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ENERGY TRANSFER PROCESS IN SPACE PLASMA TURBULENCE *

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Abstract. In weakly collisional space plasmas, the turbulent cascade provides most of the energy that is dissipated at small scales by various kinetic processes. The scaling properties of different energy channels are estimated here using a proxy of the local energy transfer, based on the third-order moment scaling law for magnetohydrodynamic turbulence. The results show the highly complex geometrical nature of the flux, and that the local contributions associated with energy and cross-helicity non-linear transfer have similar scaling properties. Consequently, the fractal properties of current and vorticity structures are similar to those of the Alfvénic fluctuations.

Keywords and phrases: Turbulence, dissipation, space plasmas, magnetosphere, singularity.

AMS subject classification (2010): 35Q35, 37K10, 37K40.

1 Introduction. The dynamics of space plasmas is characterized by a broad variety of complex processes that include turbulence, instabilities, and several mechanisms of particle-radiation interaction. Such processes are intrinsically connected across multiple scales. The energy associated with large-scale structures and instabilities is transported toward smaller and smaller scales though a turbulent cascade due to the non-linear interactions among magnetic and velocity fluctuations, throughout the so-called inertial range that may span one to more than three decades in scales [1]. When the energy reaches scales of the order of or smaller than the typical ion and electron scales (e.g., the proton Larmor radius or inertial length), a different turbulent cascade occurs [2]. At those scales, weakly collisional plasma kinetic processes arise, such as non-linear damping of waves, kinetic instabilities, particle collisions, and magnetic reconnection, that convert the energy stored in the field fluctuations into particle energization and acceleration, and plasma heating [3].

2 The local energy transfer in turbulence. The fluctuations observed in magnetohydrodynamic plasma turbulence have been shown to follow the Politano-Pouquet law [4]. This predicts the linear scaling of the mixed third-order moment of the fields fluctuations on the scale, when homogeneity, scale separation, isotropy, and time-stationarity are met, which can be written as:

$$Y(\Delta t) = (\Delta V_1(|\Delta V|^2 + |\Delta b|^2) - 2\Delta b_1(\Delta V \cdot \Delta b)) = -\frac{4}{3}[(\varepsilon)\Delta t(V)]. \tag{1}$$

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The third order moment $Y(\Delta t)$ is computed using thee increments $\psi(t,\Delta t) = \psi(t+\Delta t) - \psi(t)$ of a field ψ (either the plasma velocity v or the magnetic field $b = B/\sqrt{4\pi\rho}$ given in velocity units through the mass density ρ) across a temporal scale t, the subscript l indicating the longitudinal component, i.e., parallel to the bulk speed. The total energy flux given in Equation (1) is proportional to the mean energy transfer rate ε. The Politano-Pouquet law describes the scaling of the small imbalance between positive and negative energy flux in the turbulent cascade, and is associated with the scale-dependent intrinsic asymmetry (skewness) of the turbulent fluctuations [1, 4]. In order to attempt a description of the local energy flux from space data time series, the law (1) can be revisited without computing the average, thus giving a time series of the heuristic proxy of the local energy transfer rates at a given scale t, which can be estimated by computing the quantity:

$$\varepsilon^{\pm}(t,\Delta t) = -\frac{3}{4}(\Delta V_1(|\Delta V|^2 + |\Delta b|^2) - 2\Delta b_1(\Delta V \cdot \Delta b))/\Delta t(V). \tag{2}$$

The local energy transfer process is composed of two additive terms, one associated with the magnetic and kinetic energy advected by the velocity fluctuations, $\varepsilon_l = -3/(4\Delta t(V))[\Delta V_l(\Delta V^2 + \Delta b^2]$, and the other with the cross-helicity coupled to the longitudinal magnetic fluctuations, $\varepsilon_c = -3/(4\Delta t(V))[-2\Delta b_l(\Delta V \Delta b)]$ [3]. Such separation has been used to identify regions dominated by current and vorticity structures from regions dominated by coupled, Alfvénic fluctuations in the terrestrial magnetospheric boundary layer, revealing the presence of ion beams mostly associated with the small-scale Alfvénic fluctuations, and thus indicating a possible mechanism for the transfer of the turbulent energy to the particles [2]. Since the local energy transfer process, as well as its two separated components, are signed quantities, it may be interesting to explore the scaling properties of the mixing of the positive and negative parts of the turbulent cascade. These may be related to the direction of the energy flow, although this interpretation is not supported by theoretical evidence.

