Nonlinear entropy transfer of ETG turbulence via TEM driven zonal flow

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Abstract

A nonlinear interplay of the electron temperature gradient (ETG) mode and the trapped electron mode (TEM) is investigated by means of gyrokinetic simulation. It is found that the ETG turbulence can be suppressed by zonal flows driven by TEMs. The suppression process is quantitatively examined by the nonlinear entropy transfer analysis. In the statistically steady state where the TEM-driven zonal flows are dominant, the zonal flows induce the successive entropy transfer from ETG modes with low radial wavenumbers to those with high radial wavenumbers. The process is similar to the successive entropy transfer found in the ITG turbulence under the influence of ITG-driven zonal flows.

1. Introduction

Electron heat transport is important in a future fusion reactor where electrons absorb a large fraction of energy carried by fast alpha particles. In order to understand the mechanism of electron heat transport, a large number of gyrokinetic simulations have been carried out and have revealed the electron heat transport is a kind of multi-scale phenomenon [1]. Especially, the electron temperature gradient (ETG) turbulence has received much attention due to its potentially large contribution to electron heat transport.

Conventional gyrokinetic simulation for the ETG turbulence often employed a so-called adiabatic ion model where a significant electron heat transport is observed for strong magnetic shear cases with $\hat{s} > 0.4$. However, the recent ETG simulation employing gyrokinetic ions is reported to give a much lower transport level than the adiabatic ion cases [2]. Although a mechanism for the reduced transpsort in the kinetic ion case has not been clarified yet, it is conjectured that long-wavelength modes including trapped electron modes (TEMs) and long-wavelength ETG modes may play a leading role in the reduction of the ETG turbulence transport.

In this work, we use the GKV+ code [3] to investigate the effects of TEMs on ETG turbulence, focusing on the dynamics of TEM-driven zonal flows. For comprehensive understanding of the nonlinear interaction between the ETG turbulence and TEM-driven zonal flow, we analyze the nonlinear entropy transfer process in-between them. Nonlinear entropy transfer analysis gives the intensity of a nonlinear entropy transfer in the Fourier mode space and quantitatively shows the role of TEM-driven zonal flow in the regulation of ETG turbulence.

2. Numerical settings

Here, we briefly introduce the GKV+ code and numerical settings. The GKV+ code [3] is the continuum δf gyrokinetic simulation code, which is extended from the original GKV code to include kinetic electrons, multi-species ions and electromagnetic effects. The code employs the flux tube geometry. Since we consider the low-beta plasma, the dynamics is fully electrostatic.

Physical parameters used in this research are the Cyclon base case parameters [4] except for the increased density gradient $R_0/L_n = 3.46$ and the weaker magnetic shear $\hat{s} = 0.4$. The parameters are as follows: $m_\mathrm{i}/m_\mathrm{e} = 1836$, $R_0/L_n = 3.46$, $R_0/L_{T_\mathrm{e}} = 6.92$, $R_0/L_{T_\mathrm{i}} = 0$, $\nu_\mathrm{e} L_n/v_\mathrm{te} = 0.001$, $\nu_\mathrm{i} L_n/v_\mathrm{ti} = 0.001$, $\varepsilon = 0.18$, $\hat{s} = 0.4$, $q = 1.4$, $T_\mathrm{e}/T_\mathrm{i} = 1$, where R_0 is the major radius, L_n is the characteristic length of density gradient, L_{T_s} is the characteristic length of temperature gradient, ν_s is the collision frequency, $v_{\mathrm{t}s}$ is the thermal velocity, $\varepsilon = a/R_0$ is the inverse aspect ratio, q is the safety factor, and T_s is the temperature of each species. The subscripts s denotes each plasma species, where $s = \mathrm{i(e)}$ means ions (electrons). In the present simulations, we employ the perpendicular domain size as $L_x \times L_y = 142\rho_\mathrm{te} \times 89\rho_\mathrm{te}\,(= 3.5\rho_\mathrm{ti} \times 2.2\rho_\mathrm{ti})$, with the Larmor radius $\rho_{\mathrm{t}s}$. The x direction corresponds to the radial direction and the y direction corresponds to the poloidal direction. The time step size is set as $\Delta t = 0.025(L_n/v_\mathrm{te})$ for each simulation. The detailed settings are found in [5].

We employ the so-called adiabatic ion model for the pure ETG turbulence simulation and the kinetic ion model for the ETG-TEM turbulence simulation. The adiabatic ion model is adequate to describe the linear dynamics of ETG mode but inadequate to describe the linear dynamics of TEM. The kinetic ion model includes both linear dynamics of ETG mode and TEM. Through the comparison of these two models, we examine the effects of TEMs on ETG turbulence.

