Kelvin-Helmholtz instability and magnetic reconnection at the Earth's magnetopause : 3D simulation based on satellite data

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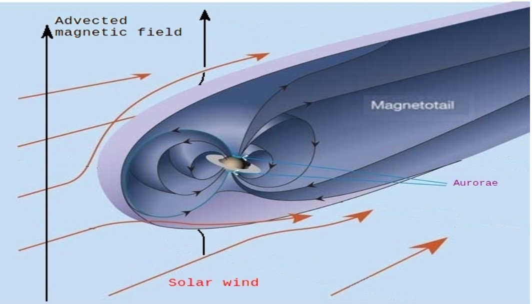
Colloque PNST 2022, 19/05/2022

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**

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[a] Wing 06, Taylor 08 & Hasegawa 09 [b] Nakai 01 [c] Kavosi 15

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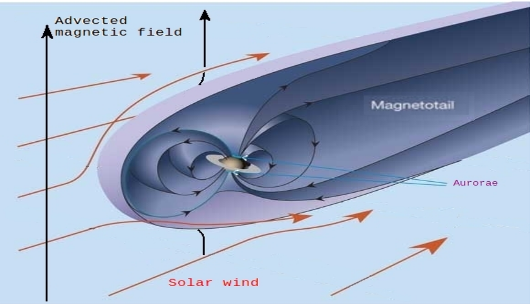

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- Different mechanisms have been proposed $\longrightarrow$

1) **"Double lobe reconnection"** can generate a Low Latitude Boundary Layer, but it is **not sufficient.**[a]
2) **Kinetic Alfvén Waves** at the magnetopause can strongly enhance cross field diffusion, but **not ofte[n] observed** and sometimes excluded[b]

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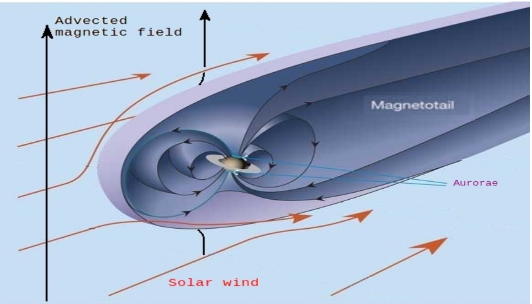

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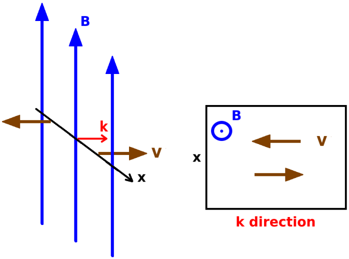
2) **Kinetic Alfvén Waves** at the magnetopause can strongly enhance cross field diffusion, but **not ofte** **observed** and sometimes excluded[b]
3) **Kelvin-Helmholtz instability**:
   - **"Robust"** phenomenon[c]
   - A good **driver** for a **rich dynamics**

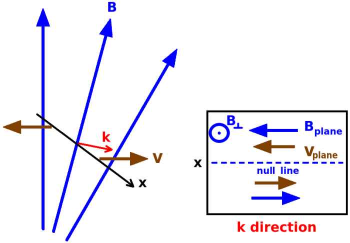
[a] Wing 06, Taylor 08 & Hasegawa 09 [b] Nakai 01 [c] Kavosi 15

KHI as a large-scale (MHD) flute mode

- KHI is **the instability** of a **sheared velocity configuration**
- Velocity shear half-width $a \sim$ several d_i $\quad\rightarrow\quad$ KHI develops as a large-scale ($\sim$ tenths of d_i), **nearly magnetohydrodynamic mode**
- $\vec{k} \cdot \Delta\vec{V}$ provides the energy source, while $\vec{k} \cdot \vec{B}$ is the sink (**magnetic tension** is **stabilizing**)
- For **magnetospheric parameters**, **KHI** develops as a **flute mode**, with $\vec{k} \cdot \vec{B} \simeq 0$

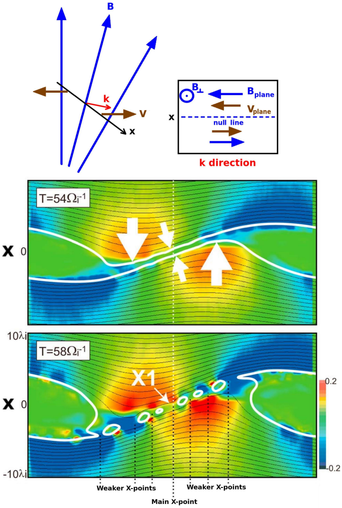


Without magnetic rotation
$\vec{k} \cdot \vec{B} = 0$ everywhere.



