POLARIZATION OF SUBMILLIMETER LINES FROM INTERSTELLAR MEDIUM

HESHOU ZHANG$^{1,2}$ & HUIRONG YAN$^{1,2}$

1Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, D-15738 Zeuthen, Germany; hyan@mail.desy.de
2Institut für Physik und Astronomie, Universität Potsdam, Haus 28, Karl-Liebknecht-Str. 24/25, D-14476 Potsdam, Germany;

ABSTRACT

Magnetic fields play important roles in many astrophysical processes. However, there is no universal diagnostic for the magnetic fields in the interstellar medium (ISM) and each magnetic tracer has its limitation. Any new detection method is thus valuable. Theoretical studies have shown that submillimeter fine structure lines are polarized due to atomic alignment by Ultraviolet (UV) photon-excitation, which opens up a new avenue to probe interstellar magnetic fields. We will, for the first time, perform synthetic observations on the simulated three-dimensional ISM to demonstrate the measurability of the polarization of submillimeter atomic lines. The maximum polarization for different absorption and emission lines expected from various sources, including Star-Forming Regions (SFRs) are provided. Our results demonstrate that the polarization of submillimeter atomic lines is a powerful magnetic tracer and add great value to the observational studies of the submillimeter astronomy.

Keywords: submillimeter: ISM–methods: observational–ISM: magnetic fields–polarization

1. INTRODUCTION

Submillimeter astronomy is an indispensable window for the study of the universe. Submillimeter spectroscopy plays a crucial role in understanding the processes such as galaxy evolution (Sparke & Gallagher 2000), the interstellar medium (ISM), e.g., molecular clouds (Stutzki et al. 1988), Photon-Dissociation Regions (PDRs) (Hollenbach & Tielens 1999), etc. In particular, submillimeter polarization arising from dust alignment is one of the major magnetic tracers with promising analytical and observational progress (see, e.g., the review by Andersson et al. 2015). Uncertainties with grain alignment do exist though due to the unknown shape and compositions of the grains. In view of the fact that limitations exist in all the magnetic diagnostics that are currently applied to the observation of magnetic field in the ISM, the exploration with independent techniques would be important and complementary to current methods.

Theoretical works have shown that the polarization of atomic lines in the submillimeter band can be used to trace magnetic fields in the ISM due to the physical effect of atomic alignment$^1$(Yan & Lazarian 2006, 2007, 2008; Shangguan & Yan 2013; Zhang et al. 2015, 2016). Submillimeter atomic lines result from the fine-structure transitions between levels in the ground state of atoms. In the diffuse ISM, the photon-excitation is the dominant mechanism to produce submillimeter atomic lines: the massive stars or clusters nearby the ISM radiate Ultraviolet (UV) photons which illuminate the ISM by pumping the atoms from the ground state to the excited states; the atoms end up on different fine-structure levels in the ground state due to the spontaneous emission from the excited states. The radiation source provides a typical anisotropic radiation field which aligns the atoms in the medium. The submillimeter lines emitted and absorbed from the aligned medium are polarized. The alignment is altered according to the direction of the magnetic field due to the fast magnetic precession, which is termed as magnetic realignment. The resultant polarization of the fine-structure lines thereby reveals interstellar magnetic fields. The magnetic strength in the ISM is generally weak ($\sim \mu G$), which means only ground state alignment occurs (see Yan & Lazarian 2012). In a totally different regime than the ISM$^2$, solar physicists have been employing spectral polarimetry to study the solar magnetism (see, e.g., Landi Degl’Innocenti 1983, 1984, 1998; Stenflo & Keller 1997). Current facilities already have the capability to cover the submillimeter band for the spectral polarimetry observation (see, e.g., Risacher et al. 2016). Nevertheless, the following questions should be addressed before the observation: the measurability for the polarization of submillimeter atomic lines and what information of the interstellar magnetic fields could be revealed. Through synthetic observations on numerical...

$^1$ For simplicity, the term ‘atom’ represents atoms and ions. The term ‘alignment’ here refers to the direction of the angular momenta of the atoms (see, e.g., the review by Yan & Lazarian 2015).

$^2$ The solar magnetic field, which is generally stronger than 1 Gauss, resides in Hanle or Zeeman regimes.
simulated ISM, the purposes of this paper are to answer the afore mentioned questions and demonstrate the value of sub-millimeter spectropolarimetry as a magnetic tracer.

