

Utilizing machine learning to classify the MHD turbulence modes in the ISM

Optimizing the Synchrotron Polarization Analysis (SPA) technique for MHD mode classification through unsupervised training on large volumes of simulation data-cubes.

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In Short

- The SPA method has been successfully proposed to diagnose MHD turbulence modes in the interstellar medium (ISM). The behavior of the SPA fitting parameters in various ISM environments, and their dependence on the plasma properties remain unaddressed.
- We will perform comprehensive test on the sensitivity of the technique on the actual physical parameters such as the magnetic field inclination angle (θ_λ), Alfvén Mach number (M_A), plasma- β and MHD mode energy partitions.
- We plan to train a neural network on characteristic physical quantities derived from a large ensemble of simulation samples, which will enable automated data classification and facilitates the accurate identification of key parameters governing MHD turbulence modes.
- We aim to improve the SPA technique for more complex turbulent environments and further understand the impact of other environmental effects such as Faraday Rotation on the mode classification.

The compressibility of magento-hydrodynamic (MHD) turbulence is extremely important in modulating a number of astrophysical processes in the ISM. On one hand, the energization and acceleration of cosmic rays require the fast magnetosonic modes to be efficient [1, 2, 3]. On the other hand, Alfvén modes are very important in quenching the formation of stars in giant molecular clouds [4]. Despite its importance, observers do not have adequate tools in characterizing how compressible the astrophysical plasma is in the context of ISM. Very recently, the development of the SPA technique [5] allows the classification of MHD modes in observation data. The information of both Alfvén and magnetosonic(MS) modes are encoded in the polarized synchrotron emissions. The statistics of Stokes parameters, primarily the emissivity $\epsilon_x = (I + Q)/2$, are observables of the MHD modes. The variance

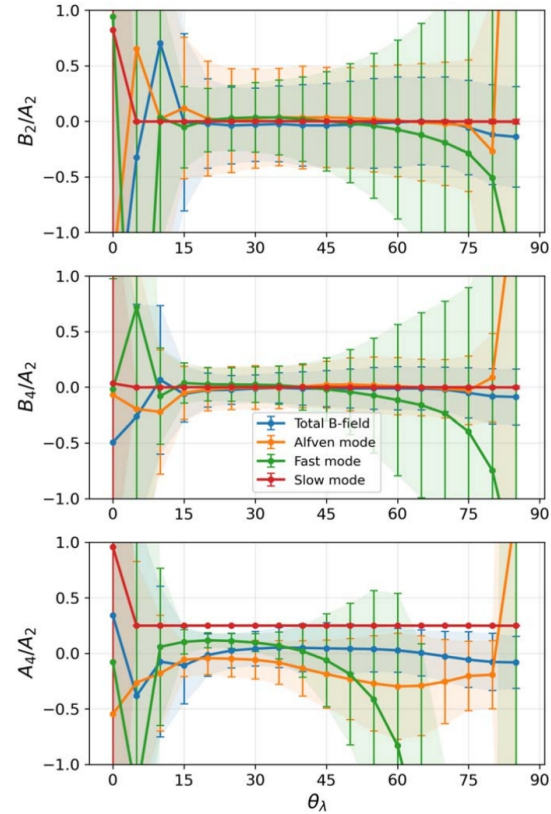


Figure 1: The averaged fit parameters B_2/A_2 (top panel), B_4/A_2 (middle panel), A_4/A_2 (bottom panel) as functions of the B-field inclination angle θ_λ , obtained from 24 synthetic synchrotron polarization observations. The synthetic maps are calculated from multiple snapshots in eight solenoidally driven MHD turbulence simulations. The error bars show 1σ uncertainties. The parameter A_4/A_2 corresponds to the symmetric part of the observed s_{xx} signatures while B_2/A_2 and B_4/A_2 reflect the asymmetry. The total magnetic field is shown in blue color, and the decomposed Alfvén, fast and slow MHD modes are represented by the colors yellow, green, and red, respectively [6].

of the emissivity of the synchrotron radiation can be analyzed to generate a parameter to classify these linear MHD modes. Based on this principle, Zhang et al. [5] successfully retrieved the mode information in the Cygnus-X region. However, they ignored the asymmetry term in the fitting function (S_{xx}) of the variance of synchrotron emissivity.

Although the SPA technique has achieved significant progress to a certain extent in identifying turbulence modes, the ISM is considerably more complex than the conditions assumed in [5]. It is yet to be fully understood how variations in the plasma properties and some physical parameters affect the

technique, and whether the method is robust for all environments in the ISM. In light of this perspective, Pavaskar et al. [6] found that the quantification and analysis of the s_{xx} parameter as a function of the magnetic field inclination angle has the potential to give us a consistent classification of the dominant MHD modes in the plasma. Therefore, they revisited the earlier steps in the SPA method to test the fitting parameters in various kinds of astrophysical plasma environments and to present a complete recipe for MHD mode classification in the ISM by utilizing a wide range of MHD simulations (see Fig. 1). In order to get a meaningful coverage of all possible plasma environments, higher resolution MHD turbulence simulations were performed with generalized forcing with both solenoidal and compressive components [7], spanning a large parameter space. Synthetic polarization observations can be obtained from these simulations in the form of I, Q and U maps.

In addition, recent studies have demonstrated that machine learning, or deep learning, is becoming an effective tool in the study of MHD turbulence in the interstellar media (ISM). Applications include developing surrogate models for MHD solvers using physics-informed neural operators (PINOs), constructing the data-driven closures for subgrid-scale turbulence in astrophysical objects like supernovae, and discovering the governing equations directly from high-resolution simulation data through sparse regression. These advances highlight the potential of artificial intelligence (AI) to accelerate simulations [8], uncover hidden physical relationships, and enhance our understanding of complex plasma dynamics in a scalable and interpretable manner.

To accomplish the objectives of understanding MHD turbulence in astrophysical fluids, we intend to use the 2nd order, staggered-grid fully compressible MHD code Athena++ [9] to perform three-dimensional, triply periodic, MHD simulations. Athena++ has both MPI as well as OpenMP for maximum efficiency and speed up for parallel computing. The code is capable in resolving turbulence as small as 8 pixels in the numerical region. The extensive numerical simulation with various physical parameters and driving mechanisms is required for obtaining a meaningful coverage of the various types of driven turbulence in the realistic plasma environments. Subsequently, we utilize the machine learning to investigate more accurately the relationship between the S_{xx} fitting parameters and the dominant turbulence modes by analyzing abundant MHD simulation data. Finally, probability distribution analysis of the signatures will be done in order to obtain the mode-classification. Additionally, we also compute multiple mean field directions (inclination angle γ) to simulate the projection effects that are seen in real

spectro-polarimetry observations.

We will also adopt different models of relativistic electron density distribution and trace the resulting synchrotron polarization from ~ 100000 different lines of sight in the post-processed module. The designated calculation requires a significant amount of numerical resources. The NHR@ZIB supercomputer is particularly well-suited for these computational demands, offering both high-performance parallel computing resources and ample storage capacity to fully support this compute project.

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More Information

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