With magnetic rotation
$\vec{k} \cdot \vec{B} = 0$ where $\partial_x V$ is max **(at magnetopause)**

Current pinching: Vortex Induced Reconnection

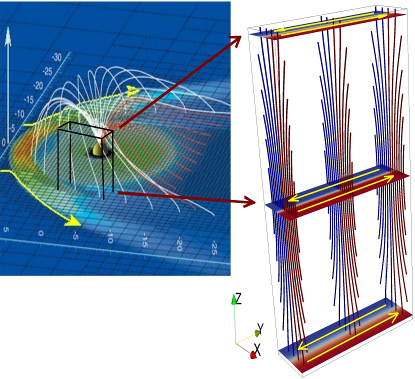


- $\partial_x V_{plane} > \partial_x V_{A,plane} \Rightarrow$ **KHI pinches** the **original current sheet** and **force reconnection** to occur $\rightarrow$ **Type I Vortex Induced Reconnection**.
- **VIR creates** field **lines crossing** the original **frontier** between the magnetospheric and SW plasmas.
- **3D kinetic** simulations show the **streaming** of **particles along reconnected lines** $\rightarrow$ formation of a **mixing layer**[a].
- Effective $D_{eff} = O(10^9 m^2/s)$ or **even higher**[b].

[a]Nakamura JGR 13; [b]Nakamura Nat 17

Bottom figures from Nakamura JGR 11

Current creation by high-latitude stabilization



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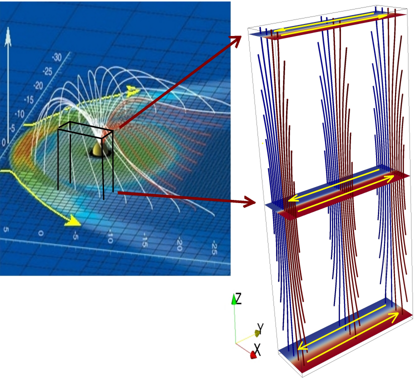
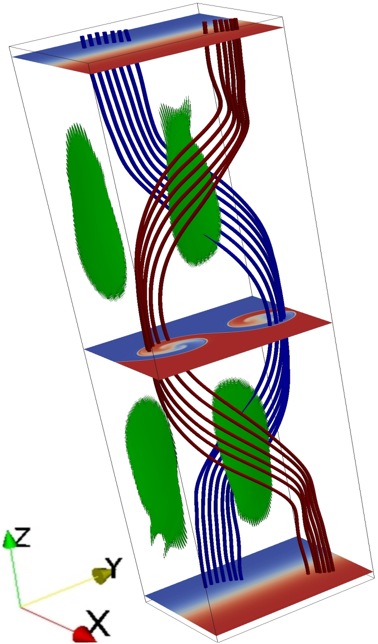


- **Vortices create** the **conditions** for reconnection **even if**, at low-latitude, there is **no magnetic rotation** (no initial current)
- The **equatorial** region is **unstable** since:
  - **velocity shear exists**
  - **reduced magnetic tension**
- **High latitudes**
  $\rightarrow$ complex configuration
  $\rightarrow$ **total stabilization**

Current sheets at mid-latitudes (resistive Hall-MHD sim.)



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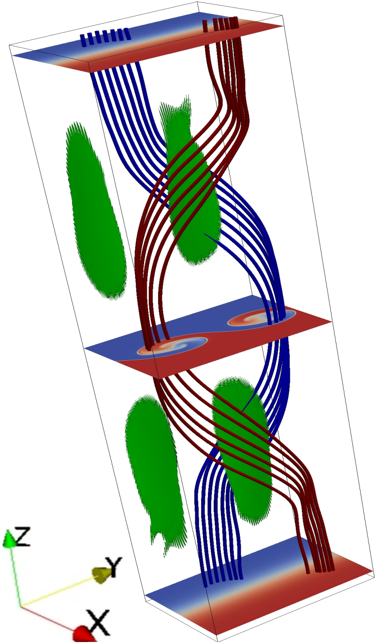

