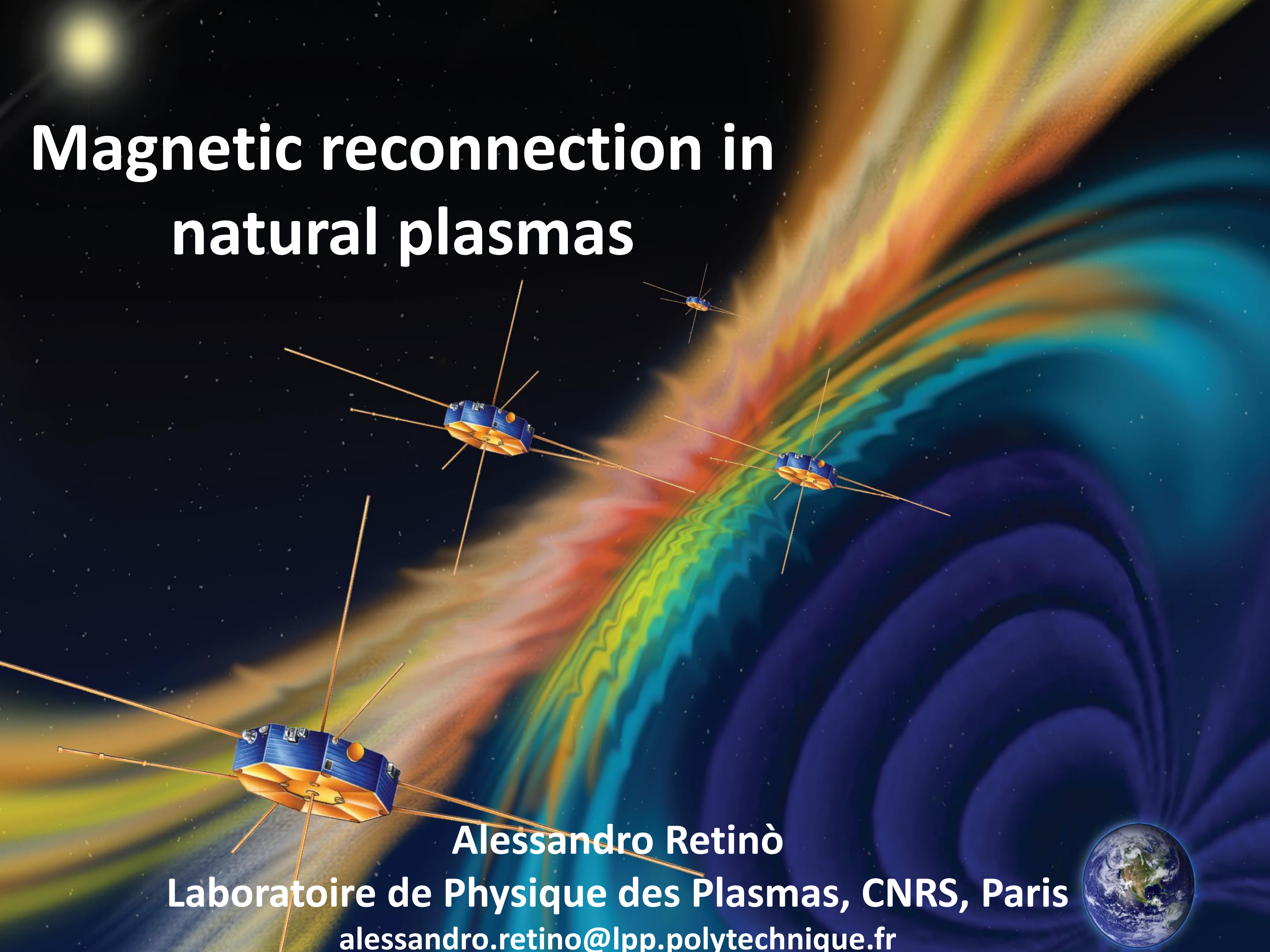
Magnetic reconnection in natural plasmas



Alessandro Retinò
Laboratoire de Physique des Plasmas, CNRS, Paris
alessandro.retino@lpp.polytechnique.fr

Other related tutorials

Monday:

- Dudok de Wit: Data Analysis
- Maksimovic: Space plasmas measurement techniques

Wednesday:

- Loureiro: Reconnection theory

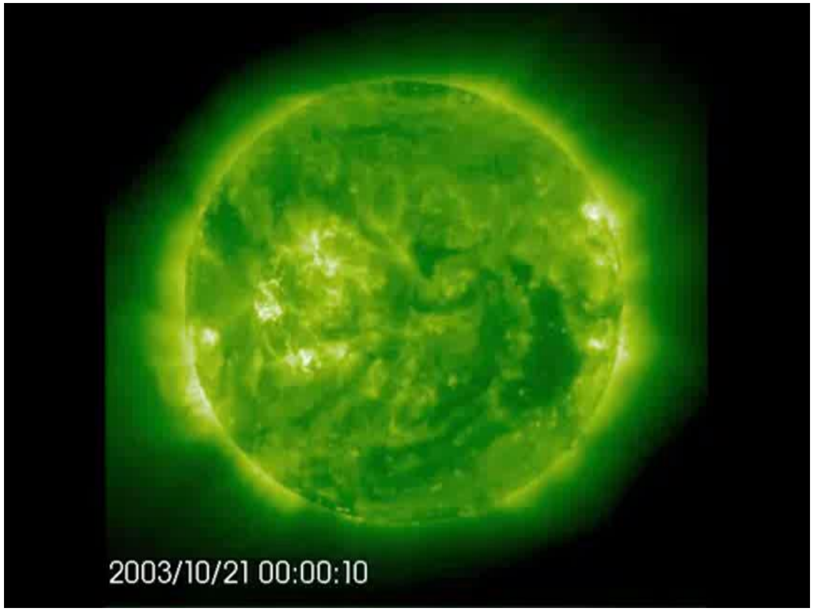
Thursday:

- Zohm: reconnection in fusion
- Cerutti: Particle acceleration in reconnection sites (astro)
- Carter: Reconnection experiments (lab)

Outline

- Magnetic reconnection
    - Basic concepts
    - key quantities
    - definition(s) of reconnection
    - models and simulations
- Measurements of reconnection in space
    - remote
    - in situ
- Key open issues:
    - Microphysics of reconnection
    - Reconnection & Turbulence
    - Particle acceleration
- Future spacecraft measurements relevant for reconnection
- Summary
- Suggested references

Basics of reconnection



Solar flare recored from the Extreme Ultraviolet Imager on ESA/ SOHO in the 195A emission line

- Magnetized plasma everywhere in Universe
- Formation of current sheets
- Dissipation of electric currents in current sheets leads to plasma energization
- R. G. Giovanelli, *A Theory of Chromospheric Flares*, Nature, 1946

The frozen-in condition

MHD approximation(L>>ρ_i):

$$\mathbf{E}' = \mathbf{E} + \mathbf{V}\times\mathbf{B} = \frac{\mathbf{J}}{\sigma}$$

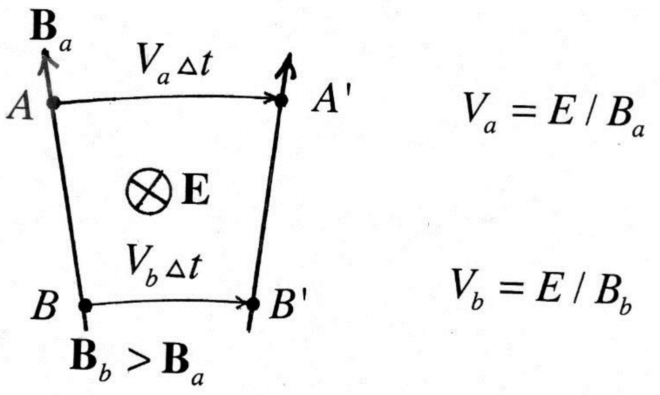
$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B}) + \frac{1}{\mu_0\sigma}\nabla^2\mathbf{B}$$

For infinitely conductive plasma ($R_m=\mu_0\sigma LV>>1$): :

$$\mathbf{E}' = \mathbf{E} + \mathbf{V}\times\mathbf{B} = 0$$

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B})$$

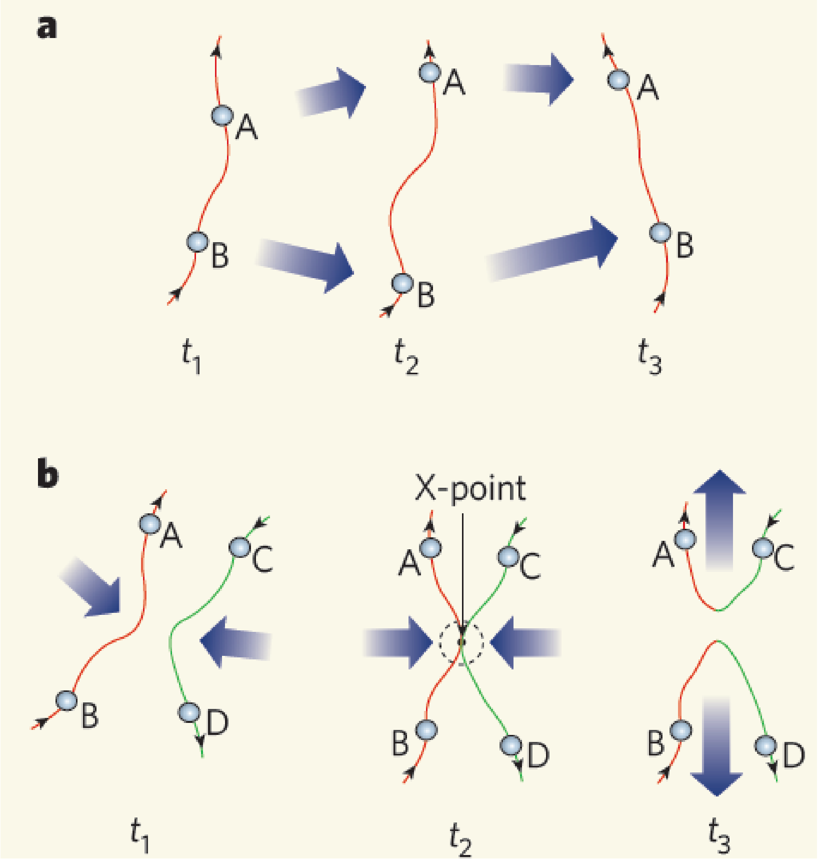
Frozen-in flux theorem (Alfvén, 1942):
The total magnetic flux through a surface delimited by a closed curve moving with an infinitely conducting plasma is constant



Implications:

- All plasma elements and magnetic flux contained at a given time in a magnetic flux tube will remain in the same flux tube at all later times
- We can define unique flux tube velocity W=ExB / B^2 so that W=$V_\perp$

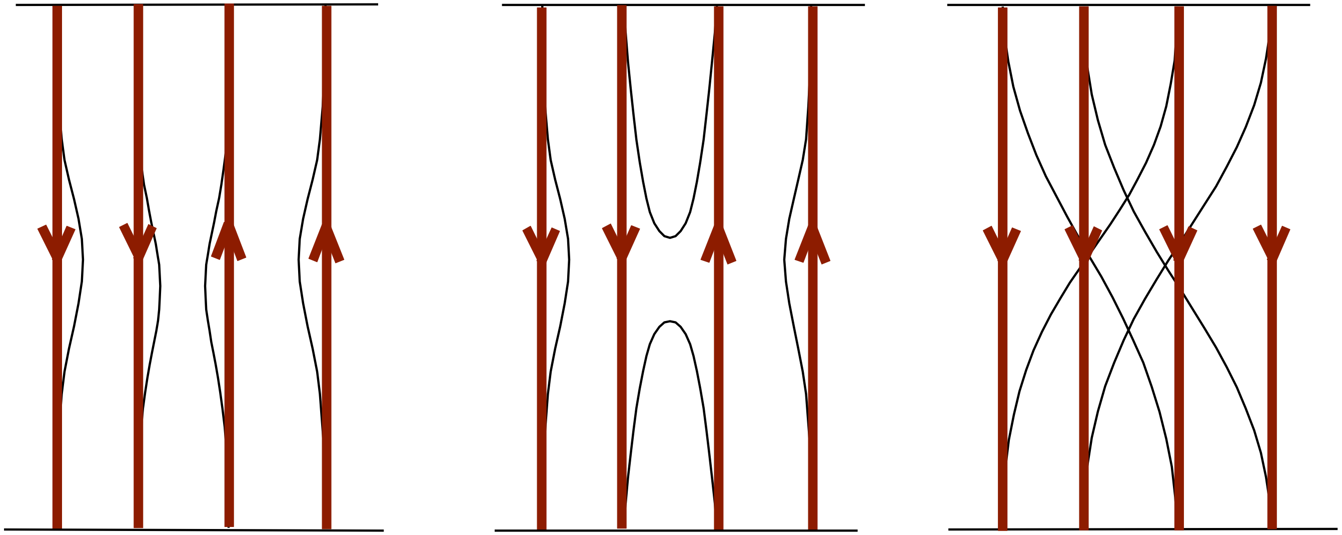
Reconnection: breaking of the frozen-in condition



[Adopted from Paschmann, Nature, 2006]

- $E' \neq J/\sigma$ (finite conductivity within the diffusion region)
- $E_{||} \neq 0$
- $\mathbf{V}_{\perp} \neq \mathbf{W}$

Magnetic topology



t1 < t2

$E_{||}=0$

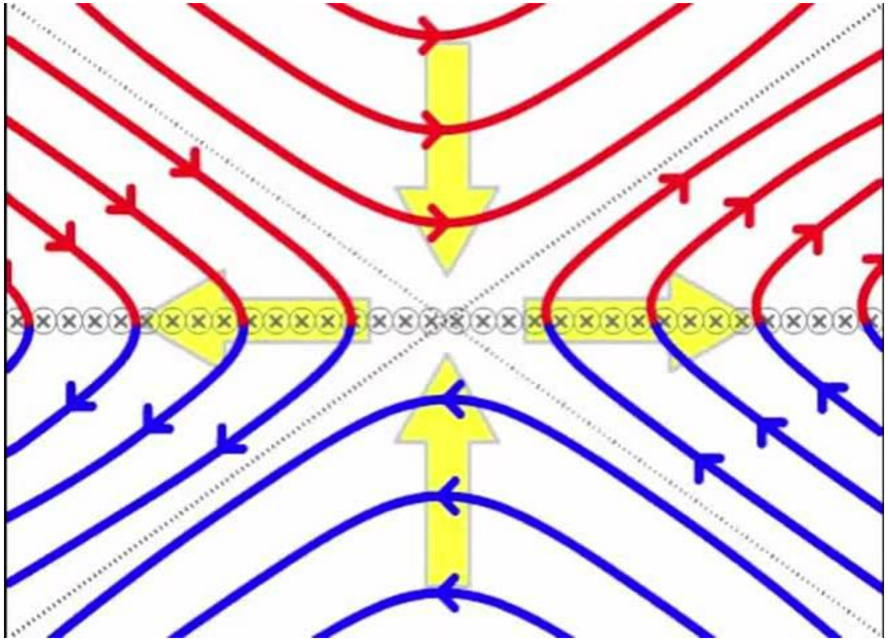
$B=0$

$E_{||}\neq 0$

Topology conserved

Topology not conserved

Reconnection: key properties

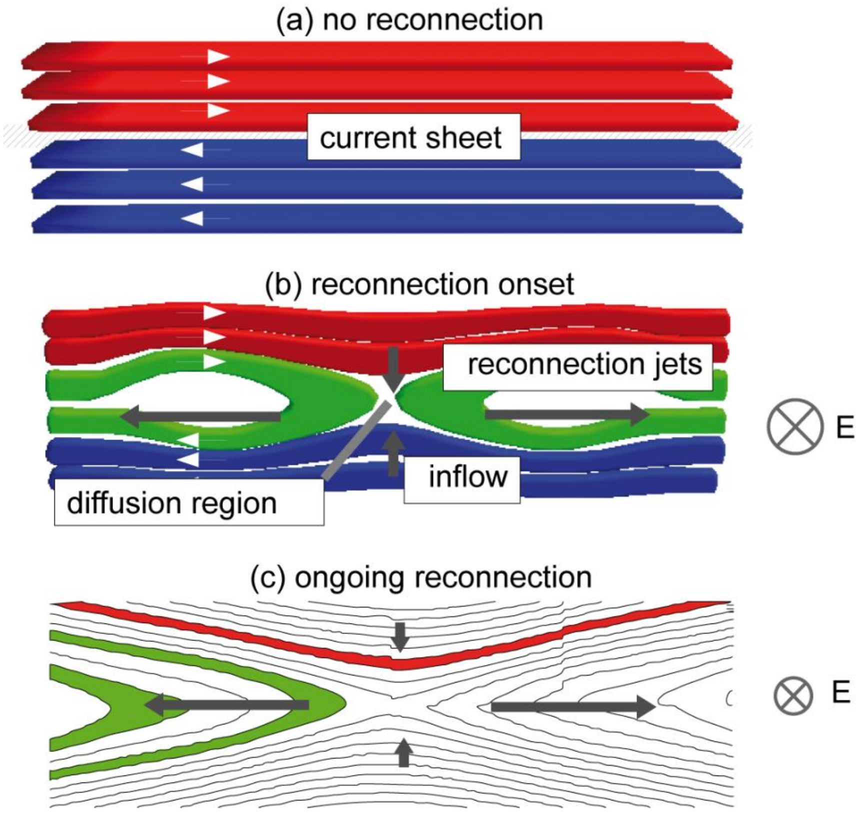


⊗ $\mathbf{J} = \nabla \times \mathbf{B}$
current sheet

Breaking of frozen-in condition in current sheets leading to:

- Magnetic topology change
- Plasma transport across current sheets
- Energy dissipation:
  - Plasma heating
  - Plasma acceleration
  - Non-thermal particle acceleration

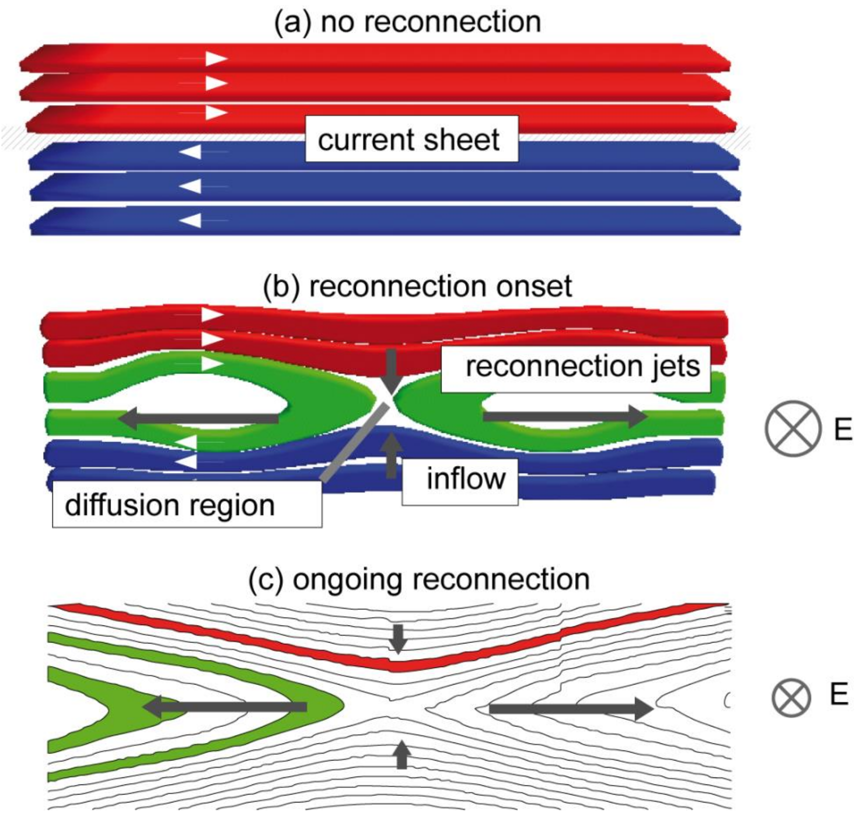
Key reconnection quantities (I)



[Adopted from Vaivads et al., Space Sci. Rev, 2006] .

- **Current sheet**: (locally) planar region of strong current
- **Reconnection plane**: plane containing reconnecting magnetic field
- **X-point/reconnection site**: region where reconnection starts
- **X-line**: line connecting X-points
- **Guide field**: B field along X-line
- **Onset**: time when reconnection starts
- **Diffusion region**: region where frozen-in condition breaks (containing X-point)

Key reconnection quantities (II)



[Adopted from Vaivads et al., Space Sci. Rev, 2006] .

- **Reconnection electric field**: out-of-plane E field due to non ideal-terms
- **Inflow**: magnetic flux tubes motion towards X-point
- **Rate R**: how fast flux tube reconnect
- **Normal component $\mathbf{B_N}$**: component of B perpendicular to reconnecting filed in reconnecting plane
- **Reconnecting jets**: accelerated plasma flows $\mathbf{J}\times\mathbf{B} = -\nabla\left(\frac{B^2}{2\mu_0}\right) + \frac{1}{\mu_0}\nabla(\mathbf{B}\cdot\mathbf{B})$
- **Reconnection bulge:** reconnected flux tube associated to increased R
- **Flux rope/magnetic island**: closed magnetic flux tube between to X-points

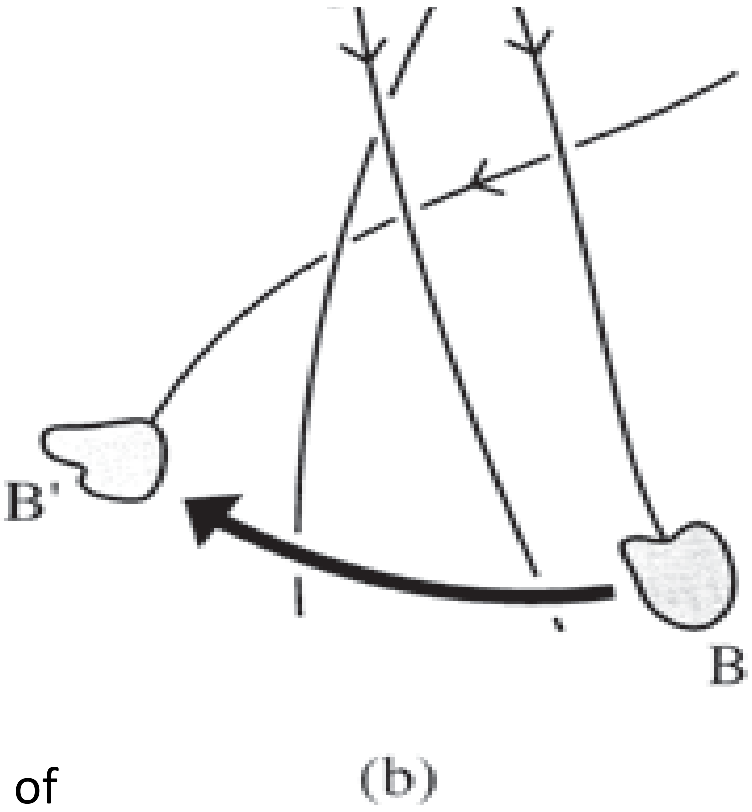
Definition(s) of reconnection

General Magnetic Reconnection (3D):
“breakdown of magnetic connection due to a localized non-idealness “
Necessary and sufficient condition:

$$\int_{D_R} E_{\parallel} ds \neq 0$$

2D definitions:

- X-point where two separatrices meet
- **E** along the X-line
- change in magnetic connectivity (violation of frozen-in condition)
- plasma flow across separatrices



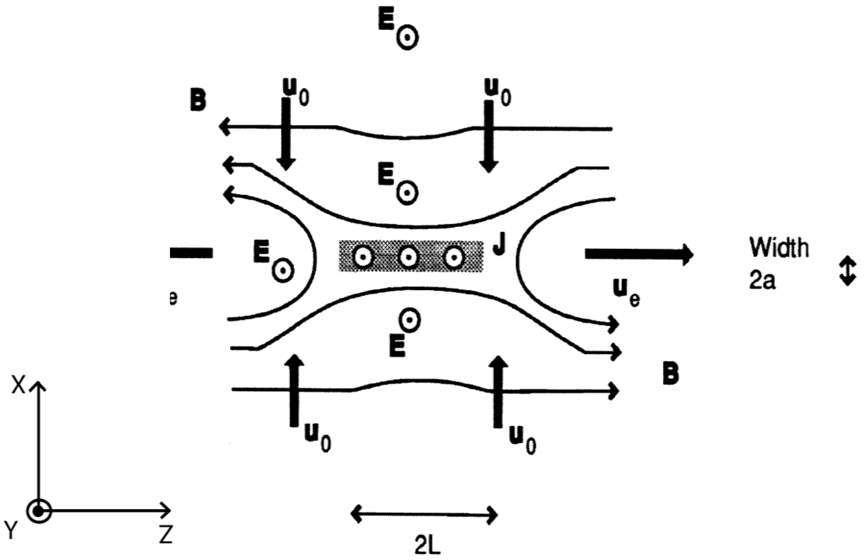
[Priest, 2000]