2. SUBMILLIMETER SPECTROPOLARIMETRY IN THE ISM

Atomic lines in the submillimeter band are magnetic dipole transitions between the fine-structure levels in the ground state of the atoms. Hence, the decay rate for the atoms from the fine-structure levels in the ground state is the magnetic dipole transition rate $A_m$, which, in ISM, is much lower than magnetic precession rate $\nu_L$. Thus, the alignment of atomic angular momentum can happen on both the upper and lower fine-structure levels of the magnetic dipole transition within the ground state. Therefore, both submillimeter absorption and emission atomic lines can be polarized (see Yan & Lazarian 2012 for details). The spectral polarization is altered depending on the direction of magnetic field, and the Stokes parameters of the spectral lines, $[I,Q,U,V]$, are modulated accordingly (Landi Degl’Innocenti 1984, see also Yan & Lazarian 2006). The circular-polarization $V$—channel does not exist since only the unpolarized background radiation is considered in this paper. The polarization of submillimeter fine-structure lines from level $J_1$ to level $J_2$ in the ground state can be obtained based on results in Yan & Lazarian (2006):

$$P = \frac{-3\sqrt{2}p_{J_1}^0 \sigma_0^2(J_1,\theta_r) \sin^2 \theta}{4 + \sqrt{2}p_{J_2}^0 \sigma_0^2(J_1,\theta_r)(2 - 3 \sin^2 \theta)}.
$$

The angles $\theta_r, \theta$ are defined in Fig. 1(a). The alignment parameter $\sigma_0^2 \equiv p_0^2 / p_{J_0}^0$, in which $p_{J_0}^0$ are the irreducible density matrices for the atoms. The quantity $\sigma_{J_1,J_2} \equiv \{1,1,2;J_1,J_1,J_2\}/\{1,1,0;J_1,J_1,J_2\}$ is related to the atomic structure, where the matrices with ‘$\{ \}$’ are $6 - j$ symbols that demonstrate the angular momentum coupling.

The polarization is measured from the projection of the magnetic field on the picture plane. Thus the sign of the polarization reveals the direction of the polarization: ‘$+$’ means parallel to the magnetic field whereas ‘$-$’ means perpendicular. As demonstrated in Fig. 1(b), the polarization is flipped from parallel to perpendicular at the flipping criteria $\theta_r = 54.7^\circ$ (Van Vleck angle, see Van Vleck 1925; House 1974). When calculating the polarization of the atomic lines, all the excitations from the ground state to multiple excited states should be included. The weight ratio of the transitions to different excited states varies with the type of radiation source. C II, for example, has two excited states: $2S_{1/2}$ and $2D_{3/2}$. The wavelength for the transition from the ground state $2P^o$ to the excited state $2S$ is 1034Å and for the transition to $2D$ is 1334Å. As demonstrated in Fig. 1(b), the photon-excitation for the magnetic dipole transition $[C\, I]\lambda_{157\mu m}$ is dominated by $2P^o \rightarrow 2D$ for the pumping stars with lower temperature and by $2P^o \rightarrow 2S$ for higher temperature. The competition between C I\lambda_{1034Å} and C I\lambda_{1334Å} is balanced at $T = 2.32 \times 10^4 K$, where no polarization is induced for $[C\, I]\lambda_{157\mu m}$. Furthermore, the photon-excitation can be stronger if the radiation source is a star with higher temperature (with younger age), a larger radius (giant stars such as AGB stars), or a cluster with a larger amount of stars. As demonstrated in Yan & Lazarian (2006), the applicable regime to study magnetic fields with spectral polarimetry would be broader with a stronger radiation field.

The submillimeter emission atomic lines are commonly observed in Star Forming Regions (SFRs), where young O,B-type stars are the dominant optical pumping source. The maximum polarizations of submillimeter emission lines from SFRs are presented in Table 1. As demonstrated in Table 1, the polarization of submillimeter emission atomic lines is quite substantial for many elements in SFRs.

