

Magnetic reconnection in the near-Earth space: Cluster results and future perspectives

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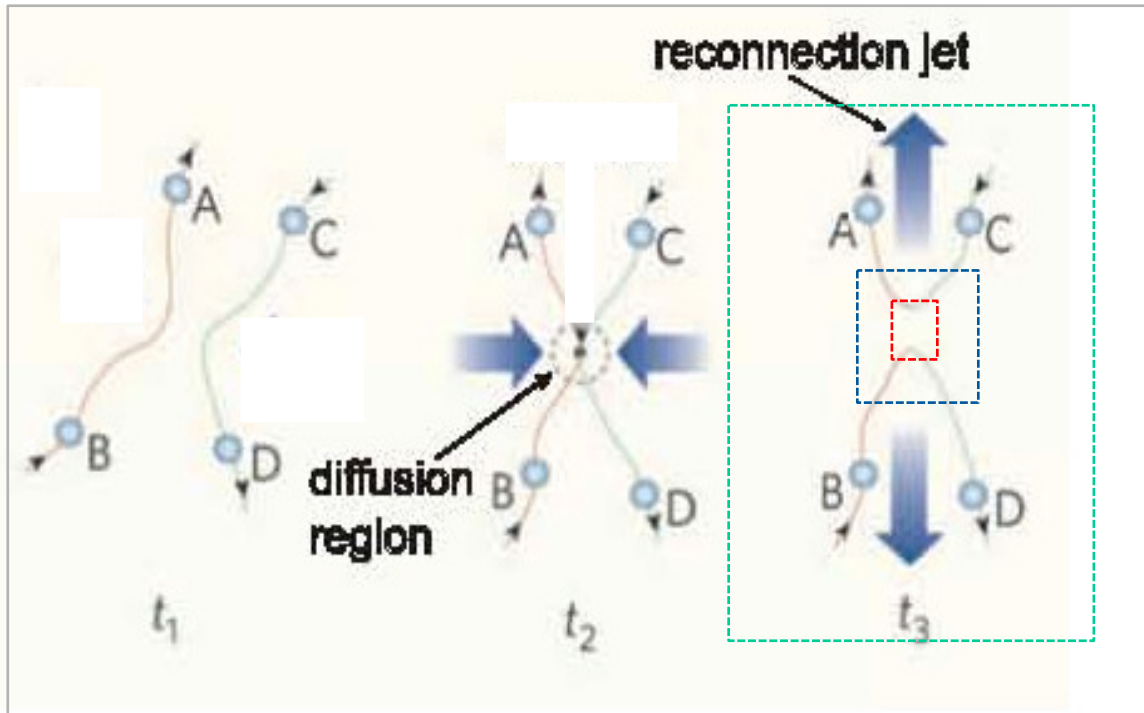
Outline

- Brief motivation
- The very basics
- Before Cluster
- Cluster era: mayor results & remaining issues
- Reconnection, quo vadis?
 - the near-future: MMS
 - the future: Scope + EidoScope (?)
- Synergies with solar and astro plasma physics
- Summary

Motivation

- Energy conversion/dissipation fundamental issue for lab, space and astro plasmas
- Reconnection mayor process
- *In situ* measurements of field and particles required to understand the physics of reconnection
- Near-Earth space ideal *laboratory*: multi-instrument / multi-spacecraft / multi-scale (limited so far)
- Reconnection key process for Sun-Earth relationships (space weather)
- Results from *in situ* observations exportable to distant plasma (with caution): universality

The very basics



[adopted from Paschmann et al., 2006]

breaking of frozen-in condition
at electron scales



local topology change (E_{\parallel})



large-scale:

- fast jets
- transport across boundaries
- particle acceleration

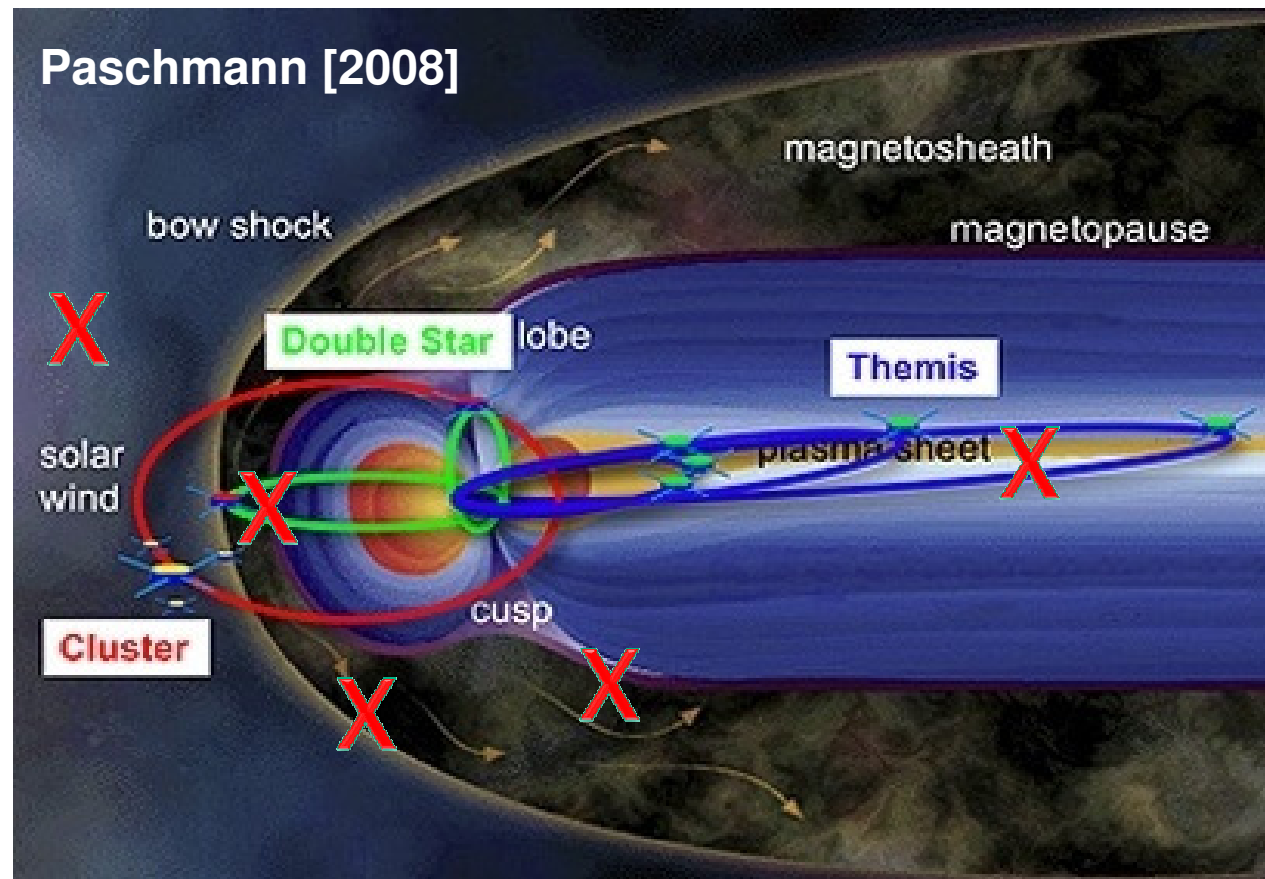
$$\mathbf{E} + \mathbf{u} \times \mathbf{B} = \underbrace{\frac{\mathbf{J}}{\sigma}}_{\text{MHD}} + \underbrace{\frac{\mathbf{J} \times \mathbf{B}}{ne}}_{\text{anomalous conductivity}} - \underbrace{\frac{\nabla \cdot \mathbf{P}_e}{ne}}_{\text{Hall}} + \underbrace{\frac{m_e}{ne^2} \frac{\partial \mathbf{J}}{\partial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

