Probing magnetic fields with fine structure lines

1. **Science aim/goal** (provide a high-level statement in 140 characters or less):
Atoms and ions with fine structure in their ground states are aligned with magnetic fields, resulting in polarized emission and absorption lines (Yan & Lazarian 2008), yielding new ways to probe interstellar magnetic fields.

2. **Presentation**

(i) Scientific Importance:

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 the diffuse interstellar medium (ISM), the magnetic field pressure may exceed the thermal pressure by a factor of ten. Magnetic fields play a fundamental role in star formation. Magnetic pressure and tension can inhibit gravitational collapse, and magnetic braking is thought to be the dominant agent for redistributing angular momentum in contracting clouds. Magnetic fields are important in all phases of star formation, from the assembly of dense clouds, through cloud collapse and accretion onto protostars, to the dissipation of the natal clouds and injection of kinetic energy into the interstellar medium by luminous stars and supernovae. Rapid, sensitive, precision mapping of polarized emission at scales of several arcseconds to several arcminutes will reveal star formation to an extent not previously realizable.

Aligned grains reveal magnetic field direction perpendicular to the line of sight. In spite of the progress in understanding of grain alignment, the natural variations in grain shapes and compositions introduce uncertainties in the expected degree of polarization. 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 technique for determining interstellar magnetic fields is a valuable development.

It has been shown that atoms and ions with fine structure in their ground states are also aligned with magnetic fields, resulting in polarized emissions and absorptions (Yan & Lazarian 2008, henceforth YL08). The information that can be inferred from polarized fine-structure emission is complementary to that provided by polarized emission from dust, yielding new ways to probe astrophysical sources and test theories of magnetic alignment.

OST can open a completely new parameter space in astrophysics by enabling the study of the polarization of fine structure lines of atomic ions such as [C II] and [O I]. These studies will enable new insights into the physical processes involved in exciting these lines in particular in Photon Dominated Regions (PDR). In combination with measurements of dust polarization, fine structure line polarimetry will significantly improve our ability to accurately determine the topology of magnetic fields in the ISM.

The basic idea of magnetic alignment: consider atoms or ions irradiated by a nearby star and embedded in a magnetic field. Anisotropic radiation pumps the atoms differentially from different magnetic sublevels, resulting in over- or under-populations of the atomic states of various magnetic quantum numbers. The non-LTE populations produce observable polarization in the absorption or emission line involved in the interaction (Yan & Lazarian 2006, 2007,2008). Similar to Lyman alpha pumping of the HI 21cm line, other species with a fine/hyperfine structure are also influenced by the photon pumping through the Wouthuysen-Field effect (Wouthuysen 1952; Field 1958), which is a redistribution of atoms on the two hyperfine levels of the ground term after absorbing and reemitting a Lyman alpha photon. An atom after absorbing a UV/optical photon will cascade down to a variety of states, which cannot be reached through direct excitation from the ground state. This indirect excitation of the metastable levels is called photon pumping/fluorescence excitation (see also Spitzer 1978). If the pumping radiation field is anisotropic, the atoms can be aligned on the metastable levels and the far infrared (FIR) emission/absorption from/to the metastable levels will be polarized (YL08). The direction of polarization directly traces the magnetic field in the pictorial plane with a 90-degree degeneracy. If two lines are measured, 3D magnetic field can be inferred.

Most fine structure FIR lines arise from PDRs, a transition region between fully ionized and molecular clouds illuminated by a stellar source of UV radiation. Observations of UV absorption by Sterling et al. (2005), find that the population ratio of $^3P_{1,0}$, the originating levels of OI 63, 145μm is about twice the LTE value in the planetary nebula 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 OI 63, 145μm lines. This technique can be used for interstellar, and intergalactic studies as well as for studies of magnetic fields in QSOs and other astrophysical objects.

The GSA is a subtle effect, requiring 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 first studied successfully in the laboratory many years ago. The predicted polarization effects, as we have shown (Yan & Lazarian 2012, Zhang & Yan 2017), can be quite substantial. Moreover, different species show different degrees of alignment and this allows separation of the GSA-induced polarization from polarization of instrumental origin. We have also discussed that effects related to 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 under astrophysical conditions. In fact, the polarization observed by Kuhn et al. (2007) in circumstellar envelopes already indicate the effect of the GSA polarization of absorption lines, as predicted in 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 at measuring the Goldreich-Kylafis effect. However, now the technique is routinely used. We feel that a similar process will take place with the practical usage of the GSA effect.