| Species | Transition | Wavelength | max(P) |
|---------|------------|------------|--------|
| [C I]   | 3P_1 \rightarrow 3P_0 | 610\mu m | 21%^{a}|
| [C I]   | 3P_2 \rightarrow 3P_0 | 370\mu m | 18%^{b}|
| [C II]  | 2P_{3/2} \rightarrow 2P_{1/2} | 157.7\mu m | 28.5%^{a}|
| [O I]   | 3P_1 \rightarrow 3P_2 | 63.2\mu m | 4.2%^{a}|
| [Si I]  | 3P_1 \rightarrow 3P_0 | 129.7\mu m | 20%^{a}|
| [Si I]  | 3P_2 \rightarrow 3P_1 | 68.5\mu m | 18%^{b}|
| [Si II] | 2P_{3/2} \rightarrow 2P_{1/2} | 34.8\mu m | 12.6%^{b}|
| [S I]   | 3P_1 \rightarrow 3P_2 | 25.2\mu m | 3.2%^{a}|
| [Fe II] | 6D_{7/2} \rightarrow 6D_{3/2} | 26.0\mu m | 4.9%^{a}|

Note: The table considers SFRs with young O,B-type stars $T \sim [1 \times 10^4 K, 5 \times 10^4 K]$. The sources inducing the maximum polarization are marked correspondingly. Simulation shows that most of the lines can reach at least 80% of the maximum polarization with all types of illuminating stars considered. The atomic emission lines are unpolarized if the upper level angular momentum $J_u = 0, 1/2$.

^{a}Maximum at $1 \times 10^4 K$ B-type stars

^{b}Maximum at $5 \times 10^4 K$ O-type stars

The submillimeter absorption atomic lines represent either the self-absorption of nebulae, or the absorption by the medium that resides on the line of sight. The maximum polarization of submillimeter absorption lines with unpolarized

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3 Otherwise, circular polarization appears in absorption lines if the alignment direction differs from the direction of polarized background radiation (see Yan & Lazarian 2007).

4 For example, the irreducible density matrix tensor for $J/F = 1$ is $p_{3/2}^0 = \{p(1,1) - 2p(1,0) + p(1,-1)\}$ (Fano 1957; D’Yakonov & Perel’ 1965; Bonnner & Sahal-Bréchot 1978).

5 It is important for the readers to note that the results in this table are not conflicted with Table in the review (Yan & Lazarian 2012). The table in that review demonstrated the polarization induced by Interstellar Radiation Field (ISRF).
background spectra and the corresponding pumping source are presented in Table 2. Note that the solar temperature \( T \approx 6 \times 10^3 K \) is close to the temperature of the maximum-polarization pumping source for most of the elements listed. Hence, an easy target to apply the polarization of submillimeter fine-structure absorption lines as a magnetic tracer could be the magnetic field in the diffuse medium in solar system (e.g., comet magnetic fields or magnetic tail of planets).

3. SYNTHETIC OBSERVATIONS

Magnetic dipole transitions within the ground state in the diffuse ISM are mainly induced by photon-excitation. Collision excitation can be ignored in the diffuse ISM, whose density is below the critical density (Draine 2011). Therefore, polarization of submillimeter fine-structure lines is a perfect magnetic tracer in the diffuse ISM. The \([C\,II]\lambda 157\mu m\) emission line is selected as the example spectral line in our simulation since \( C^+ \) is one of the most important and most common species in the ISM. Numerical simulations in this paper are performed with the PENCIL-code\(^6\). First, a bar-shaped PDR with the mean field direction along the bar is considered. Fig. 2(a) are the maps of polarization on the picture plane for the radiation source positioned with different line-of-sight angle \( \theta_0 \). The magnetic component on the picture plane is along the long-axis of the bar and the direction of the induced polarization is either parallel or perpendicular to it. Therefore, the magnetic component on the picture plane could be indicated by the dominant direction of the induced polarization with a 90\(^\circ\)-degeneracy, which is independent of the angle between line of sight and \( \theta \).

Table 2. MAXIMUM POLARIZATION FOR SUBMILLIMETER ABSORPTION LINES

| Species | Transition | Wavelength | max(\(P/\tau\)) |
|---------|------------|------------|---------------|
| \([C\,II]\) | \(3P_1 \rightarrow 3P_2\) | 370\(\mu m\) | 2\(^a\) |
| \([O\,I]\) | \(3P_2 \rightarrow 3P_1\) | 63.2\(\mu m\) | 30.8\(^b\) |
| \([O\,I]\) | \(3P_1 \rightarrow 3P_0\) | 145.5\(\mu m\) | 49.1\(^c\) |
| \([S\,I]\) | \(3P_2 \rightarrow 3P_1\) | 25.2\(\mu m\) | 30.1\(^d\) |
| \([S\,I]\) | \(3P_1 \rightarrow 3P_0\) | 56.3\(\mu m\) | 45.2\(^e\) |
| \([S\,II]\) | \(3P_1 \rightarrow 3P_2\) | 370\(\mu m\) | 2\(^a\) |
| \([Fe\,III]\) | \(a6D_{0/2} \rightarrow a6D_{7/2}\) | 26.0\(\mu m\) | 9.9\(^f\) |