MHD **anomalous conductivity** **Hall** **electron pressure inertia**

Three scales coupling

- **MHD** ($\gg \rho_i$) $10^3 - 10^4$ km
- **ion** ($\sim \rho_i$) 50-500 km
- **electron** ($\sim \rho_e$) 1-10 km

The near-Earth space



- solar wind: Gosling [2005], Phan [2006], Gosling [2007]
- magnetosheath: Retinò [2007], Sundkvist [2007], Phan [2007]
- magnetopause: Vaivads [2004], Mozer [2005], Retinò [2006], Hasegawa [2009]
- magnetotail: Øieroset [2002], Runov [2002], Eastwood [2007], Retinò [2008]

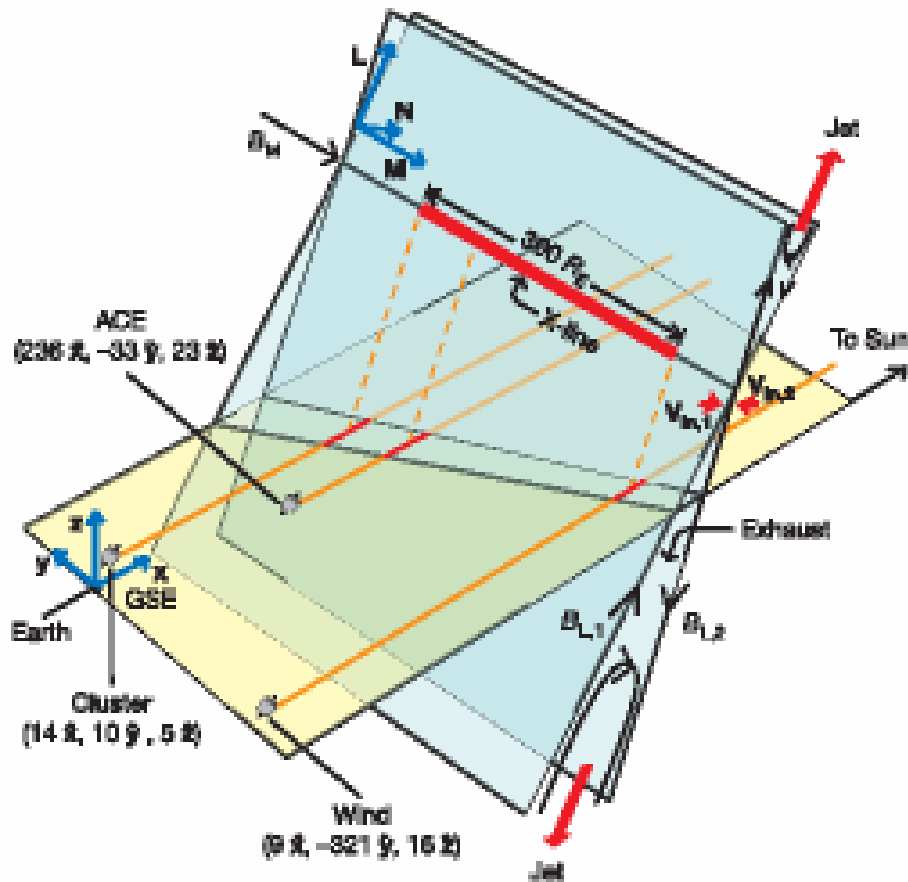
B. C. (Before Cluster)

- Reconnection first time proposed to account for rapid energization in chromospheric flares [Giovanelli, 1946]
- Reconnection as paradigm for magnetospheric convection [Dungey, 1961]
- First *in situ* evidence at magnetopause [Paschmann, 1979]
- Properties of reconnection at large scales (MHD) :
 - MP [Russell, 1979 ; Sonnerup 1981 ; Gosling 1990 ; Phan 2000]
 - Magnetotail [Hones 1981; Baumjohann 1990; Slavin 1990; Nagai 1998]
- Open issues (many already in [Sonnerup, 1979] !)
 - Spatial and temporal evolution at large scales
 - 3D reconnection
 - Microphysics (thin current sheets)
 - Particle acceleration
 - Reconnection & turbulence
 - Interactions of reconnection jets with boundaries
 - Scale coupling

Cluster: 2000 – 2010(14?)