Operational definition of reconnection

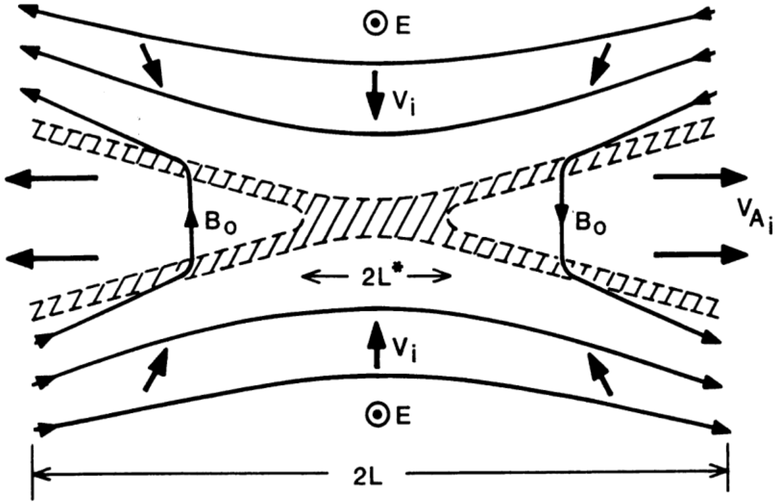
- **Change of magnetic field topology**:
    - $\int E_{||} \neq 0$
    - $B_N \neq 0$
- **Change in plasma connectivity** : $W = E \times B / B^2 \neq V_\perp$
- **Plasma transport across current sheet**
- **Energy dissipation**:
    - $E \cdot J > 0$
    - plasma acceleration (reconnection jets)
    - plasma heating
    - Non-thermal particle acceleration

Theoretical models

See Tutorial by N. Louriero



Sweet-Parker
[Parker,1958; Sweet,1958]



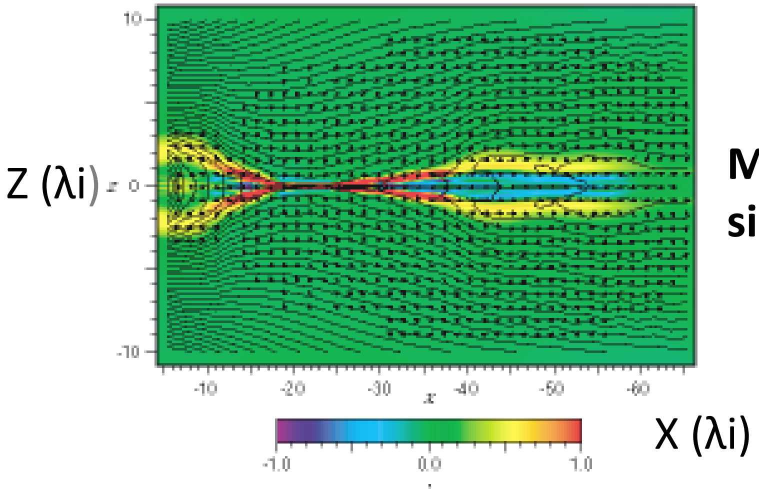
Petschek
[Petschek, 1964]

- Reconnection rate = $(u_0/u_{A0})^{1/2}$ / $R_{m0}^{1/2}$
- Alfvenic outflow: $u_e = u_{A0}$
- Energy conversion: $W_B = ½ W_K + ½ W_T$
- Reconnection too slow to explain solar flares occurring on time scale ~ 100 s

- Smaller diffusion region
- Plasma accelerated at slow shocks
- Higher reconnection rate ≈ $1/\log(R_{m0})$

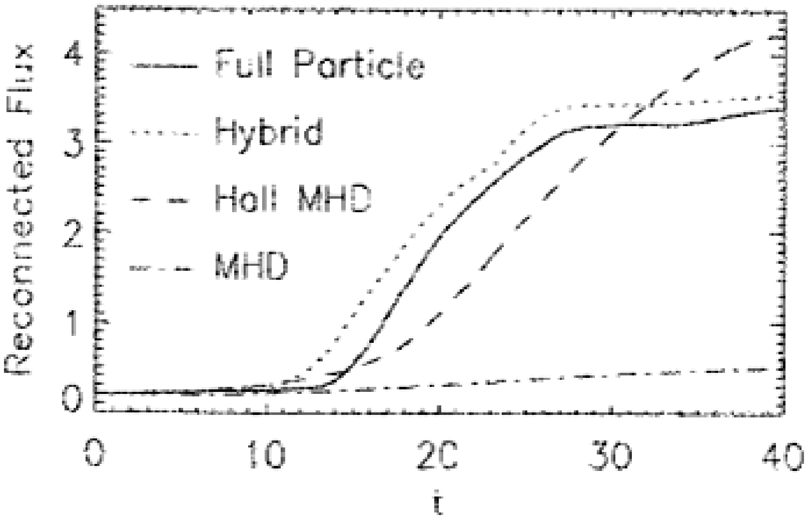
Numerical simulations

See Tutorial by N. Louriero

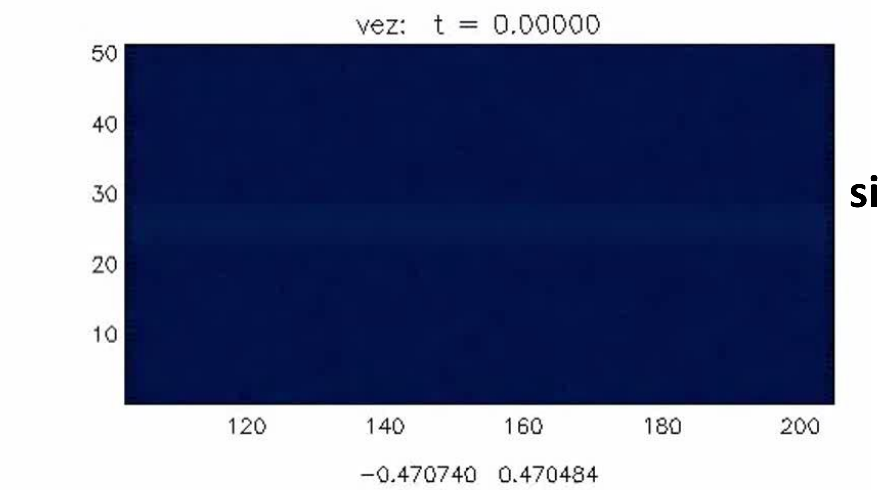


MHD simulation

[Birn & Hesse., Ann.Geophys., 2005]



[Birn et al., JGR, 2001]



PIC simulation

Courtesy M. Shay

GEM challenge:

- Reconnection fast (R ~ 0.1) for all models except MHD
- Fast reconnection due to Hall physics
- Fast collisionless reconnection (space plasma)

14

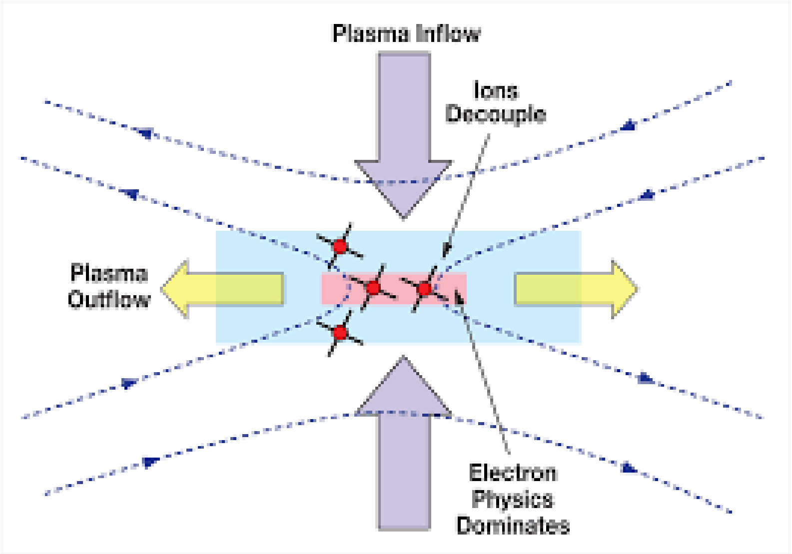
Collisionless reconnection: scales

Generalized Ohm’s law:

$$\underbrace{\boxed{\mathbf{E}+\mathbf{u}\times\mathbf{B}}}_{\text{MHD}} = \underbrace{\frac{\mathbf{J}}{\sigma}}_{\substack{\text{anomalous}\\ \text{conductivity}}} + \underbrace{\boxed{\frac{\mathbf{J}\times\mathbf{B}}{ne}}}_{\text{Hall}} - \boxed{\underbrace{\frac{\nabla\cdot\mathbf{P_e}}{ne}}_{\substack{\text{electron}\\ \text{pressure}}} + \underbrace{\frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}}_{\substack{\text{electron}\\ \text{inertia}}}}$$

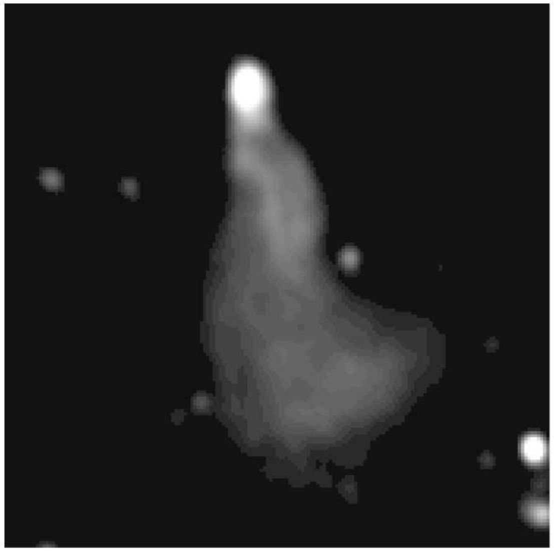
Three scales:

- MHD scales ($\gg \rho i$)
- ion scales (~ ρ_i)
- electron scales (~ ρ_e)



Reconnection: where?

astroplasmas

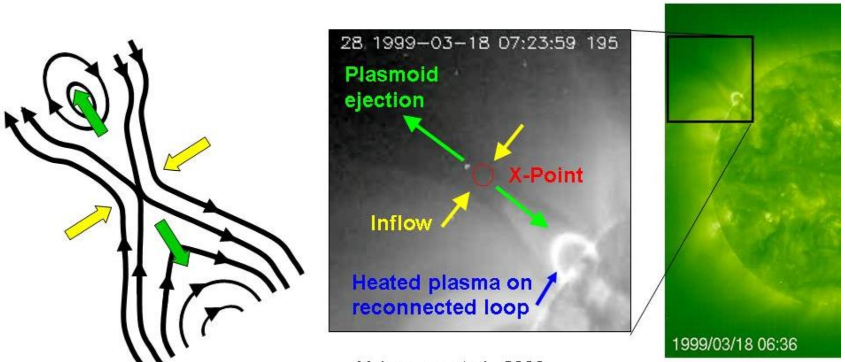


See Tutorial by Cerutti

[Kronberget al., ApJ Lett,2004]

solar corona

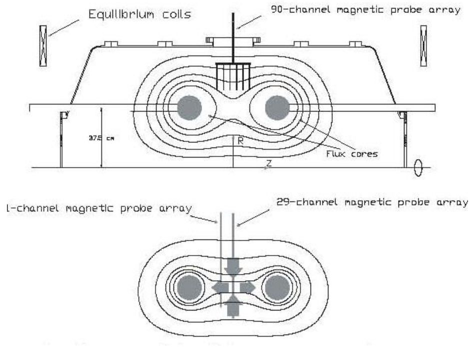
This Tutorial (a bit)



Yokoyama et al, 2000

[Yokoyama et al., ApJ Lett, 2001]

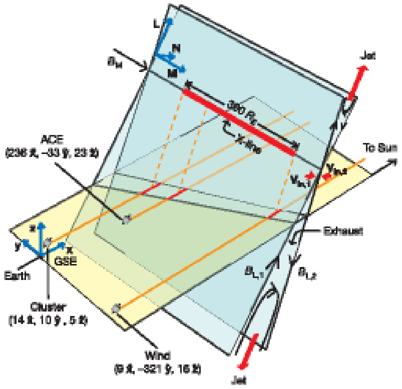
laboratory experiments



See Tutorials by Zohm and Carter

[Ren et al., PRL,2005]

heliosphere

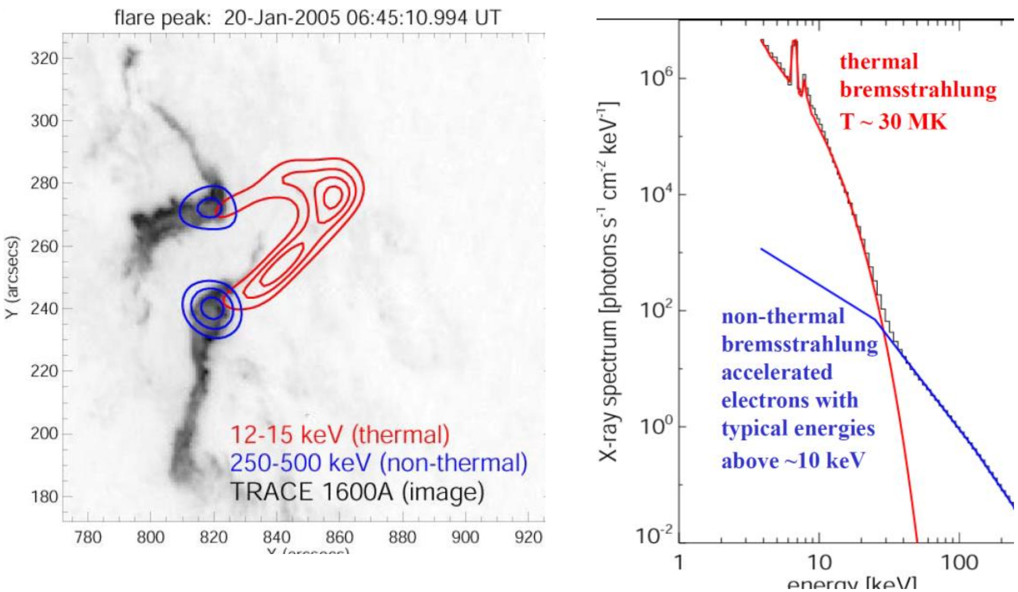


This Tutorial

[Phan et al., Nature, 2006]

Remote observations: solar corona

Hard X-Rays emission from a solar flare (RHESSI)



[Courtesy of S. Krucker, UCB]

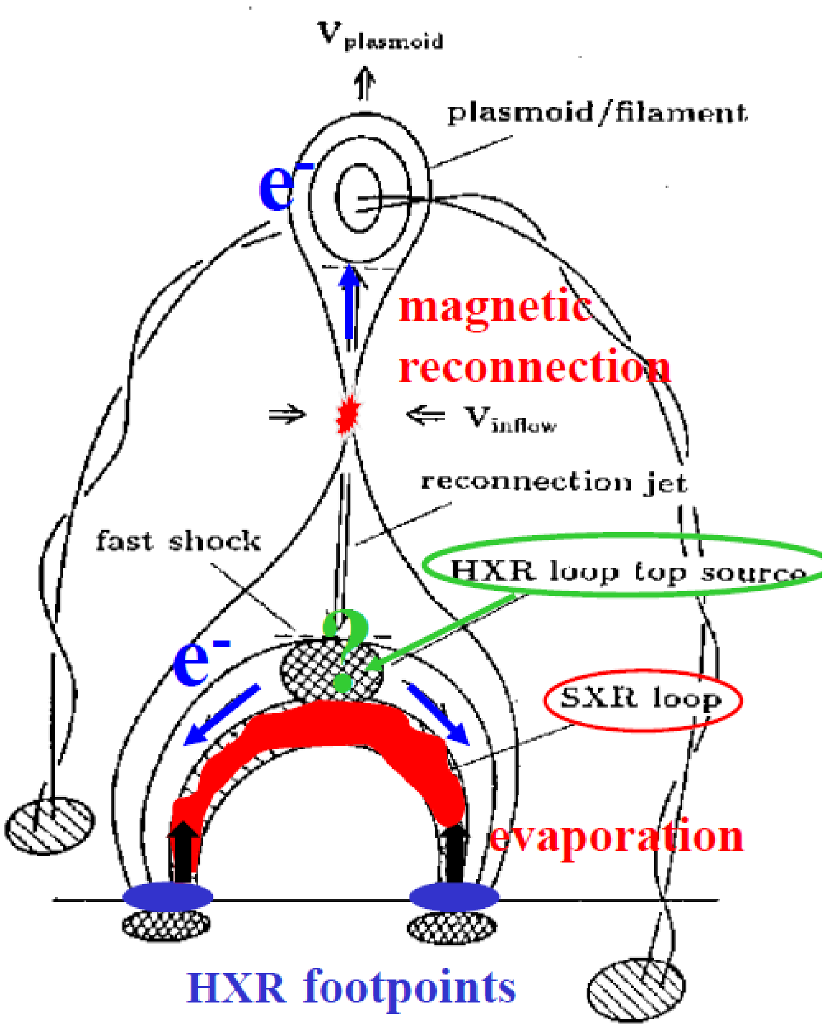
Spacecraft :

- JAXA/Yohkoh
- NASA/Rhessi
- NASA/TRACE
- ESA/SOHO
- NASA/SDO
- JAXA/Hinode

Measurement technique: spectroscopic imaging by space telescopes

- White light (images, magnetograms and dopplergrams of photosphere and chromosphere)
- UV-EUV (heated plasma)
- Soft X-ray (heated plasma)
- Hard X-ray (accelerated particles)
- Gamma ray (accelerated particles)

The flare *Standard Model*



[Courtesy: K. Shibata, Univ. Kyoto]

1)Release of magnetic energy by reconnection

2)Particle are accelerated (not understood) + heating

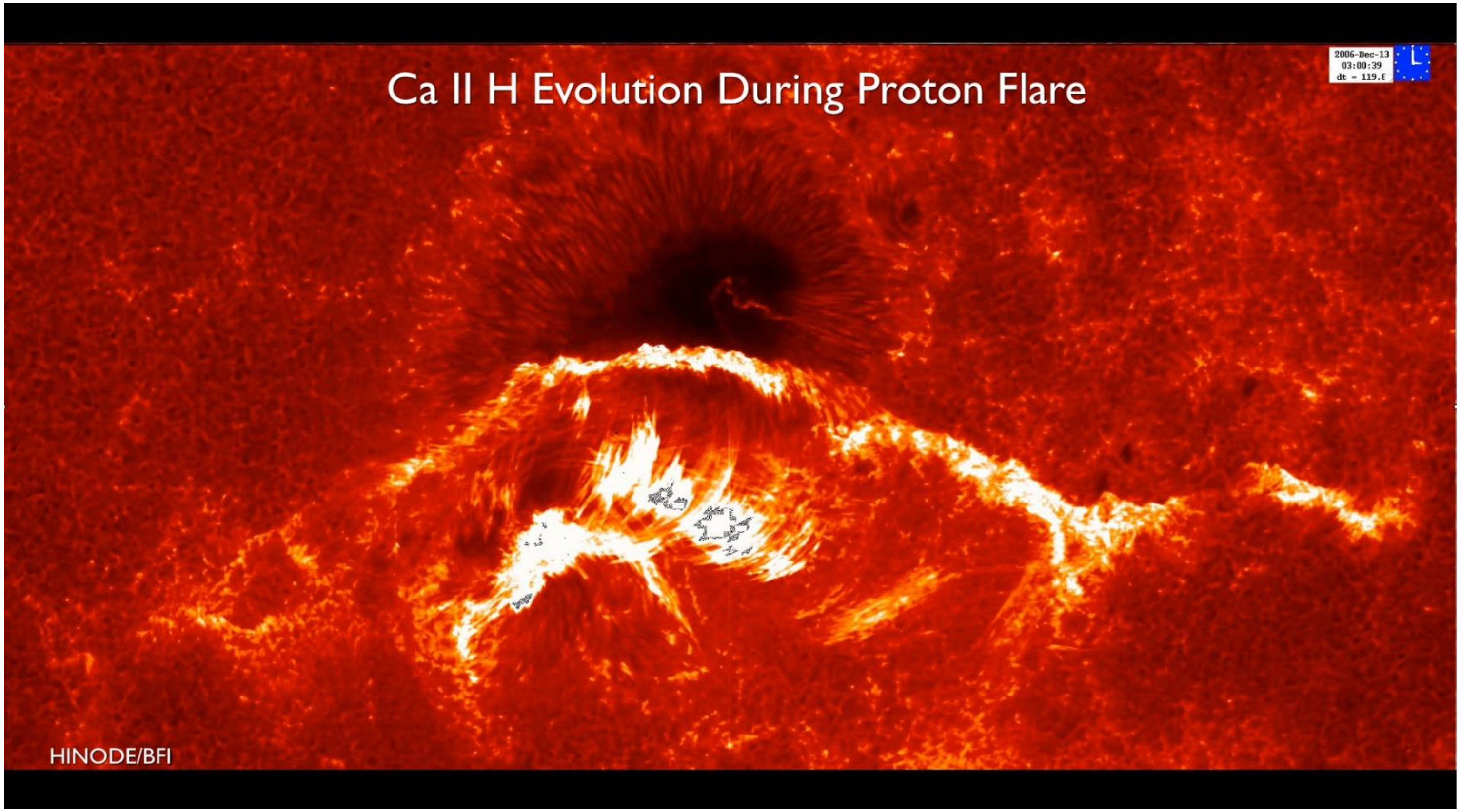
3)Accelerated electrons produce HXR emission (mostly footpoints)

4) Above loop top HXR source not understood

5)collisional loses of accelerated electrons heat plasma

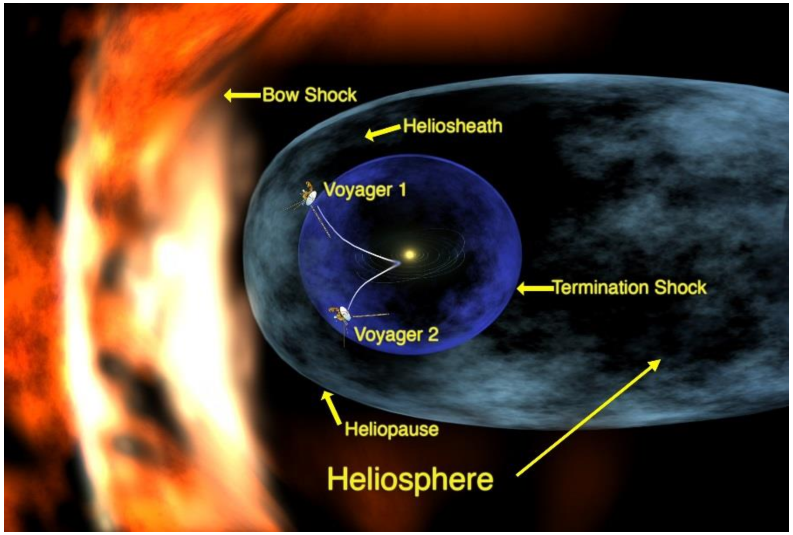
6)“evaporation” fills loop

Solar flares: laminar or turbulent ?

