Magnetic reconnection in dynamical systems driven by localized hydrodynamic instabilities

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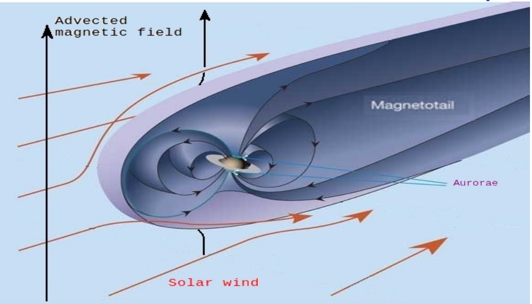
Outline

Magnetospheric environment: Northward "quiet" periods

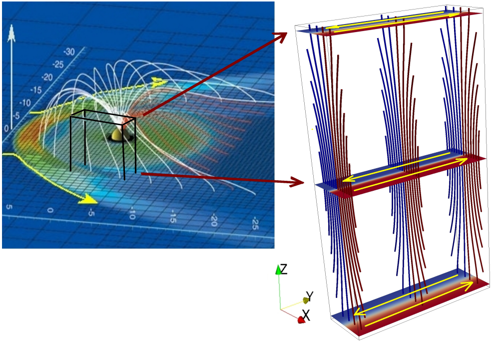


- Unexpected **efficient transport** between the solar wind and the magnetosphere
- **Inferred** $D_{eff} \simeq 10^9 m^2/s$
- **Cross-field diffusivity** (collisional or anomalous) **too small**
- Different mechanisms have been proposed $\longrightarrow$

1) "Double lobe reconnection" can generate a Low Latitude Boundary Layer, but it is **not sufficient.**[a]
2) Kinetic Alfvén Waves can contribute to the transport[b]
3) **Kelvin-Helmholtz instability**:
   - **"Robust"** phenomenon[c]
   - HD/MHD instability (no mixing) but is good **driver** for a **rich** plasma **dynamics** enhancing the transport

[a] Wing 06, Taylor 08 & Hasegawa 09 [b] Johnson [c] Kavosi 15

Minimal "geometrical" model for the magnetospheric flank



- Sheared velocity
- $\sim$ **northward** magnetic **field lines**
- **High-latitude stabilization**

- The fact that **High-Latitude** regions are **stable** with respect to the KH instability turns out to be **crucial**
- We need to simulate a **system** with at least **two inhomogeneity directions**:the one along the **velocity gradient** ($\hat{\mathbf{x}}$) and the one which KH **stability conditions change** ($\hat{\mathbf{z}}$)
- **2D equilibrium**, i.e. one **ignorable direction** along the flow ($\hat{\mathbf{y}}$)
- **3D numerical simulations** ($\hat{x}$, $\hat{k} \parallel \hat{y}$, $\hat{z}$):

$\rightarrow$ **KH** evolution & magnetic **reconnection**, **even** in the **absence** of an **initial magnetic shear layer**

2D Equilibrium: translation symmetry along y-direction

- Ideal **MHD** equations & **adiabatic** closure
- 2D (x,z) equilibrium configuration:

$$\mathbf{B} = B_y \mathbf{e_y} + \nabla\psi \times \mathbf{e_y} \ , \quad \psi = \psi(x, z)$$

- Actually a distorted 1D equilibrium configuration:

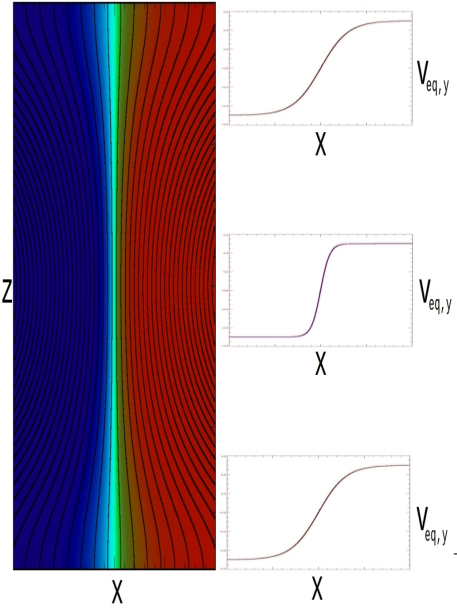
$$B_y = B_y(\psi) \ , \quad \mathbf{v} = v_y(\psi)\mathbf{e_y} \ , \quad \rho = \rho(\psi) \ , \quad p = p(\psi)$$