- The extension of the X-line
- Microphysics
 - diffusion regions
 - separatrix regions
- Particle acceleration in thin current sheets
- Reconnection in turbulent plasma

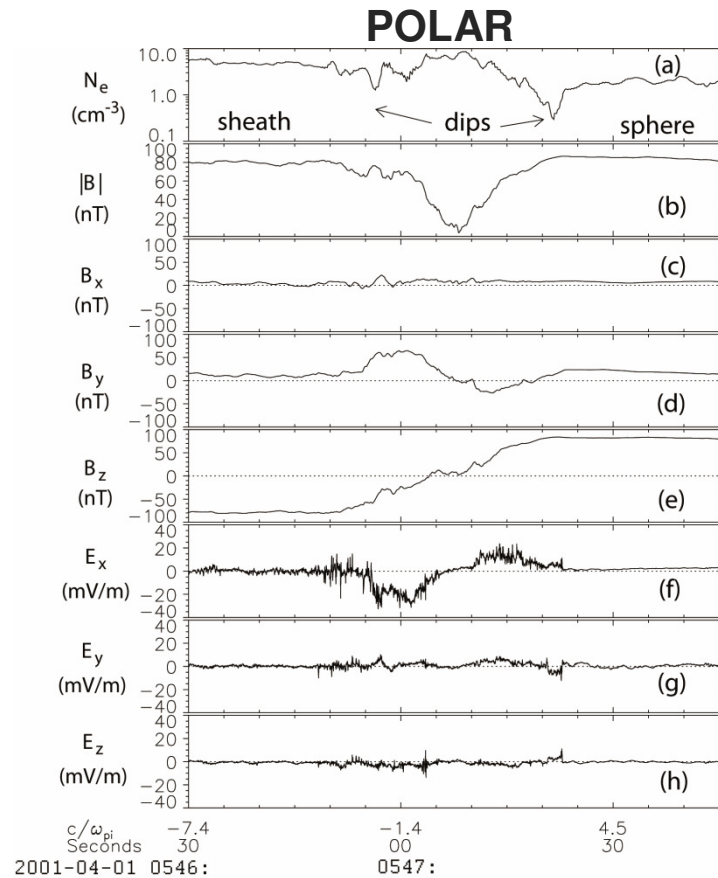
X-line extension



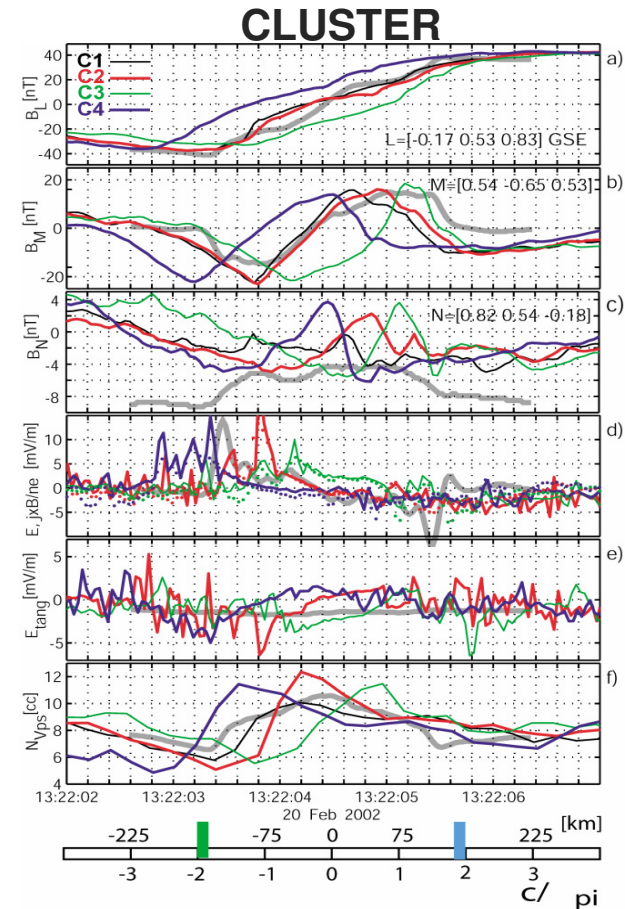
[Phan et al., 2006]

- solar wind
- steady reconnection
- $L \sim 390 R_E \sim 2.5 \times 10^6 \text{ km}$
 $\sim 2.5 \times 10^4 \rho_i$
- important for astro plasmas

The ion diffusion region (magnetopause)



[Mozer et al., 2002]

