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Description of turbulent transport in the velocity space

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Understanding plasma turbulence is key in astrophysics, and the future of clean energy generation, space weather, and space exploration. In hot plasmas, collisions are so rare that vortex-like fine scale structures develop in the phase-space of the particle distribution: coupling both real space and energy space. These structures are driven by nonlinear wave-particle interactions, which is an essentially kinetic process. Even in regimes where the phase-space vortices are microscopic, they can yield macroscopic impacts, on fluctuation statistics, large-scale structure formation, and transport [1,2,3].

In this work, we review our recent investigations of the formation, the dynamics, and the macroscopic impacts of phase-space vortices, based on first-principle kinetic numerical simulations. We cover 2 different plasma configurations.

The first configuration we consider is that of the ion-acoustic instability in 1D collisionless electron–ion plasmas with a velocity drift (current-driven ion-acoustic turbulence). Ion-acoustic waves are longitudinal electrostatic waves, which are key agents of magnetic reconnection (via anomalous resistivity), turbulent heating, particle acceleration, and play important roles in the context of laser–plasma interaction.

Linear instability requires that the velocity drift v_d exceeds some finite threshold $v_{d,cr}$. However, phase-space density holes can grow nonlinearly, even for infinitely small drifts. This subcritical instability results in an unstable domain much broader than the linear one. We observe that subcritical instabilities are absent when the initial perturbation consists of an ensemble of sine waves with random phases, except close to linear marginal stability ($v_d/v_{d,cr}>0.9$) and for large initial amplitudes ($e\varphi/T\sim1$). In contrast, a seed local negative perturbation (hole-like) in the electron phase-space can grow nonlinearly, even far below marginal stability ($v_d/v_{d,cr}<0.4$) and for small initial amplitudes ($e\varphi/T\sim10^{-3}$). Subcritical growth of phase-space holes can lead to a turbulent state with significant transport in the velocity space, which yields anomalous resistivity comparable to that of linearly unstable cases [4,5].

The second configuration we consider is that of collisionless drift-waves in the core of tokamak plasmas, which can be seen as a generalisation of the first configuration to strongly inhomogeneous magnetic fields. We focus on collisionless trapped-ion-modes (TIM), which are electrostatic, ~100Hz waves driven by resonance with the toroidal precession motion of trapped particles (a class of particles, which are trapped towards the outside of the tokamak due to the equilibrium magnetic field gradient). These modes are described by a bounce-averaged gyrokinetic model, which is implemented in the simulation code TERESA.

In the early nonlinear stage, radial transport is in qualitative agreement with quasilinear theory [6]. Figure 1 shows the structure in energy-space of the radial flux of the distribution function. It is dominated by a narrow peak around the resonant energies.

However, in the later nonlinear stage there is qualitative disagreement. In this stage the distribution function becomes strongly non-Maxwellian in the neighborhood of resonances [7]. In fact, we observe the formation and evolution of vortex-like phase-space structures, which we interpret as drift-holes [8].

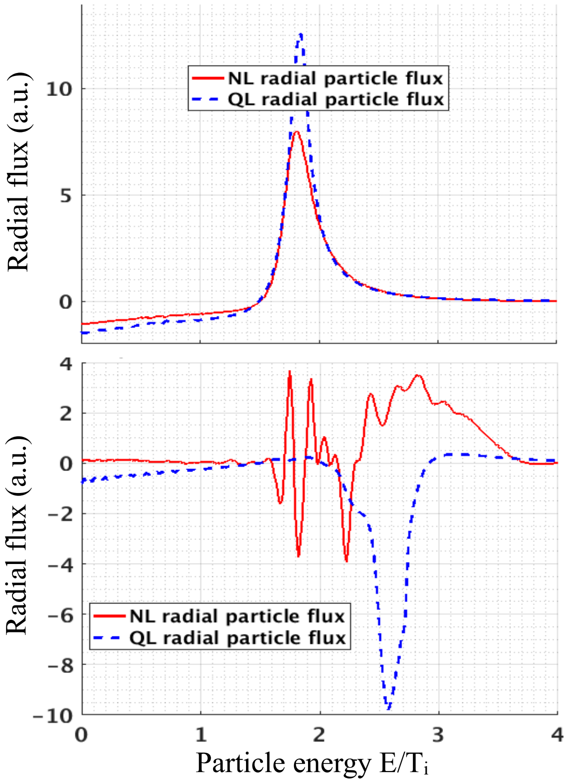

Figure 1. Nonlinear (NL) and quasilinear (QL) radial flux of phase-space density as a function of the particle energy (normalized to the ion temperature T_i). Above: early nonlinear stage. Below: later nonlinear stage.

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