Magnetic Reconnection (with emphasis on the manifestations of this fundamental plasma process in the Earth's magnetosphere).

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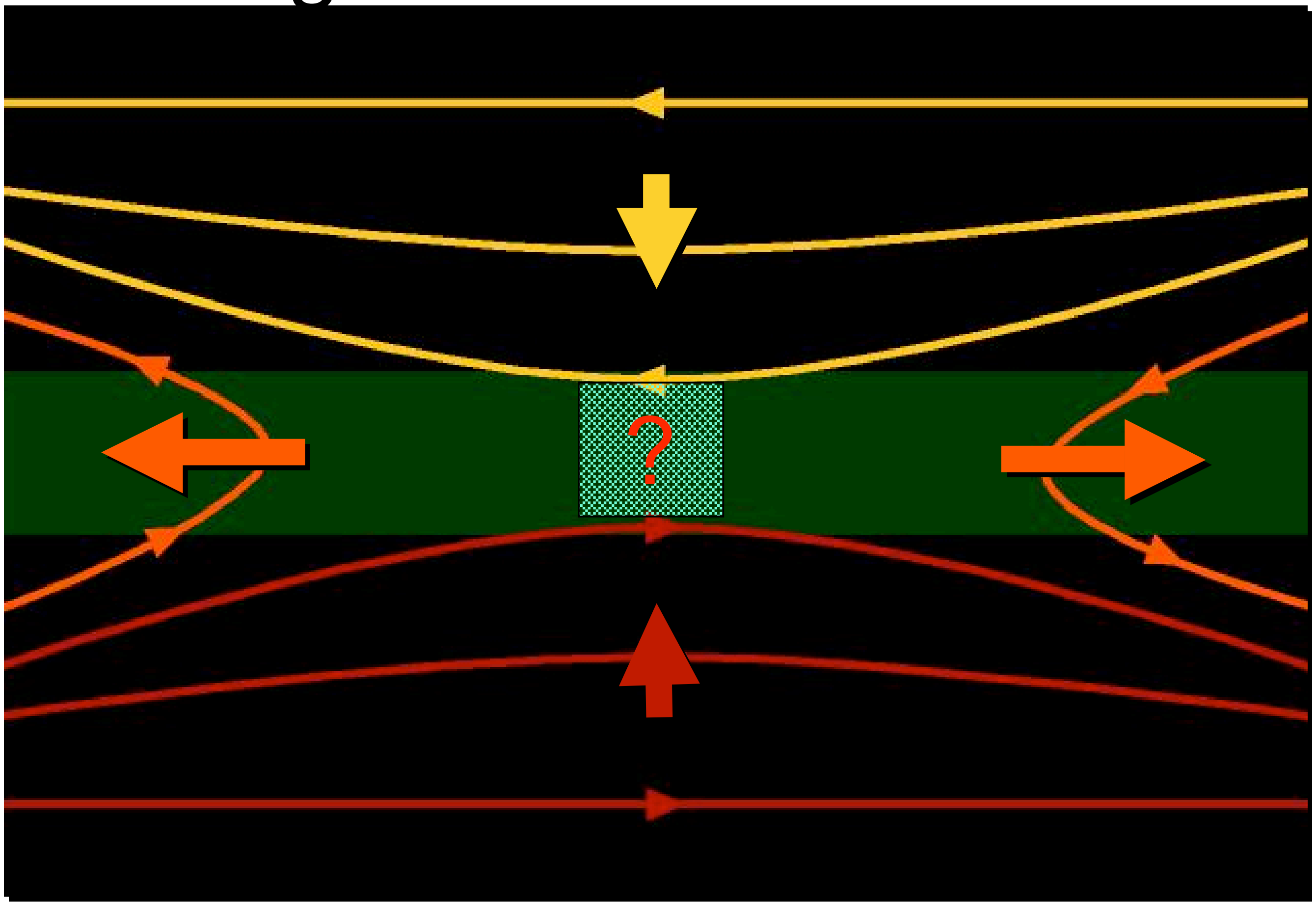
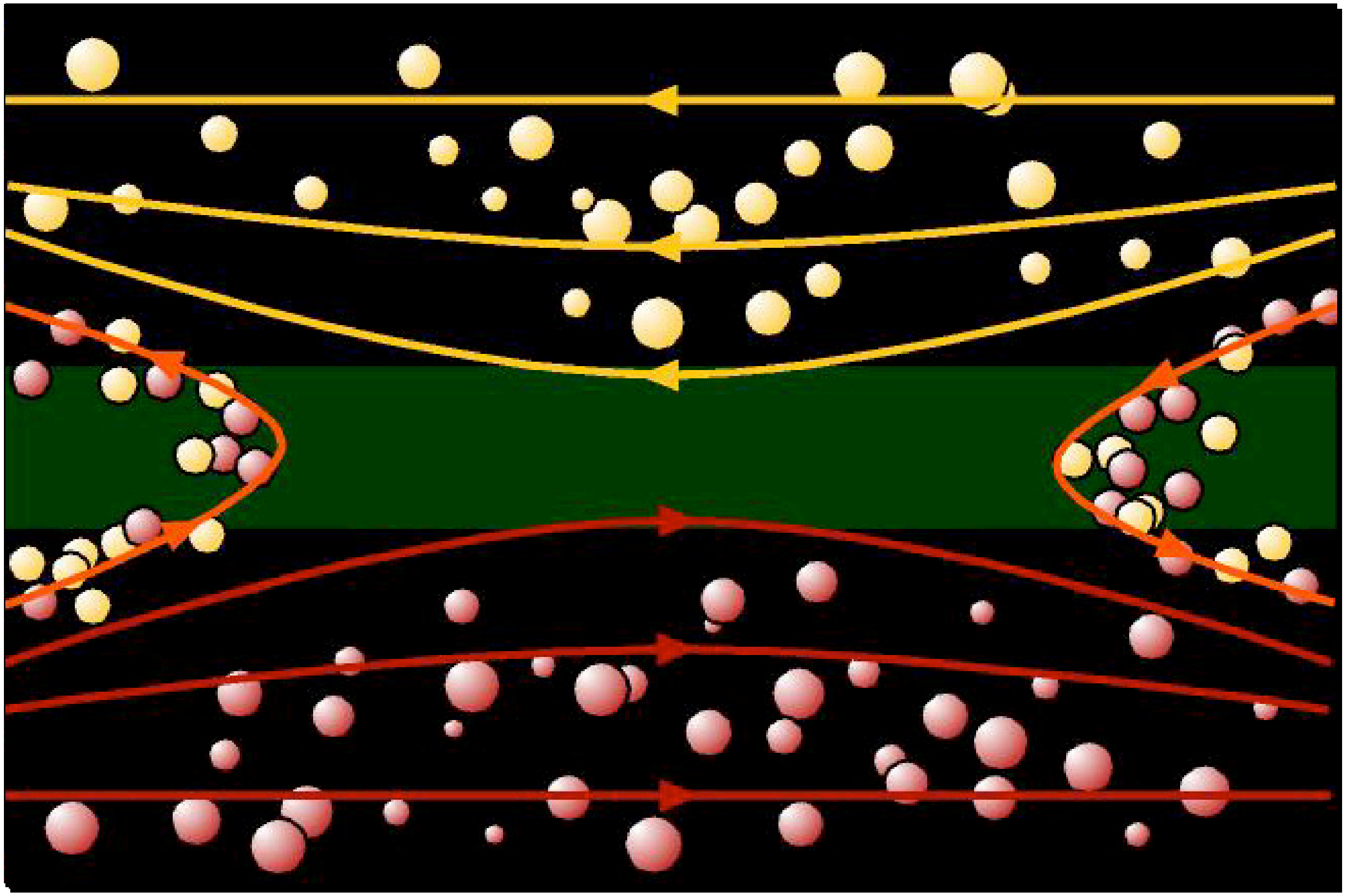
Magnetic Reconnection

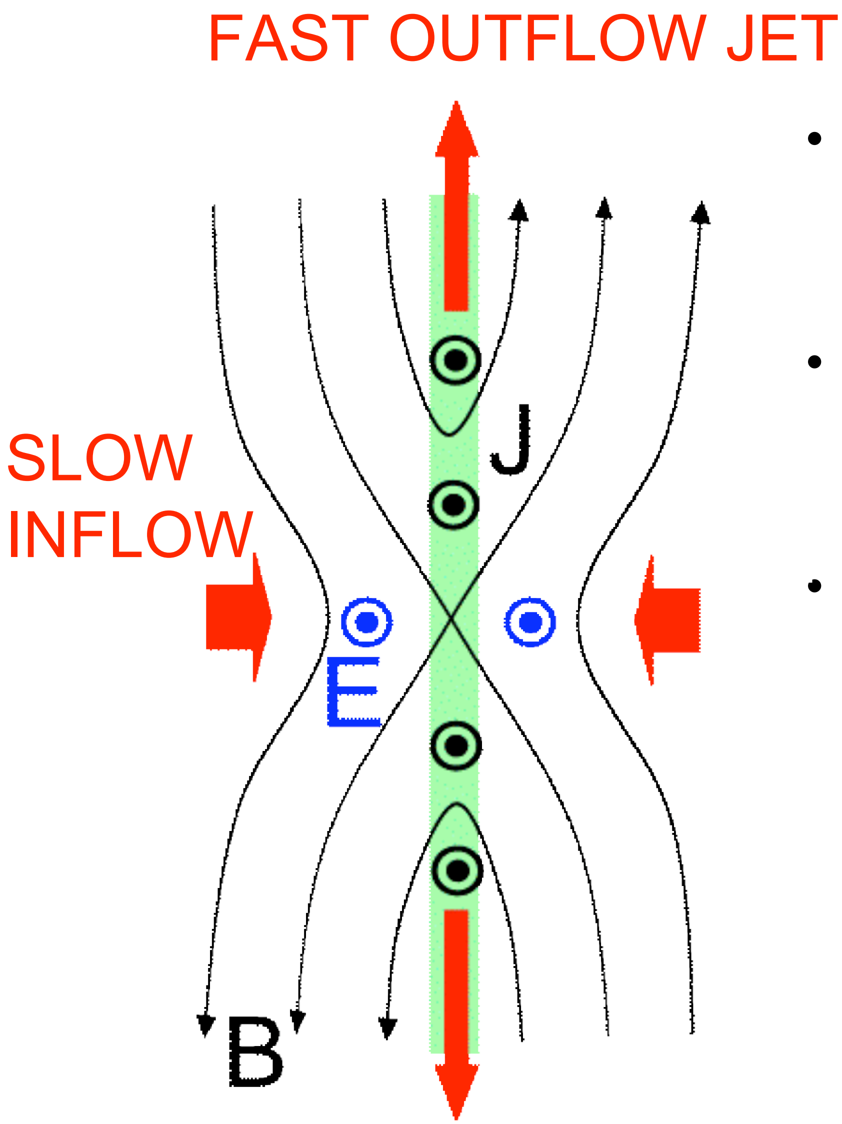


On small scale-lengths (i.e. at sharp gradients), a diffusion region (physics unknown) can form where the magnetic field can diffuse through the plasma (i.e. a breakdown of the frozen-in principle).

Mixing of Plasma Populations

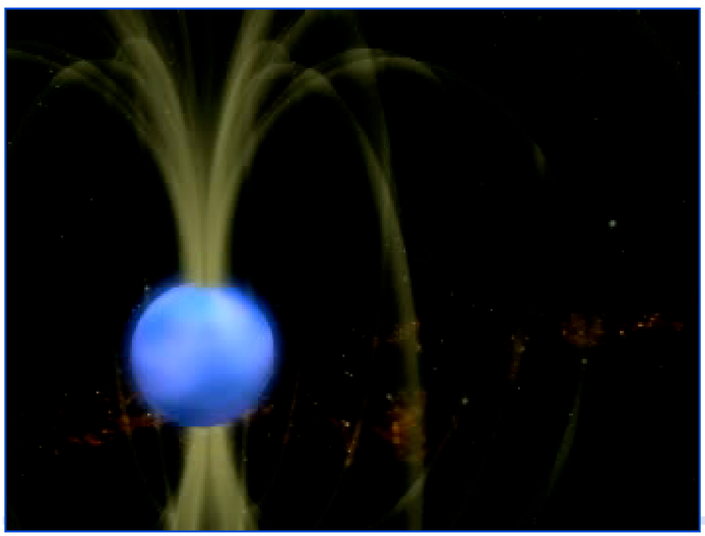


Magnetic Reconnection – Key Points



- Application of strict frozen-in flow implied that magnetic field and plasma from different sources could not mix;
- However, the frozen-in flow approximation is not always valid where gradients are sharp;
- Reconnection allows:
  1. Magnetic field regions that were previously independent to interact;
  2. The plasma populating the magnetic fields to intermix;
  3. Plasma is accelerated into jets as magnetic energy is released.