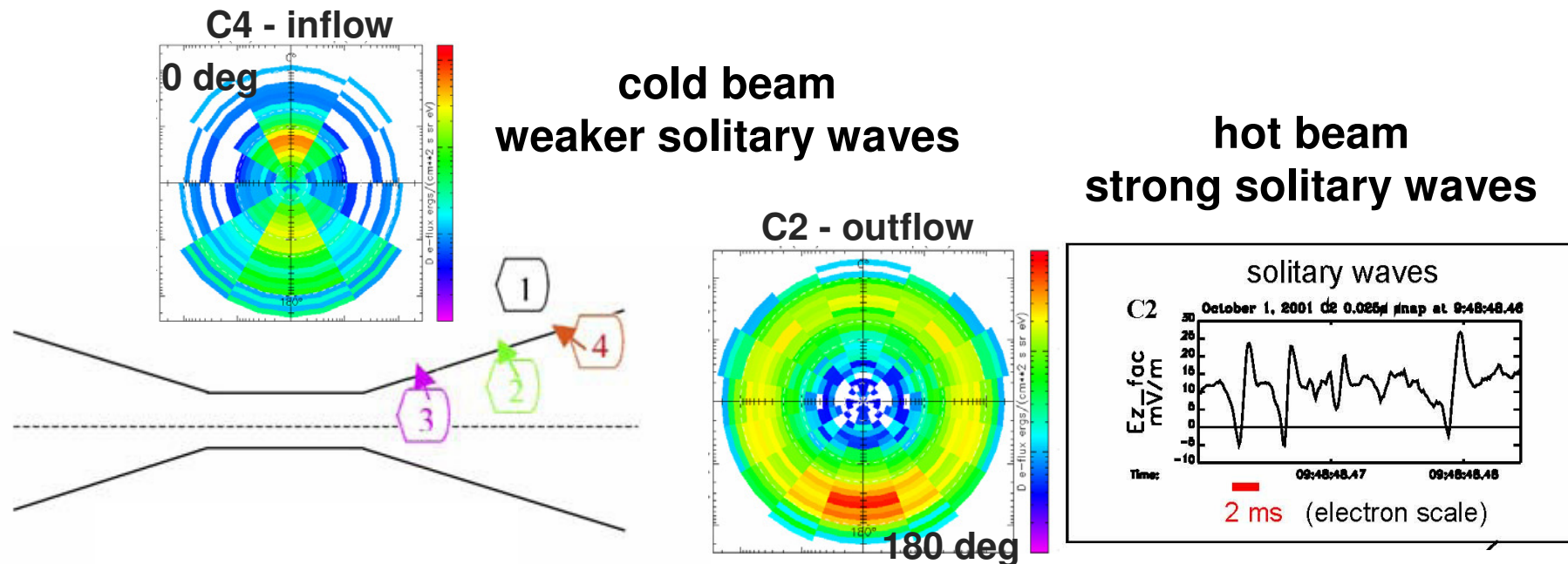


[Vaivads et al., 2004]

also [Runov et al., 2002] in the tail

- spatial structure
- current sheet thickness $\sim \rho_i$
- estimation of rate and potential drops

The separatrix region (tail)

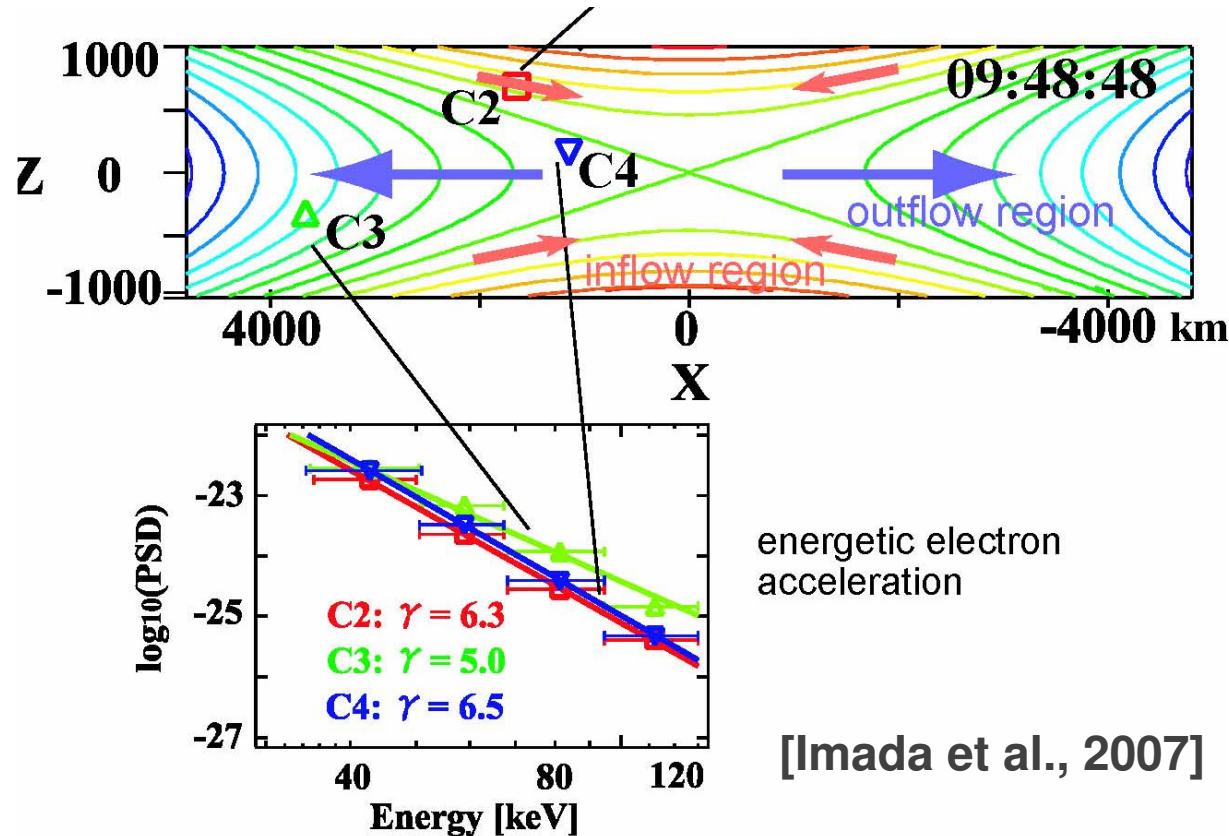


[Cattell et al., 2005]

also [Mozer 2005 ; Retinò 2006 ; Khotyaintsev 2006] at magnetopause

- Hall current system
- Solitary waves associated to electron beams

Energetic electron acceleration in thin sheets (tail)

