Mechanisms responsible for the emergence of non-diffusive transport features across zonal flows in ITG gyro-kinetic simulations

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It is widely accepted that the rate at which particles, energy or any passive quantity are transported by turbulence can be significantly lowered in the presence of a perpendicular stable sheared flow. This is a situation of particularly relevance in tokamak plasmas, in which both externally-driven mean poloidal flows and self-consistently generated (by turbulence) poloidal mean and fluctuating flows seem to be central to the formation of radial transport barriers. The reduction of turbulent fluxes along the direction perpendicular to the flow is ultimately related to the fact that the flow can somehow either reduce the amplitude of the fluctuations of the advecting and/or advected fields, or alter the cross-phase between them (or both) [1]. The way in which the flow achieves this suppression is still not well understood. However, it is customary to quantify it in practice by invoking reduced perpendicular diffusivities/conductivities. Recently [2,3], we tested the latter hypothesis and found that it fails to capture correctly the dynamics of transport across sheared flows. We found that transport across sheared radial flows exhibits a strong sub-diffusive character well beyond the turbulent decorrelation timescales [2]. In addition, we found that the way in which the zonal flow interplays with turbulence also seems to affect the transport dynamics. If the flow is self-consistently driven by turbulence, the statistics became non-Gaussian (i.e., Levy-like). However, when the flow is imposed only externally and all self-consistent interaction with the turbulence is suppressed, the statistics remain Gaussian. These observations suggest the conjecture that the mean component of flow is the one setting the subdiffusive features, whilst the fluctuating component might be responsible for the non-Gaussian statistics [3].

In this contribution we take a more careful look at the physical mechanisms lying behind these observations to try to confirm or disprove these conjectures. To that extent we have carried a more complete set of simulations of electrostatic ITG turbulence in toroidal geometry with the global, δf-gyrokinetic PIC code UCAN [4]. UCAN can easily include externally-driven, time-independent mean flows by adding an external electric potential. Physical parameters used in the runs are $a=0.56$ m, $R_0=2.5$ m, $B_0=1.87$ T, $n_0=3.1x10^{19}$ m^{-3}, $T_e=T_i=0.7$ KeV. These values have been used in the past to simulate discharges of the DIII-D tokamak. The radial resolution used is such that ~ 200 ion Larmor radii are included; the temporal resolution is 0.15 μs, much smaller than the local decorrelation time (3-10 μs).

The diagnosis of the nature of transport is done as follows [2,3]. Since UCAN is a PIC code that pushes kinetic ions along their gyro-averaged orbits, we use these orbits to compute the ion radial propagator: $P(r, t \mid r_0, t_0)$. This propagator represents the probability of finding one ion at some radius r and time t, if it was located at some another radius r_0 at a time $t_0 \leq t$. Its shape is used here to diagnose the nature of radial transport in the presence of sheared poloidal mean flows [2,3]. If motion is diffusive, the propagator should be a Gaussian law with variance growing as $\sigma^2 \sim t$. If the statistics are non-Gaussian, the propagator will exhibit a Levy-like form. And, if transport is sub- or super-diffusive, the scaling of the variance will be $\sim t^{2H}$, with H <1/2 or H > 1/2, respectively. The determination of the propagator is done using those ions initially confined in a very narrow radial region, and starting at a time deep into the non-linearly saturated phase of simulations. Various ion temperature, density and externally-driven sheared flows profiles have been used for the runs.