Credits: NASA

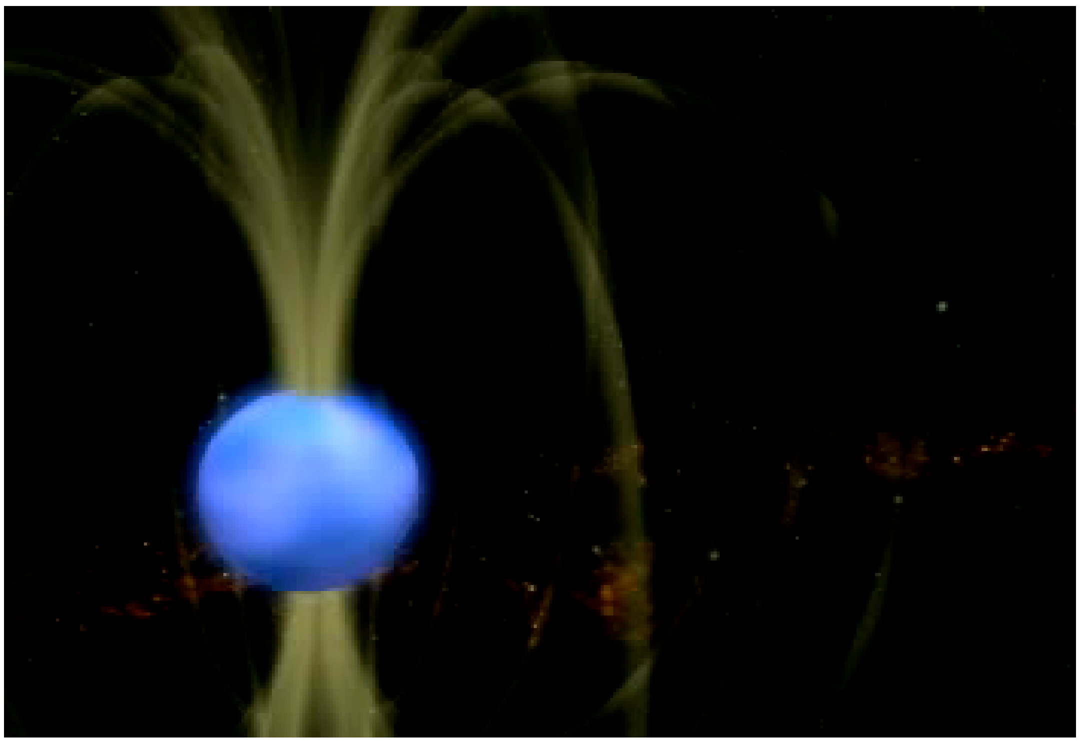


Plasmas in the Universe

- The dynamics of many astrophysical objects involve the interactions of magnetic fields and plasmas, which depend on a number of fundamental physical processes, e.g.:
  - Collisionless shocks
  - Magnetic reconnection
  - Turbulence
  - Particle acceleration
  - Wave-particle interactions

Magnetic Reconnection in the Universe

(i) Example: SGR1806-20 Magnetar produced an intense gamma-ray flare on December 27, 2004:



(Movie from NASA Web)

- Loss of equilibrium through magnetic diffusion and/or reconnection drives small cracks in the neutron star crust

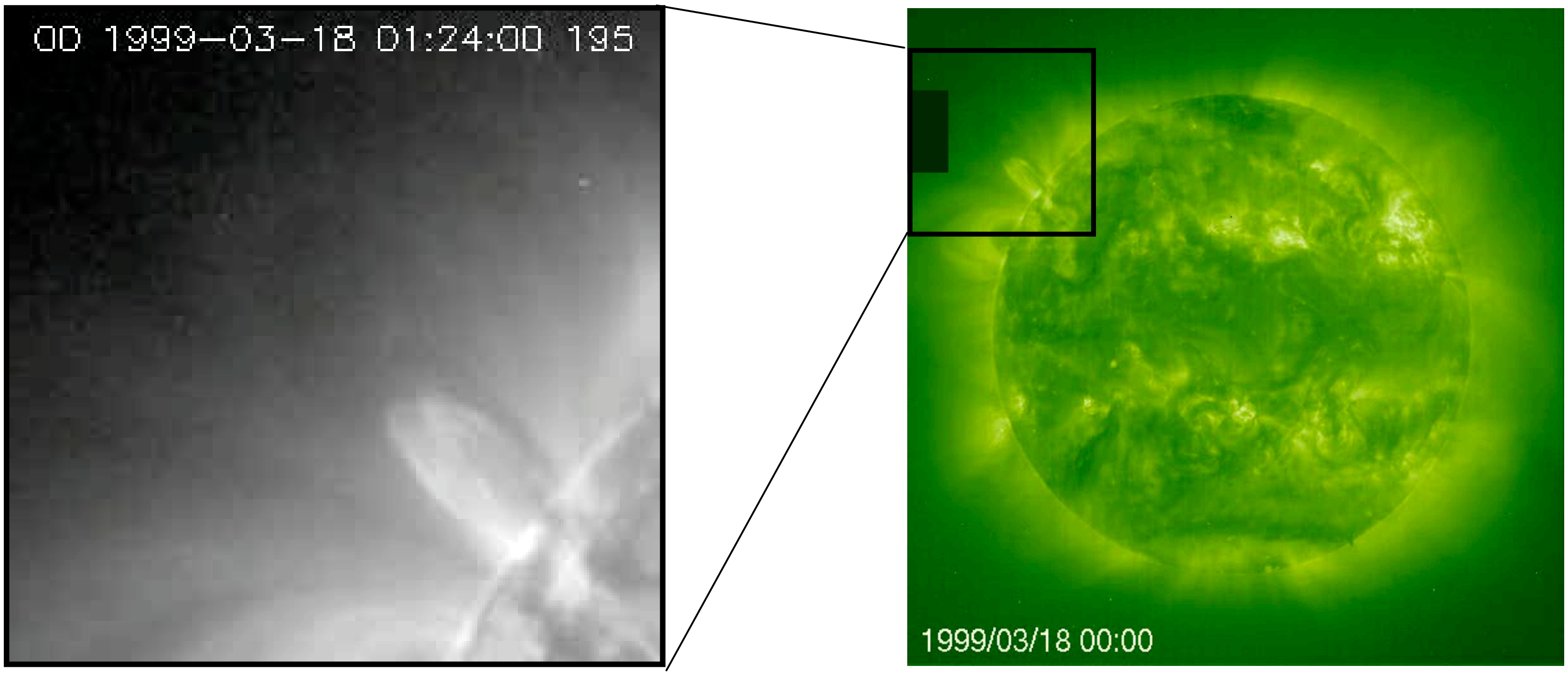
   frequent short _-ray bursts;

- Global rearrangements of the magnetic field in the interior and magnetosphere (reconnection?) of the star

   giant flares.

Reconnection – an example of a ubiquitous and multi-scale process

e.g. Magnetic reconnection associated with solar flares



Yokoyama et al, 2000

Reconnection – an example of a ubiquitous and multi-scale process

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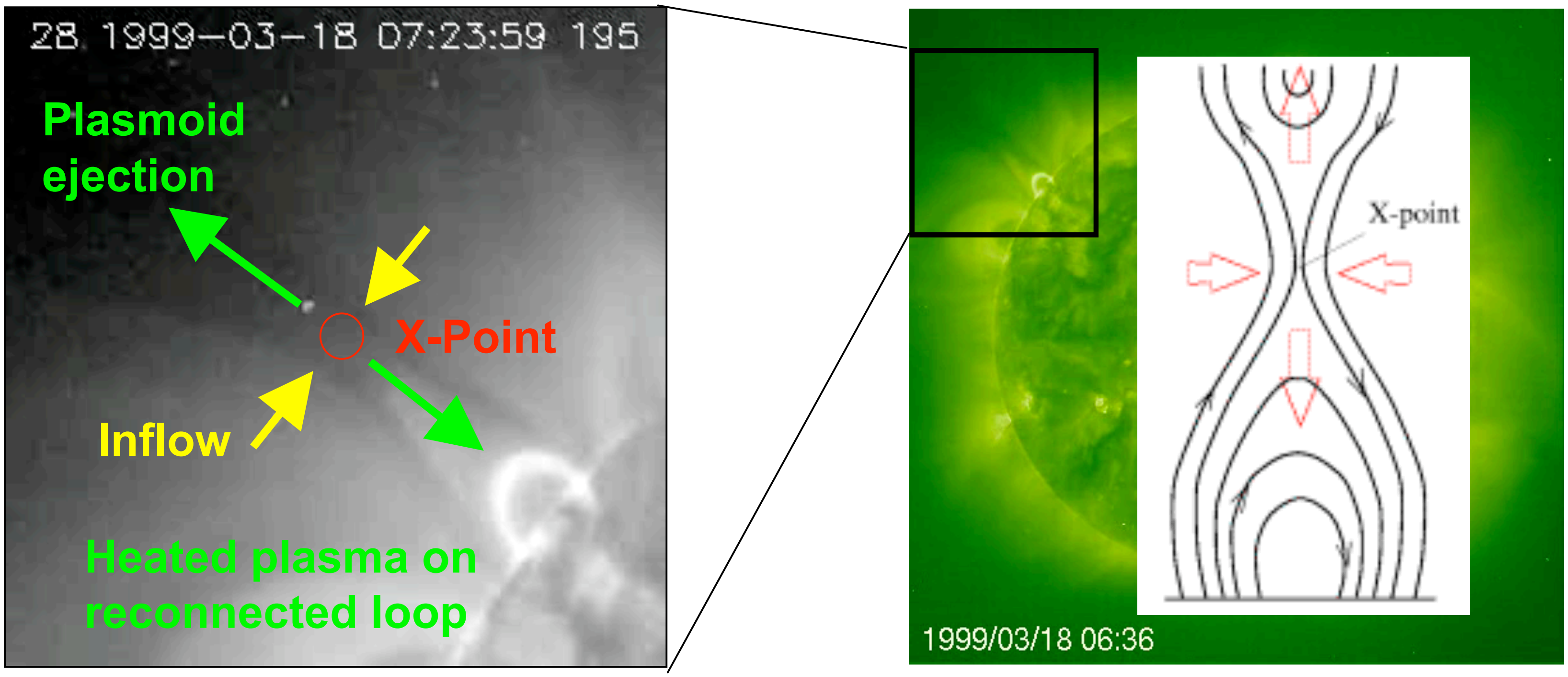


Yokoyama et al, 2000

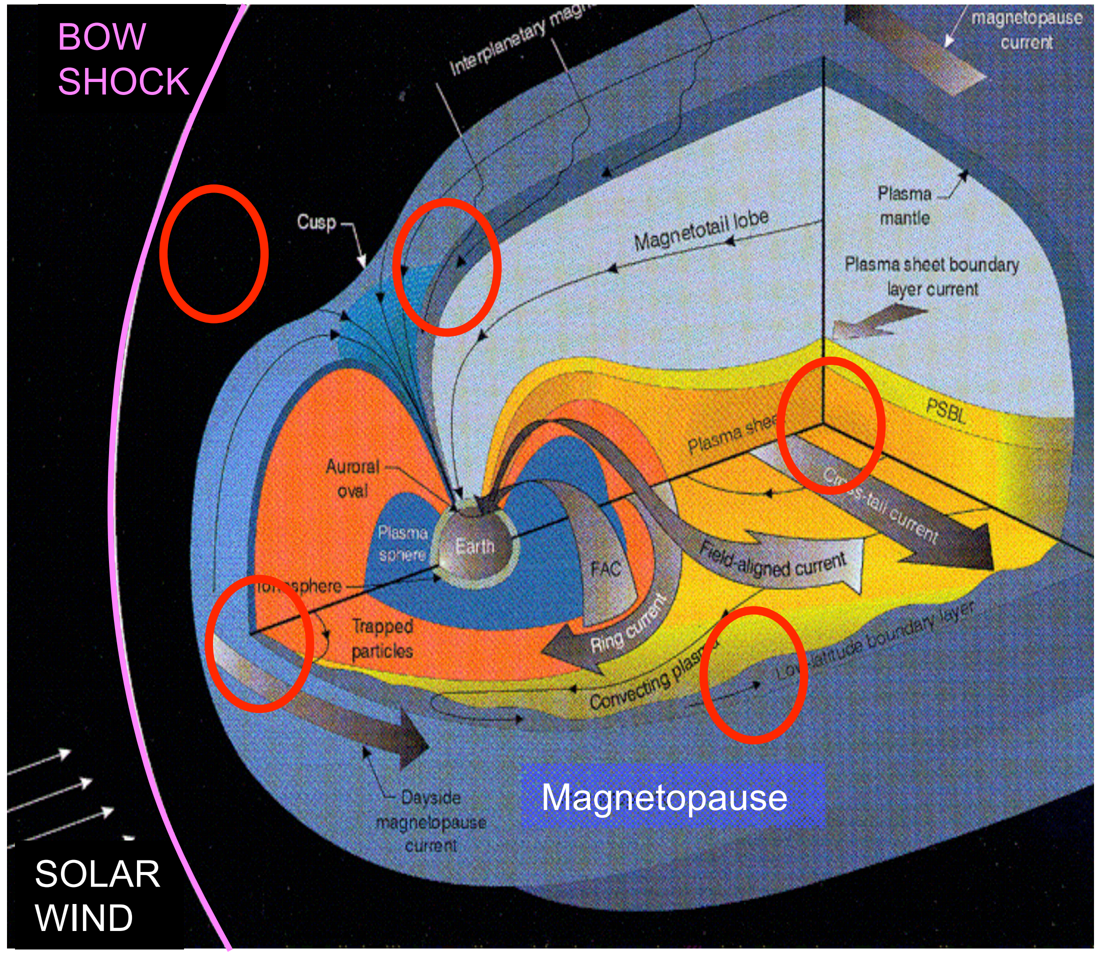
- CME ejection and coronal loop formation interpreted as a result of magnetic reconnection – the breaking and reconfiguring of the solar magnetic field.
- These are all interpretations of remotely sensed data – don't we want to be able to directly examine the physics of this process?