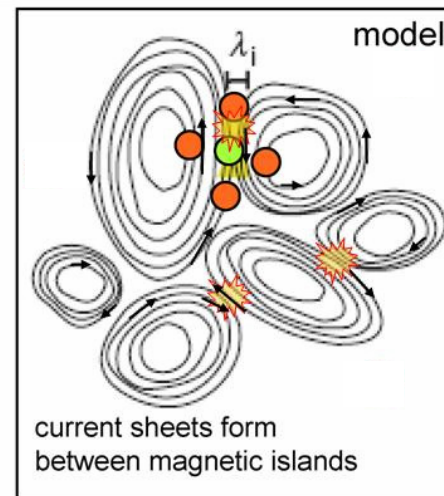
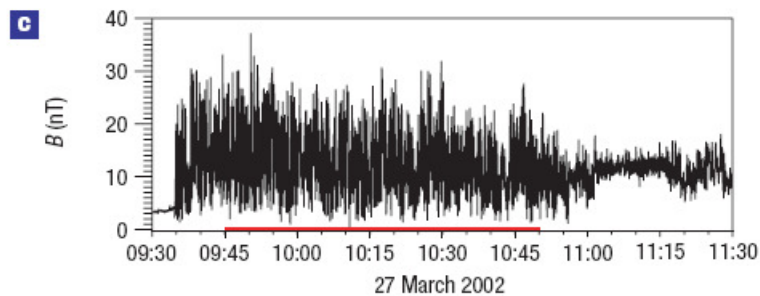
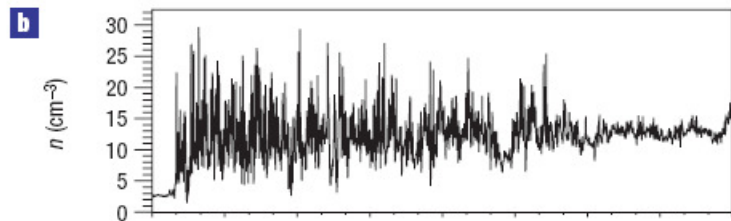
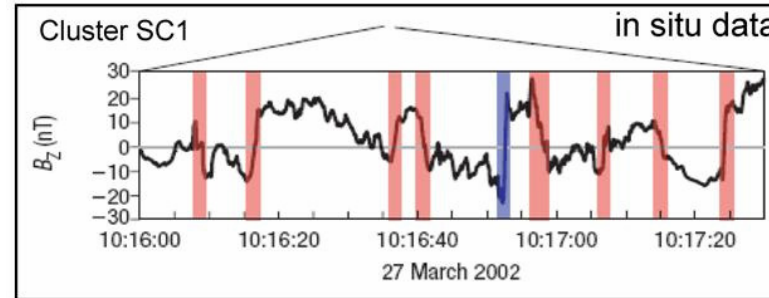
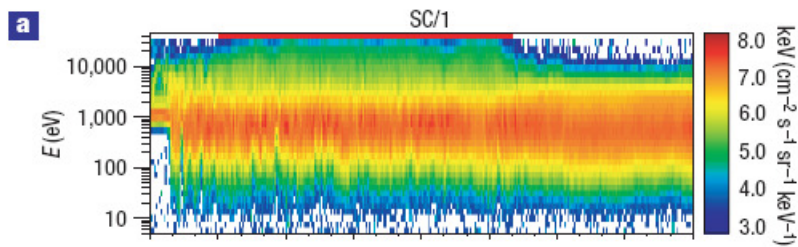


- Reconstruction of field lines from 3 SC magnetic field
- Evolution of energy spectra around X-line
- Evidence of acceleration at Bz pile-up

Other mechanisms:

- small-scale islands [Chen 2008 ; Retinò 2008]
- reconnection electric field [Retinò 2008]

Reconnection in turbulent plasma (magnetosheath)



[Mattheaus 1980]

[Retinò 2007 ; Sundkvist 2007]

- First evidence
- Current sheet thickness $\sim \rho_i$
- Estimation of conversion (dissipation) rate $E \cdot J$
- Volume-filling rec. sheets possibly important for dissipation

New findings - new questions (to be addressed with open mind)

■ **Particle acceleration:**

- Is reconnection always efficient to produce energetic particles [Gosling 2005] ? Only in some cases? Almost never?
- Is the acceleration due to reconnection or rather a by-product?
- Is reconnection in turbulent plasma important for particle acceleration?

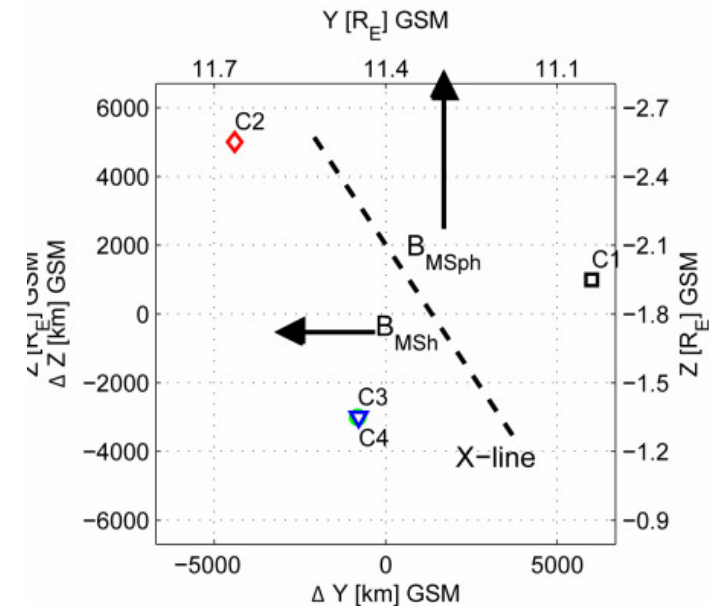
■ **Reconnection & turbulence:**

- Reconnection in turbulent plasma / turbulent reconnection / turbulence in reconnecting sheets. Same or different things?
- How do current sheets/ coherent structures form? What are their properties (not only slopes ☺)
- Reconnection always/sometimes/never important for dissipation in turbulence ?

Electron scales: Cluster input and MMS science (2014-2016)

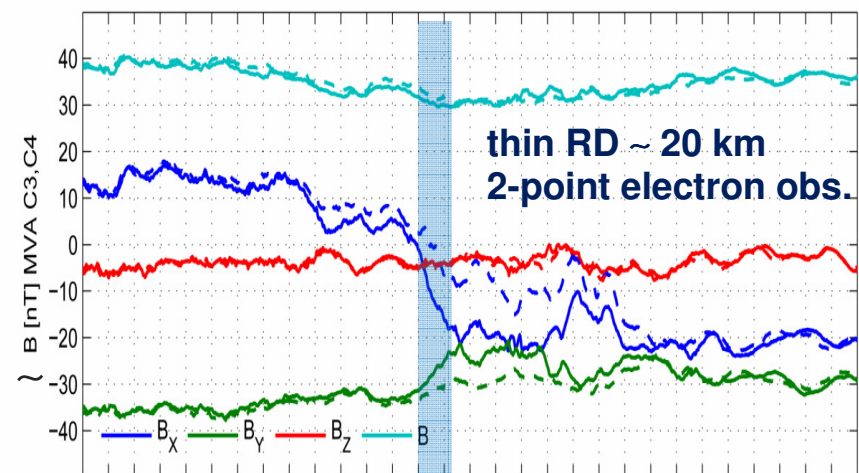
Key issues that MMS will (hopefully) solve:

- structure of the electron diffusion region
- electron acceleration in thin sheets
- reconnection & turbulence at electron scales
- determination of reconnection rate