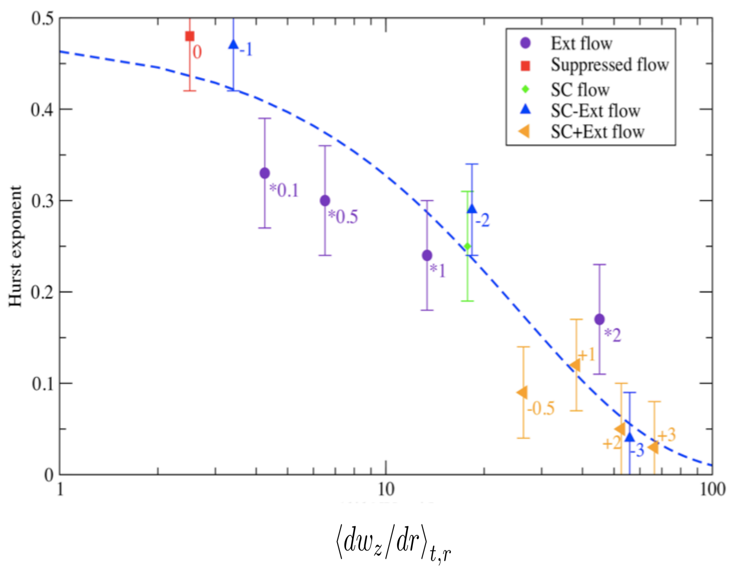

Fig 1.- Transport exponent from various UCAN runs as a function of the derivative of the axial vorticity.

The first hypothesis tested is whether the subdiffusive nature of transport is set by the mean component of the zonal flow. As conjectured in Ref. 3, the absolute value of the radial shear of the poloidal angular velocity would be the key quantity, which is related to the radial derivative of the axial vorticity in toroidal geometry. Fig. 1 shows the values of the exponent H obtained from many simulations over radial regions with a well-defined shear. Clearly, the hypothesis is confirmed, since the value of H depends very weakly on the nature of the flow. If one starts from the self-consistent run with no external flow (which has H ~ 0.26), and superimposes an externally-driven mean flow with a spatial profile similar to the temporal-average (over the nonlinearly saturated phase) of the poloidal flow from the self-consistent run, H becomes basically diffusive (i.e, H~0.5) as it should, since (almost) no net mean flow survives. If one doubles the externally-driven flow, the value of H becomes again close to the self-consistent case (H ~ 0.29), showing that it is the profile and strength of the shear (not the sigh) what matters to set H, not the nature of the flow. Similar combinations can be imagined using the results collected in Fig. 1, all of them consistent with the hypothesis that the degree of subdiffusion is set mostly by the shear in the mean component of the poloidal flow. A note of caution must be made at this point: the analysis is only meaningful if transport is quantified in a spatial region where the value of this shear is more or less uniform. Otherwise, one would average over regions with different behaviours, and the connection easily masked or distorted.

The second question to explore is the origin of the non-Gaussian features observed for the cases in which flows and fluctuations are allowed to interact via the Reynolds stress. Non-Gaussian statistics have been associated in the past to the occurrence of avalanches, but usually due to the radial propagation of profile relaxations of some sort in near-marginal turbulence [4]. Our simulations are all well above marginality, which suggests that if avalanches are present, they must have a very different character. It turns out that avalanches are present only when the self-consistent interaction between fluctuations and flows is allowed, as conjectured. Examples are shown in Fig. 2, where radial-time plots of the surface-average of the fluctuations of several quantities over the mean-level of fluctuations are shown for a run in which the aforementioned self-consistent interplay is allowed. The first two panels on the left show the time evolution of fluctuations over the mean-level of the heat flux and potential fluctuations. Naturally, both of them are correlated strongly. Avalanches are very clearly seen propagating in the radial direction. The next panel shows the fluctuations over the mean-level of fluctuations of the magnitude of the shear in the poloidal rotation.

