Turbulent transport in magnetized plasmas

F. Jenko

MPI für Plasmaphysik, Boltzmannstr. 2, D-85748 Garching, Germany

Abstract

This is a brief introduction to the area of plasma turbulence from a theoretical perspective. Hopefully, it stimulates some cross-disciplinary exchanges and collaborations.

Introduction

As is widely known, turbulent flows play a central role in magnetic confinement fusion (MCF) research. Turbulence, known for its high transport rates, causes the magnetic device to 'leak'. While in the absence of turbulence, it would be possible to create a burning (i.e., self-sustaining) plasma in a table-top device, real MCF experiments tend to have linear extensions of the order of 5-10 m. While this 'brute-force' solution (building bigger and thus more expensive experiments) to the turbulence problem works, there is a significant amount of work being done to characterize, understand, and control plasma turbulence. Encouraging results in this respect were obtained in the mid 1990s, when it became possible to create so-called 'internal transport barriers' in which the turbulent diffusivities are suppressed by up to an order of magnitude over radially extended regions. This discovery showed that turbulence control is indeed possible. The present contribution is meant as a brief introduction to the area of plasma turbulence from a theoretical perspective.

Plasma turbulence versus fluid turbulence

The classic example of a turbulent system is that of a neutral fluid at high Reynolds number. Its theoretical description is based on the Navier-Stokes equation, and many of its basic features can be described in the framework of Kolmogorov's scaling theory. Since many readers will be familiar with this kind of turbulent dynamics, it might be useful to introduce plasma turbulence by stressing the similarities and differences with respect to fluid turbulence.

First, turbulence in magnetized plasmas is quasi-two-dimensional. The strong background magnetic field leads to a strong anisotropy in the plasma particles' motion. While they are able to move more or less freely (up to magnetic mirror effects) along the magnetic field lines, the cross-field motion is restricted to slow drifts of the gyrocenters. This is reflected in the fact that the correlation lengths of the turbulent fluctuations are, respectively, of the order of 10 m and 1 cm. One may thus consider the turbulent dynamics to occur in planes perpendicular to the background magnetic field which are then coupled by the parallel motion. Interestingly, the simplest theoretical description of plasma turbulence, which is based on the two-dimensional model by Hasegawa and Mima [1], is isomorphic to the Charney equation in geophysics. This fact leads to close links between those two areas of research. Moreover, the Hasegawa-Mima-Charney equation is similar to the two-dimensional Navier-Stokes equation. This allows for many useful comparisons between these two systems.

Second, plasma turbulence is not universal. While in fluid turbulence, one is usually interested in the small spatial scales characterizing the inertial range which exhibit universal behavior, plasma turbulence is subject to a variety of drive and saturation mechanisms on different spatio-temporal scales. This means that often, an inertial range (in the strict sense of the word) does not exist. It is common to name the type of turbulence for a given set of plasma parameters after its dominant drive mechanism, i.e., after a certain microinstability caused by radial gradients in the background density, electron temperature and/or ion temperature. Under typical circumstances, the turbulent transport in a plasma is dominated by the 'drive range' scales, and simulations of the large-eddy type may be performed, keeping the inertial range rather small and neglecting backscatter effects which tend to complicate respective investigations in fluid systems.

Third, plasma turbulence may be studied within a number of frameworks, ranging from simple fluid models to fully kinetic ones, and from simple 2D geometries to complicated 3D ones. So while there is little doubt that ab initio simulations are to be based on the so-called gyrokinetic equation (here, the fast gyrophase dependence has been removed analytically) in full toroidal geometry, it turns out to be useful to also study reduced systems. The latter allow for the identification of basic physical processes in systems that are easier to understand. On the other hand, the more complicated models are necessary to avoid artefacts from over-simplifications, and they also allow for direct comparisons with experimental results. Thus such a multi-level approach is very helpful.

