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Fully developed turbulence in dusty plasma

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Turbulence consists of disordered, chaotic and multiscale flows with energy cascade often following power-law behavior. The hydrodynamic turbulence, for instance, exhibits the -5/3 scaling in energy spectrum in accordance with Kolmogorov's theoretical predications. The characteristics of turbulence get affected due to the presence of magnetic fields, compressibility, viscoelasticity, and buoyancy. These effects can lead to steeper or shallower spectra, and in some cases, break down the power-law behavior altogether. Systems with particularly rich turbulent behavior include solar wind, fusion plasmas, polymeric fluids, and activity-driven flows in soft matter, biological systems and dusty plasmas.

Turbulence in dusty plasmas is a fascinating due to their viscoelastic properties and low Reynold's number flow. Dusty plasmas consist of electrons, ions, highly charged dust particles, and neutral gas. Due to their high charge, dust particles interact strongly with one another introducing viscoelastic properties. Here, we characterize turbulence in laboratory dusty plasmas. This offers an opportunity to explore the concept of "elastic turbulence," which has been demonstrated in polymeric fluids [1]. In this paper, we discuss our efforts to explore turbulence in dusty plasma medium.

Dusty plasma in laboratory experiments usually develops steady-state and complex flows due to the presence of multiple forces and continuous influx of energy. In our experiment [2], we demonstrate fully developed Kolmogorov turbulence originating from self-excited and steady-state vortex flows of charged dust fluid. Such flows originate in a three-dimensional (3D) dust cloud formed in the diffuse plasma region. Vortices of different sizes and at distant locations in the dust cloud, formed by varying discharge conditions, all demonstrate similar results, indicating the generality of the turbulent characteristics.

The flow velocities are extracted using the Particle Image Velocimetry (PIV) technique from frame-by-frame image analysis. We further estimated the energy spectrum in wave-vector and frequency domains. These measurements establish the -5/3 scaling in the spatial and temporal domains, a typical characteristic of fully developed 3D Kolmogorov turbulence. The results are further strengthened by obtaining the 2/3 scaling in the second-order structure function. A slight deviation in the tails of the probability distribution functions for velocity gradients reflects the signature of intermittency.

To further explore a wide parameter space, we use molecular dynamics simulations that incorporate intrinsic correlation effects. Preliminary results from simulated vortex flows show features consistent with viscoelastic turbulence at low Reynolds numbers. The energy spectrum deviates from the Kolmogorov -5/3 scaling—as expected for viscoelastic systems.

This talk will summarize our current experimental and theoretical efforts to understand turbulence in dusty plasmas, particularly those driven by multiscale vortices. We will highlight the agreements and discrepancies between experiments and simulations and outline open questions for future investigation.

References:

[1] A. Groisman & V. Steinberg, Nature, Vol. 404 (2000).
[2] Sachin et al. Phys. Plasmas 31, 123704 (2024).

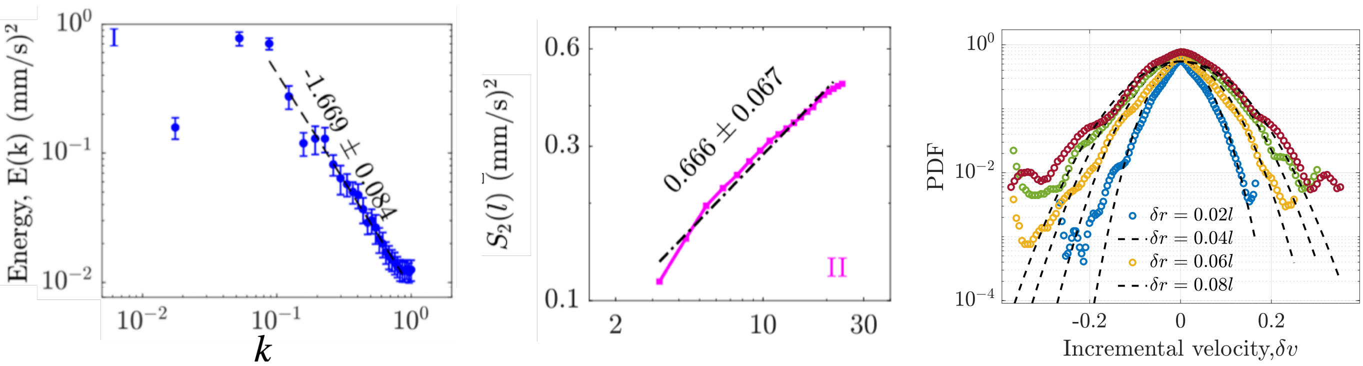

Figure 1: (I) The power spectrum with -5/3 Kolmogorov power law scaling, (II) second order structure function suggesting 2/3 scaling, and (III) the PDF of velocity gradients with different increments.