Study of turbulent universe: anisotropy analysis

Investigating the properties of 3D magnetic fields using turbulence anisotropy analysis

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In Short

- Investigating the Interstellar medium turbulence properties using the anisotropy analysis of the polarised emission.
- Reconstructing the 3D magnetic field topology using two-point correlation function analysis.
- Propose y-parameter technique for numerical testing to distinguish Fast/Slow modes
- Understand the interplay between the magnetic field topology and MHD turbulence nature.
- The multi-wavelength comparison between y-parameter analysis and radio and X-ray observations will boost our understanding of turbulence mode decomposition and 3D-magnetic fields topology

Magnetic field is perhaps the most universal and important physical process, second to self-gravity, in astrophysical environments. Knowing the 3D distribution of magnetic field in interstellar media and its relation to other physical processes are therefore one of the most important scientific questions in the astrophysical community. However, determining the properties of the magnetic field, in particular, its interplay with ubiquitous interstellar turbulence, is notoriously difficult. Measurement of magnetic field properties mainly relies on two popular observational techniques: polarization lines from synchrotron or dust emissions that only gives the line-integrated plane of sky magnetic field direction, and Zeeman splitting that gives line-of-sight magnetic field strength in the range of interstellar turbulence. Recent effort based on atomic alignment in the magnetic field suggests that the 3D magnetic field topology could be possible to be measured[1] , but currently restricted to metal absorption lines due to instrumental restrictions. The search of 3D magnetic field and its underlying relation to turbulence is therefore in a deadlock.

Recent theoretical development on magnetized turbulence theory [2] suggests that the properties of the magnetic field are encoded in the statistics of MHD turbulence. Conceptually, MHD turbulence can primarily be decomposed into three modes: Alfvén mode, and the fast and slow magnetosonic modes (also known as magneto-acoustic modes)[3]. Magnetic field lines are stretched differently by Alfven and magnetosonic modes and therefore the statistics of magnetic field observables are very different. Utilizing this fact, Yuen et al. 2023 [4] suggests that the statistics of polarized synchrotron radiation reflect the fluctuations in the embedded magnetic fields caused due to the turbulence, which in turn allows us to study the strength and morphology of magnetic field.

$$y = \frac{\text{Anisotropy}(I+Q)}{\text{Anisotropy}(I-Q)} \tag{0.1}$$

In this project, we would investigate the anisotropies of the linear combinations of Stokes parameters, namely the “y-parameter" (See Eq.0.1), are a direct measure of the inclination angle of the magnetic field relative to the line of sight, and also a measure of the energy fraction between Alfven and magnetosonic modes. In this proposal, we would like to ask for 28M core hours to expand our *quantitative* analysis to study how the y-parameter can reconstruct the 3D magnetic field topology and derive the properties of interstellar turbulence with new high-resolution magneto-hydrodynamic (MHD) simulations up to 1024^3. Testing the accuracy and applicability of our recipe of 3D magnetic field reconstruction will be crucial to understand the physics of frontier observation data from an interferometric survey like SKA, LOFAR and e-VLA.

Further, we plan to utilize the computational resources from HLRN to perform a *quantitative* analysis on how the y parameter is related to γ for general compressible turbulence. In particular,

- Perform y-parameter on high-resolution MHD data-cubes with different driving mechanisms as well as different plasma properties.
- Understanding how the line of sight angle γ will impact the value of y in a mixture of MHD modes.
- Understand how y-parameter could be applied to the case of strong Faraday rotation.

This project will deepen our understanding of interstellar turbulence. It will provide new diagnoses for the LOS inclination angle of magnetic field and properties of compressible MHD turbulence, as well as a novel perspective for other physical processes such as CR transport and star formation processes.

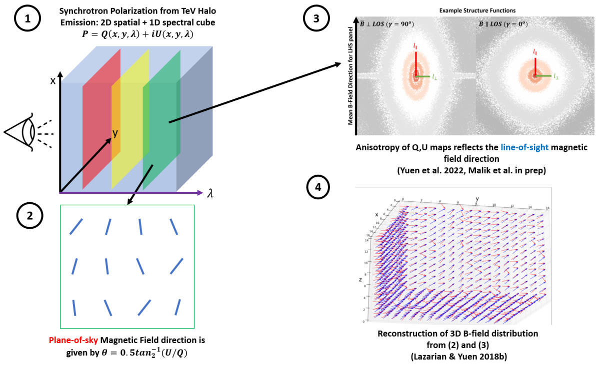

Figure 1: *A figure showing how polarized synchrotron emissions store the information of 3D magnetic field. Panel (1): Emissions from synchrotron emission are stored in a spectral-spatial 3D cube $P = P(x, y, \lambda)$, where the 3rd axis is in the unit of wavelength and it's along the line of sight. (2). For each λ, the magnetic field direction is stored in the synchrotron polarization angle assuming the Faraday rotation is weak. (3) The anisotropy of Stokes parameters stores the information of the magnetic field inclination. (4) With all this information combined, the 3D magnetic field angle can therefore be reconstructed with appropriate mathematical procedures.*

Simulation	M_A	ζ	γ
Proposal	$0.2, 0.8, 1.6$	$0, 0.5, 1$	$\pi/2, 3\pi/4, \pi/3$

Table 1: *A table of numerical simulations that we intend to perform.*

To accomplish the above objectives of understanding MHD turbulence in astrophysical fluids, we intend to use the 2nd order, staggered-grid fully compressible MHD code ZEUS-MP to perform three-dimensional, triply periodic, isothermal MHD simulations. Table 1 shows the planned numerical simulations that we want to perform.

In practice, we will separate our setup into the following few steps, each with clear objective, corresponds to the bulletin points in our proposed work:

1. **Stage 1**: How does the mode fraction alter the measurement of y? We will perform simulations with different driving mechanisms (i.e. varying ζ) and observe how y depends on the fraction of modes.

2. **Stage 2**: How does the γ alter the measurement of y? To perform these series of simulations, we have to vary both the line of sight angle γ and also the Alfvenic Mach number M_A.

3. **Stage 3**: How Faraday screening affects our reconstruction of 3D magnetic field? Synchrotron polarization have non-negligible Faraday depolarizations, and statistically there exists a particular distance, namely Faraday screen, along the line of sight that the information beyond that will be collected as noise.

The analytical results from those numerical simulations will then be applied to synchrotron polarization data observed from different surveys in the frequency range of 1.4 to 8.5 GHz. The plasma properties obtained from those analyses will further be compared with other wavebands (from Hα to γ-ray ($0.1 - 100$ Gev)) in order to investigate the role of turbulence in different physical environments in the galaxy.

WWW

http://www.unipotsdam.de/astroparticle/plasmaastrophysik.html

More Information

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[3] J. Cho, A. Lazarian, *Mon. Not. R. Astron. Soc.* **345**, 325–339 (2003). doi10.1046/j.1365-8711.2003.06941.x

[4] K.H.Yuen, H.Yan, A. Lazarian *MNRAS* **in press**, 31-45 (2023).

Project Partners

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DFG Subject Area

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