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- **Differential advection** for field **lines**
  - at V_{Solar_Wind} or $V_{Magnetosphere}$ at high latitudes
  - at $V_{phase} \simeq (V_{SW} + V_{Msph})/2$ at low latitud

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

⇒ **Mid-latitude current sheets**

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

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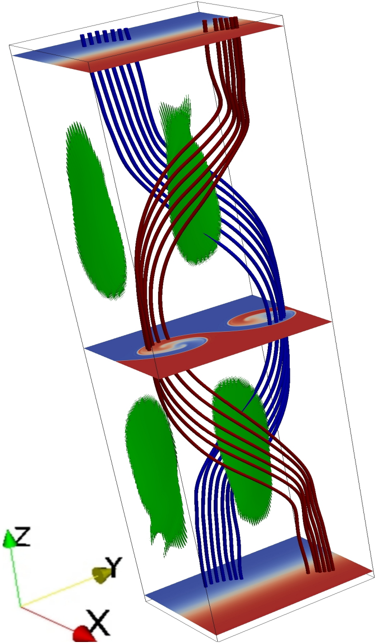

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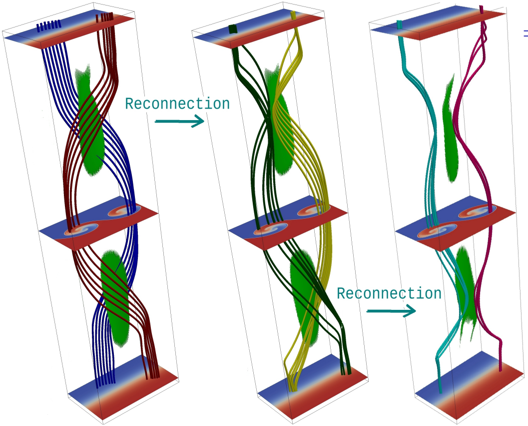
Mid-latitude reconnection



- **Reconnection** occurs in **both hemispheres**

⇒ Creates **double reconnected lines**

- They connect

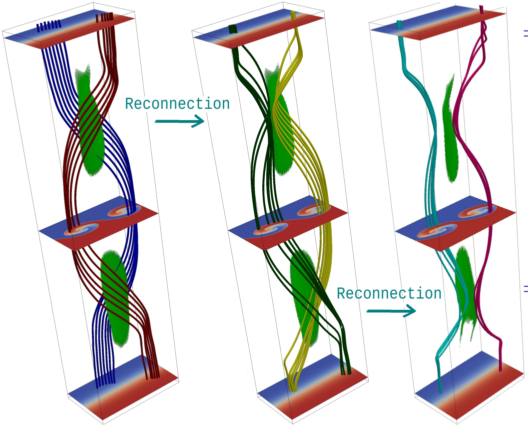
N pole → **red arm** → **N pole**

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

("Opened" flux tubes too.)

[a] Faganello EPL 2012; [b] Johnson JGR 09

Mid-latitude reconnection



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

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

- Effective[a] $D_{eff} \simeq 10^9 m^2/s$
- Specific **entropy increases**[b]

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[a] Faganello EPL 2012; [b] Johnson JGR 09

Motivations

- Signatures of **VIR** has been **measured** by **satellites**, close to the **equatorial plane**[1].
- **Signatures** of **Mid-latitude reconnection** have been found too[2]
- On **September 8th 2015**, **MMS** detected signatures of **both VIR** and **Mid-latitude reconnection**[3]
- It **observed** an **asymmetric distribution** of **"remote" reconnection events**, with **more** events **southern of** the **satellites**[3]
- We want to understand the **role** of the **two mechanism**, their **competition/cooperation** in determining the **magnetic evolution** and the **transport** properties of the **SW/magnetosphere frontier**

[1] Eriksson JGR 09, Eriksson GRL 16; [2] Faganello EPL 14; [3] Vernisse JGR 16

A model for the magnetospheric flank: 2D equilibrium with translation symmetry along the flow direction (y-direction)

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

$$\vec{B} = B_y \hat{e}_y + \nabla\psi \times \hat{e}_y \ , \quad \psi = \psi(x,z)$$

- Actually a distorted 1D equilibrium configuration:

