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Scaling Laws of Turbulence and Heating of Fast Solar Wind: The Role of Density Fluctuations

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Sorriso-Valvo *et al.* Reply: To avoid the risk of misunderstanding, let us start by recalling that the Politano and Pouquet (P&P) law has been derived from a set of equations (MHD) and under assumptions which are far from representing an exact mathematical model for the solar wind (SW) plasma. The P&P law is valid in MHD under the hypotheses of incompressibility, stationarity, homogeneity, and isotropy. Also, the form used for the dissipative terms of MHD equations is only valid for collisional plasmas, characterized by quasi-Maxwellian distribution functions, and in case of equal kinematic viscosity and magnetic diffusivity coefficients [1]. In SW plasmas the above hypotheses are only rough approximations, and MHD dissipative coefficients are not even defined [2]. At frequencies higher than the ion cyclotron's, kinetic processes are indeed present, and a number of possible dissipation mechanisms are currently discussed in the community. When looking for the P&P law in the SW, the strong conjecture that the law remains valid for any form of the dissipative term is needed. In this sense, the actual physical question is what kind of local conditions allow the surprising observation of the P&P law in some SW samples. P&P equations describe independently the cascade of the pseudoenergies associated to the Elsässer fields, which are the invariants of incompressible, ideal MHD. The observation of the predicted linear scaling on only one of the invariants suggests that the transfer on the other one can be reasonably neglected. In fact, it is well known that fast SW is characterized by predominance of the outward propagating mode. Not surprisingly, the simultaneous observation of P&P law for both modes is rare, so that the observed single mode can be safely used as a proxy total energy transfer rate (considerations on SW heating were only made in [3], where only positive values of either ϵ^\pm are used and related to heating). In this perspective, the pseudoenergy transfer rates observed when the P&P law is verified describe particular conditions and do not represent the common case.

The precise estimate of the third order moment and of its statistical accuracy requires, in general, a large number of data. However, the Sun is not a laboratory experiment where all parameters are controlled to keep the turbulence statistically stationary over long periods. This is especially critical in the ecliptic, where turbulence in fast and slow streams has different statistical and physical properties, as, for example, shown in [4]. For this reason, trying to obtain more accurate estimates by merging data from fast and slow streams introduces the risk to distort the physical meaning of observations. In the polar, fast wind spanned by Ulysses, this problem is less evident, but the data are not satisfactorily stationary over more than about 10 days (which anyway includes 50–200 correlation lengths), for instance when looking at the variance over sliding windows.

About the linear P&P scaling range, we remind the reader that a formal definition of the inertial range of a

turbulent cascade requires the linear scaling of the third order moment (P&P law). The presence of a phenomenological Kolmogorov $f^{-5/3}$ spectrum is commonly used to suggest the position of such range, but is not rigorous, nor necessarily coincident with the P&P scaling range [5]. At this point, it is necessary here to clarify a frequent misunderstanding, also concerning the causality issue raised in the preceding Comment [6]. The large scale of turbulence is generally determined by the geometrical properties of the energy injection mechanism. In the solar wind, the latter is (most probably) the signature of the spatiotemporal variability of the Sun. Frequencies of solar origin are indeed seen in the wind as space scales (through the Taylor hypothesis) when it is accelerated to supersonic, super-Alfvénic speed. Thus, in principle, phenomena occurring on a wide range of time scales concur to provide the energy injection. For example, photospheric motions can inject Alfvénic fluctuations at frequencies of a few minutes, while the solar rotation can be responsible for the formation of velocity shears on scales up to several days.

The modified law proposed in [3] is a *phenomenological* (as clearly stressed) attempt to correct the P&P law for the effects of compressibility. Even if this law cannot be formally derived from a defined set of equations, it has been observed in numerical simulations of compressive MHD turbulence [7]. The values of pseudoenergy transfer rates obtained in the compressive case can be assumed to give a reasonable order of magnitude.

In conclusion, we believe that despite the enormous difficulties in setting up a rigorous mathematical model of solar wind plasma, good physics can be done by using simplified models or phenomenological conjectures.

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