The ‘In situ’ Advantage

- How do we get to the real physics of such processes and test otherwise poorly constrained hypotheses?
- The only hope to realistically probe such processes within a reasonable timescale is through relevant in-situ measurements in regions in which they occur in and around our own magnetosphere;

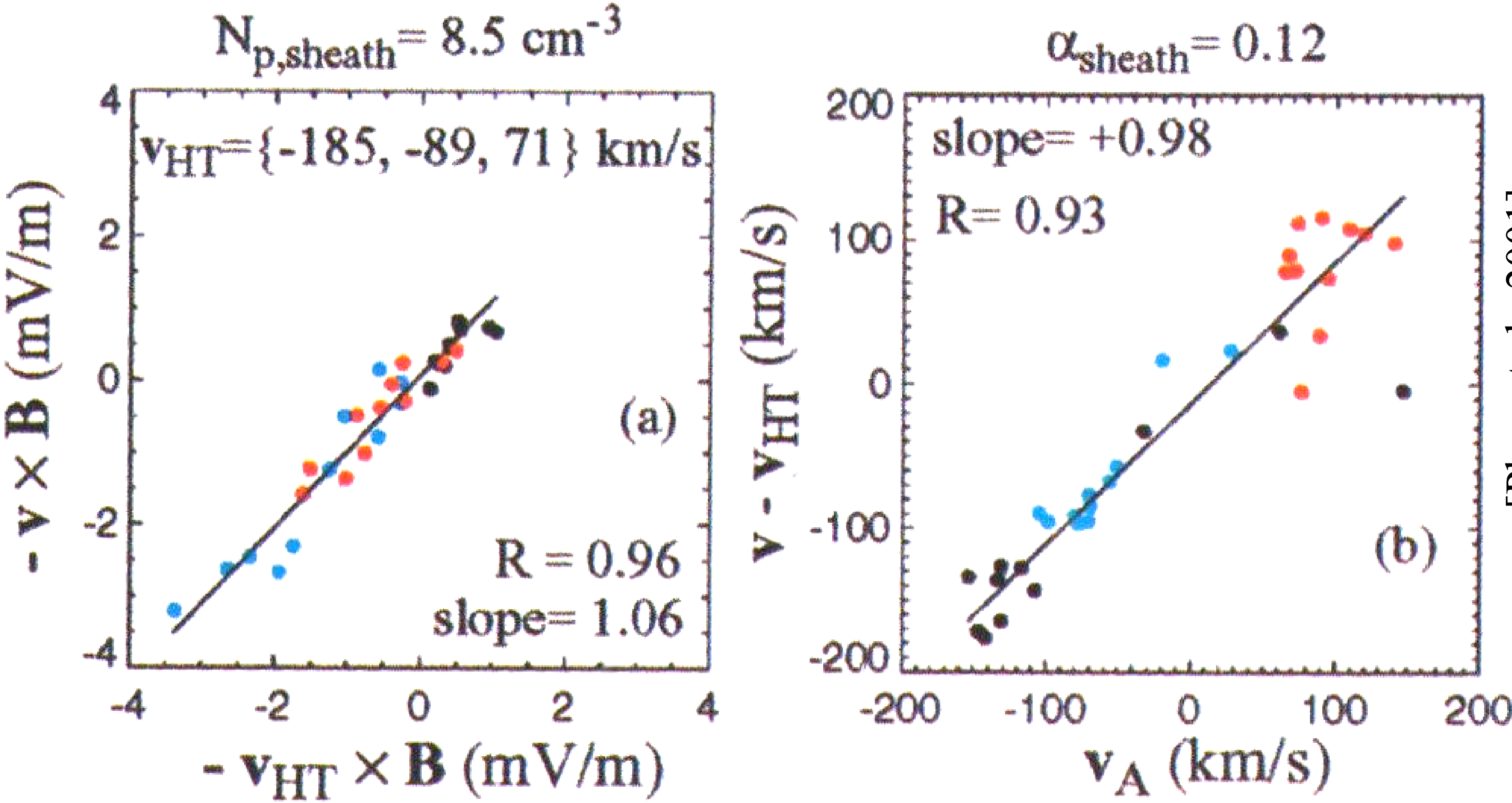
The Magnetospheric Plasma Laboratory – The *in situ* Advantage

- The terrestrial magnetosphere is a readily accessible 'laboratory'
- Reconnection occurs in a number of contexts:
- Although the parameter regimes may differ significantly, in situ measurements of processes in and around the terrestrial magnetosphere, are unique and have potential value to the broader community?



Some manifestations of reconnection in the terrestrial magnetosphere.

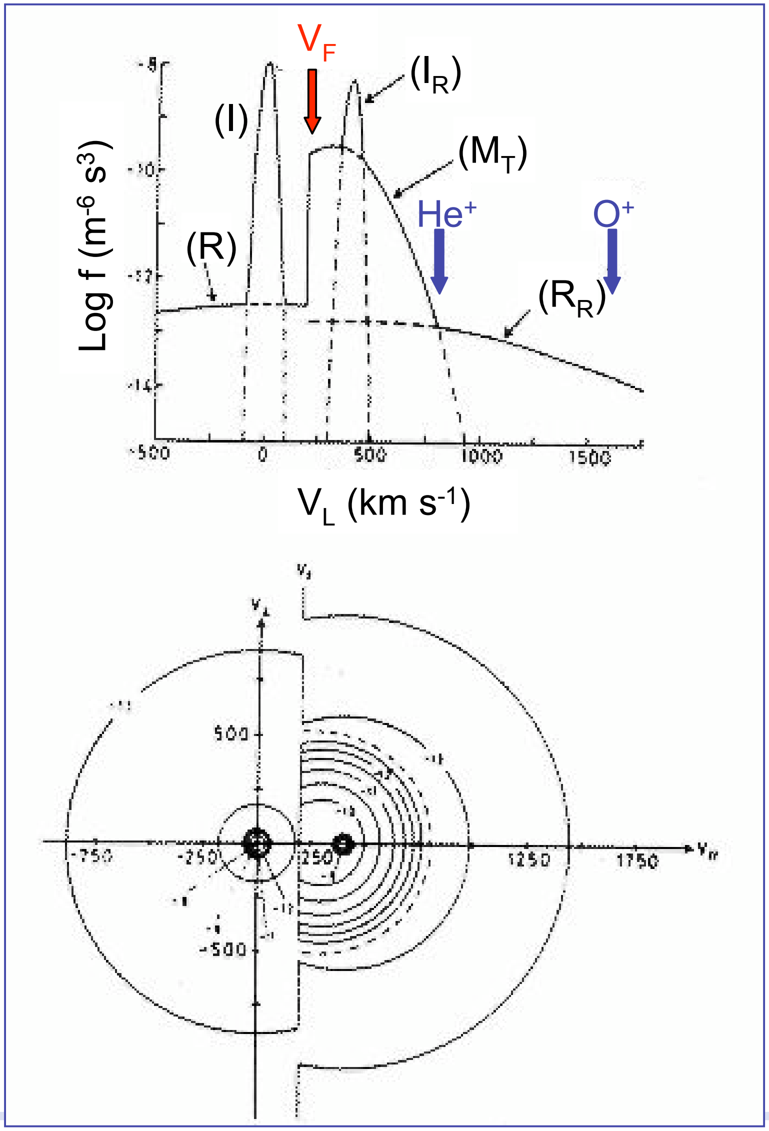
De Hoffman-Teller and Walen Tests



[Phan et al., 2001]

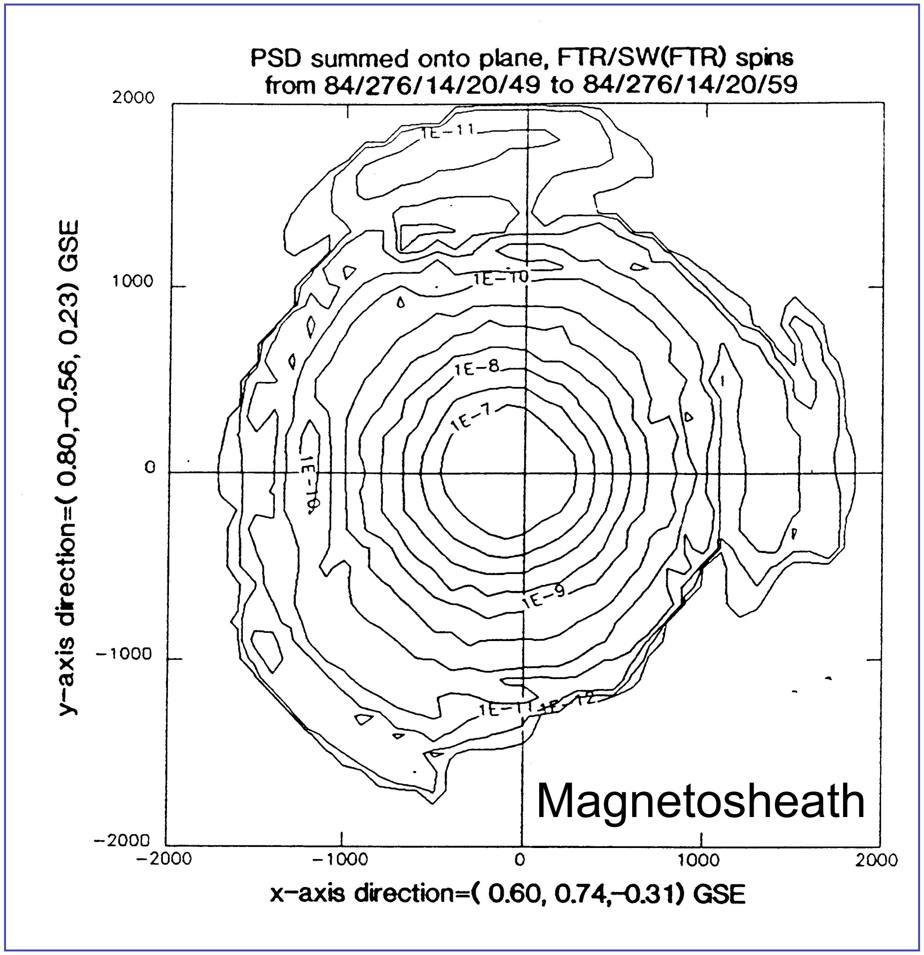
- On reconnected field lines, MHD and cold plasma theory suggests that as the plasma crosses the current layer, it should be accelerated to speeds ~VA, the *external* Alfvèn speed (± the external flow speed).

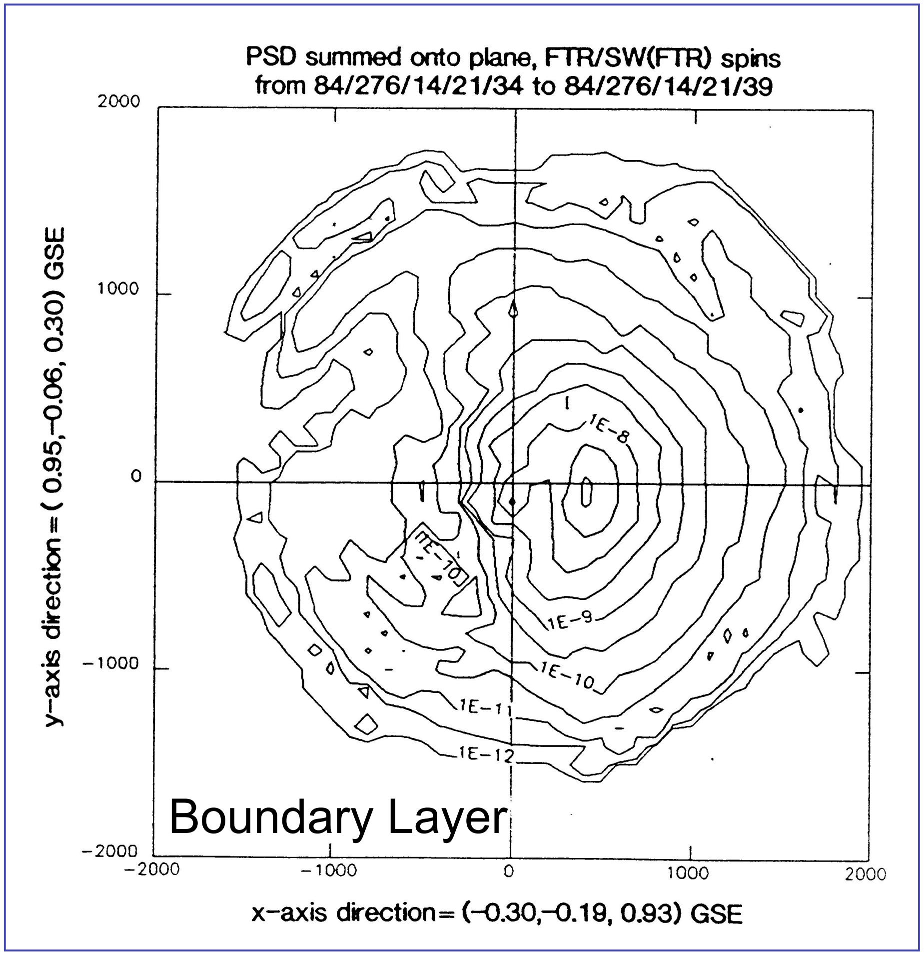
Particle Distributions in the Dayside Boundary Layer - Theory



- Magnetospheric populations of ionospheric (I) and ring current (R) origin are partially reflected and accelerated at the MP (I_R, R_R).
- The external magnetosheath population (M_T) is accelerated and transmitted through the MP.
- Only those magnetosheath particles with speeds greater than V_F (=V_{DHT}) can move into the boundary layer.
- The resulting distribution of sheath particles has a ‘D’-shape [Cowley, 1982].

