Self-similarity and Structures of Plasma Turbulence

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Abstract: Plasma edge fluctuations and induced fluxes measured in several types of confinement devices have been found to be self-similar over time scales between 10 times the turbulence decorrelation time and the plasma confinement time. These self-similarity parameters vary little from one device to another. In exploring the self-similarity properties, it has become clear that time and space measurements lead to different information on the structure of turbulence. Therefore, it is often not possible to clearly separate the poloidal and temporal structures of the turbulence with a single-point measure. This in turn implies that using the standard Taylor frozen flow hypothesis can be very misleading when applied to plasma turbulence. We have used simple 2 and 3-D turbulence models to investigate how 1) the multiple nonlinearities intrinsic to plasmas affect the self-similarity parameter for both temporal and poloidal structures and 2) how poloidal flows influence the single-point measurements. Understanding the temporal and spatial dynamics individually, as well as the relationships between the temporal and spatial dynamics for turbulent plasma systems is crucial to improving the comparison between model and experiment.

1. Introduction

Understanding the dynamics of turbulent transport has obvious important implications for controlling confined plasmas. This understanding is needed both to improve experimental designs and for the expanding the physics underlying basic transport modeling. One method for approaching these transport dynamics at a fundamental level is through investigation and understanding of the similarities, or universal properties, and differences between the dynamics of different systems and regimes. This allows one to investigate the properties of both the turbulent nonlinearities and any more "collective" transport effects such as avalanches. To do this, one must have a set of characteristic measures to compare. These measures can then be applied to various types of models of increasing complexity to determine which pieces of the physics are responsible for the various types of dynamics embodied in the measures. This can then be compared to the same measures applied to experimental data to help determine which pieces of physics are needed to accurately represent the experimental transport. The experimental measures can also be used to compare the different configurations and regimes in order to explore the issue of universality/similarity. In some such measures, plasma edge fluctuations and induced fluxes measured in several types of confinement devices have been found to be self-similar over the mesoscale range of time scales [1,2], that is, for time scales between 10 times the turbulence decorrelation time and plasma confinement time. The self-similarity parameter varies little from one device to another suggesting some type of universal behavior in the transport. The experimental evidence also suggests a different scaling of the plasma turbulent fluctuations in different time scales ranges, and the possibility of more complicated structures than a single fractal structure. Therefore, multifractal analysis can be a powerful tool in understanding deviations from self-similarity.

In exploring the self-similarity properties, it has become clear that time and space measurements lead to different information on the structure of turbulence [3]. Time measurements primarily provide information on the damping and driving mechanisms at different time scales. Simultaneous measurements at different space locations provide information on spatial structures for different scale lengths. Taylor's frozen-field hypothesis that in fluid turbulence allows the linking of these two types of measurements is often not valid in plasma turbulence. In the case of fluid turbulence, the turbulence is generated at a given position and the flow carries the turbulence across the measuring point. Therefore, measurements taken at different times at a fixed point are equivalent to simultaneous measurements at different points along the flow. In the case of plasma turbulence, there is generation and damping of turbulence at the same position where measurements are taken. Because of this, it is not possible to clearly separate for example, poloidal and temporal structures of the turbulence with a single-point measure. Plasma flows will have the effect of complicating the picture by mixing space and time information. The result of this is contamination of both the single-point time measurements and the multi point measurements by the existence of flows. Using the Taylor frozen field hypothesis can, therefore, be very misleading when applied to plasma turbulence.

There are some characteristic properties of the plasma turbulence that may help in providing an interpretation of the fluctuation measurements and further understanding of the turbulence structures. Temporal structures often show persistency in time with the Hurst self-similarity parameter $H > 0.5$. On the other hand, space structures, which are essentially of dipolar nature when linked to the eddies, show antipersistency in space with $H < 0.5$. A question that must be addressed is how plasma flow can modify these qualitatively different properties and under which circumstances can they be clearly distinguished.

2. Results

We have used simple 3-D turbulence models [4] to find out, (1) how the polarization and ExB nonlinearities affect the self-similarity parameter for both temporal and poloidal structures, and (2) how poloidal flows influence the single-point measurements. Figures 1 and 2 show time traces from calculations with only the polarization drift nonlinearity (Fig. 1) and only the ExB nonlinearity (Fig. 2).