3. Simulation results

We show the nonlinear simulation results of the ETG turbulence and ETG-TEM turbulence. Figure 1 (a) shows the time evolution of electron heat transport coefficient for adiabatic ion (blue line) and kinetic ion (red line) cases. It is found that the linear phase before $t = 100\,(L_n/v_\mathrm{te})$ is almost the same for both cases where the linear dynamics of ETG modes is dominant. The transport reduction at around $t = 1050\,(L_n/v_\mathrm{te})$ is found in the kinetic ion case, but not in the adiabatic ion case. Finally, a statistically steady state is achieved, where the low transport level is found in the kinetic ion case. The lower transport level in the kinetic ion case can be explained by the stronger zonal flow generation after $t = 1050\,(L_n/v_\mathrm{te})$ as shown in Fig. 1 (b).

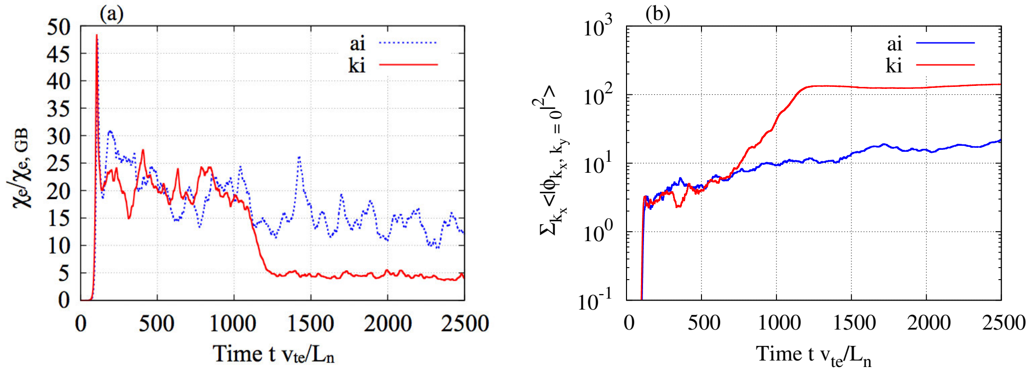

Figure 1: The time evolution of (a) the electron heat transport coefficient and (b) the zonal flow amplitude. The blue (red) line represents the adiabatic (kinetic) ion model.

4. Entropy transfer analysis

The interactions between zonal flows and ETG turbulence is quantitatively investigated by evaluating the triad entropy transfer function in the wavenumber space. The entropy transfer analysis [6] shows the structure of triad entropy transfer function in the wavenumber space which represents the intensity of nonlinear cooling between three different modes. The triad entropy transfer function $\mathscr{J}_s[\mathrm{k}_\perp|\mathrm{p}_\perp,\mathrm{q}_\perp]$ appears in the entropy transfer term $\mathscr{T}_{s\mathrm{k}_\perp}$ of the entropy balance equation (see for example Ref [6]) defined by

$$\mathscr{T}_{s\mathrm{k}_\perp} = \sum_{\mathrm{p}_\perp}\sum_{\mathrm{q}_\perp} \mathscr{J}_s[\mathrm{k}_\perp|\mathrm{p}_\perp,\mathrm{q}_\perp], \tag{1}$$

$$\mathscr{J}_s[\mathrm{k}_\perp|\mathrm{p}_\perp,\mathrm{q}_\perp] \equiv \delta_{\mathrm{k}_\perp+\mathrm{p}_\perp+\mathrm{q}_\perp,0}\left\langle \frac{c}{B_0}\mathrm{b}\cdot(\mathrm{p}_\perp\times\mathrm{q}_\perp)\int dv\frac{1}{2F_{Ms}}\mathrm{Re}\left[\delta\psi_{\mathrm{p}_\perp}h_{s\mathrm{q}_\perp}h_{s\mathrm{k}_\perp} - \delta\psi_{\mathrm{q}_\perp}h_{s\mathrm{p}_\perp}h_{s\mathrm{k}_\perp}\right]\right\rangle, \tag{2}$$

where b, B_0, c, $\delta\psi_{\mathrm{k}_\perp}$ and $h_{s\mathrm{k}_\perp}$ are the unit vector parallel to the magnetic field, the magnetic field strength, the speed of light, the electrostatic potential fluctuation averaged over the gyrophase and the non-adiabatic part of the perturbed distribution function, respectively. The equilibrium distribution function is assumed as the Maxwellian F_{Ms}. Here, $\mathrm{k}_\perp$, $\mathrm{p}_\perp$ and $\mathrm{q}_\perp$ represent the wavenumber vectors of three different modes in the perpendicular plain to the magnetic field line. We examine the role of TEM-driven zonal flow in the steady state of the ETG-TEM turbulence by means of the nonlinear entropy transfer analysis described above.

