Mode classification in magnetized ISM turbulence

Improving the Synchrotron Polarization Analysis (SPA) method for MHD mode classification in the ISM

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In Short

- We investigate into the the 'Synchrotron Polarization Analysis' (SPA) to provide a consistent recipe for MHD mode classification in the ISM.
- While SPA has been shown to successfully work in previous works, we find that a study into the behavior of the method parameters in various ISM environments, and their dependence on the plasma properties remain unaddressed.
- It is therefore important to test the dependency of the technique on the parameters such as the magnetic field inclination angle, Alfven mach number, plasma-β and MHD mode energy partitions.
- We will conduct extensive numerical analysis on synthetic synchrotron polarization maps generated from high-resolution 3D MHD turbulence simutions.

The compressibility of magento-hydrodynamic (MHD) turbulence is extremely important in modulating a number of astrophysical processes in interstellar media (ISM). On one hand, the energization and acceleration of cosmic rays require the fast magnetosonic modes to be efficient (Yan & Lazarian 2002, 2004, 2008). On the other hand, Alfven modes are very important in quenching the formation of stars in giant molecular clouds (Federrath et al. 2010). Despite its importance, observers do not have adequate tools in characterizing how compressible the astrophysical plasma it is in the context of ISM. Very recently, the development of the "Synchrotron Polarization Analysis" (SPA) Zhang et al. (2020) allows the classification of MHD modes in observation data. The information of both Alfven and magnetosonic(MS) modes are encoded in the polarized synchrotron emissions, in the form of Stokes parameters. The statistics of Stokes parameters, primarily the emissitivity ϵ_x, are observables of the MHD modes. Based on this principle, Zhang et al. (2020) successfully retrieved the mode information in the Cygnus-X region.

The SPA technique is based on the phenomena that when relativistic electrons travel in the presence

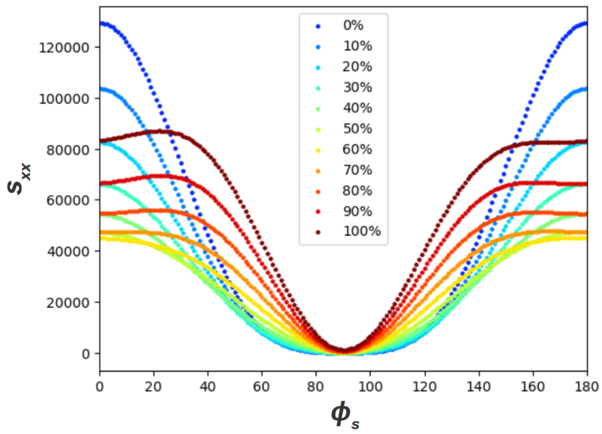

Figure 1: *The SPA signature parameter s_{xx} as a function of the mean magnetic field polar angle for different mode energy fractions. The legend shows the percentage contribution of Alfven modes in the total energy, the rest being from the magnetosonic (compressible) modes. The signature is observed by rotating the Stokes frame and calculating the variance of the emissivity of synchrotron polarization radiation ($\epsilon = (I+Q)/2$). The analysis of this function can give information on the dominant MHD modes in the ISM.*

of an external magnetic field, diffuse synchrotron radiation is emitted, which is polarized according to the mean magnetic field orientation. The properties of the plasma and the information of the magnetic field fluctuations are embedded in these polarization signals. Owing to the fact that the turbulence is statistically symmetrical around the mean magnetic field axis, the decomposition of the turbulence into its linear modes is possible. The variance of the emissivity of the synchrotron radiation can be analyzed to generate a parameter to classify between these linear MHD modes. Zhang et al. (2020) noticed that the main classification parameter r_{xx} in SPA behaves differently in the magneto-sonic and Alfvénic modes, and the corresponding dominating plasma modes also dominate the turbulence.

Despite the success of Zhang et al. (2020), the ISM environment is much more complicated than what Zhang et al. (2020) considered. For example, it is yet to be fully understood how variations in the plasma properties and mode energy fractions affect the technique, and whether the method is robust for all environments in the ISM. Recent numerical tests suggest that the parameter r_{xx} is not yet completely understood, and that it has dependencies on multiple external parameters which haven't been rigorously studied previously eg. the mean magnetic field inclination angle with respect to the line-of-sight, the turbulence forcing mechanisms, etc. Within the scope of this project, we plan to not only study the relation between the behavior of r_{xx} and these parameters but also consider another classification parameter from the SPA technique viz. s_{xx} (see Fig. 1). We find that the quantification and analysis of the s_{xx} parameter as a function of the magnetic field polar angle (in the observational Stokes frame) has the potential to give us a consistent classification of the dominant MHD modes in the plasma.

Thus, we would like to revisit the earlier steps in the SPA method to make the technique more robust as a whole through extensive numerical testing with synthetic observations. The aim of our project is to test the method parameters in various kinds of astrophysical plasma environments and to present a complete recipe for MHD mode classification in the ISM. We plan to utilize a wide range of MHD turbulence simulations and generate synthetic synchrotron polarization observations. Using these observations, we want to further understand the behavior of the classification parameters of the method and study their dependence on a wider set of plasma parameters in the ISM. In order to get a meaningful coverage of all possible plasma environments, we plan to compute MHD turbulence simulations with a high pixel resolution, generated by driving the turbulence both solenoidally and compressively, while also considering a large parameter space. Synthetic polarization observations can be obtained from these simulations in the form of I, Q and U maps. We will then employ the SPA method to analyze these maps using multiple classification parameters. Once this goal is achieved, additional astrophysical effects such as the transition between weak and strong turbulence and the effect of Faraday rotation on the observations will also be considered.

To accomplish the objectives of understanding MHD turbulence in astrophysical fluids, we intend to use the 2nd order, staggered-grid fully compressible MHD code ZEUS-MP[6] to perform three-dimensional, triply periodic, isothermal MHD simulations. ZEUS-MP 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. To obtain a meaningful coverage of the various types of driven turbulence in the realistic plasma environments in the ISM, the generation of a series of simulations with different driving forces is very important. The compressibility of the forcing can be controlled in the code, making it possible to achieve turbulence with different energy partitions among MHD modes. Turbulence will be continuously driven into the numerical region via Ornstein–Uhlenbeck process. Furthermore, we want to compute multiple mean field directions (inclination angle γ) to simulate the projection effects taht are seen in real spectropolarimetry observations.

We will adopt different models of relativistic electron density distribution and trace the resulting synchrotron polarization from ~ 100000 different lines of sight. All simulations will be post-processed with a synchrotron polarization synthesis module to obtain the Stokes parameter maps, following which we will perform the SPA analysis while also considering the statistics of the s_{xx} parameter for method calibration. The maps will be passed through various filters including scale thresholds to make sure that only the eddy-scales in the inertial range of the turbulence are analyzed. Finally, probability distribution analysis of the signatures will be done in order to obtain the mode-classification.

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More Information

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