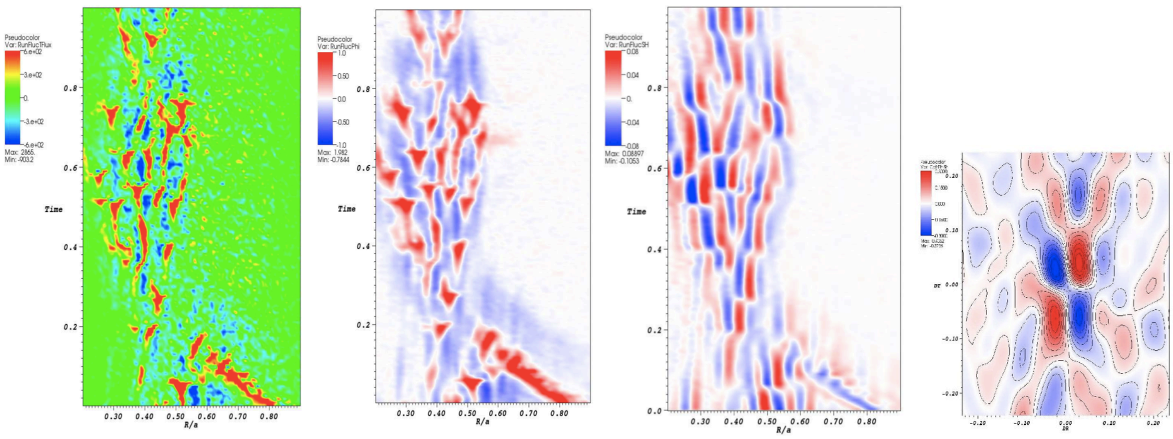

Fig 2.- R-T contours of surface-averaged fluctuations over mean fluctuation levels for <u>the self-consistent case</u>. From left to right: heat flux, potential fluctuations and magnitude of shear of the poloidal rotation. Right: coherence between potential fluctuations and magnitude of shear of the poloidal rotation.

Here, the same avalanches are present and strongly correlated with those of the other two, as shown in the last panel on the right. This last panel shows that the coherence between those two is such that appears consistent with a predator-prey type of interaction. More importantly, these avalanche-like dynamics is absent when the self-consistent interaction is suppressed, as shown in Fig. 3. Thus, the interplay between shear and fluctuations is essential for the lack of non-Gaussianity, which allows us to attribute its presence to the fluctuating flows.

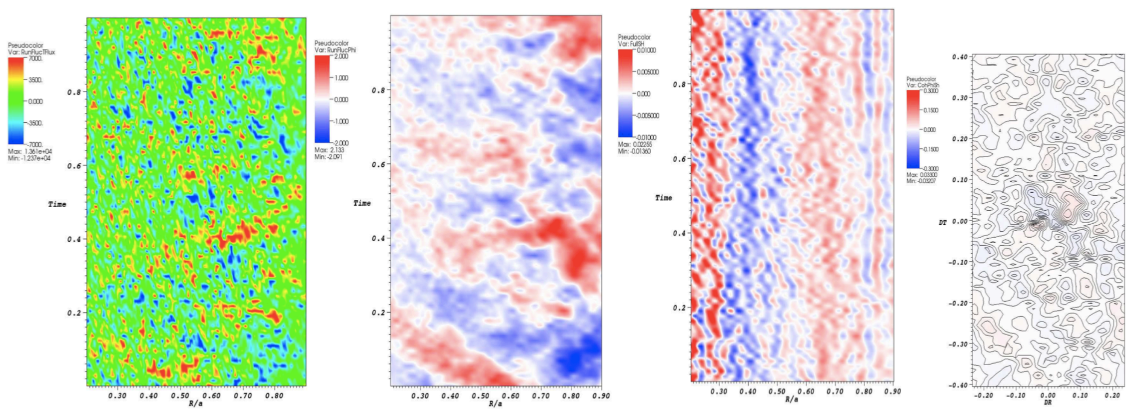

Fig 3.- R-T contours of surface-averaged fluctuations over mean fluctuation levels for the case where <u>interactions between fluctuations and flow are suppressed</u>. From left to right: heat flux, potential fluctuations and magnitude of shear of the poloidal rotation. Right: coherence between potential fluctuations and magnitude of shear of the poloidal rotation.

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