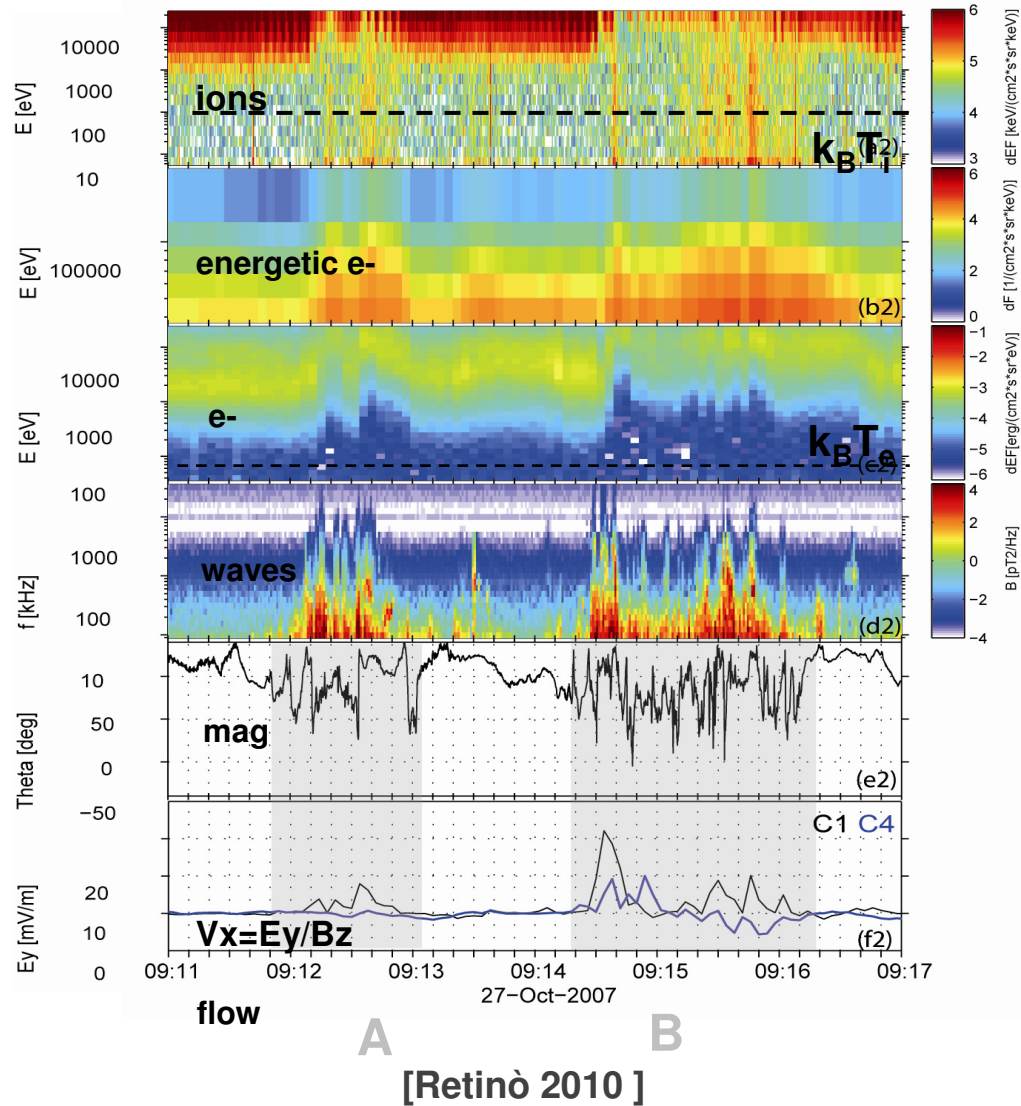


Cluster orbits 2008-2009 for MMS preparation:

- subsolar magnetopause reconnection
- two-sc methods OK (EidoScope)
- two spacecraft at sub-ion scales ~ 20 km $10\rho_e$

