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Nonlinear wave-particle interactions and phase-space structures

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Wave-particle interaction is a defining paradigm of plasma physics. Nonlinear problems arise in the ITER-relevant context of energetic particle (EP) interaction with Alfvén waves, collisionless trapped electron mode turbulence and transport, trapped ion ITG instabilities, radio-frequency heating and magnetic reconnection. In this paper, we report on fundamental advances in the understanding of nonlinear trapping and its effects on stability, saturation, turbulence and transport. These results have broad implications for EP instabilities, drift-wave turbulence and transport, and many other applications to fusion physics.

1. Introduction

Wave-particle interactions lead to the formation of self-trapped structures in phase-space (PS), where particles are trapped by their own potential. PS structures are not waves, in the sense that $f_{k,\omega}$ is not proportional to $\varphi_{k,\omega}$. PS structure formation is a kinetic nonlinearity, which cannot be described by fluid models, unlike other nonlinearities such as higher harmonic generation, mode coupling, vortex, etc. PS structures are an important feature of plasma turbulence [1]. They can drive nonlinear instabilities, intermittency in drift-wave turbulence, cause transport that departs from quasilinear predictions, and interact with zonal flows. We aim at a comprehensive understanding of turbulence, not merely as an ensemble of waves, but as a mixture of coupled waves and localized structures. Thus, we venture out of the traditional realm of applicability of quasilinear theory. This work focuses on PS structures in 1D plasmas that exhibit complex nonlinear phenomena [2,3], which are relevant to laboratory plasma dynamics, such as frequency sweeping modes observed in Alfvén wave experiments [4].

2. Phase-space structure growth

We present a new theory which describes the growth of holes and clumps, which are self-trapped structures in the 2D PS. This growth results from momentum exchange between trapped structures and wave, which is due to the dissipation acting on structures. The evolution of holes and clumps is a self-organization process. A hole provides the energy required to balance dissipation by climbing the gradient of f_0. We use phase-space enstrophy (phasestrophy) as a measure of structure's strength. We derive a kinetic counterpart of the Charney-Drazin non-acceleration theorem, which gives a general relation between wave energy and phasestrophy. This relation can be used to determine structure growth rate or the saturation level of structures in the steady-state.

As an application, we start with a kinetic model for the bump-on-tail instability, which describes interactions between a single electrostatic Langmuir wave and single-species plasma with EP population. This model includes an extrinsic wave damping to account for linear dissipative mechanisms of the wave energy to the background plasma. The fixed rate of dissipation, γ_{d}, is such that the total growth rate is $\gamma \approx \gamma_L - \gamma_d$, where $\gamma_L \sim \partial_v f_0$ is the familiar (in the bump-on-tail context) linear drive by EPs. We find that the growth rate of a structure of size Δv is proportional to $\gamma_d \Delta v \partial_v f_0$. Numerical simulations confirm the validity of this result in both subcritical and supercritical regimes. Fig.1 shows quantitative agreement for the growth of phasestrophy (including the negative contribution from collisions). The structure growth rate is in contrast to usual linear growth of waves, at a rate $\gamma_L - \gamma_d$. This expression shows that dissipation drives a nonlinear instability ($\Delta v \sim \sqrt{\varphi}$) of holes and clumps via momentum exchange.

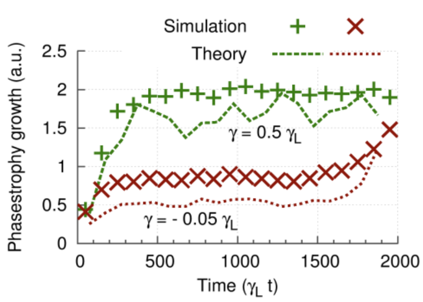

Fig.1. Growth of an isolated hole. Plusses and crosses: phasestrophy growth, above and below marginal stability, respectively. Dashed curves: analytic theory.

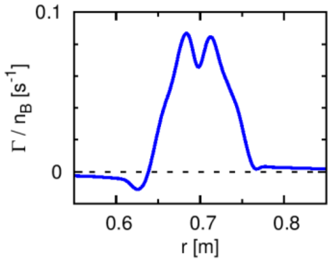

Fig.2. Radial particle flux due to hole/clump growth in the neighborhood of a resonance. Here, n_B is the beam density.

Hole/clump growth drives transport in the velocity direction. When applied to a toroidal Alfvén eigenmode in JT-60U, which is essentially 1D in the neighborhood of the resonance, velocity is transformed into the opposite of toroidal canonical angular momentum. Then this model qualitatively predicts significant radial particle flux (Fig.2). Namely, holes and clumps can transport the whole beam population outward in 10 seconds.