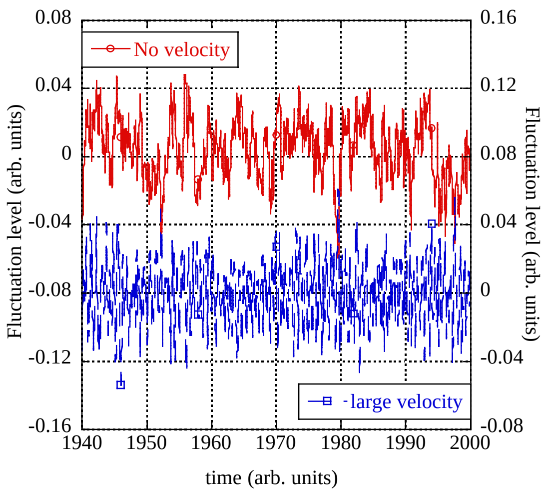

Fig. 1

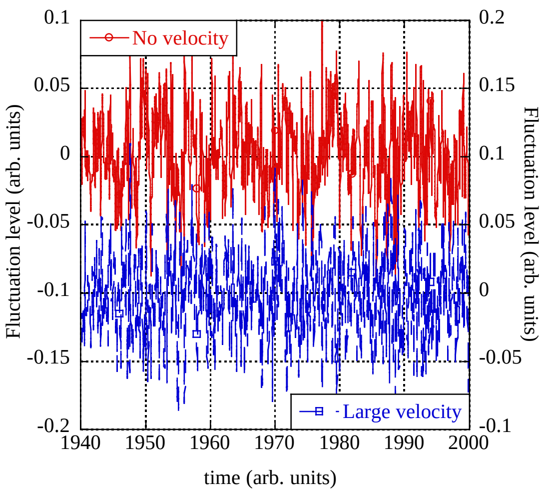

Fig. 2

In each there are 2 time traces, the upper one is in the plasma rest frame while in the lower trace the plasma has a large poloidal velocity (rotation) relative to the measurement point.

Other then two notable features one can “see” very little difference in the effect of the rotation on the trace. The two notable features are the apparent lower frequency component in the rest frame polarization drift nonlinearity case, coming from the dual cascade nature of that nonlinearity, and the larger amplitude of the oscillations in the ExB only case due to it’s different saturation mechanism. In both cases one can see the expected increase in frequency from the rotation velocity and little else.

Looking at the system in more detail, using for example the Hurst exponent, some important differences are found. When the ExB nonlinearity dominates, the parameter *H*, calculated for time series at a single-space position, is about 0.5 within the error bars of the calculation (Fig. 3). However, for the polarization drift nonlinearity, the value that *H* oscillates around is an average of about 0.5, but may be as high as 0.6 (Fig. 3). From the multi-point measurements, the spatial value for *H* is found to be about 0.4. This is consistent with the idea that the structures are generally dipolar in nature, which leads to anti correlation in space after the initial correlated region within a single eddy.

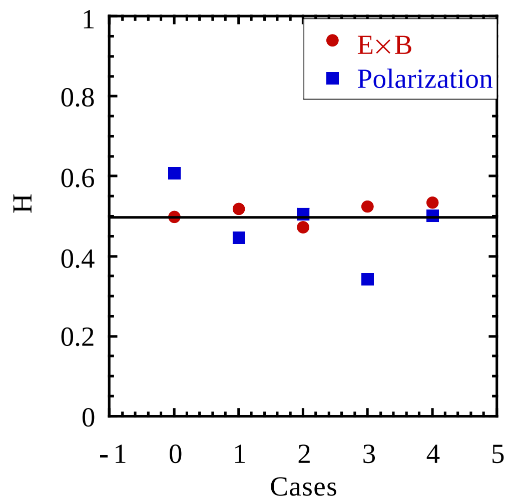

Fig. 3

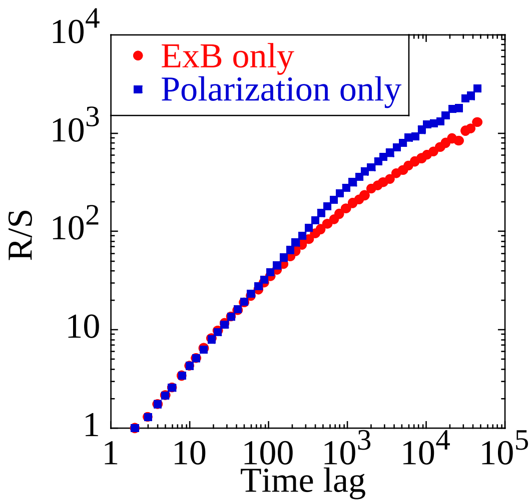

Fig. 4

The numerical results from the polarization drift nonlinearity are in qualitative agreement with the experimental analysis of fluctuation structure. Figure 4 shows the R/S analysis that leads to the Hurst exponents. The asymptotic (long lag) region for these 2 cases give H values of approximately 0.58 for the polarization drift nonlinearity only case and 0.50 for the ExB nonlinearity only case. The two cases also have different short time dynamic signatures in the R/S analysis. The polarization drift n.l. case has a larger short time lag region consistent with larger structures and longer decorrelation times due to the inverse cascade. At the same time the ExB n.l. case has a smaller short time lag region consistent with the direct cascade exhibited by that nonlinearity. However, in neither case have we obtained the large values of *H* reported elsewhere [5] from the analysis of time series using data from similar turbulence models.