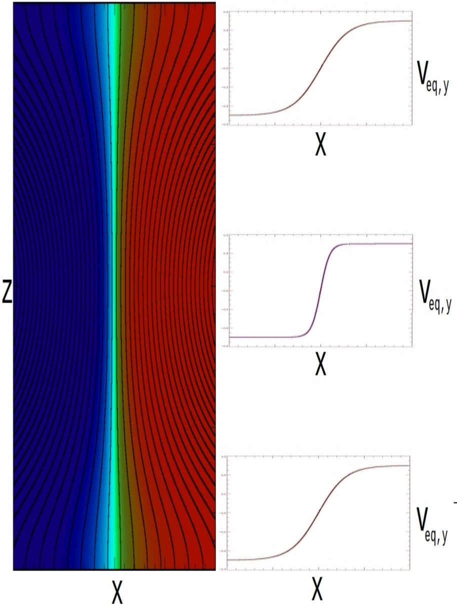
$$B_y = B_y(\psi) \ , \quad \mathrm{V} = V_y(\psi)\hat{e}_y \ , \quad \rho = \rho(\psi) \ , \quad p = p(\psi)$$

- **Simplified Grad-Shafranov** equation:

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

- Π uniformity $\rightarrow$ **Laplace equation**: $\nabla^2\psi = 0$
- A **suitable 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

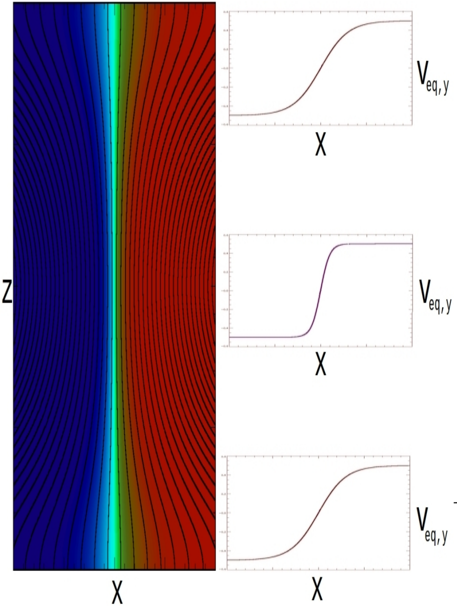


- **Hourglass-like** ψ-isosurfaces (provide the dominant z-component of the magnetic field)
- $V_{eq,y} = \Delta V_{eq}/2 \tanh(\psi/a)$

$\rightarrow$ **Stronger gradient** at the **equators**

[a] Faganello *PPCF* 2012

High-latitude stabilization



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- $V_{eq,y} = \Delta V_{eq}/2 \tanh(\psi/a)$

$\rightarrow$ **Stronger gradient** at the **equators**

- $\gamma_{KH} \propto$ gradient

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

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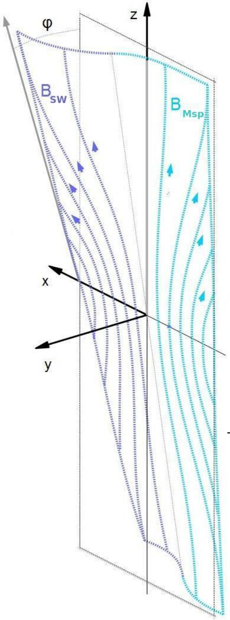
[a] Faganello *PPCF* 2012

High-latitude stabilization & magnetic rotation

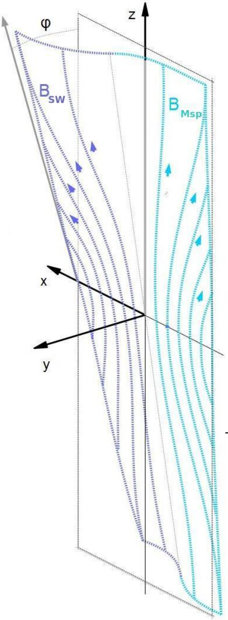


- $B_{eq,y} = B_{\parallel flow}(1 + \tanh(\psi/a))$

→ **Magnetic rotation**

[a] Fadanelli JGR 18

High-latitude stabilization & magnetic rotation



- $B_{eq,y} = B_{\| flow}(1 + \tanh(\psi/a))$

$\rightarrow$ **Magnetic rotation**

- Magnetic **rotation** & **High-latitude stabilization**

$\Rightarrow$ **VIR** and **Mid-latitude** reconnection, **both at play**.

- $B_{\| flow}$ **breaks** the N-S **symmetry** is **broken**, for KH vortices and reconnection too[a].