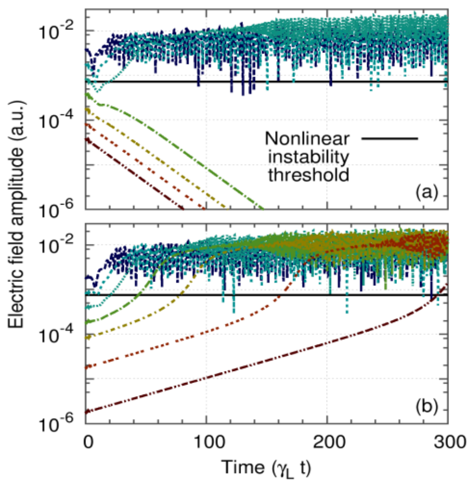

Fig.3. Dashed: time-series of electric field amplitude for different initial amplitudes. (a) Subcritical case. (b) Supercritical case. Solid: theoretical instability threshold.

3. Nonlinear instabilities

Theory shows that the stability of structures is independent of the sign of γ. Nonlinear growth requires $\gamma_d > 0$ to enable momentum exchange, $\partial_v f_0 > 0$ to provide free energy, and a seed structure of width Δv large enough to overcome collisions. This explains the existence of subcritical instability. Fig.3(a) shows simulations with $\gamma < 0$, which are stable or unstable depending on the initial perturbation amplitude. In addition, our theory predicts for the first time the existence of a nonlinear instability for $0 < \gamma \ll \gamma_L$. Fig.3(b) shows the first simulation of this new *barely supercritical* nonlinear instability.

Our theory yields a criterion for nonlinear instability, which sets a minimum electric field amplitude. Fig. 3. shows a good agreement between prediction and simulation, in both subcritical and supercritical regimes.

4. Phase-space turbulence

In the presence of multiple resonances, we observe avalanches in velocity-space due to the evolution of PS structures. Several holes and clumps emerge from neighboring resonances and interact with each other. Ultimately, holes coalesce into macro-scale structures, whose lifetimes are much larger than the classical quasilinear diffusion time and which thus dominate the nonlinear evolution. This finding reinforces the need for theoretical efforts toward a comprehensive theory of PS turbulence.

When the evolution of ions and electrons are accounted for, the ion-acoustic wave (IAW) can be excited in addition to Langmuir wave. The IAW is linearly unstable when the velocity drift between ions and electrons exceeds some threshold. Even when the drift is much below this threshold, we find that IAW are driven nonlinearly by PS structures (Fig.4), but not by high-level random noise, which contradicts earlier numerical work [5]. We find that PS structures have a significant effect on anomalous resistivity. When PS structures are negligibly small compared to the equilibrium particle distribution, but present in large number, they can have significant impacts, collectively.

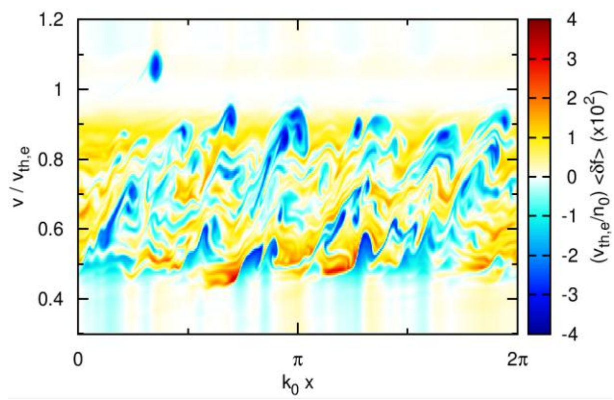

Fig.4. Perturbed distribution of electrons in PS (position horizontally, velocity vertically), in a simulation of IAW, below marginal stability. Holes are blue, clumps are red.

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References:

[1] T.H. Dupree, Phys. Fluids **15**, 334 (1972); R.H. Berman *et al.*, Phys. Rev. Lett. **48**, 1249 (1982)
[2] H.L. Berk *et al.*, Phys. Rev. Lett., **76**, 1256 (1996)
[3] M. Lesur *et al.*, Nucl. Fusion **52**, 094004 (2012)
[4] M. Lesur *et al.*, Phys. Plasmas **17**, 122311, (2010)
[5] R.H. Berman *et al.*, Phys. Fluids **26**, 2437 (1983)