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Kinetic Alfvén wave cascade in the sub-ion range of plasma turbulence

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Observations of solar wind turbulence have shown the presence of a power-law energy cascade below the ion kinetic scales. This indicates the presence of wave modes that carry energy from ion scales to electron scales. The nature of these wave modes is an open question. Kinetic Alfven waves (KAWs) and whistler waves are some of the modes proposed to operate at these kinetic scales.

We perform particle-in-cell simulations that are initialized by an ensemble of either KAW modes or whistler modes at scales slightly larger than the ion skin depth. Earlier work performed in 2.5D[1] is generalized to 3D. Analytical two-fluid dispersion relations are used to initialize these modes. Earlier, we found that these two-fluid relations are very good at producing the hot plasma dispersion properties in these simulations. The polarization relations of the various perturbed fields (electric, magnetic, density, and velocity fields) are obtained in 2D and rotated to initialize the simulations in 3D.

The nonlinear interactions of these wave modes transfer energy to smaller scales where further wave modes are excited. We find an energy transfer to the sub-ion scales in the energy spectrum. We measure the polarization ratios of the different perturbed fields at these sub-ion scales. For ex., fig. 1 shows the ratio $|\delta B_x/\delta B_z|$ measured in simulations at different times. We notice that simulations initialized with whistler modes at $k_y d_i=0.5$ show a whistler polarization at time t=0. Similar is the case for simulations initialized with KAWs. The higher wavenumbers are not initialized with any mode, so their polarizations are arbitrary at t=0. We see that at later times, the polarization ratios in both whistler and KAW simulations lie closer to the analytically expected polarization ratios of KAWs. Similar results are seen in other magnetic and velocity fields' components, where the observed polarization at sub-ion scales is closer to the analytically expected KAW polarization. The density perturbations in both KAW and whistler simulations show similar fluctuation levels, whereas whistler modes are expected to be incompressible. These results indicate that KAW modes are preferentially excited at sub-ion scales $(kd_i \lesssim 1)$.

The power spectrum is calculated in the field-perpendicular direction. We find the magnetic energy spectrum with an index in the range of -2.8 to -3.2. As the ion-to-electron mass ratio increases, we find that the sub-ion range spectrum extends to smaller scales. The spectral slope also depends on the plasma beta. The 2D power spectrum in the parallel-perpendicular wavenumber space shows the typical anisotropic energy cascade in the perpendicular direction. These spectra are similar to those observed in solar wind turbulence[3] in the sub-ion (transition) range. This work shows that KAWs are the wave modes possibly mediating the sub-ion range of plasma turbulence.

References

[1] K. D. Makwana et. al., Plasma Phys. Rep. **49**(6), 759-771 (2023)

[2] J. Sharma & K. D. Makwana, (2024) under review

[3] S. Huang et al., Astrophys. J. Lett. **909** L7 (2021)

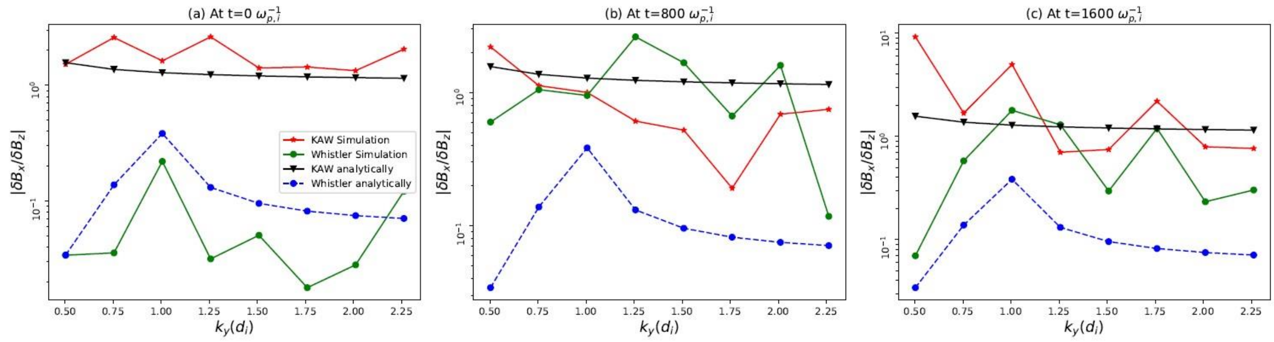

Figure 1. $|\delta B_x/\delta B_z|$ ratios from analytical KAW relations (black), analytical whistler relations (dotted blue), KAW simulation (red), and whistler simulation (green) at time (a) $\omega_{pi}t=0$, (b) $\omega_{pi}t=800$, and (c) $\omega_{pi}t=1600$. Here the $k_x=0$. At t=0 the whistler simulation shows polarization ratios close to the whistler expectation values, while the KAW corresponds to its analytical expectation. At time $\omega_{pi}t=1600$ we find that the modes at higher wavenumbers in both simulations lie closer to the KAW expectation, indicating the excitation of KAW modes even in the whistler simulations.