*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-1.186 (2006)*

Self-organization in plasma and 2D fluid turbulence: similarities and analogies

M. G. Shats, H. Xia, H. Punzmann

The Australian National University, Canberra, Australia

I Introduction

Transitions to improved confinement modes in toroidal plasma are often, if not always, accompanied by formation of transport barrier, whose presence is manifested as a steep density (or temperature) gradient, strong sheared radial electric field and reduced turbulence level. Generation of zonal flows, or radially localised $m = n = 0$ potential structures whose frequency is $f \approx 0$ [1] is a well-recognised mechanism of the turbulence "stabilization". Though the role of zonal flows in the transport barrier formation is being broadly accepted, it is still not quite clear how zonal flows are formed initially from a broadband turbulence, how and whether they affect turbulence and/or turbulent transport, and how zonal flows are sustained (if they are) in the improved confinement mode after turbulence is reduced.

Zonal flows are not unique to toroidal plasma. Self-organization of turbulence into large coherent structures is also known in two-dimensional fluids, so it is instructive to compare processes of the turbulence self-organization in fluids and in plasma in order to obtain further insight into a phenomenon of improved confinement. Such an approach certainly has many limitations (first, due to the inevitable complications arising from complex geometry of toroidally confined plasma discussed in [2]), nevertheless, it may trigger some first-principle ideas.

We have already reported the first results of such a comparison [3]. Here we discuss more results triggered by comparison of the turbulence self-organization in quasi-two-dimensional (2D) fluid and in magnetically confined toroidal plasma in the H-1 heliac. Fluid turbulence self-organizes through the mechanism of spectral condensation which is an accumulation of the spectral energy at the largest scale (system size). The energy is delivered there *via* the inverse energy cascade. This occurs when the resistive scale determined by linear damping of the flow becomes larger than the size of the fluid cell. Such spectral redistribution of the turbulence energy leads to the generation of a strongly anisotropic coherent flow (condensate), reduction in the turbulence level in the range of scales between the energy injection scale and the condensate scale, and dramatic changes in the diffusive properties of the flow.

II Generation of large structures in 2D fluid turbulence

The inverse energy cascade in 2D turbulence is responsible for spreading spectral energy from the scale at which it is injected in the system, k_i, towards larger scale, and the generation of a broad spectrum $E(k) \sim k^{-5/3}$ (energy inertial range) [4]. At the same time, the enstrophy (squared vorticity) cascades to smaller scales, such that at $k > k_i$ the spectrum scales as $E(k) \sim k^{-3}$ (enstrophy inertial range). Kraichnan [4] has predicted that in a system of finite size spectral energy delivered via the inverse cascade mechanism can, in principle, pile up at the largest available scale to form *spectral condensate*, which he also likened to the Bose-Einstein condensation of the 2D quantum gas. The condensate formation in 2D fluids has been confirmed in experiments [5], [6]and in numerical simulations [7], [8].

In [3] we have reproduced experimental results on the formation of spectral condensate [6] to compare spectral characteristics of the turbulence evolution with those in toroidal plasma during L-H transitions. Figure 1 illustrates evolution of spectra as energy is injected into the system (time t_1), through the inverse energy cascade stage (time t_2), to the stage when it is accumulated in one large vortex (time t_2).

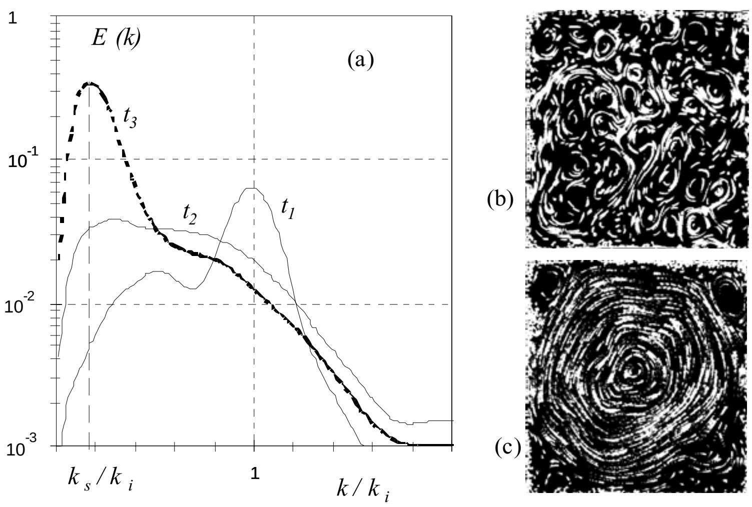

Figure 1. (a) Evolution of spectra during spectral condensation in 2D fluid ($t_1 > t_2 > t_3$). The trace particle orbits in 2D fluid flow (b) during the inverse energy cascade stage, and (c) after spectral condensate formation.

It is seen that spectral energy is redistributed during spectral condensation, such that the formation of a condensate (t_3) coincides with the reduction in the level of broadband turbulence compared with t_2. The formation of a condensate leads to a substantially more regular orbits of trace particles in the flow after the condensate vortex becomes dominant (Fig. 1b,c). This reduction in turbulent diffusion via generation of the largest coherent structure is somewhat similar to confinement improvement from L to H mode in plasma.

