Reconnection-driven turbulence in fast coronal hole jets

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Abstract

Our analysis of adaptive 3D MHD simulation runs confirms the presence of a reconnection-driven magnetic turbulence in the simulated plasma jet. We found the spatial correlations of magnetic fluctuations inside the jet to be in a quatitative agreement with the scaling model of intermittent MHD turbulence by Muller and Biskamp (PRL, 2000). This model implies that the turbulent cascade inside the jet is supported by filamentary structures representing fluid vortices, and is formed predominantly in the lower ($r<R_S$) portion of the jet. The anisotropy of the magnetic fluctuations and the mutual spatial orientation of the current sheets could reflect torsional Alfven wave packets.

The obtained signatures of turbulent dynamics are indicative of reconnection-driven exhaust jets possessing helical geometry. Some of these signatures can be detected from single-point *in situ* observations by future solar missions such as SPP and SO.

Statistical models of turbulence

Refined similarity hypothesis: scaling of structure functions and energy dissipation field

$$\langle \delta v_l^p \rangle \sim l^{\zeta_p} \qquad \langle \epsilon_l^p \rangle \sim l^{\tau_p}$$

$$\zeta_p = p/3 + \tau_{p/3}$$

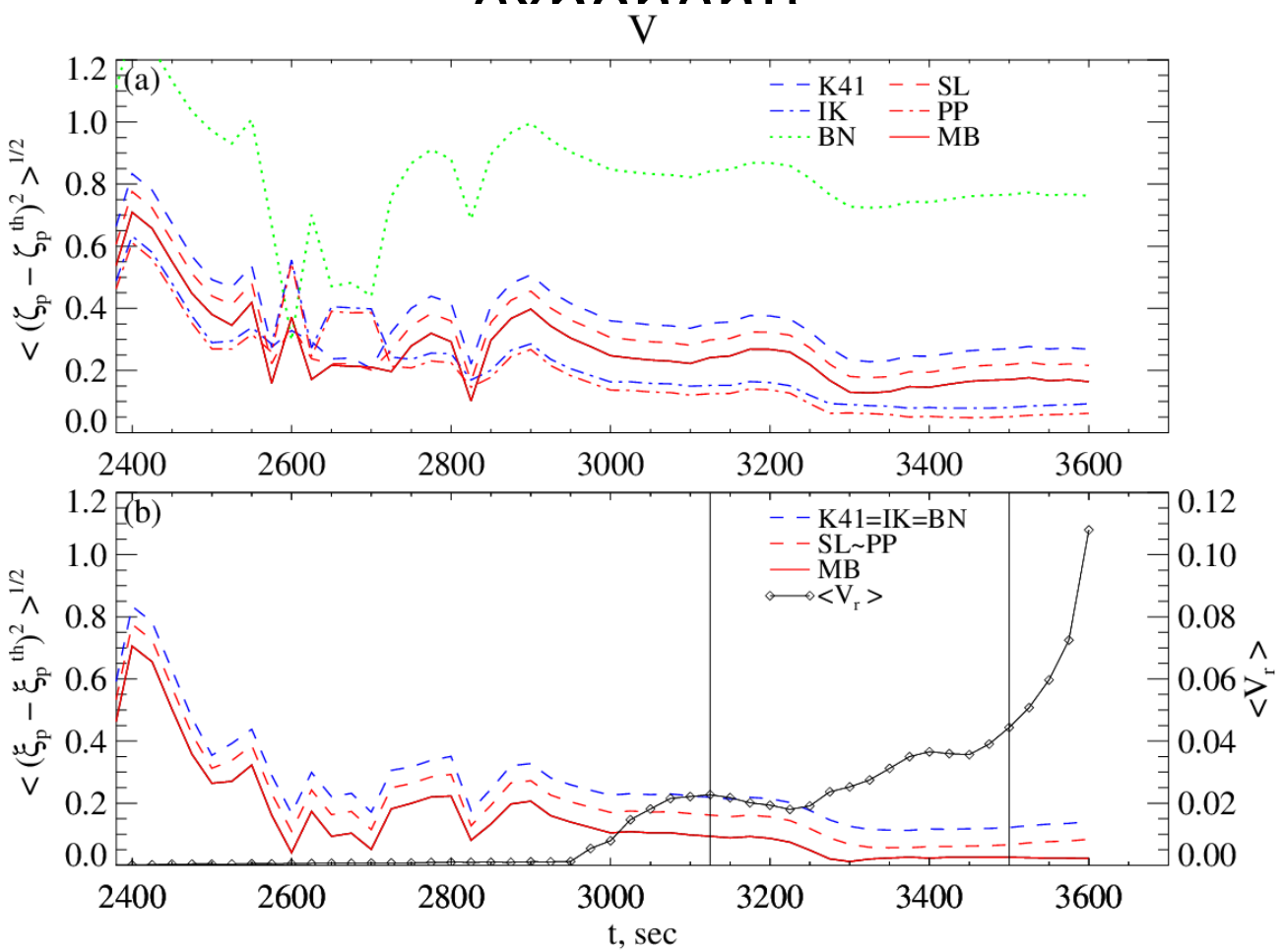
Hierarchical model of turbulence unifying several commonly observed scaling regimes (She & Leveque, 1994; Muller & Biskamp, 2000). See the table for the parameter values.

