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Avalanche-like heat transport events related to microscopic turbulent vortex dynamics

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In global gyrokinetic simulations of ion temperature gradient (ITG) driven turbulence in magnetically confined fusion plasmas, avalanche-like heat transport events have been observed, where regions of intense ion heat flux propagate in the radial direction of a torus [1]. The avalanche-like events, exhibiting mesoscale propagation and intermittent bursts, have attracted significant attention due to their potential impact on the formation and collapse of transport barriers. The avalanche-like events are believed to result from relaxation of background pressure gradients due to turbulent transport. On the other hand, it is known that the timescale of avalanche-like events differs by orders of magnitude from the relaxation time of the background profile. Moreover, similar avalanche-like events have also been observed in local flux-tube gyrokinetic simulations with fixed background density and temperature gradients [2]. The conventional global picture of the mechanism of avalanche-like events should be reconciled with these observations.

This study aims to characterize the spatiotemporal properties of avalanche-like heat transport events, by analyzing the results of local flux-tube simulations from the perspective of microscopic fluctuations and turbulent vortex structures.

As shown in Fig. 1, avalanche-like events are observed in our flux-tube gyrokinetic simulations of the ITG turbulence using the GKV code [3]. These simulations have confirmed a correlation between the propagation direction of avalanche-like events and the sign of the zonal flow shear, represented by the radial derivative of the radial electric field dE_r/dr, in agreement with the previous studies [1, 2]. We have also identified a novel correlation involving the sign of the mean radial wavenumber k_x of turbulence fluctuations: in regions where avalanche-like events propagate outward (inward), the positive (negative) k_x component of turbulent vorticity is dominant. The correlations are summarized in Fig. 2, which shows that the propagation direction is determined by the tilt of turbulent vortices deformed by zonal flows.

It has also been found that avalanche-like events consist of spatially localized heat fluxes that propagate together with microscopic vortex pairs. Due to this spatial localization, the propagation velocity is approximated by the group velocity of plane waves. In fact, the group velocity obtained from a linear ITG simulation using the GKV code is approximately $2.0\, v_{ti}\rho_{ti}/R_0$, which is comparable to the propagation speed of avalanche-like events estimated from Fig. 1, that is $2.7\, v_{ti}\rho_{ti}/R_0$. The positive and negative group velocities correspond to the outward and inward propagation, respectively, which is consistent with the schematic illustration shown in Fig. 2.

The present study has unveiled a new physics mechanism of avalanche-like heat transport events in flux-tube simulations, in which microscopic turbulent vortex dynamics play a leading role through interaction with zonal flows.

References
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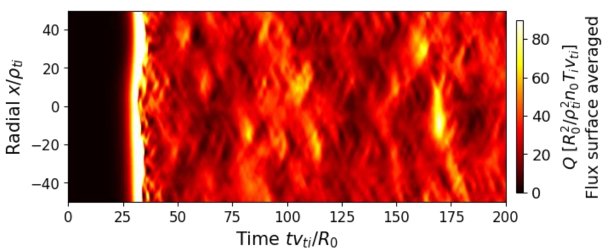

Fig. 1: Spatiotemporal structure of ion heat flux averaged over a magnetic flux surface. Avalanche-like events propagating outward and inward are identified as upward- and downward-sloping structures, respectively.

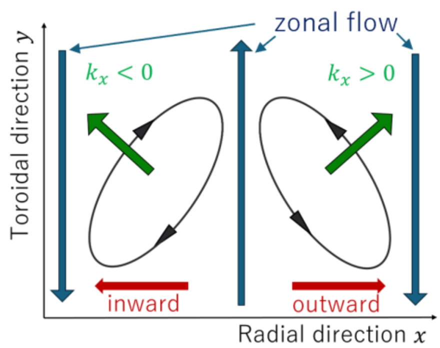

Fig. 2: Schematic illustration of the correlation among the propagation direction of avalanche-like events, the zonal flow shear, and the radial wavenumber component of turbulent vortices. Blue allows indicate the direction of zonal flows.