Note: The table considers all different types of illuminating star with temperature range \( [2.5 \times 10^3 K, 5 \times 10^4 K] \). The environments that induce the maximum polarization are marked. Simulation shows that most of the lines can reach at least 80\% of the maximum polarization in any environment for strong pumping. The atomic absorption lines are unpolarized if the lower level angular momentum \( J_i = 0, 1/2 \).

\(^a\) Almost no variation of maximum polarization with different sources.
\(^b\) Maximum at \( 5 \times 10^3 K \) K-type stars
\(^c\) Maximum at \( 6 \times 10^3 K \) F-G-type stars (e.g., the Sun)
\(^d\) Maximum at \( 3.7 \times 10^4 K \) M-type stars, AGB stars, etc
\(^e\) Maximum at \( 4.1 \times 10^4 K \) K-type stars
\(^f\) Maximum at \( 1 \times 10^4 K \) B-A-type stars

\( \tau \) is the optical depth. See https://code.google.com/archive/p/pencil-code/ for details.
Polarization(%) vs source inclination

θ₀ = 90°
θ₀ = 75°
θ₀ = 60°
θ₀ = 45°
θ₀ = 30°
θ₀ = 15°
θ₀ = 0°

Figure 2. (a) [C II]λ157µm polarization maps for a bar-shaped PDR with different inclination angle of the radiation source θ₀. The mean magnetic direction is along the bar; (b) Polarization of [C II]λ157µm emission line on the picture plane with different magnetic direction for θ₀ = 90° with a B9-type pumping star (T = 1 × 10⁴K). The black bars are the direction of polarization expected. The degree of polarization is marked by the length of bars and the background color. The magnetic magnetic field on the picture plane is marked as orange arrows.

dient of the direction of incidental radiation. Furthermore, the magnetic direction is varied in the whole space and the resultant polarization is compared with the magnetic component on the picture plane. As shown in Fig. 2(b), 2-dimensional (2D) polarization direction readily reveals the projection of magnetic field on the picture plane with a 90°-degeneracy. Furthermore, 3D magnetic direction can be deduced given enough prior information, such as the detection of the polarization of multiple (≥ 2) submillimeter lines at the same spot. In addition, the maximum polarization for the 'parallel' and 'perpendicular' case are different. As demonstrated in Fig. 2, the 'parallel' case has a maximum of 12% polarization whereas the 'perpendicular' case is very likely to produce more than 20% polarization. Hence, the measurement of the degree of polarization will help break the 90°-degeneracy and thus provide us with an accurate measurement of the magnetic fields.

On the scale equal or smaller than a few pc, the magnetic field can be approximated with a mean direction because the coherence length of interstellar magnetic field is in the hpc scale (see Armstrong et al. 1995; Chepurnov & Lazarian 2010). MHD simulations are performed to generate a 512 × 512 × 16 trans-alvenic turbulence data cube with the mean magnetic field B₀ = 3µG, a typical H II Region. The Alvenic-Mach number of the generated ISM is 1.06. A massive B9-type star radiates UV-photons to illuminate the medium. As demonstrated in §2, the atoms in the ISM are aligned and thus the submillimeter transitions within the ground state of atoms are polarized. Synthetic observations for the polarization of fine-structure emission lines are performed on the simulated ISM with the xy-axis being the coordinates system for the polarimeter of the telescope. Presented in Fig. 3(a) is the schematic of the synthetic ISM. The simulated area corresponds to an 1pc × 1pc area on the picture plane. The ISM is observed along the z-direction. The line-of-sight optical depth τ₀ = 0.2pc is sliced into 16 layers. The velocity at each grid is assumed to have a Gaussian-distribution broadening with σ = vₐ = 0.36km/s, in which vₐ is the Alfven speed obtained from the simulation. The angle between the magnetic direction at the kth layer and the x-axis is ψk and the line-of-sight velocity at the kth layer is v_k. The line-of-sight velocity is resolved with a spectral resolution δv = 0.2km/s, which is depicted by the color of the velocity contour in Fig. 3(a). A line-of-sight integration at the velocity cut v₀ = v_k with a spectral resolution δv is performed by selecting the grids with corresponding line-of-sight velocity v₀ ≤ v_k ≤ v₀ + δv, and considering the density of the grid as the weighting parameter. The Stokes parameters at the kth layer are denoted by [I_k, Q_k, U_k, V_k]. The linear terms of the observed Stokes parameters at velocity v₀ are therefore:

\[
Q(v₀) = \int_0^{τ₀} \int_{v₀-δv}^{v₀+δv} \mathcal{N}(v_k, σ^2) \rho(Q_k \cos 2ψ_k + U_k \sin 2ψ_k) dv dτ,
\]

\[
U(v₀) = \int_0^{τ₀} \int_{v₀-δv}^{v₀+δv} \mathcal{N}(v_k, σ^2) \rho(-Q_k \sin 2ψ_k + U_k \cos 2ψ_k) dv dτ.
\]

(2)

Fig. 3(b) demonstrates the full polarization map with the 17” angular resolution cutting at v = 0km/s. The bars on the map depict the direction of polarization at the corresponding grid. The length of the bars are proportional to the degree of polarization, which is also marked by the color on the background contour. As seen from Fig. 3(b), the dominant polar-
Figure 3. (a) The schematic for H II Regions. The mean magnetic direction $B_0$ is parallel to the $x$–axis. Blue arrows are the magnetic direction at the corresponding grid. The radiation source is a B9-type star ($T = 1 \times 10^4 K$). Different line-of-sight velocities $v_z$ are marked with different colors in the velocity contour map in the upper right; (b) The full polarization map cutting at $v_z = 0 \text{km/s}$ with the 17" angular resolution. Bars represent the direction of polarization at the corresponding grid with the length of bars and the color on the background showing the degree of polarization. The dashed-dot purple lines denote the theoretical sign-flipping criteria for polarization (see §2); (c)(d) The polarization maps with the 4.5" angular resolution for the white-square region in (b) cutting at $v_z = +1 \text{km/s}$ and $v_z = -1 \text{km/s}$, respectively. The orange lines are the projection of magnetic field lines on the picture plane. Blank areas on the contour mean there being no cell with the cutting velocity along the line of sight in the corresponding grid.

By comparing with Fig. 3(b), Fig. 3(c) and Fig. 3(d) demonstrate that the polarization of the submillimeter fine-structure lines reveals the magnetic pattern in a smaller scale with the telescope of a higher angular resolution (e.g., the fluctuation in the upper left area of Fig. 3d). In addition, the difference between Fig. 3(c) and Fig. 3(d) shows that the polarization measured at different velocity slices can be used to depict the line-of-sight magnetic fluctuation. Analyzing the polarization of submillimeter lines with a higher spectral resolution...
thus gives us ample information of magnetic field on various scales along the line of sight.

4. CONCLUSION

In summary, we have, for the first time, applied numerical simulations to study the polarization of submillimeter fine-structure lines in the ISM. The main aims of our simulations are to evaluate the measurability of the polarization of submillimeter atomic lines and to investigate what information of the interstellar magnetic field it can provide. The MHD simulations are carried out to generate the diffuse ISM. The synthetic observations of the submillimeter atomic lines are performed on the simulated ISM. The polarization maps produced from the observations are compared with the magnetic fields in the ISM. We should emphasize that all the conclusions from the simulations throughout the paper are not limited to the example [C II]λ157µm emission line but generally applicable to all the submillimeter absorption and emission atomic lines. Our main conclusions are:

- Measurable polarization can occur in submillimeter absorption and emission atomic lines from the diffuse ISM due to the alignment from UV photon-excitation.

- The direction of polarization of submillimeter atomic lines reveals the 2D magnetic field in the plane of sky with a 90°-degeneracy; 3D magnetic fields can be detected if polarizations of multiple (≥ 2) submillimeter lines are detected.

- The degree of polarization is affected by the temperature of the pumping star.

- Submillimeter spectropolarimetry provides us with multi-scale magnetic patterns of the ISM. In particular, observations with resolved spectrum reveal the magnetic fluctuation along the line of sight.

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