$$\delta v_l \sim l^{1/g} \qquad t_l \sim l^x \qquad C = 3 - D$$

$$\zeta_p = (p/g)(1-x) + C[1-(1-x/C)^{p/g}]$$

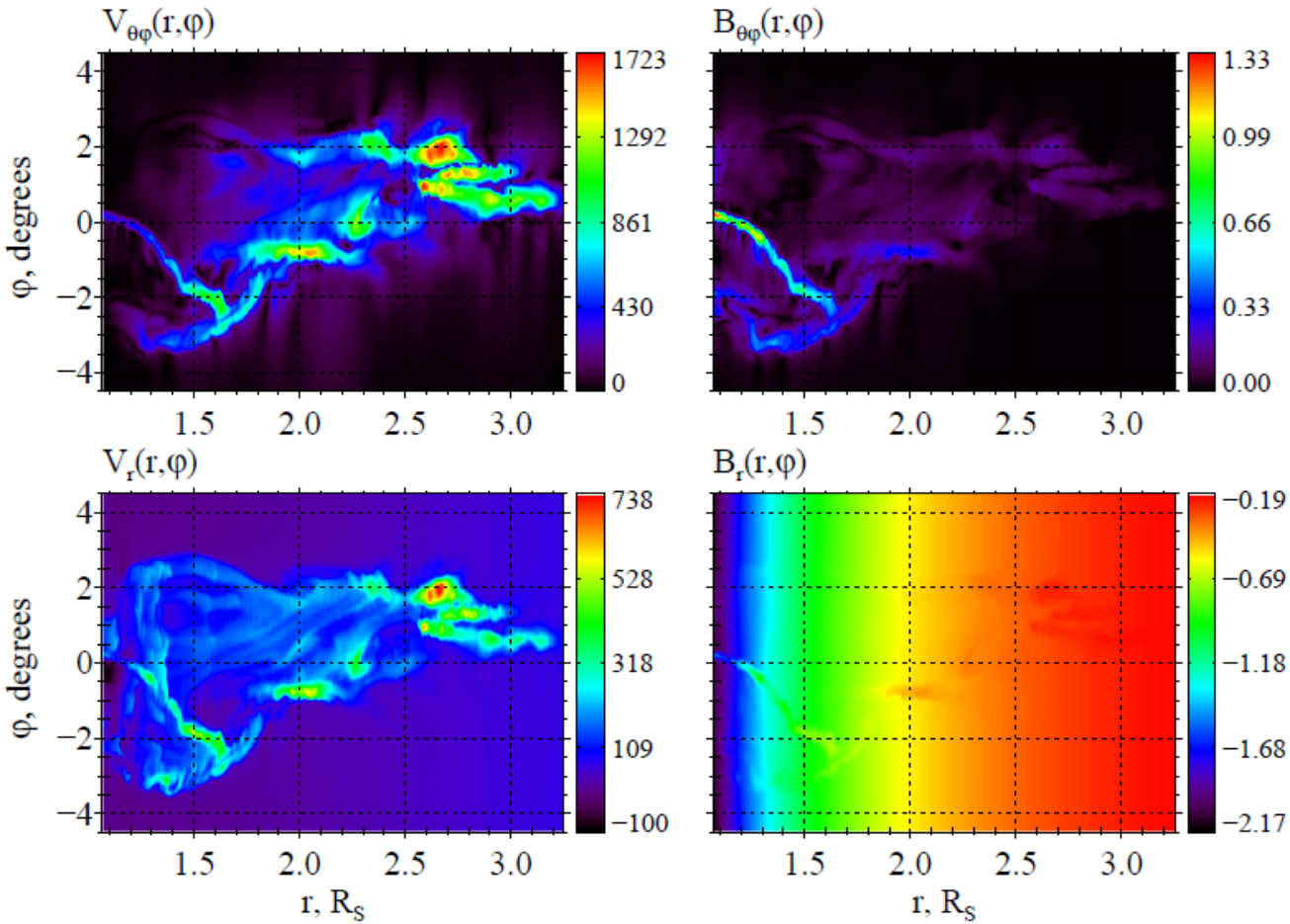
Model	*q*	*x*	*C*	Cascading structure	Dissipative structure
			non-intermittent		
Kolmogorov 1941 (K41)	3	0	-	Fluid filaments	-
Iroshnikov & Kraichnan (IK)	4	0	-	Alfven wave packets	-
Brownian noise (BN)	2	0	-	-	-
			intermittent		
She & Leveque (SL)	3	2/3	2	Fluid filaments	Fluid vortices
Politano & Pouquet (PP)	4	1/2	1	Alfven wave packets	Current sheets
Muller & Biskamp (MB)	3	2/3	1	Vortex filaments	Current sheets

Temporal evolution of velocity SF exponents



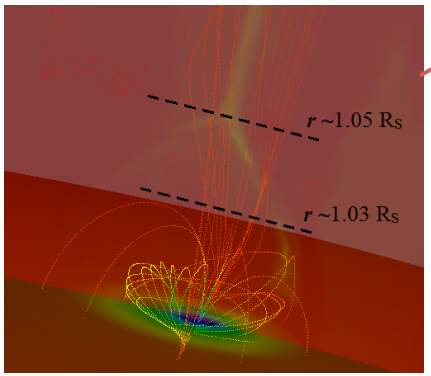
Temporal evolution of root mean square discrepancies between the measured and the theoretical values of velocity SF exponents estimated using the direct (a) and the ESS-transformed (b) structure functions, for several hierarchical models of intermittent turbulence defined earlier, as compared to the average radial velocity, for phi=0.