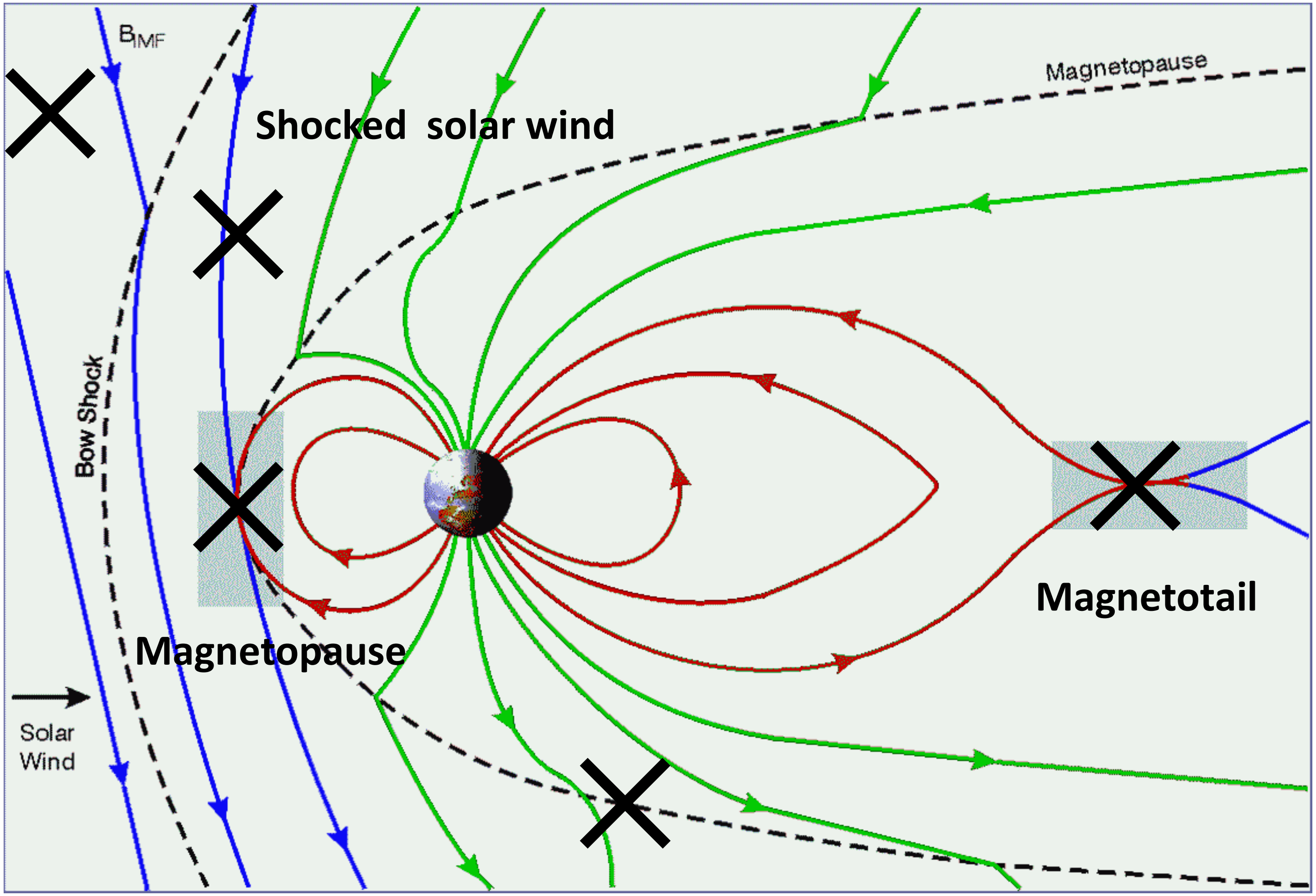


In situ observations: heliosphere

- **Solar wind**: Gosling et al., 2005; Phan et al., 2006; Gosling et al., 2007; Retino et al., 2007
- **Earth's magnetosphere**:
    - Magnetopause: Paschmann et al., 1986; Phan et al., 2002; Mozer et al., 2002; Vaivads et al., 2004; Retino et al.2006, Burch et al, 2016
    - Magnetotail; Hones et al., 1985; Øieroset et al., 2001; Chen et al., 2008; Fu et al., 2013; Fu et al., 2015
    - Kelvin-Helmoltz vortexes: Hasegawa et al., 2009; Eriksson et al, 2016
- **Planetary magnetospheres**: Mercury (Slavin et al. 2009), Mars (Eastwood et al., 2008), Jupiter (Huddleston et al., 1997), Saturn (Arridge et al., 2016); Uranus (Masters et al., 2014)
- **Comet tail**: Russell et al., 1986
- **Heliopause**: Swisdak et al., 2013



In situ observations: near-Earth space



Pristine solar wind

Shocked solar wind

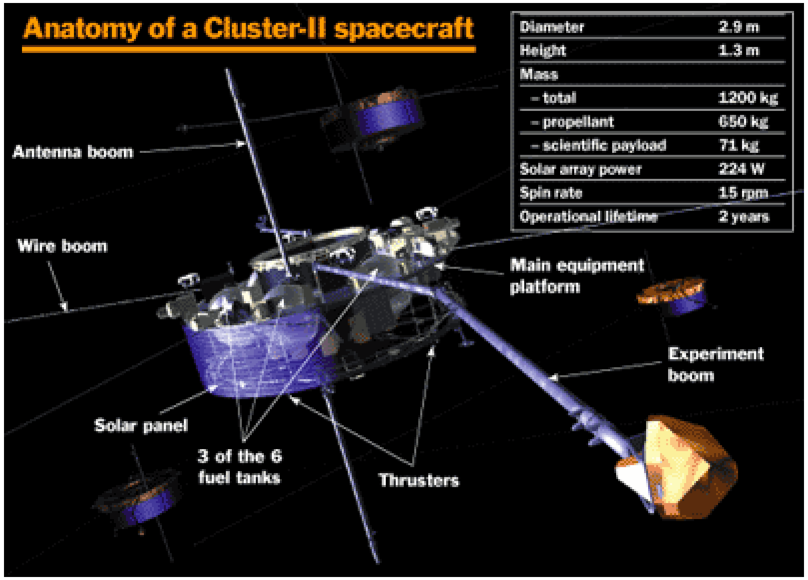
Magnetopause

Magnetotail

Kelvin-Helmoltz vortexes

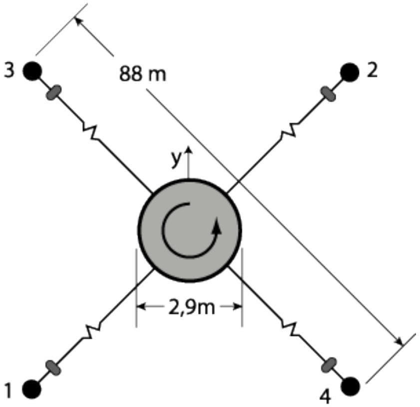
Best available in situ measurements !!!

In situ observations: instrumentation

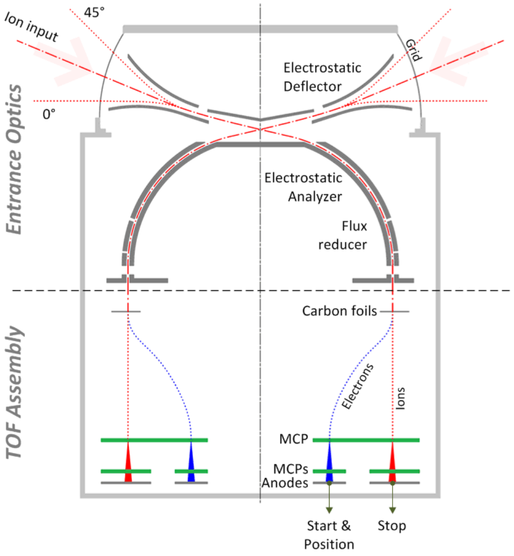


Diameter	2.9 m
Height	1.3 m
Mass	
– total	1200 kg
– propellant	650 kg
– scientific payload	71 kg
Solar array power	224 W
Spin rate	15 rpm
Operational lifetime	2 years

See Tutorial
by Maksimovic



Langmuir probes (**E** field)



Electrostatic Analyzer (ions and electrons)

Magnetometers

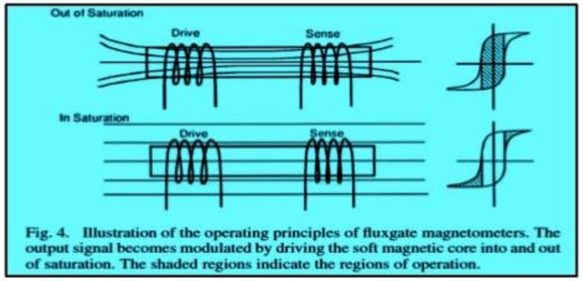
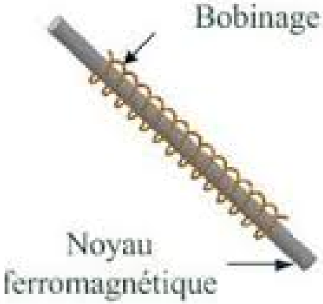


Fig. 4. Illustration of the operating principles of fluxgate magnetometers. The output signal becomes modulated by driving the soft magnetic core into and out of saturation. The shaded regions indicate the regions of operation.

Fluxgate (DC)

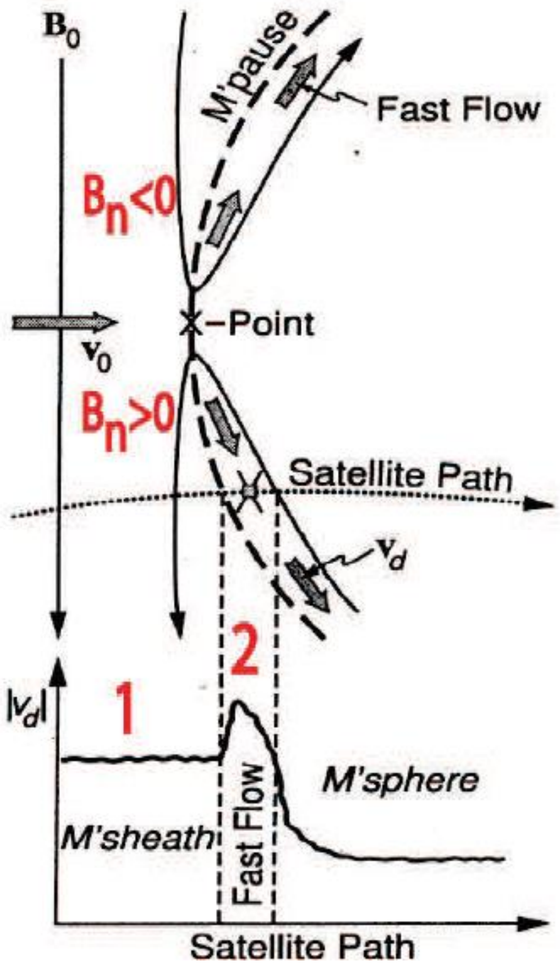


Search-coil (AC)

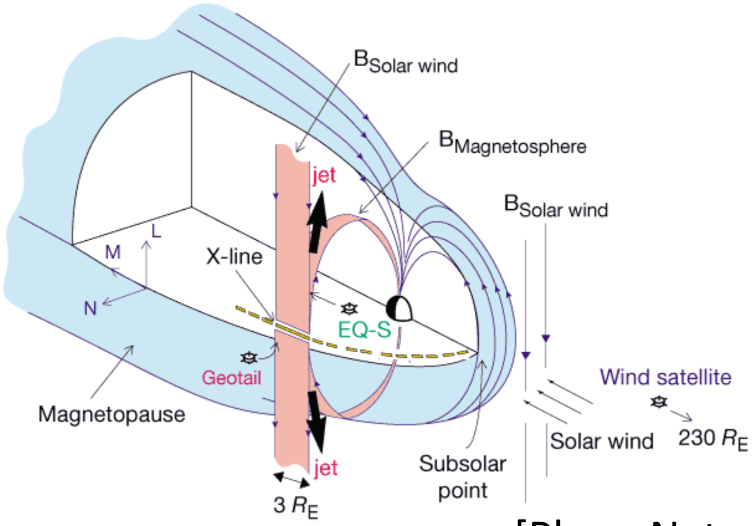
Three ages of in situ reconnection spacecraft measurements

- BC: *Before Cluster* (ISEE, AMPTE, Geotail, WIND, Equator-S) -> MHD scales
- *Cluster* -> ion scales
- AC: *After Cluster* (MMS) ->electron scales

In situ evidence of reconnection at MHD scales: reconnection jets



Expected signatures away from X-point



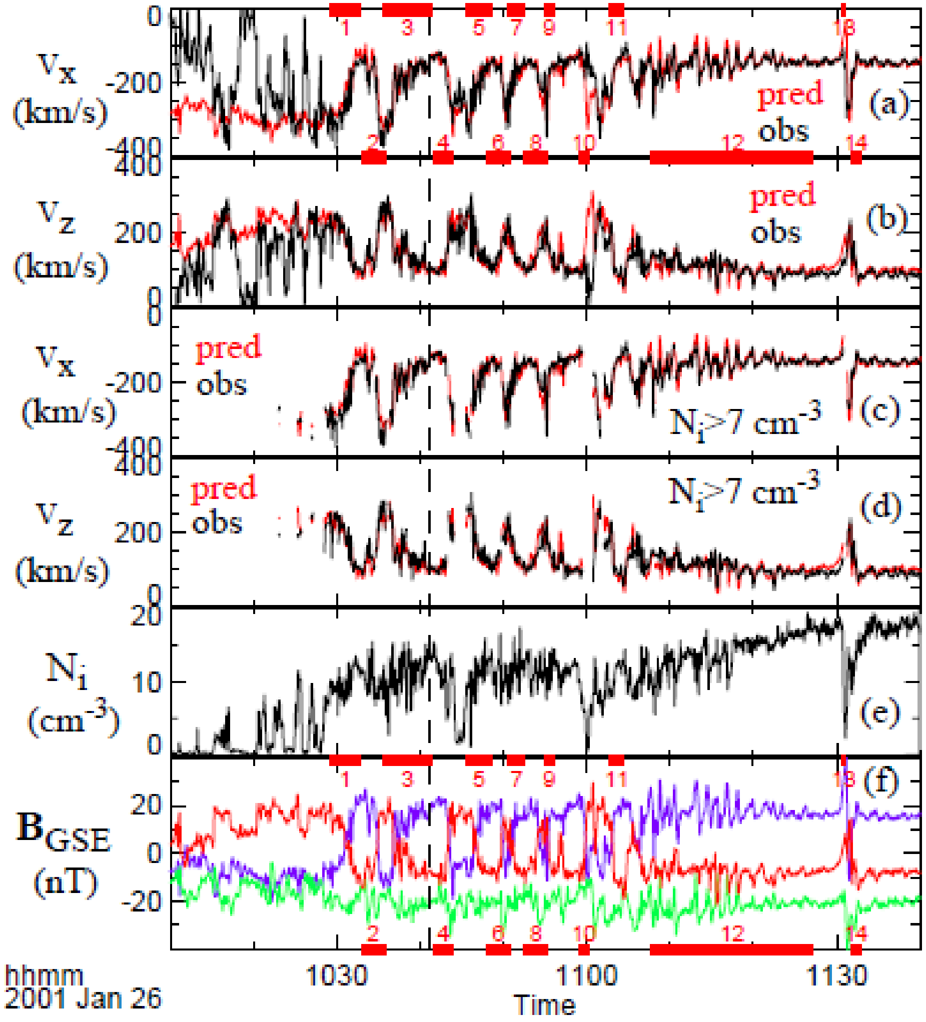
[Phan, Nature, 2000]

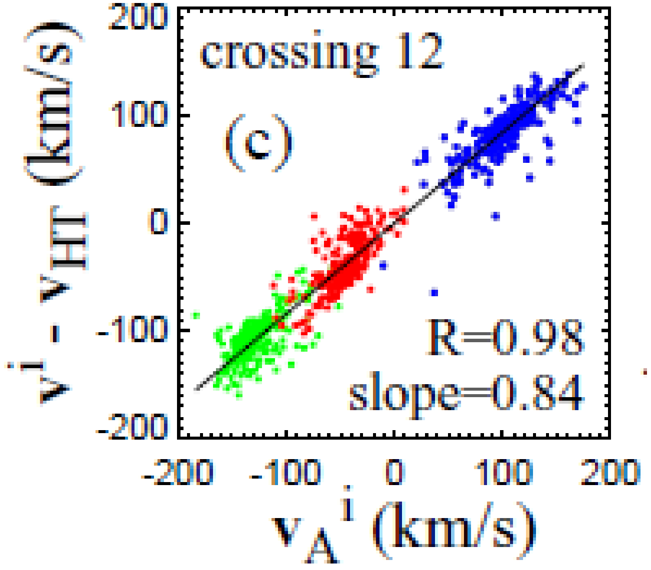
- First evidence: Paschmann et al., Nature, 1986
- Tangential stress balance:

$$\Delta \mathbf{V}_{\mathrm{th}} = \mathbf{V}_{\mathrm{t2}} - \mathbf{V}_{\mathrm{t1}} = \pm(\mu_0\rho_1)^{-1/2}(\mathbf{B}_{\mathrm{t2}} - \mathbf{B}_{\mathrm{t1}})$$

$$\mathbf{v} - \mathbf{V}_{HT} = \pm(1-\alpha)\mathbf{B}[\mu_0\rho_1(1-\alpha_1)]^{-1/2}$$

Observations of reconnection jets

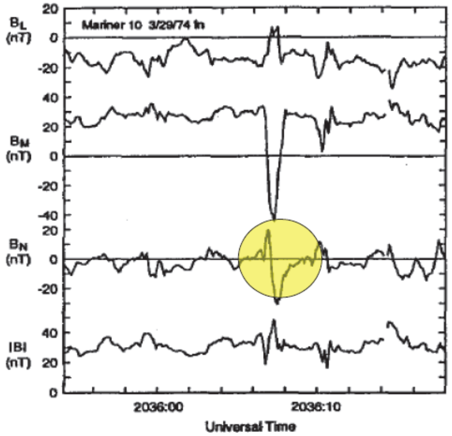




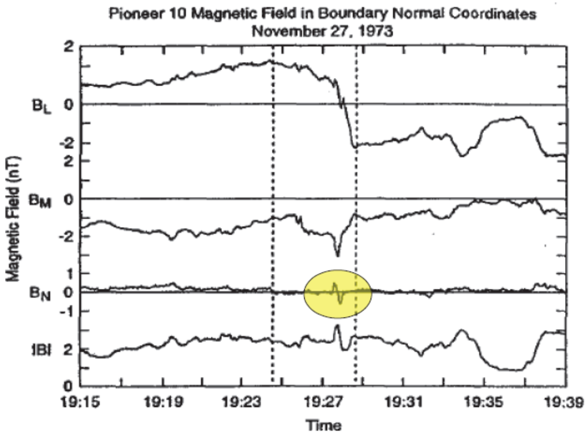
[Phan et al., Ann. Geophys., 2004]

In situ evidence of reconnection at MHD scales: flux transfer events

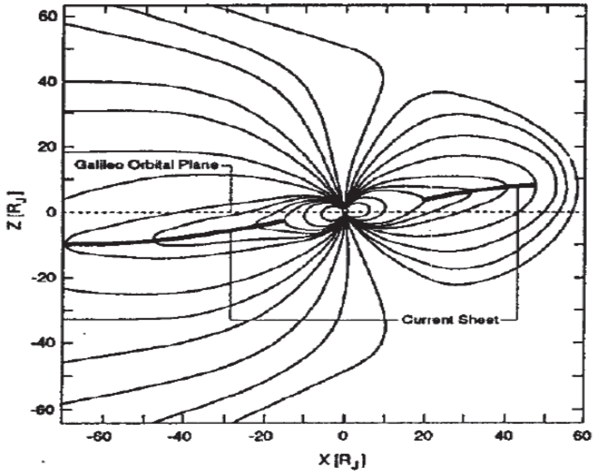
Jupiter



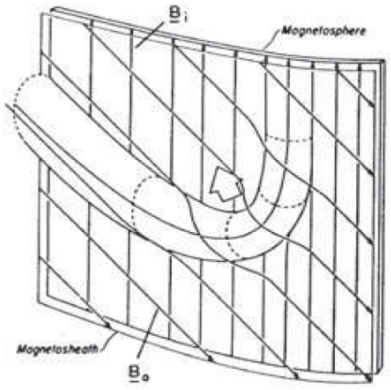
Mercury



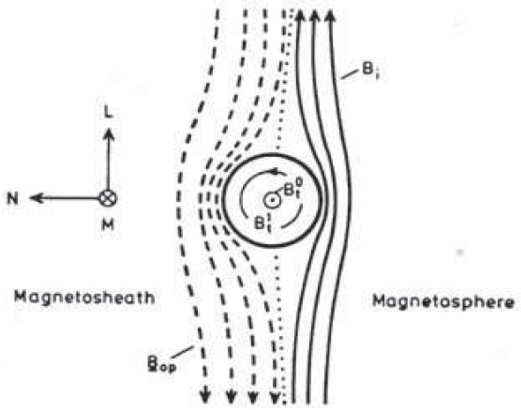
- ✔ Flux Transfer Events - unsteady reconnection
- ✔ Bipolar Bn signature



[Russell 2000, ASR]



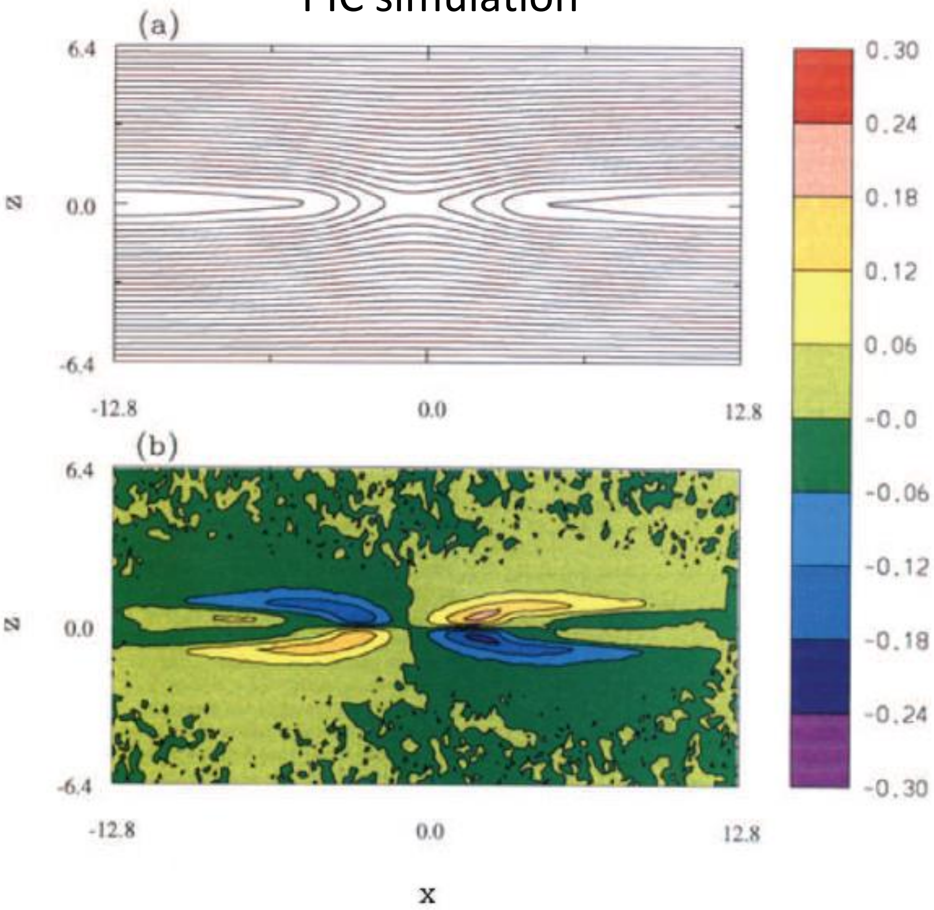
(a)



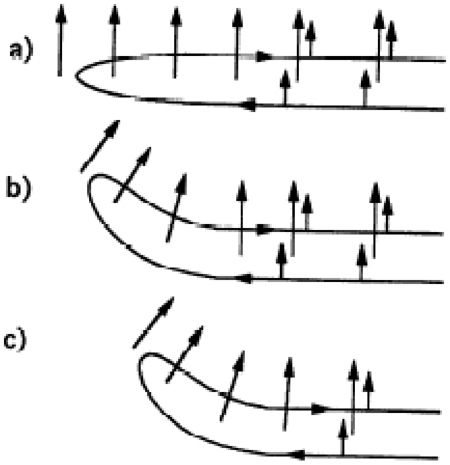
(b)

