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Origin of Multifractality in Solar Wind Turbulence

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The solar wind plasma is known to be in a turbulent state, with magnetic field fluctuations commonly displaying time series with intermittent extreme events. In previous works, strong intermittency has been associated with the presence of multifractality in solar wind magnetic fluctuations, as measured by the nonlinearity of the ζ scaling exponent of the structure functions. The present work shows that multifractality may be present even in time series without strong intermittency, thus the scaling exponent is not an adequate tool to measure multifractality. A multifractal framework is proposed to investigate the effects of current sheets in solar wind turbulence found in Cluster-I data. By using multifractal detrended fluctuation analysis (MFDFA) coupled with surrogate methods and volatility, two solar wind magnetic field time series are investigated, one with large-scale current sheets (Fig. 1a) and one without such current sheets (Fig. 1b). Despite the lack of extreme events in the current sheet-free series, both series are shown to be strongly multifractal, although the current sheet-free series displays an almost linear behavior for the scaling exponent of structure functions (Fig. 1d). Long-range correlations are shown to be the main source of multifractality for the series without current sheets, while a combination of heavy-tail distribution and nonlinear correlations are responsible for multifractality in the series with current sheets. The multifractality in both time series is formally shown to be associated with an energy-cascade process using the p-model[1].

Figure 1(c) compares the scaling exponents of the time series with current sheets (red line with circles) with the scaling exponents of a surrogate series (magenta line with triangles) formed by randomly shuffling the phases of the Fourier components of the original series, while keeping the original power spectrum. The surrogate series has a Gaussian PDF, without the intermittent strong energy bursts of the original series and the scaling exponent becomes linear, following the Kolmogorov (K41) monofractal line (dashed line). In Fig. 1(d), the same analysis is done for the time series without current sheets. This time series does not have a fat-tailed PDF, although it has a multifractal spectrum[1]. Both the original series and its random phases surrogate show an Iroshnikov-Kraichnan (IK) linear behavior.

Since both time series are multifractal, but only the series with current sheets has a nonlinear scaling function, it is clear that the ζ-function is only useful for measuring multifractality when it is related to intermittency. We show that the Renyi scaling exponent, obtained from MFDFA analysis, is better than the ζ-function scaling exponent to study multifractality in the solar wind. Our results suggest that the solar wind is always multifractal, but for time series with current sheets, the magnetic-field turbulence follows a K41-scaling and multifractality is due to both intermittency and nonlinear correlations; for time series without current sheets, turbulence follows an IK-scaling and multifractality is due to long-range correlations.

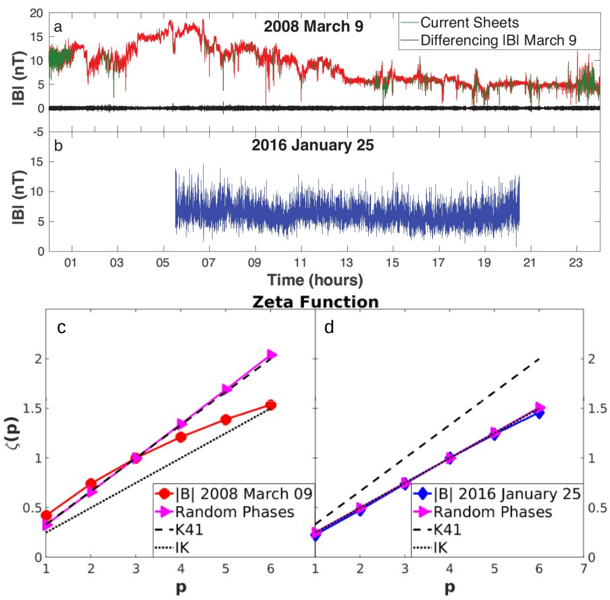

Figure 1. (a) Solar wind time series of |**B**| for 2008 March 9 (red), containing current sheets (green), and its first-order differencing (black); (b) time series of |**B**| for 2016 January 25 (blue), without current sheets; (c) Zeta functions of |**B**| for 2008 March 9 (red circles) and its random phases (magenta triangles); (d) Zeta functions of |**B**| for 2016 January 25 (blue diamonds) and its random phases (magenta triangles). The dashed lines represent the K41 scaling and the dotted lines represent the IK scaling.

References
[1] L.F. Gomes *et al*, MNRAS **519**, 3623 (2023)