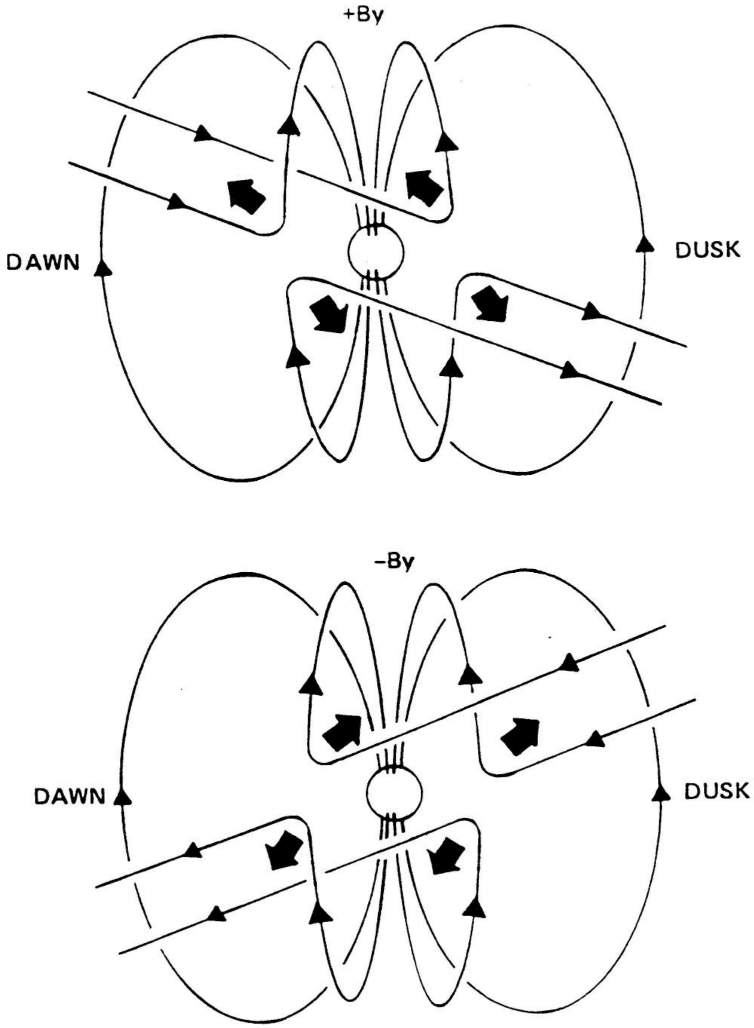
Particle Distributions in the Dayside Boundary Layer - Observation

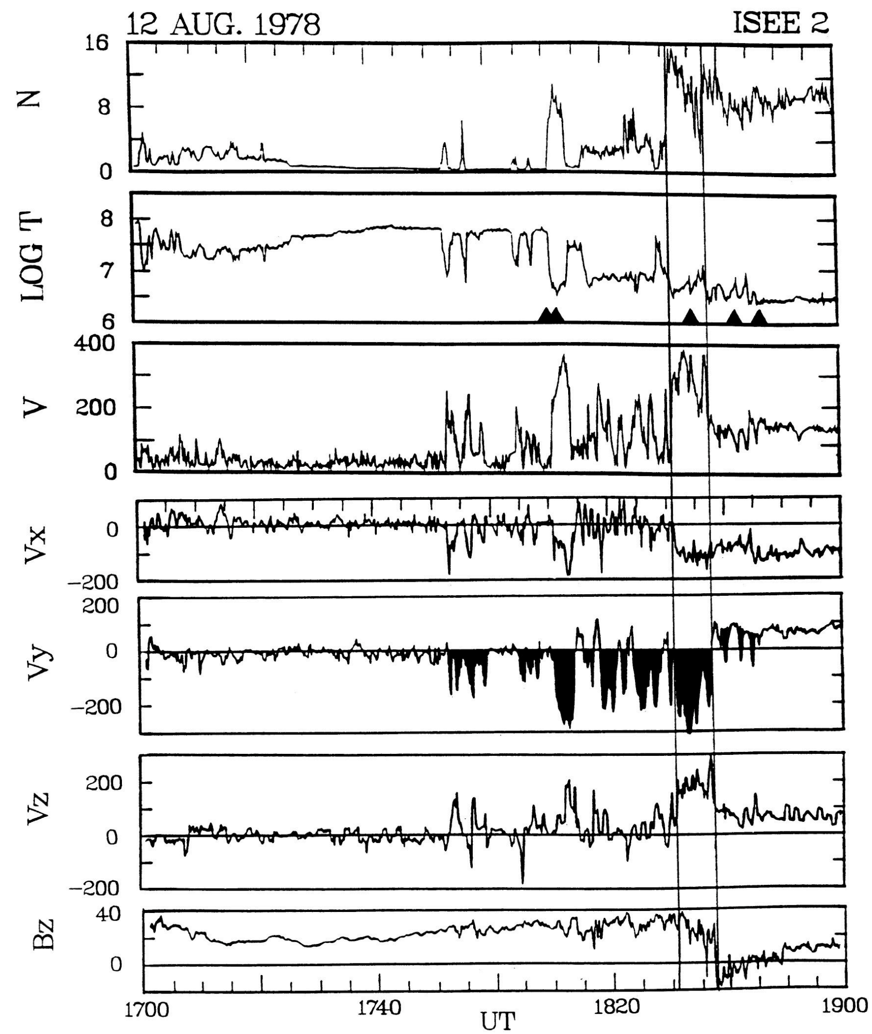




Smith and Rodgers [1992]

Effects of IMF B_Y

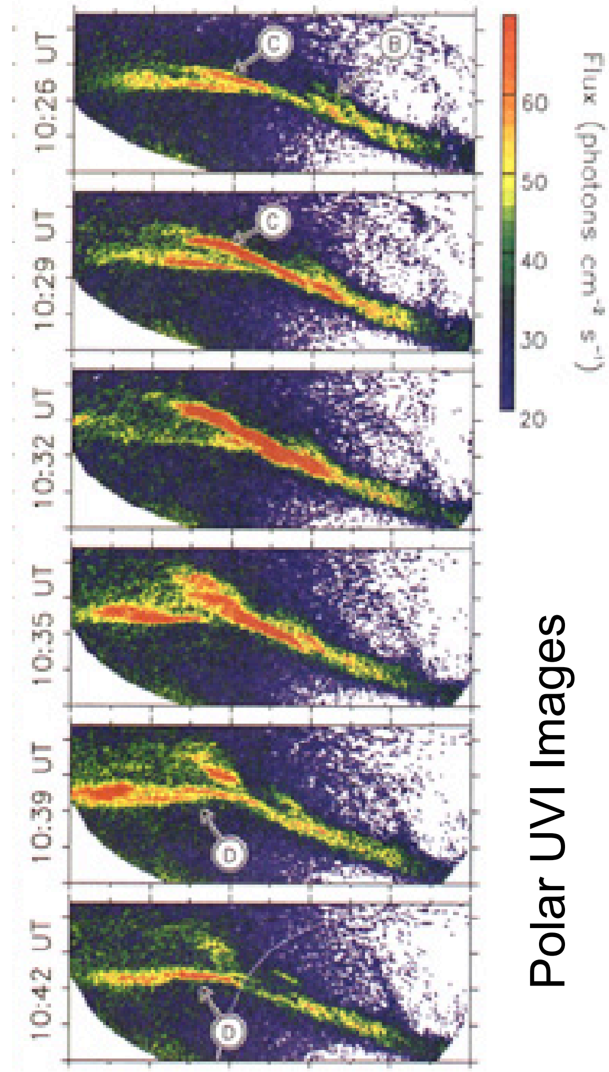




Gosling et al., [1990]

Contributions from the Global Scale

- The various ground-based facilities and space-based imagers provide a means through which the global effects of reconnection can be remotely monitored:
  - E.g., at the ionospheric magnetic footprint of the reconnection site, where characteristic auroral transients and plasma flow events have been identified (e.g. Milan et al., 2000, _).
  - These ionospheric observations remotely-sense an extended region (> MHD scale) of the magnetosphere and provide a context (e.g. scale-size of an event) which may not be obtainable from in situ data.
  - On an even larger scale, observations of the size of the auroral oval allow the global reconnection rates to be measured (Milan et al., 2003), for example, allowing the assessment of the relative importance of an in situ event to the global system.



Polar UVI Images

….and many more…

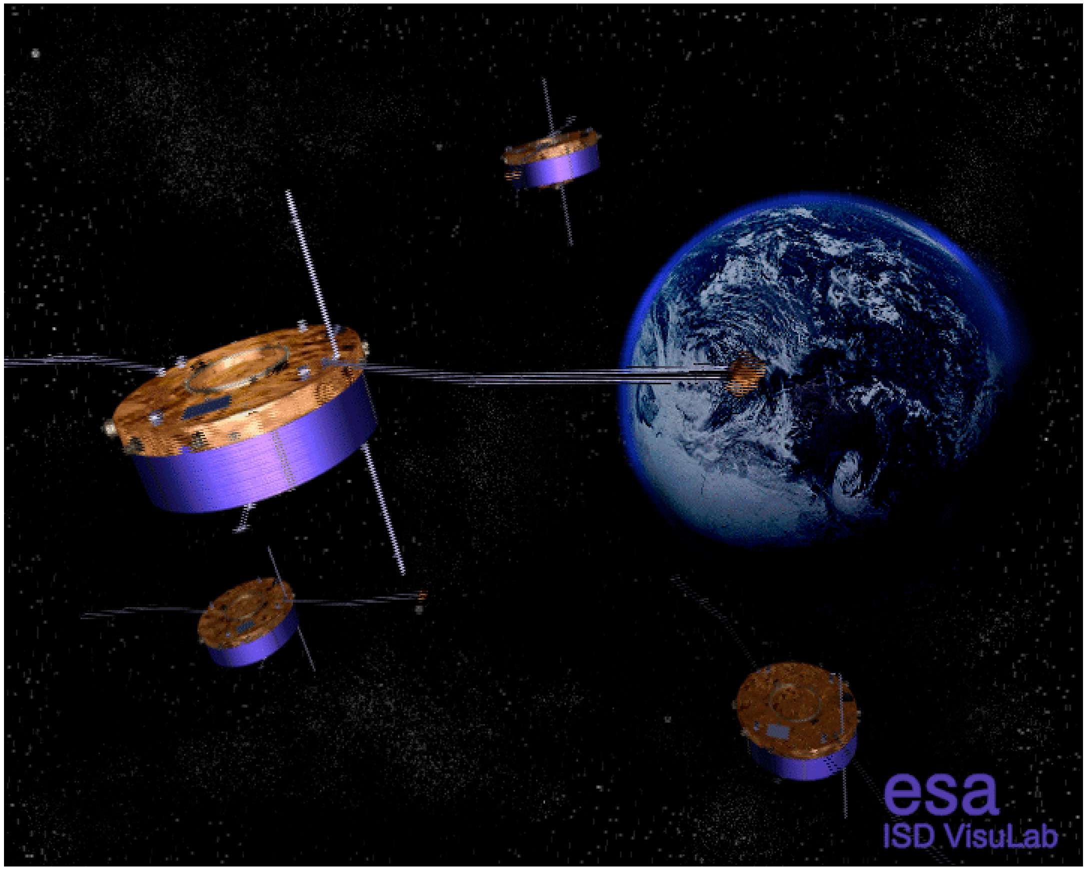
- Flux Transfer Events;
- Magnetospheric substorms;

Manifestations of time dependent reconnection modulated by the interplanetary magnetic field.

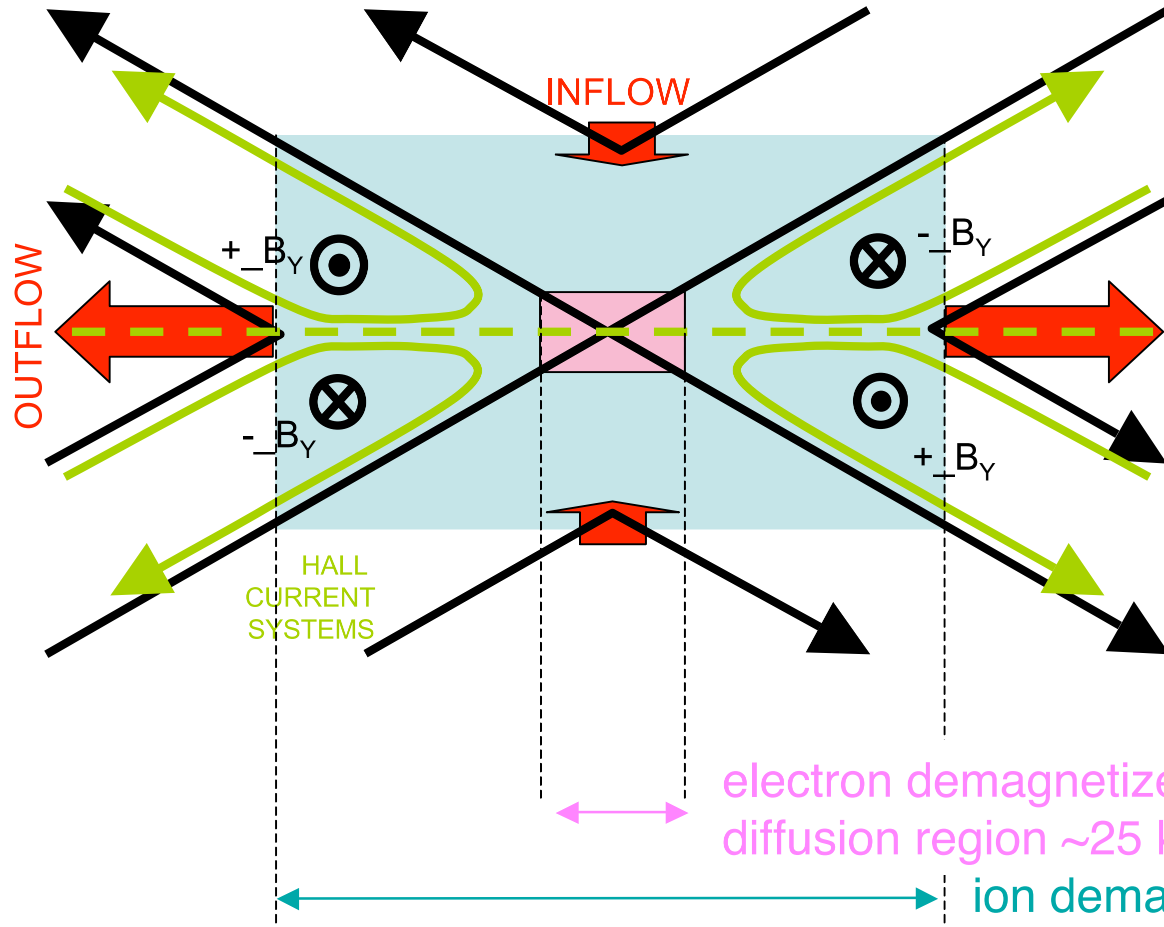
- Twisting of the magnetosphere by magnetic torques applied by reconnected field lines;
- Asymmetric plasma entry into magnetosphere;
- Reconnection in Kelvin-Helmholtz vortices;
- Velocity-dispersed plasma entry into the boundary layers and magnetic cusps;
- Etc.

