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Non-Equilibrium and Extreme State - Phase-Space Jet: a New Structure to Drive Anomalous Heating and Resistivity -

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In the presence of wave dissipation, phase-space structures spontaneously emerge in nonlinear Vlasov dynamics. These structures include not only well-known self-trapped vortices (phase-space holes), but also elongated filaments, resembling jets, whose discovery is reported in this work. These jets are formed by straining due to interacting holes. Jets are highly anisotropic, and connect low and high velocity regions over a range larger than the electron thermal velocity. Jets survive long enough for particles to scatter between low and high phase-space density regions. Jets are found to contribute significantly to electron redistribution, velocity-space transport, anomalous electron heating, and anomalous resistivity.

1. Introduction

The nonlinear evolution of collisionless or weakly collisional plasmas is often accompanied by the formation and ballistic propagation of BGK-like, self-trapped vortices in phase-space (PS), also called PS holes [1]. These coherent structures are spontaneously formed in PS by resonant nonlinear wave-particle interactions, which trap particles in a trough. These trapped particles in turn generate a self-potential, leading to a self-sustained structure, which can break ties from resonance. Existing literature on PS structures focuses on holes and granulations [2]. In this paper, we report on the discovery and effects of a new kind of phase-space structure, called as jet [3].

2. Numerical experiment

We develop the example of current-driven ion-acoustic turbulence in one-dimensional, collisionless electron-ion plasma. The mass ratio is $m_i/m_e=4$, the temperature ratio is $T_i/T_e=1$, the system size is $10\pi\ \lambda_D$, the initial current is zero, and the system is driven by a constant and uniform external electric field $E_{ext}=10^{-4}\ T_e/e\lambda_D$.

Figure 1 shows the time evolution of the mean square potential ϕ, and anomalous resistivity η. The external electric field drives a series of bursts, during which electrons are strongly redistributed. Ion redistribution is much weaker. We focus on the second burst, which peaks at $t \approx 10560$ (normalized to electron plasma frequency).

Figure 2(a) is a snapshot at $t = 10560$ of the perturbed electron distribution, $\tilde{f}_e=f_e-\langle f_e\rangle$, where angled brackets denote spatial average. Consistent with theory [4] and earlier simulations [5], we

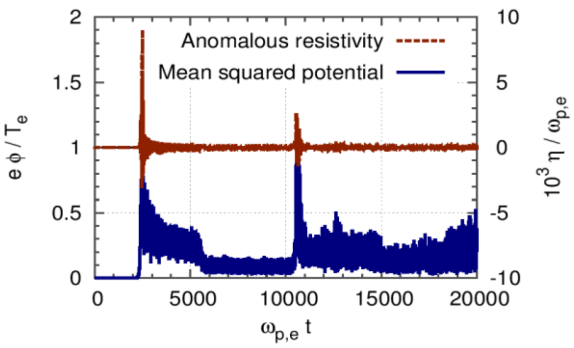

Fig.1. Time-evolution of the mean square potential (left axis) and anomalous resistivity (right axis).

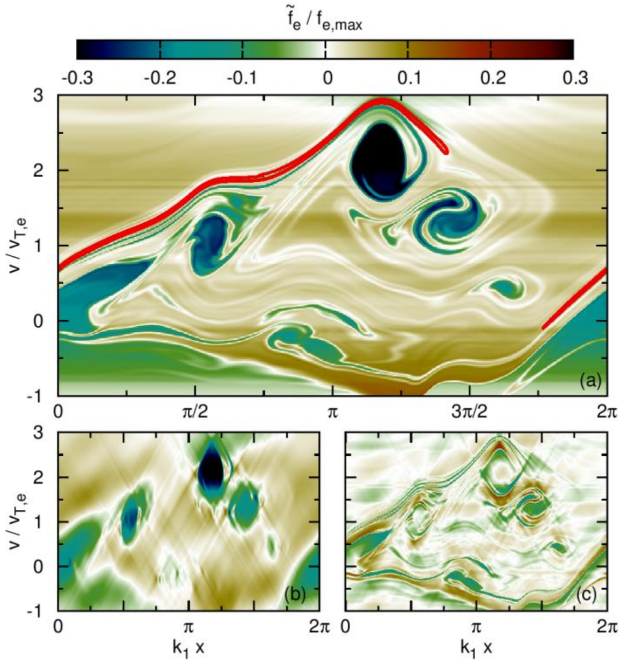

Fig.2. Snapshot at $\omega_{p,e}\,t = 10560$ of the perturbed electron distribution normalized to $f_{e,max}=n_e(m_e/2\pi T_e)^{1/2}$. A jet is emphasized by a closed contour of f_e (red curve).