- **Simplified Grad-Shafranov** equation:

$$\nabla^2\psi = -4\pi \frac{d\Pi}{d\psi} \ , \quad \Pi = \Pi(\psi) = p + \frac{B_y^2}{8\pi}$$

- $B_y = 0$ & p uniformity $\rightarrow$ **Laplace equation**: $\nabla^2\psi = 0$
- A **simple solution**:
  $\psi(x, z) = 1/2\,[(1 + A)\,x + (1 - A)L_z/2\pi \ \sinh(2\pi x/L_z)\cos(2\pi z/L_z)]$

High-latitude stabilization



- **Hourglass-like** field **lines** (plane $x - z$)
- $v_{eq,y} = \Delta V_{eq}/2 \tanh(\psi/L_{eq,x})$

$\rightarrow$ **Stronger velocity gradient** at the **equators**
$\rightarrow$ KH vortices develop far faster here ($\gamma \propto \nabla v_{eq,y}$)

$\Rightarrow$ **High-Latitude stabilization**[a]

- Note that **strong magnetic gradient** exists at the x-**boundary**, even if **magnetic pressure** and **tension counterbalance**

$\Rightarrow$ **Hard** to **deal** using **kinetic codes**

[a] Faganello *PPCF* 2012

The advantage of a fluid description (MHD or Hall-MHD)

- **Compressible MHD** has an **hyperbolic set** of equations

$\Rightarrow$ At the x-boundaries we can use the **MHD characteristic decomposition**

$(\rho, T, \mathbf{v}, B_y, B_z) \leftrightarrow (L_a^{\pm}, L_s^{\pm}, L_f^{\pm}, L_0)$
where the Ls are the "non-linear contributions" of the alfvénic, magnetosonic and entropy modes

$$\partial/\partial t\ (\rho, T, \mathbf{v}, B_y, B_z) = F(L_a^{\pm}, L_s^{\pm}, L_f^{\pm}, L_0)$$

$$(L_a^{\pm}, L_s^{\pm}, L_f^{\pm}, L_0) = G(a, s, f, \rho, T, \mathbf{v}, B_y, B_z, \partial_x)$$

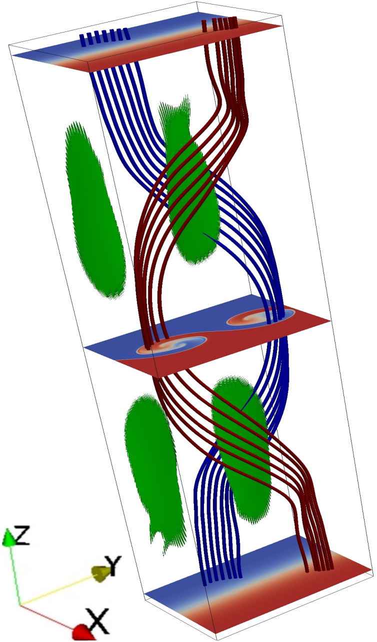
- In such a way: **Non-reflective** boundary conditions and **equilibrium sustainment**:[1]

$\rightarrow$ $L^{\pm}_{0,a,s,f} = L^{\pm}_{0,a,s,f}|_{internal\ \ points}$ for outgoing waves

$\leftarrow$ $L^{\pm}_{0,a,s,f} = L^{\pm}_{0,a,s,f}|_{equilibrium}$ for incoming waves

- In the case small-scale ($\sim d_i$) perturbations stay inside the box, we can include there the Hall term, resistivity, electron inertia, etc.

Simulation results



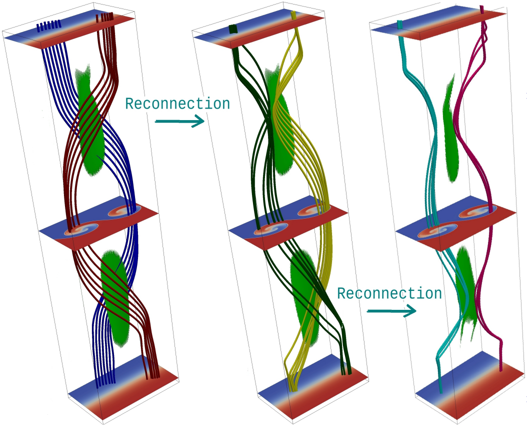
- **Low-latitude** region → **vortices**
- **High-latitude** regions → **stable**
- **Differential advection** for field **lines**
  - at V_{Solar_Wind} or $V_{Magnetosphere}$ at high latitudes
  - at $V_{phase} \simeq (V_{SW} - V_{Msph})$ at low latitud