As astrophysical magnetic fields cover a large range of scales, it is important to have techniques to them at different scales. In this respect, atomic realignment fits a unique niche, as it reveals small scale structure of the magnetic field. For instance, we have discussed the possibility of studying magnetic fields in the interplanetary medium (Shangguan & Yan 2012). This can be done without the conventional, expensive, probes by studying the polarization of spectral lines. In some cases, the 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.

ii) <u>Measurements Required:</u>

Magnetic field properties will be extracted from the maps of the fine line emission or absorption. The main target lines are [CII], [OI] and [CI]

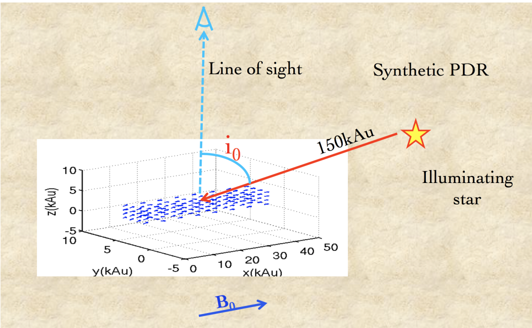
iii) <u>Uniqueness to 10μm to few mm wavelength facility:</u>

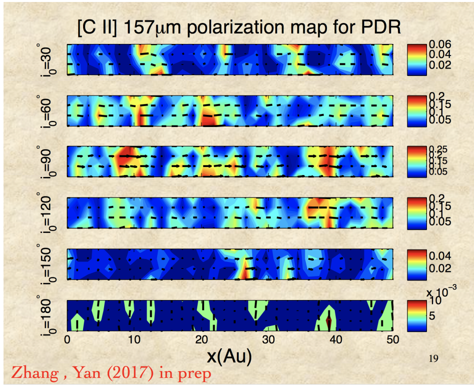
Does the far-IR address this science question uniquely? Can other facilities address the science topic and reach the same objective?

(iv) **<u>Longevity/Durability:</u>** (with respect to expected 2025-2030 facilities) **JWST, ALMA, WFIRST, SOFIA, EELT, etc.**

Same as (iii) but extrapolate to facilities in the next decade and reasonable potential upgrades.

3. Figure: Feel free to include one key figure related to the science goal. And include a brief caption.





Example of predictions linear polarization in a PDR. The left panel shows the geometry and the right panel the expected [CII] linear polarization. The polarization is strongest for an edge-on geometry (from Zhang & Yan 2017, in preparation).

4. Table: Please fill the table below. Required value can be interpreted as the minimum value essential for the science goal and desired value as the best-case scenario. If necessary, state ranges. If any entries are not applicable leave as N/A. Use table footnotes to expand on the comment field to justify any numbers that may not be easily comprehensible. [feel free to remove these explanatory lines for additional space].
(entries in italic are added specifically for the heterodyne instrument.)

Parameter	Unit	Required value	Desired Value	Comments
Name of line(s)		[CII], [OI] and [CI]	[CII], [OI] and [CI], [SiII], [SI], [FeII]	
Wavelength/band *Species*	μm/ *GHz*	158, 63, 145, 370 and 610 μm	158, 63, 145, 370 and 610 μm, 35, 25, 26 μm	
Number of targets		50		
Survey area	deg.[2]	3'x3'		Source sizes of few arcmin up to degrees
Angular resolution	arcsec	10	5	

Spectral resolution	Δλ/λ or km/s	0.5 km/s		Spectrally resolved line profiles are better to isolate components and separate emission and absorption features
Full Line Bandwidth	*GHz or km/s*	5 to 500 km/s		From nearby PDRs to galactic nuclei
Continuum Sensitivity (1 σ)	μJy	NA	NA	--
Spectral line sensitivity (1 σ)	W m-2 *K*	0.1 K	0.1 K	For [CII]
Signal –to-noise		50	200	Polarization fraction of a few % up to 20%.
Dynamic range				
Field of Regard				
Cadence (*observable sky during mission)*				
Any other requirement				
Heterodyne Rx specific questions:				
Required Tuning range (Dopplershift)	*km/s*	*-300 to 1000*		
Dual frequency requirement?				
Polarization Normally we will observe one linear polarization, does the orientation matter for your science?		*Yes*	*yes*	
Polarization measurements required?		*Yes*	*Yes*	
Off position requirements: Fixed throw, or dedicated off?				*Dedicated off is better, or cold load.*
if fixed throw, minimum distance		*>5'*		

5. Key references: (Optional, at most three, reviews preferred)

Field, G. 1958, Proceedings of the IRE, 46, 240
Kuhn, J. R., Berdyugina, S. V., Fluri, D. M., Harrington, D. M., & Stenflo, J. O. 2007, ApJ, 668, L63
Shangguan, J., & Yan, H. 2012, Ap&SS, 358
Spitzer, L. 1978, Physical processes in the interstellar medium, New York Wiley-Interscience
Sterling, N. C., Dinerstein, H. L., Bowers, C. W., & Redfield, S. 2005, ApJ, 625, 368
Wouthuysen, S. A. 1952, AJ, 57, 31
Yan, H., & Lazarian, A. 2006, ApJ, 653, 1292
—. 2007, ApJ, 657, 618
—. 2008, ApJ, 677, 1401
—. 2012, J. Quant. Spectrosc. Radiat. Transfer, 113, 140
Zhang, H. & Yan, 2017, ApJL submitted

6. Class your science in at least one of the 4 overall topics (delete the rest)

- Tracing the Signatures of Life and the Ingredients of Habitable Worlds
- Unveiling the Growth of Black Holes and Galaxies over Cosmic Time