Beyond scale separation in gyrokinetic turbulence

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Motivation

- Semi-lagrangian GYSELA code:
  - fixed grid, follows trajectories backwards,
  - global, full F code,
  - keeps // non linearity.
- Alternative to eulerian and PIC codes.
- Appropriate for situations where:
  - scale separation assumption is questionable.
  - the distribution function departs from a Maxwellian.
Outline

• Flux driven turbulence and intermittency.
• Fluid vs kinetic descriptions:
  - fluid closures,
  - the water bag representation.
• Effect of large scale flows on turbulence:
  - transport barriers produced with peaked density profiles,
  - impact of initial distribution function on gyrokinetic simulations.
Flux driven kinetic interchange turbulence

- 3D kinetic interchange

\[ \partial_t F + [\phi, F] + \nu_d E \partial_y F = S(E) \]
\[ \phi - \langle \phi \rangle - \nabla^2 \phi = \int_0^{+\infty} dE F - 1 \]

- Intermittency due to interplay between zonal flows, fluctuations and temperature.

- \( F \) is not Maxwellian.
Large differences between fluid and kinetic fluxes

- 2D fluid interchange

\[
\partial_t N + [\phi, N] + v_d \partial_y P = 0
\]
\[
\partial_t P + [\phi, P] + v_d \partial_y Q = 0
\]

\[
Q = \int_0^{+\infty} dE E^2 F
\]

- Closure $Q(T, P)$ is diffusive.

- Differences not only due to zonal flows: $F$ departs significantly from a Maxwellian.
An alternative to conventional fluid closures: the water bag representation

- 4D ITG turbulence in a cylinder:
\[
\partial_t F + [\phi, F] + v_{\parallel} \nabla_{\parallel} F - \nabla_{\parallel} \phi \partial_{v_{\parallel}} F = 0 + \text{Poisson eq.}
\]

- Multi-step distribution function.
- Reproduces linear stability with a limited number of bags.
Transport barriers with peaked density profiles

- GYSELA simulations of slab ITG modes
- Transport barrier appears for a peaked density profile.
- Zonal flows are mainly responsible for the barrier formation.
Full F simulations of toroidal ITG turbulence

- Conventional 5D gyrokinetic equations

\[ \partial_t F + \mathbf{v}_E \cdot \nabla F + \mathbf{v}_g \cdot \nabla F + v_{\parallel} \nabla_{\parallel} F + \dot{v}_{\parallel} \partial_{v_{\parallel}} F = 0 \]

+ Poisson eq.

- Tested on Cyclone base case: linear stability correctly reproduced.

- Flows behave as expected (Rosenbluth-Hinton).
Standard ITG turbulence without flows

- Without zonal flows: standard ITG turbulence
- Numerics
  - resolution: \((r, \theta, \phi, v_\parallel, \mu)\) = (256, 256, 16, 32, 8)
  - \(\rho_* = 0.005, \Omega_c \Delta t = 5\)
  - CPU time: 21hrs on 64 processors.
Turbulence quench due to large scale flows

- With zonal flows: turbulence is quenched.
- Due to initial $F_M(r,E)$: no parallel flow to balance the vertical drift.
An initial canonical distribution function avoids the onset of unphysical large scale ExB flows

- Remedy: initial $F(P_\phi, E)$ Idomura '03, Angelino '05
- Crucial for full F simulations.
Conclusions

• Semi-lagrangian scheme is reliable.
• Full F kinetic effects:
  - flux driven kinetic turbulence is intermittent.
  - difference between kinetic and fluid simulations due to zonal flows and non Maxwellian F.
  - water bag models offer an alternative.
• Effect of large scale flows:
  - transport barriers with large $\nabla n$ due to zonal flows
  - important to start with canonical F to avoid charge imbalance and large scale shear flows.