Some special aspects of plasma turbulence: Structure formation, multi-scale dynamics, and particle statistics

One of the most fascinating aspects of plasma turbulence research is the tendency of the turbulent system to form spatial and spatio-temporal structures. As has been discovered a few years ago, the dominant eddies are sometimes strongly elongated in the radial (background gradient) direction.[2] These structures were named 'streamers', and their importance lies in the fact that the associated turbulent transport can exceed basic mixing-length type estimates by more than one order of magnitude. On the other hand, plasma turbulence is also often characterized by strong shear flows whose potential (stream function) depends solely on the radial coordinate.[3] These 'zonal flows' are also observed in a large number of other physical systems, ranging from laboratory shallow water experiments to atmospheric jets to zonal flows on the solar system's giant planets to accretion disks. Some examples are presented in other contributions to this book of proceedings. Since streamers and zonal flows are associated with flows in different perpendicular directions, one might expect that the plasma shows a tendency to create states which are dominated by either one or the other. Simulations confirm this intuition, and experiments looking for turbulent structures are also underway. The understanding of structure formation has seen some progress in recent years, but a lot of physics remains to be unravelled.

Another challenge in plasma turbulence research has to do with the fact that it tends to be driven simultaneously by several microinstabilities on different spatio-temporal scales. Only very recently have multi-scale simulations become feasible. The first of their kind are shown in Ref. [4]. This work allows for the conclusion that, in general, the superposition principle is violated. Some underlying mechanisms are discussed in that paper. More work is underway. In particular, the idea of catastrophy-like transitions between different flow states has been put forward by Itoh and co-workers (see Refs. [23,25] in Ref. [4]). It will be a prime goal in our future work to verify or else falsify this scenario, especially since it might be closely linked to the physics of transport barriers in which the turbulent diffusivities are suppressed by up to an order of magnitude over radially extended regions.

A third area of active research centers around the statistics of passive particles in turbulent plasmas. Although the transported plasma particles are usually not passive, this simplification still allows for valuable insights into the turbulent dynamics. E.g., Vlad and co-workers have shown in a series of papers since 1998 (see Ref. [5] and references therein) that their newly developed 'decorrelation trajectory method' is able to capture the trapping of particles in turbulent eddies, an effect which is lost if the commonly used Corrsin approximation is used. Recently, we were able to confirm their results by means of direct numerical simulations.[6] In the presence of finite Larmor radius effects, the transport coefficients can even increase with respect to the zero Larmor radius limit, in contrast to naive expectations. Moreover, it was shown that particles embedded in a turbulent plasma may exhibit 'strange' (i.e., non-Gaussian) kinetics which can be described as a continuous time random walk (CTRW).[7] Such an approach may be of help in the attempt to understand nonlocal transport phenomena in MCF plasmas which cannot be captured by a conventional (Fickian) diffusion Ansatz.

Final remarks

In this short note, we tried to give the reader at least a flavor of some of the pressing open problems in plasma turbulence research. What makes this field particularly interesting is that it combines fundamental issues like structure formation or the statistics of particles in turbulent fields with the quest for a novel source of energy. We believe that an intensified dialogue between people working in plasma physics and those working in neighboring areas like fluid dynamics, geophysics, or astrophysics, would be beneficial to both sides. Maybe this paper is useful in that respect.

Acknowledgements

I would like to thank my co-workers T. Dannert and T. Hauff for valuable discussions, and the Helmholtz-Gesellschaft for financial support in the framework of the Helmholtz-University Young Investigators Group "Theory and ab initio simulation of plasma turbulence."

References

[1] A. Hasegawa and K. Mima, Phys. Rev. Lett. **39** (1977) 205; Phys. Fluids **21** (1978) 87.

[2] F. Jenko, W. Dorland, M. Kotschenreuther M, and B.N. Rogers, Phys. Plasmas **7** (2000) 1904.

[3] P.H. Diamond, S.I. Itoh, K. Itoh, and T.S. Hahm, Plasma Phys. Control. Fusion **47** (2005) R35.

[4] F. Jenko, Journal of Plasma and Fusion Research SERIES **6** (2004) 11.

[5] M. Vlad *et al.*, Plasma Phys. Control. Fusion **46** (2004) 1051.

[6] T. Hauff and F. Jenko, to be published.

[7] D. del-Castillo-Negrete, B.A. Carreras, and V.E. Lynch, Phys. Rev. Lett. **94** (2005) 065003.