§29. Zonal Flows in Plasma – A Review

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Zonal flows, by which we mean azimuthally symmetric band-like shear flows, are a ubiquitous phenomena in nature and the laboratory. The well-known examples of the Jovian belts and zones, and the terrestrial atmospheric jet stream are familiar to nearly everyone - the latter especially to travelers enduring long, bumpy airplane rides against strong head winds. Zonal flows are also present in the Venusian atmosphere (which rotates faster than the planet does!) and occur in the solar tachocline, where they play a role in the solar dynamo mechanism. In the laboratory, the importance of sheared $\boldsymbol{E}\times\boldsymbol{B}$ flows to the development of L-mode confinement, the L-to-H transition and internal transport barriers (ITBs) is now well and widely appreciated. It is now widely recognized and accepted that zonal flows are a key constituent in nearly all cases and regimes of drift wave turbulence - indeed, so much so that this classic problem is now frequently referred to as "drift wave-zonal flow turbulence". This paradigm shift occurred on account of the realization that zonal flows are ubiquitous in dynamical models used for describing fusion plasmas (i.e. ITG, TEM, ETG, resistive ballooning, and interchange, etc.) in all geometries and regimes (i.e. core, edge, etc.), and because of the realization that zonal flows are a critical agent of self-regulation for drift wave transport and turbulence.

A comprehensive review of zonal flow phenomena in plasmas is presented [1]. While the emphasis is on zonal flows in laboratory plasmas, planetary zonal flows are discussed as well. The review presents the status of theory, numerical simulation and experiments relevant to zonal flows. The emphasis is on developing an integrated understanding of the dynamics of drift wave - zonal flow turbulence by combining detailed studies of the generation of zonal flows by drift waves, the back-interaction of zonal flows on the drift waves, and the various feedback loops by which the system regulates and organizes itself. The implications of zonal flow phenomena for confinement in, and the phenomena of fusion devices are discussed. Special attention is given to the comparison of experiment with theory and to identifying directions for progress in future research.

The review explains the following issues:

1. Introduction
2. Basic Physics of Zonal Flows: A Heuristic Overview
    - 2.1 Introduction
    - 2.2 Basic dynamics of zonal flows
    - 2.3 Self-consistent solution and multiple states
    - 2.4 General comments
    - 2.5 Implications for experiments
3. Theory of zonal flows
    - 3.1 Linear Dynamics of Zonal Flow Modes
    - 3.2 Generation mechanism
    - 3.3 Shearing and back reaction of flows on turbulence
    - 3.4 Nonlinear Damping and Saturation: Low Collisionality Regimes
    - 3.5 The Drift Wave - Zonal Flow System: Self-consistent State
    - 3.6 Suppression of Turbulent Transport
4. Numerical Simulations of Zonal Flow Dynamics
    - 4.1 Introduction
    - 4.2 Ion Temperature Gradient Driven Turbulence
    - 4.3. Electron Temperature Gradient Driven Turbulence
    - 4.4. Fluid Simulations with Zonal Flows
    - 4.5 Edge turbulence
    - 4.6 Short summary of the correspondence between theoretical issues and numerical results
5. Zonal Flows in Planetary Atmospheres
    - 5.1 Waves on a rotating sphere.
    - 5.2 Zonal Belts of Jupiter
    - 5.3 Superrotation of the Venusian Atmosphere
6. Extensions of Theoretical Models
    - 6.1 Streamers
    - 6.2 Noise Effects and Probabilistic Formulations
    - 6.3 Statistical properties
    - 6.4 Non-Markovian Theory
    - 6.5 Envelope Formalism
7. Laboratory Experiments on Zonal Flow Physics
    - 7.1 Characteristics of Zonal Flows
    - 7.2. Zonal Flow Dynamics and Interaction with Ambient Turbulence
    - 7.3. Suggestions on future experiments and information needed from simulations and theory
8. Summary and Discussion

Acknowledgements
Appendix A Ray of Drift Wave Packet and Trapping
Appendix B Hierarchy of Nonlinear Governing Equations
Appendix C Near isomorphism between ETG and ITG

[1] P. H. Diamond., S.-I. Itoh, K. Itoh and T.S. Hahm, Plasma Phys. Control. Fusion, **47** No.3 (2005) R35; See also NIFS Report 805 (2004)