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Fundamental Results from the World's Largest Simulation of Compressible MHD turbulence: Applications to Astrophysical and Space Plasmas

James R. Beattie[1,2] & Amitava Bhattacharjee[2]
[1]Department of Astrophysical Sciences, Princeton University, [2]Canadian Institute for Theoretical Astrophysics, University of Toronto
e-mail: james.beattie@princeton.edu

We present fundamental insights into the nature of compressible magnetohydrodynamic (MHD) turbulence using the world's largest numerical simulation to date [1,2,3], executed at a resolution of $10{,}080^3$ grid points (equivalent to Plasma Reynolds numbers of order a million), and complemented by *in-situ* spacecraft data. These results reveal new features of turbulence relevant to the interstellar medium (ISM) of our Galaxy, solar wind, and planetary magnetosheaths, challenging several long-standing theoretical results within MHD turbulence.

The simulation is driven into a statistically stationary state with finite correlation-time forcing and turbulent Mach number $\mathscr{M} \approx 4$ on the outer-scale, resolving both supersonic ($\mathscr{M} > 1$) and subsonic ($\mathscr{M} < 1$) turbulent modes throughout the cascade. The magnetic field is generated and sustained via a turbulent dynamo, creating an approximately energy equipartition field with the turbulence. Across the four-orders of magnitude in dynamic range, we identify two co-existing kinetic energy cascades: a supersonic, non-local cascade with a Burgers-like spectrum $\mathcal{E}_{\rm kin}(k) \propto k^{-2}$ and a subsonic, local, magnetically dominated cascade with an Iroshnikov-Kraichnan-like spectrum $\mathcal{E}_{\rm kin}(k) \propto k^{-3/2}$. The magnetic energy exhibits a distinct $k^{-9/5}$ local cascade that does not conform to classical MHD theories, and has an outer-scale on the Alfvenic scale.

We observe a new scale-dependent alignment relation between velocity and magnetic field, $\theta(\lambda) \propto \lambda^{1/8}$, in contrast to the predicted $\theta(\lambda) \propto \lambda^{1/4}$ scaling from dynamical alignment theory [4]. The alignment is broadly linked to the suppression of all the nonlinearities in the MHD equations, which are realized through the emergence of global force-free states, as well as local cross-helical regions in the plasma that have sizes close to the Alfvenic scale. This has direct implications for the turbulent dynamo saturation, and connections to magnetic reconnection.

The broad range of $\mathscr{M}$ we resolve on each scale in the simulation enables a comparison to multiple intervals in the Magnetospheric Multiscale (MMS) spacecraft observations of Earth's turbulent magnetosheath. Both simulation and observations confirm that the normalized mass density fluctuations $\delta\varrho/\varrho_0$ scale linearly with $\mathscr{M}$, validating $\delta\varrho/\varrho_0 \propto \mathscr{M}$ even in strongly compressible regimes. This result solidifies the robustness of weakly compressible MHD theory beyond its asymptotic limits.

These results suggest that the statistical structure of compressible MHD turbulence still has many mysteries to unravel and establish a benchmark for interpreting radio telescope ISM observations. They also mark the beginning of a frontier in running $>10{,}000^3$ grid turbulent boxes by harnessing the power of exascale computing, advancing turbulence theory by accessing regimes previously outside of the realm of computational tractability.

References

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