The Cluster Contribution

- In situ measurements by Cluster reveal that large-scale dynamics are controlled by processes such as shock formation and magnetic reconnection;
- In turn, these are complex, 3-D and time-dependent microphysical processes occurring on time and space scales beyond our current measurement capability;
- Nevertheless, we have been able to directly test some aspects of theoretical models.



‘Hall’ Reconnection Geometry



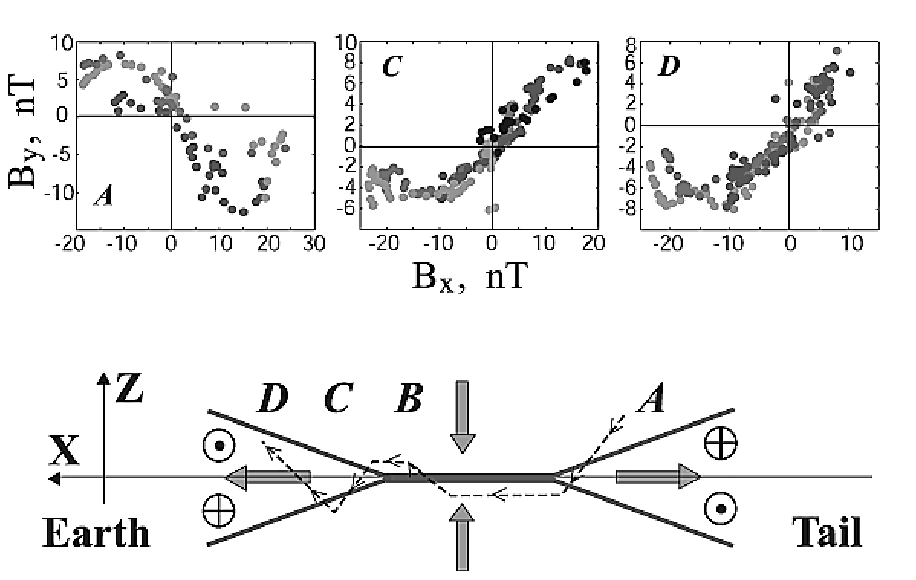
- Fast ion flows associated with field reconfiguration
- Ion and electron decoupling
  - → Hall electric current
- Quadrupole out-of-plane magnetic field components
- Electron diffusion

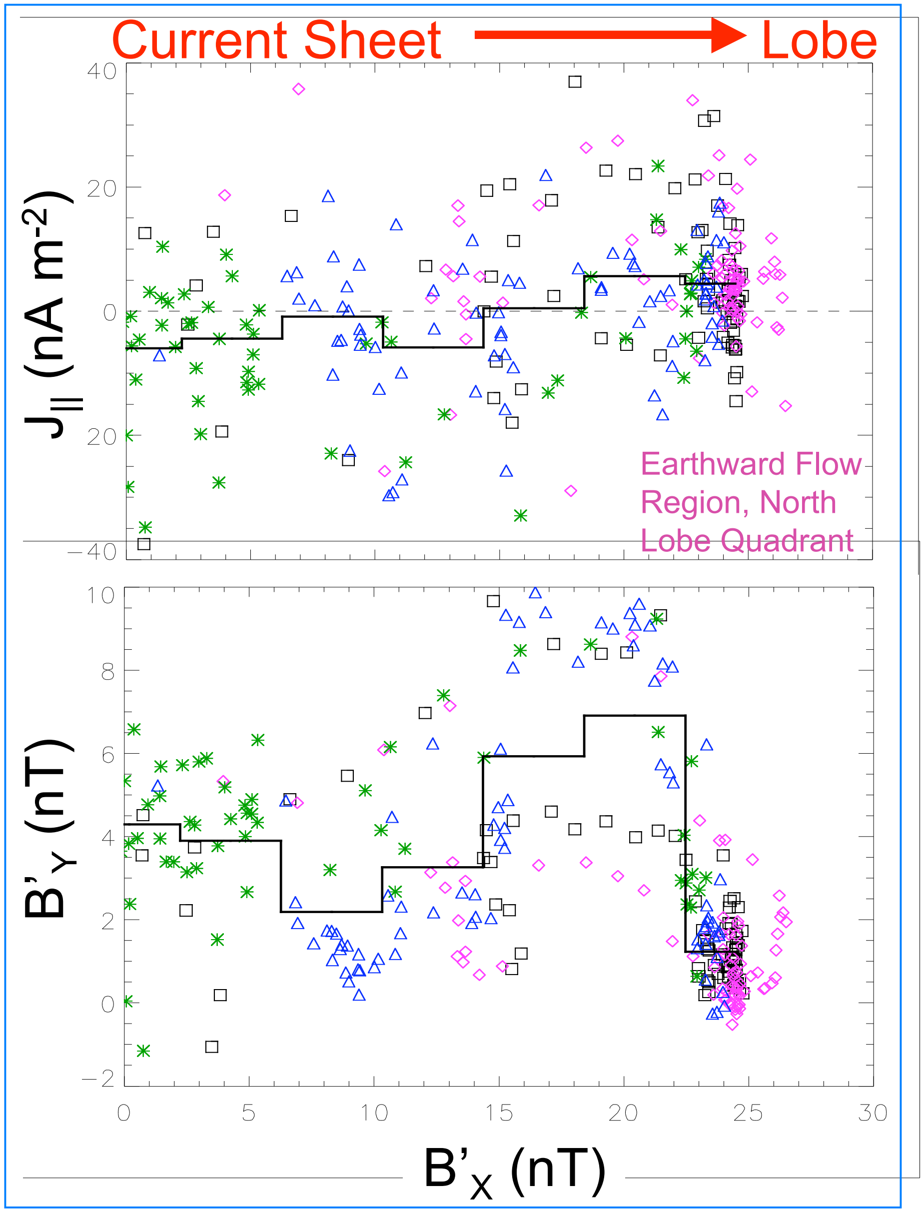
3D Multi-scale process!

electron demagnetized, (electron diffusion region ~25 km, T ~ 0.1s)

ion demagnetized (ion diffusion region ~1000 km T ~ 1s)

Outflow jets (Global scale ~10s R_E, T ~ secs _ mins)

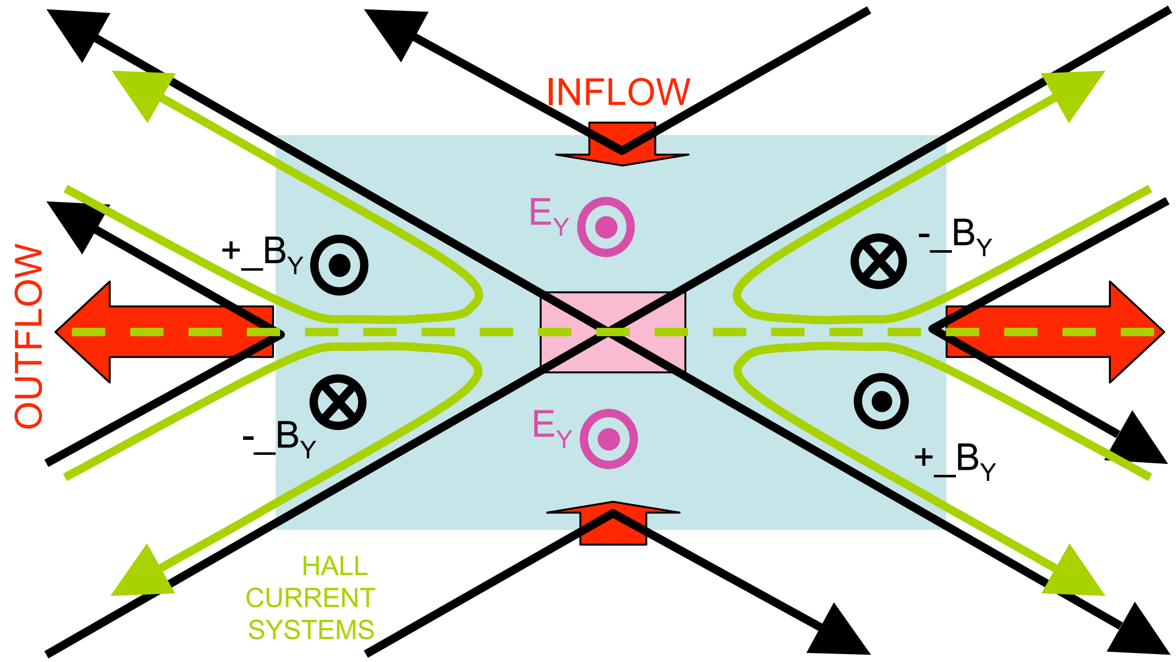




_Runov et al., [2003] demonstrated the existence of quadrupolar B_Y structure during multiple Cluster crossings of the current sheet;

_Alexeev et al., [2005] determined parallel currents carried by electrons and showed *average* electron $J_{||e}$ reverses at B'_X ~ 15-18 nT, with a corresponding enhanced +ve B'_Y.

‘Hall’ Reconnection Geometry



- A cross-tail electric field E_Y drives reconnection. How is this electric field supported?
- Consider the generalised Ohms Law:

$$\underline{E} = -\underline{v}_i \times \underline{B} + \eta \underline{j} + \frac{\underline{j} \times \underline{B}}{en_e} - \frac{m_e}{e}\frac{d\underline{v}_e}{dt} - \frac{\nabla . \underline{\underline{P}}_e}{en_e}$$

Ohm's Law – Reconnection Electric Field

Hall-MHD simulations by Yin et al., Phys. Plasmas, 2003:

A) Ideal MHD contribution is significant on the large scale;

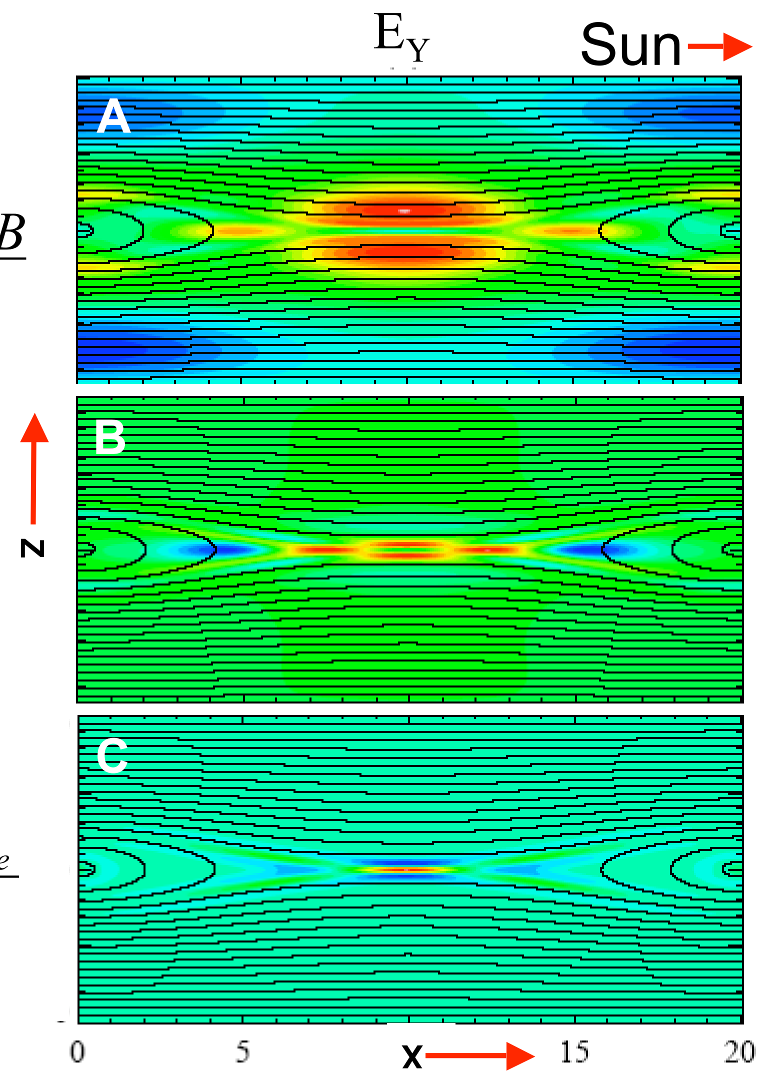
B) Ion decoupling scale (Hall) contribution appears around central sheet;

C) The contribution from the electron pressure tensor term is very localised. This originates from the derivatives of the off-diagonal terms.