In situ evidence of reconnection at ion scales: Hall reconnection

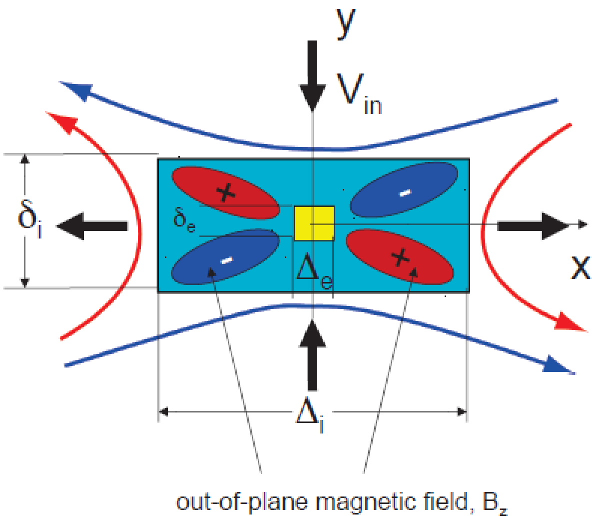
PIC simulation



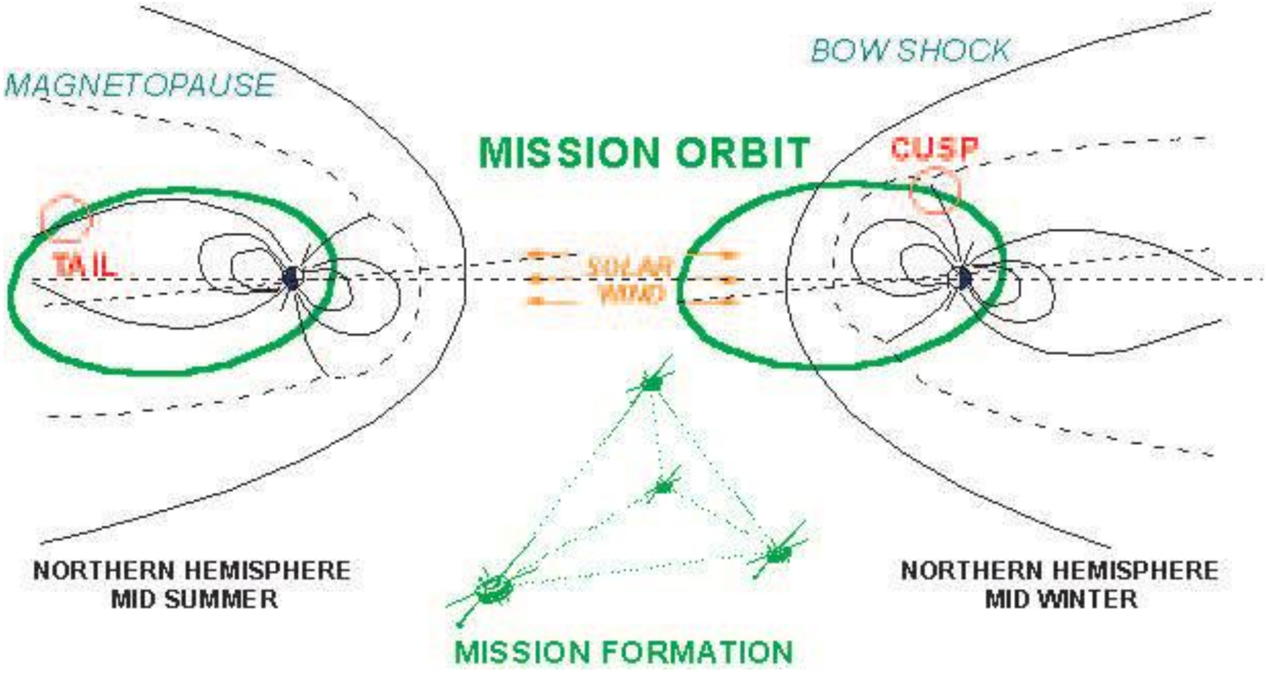
[Pritchett et al., JGR, 2001]



[Mandt et al. GRL, 1994]



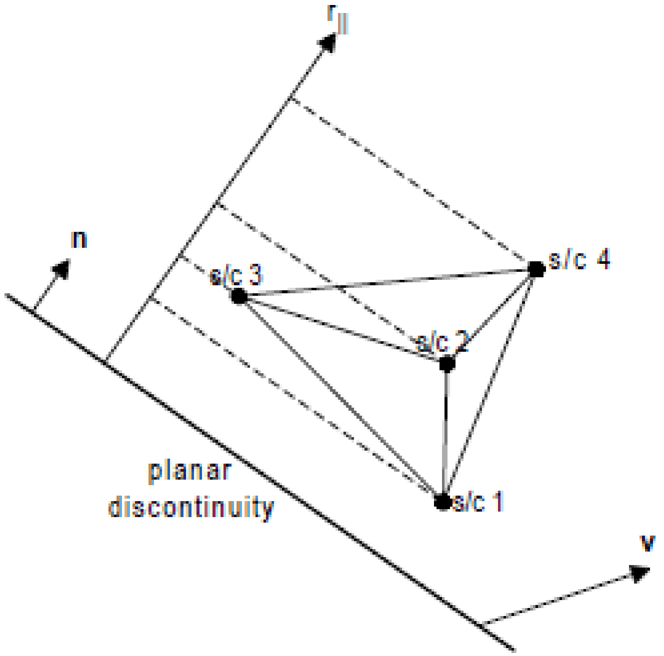
The ESA/Cluster mission



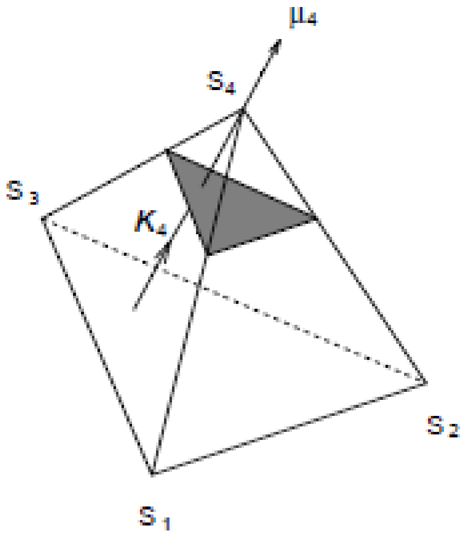
- first 4 SC mission to study the near-Earth space
- distinction between spatial and temporal variations
- measurement of 3D quantities
- tetrahedrical configuration with variable separation from 100 to 10000 km: observations at different scales

Multi-spacecraft analysis methods

See Tutorial
by Dudok de Wit



Timing (normal direction and velocity)



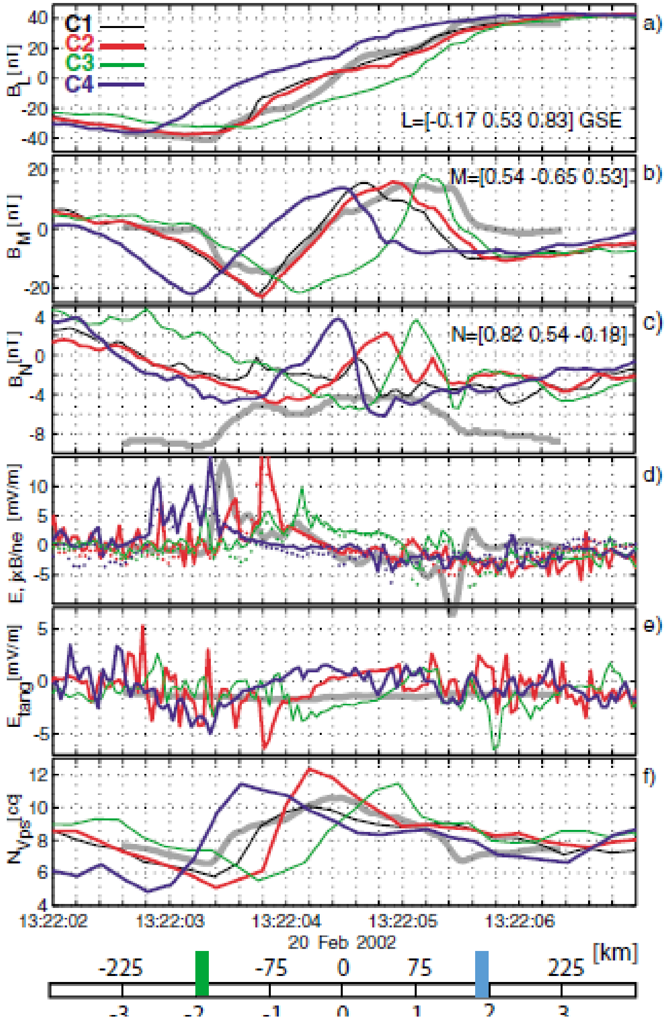
Curlometer ($\mu_0\mathbf{J} = \nabla \times \mathbf{B}$)

Examples of other quantities:

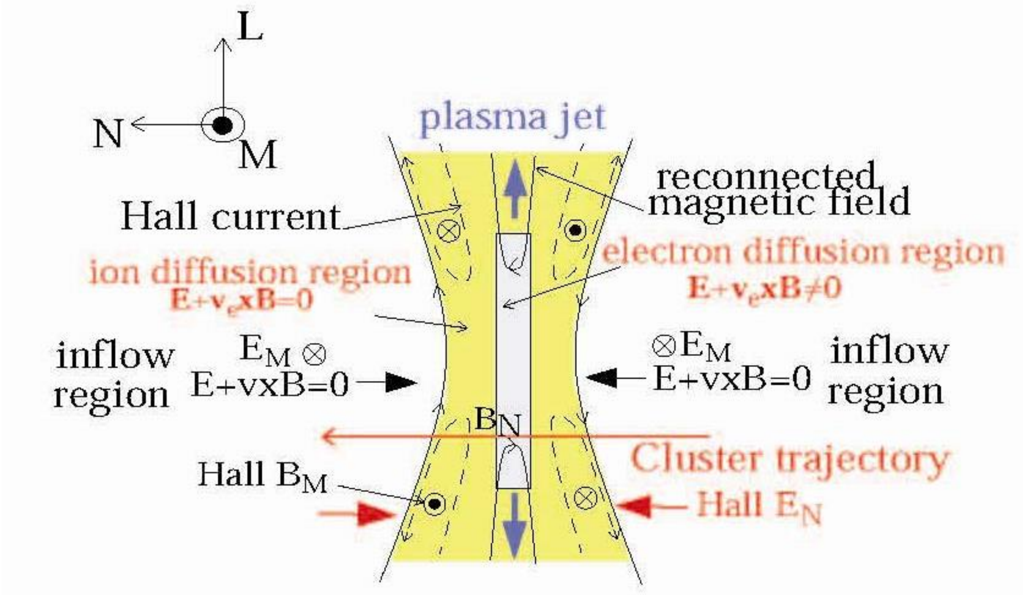
- $\nabla \cdot \mathbf{P}$ (divergence of pressure tensor)
- $\nabla \times \mathbf{V}$ (vorticity)

Observations of Hall reconnection

Cluster 4 point measurements



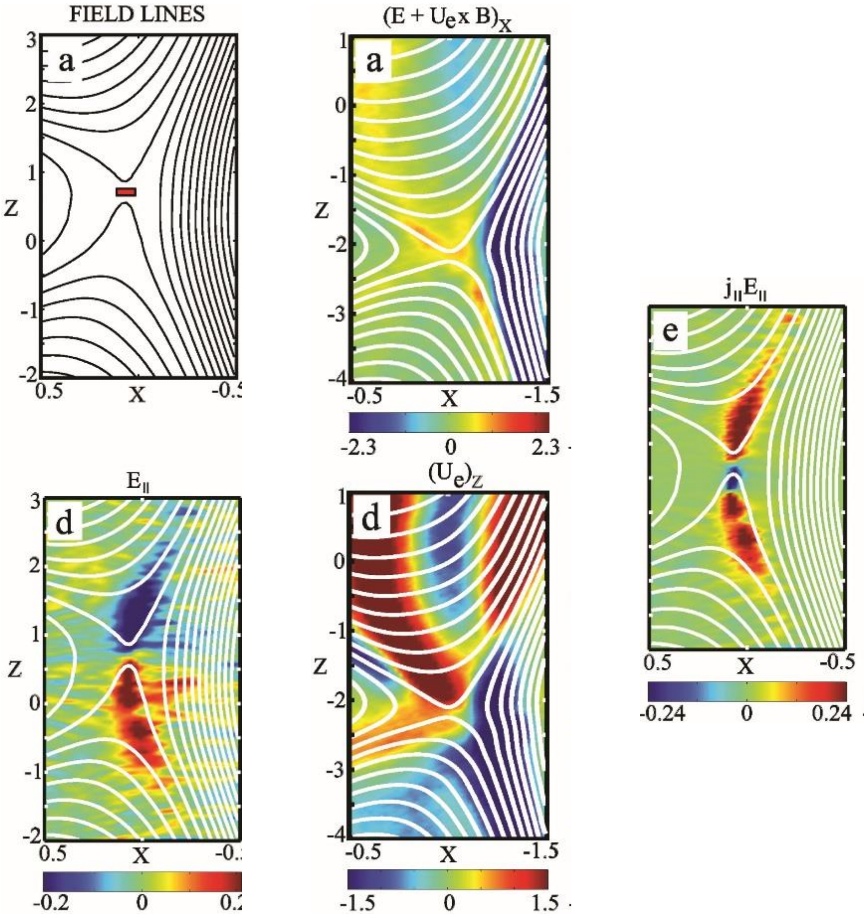
[Vaivads et al., PRL, 2004]



- Quadrupolar Hall Magnetic field
- Bipolar Hall electric field balanced by (1/N·e) **JxB**
- Reconnection rate R ~ 0.1 (fast reconnection)
- **Resolution of plasma data not sufficient to resolve ion scales !**

In situ evidence of reconnection: electron scales

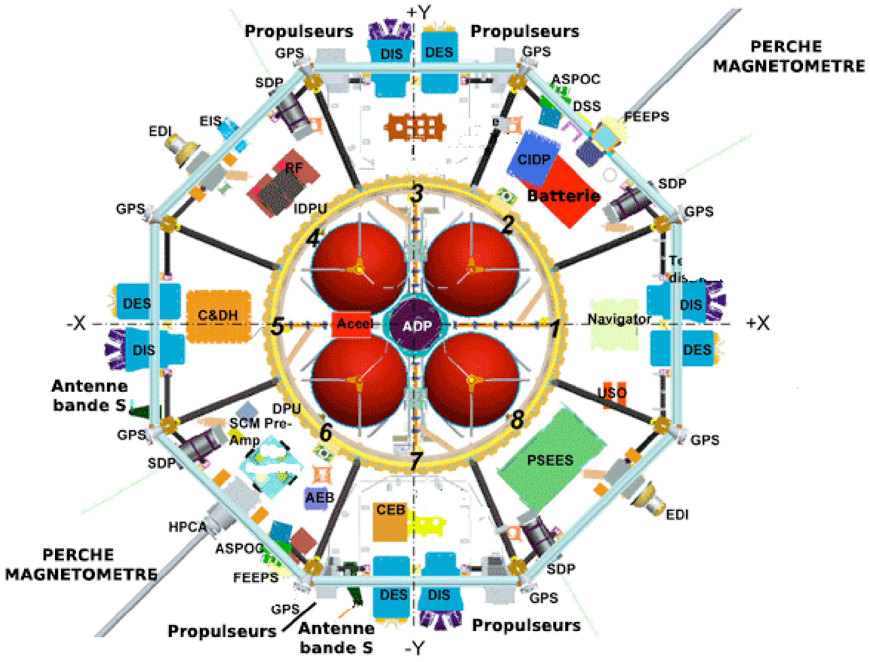
Asymmetric reconnection (e. g. magnetopause)

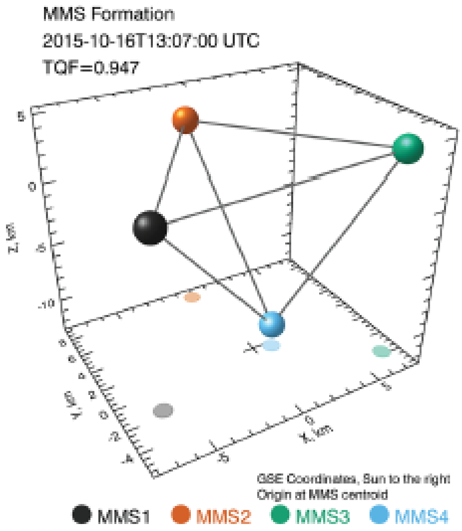


[Pritchett & F. S. Mozer; Phys. Plasmas 2009]

- Expected signatures mostly from full PIC simulations:
    - Parallel electric field
    - Violation of frozen-in (slippage)
    - Super-Alfvenic electron jet
    - Energy dissipation **E·J**
- Signatures depend on boundary conditions (guide field, density and B asymmetries, etc.)
- Signatures do not unambiguosly identify the x-point.
- New observations required to resolve electron scales (1-50 km in near-Earth space)

The NASA/MMS mission

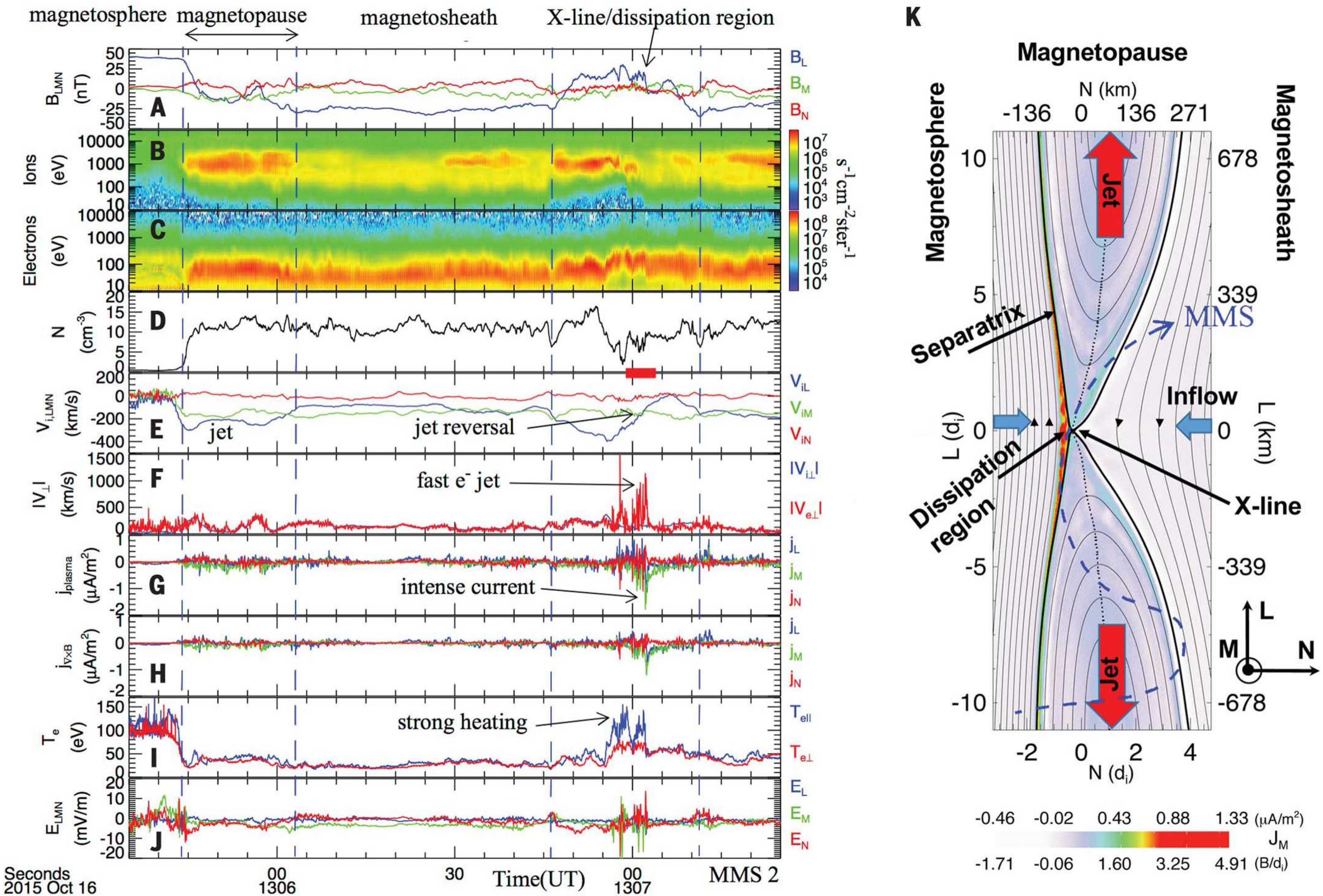



MMS Formation
2015-10-16T13:07:00 UTC
TQF=0.947

- 4 SC mission fully dedicated to study reconnection at electron scales
- tetrahedrical configuration with variable separation down to 7 km -> sub-ion/electron scales
- High temporal resolution of plasma measurements: 30 ms for electrons, 150 ms for ions

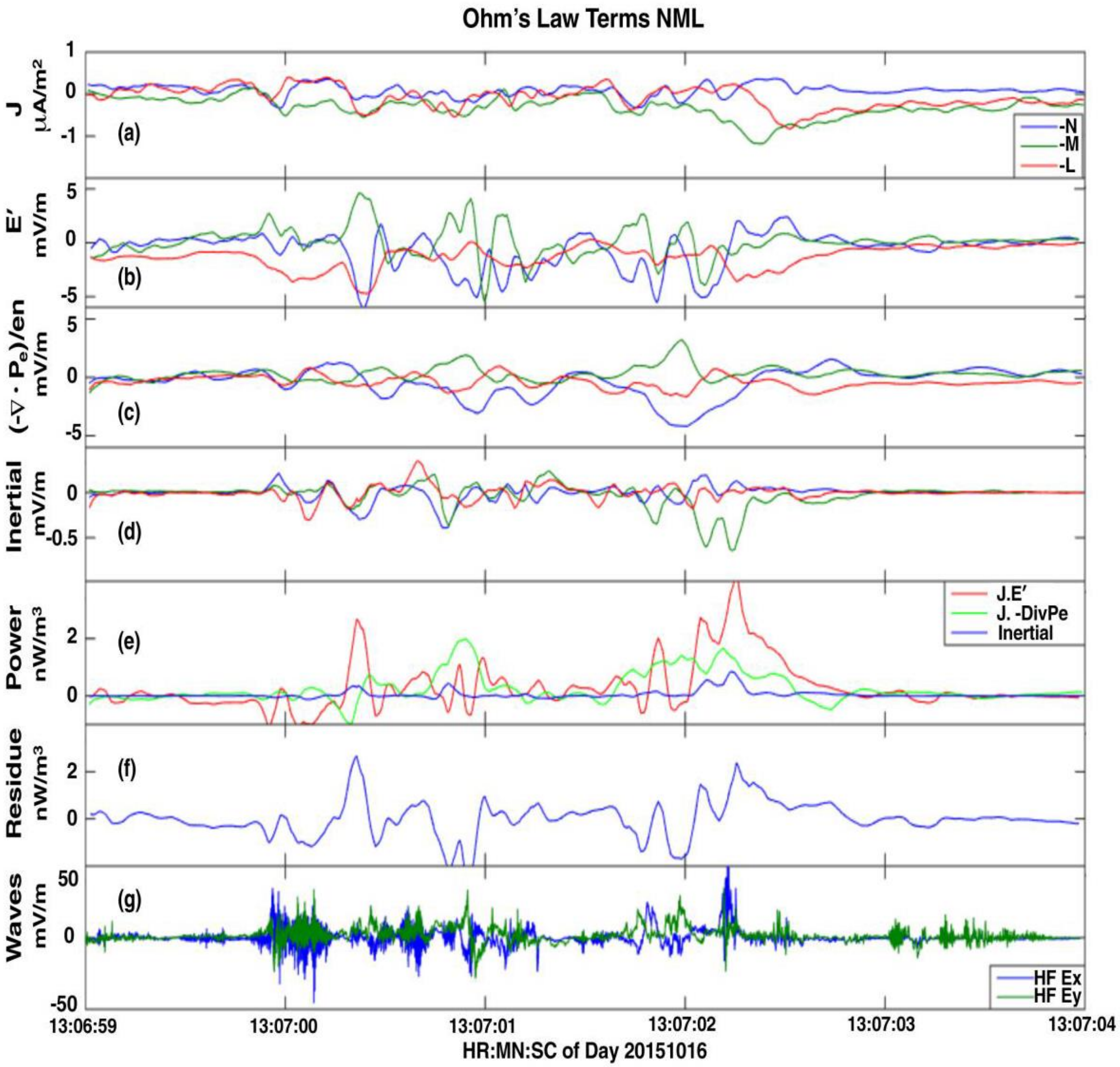
Electron-scale observations of reconnection

