Zonally dominated dynamics and the transition to strong turbulence in ion-scale plasma turbulence

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We present a study of the low-transport Dimits state [1] and the transition to a high-transport saturated state in plasma turbulence driven by the ion-temperature-gradient instability. Our focus is on a fluid model derived in the cold-ion, long-wavelength asymptotic limit of the ion gyrokinetic equation in a magnetic field with constant curvature and in the presence of an equilibrium temperature gradient. Numerical simulations reveal that the Dimits state is dominated by a quasi-static staircase-like structure of the temperature gradient intertwined with zonal flows, reminiscent of the so-called '$E \times B$ staircase' [2]. It suppresses turbulence in two complementary ways: first, by shearing turbulent eddies in regions of strong zonal shear, and, secondly, by flattening the background temperature gradient at the turning points of the zonal flow. The breakup of the low-transport Dimits regime is linked to the competition between the two different sources of poloidal momentum in the system — the Reynolds stress and the advection of the diamagnetic flow by the $E \times B$ flow. The former acts to support the staircase by providing a net negative turbulent viscosity for the zonal flows and is opposed by the latter. When the Reynolds stress dominates, the system enters the Dimits regime which is characterised by the aforementioned zonal staircase. Otherwise, if the diamagnetic stress prevails, strong turbulence-suppressing zonal flows cannot be maintained and turbulence reigns supreme. We show that the transition from low to high transport can be understood by analysing the linearly unstable ion-temperature-gradient modes. This is demonstrated by a semi-analytic model for the Dimits threshold in 2D. In 3D, unless the system is restricted in the magnetic-field direction, a Dimits state arises for all values of the equilibrium parameters. This is explained by the existence of a 'parasitic' small-scale slab-ITG instability that is driven by the gradients of large-scale perturbations. These parasitic modes enhance the Reynold stress and thus extend the Dimits state to larger temperature gradients. In the strongly turbulent regime, they provide an effective thermal diffusion at large scales and act to move energy from large scales to small viscous scales where dissipation takes place, thus providing a mechanism for saturation.

References

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