Zonal flows: from Hasegawa-Mima equation to gyrokinetic simulation

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Hasegawa-Mima equation [1] has been one of the most influential fluid models for describing turbulence in magnetized plasmas during the past five decades. This model predicts that the inverse cascade of turbulent spectral energy toward minimal wavenumbers nonlinearly generates zonal flows [2]. In turn, zonal flows suppress turbulent transport, leading to a self-organized state in the nonuniform plasmas [3].

Hasegawa's theory provides valuable physical insights into the complex microturbulence in toroidal fusion plasmas, where kinetic effects and magnetic geometry critically influence zonal flow dynamics. With the advent of high-performance computing, realistic global gyrokinetic simulation has clearly revealed how zonal flows are generated by — and suppress — ion temperature gradient (ITG) turbulence in a tokamak [4]. This massively parallel simulation has inspired intense experimental and theoretical research worldwide, investigating zonal flows as a key mechanism driving the transition to enhanced confinement regimes in tokamak plasmas. Since then, the self-regulation of turbulence by zonal flows has remained one of the most actively studied topics in fusion research and now serves as the foundation of modern plasma turbulence theory [5,6,7].

Subsequent gyrokinetic simulations have demonstrated that plasma self-organization by zonal flows is a universal phenomenon in magnetized plasmas, transcending specific physical processes and magnetic geometries. The physics of turbulence self-regulation by zonal flows has been extended beyond ITG instability to include other microinstabilities such as trapped electron mode and kinetic ballooning mode, as well as from tokamak to stellarator and field-reversed configuration. Recent gyrokinetic simulations have shown that zonal flows also regulate various meso-scale Alfvén eigenmodes excited by energetic particles [8], as well as macroscopic magnetohydrodynamic (MHD) modes like kink and fishbone instabilities [9]. Notably, zonal flows can facilitate cross-scale interactions that ultimately govern the confinement properties of both thermal plasmas and energetic particles in burning plasmas.

These continuing studies have deepened our understanding of zonal flow physics, aiding in the design and optimization of future fusion reactors. Nearly half a century after introducing the concept of zonal flows to the plasma physics community, Hasegawa's legacy continues to profoundly influence plasma physics and fusion energy science.

References:

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