Possible crossing of the electron diffusion region



[Burch et al., Science, 2016]

Experimental verification of Generalized Ohm's Law

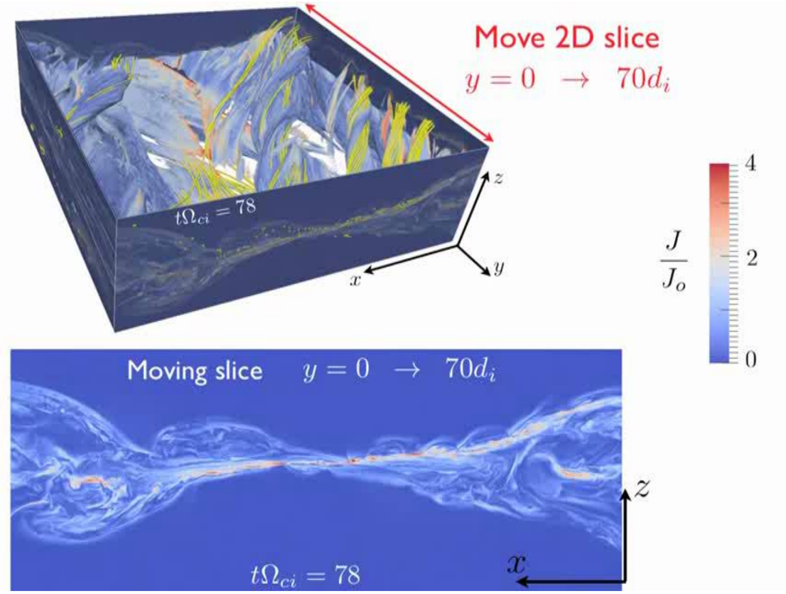


[Torbert et al., GRL, 2016]

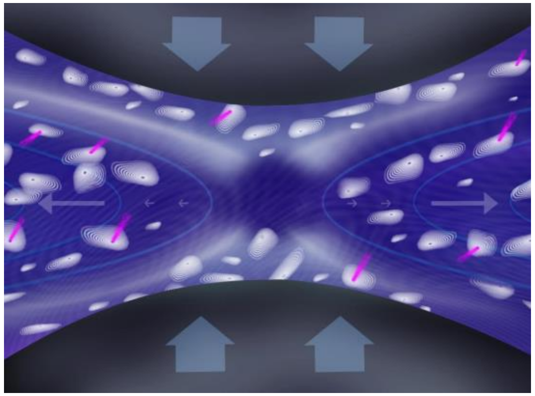
- Estimation of Ohm's law for electron diffusion region as in Burch et al., 2016
- Divergence of electron pressure tensor balances **E**
- Possible role of anomalous resistivity
- Caveat: instrument calibrations

Microphysics of reconnection: (some) open questions

- What are the actual signatures of the electron diffusion region?
- What is the structure of the diffusion region: laminar or turbulent?
- Is anomalous resistivity due to turbulence waves/turbulence important? Which fluctuations are relevant (e.g. lower-hybrid, whistler, KAW, …)
- What are the mechanisms that heat electrons in the diffusion region (parallel electric field, wave-particle interactions, …)

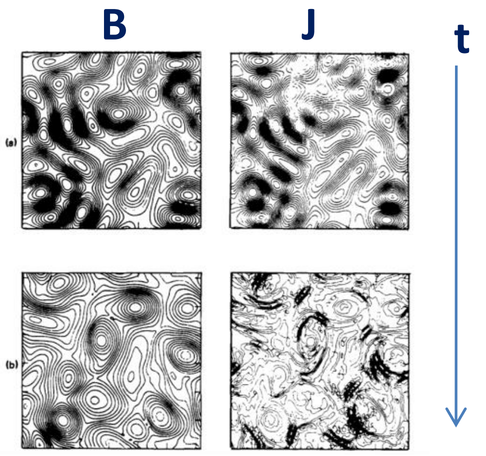


[Daughton et al., Nature Physics, 2011]



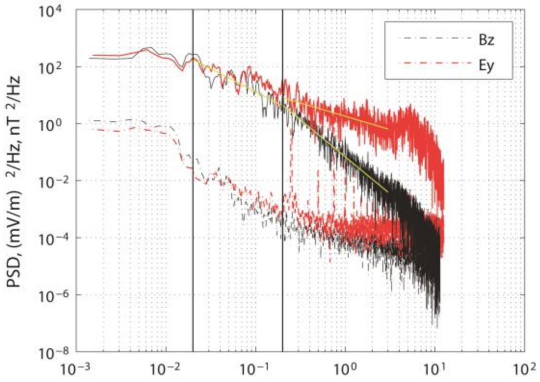
[Fu et al., GRL, 2016]

Reconnection & Turbulence



Reconnection in turbulent plasmas

[Matthaeus & Lamkin, Phys. Fluids,1986; Dmitruk & Matthaeus, Phys; Plasmas, 2006; Servidio +, PRL 2009]

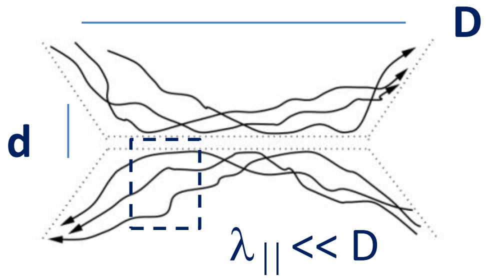


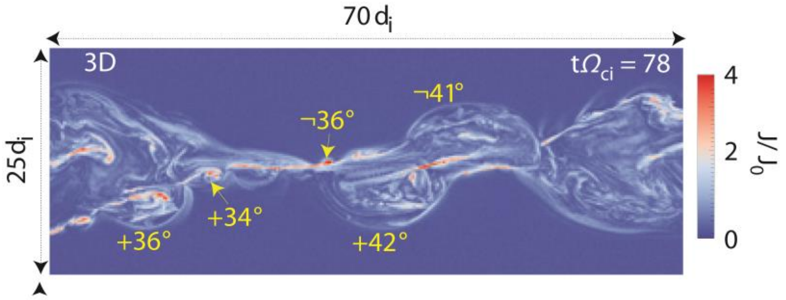
Turbulence/waves in current sheets

[Bale+, GRL, 2002; Vaivads+, GRL, 2004; Khotyaintsev+, Ann Geo, 2004; Retinò+, GRL, 2006; Eastwood+; PRL, 2009; Huang+, JGR, 2010]

Turbulent current sheet

[Lazarian & Vishniac, ApJ, 1999; Lapenta, PRL, 2008; Loureiro+, MNRAS, 2009; Daughton+, Nature Physics, 2011; Che+, Nature, 2011]

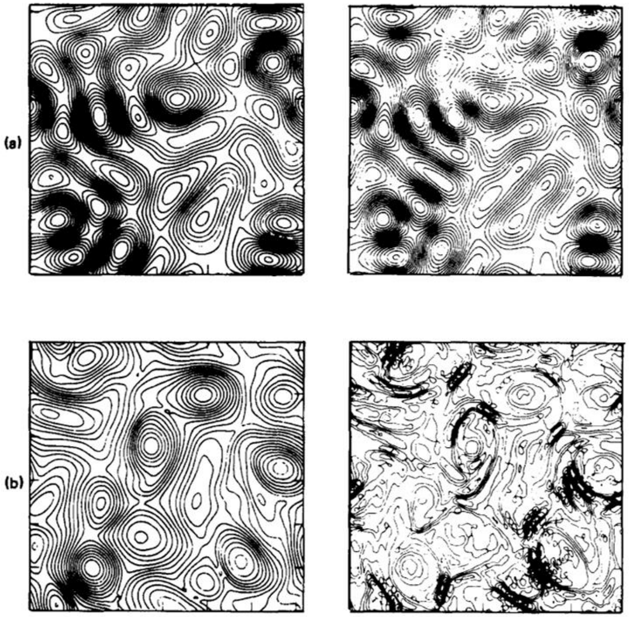




Reconnection in turbulent plasma

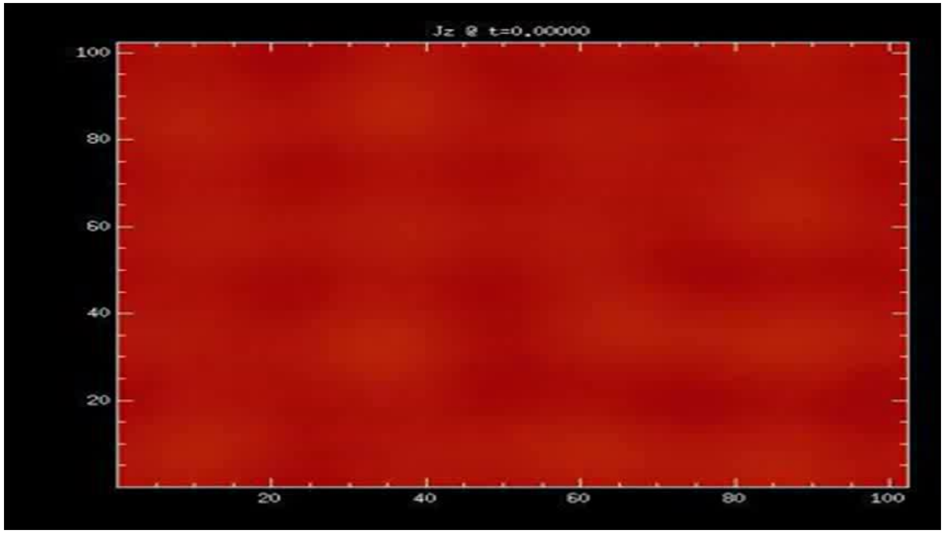
2D MHD simulation

Magnetic field lines | Current density



[Matthaeus & Lamkin, Phys. Fluids, 1986]

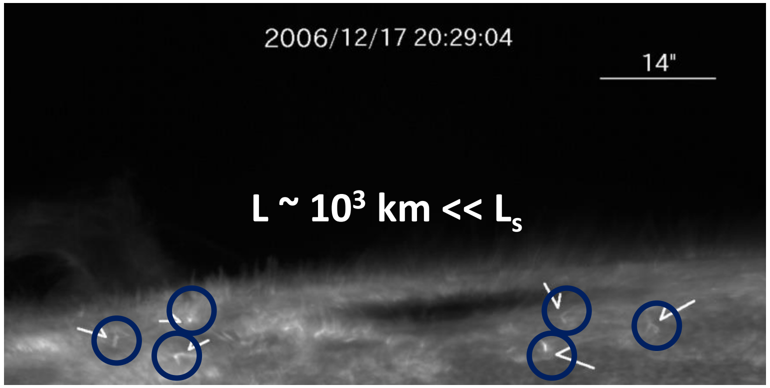
PIC simulation



[from Wu et al., 2013]

Many different simulations supports this scenario (MHD, Hall-MHD, PIC, Vlasov):
Servidio 2009, Servidio 2011, Camporeale2011, Wan 2012, Karimabadi 2013, Haynes 2014, Valentini2014, Wan 2015)

In situ data scarce



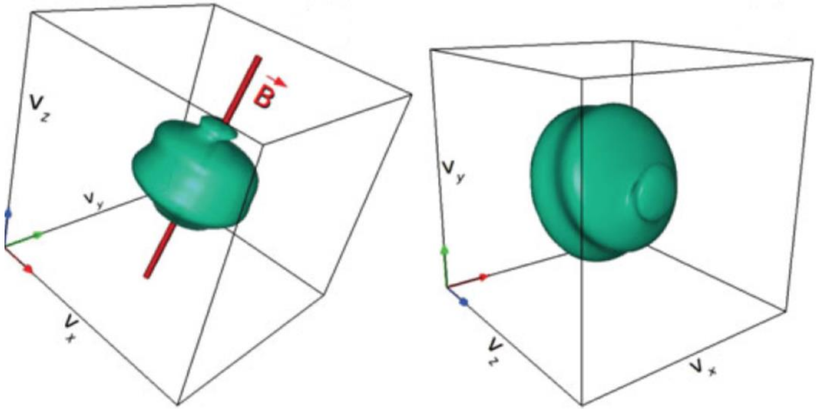
$L \sim 10^3$ km << L_s

[Shibata +, Science, 2007]

Proton heating

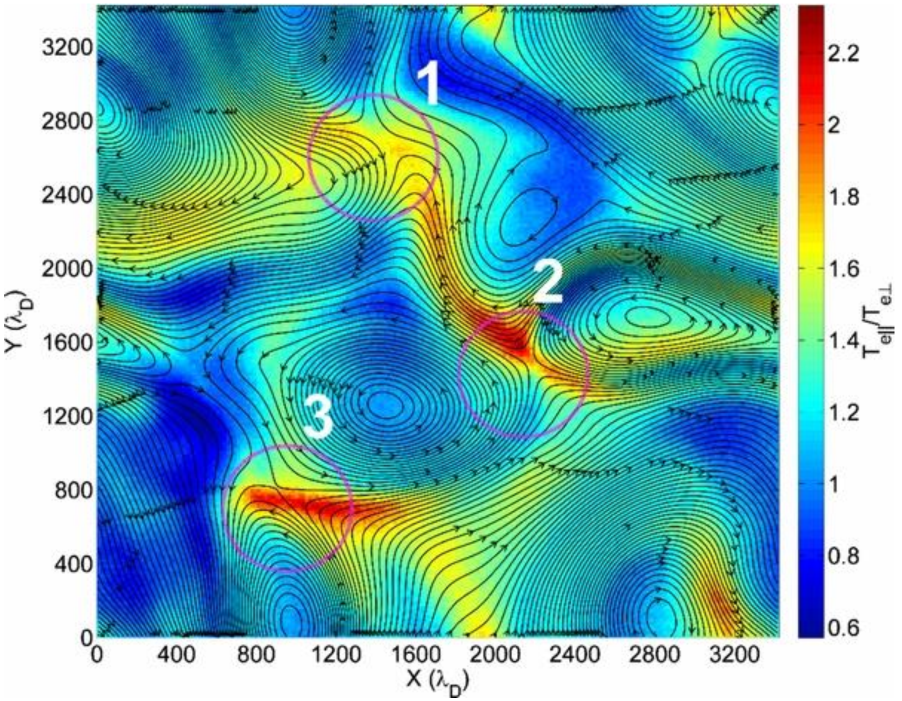
- important proton heating in régions of strong gradients having scale ~ ρ_i e.g. regions of high current (current sheets)

- proton distribution function highly anisotropic

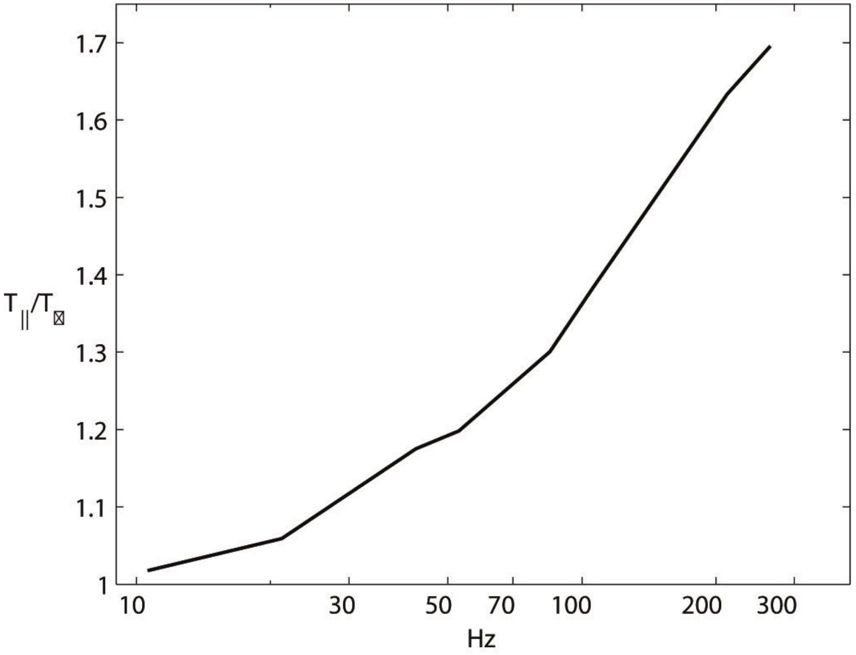


[courtesy F. Valentini]

Electron heating



[Haynes+, ApJ,2014]

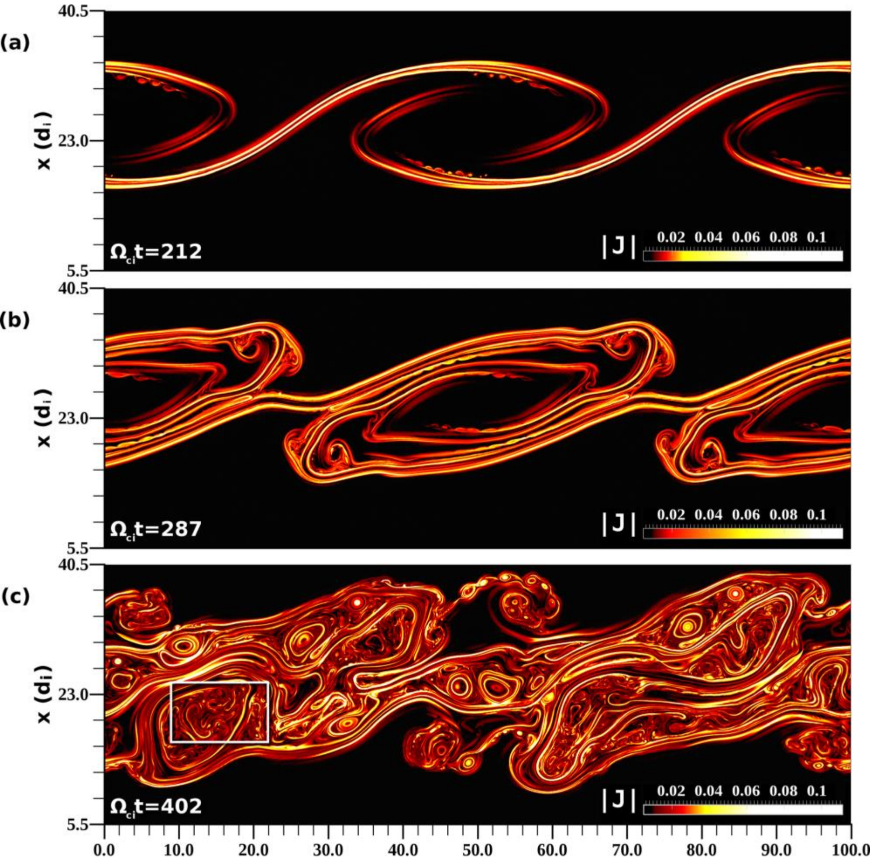


[Camporeale+, ApJ,2011]

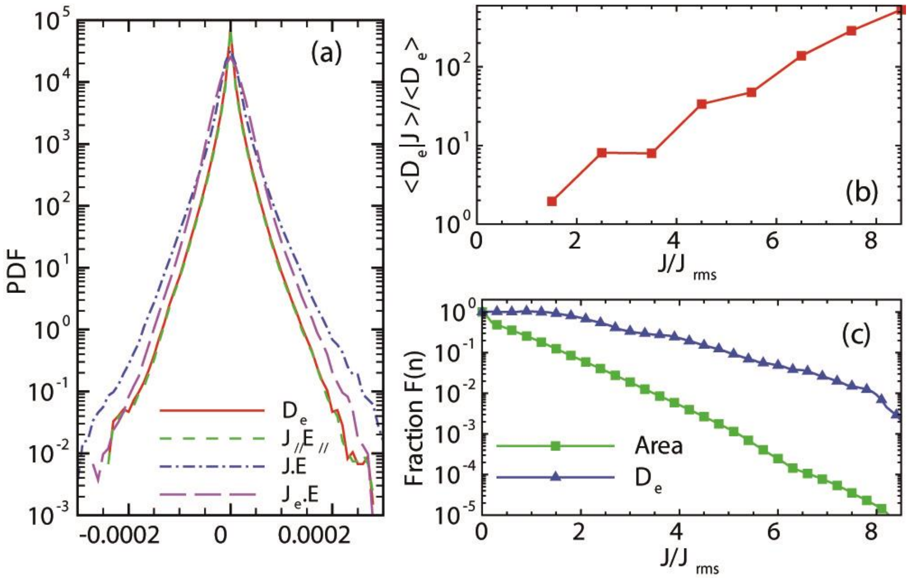
- electron heating within thin current sheets
- anisootropy expected around reconnection sites

alessandro.retino@lpp.polytechnique.fr

Intermittent dissipation



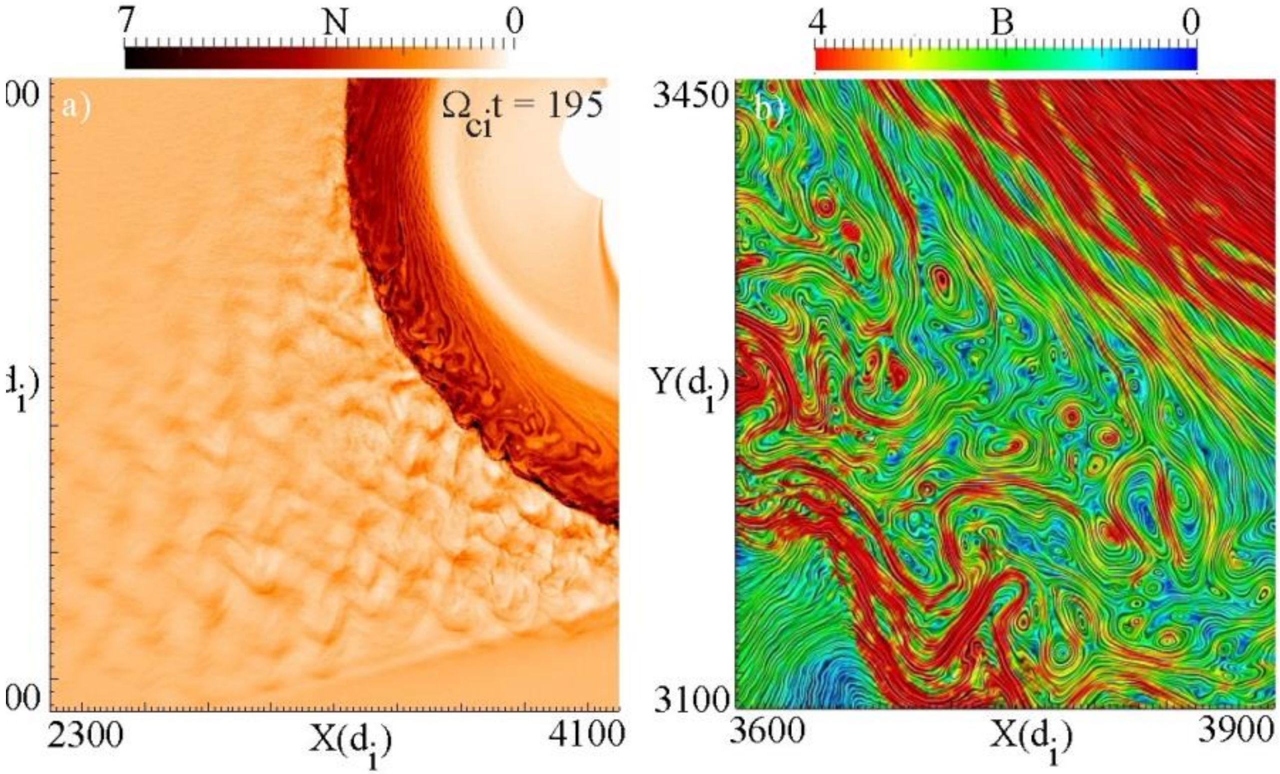
[Karimabadi+, Phys. Plasmas, 2013]



[Wan+,PRL, 2012]