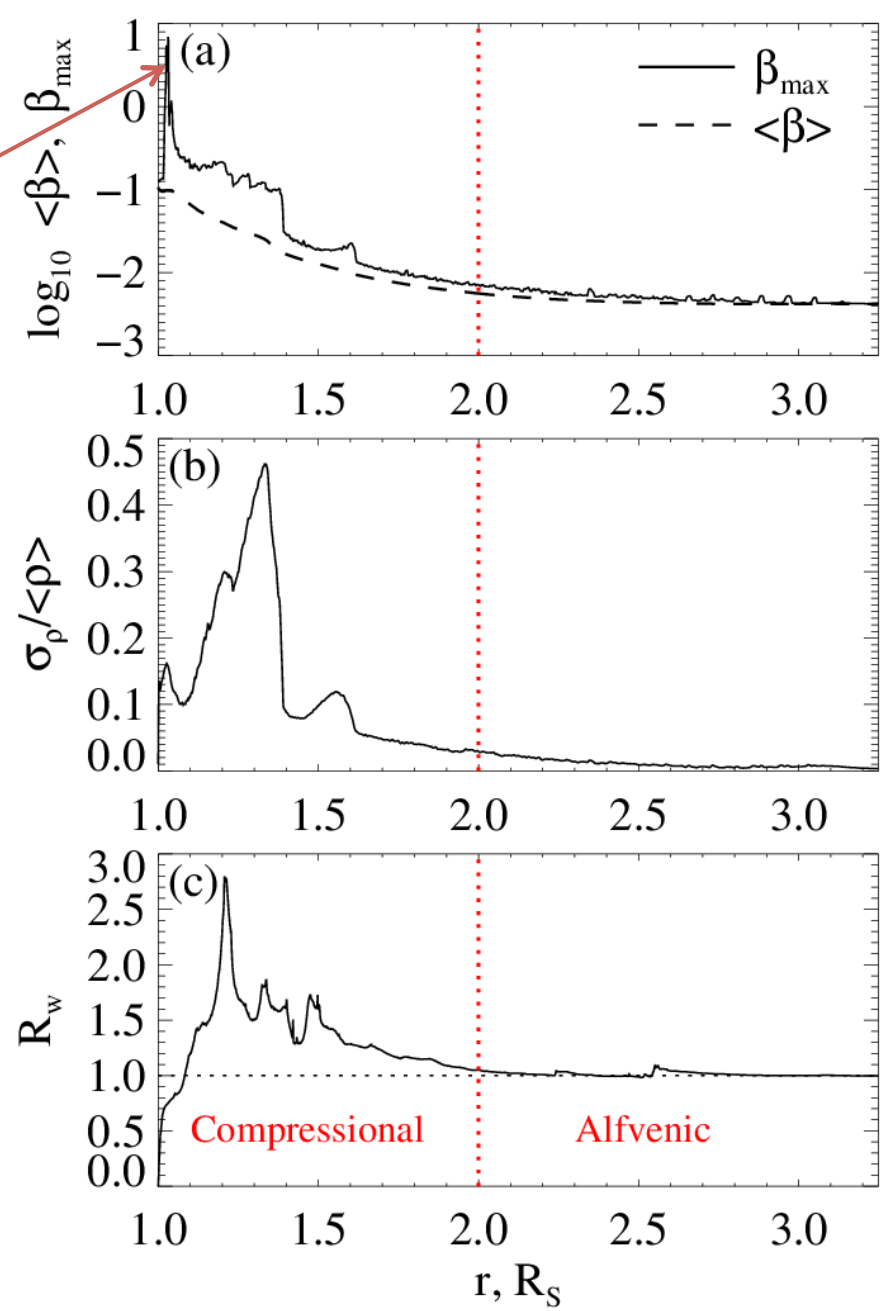
Multiscale structuring of velocity and magnetic field fluctuations



Radial cross-sections (theta = 0◦) of transverse and radial components (top and bottom panes, correspondingly) of velocity and magnetic field at *t* = 3500 s.