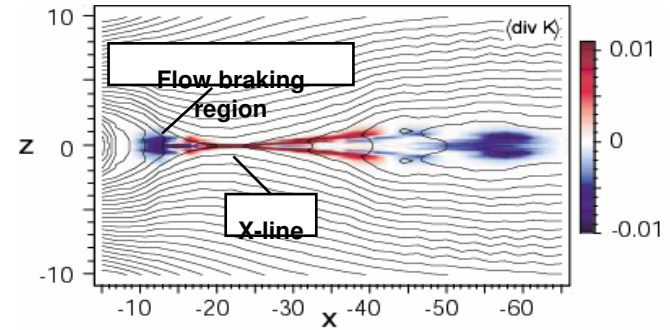


Multi-scale physics: Cluster input

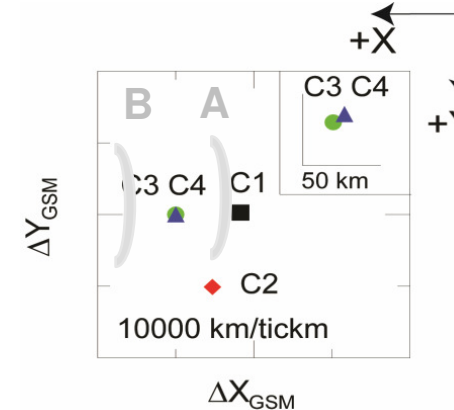


Jet braking one of four goals of EidoScope

Near-Earth jet braking region



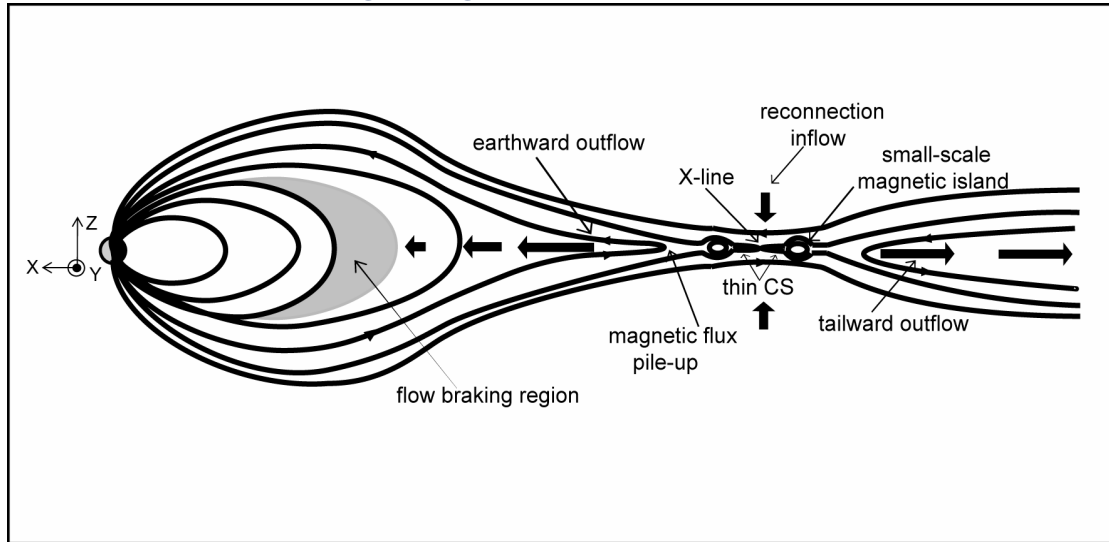
Multi-scale at $\sim 10 R_E$



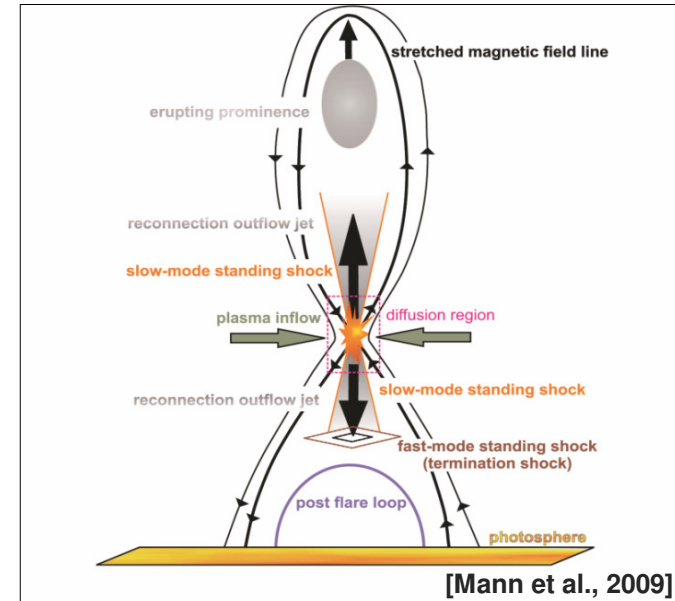
- Braking between C1 - C4 (MHD scales)
- Thin layers at sub-ion scales (C3 and C4). Strong particle acc. therein.
- Evidence for shock-like structures
- Cluster 2007-2008 + Themis 2010

Synergy with solar plasmas (caution)

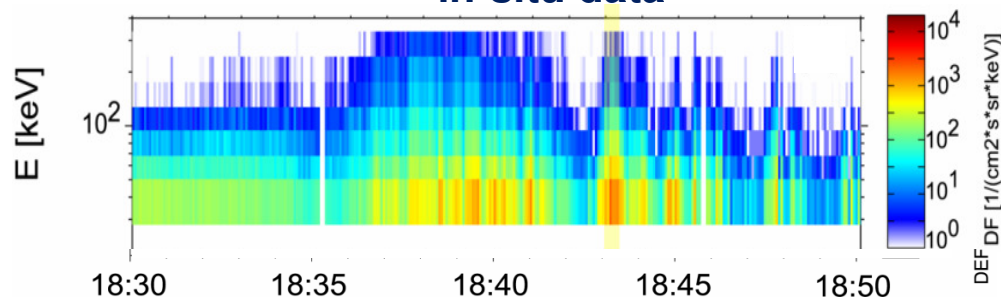
Cartoon of multi-step acceleration during magnetotail reconnection



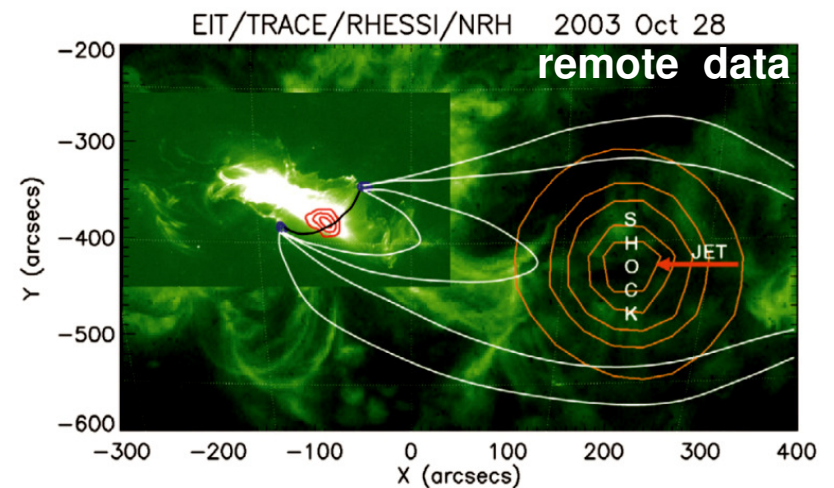
Cartoon of multi-step acceleration during solar flares



in-situ data

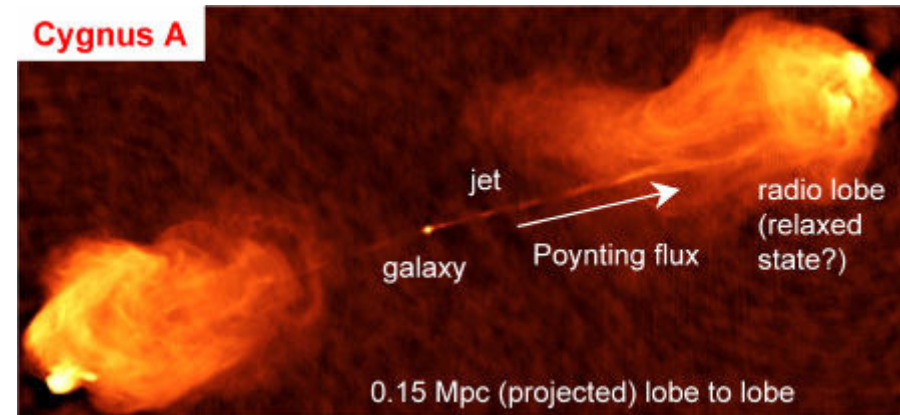


SolarOrbiter (2017) : first simultaneous *in situ* & remote observations in the solar corona/wind

