Turbulent Reconnection, Flux-Freezing, and Coarse-Graining

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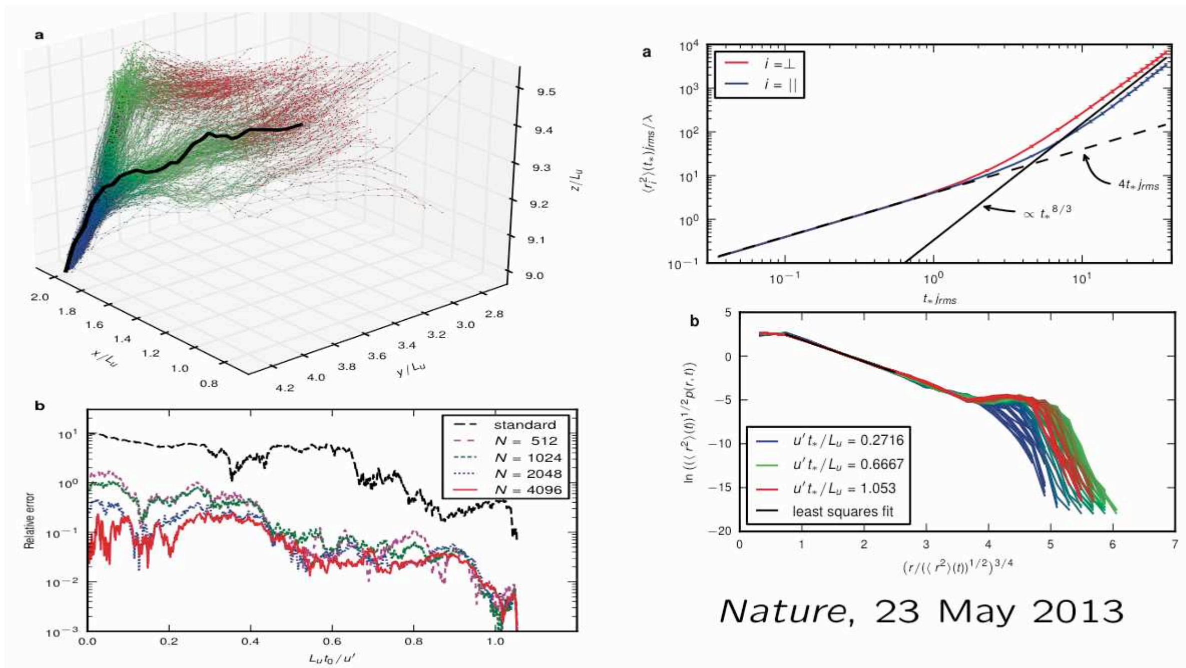
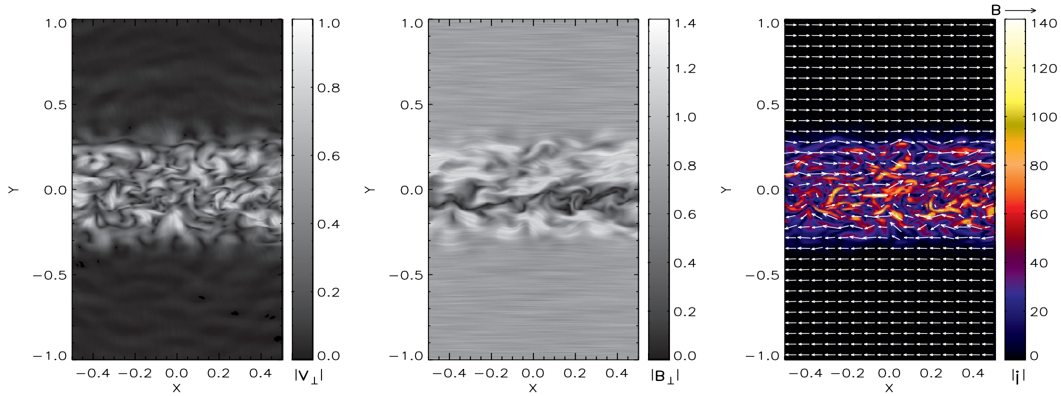
Flux-Freezing in NOT Violated in Turbulence, but Becomes Intrinsically Stochastic



Richardson dispersion of field-lines underlies the Lazarian-Vishniac 1999 theory (LV99).