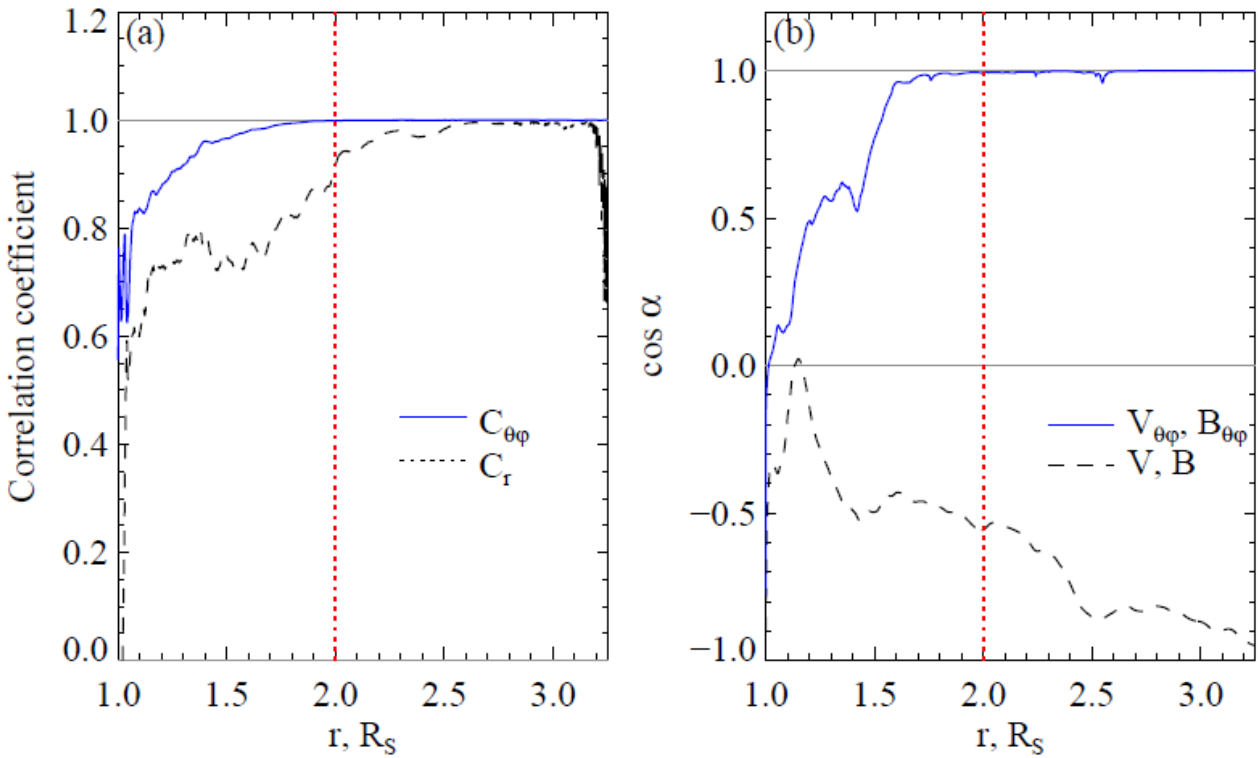
Radial dependence of jet parameters





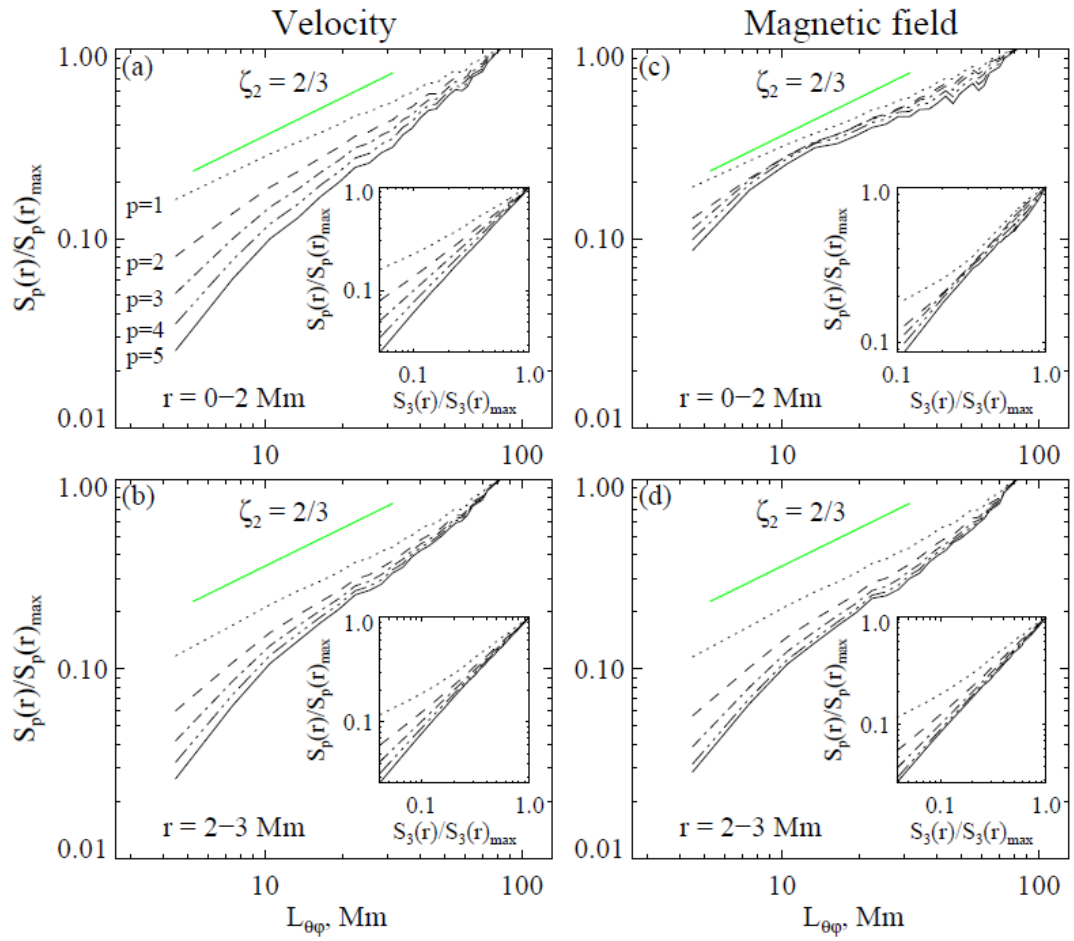
Radial dependence of plasma parameters revealing two distinct jet regions shaped by compressional and Alfvenic perturbations: average and maximum values of plasma beta (a), normalized standard deviation of mass density fluctuations (b), and the Walen ratio (c).

Cross-correlation of velocity and magnetic field



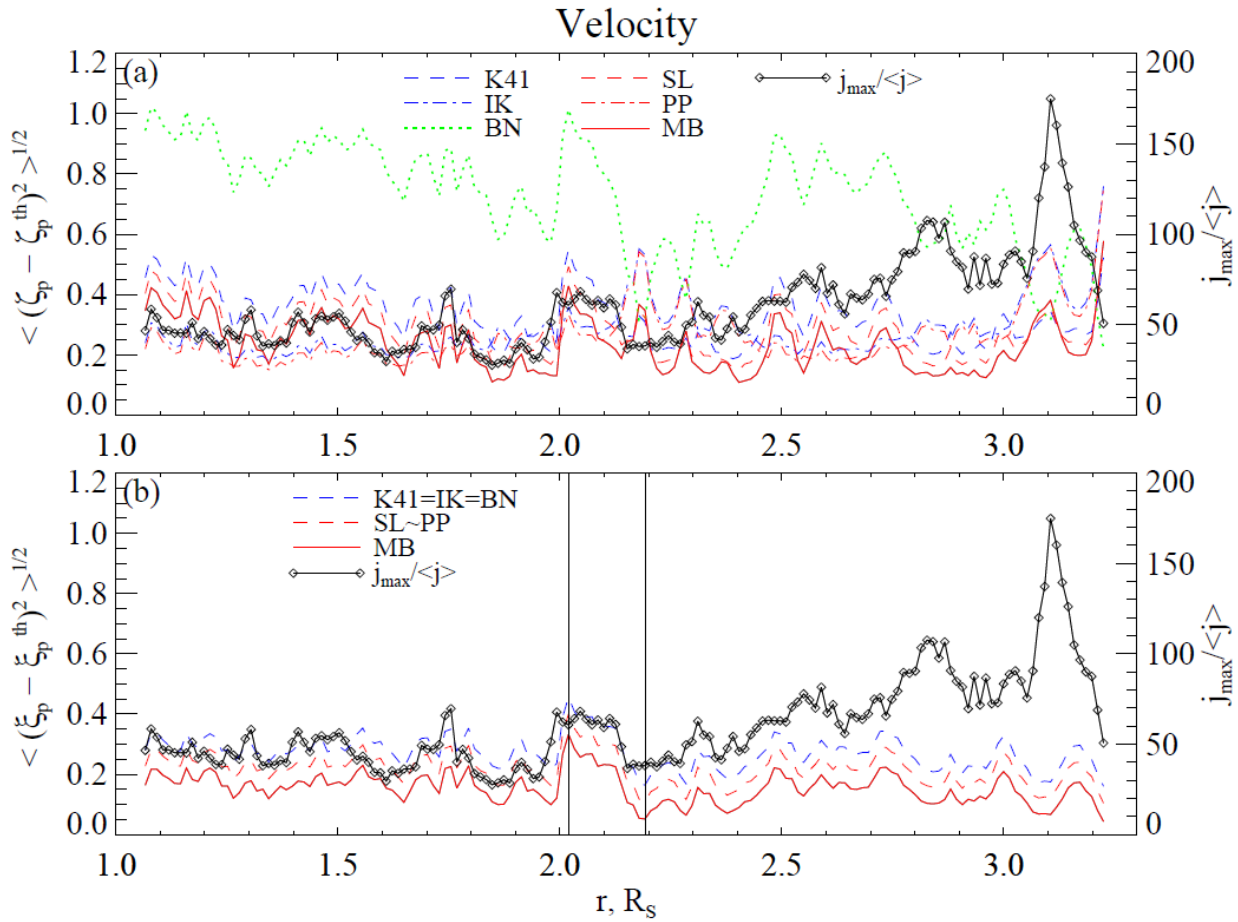
Left: *r*-dependence of linear Pearson coefficients characterizing correlation between velocity and magnetic field fluctuations in the transverse ($C_{\vartheta\phi}$) and radial (C_r) directions (left). Right: average cosine angles between the two fields in the ϑ-ϕ plane and in the 3D volume, also as a function of *r*.

