A Lagrangian Perspective on Anisotropy in Turbulent Flows

Lagrangian Studies of Incompressible Turbulence in Plasmas

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In Short

- Numerical investigation of fundamental properties of incompressible (deeply subsonic) turbulence in electrically conducting fluids (solar wind, stellar interiors, interstellar medium) and electrically neutral fluids (oceans, the atmosphere).
- Statistical analysis in the Lagrangian frame of reference (co-moving with the fluid) as opposed to standard Eulerian frame of reference.
- Millions of passive tracers followed in pseudospectral direct numerical simulations of high Reynolds number turbulence.
- Physical model: single fluid incompressible magnetohydrodynamics (MHD) subject to a mean magnetic field; Navier-Stokes for electrically neutral fluid.
- Investigation of nonlinear dynamics, transport properties, anomalous diffusion, particle dispersion, anisotropy, and the effects of quasi-two-dimensionalization.
- Influence/development of numerical turbulence-excitation mechanisms.

Turbulent flows are fundamental to a tremendous variety of physical systems on earth and throughout the universe. Examples include the transport of nutrients in the oceans, climate and weather prediction, flows in turbo-machinery and around vehicles, the solar wind, magnetic field-generation in celestial bodies, the propagation of cosmic rays, and star formation from molecular clouds in the interstellar medium. In astrophysical systems, a mean magnetic field often constrains the turbulent dynamics while adding large-scale wave modes, and a fundamental anisotropy to the system.

Due to the nonlinearity of the underlying partial differential equations, magnetohydrodynamic (MHD) turbulence is complex; a comprehensive theory has not yet been formulated. Insights gained from direct numerical simulations are essential to drive progress toward a theoretical understanding of turbulence. This project investigates homogeneous incompressible (the limit of deeply subsonic) MHD turbulence and Navier-Stokes turbulence using pseudospectral direct-numerical simulations at high-resolution.

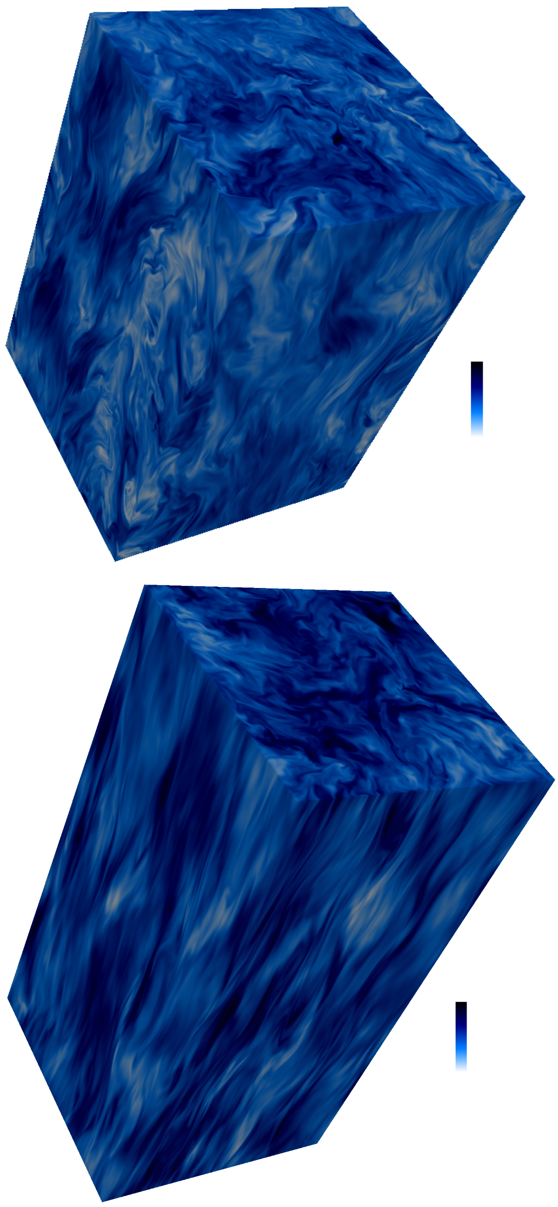

Figure 1: *Amplitude squared of magnetic field fluctuations in three-dimensional MHD turbulence subject to a strong mean magnetic field directed perpendicular to the top-side of the volume. The magnitude of the mean magnetic field in the top panel of this figure is 2 times larger than the RMS magnetic fluctuations. The magnitude of the mean magnetic field in the bottom panel is 5 times the RMS magnetic fluctuations. An electrically conducting fluid streams freely in the direction of the magnetic field. As the mean magnetic field is increased, a more elongated simulation box at fixed numerical resolution becomes necessary to deal with the stronger anisotropy of the turbulent eddies. A remarkable increase in the anisotropy of the flow is visible between the simulations. This anisotropy affects not only the direction of the mean magnetic field, but also changes the characteristics of the flow in the perpendicular plane.*

Our simulations are currently being run with 2048^3 collocation points and millions of tracer particles, producing well-resolved anisotropic MHD flows with Reynolds numbers $\gtrsim \mathcal{O}(10^4)$. We are experienced at studying both Eulerian and Lagrangian properties of the flow [5], [6],[7], and have recently published several new works on Lagrangian statistics [1], [2], [3], [4].