⇒ **Arched solar wind & magnetospheric** field lines

⇒ **Mid-latitude magnetic shear layers**

→ **Favorable** conditions for **reconnection** to occur

Double mid-latitude reconnection



- **Fast reconnection** (Hall dominated) occurs in **both hemispheres**

⇒ Creates **double reconnected lines**

- They connect

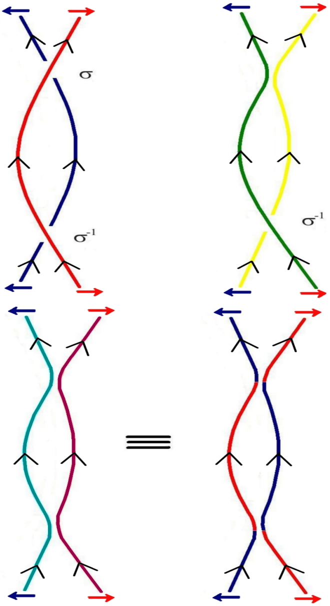
N pole → **red arm** → **N pole**

Flux tubes "closed" on the **Earth populated** by **solar-wind particles**

("Opened" flux tubes too.)

⇒ **Solar wind particles enter** the **magnetosphere**

Double mid-latitude reconnection: a dynamical mechanism



0) before reconnection → **not braided**

1) **First reconnection** → **braided** in the **southern hemisphere**

\+ **line feet** still **advected** in **opposite directions**

2) **Second reconnection** thus **must occur**

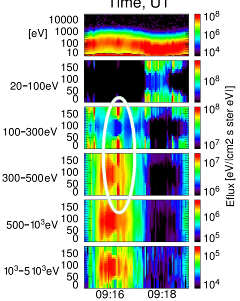
- Creates **double-reconnected field lines**
- If we suppose that **solar wind** plasma **captured** by "closed" line is added to the **magnetosphere** ⇒ $D_{KH} \sim 10^9 m^2/s$ **as expected**.

What is the model lacking?

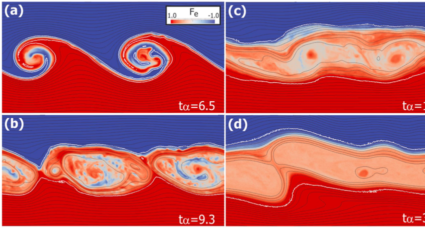
- **Magnetospheric** and **solar wind** plasmas have really **different densities** and **temperatures**.
- As soon as **new field lines connect** them **particles** (in particular electrons) **freely stream** along field lines
- As a consequence **important parallel fluxes** develop as **observed by satellites** (Bavassano 10, Faganello 14, Eriksson 16, Vernisse 16)
- Similar fluxes have been **reproduced** by **kinetic simulations** (Nakamura 14) **BUT** when looking only at the **“local” equatorial** dynamics and **neglecting** the **actual topology** of the magnetic field.

(when neglecting H-L stabilization, reconnection can occur

“locally” when an initial magnetic shear layer is considered.)



Electron flux Vs pitch angle and energy as observed by the THEMIS mission (Faganello 14)



Electron mixing ratio $F_e = n_{SW} - n_{Msph}/(n_{SW} + n_{Msph})$ (modified by parallel streaming) and in-plane magnetic field lines (in black) in a kinetic simulation of the “local” equatorial dynamics of KH vortices (Nakamira 14).

Model improvement

- A **kinetic code would** naturally **reproduce** the fluxes, for each energy band, but it would be **difficult to menage** the **BC** at the x-boundary in order **to sustain** the **equilibrium** gradients.
- The **characteristic decomposition** of the boundary is a **powerfull tool**
$\Rightarrow$ A **fluid code** (plus a possible "buffer zone" that gradually switchs off non-MHD terms at the boundaries) **can menage** such **equilibria**.
- **Adding** parallel **fluxes to** the **fluid model** could be the **practical solution**:
- Including fluxes **at different energies** (for reproducing satellite data) seems to be an **"impossible dream"**.
- **Adding** an electron/ion **heat flux** to the pressure evolution equation would at least **reproduce** plasma **mixing along** a reconnected **field lines**, for a **better estimation of** D_{KH}.

Model improvement

- **Note** that:
  - **Collisions** are largely **negligible**: a **diffusive heat** flux ($K_{\|}\nabla^2 T$)would be **hardly justified**.
  - **Collisionless heat fluxes** such those included in **Landau-fluid** models (see Passot's presentation) suppose a **nearly constant temperature** along field lines + small perturbations **while** in our case $\mathbf{\Delta T/T \sim 1}$.
- **Any suggestion is welcome** :))))