Structure function analysis of jet turbulence



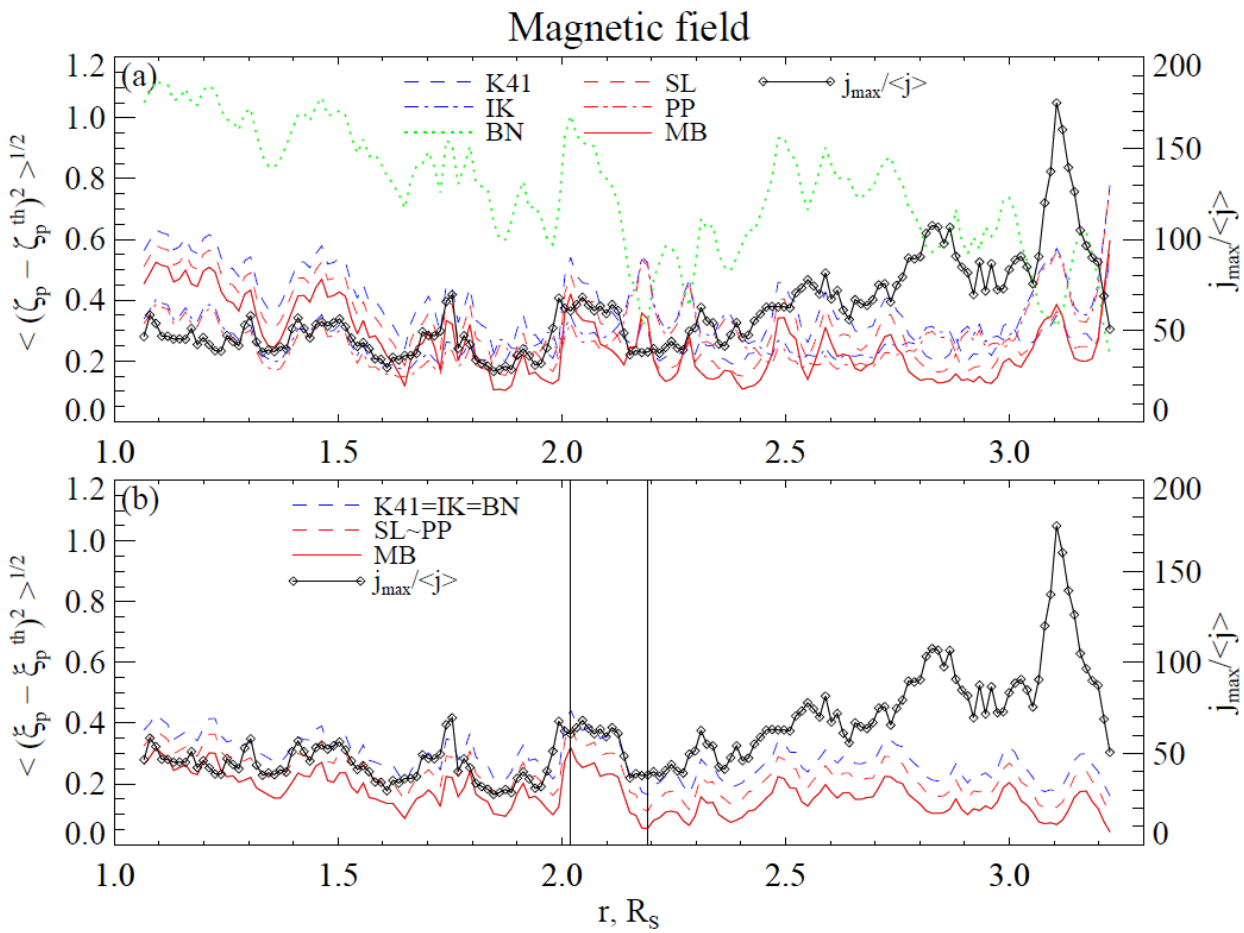
Structure functions (SFs) of the transverse velocity (a, b) and magnetic field (c, d) fluctuations below and above the altitude $r = 2.0R_s$ separating respectively compressional and Alfvenic regimes. Main panels show the origial SFs before applying the extended self-similarity (ESS) normalization, with solid green lines marking K41 slopes for comparison. The ESS-transformed SFs with improved inertial ranges are provided in the insets.

