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Two-dimensional electrostatic turbulence in a magnetized plasma based on a kinetic theory

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Plasma turbulence takes place in a collisionless or weakly-collisional condition in most astrophysical and laboratory environments.
Electrostatic turbulence in weakly-collisional, magnetized plasmas exhibits a direct cascade of collisionless invariant, i.e. entropy, in phase space [1].
Here we consider phase mixing that arises from nonlinear ExB motions (nonlinear phase mixing).
Particles execute drift in addition to gyration (Larmor rotation) around the field line in magnetized plasmas, and the distribution of their radii contain a spread proportional to the thermal velocity.
For small-scale electric fluctuations, particles with different gyroradii execute different ExB motions on average because they see different effective potentials [2].
Thus each particle responds differently corresponding to its velocity perpendicular to the ambient field, which introduces the velocity-space structure of the distribution function.
Therefore, the kinetic turbulent cascade induced by nonlinear phase mixing proceeds in position and velocity space simultaneously at scales smaller than the thermal Larmor radius of the particles (inertial range).
At even smaller scales, collisions finally smooth out the velocity-space structure (dissipation range).
This phase mixing corresponds to an "entropy cascade."
In the two-dimensional configuration, there is another collisionless invariant corresponding to the kinetic energy of plasmas in the large-scale limit.
As two invariants cannot share the same local-interaction space in a Kolmogorov-like phenomenology, this second invariant introduces an inverse cascade in addition to the direct cascade of entropy.

We present our recent results from numerical simulations of the phase-space cascade in magnetized weakly collisional plasmas, using the electrostatic gyrokinetic model.
Gyrokinetics is a reduced model of Fokker-Planck equation in the low-frequency limit.
Gyro-angle is removed from velocity coordinates due to the average of gyro-motion around the ambient magnetic field.
Ignoring variation along the field line, we focus on a freely-decaying turbulence problem using AstroGK [3] in a simplified four-dimensional phase space (2D in position space perpendicular to the field line and 2D in velocity space).
In order to see the coupling between position and velocity space scales, we make Fourier and Hankel transform in position and velocity spaces, respectively.
By making use of the shell average usually made in the wave-number space, two-dimensional spectrum in the Fourier-Hankel space is investigated.

In addition to the direct cascade associated with the first invariant (entropy) reported in Ref. [1], we show the evidence of the inverse cascade associated with the second invariant.

By means of the numerical diagnostics of nonlinear transfer function, we show a clear signature of dual-cascade transfer associated with both invariants, i.e. the flux of first invariants to small scales and that of the second to large scales.
Extension of Fjortoft's argument [4] into Fourier-Hankel space is made in order to explain this behavior by the nonlinear three-mode interactions.
In this talk, we also plan to present scaling arguments of two-dimensional freely-decaying turbulence.

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