$$-\underline{v}_i \times \underline{B}$$

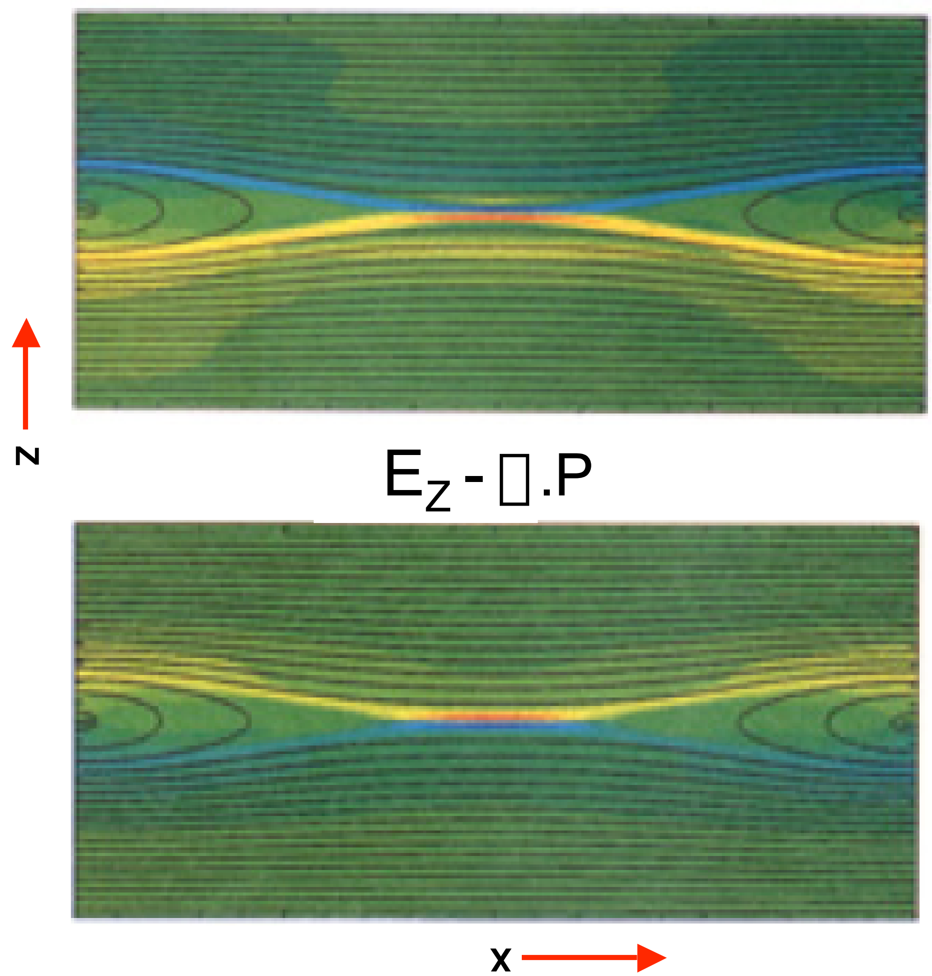
$$+\frac{\underline{j} \times \underline{B}}{en_e}$$

$$-\frac{\nabla \cdot \underline{\underline{P}}_e}{en_e}$$



Ohm’s Law – Other components of E

E_Z - Hall



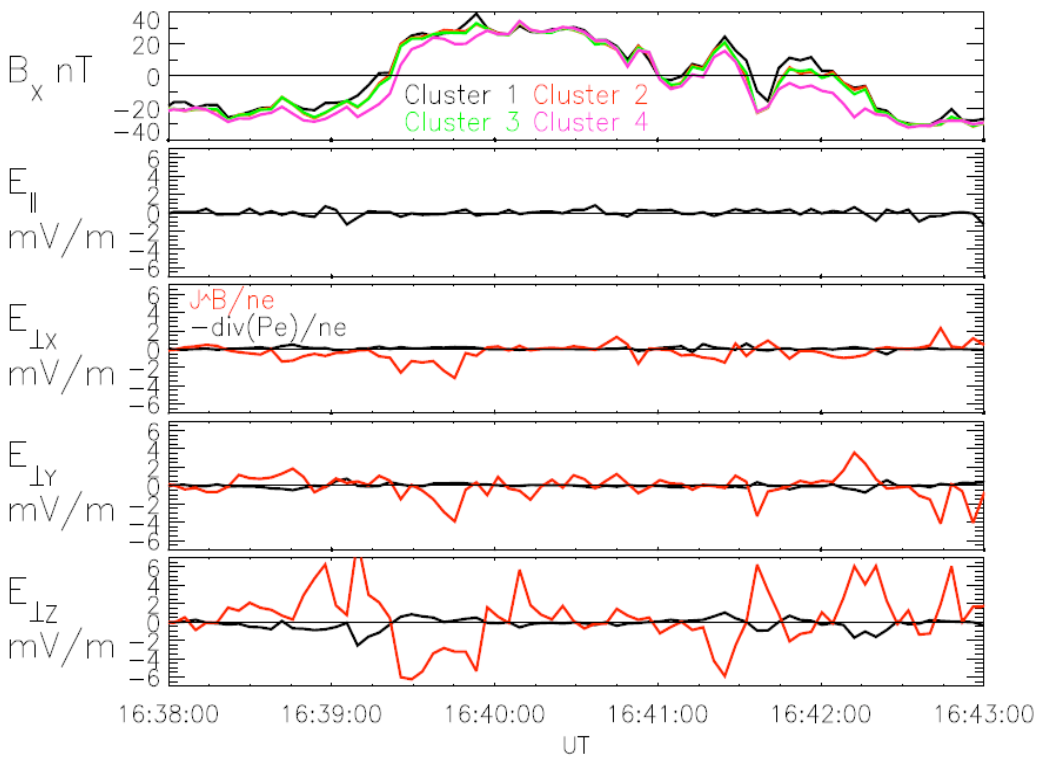
- Contributions to E_Z from Hall and electron pressure tensor are spatially more extended;
  - The field from the Hall term points towards the sheet.
  - The field from the □.P term points away from the sheet.

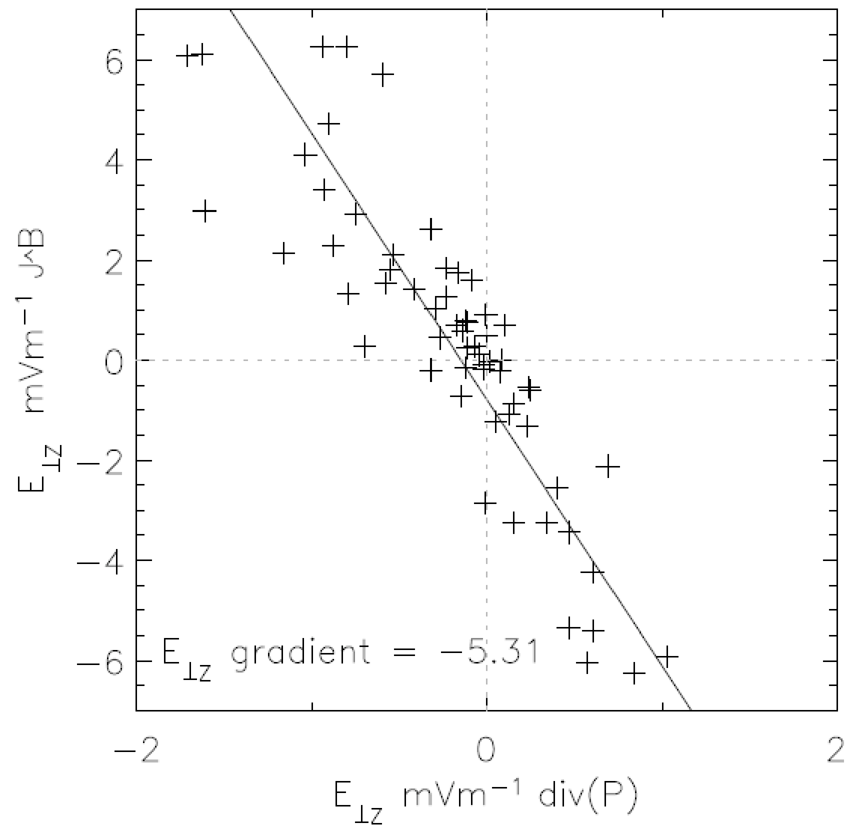
Observing these parameters

- Note both $\underline{j} \times \underline{B} = \left(\left(\underline{\nabla} \times \underline{B}/\mu_o\right) \times \underline{B}\right) and\ \underline{\nabla} \cdot \underline{\underline{P}}_e$ are derived from gradient terms, and thus both need multi-point, i.e. Cluster, measurements;

- Henderson et al. (2006) attempted to measure and compare these two terms;
  - Looked at small Cluster tail separations: ~ 200 km in 2003.
  - Calculated spatial derivatives of the full tensor
    - required non-trivial inter-spacecraft calibration efforts by PEACE team at MSSL

Henderson et al., (2006)

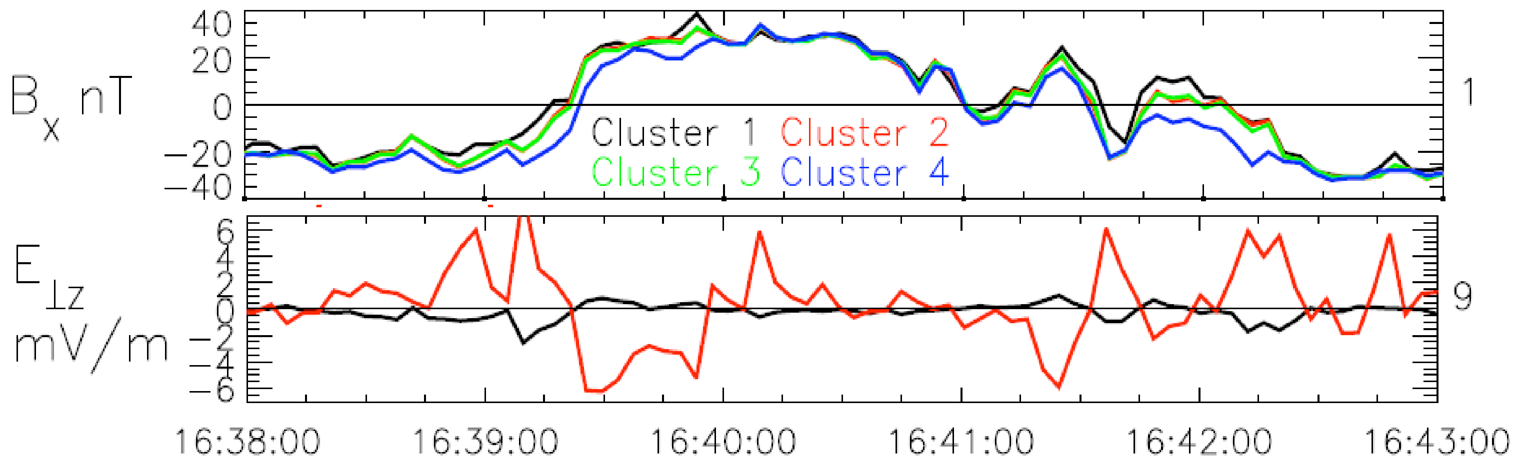




- Observations taken close to an active X-line on 17th Aug 2003;
- No encounter with the diffusion region, but observed an anti-correlation in $\nabla . \underline{\underline{\mathbf{P}}}_e$ and Hall terms in the component normal to the neutral sheet.

