Generation and Instability of Spiral Wakes in Sheared Electron Flows

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***Abstract*—Images of the electron density of a magnetized electron column illustrate the dynamics of intense vortices moving in a weaker background vorticity. A moving retrograde clump of vorticity generates a spiral wake that then evolves into many long-lived holes, contributing to the late time fluctuations.**

***Index Terms*—Electron plasmas, rotational shear, two-dimensional vortex dynamics, turbulent rotational flows, vortex.**

MANY FEATURES of turbulent relaxation in two-dimensional (2-D), nearly inviscid, incompressible flows have been studied using electron plasmas confined in Penning–Malmberg traps. With low viscosity, circular free-slip boundary conditions, simple manipulating technique, and accurate diagnostics, magnetized electron columns provide quantitative tests of theory. The interaction of intense vortices with a background vorticity gradient plays an important role in 2-D hydrodynamics, including various aspects of relaxation toward an ordered state and self-organization of turbulence. By employing CCD-imaging diagnostics, we examine key elementary processes in such systems.

Detailed description of the experimental apparatus may be found in [1], [2]. In the experiment, we first inject and trap a stable symmetric electron column with initial density profile $n_0(r)$. The trapped column typically has maximum density $n_0 \approx 10^7$ cm^{-3}, characteristic radius $R_p \approx 2$ cm, axial length $L_p \approx 35$ cm, and electron thermal energy $T \approx 1$ eV. The column $\mathbf{E} \times \mathbf{B}$ drift rotates with angular velocity $\Omega(r)$; typically, Ω decreases with r, so the column has negative shear. This causes the clump to be classified as a retrograde vortex. The axial bounce time of individual electrons ($\sim$1 μs) is short compared with the bulk column rotation time ($\sim$50 μs), so the electrons effectively average over any z variations.

The $\mathbf{E} \times \mathbf{B}$ drift flow in (r, θ) plane of these electrons is mathematically isomorphic to the (r, θ) flow of vorticity in an incompressible inviscid fluid [3]. Here, the electron density corresponds to vorticity, and the electrostatic potential corresponds to the stream function with free-slip boundary conditions.

We study the motion of intense vortices on a weaker background vorticity by combining two separate electron columns of different densities and sizes. We can easily create clumps characterized by approximately "Gaussian" density (vorticity) distributions, with maximum density comparable to the background column density, and with radial extent $\rho_c \approx 0.1 R_p$. The column with a clump then evolves during a time t, after which it is dumped axially onto a phosphor screen biased to $+15$ kV. The 2-D density image $n(r, \theta.t)$ is recorded with a low-noise CCD camera with pixel area of (.13 mm)^2 on the screen. Although this imaging technique is destructive, the shot-to-shot variations for nearly identical initial conditions are small (<1% in azimuthally averaged local density), so the time evolution of a flow can be studied.

Our experiments with retrograde clumps placed initially at plasma column periphery $(r_c \approx R_p)$ have shown that the clump rapidly accelerates to an approximately constant radial velocity, and then spirals toward the center of background density distribution. The measured rates of this motion are in quantitative agreement with theoretical predictions and numerical simulation [4]. After the clump reaches the center of the background $(r_c \sim \rho_c)$, it forms a stable dipolar structure.

The experiments also show that the spiral wake behind a moving clump can generate "a sea" of secondary self-trapped holes, giving turbulence; this is not understood theoretically. Fig. 1 shows the initial $n(r, \theta)$ of the background column combined with the intense clump; and images of the azimuthally asymmetric components $\delta n(r, \theta)$ of the density perturbations at three successive times during an ascending clump motion. Here, the θ-symmetric component $n_0(r)$ of the background electron density has been subtracted from the raw CCD-images, leaving only the asymmetric perturbation. The moving clump redistributes the background density as it moves inward, which forms a spiral wake with low density at its inner side and increased density at its outer side [4]. This wake rotates differentially with respect to the clump, as seen in Fig. 1. The space charge density induced by the spiral wake on the background electron column generates an azimuthal electric field at the position of the clump and drives it radially. This wake shows long-lasting behavior, and it remains long after the clump has reached the center of the background. The wake gradually spirals outward, and also evolves through high m-modes of the Kelvin–Helmholtz instability into an ordered set of small holes located near the plasma periphery. Typically these holes are evenly spaced in θ at close radii. The slow drift of these long-lived holes out of the vorticity distribution controls the later stages of relaxation of this secondary small-scale turbulence. The slow outward spiral of the prograde holes does not form a strong wake due to the more thorough mixing of the background density distribution by the prograde vortex.