[a] Fadanelli JGR 18

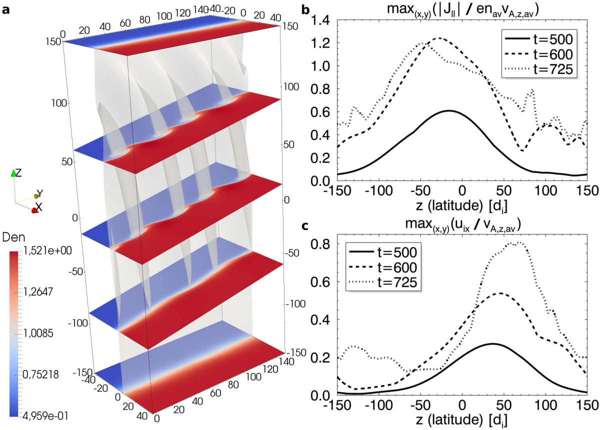
Data-based parameters for Hall-MHD simulation

- $\Delta V_{eq} \simeq 350 Km/s$
- $B_z \simeq 67 nT$
- $B_{flow} \simeq -20 nT$
- $n \sim 5.7 cm^{-3} \longrightarrow 20.1 cm^{-3}$
- $T_{th} \sim 2800 eV \longrightarrow 200 eV$
- Shear half-width $a \simeq 900 Km$ so that $\lambda_{KH} \sim 12000 Km$

- $L_y = 2\lambda_{KH}$ (two vortices in the box) ; $ny = 512$
- $L_z = 8\lambda_{KH} \sim 10^5 Km$ i.e. $\pm 45^\circ$; $nz = 512$
- $L_x = 2.4\lambda_{KH}$; $nx = 900$ $\tau_{res,eq} = a^2/\eta \simeq 20\, t_{max,sim}$

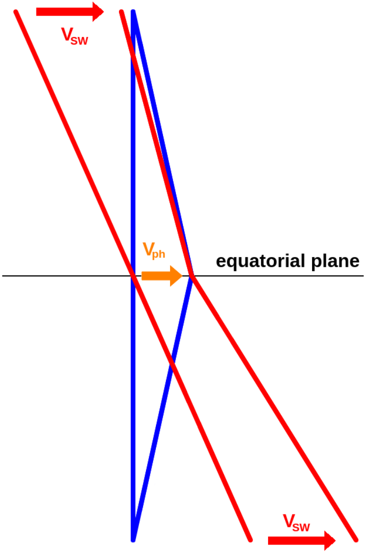
- Periodic boundary conditions (BC) along $y - z$ directions.
- BC along x-direction based on MHD characteristics:
  • Transparent boundaries • Sustains the 2D equilibrium

KH and current dynamics (resistive Hall-MHD simulation)



- **Oblique** $\vec{k}$, with $\vec{k} \cdot \vec{B}|_{magnetopause} \simeq 0$
- High-latitude stabilization
- **Asymmetric evolution**
- Folded magnetopause ($\psi = 0$ isosurface)

Differential advection & N-S asymmetry



- As soon as **field lines** are **caught into** the **vortices**, field **lines** are **advectect differently** at **low/high**-latitudes
- As a consequence **magnetic rotation** is **enahanced** in **one hemisphere** (the southern one for $B_{||flow} < 0$) while it is **lowered** in the **opposite one**.
- KH **vortices shift** where **rotation lowers** (smaller stabilization)

[a] Vernisse JGR 16, Vernisse JGR 20

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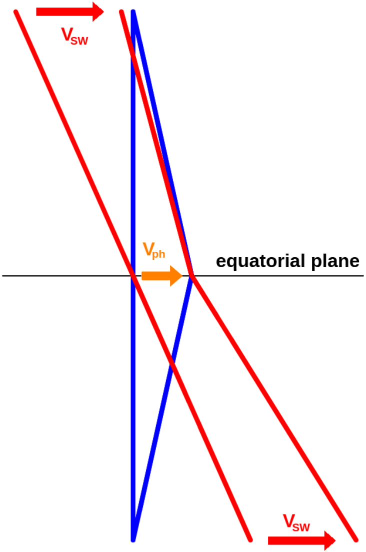

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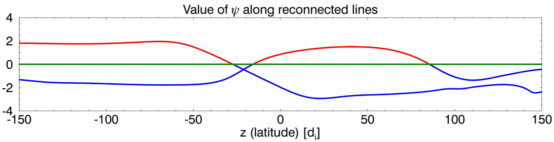
- KH **vortices shift** where **rotation lowers** (smaller stabilization)
- Reconnection occurs as **both VIR** and **Mid-latitude one** but prefers the hemisphere where rotation (and J) rises.
- We **expect more reconnection** events in the **southern hemisphere**, as **observed** by **MMS** on 08/09/2015[a].