Theoretical vs empirical SF exponents



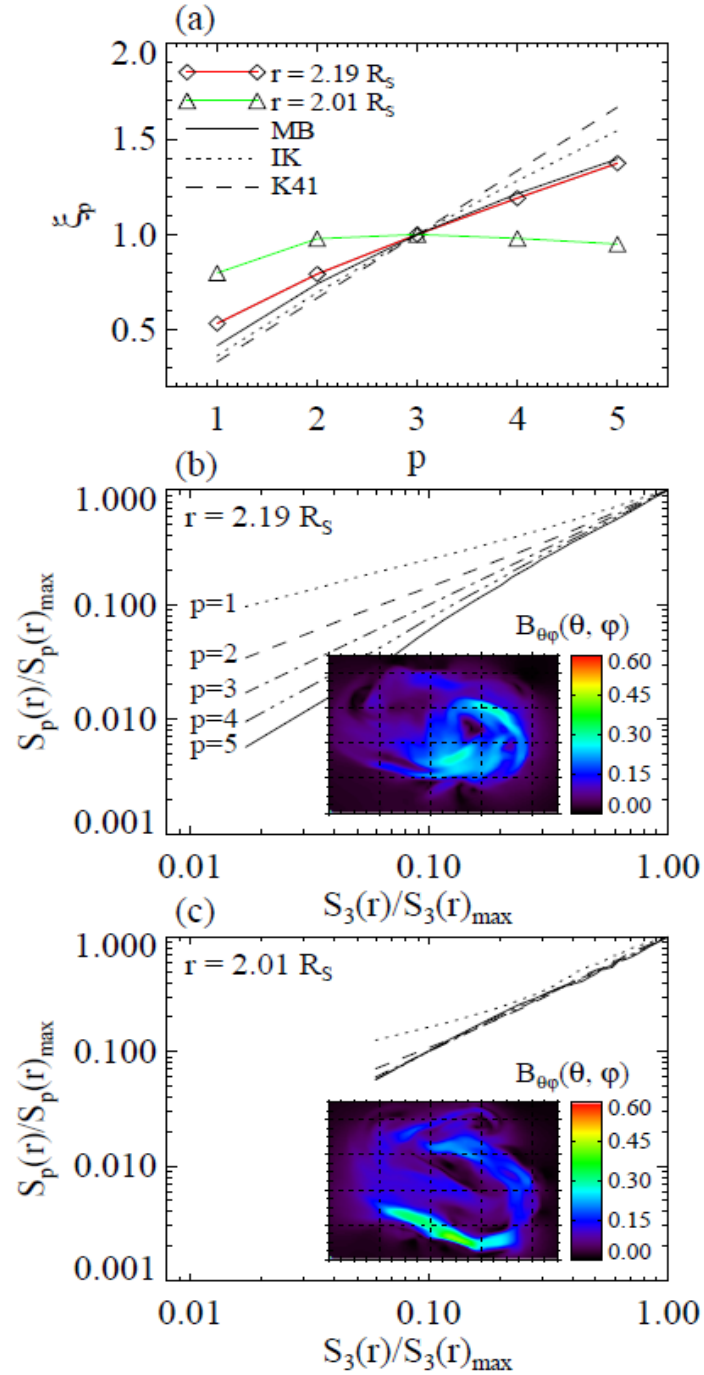
Radial dependence of root mean square discrepancies between the measured and the theoretical values of the velocity SF exponents estimated using the direct (a) and the ESS-transformed (b) structure functions, for several hierarchical models of intermittent turbulence defined earlier.

Numerical vs theoretical SF exponents



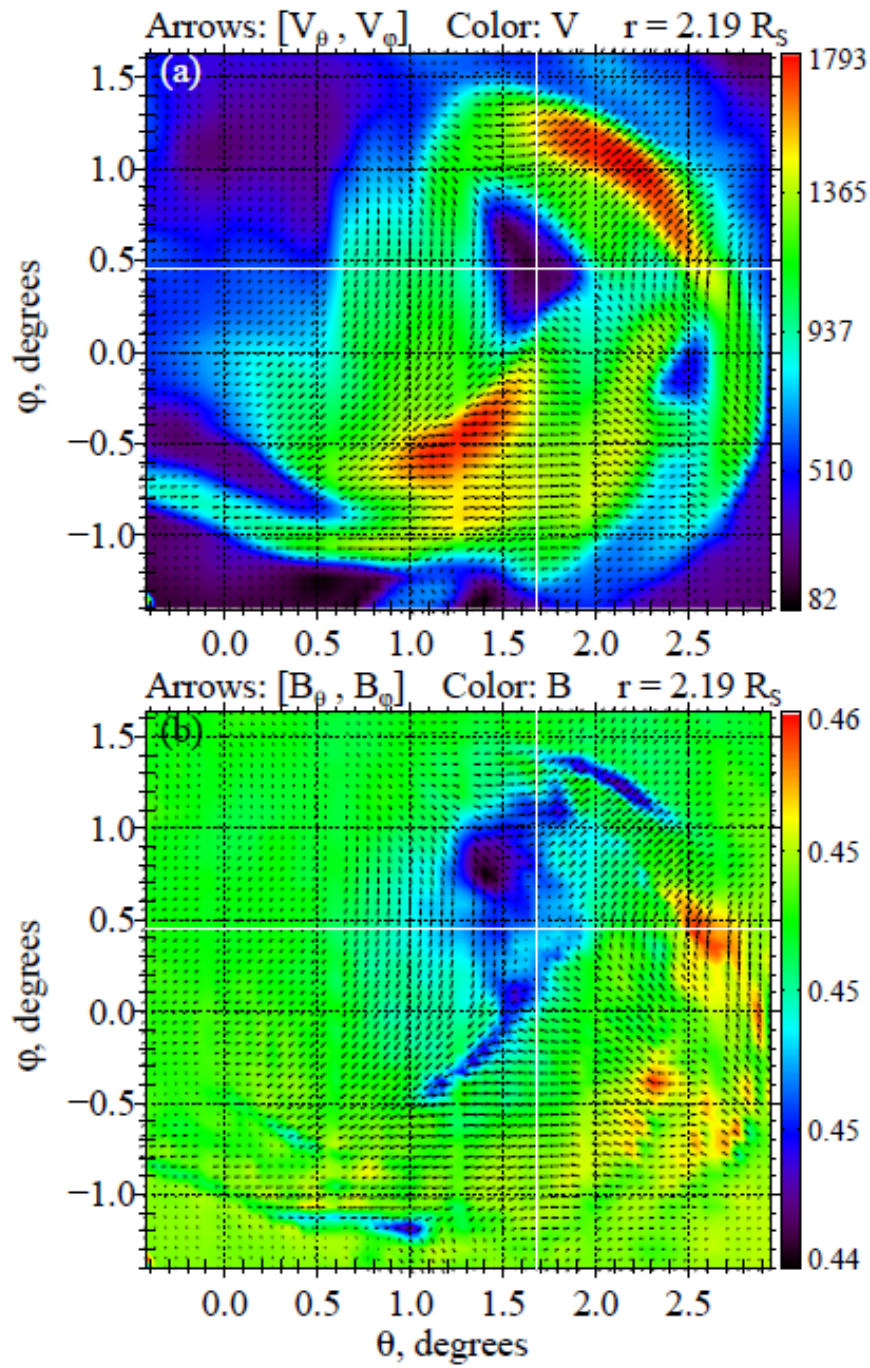
Same, for magnetic field SF exponents. Vertical lines mark radial positions showing the lowest and the highest discrepancies. The nature of this difference is investigated in the next slide.