Reconnection in the sense of violation of standard magnetic-flux conservation (J. M. Greene, 1993) occurs everywhere in a turbulent flow, not (only) at intense current sheets!

Large-Scale Turbulent Reconnection Involves Coherent Transport of Magnetic Flux



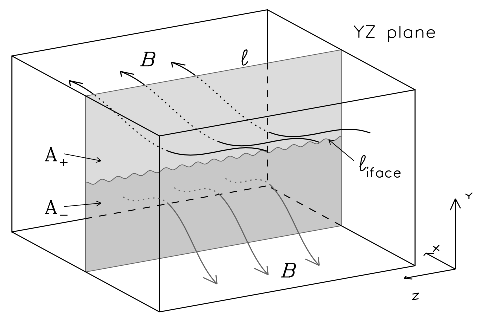


Figure 4. Schematic three-dimensional visualization of the reconnection rate evaluation. A_+ and A_- areas are defined by the sign of the B_x-component.

reconnection rate$=\int_{\text{iface}} 2\mathbf{E}\cdot d\mathbf{x}$, the rate of annihilation of reversed field-component

Note $\int_{\text{iface}} 2\mathbf{E}\cdot d\mathbf{x} = \int \partial_t |B_x| dA - \oint \text{sign}(B_x)\mathbf{E}\cdot d\mathbf{x}$, time evolution + transport thru boundaries

(Kowal et al., 2009)

The dominant "reconnection" electric field is motional field $\mathbf{E} = -\mathbf{u}\times\mathbf{B}$ *induced by outflow of already-reconnected field lines*

Challenge: The width of turbulent reconnection zone $\Delta = L_x M_A^2 \min\{(L_x/L_i)^{1/2}, (L_i/L_x)^{1/2}\}$ predicted by LV99 can be much smaller than L_i and L_x for $M_A = u_{rms}/v_A < 1$.

Coarse-Grained MHD can Account for Fast Reconnection without Microscale Physics

The *turbulent electric field* $\mathbf{E}_\ell^{\mathrm{turb}} = -\left[\overline{(\mathbf{u}\times\mathbf{B})}_\ell - \overline{\mathbf{u}}_\ell\times\overline{\mathbf{B}}_\ell\right]$ is of order $\delta u(\ell)\delta b(\ell)$. Note that

$$\overline{\mathbf{E}}_\ell^{\mathrm{Ohm}} = \eta\overline{\mathbf{j}}_\ell \sim \eta\delta B(\ell)/\ell \ll \mathbf{E}_\ell^{\mathrm{turb}} \text{ for } \ell\delta u(\ell) \gg \eta, \quad \overline{\mathbf{E}}_\ell^{\mathrm{Hall}} \sim \delta_i(\delta b(\ell))^2/\ell \ll \mathbf{E}_\ell^{\mathrm{turb}} \text{ for } \ell \gg \delta_i$$

Consider the *turbulent loop-voltage*

$$\overline{\Phi}_\ell(C,t) = \oint_{\overline{C}_\ell(t)} \mathbf{E}_\ell^{\mathrm{turb}}(\mathbf{x},t)\cdot d\mathbf{x}$$

with $\overline{C}_\ell(t)$ advected by the coarse-grained velocity $\overline{\mathbf{u}}_\ell$. Turbulent voltage is independent of the filtering scale ℓ (inside the inertial range) if and only if at least one of the following holds (Eyink & Aluie, 2006):

(i) Either $\mathbf{u}$ or $\mathbf{B}$ (or both) diverge to infinity at a point on the loop $C(t)$

(ii) A joint tangential discontinuity of $\mathbf{u}$ and $\mathbf{B}$ (current and vortex sheet) intersects the loop $C(t)$ in a set of finite length.

(iii) The material curve $C(t)$ is a fractal with infinite length.

(iii) is inapplicable in 2D, but it is expected in 3D. (iii) implies that small-scale turbulent reconnection can occur with vanishing micro-scale electric fields.

In GS95 and other theories ignoring intermittency

$$\mathbf{E}_\ell^{\mathrm{turb}} \sim (\varepsilon\ell_\perp)^{2/3}, \quad \mathbf{E}^{\mathrm{Ohm}} = \eta\mathbf{j} \sim (\eta\varepsilon)^{1/2}$$