[a] Vernisse JGR 16, Vernisse JGR 20

How to find reconnected lines in 3D, complex simulations ?

- ψ and $\vec{B}$ are **advected independently**:
  - ψ follows an **ideal evolution**
  - $\vec{B}$ the **true** resistive Hall-MHD one and **reconnects**.
- A jump of ψ along a line indicates reconnection.
- Current sheets, and reconnection, are at the magnetopause.
- Define a **line** as **"reconnected"** if $|\Delta\psi|_{along\ line} > a/2$ **across the magnetopause** ($\psi = 0$ isosurface).



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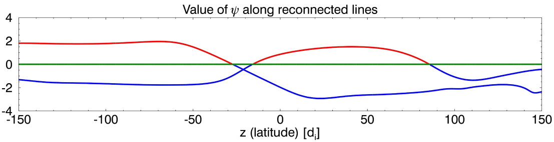
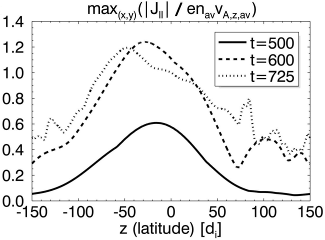
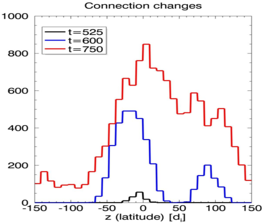


- 22500 lines integrated at each time $\longrightarrow$ **statistical analysis**
- Define **reconnection event** as a **crossing** of the **magnetopause** by a reconnected line.

Reconnection dynamics and its latitude distribution





- **Early nonlinear evolution** ($t = 500\Omega_{ci}^{-1}$ and $600\Omega_{ci}^{-1}$):
  - The **original current sheet** is **compressed** around the **equators** $\rightarrow$ **VIR**
  - This **main current sheet** gradually **shifts southward** as well **as VIR** events
  - A **second current peak** arises in the **northern hemisphere** $\rightarrow$ **mid-latitude reconnection**.

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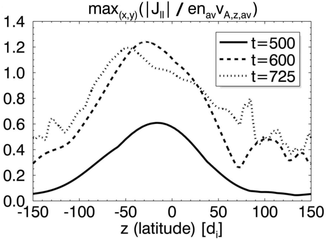

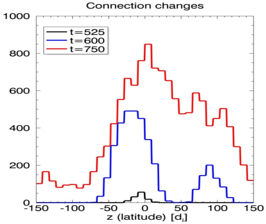

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- Late nonlinear evolution ($t = 725$): secondary small-scale KH vortices grows in between the two main current peaks. Reconnection is forced there and a wider distribution is formed.

Number of *in-situ* and *remote* events

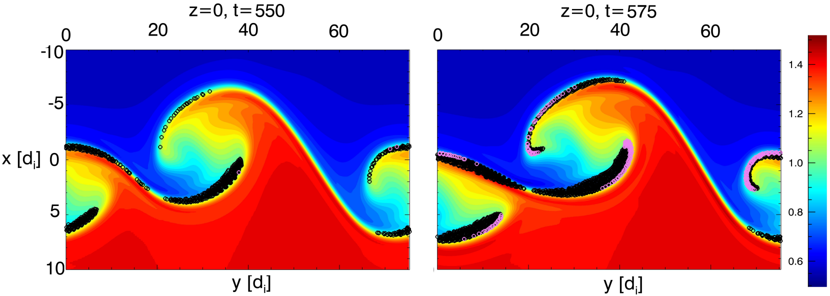
- Defined **with respect** to a virtual **satellite** at the **equators**.