In order to study the cancelation properties of the local energy transfer rate proxy LET, and of its two components, we have selected two magnetospheric plasma intervals measured by the Magnetospheric Multiscale mission (MMS) [4], which provides data at high cadence, and one longer interval of fast solar wind measured by the Wind spacecraft [3]. The data labeled as MMS-KH, was recorded on September 8, 2015 between 10:07:04 and 11:25:34 UTC, while MMS was in the dusk-side magnetopause, moving across a portion of plasma dominated by the Kelvin-Helmholtz instability (KH) formed at the boundary between the magnetosheath and the magnetosphere.

The formation of small-scale structures, typical of intermittency, is evidenced by the (roughly) power-law increase toward the small scales of the normalized fourth order moment (kurtosis) of the magnetic fluctuations, $K_i(t) = B_i^4/B_i^2$ (Fig. 1), the subscript i indicating the component x, y, or z. Note that the Gaussian value $K = 3$ is observed for scales larger than the estimated inertial range (right gray vertical line). The Power-law decrease with the scale is a direct consequence of the structure function scaling in turbulent fields. The fitted scaling exponents are indicated in each panel, and are proportional to the degree of intermittency of the system [4]. These results show the weakly intermittent nature of the MMS-KH sample.

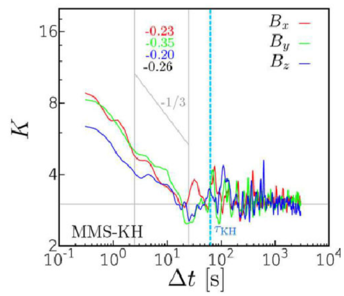

Figure 1: Scale-dependent kurtosis of the magnetic field components, for the three samples.

The Politano-Pouquet law (1) can be estimated in the samples under study, both in terms of total energy transfer, and in terms of the averaged components ε_l and ε_c. The resulting scaling functions are shown in Fig. 2 . The observed case doesn't display a clear linear scaling. This might be due to the violation of the several requirements necessary for the Politano-Pouquet law to hold (e.g., incompressibility, isotropy, stationarity, large Reynolds number), to the presence of large-scale features advected by the flowing plasma, or simply to the lack of statistical convergence of the third-order moment, due to intrinsic finite-size limitation of space data.

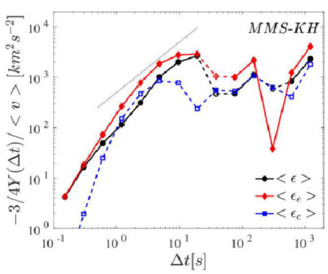

Figure 2: The Politano-Pouquet law (1) for the three samples, indicated as in the legend (black), and in terms of its averaged components ε_l (red) and ε_c (blue).

3 Conclusions. The nature of the turbulent energy cascade has been analyzed in space plasma by means of cancelation analysis applied to heuristic proxies of the local energy transfer. The analysis provided information on the sign alternation of the local mixed third-order fluctuations, which may be related to the fractal properties of the associated energy transfer and thus to small-scale dissipative processes. In KH instability at the magnetospheric boundary layer, the turbulent cascade is well described by the proxies, and cancelation analysis captures the increasing complexity of the alternating positive and negative fluctuations. In these two samples, the energy is transferred to small scales eventually generating disrupted current and vorticity structures, as well as Alfvénic structures.

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