The addition of a poloidal flow further complicates the picture by mixing the spatial structures, for which we obtained H~0.4 with the temporal dynamics for which we obtained H~0.6 in the polarization drift nonlinearity only case. The mere fact that in this case without flow there is a different Hurst exponent for the temporal and spatial dynamics should cause concern about using the frozen field hypothesis. In Figure 5 for the polarization drift n.l. case, we can see the continuous change of the *H* parameter with poloidal velocity from this mixing of dynamics and structure. We see a change from at least a weak persistency to antipersistency; however, to do so very large poloidal velocities are needed. The value of *H* at high poloidal velocity tends to the value obtained from a multi-point determination. This is the only time that the frozen field hypothesis is likely to be valid. That is when the velocity is so large that the intrinsic correlation time of the temporal dynamics is very much longer than the time it takes to sweep the frozen poloidal structures past.

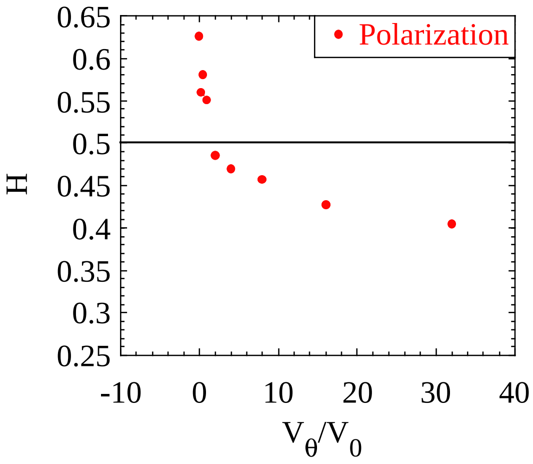

Fig. 5

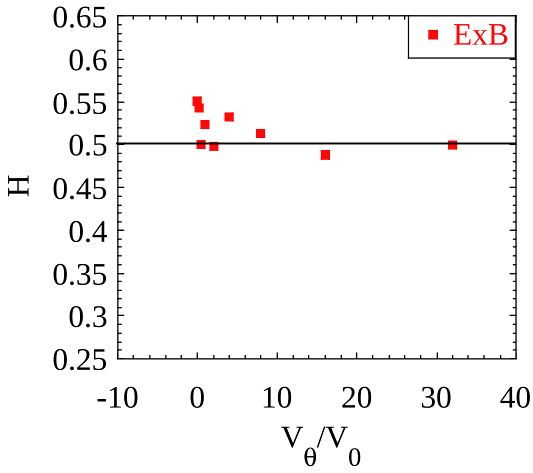

Fig. 6

Figure 6 shows the results of a poloidal rotation for the ExB only nonlinearity case. There is no obvious change in the Hurst exponent with the exponent staying around 0.5, the value expected for a random gaussian process. The inclusion of both nonlinearities and the interaction between them is yet to be completed due to the need for very high resolution in order to resolve both the regimes dominated by each nonlinearity separately as well as the crossover regime.

However, this turbulence model completely fails to explain the strong long-term persistency in time. To be able to explain this persistency, we must include the dynamics of the average profiles.

3. Conclusions

In order to compare models to models, models to experiments, and experiments to each other, a set of characteristic measures must be developed. These measures must be able to distinguish differences and similarities in the dynamics of both the fluctuations and the transport. One such measure, discussed here, is the Hurst exponent. In comparing two simple turbulence models, one with the ExB nonlinearity and one with the polarization drift nonlinearity, differences in the long time dynamics and in the spatial structures were found. The polarization drift nonlinearity was found to produce a weak long time persistence and a spatial anti persistence. The ExB nonlinearity produced an exponent consistent with a random process. However with the addition of a flow the different spatial and temporal dynamics found can get mixed together. This was seen in the change in Hurst exponent from the persistent value to the anti persistent value as the flow was increased. Without knowing at least one of the values before hand it is very difficult to determine them in a system with flow. Therefore, it is often not possible to clearly separate the poloidal and temporal structures of the turbulence with a single-point measure. This in turn implies that using the standard Taylor frozen flow hypothesis can be very misleading when applied to plasma turbulence. Understanding the temporal and spatial dynamics of both the fluctuations and the transport individually, as well as the relationships between the temporal and spatial dynamics for turbulent plasma systems is crucial to improving the comparison between model and experiment. Finally, in these numerical experiments no evidence was found for a strong, long time correlation that has been reported in the transport dynamics in some experiments. These computer experiment were done with a fixed drive for the turbulence that is the equivalent of a fixed profile. Since it has been seen before that with an evolving profile the long time correlations can be found, these results suggests that the long time correlations might depend on this profile evolution.

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