These images show a new nonviscous mechanism of effective energy transfer from the large-scale to the small-scale tur-

Manuscript received July 2, 2001. This work was supported by the National Science Foundation under Grant PHY-9876999 and by the Office of Naval Research under Grant N00014-96-1-0239.

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Publisher Item Identifier S 0093-3813(02)03160-0.

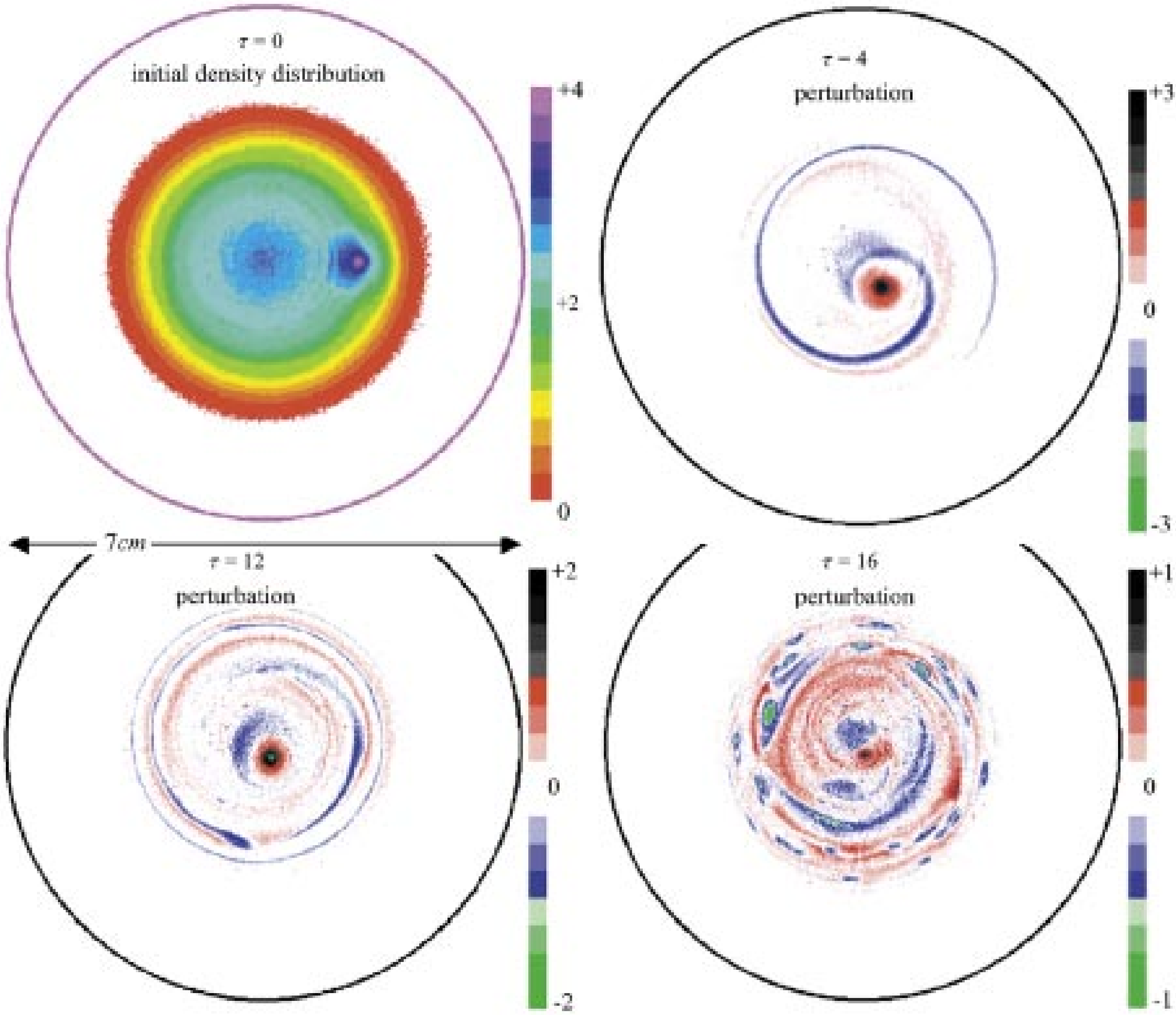

Fig. 1. Initial density distribution and density perturbations left by an ascending clump at three successive times. The positive/negative color scales are shown at the right of each figure (densities have units of 10^6 cm^{-3}). The background column rotates counterclockwise. Time is measured in units of the background rotation period, $\tau \equiv 2\pi/\Omega$. The outer circles show cylindrical wall of the trap, $R_w = 3.5$ cm.

bulence and provide additional insight into the nature and development of relaxation processes in turbulent plasma flows.

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