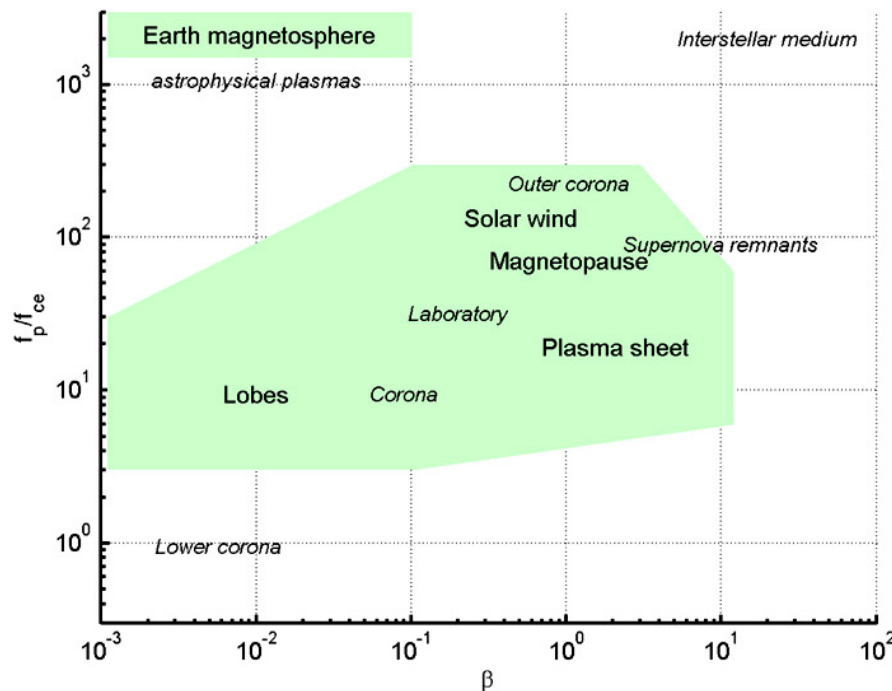


Synergy with astropasmas (more caution)

- Reconnection in the interstellar medium [Zweibel 1997]
- Astrophysical jets
- Cosmic ray acceleration (radio galaxies [Kronberg 2004], anomalous cosmic rays [Lazarian 2009, Drake 2010])



Radio galaxy [adopted from <http://www.ece.unm.edu/~plasma/Space/jets.htm>]



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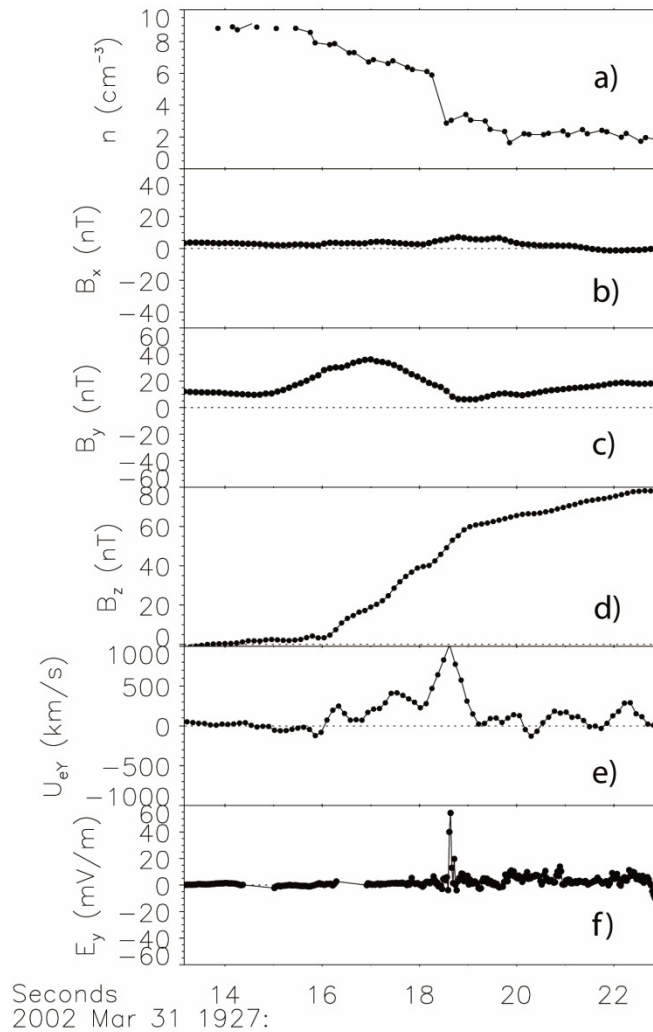
Much caution is needed:
crucial to understand differences and similarities between environments before making scaling laws etc.

Summary

- Reconnection key process that must be studied more
- Some key Cluster findings: large-scale spatial & temporal evolution, microphysics, particle acceleration, reconnection & turbulence
- Two major remaining issues: electron-scale and multi-scale physics
- Cluster can only partially address both
- MMS will solve the first but cannot solve the second
- Multi-scale measurements (≥ 5 spacecraft) required to close the circle (SCOPE + EidoScope ?)
- Synergies with other plasma communities important. Timely with solar (RHESSI/SOHO/Hinode + CLUSTER/THEMIS)

...maybe of interest...

- ongoing ISSI group on particle acceleration in magnetosphere and solar corona
- session ST 1.3 at next EGU on this topic (convener)
- proposal submitted for Cluster Guest Investigator to study multi-scale physics (we can choose ourselves sc separation and instrument modes)



[Mozer 2003]

Subsolar magnetopause:

- Electron scale current sheet
- Parallel electric field
- Super-alfvenic electron jet

very limited information !!!

also [Mozer 2005, Phan 2007, Henderson 2008]