Heating strongly intermittent heating at kinetic scales

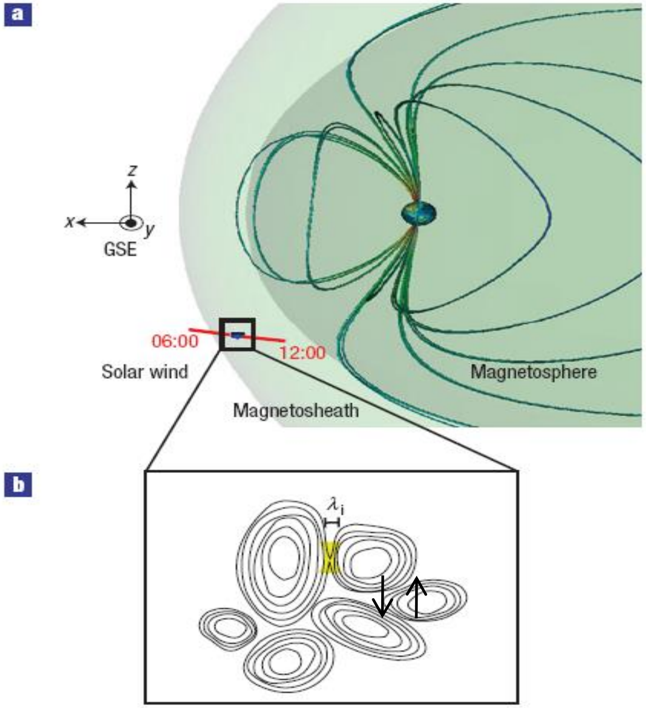
Turbulence at quasi-parallel shocks

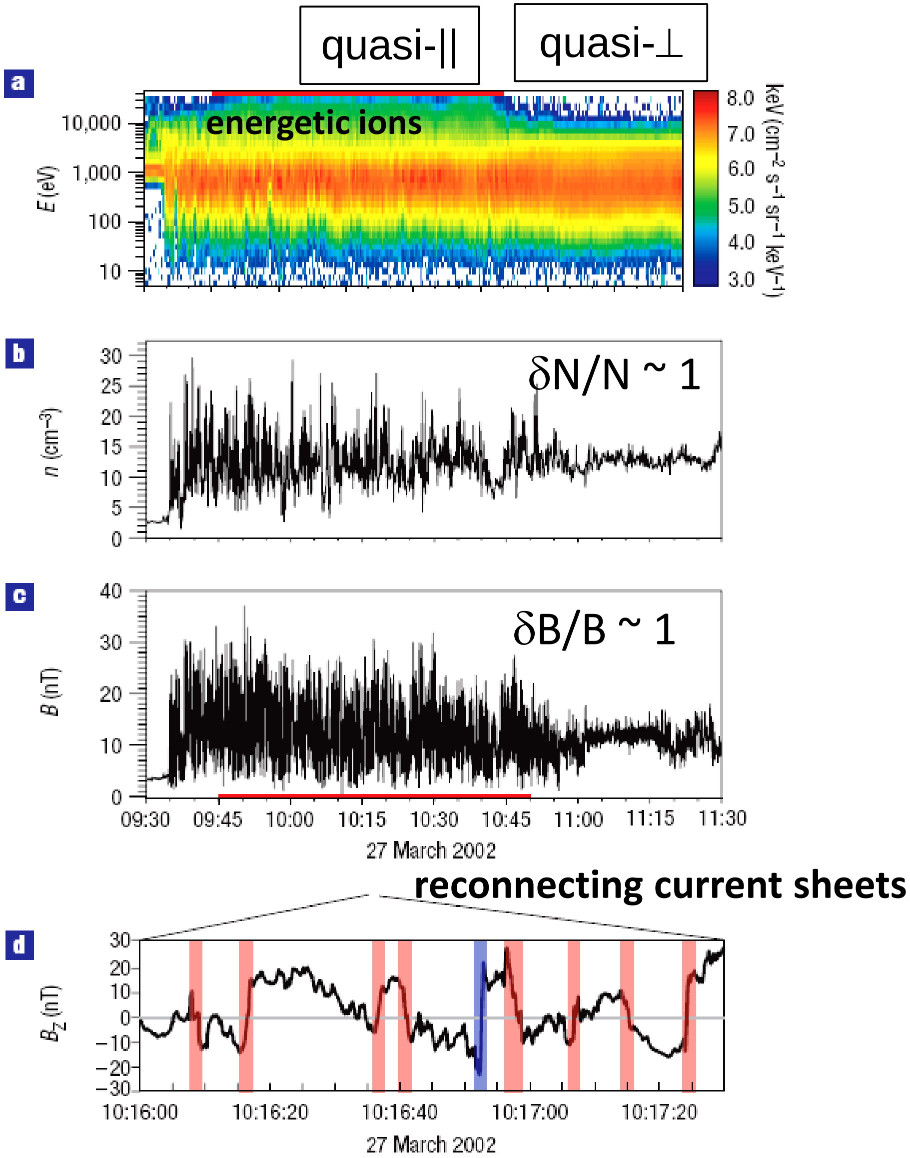


[Karimabadi+, Phys. Plasmas, 2014]

- Zoo of structures such as magnetic islands, current sheets, shocklets, vortexes
- Reconnecting current sheets play important role for dissipation

Reconnection in turbulence

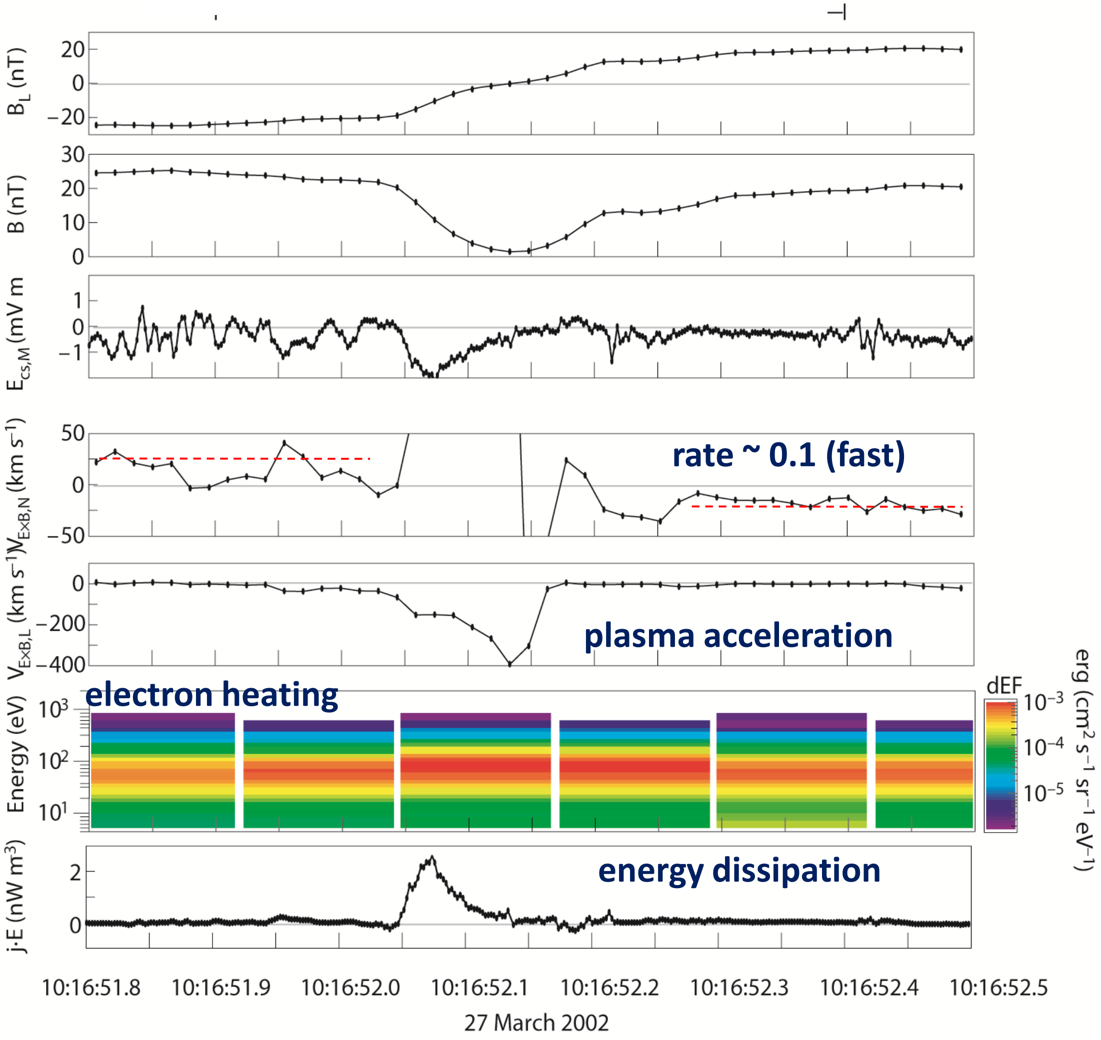




[Retinò+, Nature Physics, 2007]

See also [Gosling+, ApJL, 2007; Chian+, ApJL, 2011; Perri+, PRL, 2012; Osman+, PRL, 2014]

Reconnection in turbulence: in situ evidence



rate ~ 0.1 (fast)

plasma acceleration

electron heating

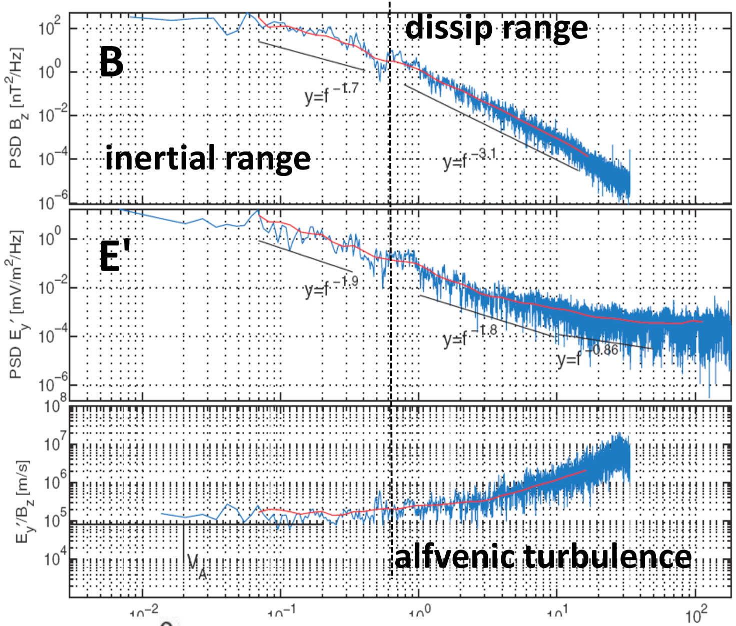
energy dissipation

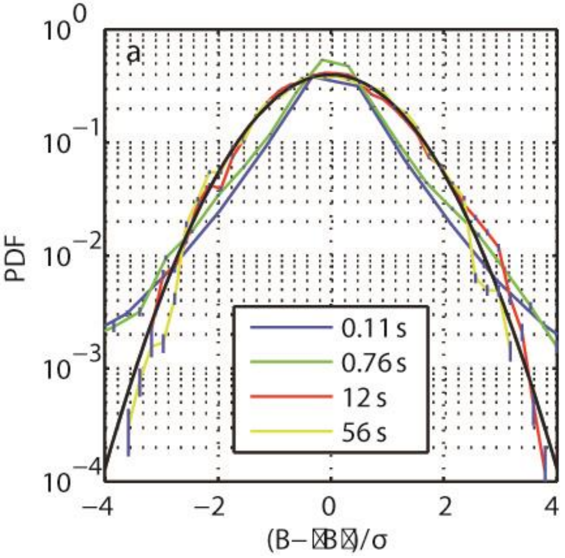
[Retinò+, Nature Physics, 2007]

Properties of the turbulence

- Alfvenic turbulence with steeper spectrum below proton scales
- Intermittency at scales λ_i - ρ_i (close to dissip. range) related to small-scale coherent structures (magnetic islands and current sheets)
- dissipation in coherent structures with d~ λ_i larger than wave damping around ω_{ci} -> turbulent reconnection possibly dominant mechanism for energy dissipation at ion scales

Cluster measurements

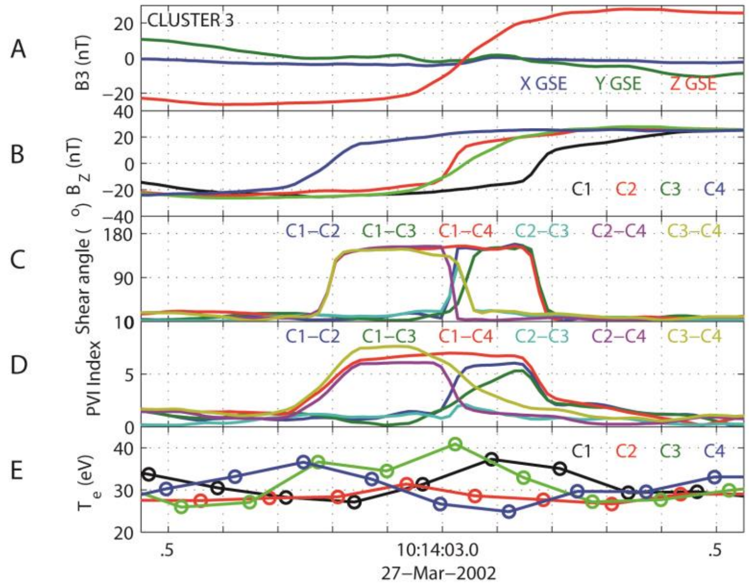


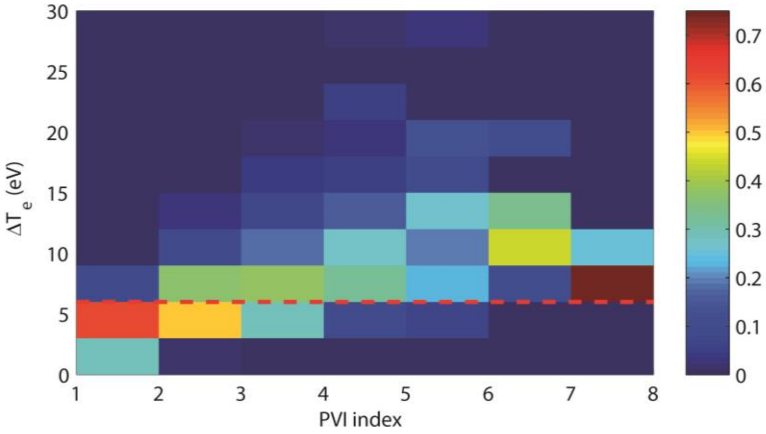


[Sundkvist +, PRL, 2007]

Electron heating in thin current sheets

PVI [Greco+, GRL, 2008] $\mathcal{I}(s,\Delta s) = \frac{|\Delta \boldsymbol{b}(s,\Delta s)|}{\sqrt{\langle|\Delta \boldsymbol{b}(s,\Delta s)|^2\rangle}}.$



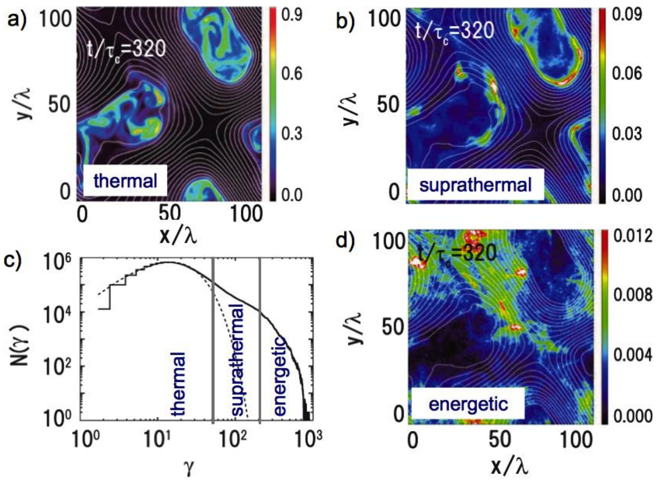


[Chasapis+, ApJLett., 2015]

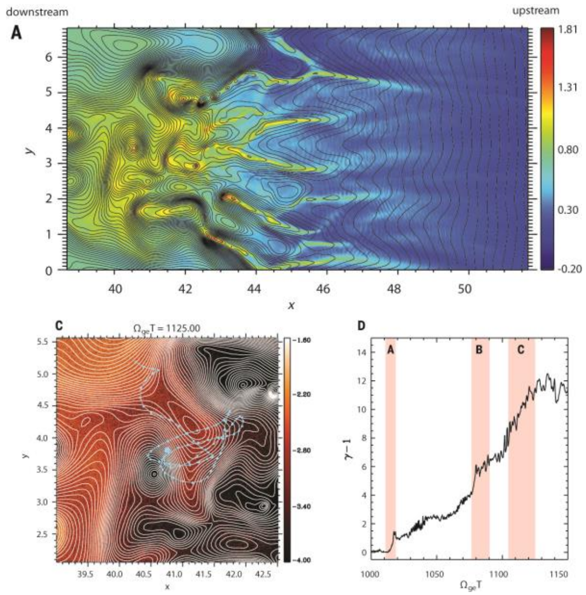
- First evidence of local electron heating in thin cureent sheets within turbulence. Current sheets have scales ≤ d_i. Cluster results recently confirmed by MMS (Chasapis et al, ApJ Lett., 2017)
- No significant heating occurs in low PVI structures (<3). Important heating occurs in high PVI >3 structures (current sheets show)
- Results consistent with earlier statistical studies in pristine solar wind [Osman+,ApJL, 2011]

Reconnection & turbulence: (some) open questions

- What is the role of reconnection for energy dissipation in turbulence dissipation range?
- How the relative role between reconnection and wave-like dissipation depends on the properties of trbulence (e.g. weak vs strong, 2D vs 3D, etc.)?
- Can turbulence enhance reconnection rate? (Lazarian &Vishniac, ApJ,1999; Servidio et al., PRL,2009)
- What is the role of turbulent reconnection for accelerating energetic particles ?



[adopted from Hoshino, PRL, 2012]

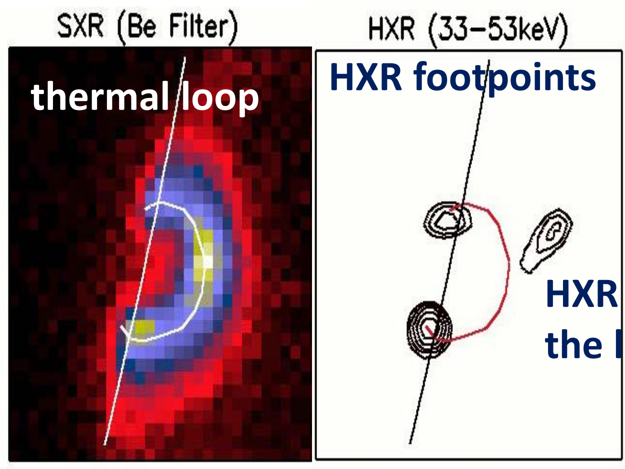


[Matsumoto+, Science, 2015]

Non-thermal particle acceleration

See Tutorial
by Cerutti

SUN

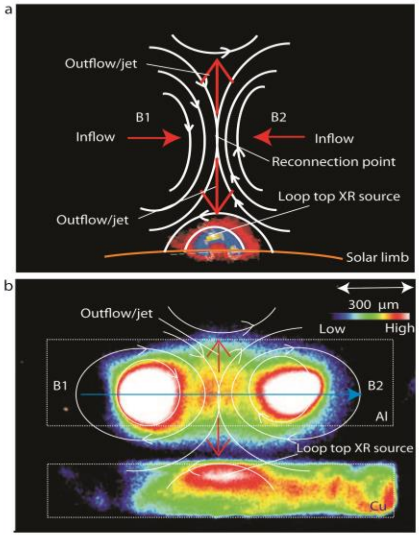


thermal loop

HXR footpoints

HXR above
the loop

LAB



[Zhong+, Nature Physics, 2010]

- reconnection main process invoked to explain solar flares [Giovanelli, Nature, 1946] and other astrophysical energetic phenomena
- observed X-rays produced by accelerated particles during reconnection
- accelerated particles only available tool to study reconnection in distant objects (through emitted radiation)
- accelerated particles in the magnetosphere account for only a few % of dissipated magnetic energy but acceleration mechanisms can be studied in situ (estimated 50% in flares and even more in astrophysical objects)

Definitions (not firm)

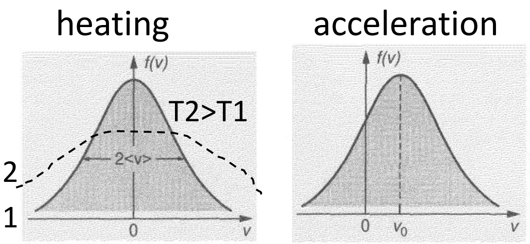
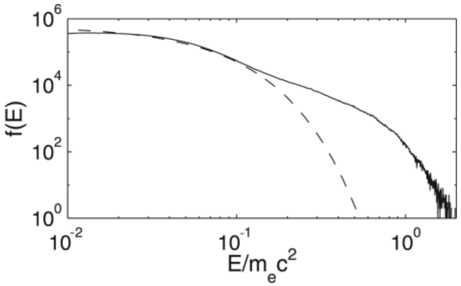


Fig. 6.5. Maxwellian and drifting Maxwellian velocity distributions.

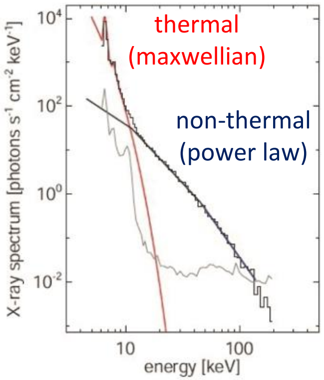
collisional plasma
(f(v) maxwellian)

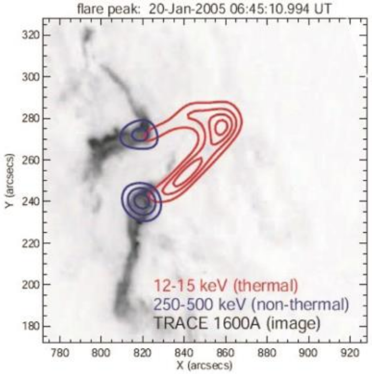
- *acceleration* vs *heating*



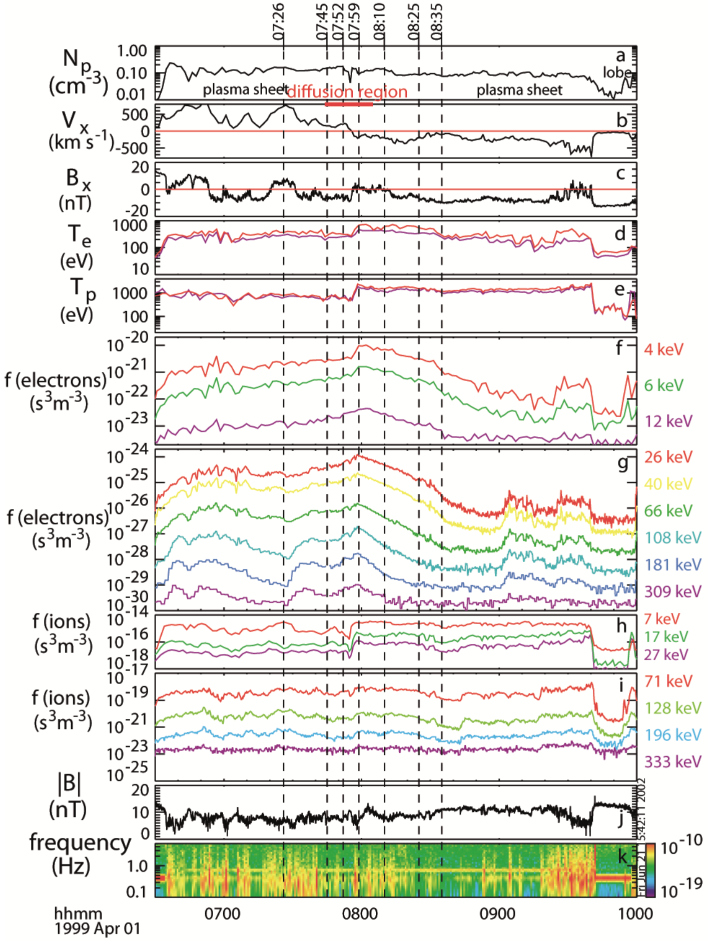
collisionless plasma
(f(v) not maxwellian)