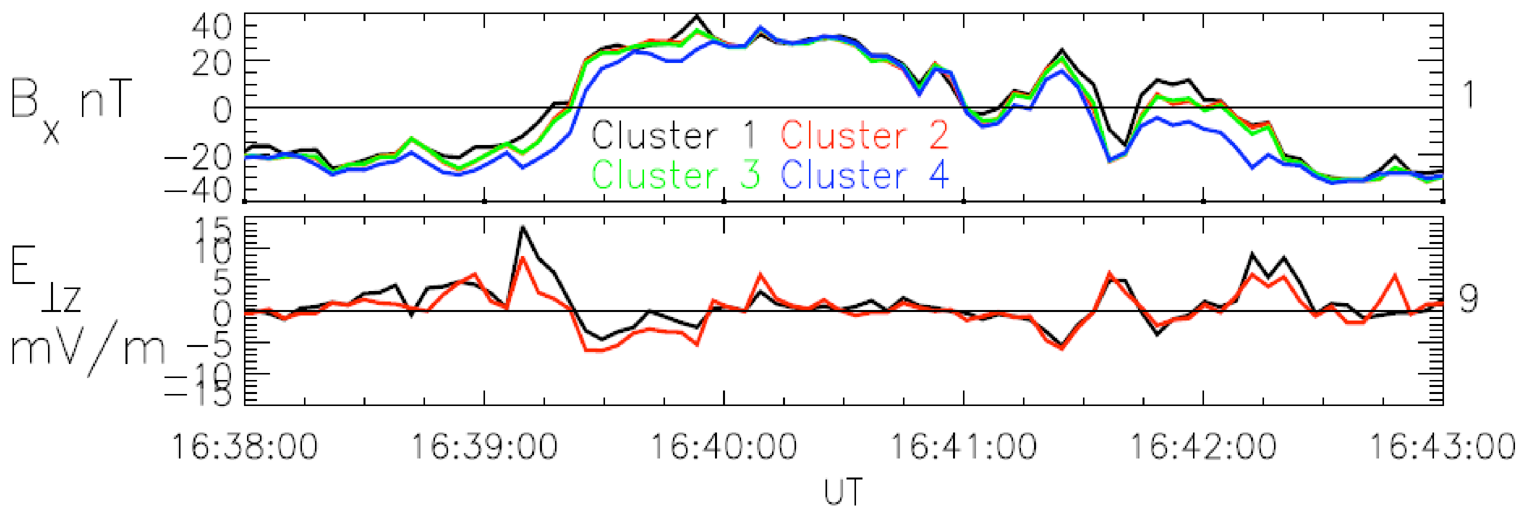
JxB/n_e

$(-\nabla.P/n_e)$

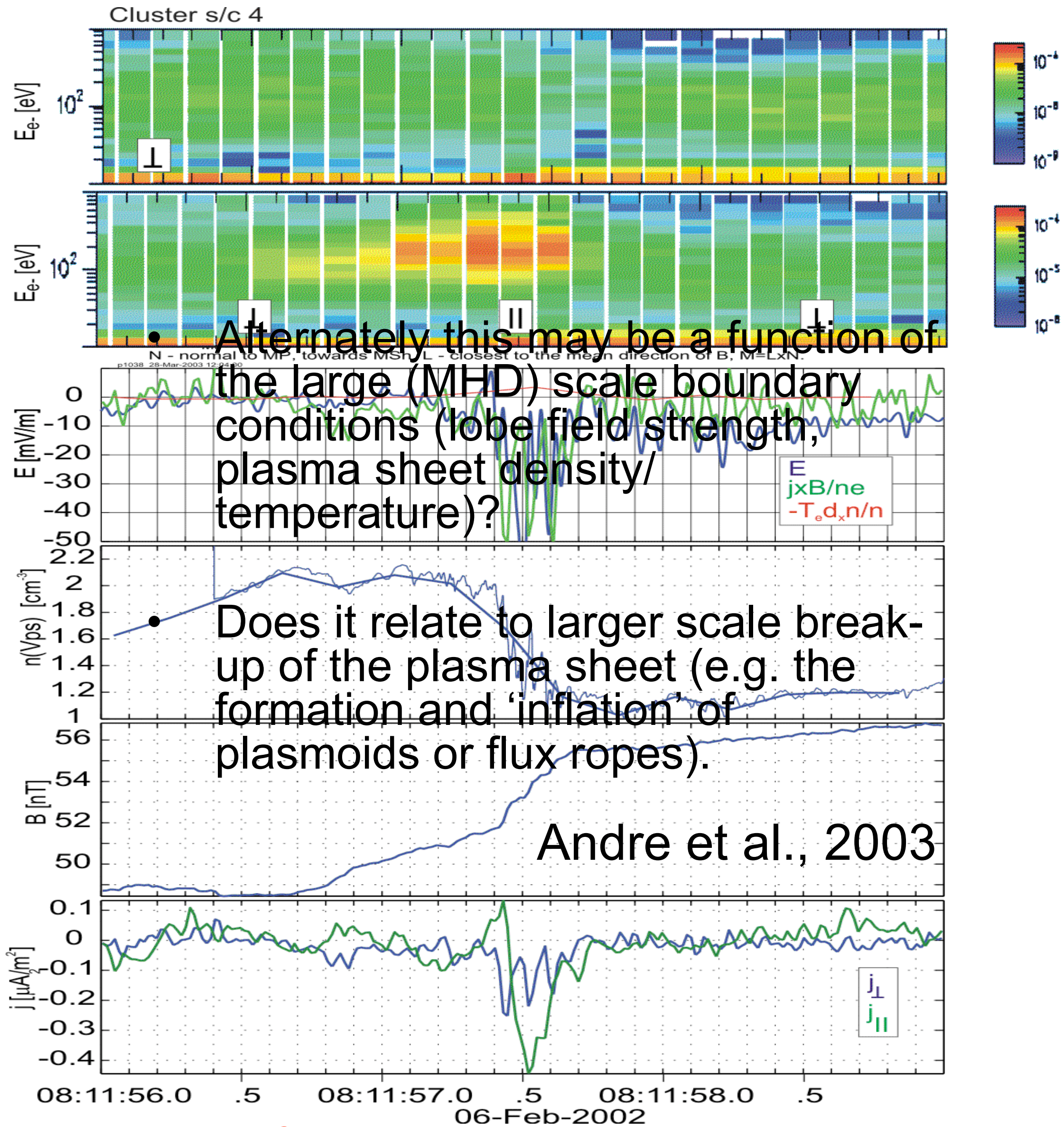


JxB/n_e

$(-\nabla.P/n_e) \times -5.3$



- So this is ‘a discovery’, but what are the wider implications?
  - We are looking at other events and find the result is repeatable, although the ratio of the two terms varies;
- Is this a function of plasma conditions/reconnection rates at the X-point itself (electron scale)?
- Here the electrons play a crucial role, but the relevant variations occur on time and spatial scales (0.1sec, 10 km) not resolved by Cluster.
- E.g. Electron scale current layers shown here (~20km, 5-10 □$_e$,□$_e$) seen for only a fraction of a spin (4 secs, minimum time needed to resolve full particle distribution)



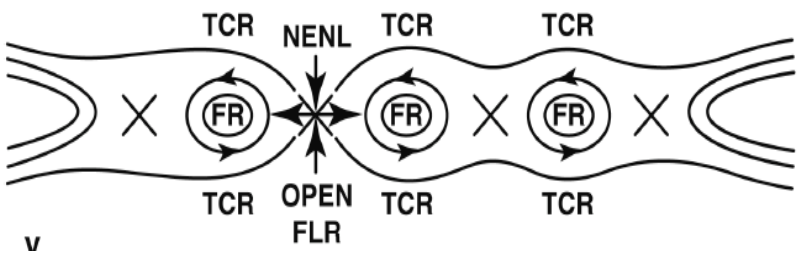
- Alternately this may be a function of the large (MHD) scale boundary conditions (lobe field strength, plasma sheet density/ temperature)?
- Does it relate to larger scale break-up of the plasma sheet (e.g. the formation and ‘inflation’ of plasmoids or flux ropes).

Andre et al., 2003

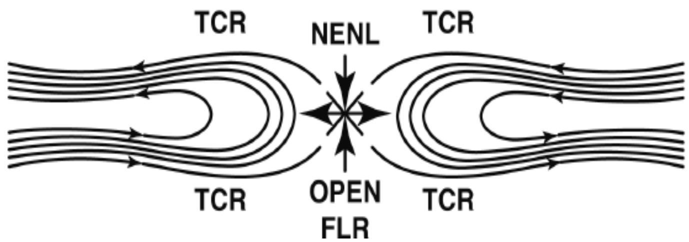
3 secs

Break-up of the Magnetotail Current Sheet

a) Multiple X-line Reconnection:

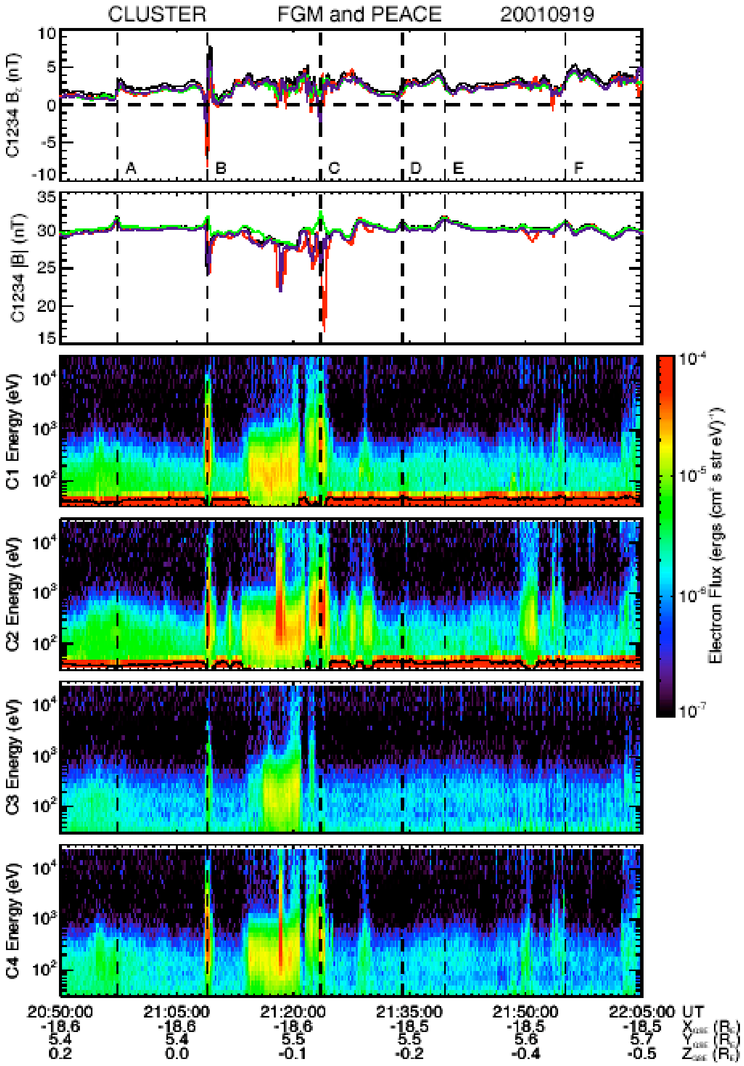


b) Impulsive Reconnection:

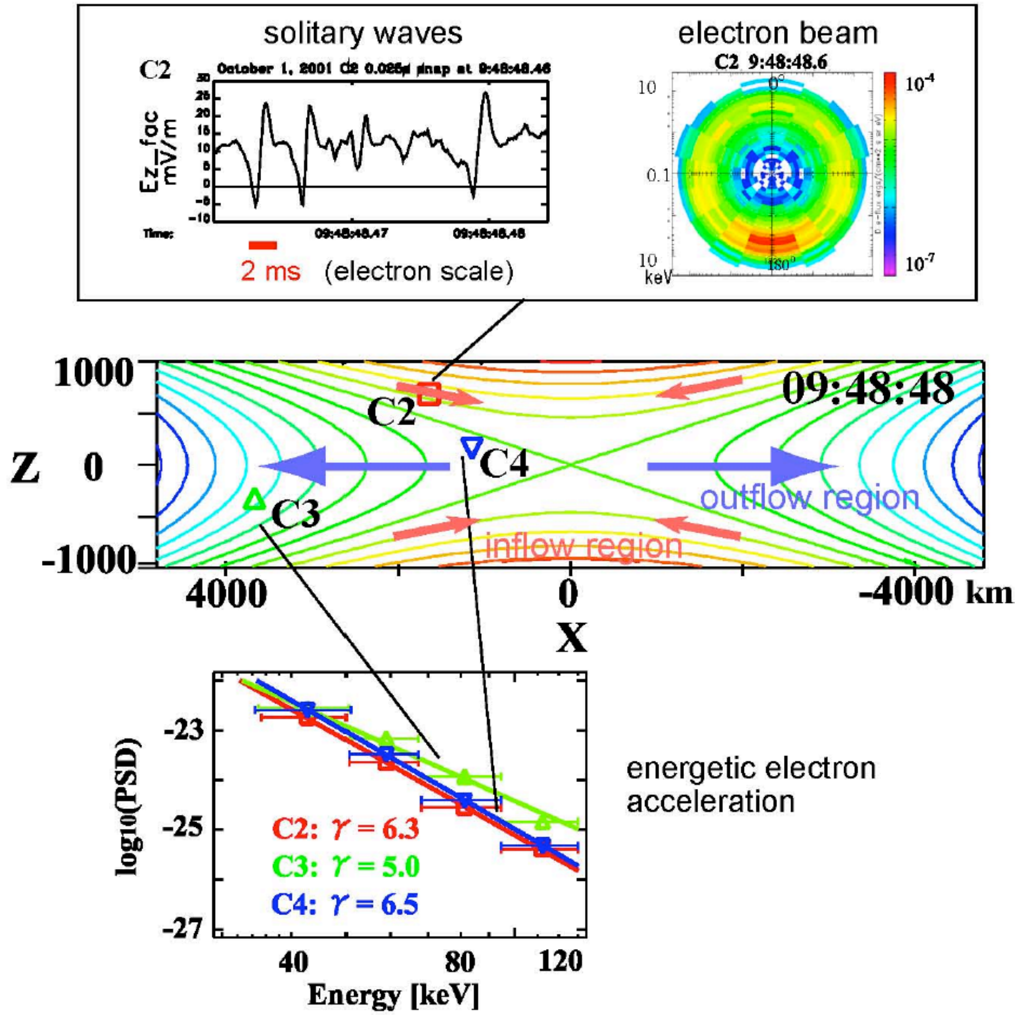


_ Slavin et al. [2005]

Owen et al., [2005] _



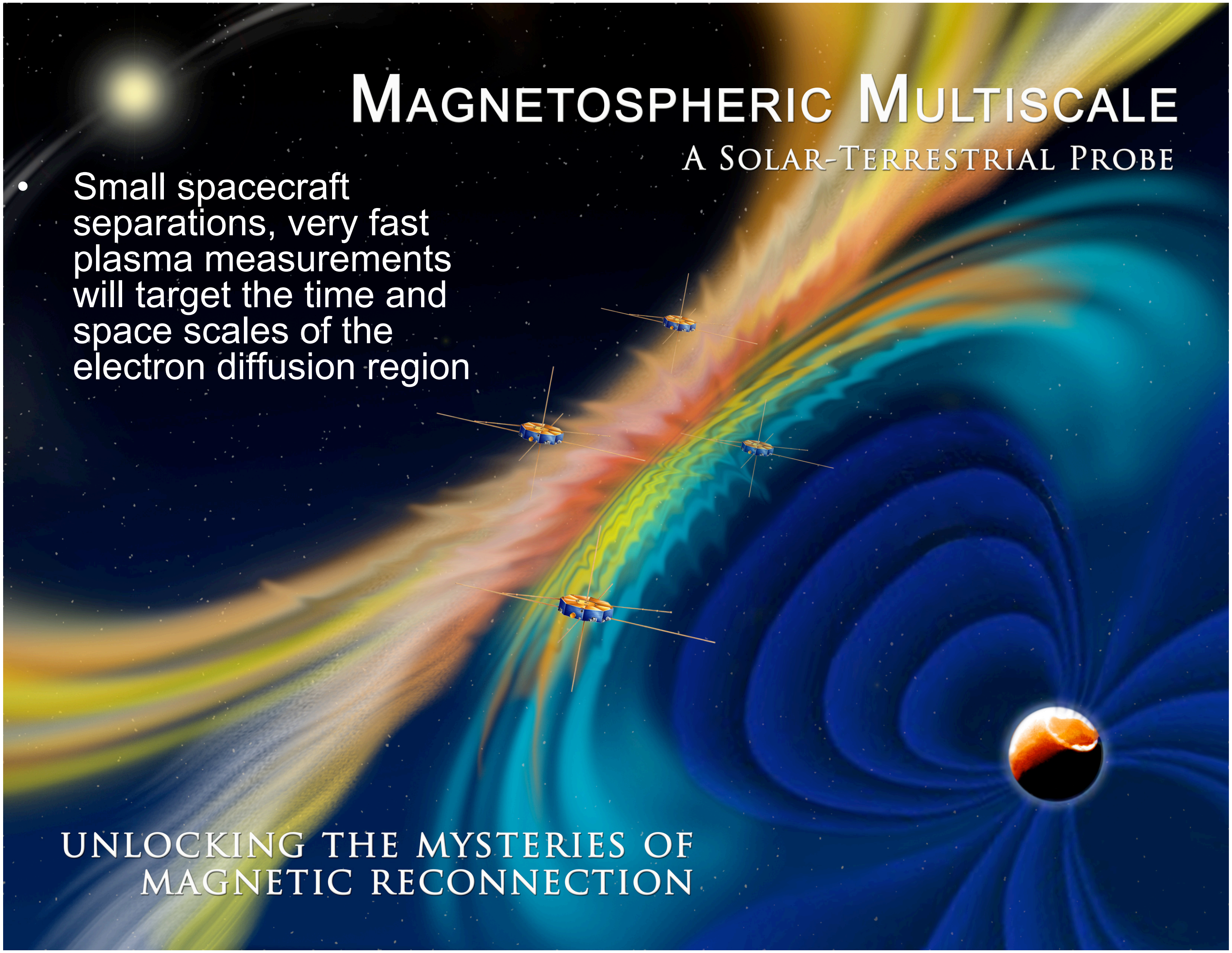
Energetic Particle Acceleration



- Electron acceleration within the reconnection region:
  - Cold electrons are accelerated to keV energies by very small timescale (millisecond) interactions with electric field solitary waves [Cattell et al., 2005].
  - Further acceleration to 100's keV involves non-adiabatic processes in the outflow region [Imada et al., 2007].