The Lagrangian viewpoint is the natural viewpoint for addressing problems related to mixing, turbulent intermittency, and transport. We study Lagrangian single-particle, particle-pair, and multi-particle statistics, including the separation speed of particle pairs (see Figure 2). As simulations of higher Reynolds number turbulence become possible, new aspects of turbulent dispersion are revealed.

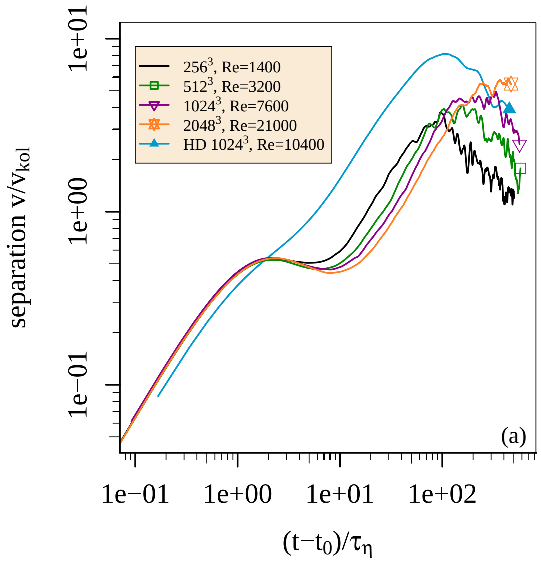

Figure 2: *Average separation speed particle pairs initially separated by 2 $\eta_{\rm kol}$, the smallest physical length scale for turbulent motion. Anisotropic MHD simulation run with 8 million tracer particles, for a range of Reynolds numbers and corresponding grid sizes up to 2048^3.*

In addition, we focus on developing new diagnostics that can reveal aspects of the dynamics specific to anisotropic MHD turbulence. One such diagnostic is a convex hull analysis of Lagrangian droplets, which consist of densely packed Lagrangian particles (see Figure 3). The convex hull analysis produces the surface area and volume of droplets as they disperse in the flow. Statistics that use many Lagrangian tracer particles are fundamentally different from those that use a small number of particles. Many particles can provide a higher resolution of the volume of fluid, allowing extremes of dispersion to be quantified more precisely. In a large group of particles, the particles on the inside and on the outside of the group can be distinguished, and the turnover of particles at this outer surface can be quantified. These results indicate that the advective transport is considerably different in MHD turbulence than in Navier-Stokes turbulence, and is also different as the MHD turbulence becomes more anisotropic.

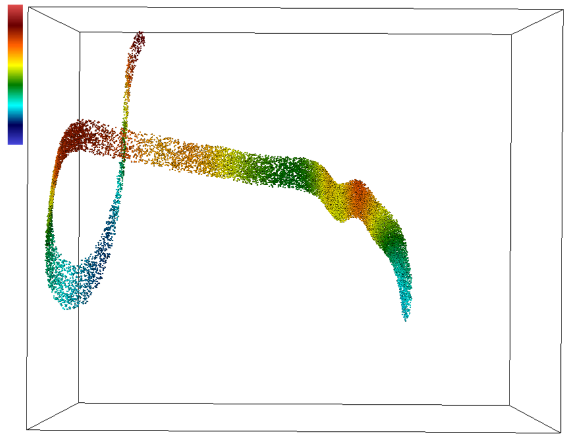

Figure 3: *A high-density spherical droplet, represented by 16 thousand Lagrangian particles, after dispersing for nearly 40 Kolmogorov time-scales τ_η in anisotropic MHD turbulence, as described in [4]. Particles are colored by the kinetic energy of the fluid. This is a typical visualization of the* ribbon-like dispersion *that occurs in these simulations.*

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http://www-astro.physik.tu-berlin.de/de/node/340

More Information

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[3] J. Pratt, A. Busse, W.-C. Müller. *JGR: Space Physics* **125.11**, e2020JA028245 (2020).

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Project Partners

A. Busse, Univ. Glasgow; J. Pratt, Georgia State Univ.

Funding

TU Berlin, National Science Foundation