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Multi-spacecraft Observations of the Alfvénic Transition from Weak to Strong Magnetohydrodynamic Turbulence

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Plasma turbulence is a ubiquitous dynamical process that transfers energy across many spatial and temporal scales in astrophysical and space plasma systems. Although the theory of anisotropic magnetohydrodynamic (MHD) turbulence has successfully described phenomena in nature, its core prediction of an Alfvénic transition from weak to strong MHD turbulence when energy cascades from large to small scales has not been observationally confirmed. Here we report the first observational evidence for the Alfvénic weak-to-strong transition in MHD turbulence in the terrestrial magnetosheath using the four Cluster spacecraft. This study presents four pieces of evidence to support the presence of the Alfvénic transition. First, the change in energy spectra from purely perpendicular/2D cascade to scale-dependent Goldreich-Sridhar cascade (Fig. 1).

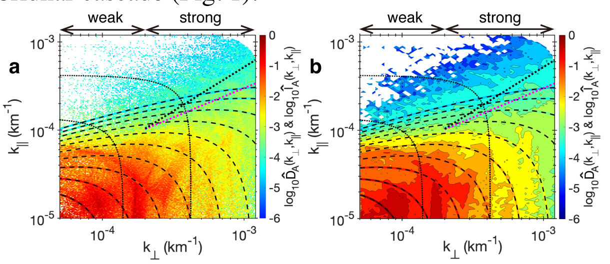

Fig. 1 | The comparisons of $k_\perp - k_\parallel$ distributions of magnetic energy between observations (color spectra) and theoretical expectations (dashed contours). **a**, high-resolution spectral image. **b**, low-resolution contours.

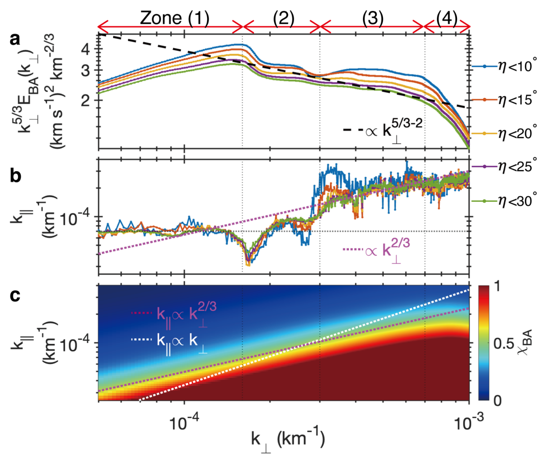

Fig. 2 | **a**, Compensated magnetic spectrum $k_\perp^{\frac{5}{3}} E_{B_A}(k_\perp)$. **b**, Variations of $k_\parallel$ versus $k_\perp$. **c**, nonlinearity parameter $\chi_{B_A}(k_\perp, k_\parallel)$. η is the angle between different wavevectors determined by SVD method and timing analysis.

Second, a change in spectral slopes of energy spectral density from wave-like (-2) to Kolmogorov-like (-5/3) (Fig. 2**a**). Third, nonlinear parameter ($\chi \equiv \frac{\tau_A}{\tau_{nl}}$; τ_A =linear Alfvén wave time; τ_{nl} =nonlinear cascade time) follows a Goldreich-Sridhar scaling in terms of wavenumber (Fig. 2**c**). Fourth, turbulent fluctuations start to deviate from wave dispersion relations when it arrives at the Alfvénic transition scale (Fig. 3).

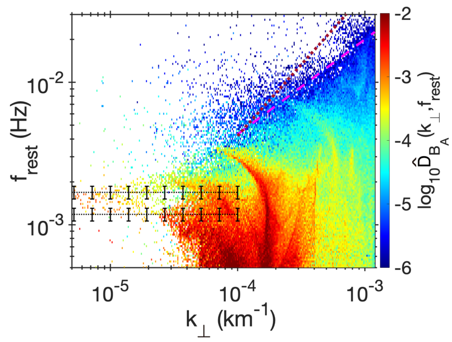

Fig. 3 | $f_{rest} - k_\perp$ distributions of magnetic energy in the plasma flow frame. The dashed lines with error bars represent theoretical Alfven frequencies. The pink and red dashed lines mark the scaling $f_{rest} \propto k_\perp^{2/3}$ and $f_{rest} \propto k_\perp$.

The observed transition indicates the universal existence of strong turbulence regardless of the initial level of MHD fluctuations. Our work takes a critical step toward understanding the complete picture of turbulence cascade, connecting the weak and strong MHD turbulence systems. It will have broad implications in star formation, energetic particle transport, turbulent dynamo, and solar corona or solar wind heating.

References

[1] Siqi Zhao, Huirong Yan, Terry Z. Liu, et al. (under review; 2003). arxiv: 2301.06709