Time interval	Southern h.	In-situ	Northern h.
501-525	35	81	2
526-550	377	201	7
551-575	677	321	327
576-600	730	268	590
601-625	544	145	686
626-650	694	247	953
651-675	488	356	1346
676-700	147	328	747
701-725	-	120	757

- **Early nonlinear** phase, as in the **MMS event**[1]:
  more remote events in the **southern hemisphere**
- We expect more *remote* events in the northern hemisphere if satellites would be further downstream along the flank

[1] Vernisse JGR 20

Topology chart in the equatorial plane: satellite comparison



- **Black circles**: **crossing** points of **once-reconnected** lines
  $\longrightarrow$ **expected** *in-situ* signatures or *remote* **signatures coming from** the **south**.
- **Purple circles**: **crossing** points of **double-reconnected** lines
  $\longrightarrow$ **also** *remote* **signatures coming from** the **north**.
- In very **good agreement** with particle **distribution functions** observed by **MMS**[1].

[1] Eriksson Front 2021

Conclusions

- **VIR** and **mid-latitude reconnection cohexist** when an **initial magnetic rotation** is **present**.
- They lead to a **complex magnetic evolution** with an **asymmetric distribution** of **reconnection** events[1].
- The **predicted locations** for magnetic **reconnection** are **in good agreement** with reconnection **signatures** observed by **MMS**[2].
- **Even if** the system evolves **asymmetrically**, the number of **double-reconnected lines** reaches **40% of reconnected lines**[1] and **could explain** the **specific entropy incresing** that is observed **across the magnetopause**[3].
- The **effective diffusion coefficient** associated to reconnection is **large enough** for explaining the **observed transport**[1]

[1] Sisti GRL 19, Faganello PPCF 22; [2] Vernisse JGR 16, Eriksson Front 21; [3] Johnson JGR 09

Thank you for your attention.

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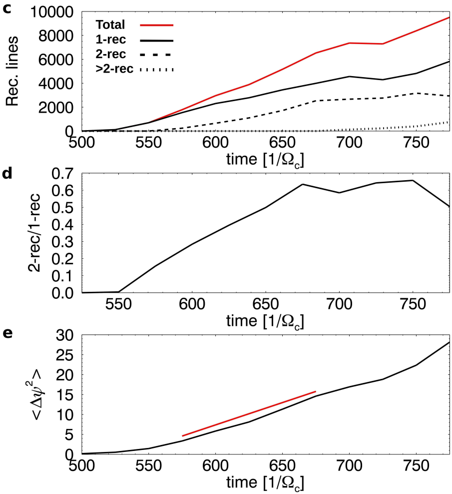
Once/double reconnected lines and effective diffusion



- # of reconnected lines growth with time
- # of **double-reconnected** lines reaches **70%** of # of **once-reconnected**.
- ψ **measures** the **distance from** the perturbed **magnetopause** (at $\psi = 0$).

$\Rightarrow$ $< \Delta\psi^2 >$ over all lines **measures** the **effective** magnetic **diffusion** due to **reconnection**.

- Effective $D_{eff} \approx 10^{10} m^2/s$:)))

A minimal plasma model: resistive Hall-MHD

Continuity equation

$$\partial n / \partial t + \nabla \cdot (n\vec{U}) = 0$$

Momentum equation

$$\partial (n\vec{U}) / \partial t + \nabla \cdot [(n\vec{U}\vec{U}) + (P\overleftrightarrow{I} - \vec{B}\vec{B})] = 0 \quad ; \quad P = P_i + P_e + |\mathrm{B}|^2/2$$

Adiabatic closures

$$\partial (nS_{i,e}) / \partial t + \nabla \cdot (nS_{i,e}\vec{u_{i,e}}) = 0 \quad ; \quad S_{i,e} = P_{i,e} n^{-5/3}$$

Faraday & current equations

$$\partial \vec{B} / \partial t = -\nabla \times \vec{E} \quad ; \quad \vec{J} = \nabla \times \vec{B}$$

Generalized Ohm's law

$$\vec{E} = \underbrace{-\vec{U} \times \vec{B} + \vec{J}/n \times \vec{B}}_{-\vec{U}_e \times \vec{B}} - \frac{1}{n} \nabla P_e + \eta \vec{J}$$

Boundary conditions

- **MHD characteristic decomposition** at the x-**boundaries**

$$(L_a^\pm, L_s^\pm, L_f^\pm, L_0) \leftrightarrow (\rho, T, \mathrm{v}, B_y, B_z)$$

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

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

- **Non-reflective** boundary conditions (left boundary) and **equilibrium sustainment**:[a]

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

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

[a] Faganello *NJP* 2009

Late nonlinear evolution