III Redistribution of spectral energy during L-H transitions

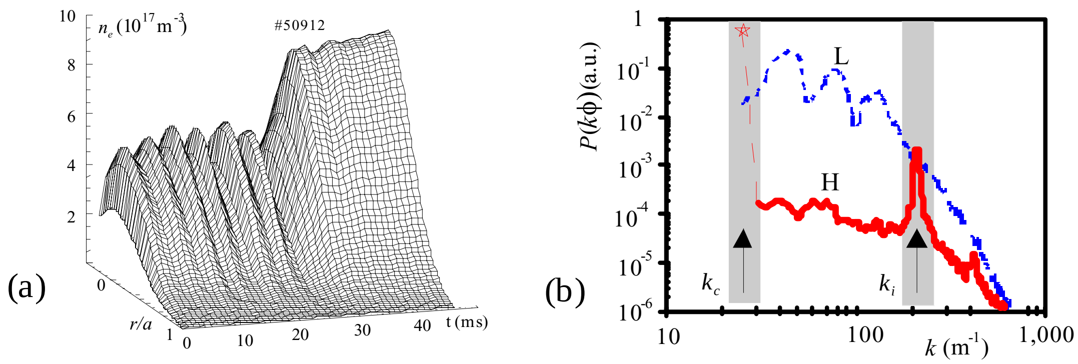

Figure 2. (a) Evolution of electron density during L-H transition in the H-1 heliac. (b) Modification to the spectrum of potential fluctuations from L to H mode.

It has been suggested in [3] that the reduction in the turbulence level during L-H transitions (example from H-1 is shown in Fig.2b) may be due to spectral energy redistribution similar to that in 2D fluids, namely, the energy of the broadband turbulence is accumulated into the energy of stationary zonal flow, shown as a star in Fig.2b. Recently, this suggestion has been partially confirmed in the H-1 experiments as shown in Fig. 3. During L-H transition, in the radial region in the plasma where pedestal forms in H-mode, low frequency (<0.6 kHz) $m = n = 0$ zonal flow develops in the vicinity of transport barrier. This result to some extent supports the hypothesis of spectral condensation of the turbulence energy in plasma. Fig. 3 shows modifications to the frequency spectrum of the potential fluctuations during L-H transition. Radial position where spectra were measured is near the top of the pedestal in H-mode, at $\rho \sim 0.7$. Though the fluctuation level is reduced in a broad frequency range, a $f < 0.6$ kHz $m = n = 0$ zonal flow is substantially increased. In the H-1 heliac radial position of zonal flow coincides with radial localisation of the zero magnetic shear and low-order rational flux surface ($\iota = 1.4 = n/m = 7/5$).

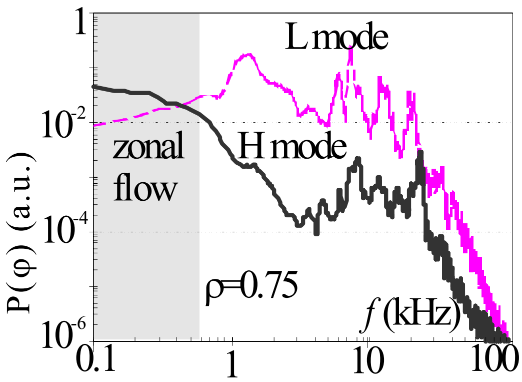

Figure 3. Power spectra of the floating potential fluctuations in L and H modes at the radial location near the pedestal top in H-mode.

Physics of spectral condensation in 2D fluid turbulence also remains unclear. It was thought initially [3] that the condensation of spectral energy can be achieved when the dissipative scale $\lambda_E \sim 1/k_E \approx \left(\mu^3/\varepsilon\right)^{-1/2}$ (where μ is linear damping, and ε is the energy dissipation rate), exceeds the size of the experimental system λ_c. Under conditions when λ_E is sufficiently large and λ_c is small, condensation can be induced by artificially introducing relatively small anisotropy in the energy injection. An injected larger structure can grow in time to eventually dominate turbulent flow.

Numerical simulations also indicate an important role played by a boundary in spectral condensation [9]. The largest scale vortex is formed only in the presence of the solid no-slip boundary, which is believed to be a source of vorticity filaments, presumably affecting flow evolution in the interior. Sensitivity of the condensate generation to the properties of a boundary, adds to the list of similarities between self-organization in 2D fluid and in plasma.

[1] Diamond P.H. et al. 2005 *Plasma Phys. Control. Fusion* 47 R35-R161.

[2] Shats M G, Xia H and M. Yokoyama 2006 *Plasma Phys. Control. Fusion* 48 S17-S29.

[3] Shats M G, Xia H and Punzmann H 2005 *Phys. Rev. E* 71 046409.

[4] Kraichnan R. H., 1967 *Phys. Fluids* 10 1417.

[5] Sommeria J, J. Fluid Mech. 170, 139 (1986).

[6] Paret J. and Tabeling P., 1998 *Phys.Fluids* 10 3126.

[7] Hossain M., Matthaeu W. H., Montgomery D., 1983 *J. Plasma Phys.* 30 479.

[8] Smith L.M., Yakhot V., 1993 *Phys. Rev. Lett.* 71 352.

[9] Van Heijst G.J.F., 2006 *J. Fluid Mech.* 554 411.