In some cases spreading of small amounts of sodium or other alignable species can produce detailed magnetic field maps of a particular regions of interplanetary space, e.g. the Earth magnetosphere.

\footnote{incidentally, these studies induced a local revolution in understanding of the solar spectra. We expect even deeper impact of the GSA studies. Indeed, the domain of the applicability of the GSA is really extensive and the consequences of the magnetic field and abundance studies are extremely important.}
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References

Abel, N. P., Ferland, G. J., O’Dell, C. R., Shaw, G., & Troland, T. H. 2006, ApJ, 644, 344
Beck, R. 2011, in American Institute of Physics Conference Series, Vol. 1381, American Institute of Physics Conference Series, ed. F. A. Aharonian, W. Hofmann, & F. M. Rieger, 117–136
Brossel, Jean, Kastler, Alfred, & Winter, Jacques. 1952, J. Phys. Radium, 13, 668
Budker, D., & Romalis, M. 2007, Nature Physics, 3, 227
Carciotti, A. C., Bjorkman, J. E., & Bjorkman, K. S. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 343, Astronomical Polarimetry: Current Status and Future Directions, ed. A. Adamson, C. Aspin, C. Davis, & T. Fujiiyoshi, 417
Cohen-Tannoudji, C., Dupont-Roc, J., Haroche, S., & Laloe, F. 1969, Physical Review Letters, 22, 758
Crutcher, R. M., Hakobian, N., & Troland, T. H. 2010, MNRAS, 402, L64
Crutcher, R. M., & Troland, T. H. 2008, ApJ, 685, 281
Esquivel, A., & Lazarian, A. 2005, ApJ, 631, 320
—. 2011, ApJ, 740, 117
Field, G. 1958, Proceedings of the IRE, 46, 240
Furlanetto, S. R., Oh, S. P., & Briggs, F. H. 2006, PhysRep, 433, 181
Grandi, S. A. 1975a, ApJ, 199, L43
—. 1975b, ApJ, 196, 465
Happer, W. 1972, Reviews of Modern Physics, 44, 169
Hawkins, W. B. 1955, Physical Review, 98, 478
Hawkins, W. B., & Dicke, R. H. 1953, Phys. Rev., 91, 1008
Hernández-Monteagudo, C., Rubiño-Martín, J. A., & Sunyaev, R. A. 2007, MNRAS, 380, 1656
Hildebrand, R. H. 2009, in Astronomical Society of the Pacific Conference Series, Vol. 417, Submillimeter Astrophysics and Technology: a Symposium Honoring Thomas G. Phillips, ed. D. C. Lis, J. E. Vaillancourt, P. F. Goldsmith, T. A. Bell, N. Z. Scoville, & J. Zmuidzinas, 257
Kastler, A. 1950, J. Phys. Radium, 11, 255
Kastler, A. 1957, Journal of the Optical Society of America (1917-1983), 47, 460
Kuhn, J. R., Berdyugina, S. V., Fluri, D. M., Harrington, D. M., & Stenflo, J. O. 2007, ApJ, 668, L63
Landi Degl’Innocenti, E. 1983, Solar Physics, 85, 3
—. 1984, Solar Physics, 91, 1
—. 1998, Nat, 392, 256
Landi Degl’Innocenti, E., & Landolfi, M., eds. 2004, Astrophysics and Space Science Library, Vol. 307, Polarization in Spectral Lines
Landolfi, M., & Landi Degl’Innocenti, E. 1986, A&A, 167, 200
Lazarian, A. 2007, Journal of Quantitative Spectroscopy and Radiative Transfer, 106, 225
Lazarian, A., & Pogosyan, D. 2012, ApJ, 747, 5
Lazarian, A., Pogosyan, D., & Esquivel, A. 2002, in Astronomical Society of the Pacific Conference Series, Vol. 276, Seeing Through the Dust: The Detection of HI and the Exploration of the ISM in Galaxies, ed. A. R. Taylor, T. L. Landecker, & A. G. Willis, 182
Lequeux, J. 2005, The Interstellar Medium, ed. Lequeux, J.
Liu, Y. C.-M., Opher, M., Cohen, O., Liewer, P. C., & Gombosi, T. I. 2008, ApJ, 680, 757
Nordsieck, K. 2008, ArXiv e-prints
Nordsieck, K., & Ignace, R. 2005, in Astronomical Society of the Pacific Conference Series, Vol. 343, Astronomical Polarimetry: Current Status and Future Directions, ed. A. Adamson, C. Aspin, C. Davis, & T. Fujiyoshi, 284
Shangguan, J., & Yan, H. 2012, Ap&SS, 358
Sharpee, B., Baldwin, J. A., & Williams, R. 2004, ApJ, 615, 323
Stenflo, J. O., & Keller, C. U. 1997, A&A, 321, 927
Sterling, N. C., Dinerstein, H. L., Bowers, C. W., & Redfield, S. 2005, ApJ, 625, 368
Thomas, N. 1992, Surveys in Geophysics, 13, 91
Toth, G., Sokolov, I. V., Gombosi, T. I., Chesney, D. R., Clauer, C. R., De Zeeuw, D. L., Hansen, K. C., Kane, K. J., Manchester, W. B., Oehmke, R. C., Powell, K. G., Ridley, A. J., Roussev, I. I., Stout, Q. F., Volberg, O., Wolf, R. A., Sazykin, S., Chan, A., Yu, B., & Kóta, J. 2005, Journal of Geophysical Research (Space Physics), 110, 12226
Trujillo Bueno, J., & Landi Degl’Innocenti, E. 1997, ApJ, 482, L183
Trujillo Bueno, J., Landi Degl’Innocenti, E., Collados, M., Merenda, L., & Manso Sainz, R. 2002, Nat, 415, 403
Varshalovich, D. A. 1968, Astrofizika, 4, 519
—. 1971, Soviet Physics Uspekhi, 13, 429
Varshalovich, D. A., & Chorny, G. F. 1980, Icarus, 43, 385
Wouthuysen, S. A. 1952, AJ, 57, 31
Yan, H., & Lazarian, A. 2006, ApJ, 653, 1292
—. 2007, ApJ, 657, 618
—. 2008, ApJ, 677, 1401
Yan, H., & Lazarian, A. 2009, in Revista Mexicana de Astronomia y Astrofisica Conference Series, Vol. 36, 97–105
—. 2012, J. Quant. Spectrosc. Radiat. Transfer, 113, 1409