observe in the nonlinear phase that PS holes spontaneously form in the region of strong overlap between ion and electron distributions. The holes accelerate and grow by climbing the velocity gradient in the electron distribution. Particles that are trapped inside a hole are convected along with it, leading to velocity-space transport. All of the above physics was already documented in the literature.

3. Phase-space jet

Interestingly, we also observe elongated structures, such as the one highlighted in Fig. 2(a) by a curve of constant PS density (or instantaneous electron trajectory). We refer to these structures as *jets* when they satisfy the three following properties:

1. Anisotropy much higher than that of holes,
2. Extent in velocity space $\gtrsim$ thermal velocity $v_{T,e}$.
3. Lifetime $\gtrsim$ average time it takes a particle to change its velocity by $v_{T,e}$.

Based on these properties, jets have a potential to cause significant particle transport. This is confirmed by measuring the particle flux Γ_v after splitting (via 2D Fourier filtering) the distribution function into two parts, one containing mainly holes, see Fig. 2(b), the other one containing mainly jets, see Fig. 2(c). Here, the particle flux Γ_v is defined by

$$\frac{\partial \langle f_e \rangle}{\partial t} + \frac{\partial \Gamma_v}{\partial v} = 0. \quad (1)$$

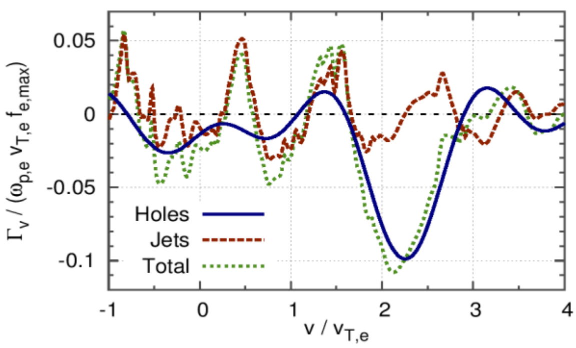

Fig.3. Velocity-direction particle flux at $\omega_{p,e}\, t = 10560$.

Figure 3 shows the particle flux at t = 10560. Redistribution, which leads to both anomalous electron heating and anomalous resistivity, is driven by a negative (positive) flux in the $v/v_{T,e}>1$ (<1) region. Our main observation is that **the contributions of jet part and hole part are of the same order**. Jets can either enhance or mitigate redistribution, depending on velocity and time.

In addition, we observe that the hole-driven flux is mostly negative, while the jet-driven flux oscillates around zero. This reinforces the intuitive idea that jet transport is essentially stochastic, while hole transport is essentially convective.

4. Conclusions and additional information

Jets are highly anisotropic structures, with an extent in velocity of the order of the electron thermal velocity. They are formed by straining between interacting holes with different velocities [3]. This process is similar to the formation of a bridge of material between two colliding galaxies.

Though less coherent than holes [3], jets survive long enough for particles to scatter between low and high phase-space density regions. In other words, though transient, they efficiently drive significant transport and anomalous resistivity. They strongly impact non-equilibrium states.

Time-scales of holes and jets are ordered as follows [3]: jet lifetime ~ particle travel time on a jet ~ hole trapping time << hole lifetime. The lengthscale of jets is of the order of 10 Debye length. The velocity extents are ordered as follows: jet-driven convective acceleration $\lesssim$ hole size $\lesssim$ particle mean-free-path on a jet ~ jet size ~ electron thermal velocity.

Jets and holes are associated with convective and stochastic transport, respectively. In terms of magnitude, holes and jets each account for roughly half of the total particle flux.

We repeated the analysis with larger system sizes and larger mass ratios, and found qualitatively similar conclusions, except that the jets are completely wound up around the holes when m_i/m_e=1836 [3].

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