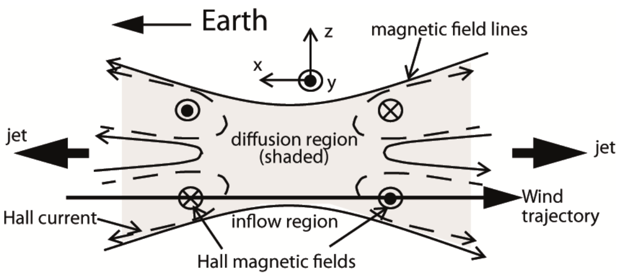
- *thermal* vs *non-thermal*

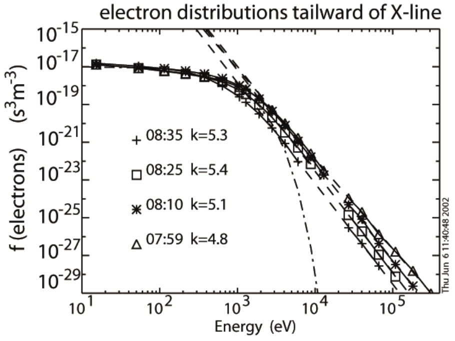


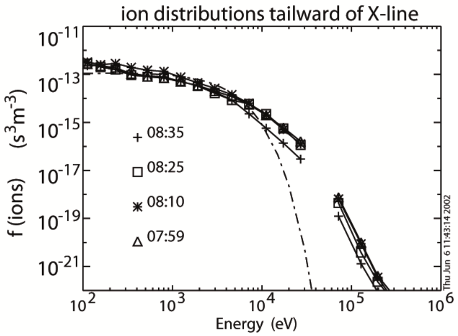


Evidence of non-thermal particle acceleration





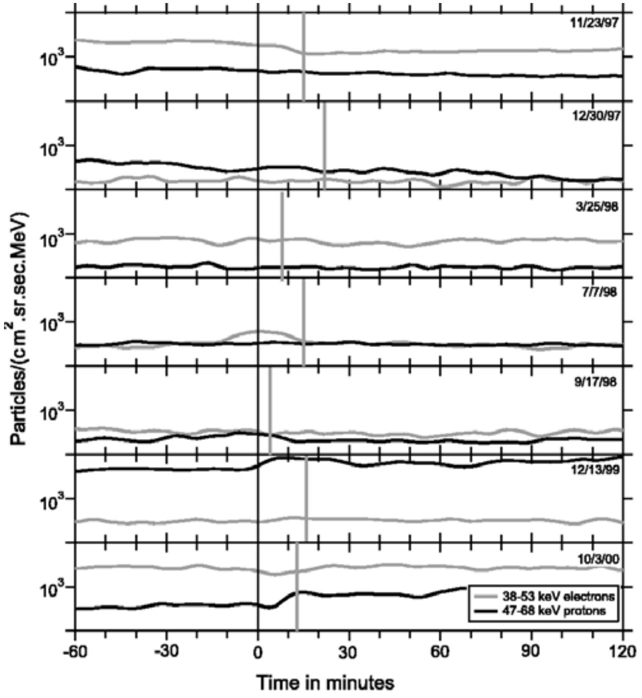




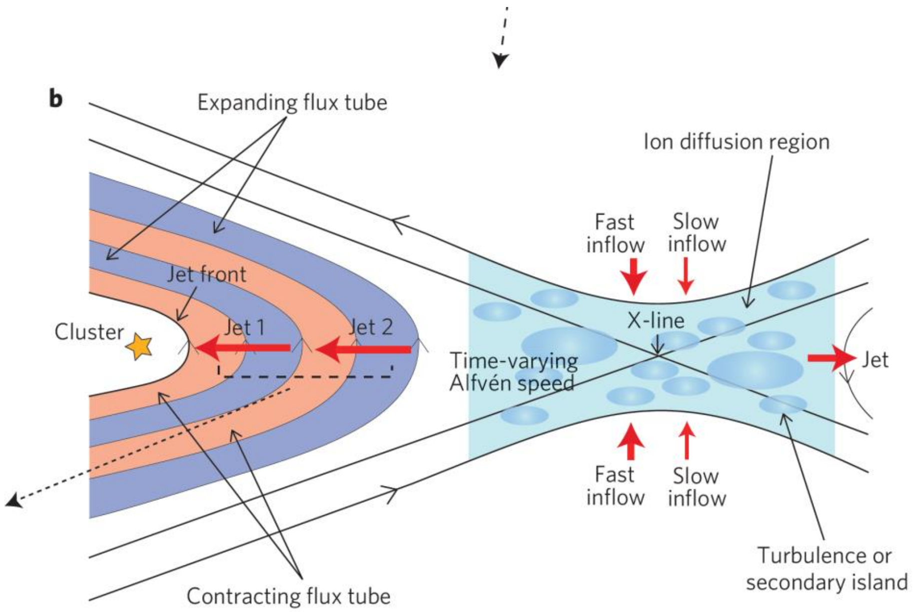
- in situ evidence in the magnetotail
- non-thermal electrons $f(E) \sim E^{-\gamma}$ with $\gamma \sim 5$ for E> 2 keV
- no clear ion acceleration

[adopted from Øieroset et al., PRL,2002]

Particle acceleration is not always efficient



[adopted from Gosling+,GRL, 2005]



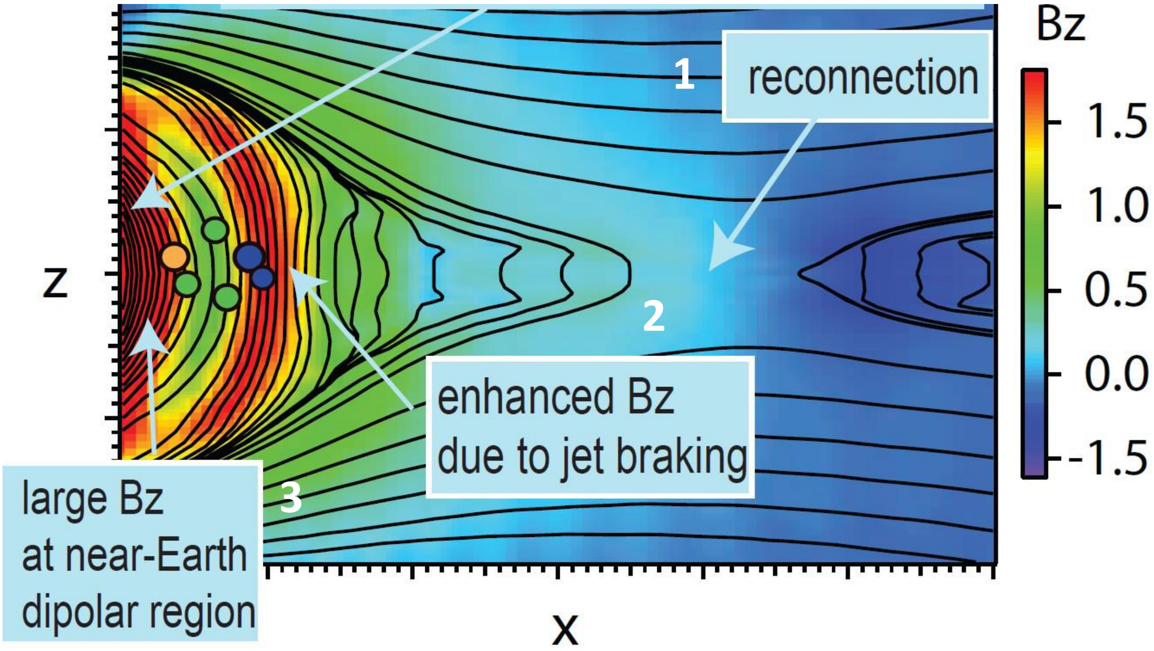
[Fu et al. Nature Physics,2013]

absence of energetic particles
in solar wind reconnection events
(steady reconnection)

Strong particle acceleration in
magnetotail (unsteady reconnection)

particle acceleration depends on reconnection conditions:
steady vs unsteady, beta, laminar vs turbulent, etc.

Where does particle acceleration occur?

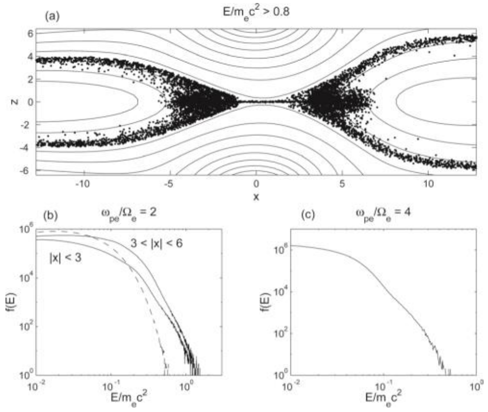


[Birn et al., JGR, 2011]

Three regions important for acceleration:

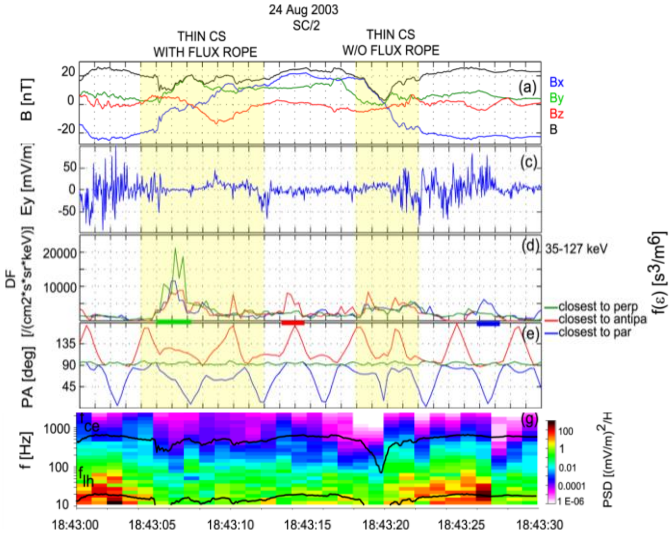
1. **X-line** [Øieroset+, PRL, 2002; Imada+, JGR,2007; Retinò+, JGR,2008;Chen+,Nature Physics, 2008]
2. **Outflow/jet fronts** [Fu+, GRL,2011; Ashour-Abdalla+, Nature Physics,2011]
3. **Interaction with dipolar field and obstacles** [Sergeev+, GRL, 2009; Zieger+, GRL, 2011]

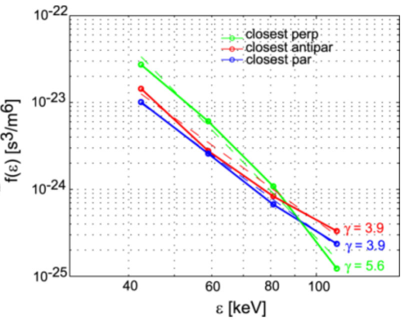
Acceleration by reconnection electric field at X-line



[Pritchett+,GRL, 2006]

- 3D full PIC simulations
- acceleration by reconnection electric field up to relativistic energies; non-thermal electrons $f(E) \sim E^{-g}$ with g~5
- unsteady reconnection
- acceleration by $E_{||}$ in the case of guide field [Pritchett+, JGR, 2006]



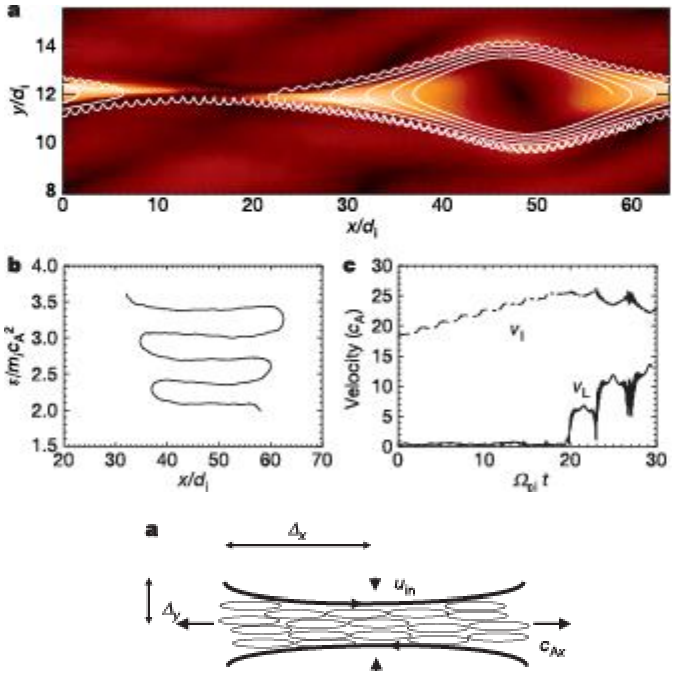


- direct X-line acceleration by Ey ~ 7 mV/m (unsteady reconnection)
- further acceleration within magnetic island

[Retinò+, JGR, 2008]

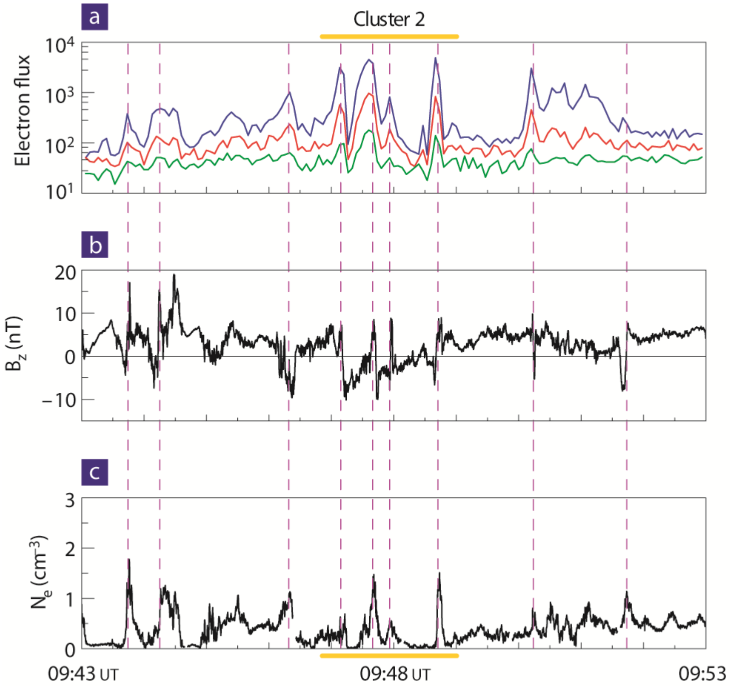
Acceleration in magnetic islands

acceleration in small-scale islands



[adopted from Drake+, Nature, 2006]

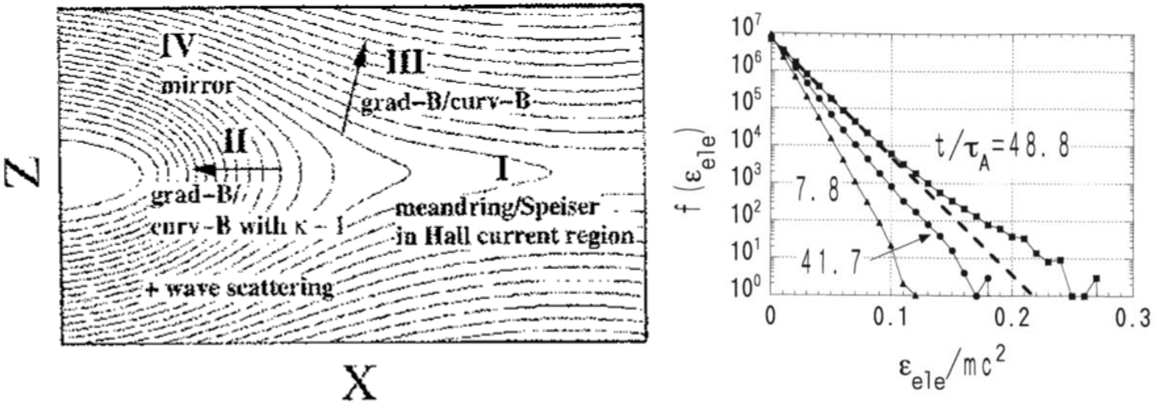
In situ observations



[adopted from Chen+, Nature Physics, 2008]

Acceleration at magnetic flux pile-up

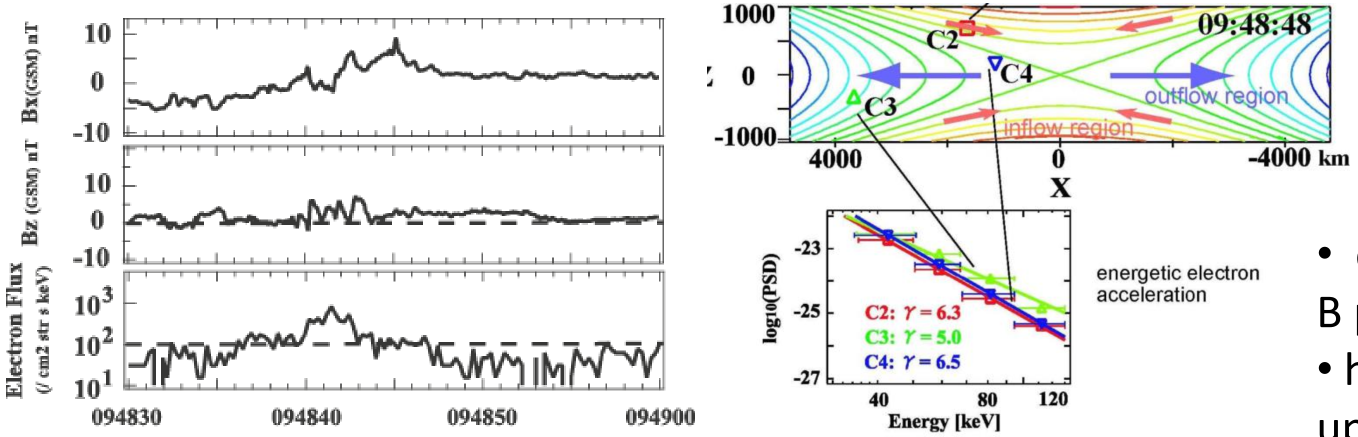
PIC simulation



[adopted from Hoshino+, JGR, 2001]

- acceleration by Ey in strong B-gradient region
(« magnetic flux pile-up »)
- magnetic mirror and ∇B / curvB drift keep
particles in acceleration region
- non-adiabatic mechanism (gyroradius comparable to B-gradients + wave scattering)

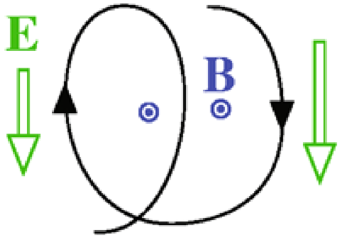
in situ evidence



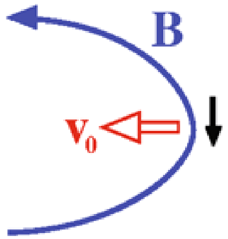
- electron acceleration at B pile-up
- harder spectrum in pile-up region than at X-line

[adopted from Imada+, JGR, 2007]

Betatron/Fermi acceleration at jet fronts



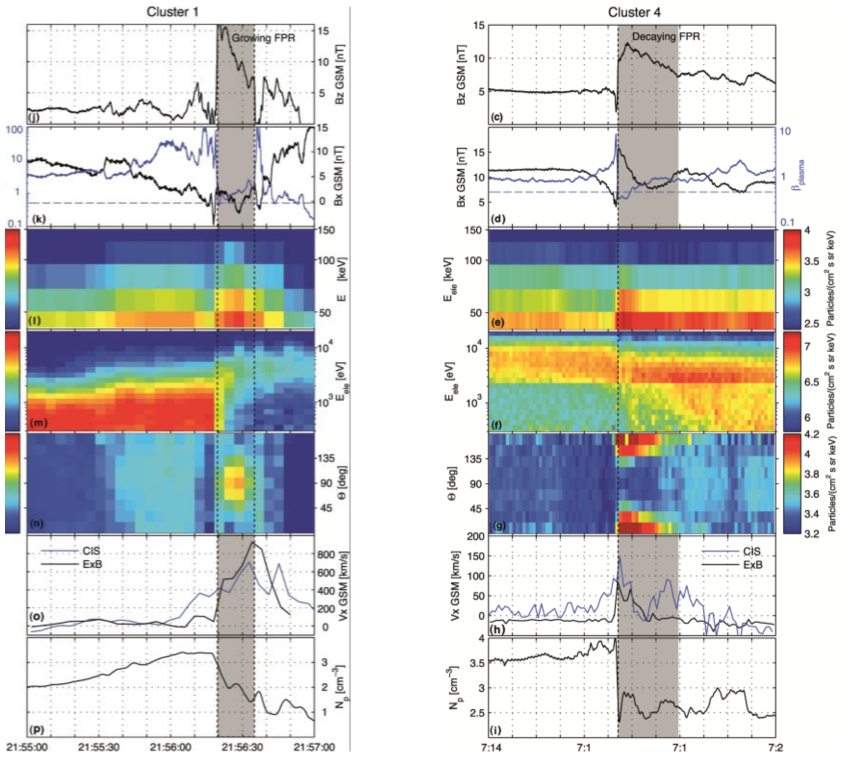
betatron



Fermi

[adopted from Birn+, 2012]

PA 90°



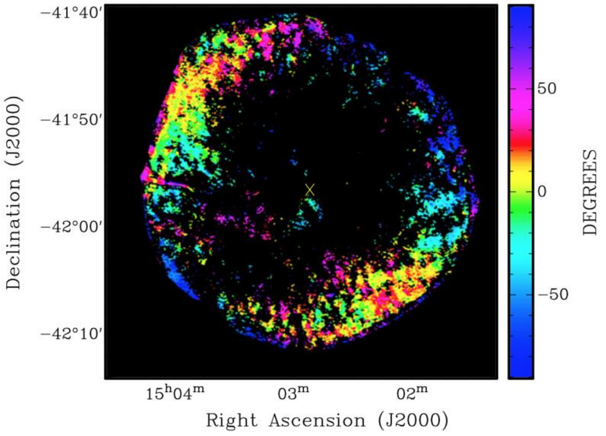
PA 0° & 180°

[adopted from Fu+, 2011]

Particle acceleration: (some) open questions

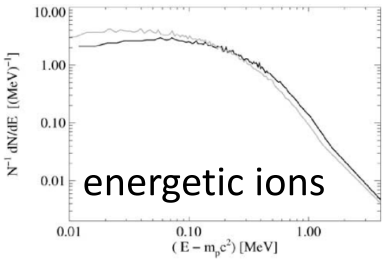
1. How particle acceleration depends on plasma parameters, boundary conditions, stages of reconnection etc.
2. Which reconnection regions produce the strongest acceleration ?
3. What is the role of turbulent reconnection for particle acceleration?
4. How energy is partitioned among energetic electrons, protons and heavy ions?