The successive entropy transfer process of the dominant ETG mode with $\mathrm{p}_\perp = (0, 0.21)$ in the steady state of the ETG-TEM turbulence is summarized in Fig. 2. Figure 2 (a) shows the element of the diagram which represents the relationships between the three different modes $\mathrm{k}_\perp$, $\mathrm{p}_\perp$ and $\mathrm{q}_\perp$. The arrows represents the signs of $\mathscr{J}_e[\mathrm{k}_\perp|\mathrm{p}_\perp,\mathrm{q}_\perp]$, $\mathscr{J}_e[\mathrm{p}_\perp|\mathrm{q}_\perp,\mathrm{k}_\perp]$ and $\mathscr{J}_e[\mathrm{q}_\perp|\mathrm{k}_\perp,\mathrm{p}_\perp]$, respectively, where $\mathscr{J}_e[\mathrm{k}_\perp|\mathrm{p}_\perp,\mathrm{q}_\perp] > 0$, $\mathscr{J}_e[\mathrm{p}_\perp|\mathrm{q}_\perp,\mathrm{k}_\perp] < 0$ and $\mathscr{J}_e[\mathrm{q}_\perp|\mathrm{k}_\perp,\mathrm{p}_\perp] < 0$ in Fig. 2 (a). Figure 2 (b) shows the diagram for the entropy transfer process in the steady state of ETG-TEM turbulence, where the time-average is taken from $t = 2300\,(L_n/v_{\mathrm{te}})$ to $t = 2500\,(L_n/v_{\mathrm{te}})$.

As shown in Fig. 2 (b), the ETG mode $\mathrm{p}_\perp = (0.044, 0.21)$ receives the entropy from the dominant ETG mode $\mathrm{p}_\perp = (0, 0.21)$ with the value of 0.27×10^{-3} and from the zonal mode $\mathrm{k}_\perp = (0.044, 0)$ with the value of 0.2×10^{-3}. Then, the ETG mode $\mathrm{p}_\perp = (0.044, 0.21)$ transfers the entropy to the mode with $\mathrm{p}_\perp = (-0.088, -0.21)$ via the zonal mode $\mathrm{k}_\perp = (0.044, 0)$. Starting from the dominant ETG mode with $\mathrm{p}_\perp = (0, 0.21)$, the entropy is successively transferred from the low to high radial wavenumber mode. This process is similar to the successive entropy transfer found in the ITG turbulence under the influence of ITG-driven zonal flows [6].

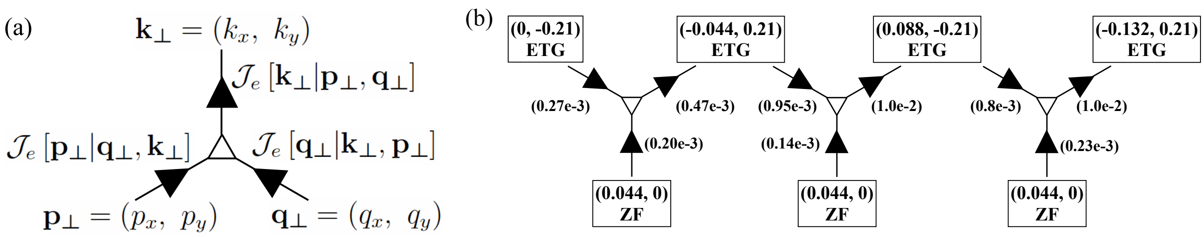

Figure 2: Diagram for the nonlinear entropy transfer in the perpendicular wavenumber space: (a) an element of the diagram representing the relationships between the three different modes $\mathrm{k}_\perp$, $\mathrm{p}_\perp$ and $\mathrm{q}_\perp$, (b) the diagram of the entropy transfer of the ETG modes under the TEM-driven zonal flow. The successive entropy transfer from the ETG mode with low k_x to high k_x is shown.

5. Conclusion

The entropy transfer analysis was applied to the gyrokinetic simulation results of the ETG turbulence and ETG-TEM turbulence. In the steady-state, it is found that the zonal flow driven by TEM induce the successive entropy transfer from ETG modes with low radial wavenumbers to those with high radial wavenumbers. This process is similar to the successive entropy transfer found in the ITG turbulence under the influence of ITG-driven zonal flows.

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