Examples of B-scaling consistent and inconsistent with the hierarchical turbulence models



(a) ESS SF exponents of transverse magnetic field fluctuations for two characteristic radial positions (see prev. slide) marked by the lowest and the highest discrepancies with the theoretical models. (b, c) ESS-transformed SF functions and the maps of transverse magnetic field magnitudes for the two radial positions. Note the presence of a single highly intermittent structure at r = 2.01R_s leading to a violation of the normal SF hierarchy.

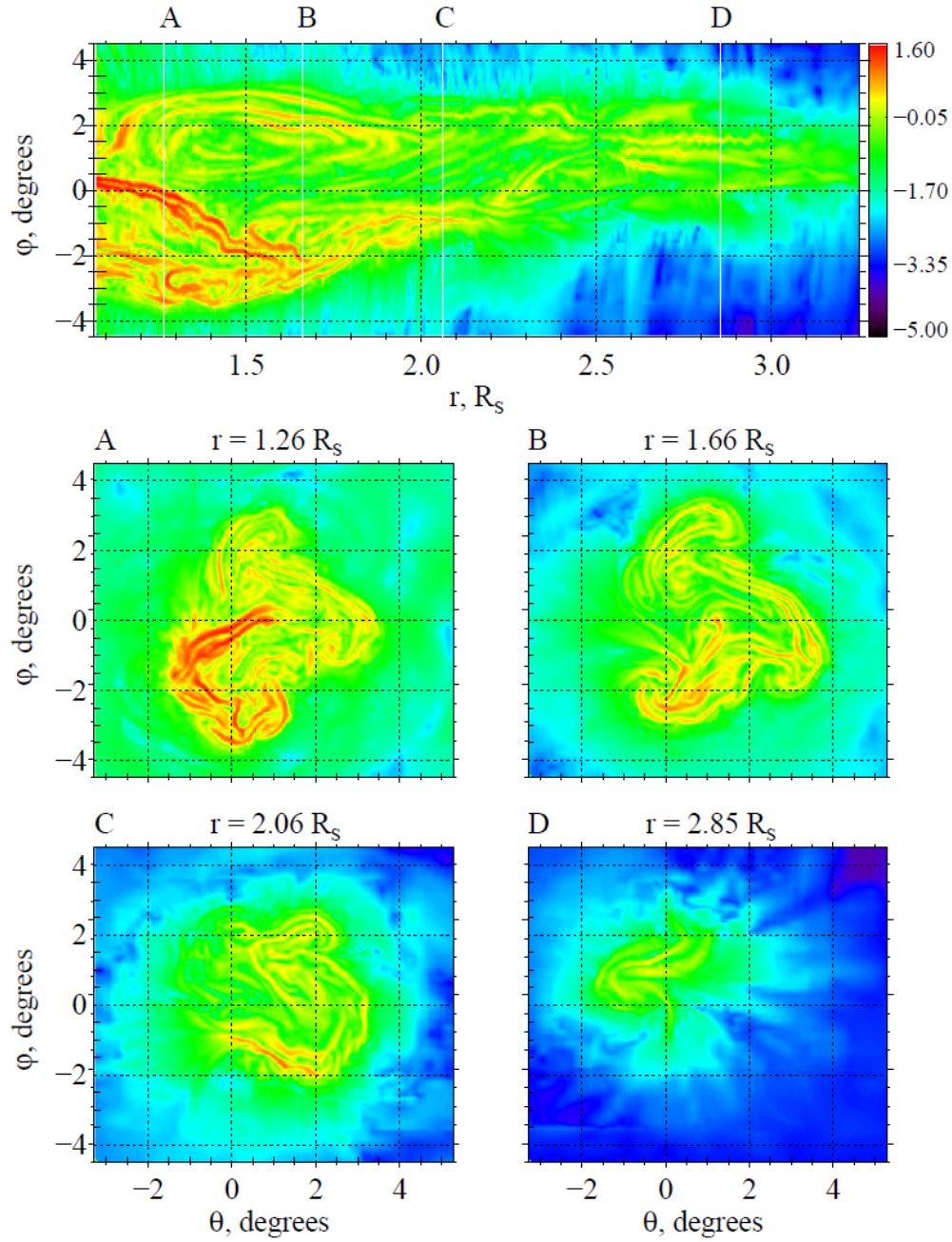
v-B coupling in the low-beta jet region



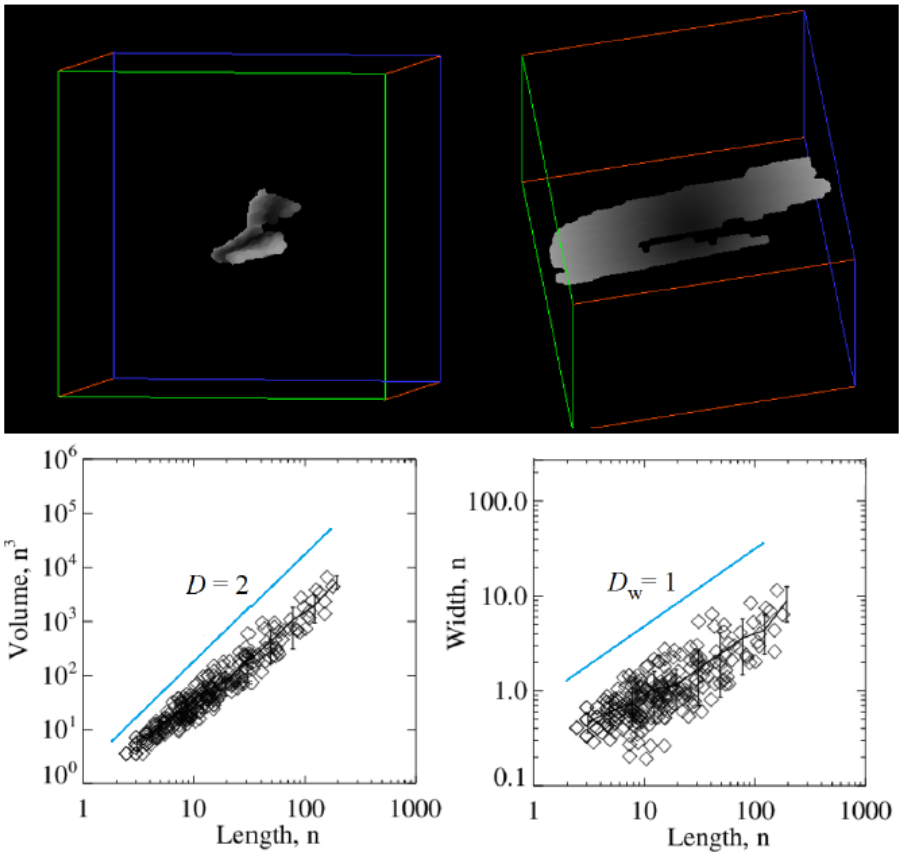
Transverse velocity (a) and magnetic field (b) vectors overplotted with the magnitudes of the respective fields, at $r = 2.19R_s$. The flow pattern around the stagnation point at the intersection of two white lines is formed by magnetic pressure gradients.

