The complex dynamics of turbulent plasmas of interest for fusion energy

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In nature there are many systems that exhibit some form of self-organization from which a priori unexpected structures and dynamical behaviors emerge. These behaviours are unexpected specially when examined in the light of the physical mechanisms that govern each of the individual elements that form the system. Several common ingredients seem to be needed for complex dynamics to emerge: strong nonlinear interactions between many independent elements or degrees of freedom, the presence of instability thresholds, fluctuations and external drives for the system. Examples of complex behaviours can be found in systems like sandpiles[1], solar flares[2], earthquakes, magnetic substorms[3] and even aspects of economics and society itself.

Magnetically confined toroidal plasmas of interest for the production of fusion energy and its conversion into electricity may also exhibit self-organized behavior. Although the underlying equations governing these plasmas are apparently simple, their behavior can be extraordinarily varied and subtle as a result of their extreme susceptibility to the presence of electric and magnetic fields. Complexity in these toroidal plasmas is manifested via the spontaneous formation of interesting spatial structures and complex dynamical behaviors that span a wide range of length and time scales.

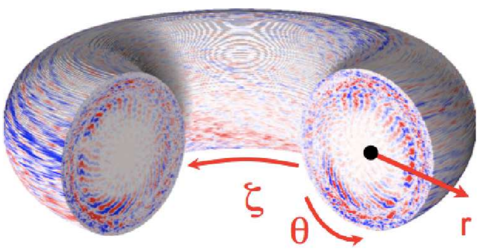

FIG. 1. Gyrokinetic simulation from the UCAN code showing the formation of a strong poloidal zonal flow via the Reynolds stresses in a toroidal plasma and its concomittant action on the radial turbulent structures.

The excitation of poloidal zonal flows by the plasma turbulence via the Reynolds stresses, and the way in which these poloidal zonal flows may control and reduce the leakage of energy and particles out of the toroidal magnetic traps that contain them is one such example (see Fig. 1). In fact, it can be shown that transport across these flows is not only reduced, but its nature suffers a dramatic change in which non-Gaussian, subdiffusive features become important[4]. This has particularly important practical consequences, specially in the era of the next-step $20-billion ITER tokamak experiment actually in construction in the south of France, due to the reliance on strong edge poloidal zonal flows in the standard regime of functioning of this device.

Another regime in which the dynamics of energy confinement in these plasmas is strongly complex is in near-marginal turbulent conditions. By near-marginal, we mean that the local values of temperature and pressure radial gradients wander around their threshold value for the excitation of instabilities. Near-marginality then allows for the formation of strong temporal and spatial correlations imprinted on the plasma profiles that result in strong super-diffusive transport with fat-tailed statistics for the energy distribution of transport events[5,6]. This near-marginal regimes may be of great practical importance in ITER, since turbulence-induced heat fluxes scale with a cubic power of the plasma temperature, what will facilitate the relaxation of unstable profiles below their marginal values quiet rapidly. Thus, understanding the impact of intermittent, superdiffusive transport that will dump its energy on the first wall and divertor parts of tokamaks is quite essential.

In this contribution, the dynamics of these regimes are reviewed and illustrated with the help of experimental results, numerical simulations and theoretical calculations. Some light will be shed on identifying the physical mechanisms that set them in motion. The way in which tools and ideas imported from the so-called 'science of complexity' have helped (and will continue helping) to understand the underlying physics and to thrust the further development of these prototype fusion reactors will also be described in detail. Finally, we will discuss the current efforts towards finding effective mean transport models and equations capable of incorporating these complex dynamics, which require the use of fractional differential operators.

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[1] P. Bak et al, Phys. Rev. Lett. 59, 381 (1987).
[2] E. Lu, R. Hamilton, Astrophys. Journal 380, L89 (1991).
[3] A.J. Klimas et al, J. Geophys. Res. 105, A8 (2000).
[4] R. Sanchez, et al., Phys. Rev. Lett. 101, 205002 (2008).
[5] B.A. Carreras et al, Phys. Plasmas 3, 2903 (1996).
[6] J.A. Mier, et al., Phys. Rev. lett. 101, 165001 (2008).