Wave kinetics of drift-wave turbulence and zonal flows beyond the ray approximation

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Inhomogeneous drift-wave turbulence can be modeled as an effective plasma where drift waves act as quantumlike particles and the zonal-flow velocity serves as a collective field through which they interact. This effective plasma can be described by a Wigner–Moyal equation (WME), which generalizes the quasilinear wave-kinetic equation (WKE) to the "full-wave" regime, i.e., resolves the wavelength scale [1]. Unlike waves governed by manifestly quantumlike equations, whose WMEs can be borrowed from quantum mechanics and are commonly known, drift waves have Hamiltonians very different from those of conventional quantum particles. This causes unusual phase-space dynamics that is typically not captured by the WKE. We demonstrate how to correctly model this dynamics with the WME instead [2]. Specifically, we report the first consistent phase-space simulations of the zonal-flow formation (zonostrophic instability), deterioration (tertiary instability), and the so-called predator–prey oscillations. We also show how the WME facilitates analysis of these phenomena, namely: (i) we show that full-wave effects critically affect the zonostrophic instability, particularly, its nonlinear stage and saturation; (ii) we derive the tertiary-instability growth rate; and (iii) we demonstrate that, with full-wave effects retained, the predator–prey oscillations do not require zonal-flow collisional damping, contrary to previous studies. We also show how the famous Rayleigh–Kuo criterion, which has been missing in wave-kinetic theories of drift-wave turbulence, emerges from the WME.

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