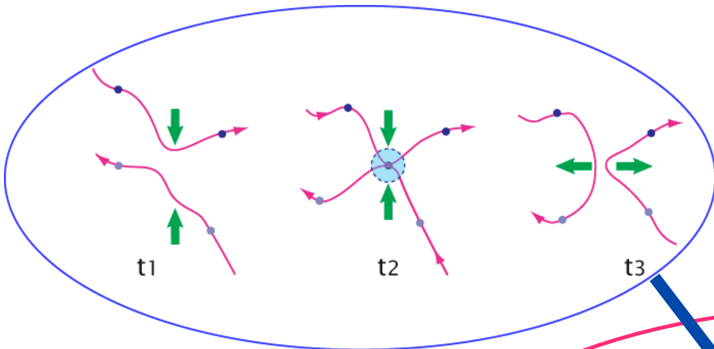
Mission Opportunities - Multi-Scale, Multi-Point Measurements

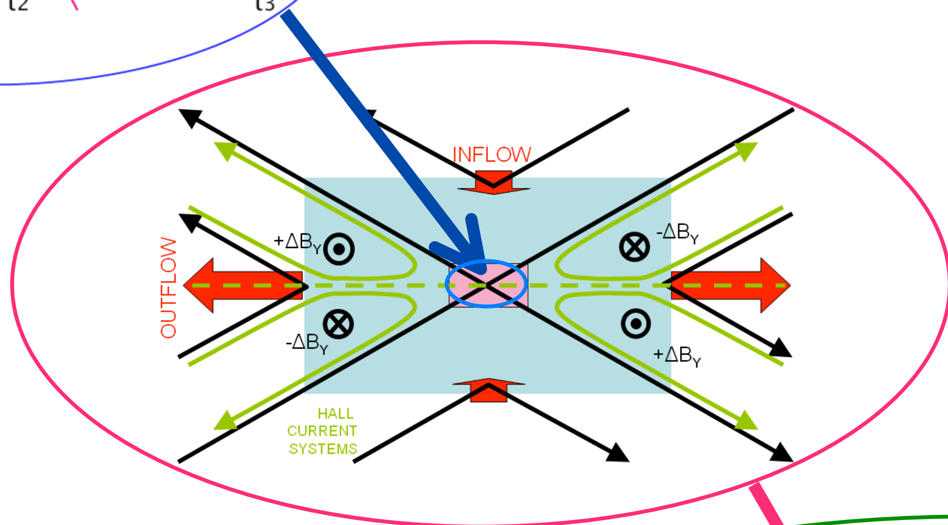
- Even within the limited parameter regimes available, multi-point, in situ measurements provide information that go right to the heart of the broadest astrophysical plasma questions;
- Cluster (and other multi-point missions) provides some real constraints for hypothesis testing, but is unable, for example, to resolve the controlling microphysics of the electron diffusion region;

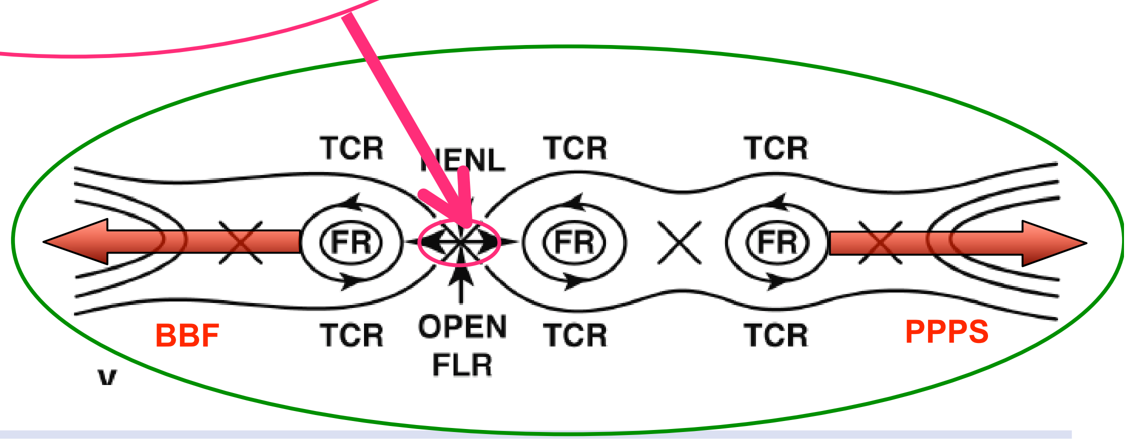


- Small spacecraft separations, very fast plasma measurements will target the time and space scales of the electron diffusion region

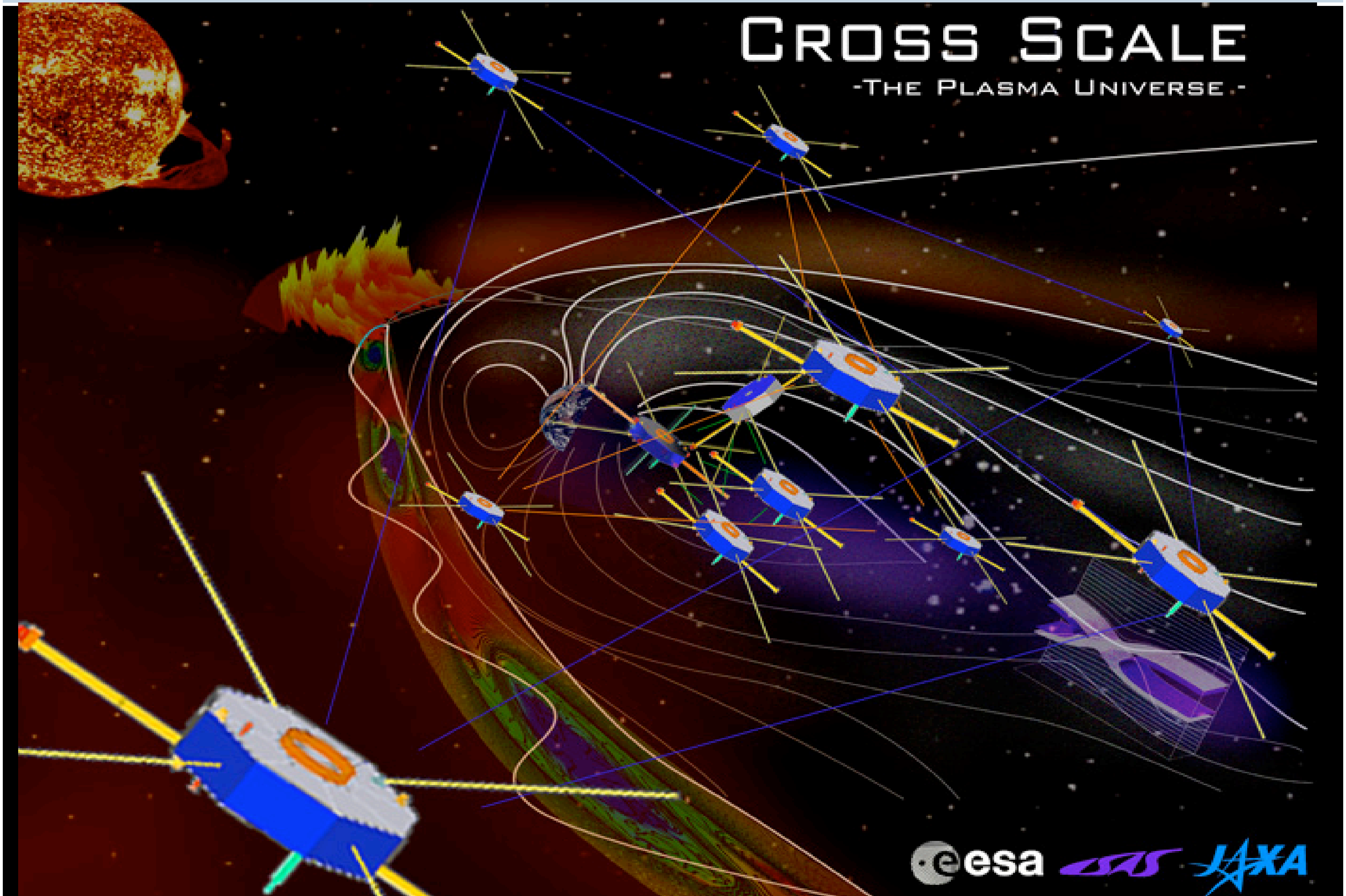
Multi-Scale Process







In order to resolve the interdependencies between each of these scales, we need to make appropriate measurements on each scale simultaneously!


CROSS SCALE
-THE PLASMA UNIVERSE-
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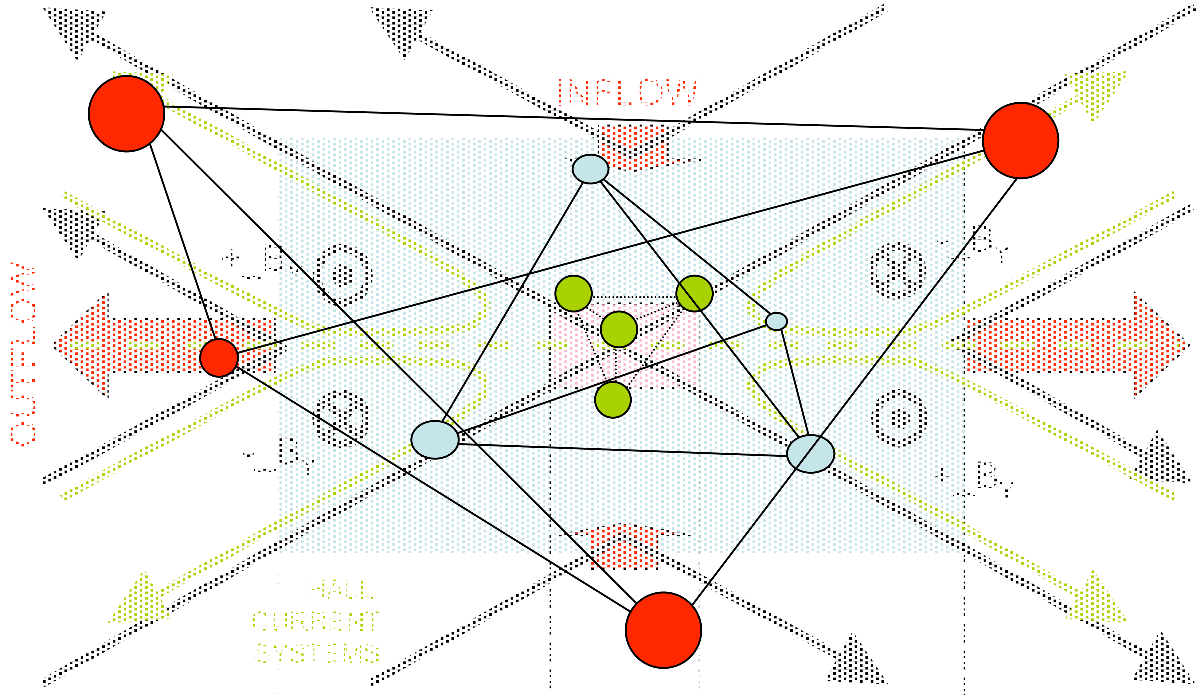
'Hall' Reconnection Geometry



- Nanosat instrumented to examine electron scales
- Microsat instrumented to examine ion scales
- Microsat instrumented to examine MHD scales

electron demagnetized (electron diffusion region ~25 km)

ion demagnetized (ion diffusion region ~1000 km)

Outflow jets (Global scale ~10s R_E)

Conclusion: Some Key Questions on Magnetic Reconnection

- **How is reconnection initiated?**
  - What triggers reconnection within a current sheet?
  - How are thin current sheets formed?
  - What is the role of external driving in reconnection onset?
- **What parameters control the spatial/temporal characteristics of reconnection site?**
  - How is a reconnection neutral line (or multiple X-line) structured ?
  - Why (when?) is reconnection bursty/steady/intermittent ?
  - How significant are the effects of a guide field, velocity shear and density gradients?
  - What are the effects of different particle populations on the reconnection process?
- **What are the consequences of reconnection?**
  - How are ions and electrons energized as a consequence of reconnection ?
  - How are Alfvén waves and other plasma waves generated near the reconnection site?; how these waves interact with ambient plasma?
  - How does the reconnection jet interact with Earth dipole field?