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Roles of phase space turbulence related to zonal flows in magnetically confined plasmas

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Transport of particle and heat in magnetically confined plasmas is dominated by the nonlinear evolution of turbulence. Drift wave type turbulence, which is driven by the inhomogeneities of density and temperature, has a quasi-two-dimensional structure; it has the long/short wavelength along/perpendicular to the magnetic field [1]. Such turbulence nonlinearly drives larger scale structures, such as zonal flows and streamers [2]. The spatio-temporal dynamics of turbulence is dominated by the zonal flows and the streamers. Consequently, abrupt transport, ballistic propagation [3-5] or formation of stationary (long-lived) corrugations of plasma profiles occur [6, 7]. In this study, the fundamental processes which trigger these various turbulence behaviors is focused on by considering the nonlinear interaction between turbulence and larger scale structures theoretically.

Wave-kinetic theory is one of the theoretical frameworks to treat the interaction between the turbulence and the larger scale structures [2]. In this framework, the turbulence wave-packet is treated as a quasi-particle, and its distribution function in the phase space is considered, where the phase space consists of the wavenumber space and real space. Namely, the wavenumber spectrum of turbulence intensity which distributes in space is obtained by solving the wave-kinetic equation. The evolution equation for the turbulence distribution function has a same mathematical structure as the Boltzmann equation. Turbulent quasi-particles propagate at group velocities determined by the drift wave dispersion relation and are subject to eddy stretching effect due to the spatial inhomogeneous Doppler shifts caused by the macroscopic structures. A mechanism of the particle trapping by electrostatic potentials exists for the Boltzmann equation, and the typical vortex structure called BGK vortex exits in the phase space. Similarly, the turbulence trapping occurs for the wave-kinetics. In this study, the turbulence trapping in the phase space is focused on, and the resulting turbulence dynamics is discussed.

The interaction between the turbulence and the zonal flows is considered by performing the direct numerical simulation of the wave-kinetics. The zonal flows have the shear in the radial direction, so that the turbulence eddy suffers the stretching effect, and the turbulence trapping occurs. The turbulence trapping in the phase space corresponds to the phase locking of turbulence clump in the zonal flow. For the cases of the drift wave turbulence, the turbulence clump accumulates in the negative curvature (2nd radial derivatives) of the zonal flow, and the exclusion of turbulence occurs in the positive curvature region. Similar asymmetry of turbulence with respect to the sign of flow curvature can be seen in turbulence simulations e.g. [9]. In toroidal plasmas, there are two zonal flow branches; non-oscillation branch of stationary zonal flows (ZFs), and the oscillation branch of geodesic acoustic modes (GAMs). Based on the turbulence trapping, the turbulence behavior is very different in each state. For the ZFs case, the turbulence clump is spatially localized, because the ZFs does not propagate in space (left panel of Fig. 1). As a result, the stationary profile corrugation occurs [6]. On the other hand, for the case of the GAMs, which propagate radially, the ballistic propagation of turbulence is driven, like avalanches [5], as shown in the right panel of Fig. 1. In this way, the vortex formation in the phase space drastically affects the spatio-temporal dynamics of turbulence.

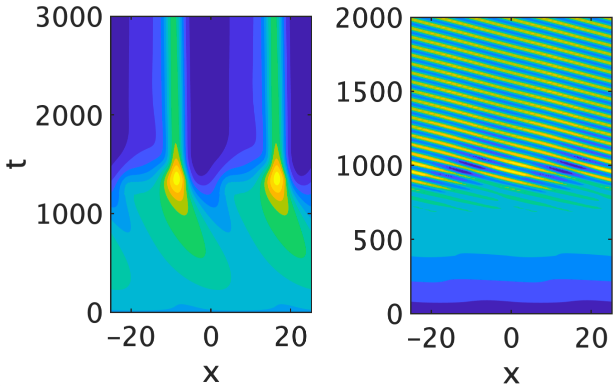

Fig.1: Spatio-temporal dynamics of turbulence intensity for cases of ZF (left) and GAM (right).

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