[Reynoso+, AJ, 2013]



SN 1006

most efficient particle acceleration and generation of magnetic turbulence at quasi-par shocks



energetic ions

[Dmitruk & Matthaeus, Phys. Plasmas, 2006]

Future spacecraft measurements relevant for reconnection

ESA/BepiColombo (2018): Mercury’s magnetosphere

NASA/SolarProbePlus (**2018)**: near-Sun corona (8.5 Rs)

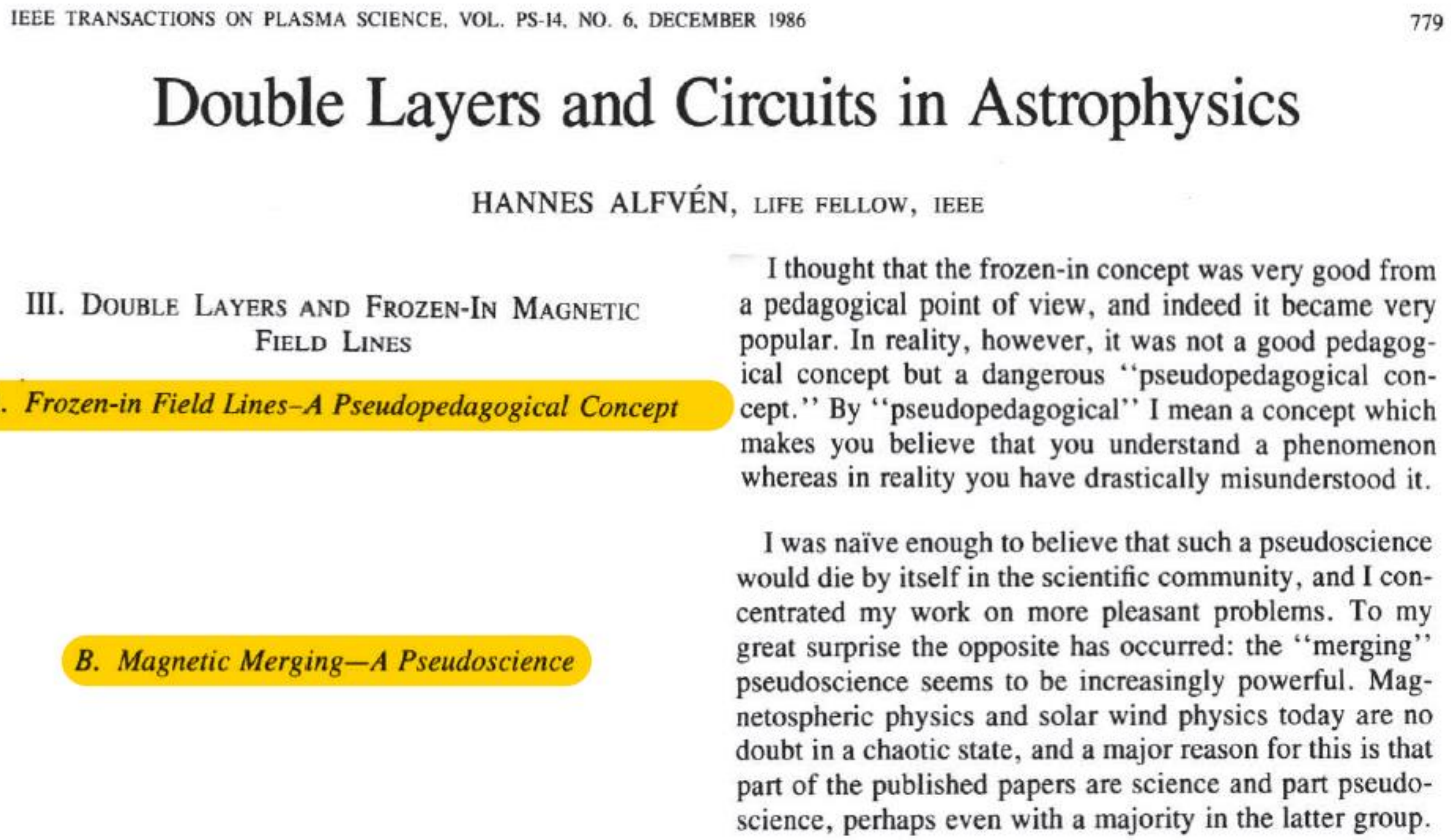
ESA/SolarOrbiter (2019): near-Sun corona (62 Rs)

ESA/JUICE (2022): Jupiter’s and Ganymede’s magnetopshere

ESA/THOR (2026?): under evaluation as ESA M4 mission. Focus on plasma energization by turbulence

Reconnection: Alfvén’s opinion

1. *Topology*



IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. PS-14, NO. 6, DECEMBER 1986 779

Double Layers and Circuits in Astrophysics

HANNES ALFVÉN, LIFE FELLOW, IEEE

III. Double Layers and Frozen-In Magnetic Field Lines

A. Frozen-in Field Lines–A Pseudopedagogical Concept

I thought that the frozen-in concept was very good from a pedagogical point of view, and indeed it became very popular. In reality, however, it was not a good pedagogical concept but a dangerous ‘‘pseudopedagogical concept.’’ By ‘‘pseudopedagogical’’ I mean a concept which makes you believe that you understand a phenomenon whereas in reality you have drastically misunderstood it.

B. Magnetic Merging—A Pseudoscience

I was naïve enough to believe that such a pseudoscience would die by itself in the scientific community, and I concentrated my work on more pleasant problems. To my great surprise the opposite has occurred: the ‘‘merging’’ pseudoscience seems to be increasingly powerful. Magnetospheric physics and solar wind physics today are no doubt in a chaotic state, and a major reason for this is that part of the published papers are science and part pseudoscience, perhaps even with a majority in the latter group.

Figure 1.3.: A few quotes from the Hannes Alfvén paper on double layers [Alfven, 1986].

Summary

- Reconnection does occur in plasmas

- In situ spacecraft measurements required to understand the physics of reconnection. Synergy with remote and laboratory measurements crucial.

- Interpretation of in situ data requires much carefulness. Often small quantities with large errors are important.

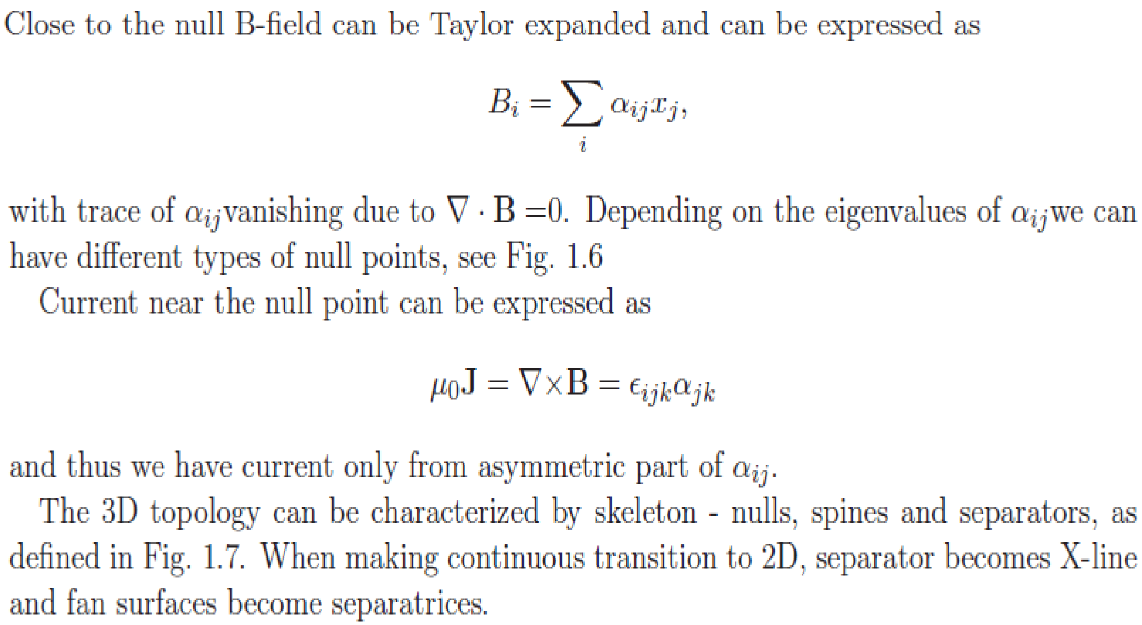
- We know much on reconnection but there are still many open issues:
  - Microphysics (electron scales)
  - Relationship with turbulence
  - Paricle acceleration mechanisms

- There is a lot of data from current spacecraft missions and more will come in next 10-15 years

Suggested references

- B. Sonnerup, *Magnetic field reconnection*, in Solar system plasma physics, p. 45-108, 1979
- E. Zweibel and M. Yamada, *Magnetic Reconnection in Astrophysical and Laboratory Plasmas*, Annual Review of Astronomy and Astrophysics, Vol. 47:291-332, 2009
- E. Priest and T. Forbes, *Magnetic Reconnection: MHD Theory and Applications*, Cambridge University Press, 2000
- M. Yamada, R. Kulsrud and H. Ji, *Magnetic reconnection*, Rev. Mod. Phys. 82, 603, 2010
- W. Gonzalez and E. Parker, *Magnetic Reconnection: Concepts and Applications*, Springer, 2016

Magnetic nulls (B=0)



Close to the null B-field can be Taylor expanded and can be expressed as

$$B_i = \sum_i \alpha_{ij} x_j,$$

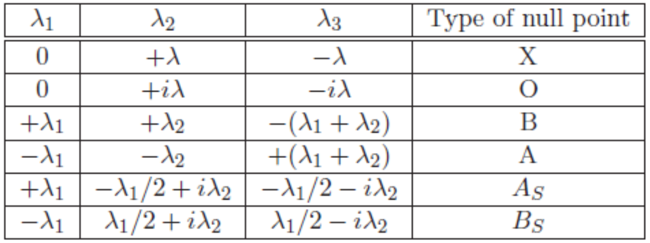
with trace of α_{ij}vanishing due to $\nabla \cdot \mathrm{B} = 0$. Depending on the eigenvalues of α_{ij}we can have different types of null points, see Fig. 1.6

Current near the null point can be expressed as

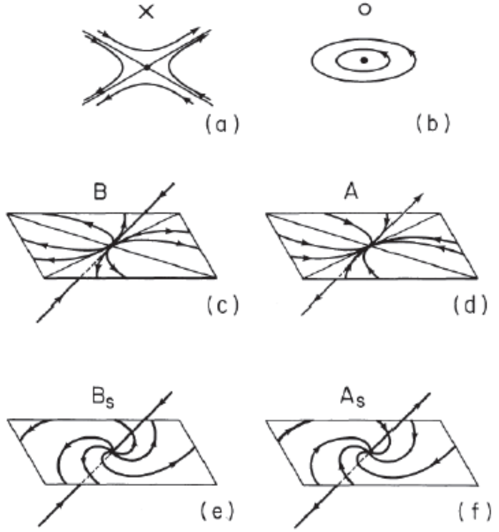
$$\mu_0 \mathrm{J} = \nabla \times \mathrm{B} = \epsilon_{ijk} \alpha_{jk}$$

and thus we have current only from asymmetric part of α_{ij}.

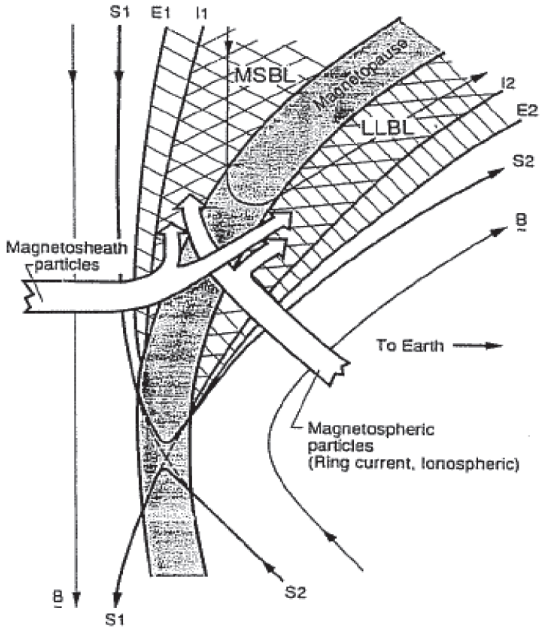
The 3D topology can be characterized by skeleton - nulls, spines and separators, as defined in Fig. 1.7. When making continuous transition to 2D, separator becomes X-line and fan surfaces become separatrices.



λ_1	λ_2	λ_3	Type of null point
0	$+\lambda$	$-\lambda$	X
0	$+i\lambda$	$-i\lambda$	O
$+\lambda_1$	$+\lambda_2$	$-(\lambda_1+\lambda_2)$	B
$-\lambda_1$	$-\lambda_2$	$+(\lambda_1+\lambda_2)$	A
$+\lambda_1$	$-\lambda_1/2+i\lambda_2$	$-\lambda_1/2-i\lambda_2$	A_S
$-\lambda_1$	$\lambda_1/2+i\lambda_2$	$\lambda_1/2-i\lambda_2$	B_S



In situ evidence of reconnection at MHD scales: particle distribution functions

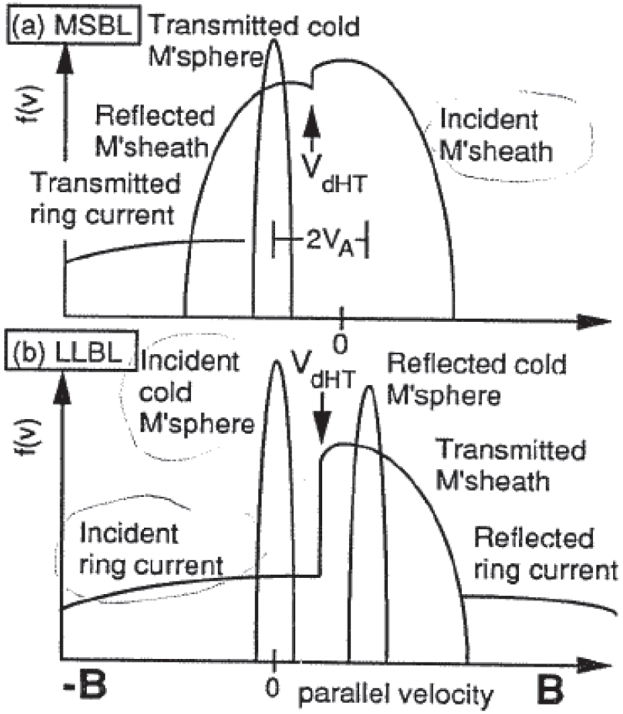


LLBL - low latitude boundary layer (transmitted magnetosheath & reflected magnetospheric)

MSBL – magnetosheath boundary layer (transmitted magnetospheric & reflected magnetosheath)

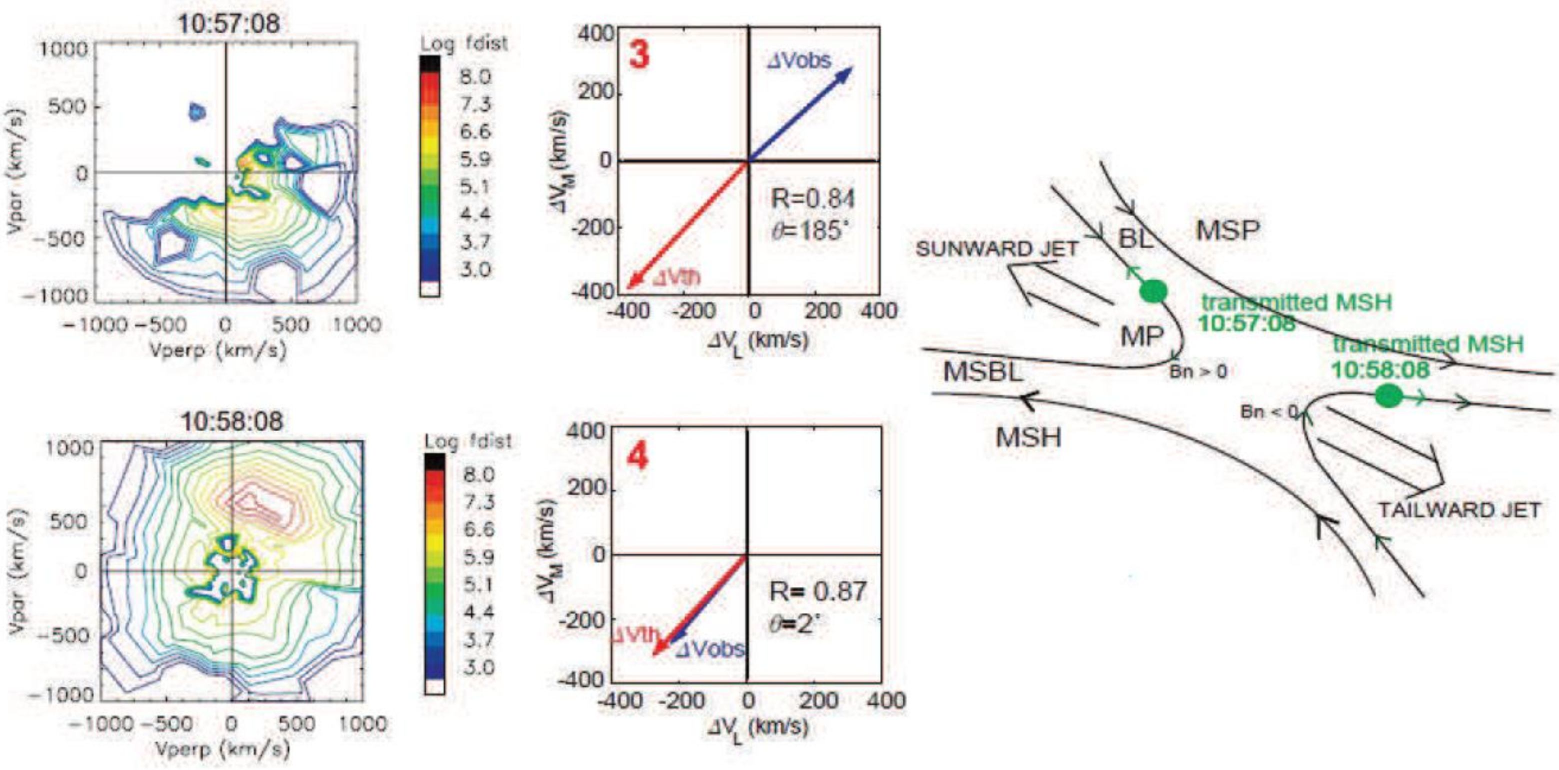
[Gosling, JGR, 1986]

MSBL & LLBL



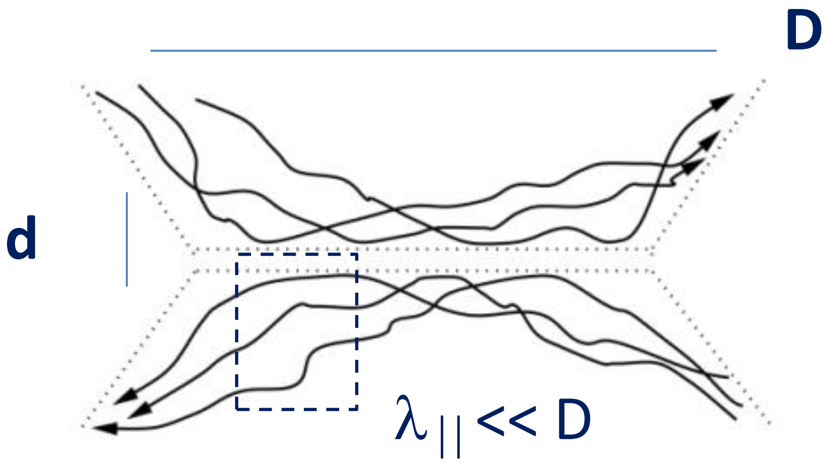
[Fuselier, 1995]

Observations of distribution functions on reconnected flux tubes



[Retino et al., Ann. Geophys., 2005]

« Turbulent reconnection » (I)



[adopted from Lazarian & Vishniac, ApJ, 1999]

See also recent review paper by Lazarian+,Phys. Plasmas, 2012.

- analytical calculation

- assume small-scale turbulent magnetic field on top of large-scale laminar field (*ad hoc* scaling law)

- reconnection rate enhanced $R_{LV} \geq L^{-3/16} * M^{3/4}$ where L is the Lundquist number and M the Mach number of the turbulence (compare with $R_{SP} \sim L^{-1/2}$ and $R_{Petschek} \sim 1/\text{Log}(L)$)

- no clear in situ evidence (in my knowledge)

Waves/turbulence and anomalous resistivity

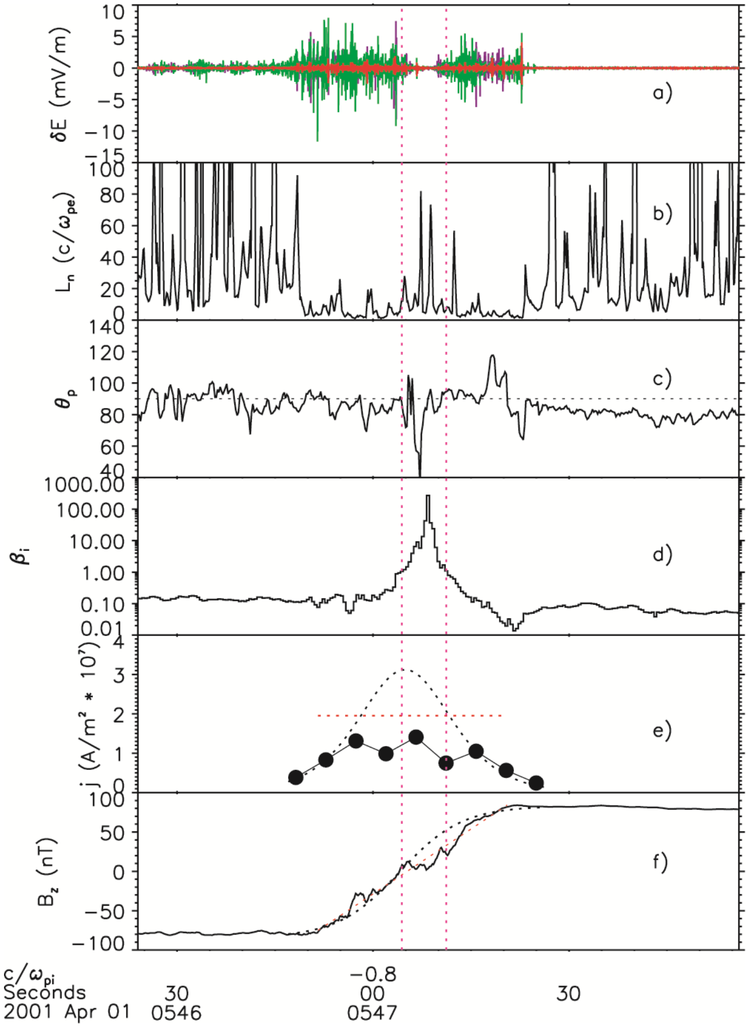
$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \boxed{\eta \mathbf{j}} + \frac{1}{ne}\mathbf{j} \times \mathbf{B} - \frac{1}{ne}\nabla \cdot \mathbf{P}_e + \frac{m_e}{ne^2}\frac{\partial \mathbf{j}}{\partial t}$$

- in collisionless plasmas η (if any) can only comes from wave-particle interaction

- two major wave modes/turbulence invoked to explain η:
  - lower-hybrid (drift) waves: electrostatic
  - whistler waves: electromagnetic

- other wave modes also possible (e.g. ion-acoustic waves etc.)

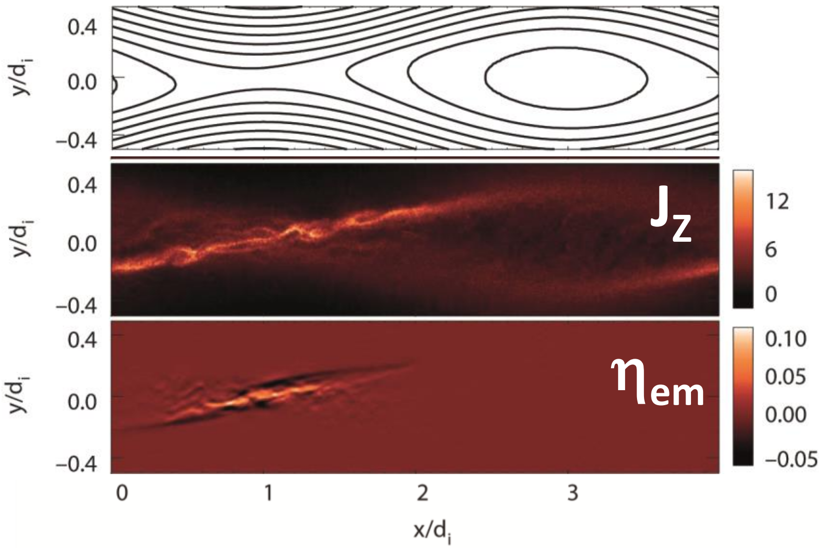
Lower-hybrid waves vs resistivity

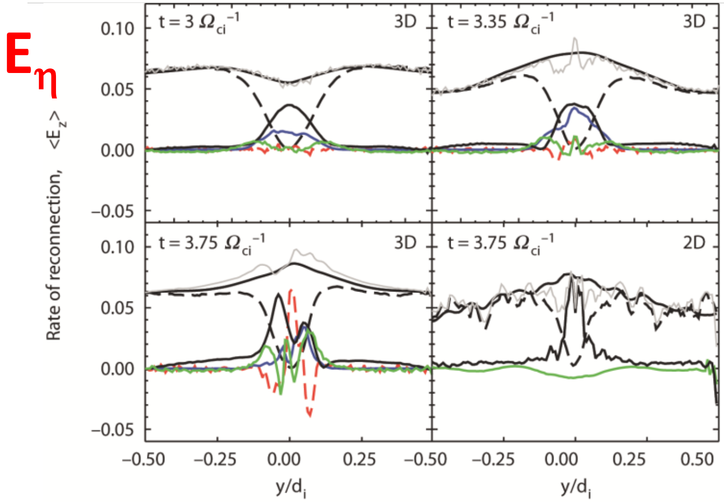


[adopted from Bale+, GRL, 2002]

- unimportant in the diffusion region (they are damped in high β - center of current sheet where B ~0)
- however can develop at current sheet separatrices (density gradients) and contribute to current sheet thinning
- recent THEMIS observations indicate that the electrostatic contribution to η is negligible (e. g. Mozer+, Phys. Plasmas, 2011).

Whistler waves vs resistivity





- •electromagnetic component of η associated to whistler waves/turbulence important

- no clear observations (η_{em} very difficult to estimate from current spacecraft data – MMS)

[adopted from Che+, Nature, 2011]