Multiscale current sheets formed by the flow

Radial and transverse cross-sections of the logarithmic current density magnitude revealing multiple complex-shaped current sheets of various sizes.

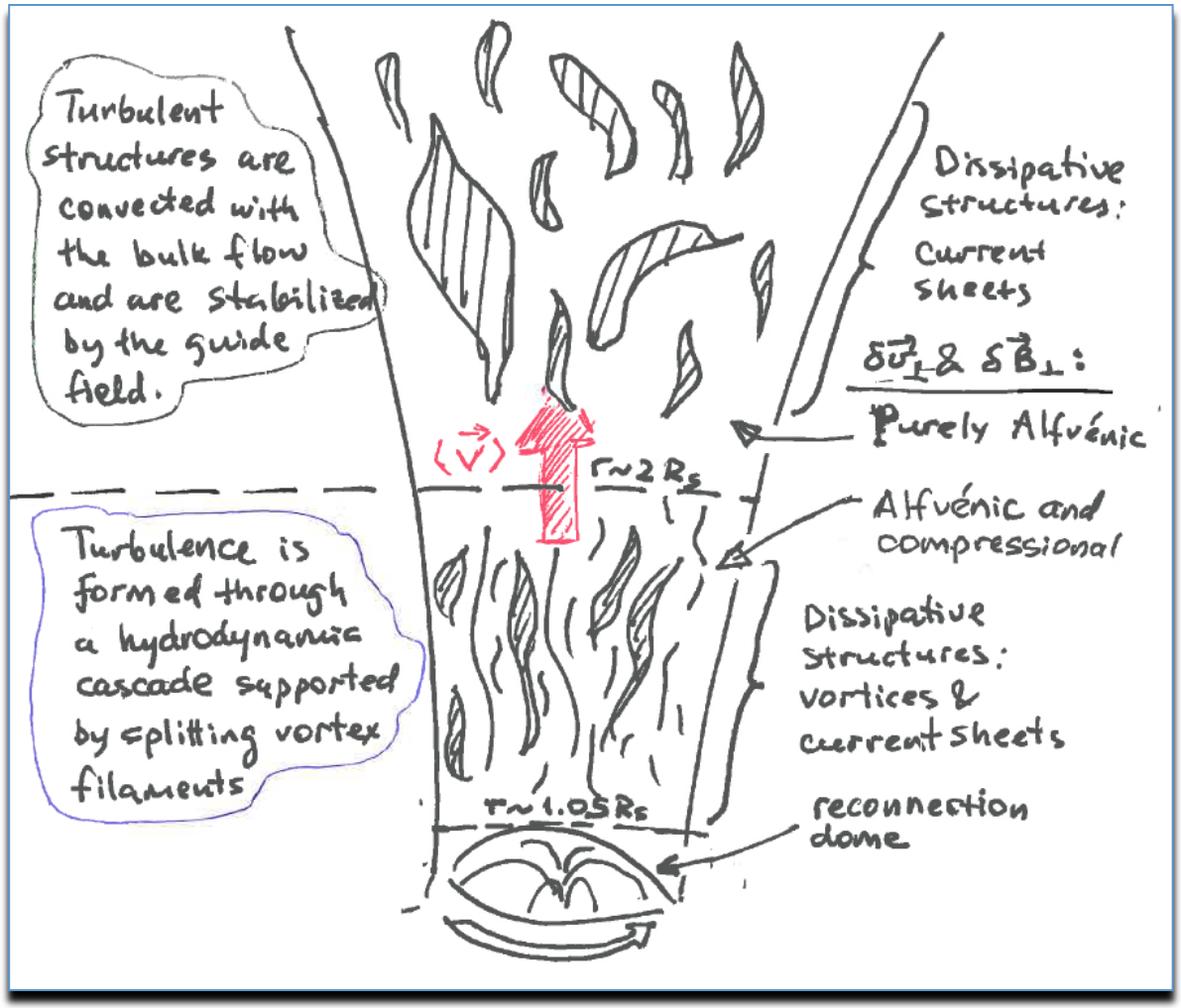


Confirming the 2D geometry of the dissipative structures



Top: one of the 3560 current sheets identified using cluster detection algorithm using an altitude-adjusted threshold set at 2 standard deviations above the local mean current density. Bottom: Scatterplots showing the dependence of current sheet volume and width on the linear size.

Schematic illustration of the two jet regions responsible for the production and transport of turbulent structures



Conclusions

- Our analysis of adaptive 3D MHD simulation runs confirms the presence of a reconnection-driven magnetic turbulence in the simulated plasma jet.
- We found spatial correlations of magnetic fluctuations inside the jet to be in an agreement with an intermittent scaling model of MHD turbulence proposed by Muller and Biskamp (PRL 2000).
- The jet contains two distinct spatial regions below and above $r = 2.0\ R_S$ dominated by compressional and shear-Alfven modes, correspondingly.
- <u>The lower portion of the jet</u> ($r<2R_S$) plays the leading role in the generation of the observed turbulent structures supported by a quasi one-dimensional energy cascade (splitting vortex filaments) and a two-dimensional dissipation (current sheets).
- <u>The upper portion of the jet</u> ($r>2R_S$) is marked by a passive outward propagation of already formed turbulent structures stabilized in this region by the mean magnetic field.
- The anisotropy of the magnetic fluctuations and the mutual spatial orientation of the current sheets are indicative of torsional Alfven wave packets consistent with the helical geometry of the jet imposed by the geometry of the reconnecting field.
- Some of the detected turbulent signatures can be recovered from single-point *in situ* observations.