# Magnetospheric Boundaries in Spacecraft Data


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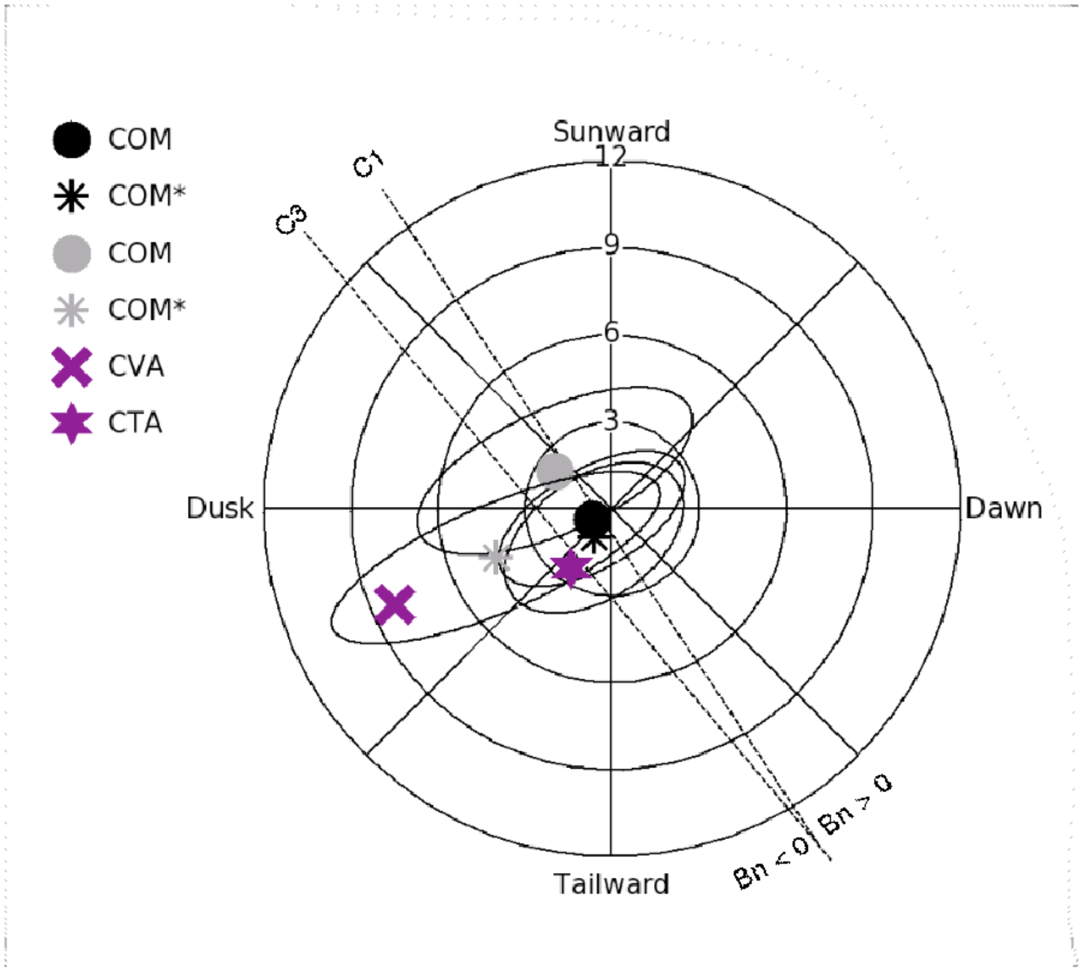
# Magnetopause

- Orientation &Motion
- Thickness & Currents
- Intrinsic Electric Fields
- Grad-Shafranov Reconstruction
- Reconnection Effects
- Ion & Electron Scales

| Timing Methods | | Normal | Velocity | Acc. |
|---|---|---|---|---|
| CVA | (Constant Velocity Approach) | *YES* | *YES* | *NO* |
| CTA | (Constant Thickness Approach) | *YES* | *YES* | *YES* |
| MTV | (Minimum Thickness Variation) | *YES* | *YES* | *YES* |
| MVV | (Minimum Velocity Variation) | *YES* | *YES* | *YES* |
| DA | (Discontinuity Analyzer) | *YES* | *YES* | *YES* |
| **Gradient Methods** | | | | |
| GRA | (Gradient of any Quantity) | *YES* | *NO* | *NO* |
| MVAJ | (Minimum Variance of **J**) | ***YES*** | ***YES*** | *NO* |
| MVAcE | (Minimum Variance of $\nabla \times \mathbf{E}$) | ***YES*** | ***YES*** | *NO* |
| MDD | (Minimum Directional Derivative) | *YES* | *NO* | *NO* |
| STD | (Spatio Temporal Derivative) | *NO* | *YES* | *YES* |
| **Single-spacecraft Methods** | | | | |
| MVAB | (Minimum Variance of B) | ***YES*** | ***NO*** | ***NO*** |
| HT | (deHoffmann-Teller Analysis) | ***NO*** | ***YES*** | ***YES*** |
| MFR | (Minimum Faraday Residue) | ***YES*** | ***YES*** | ***NO*** |
| MMR | (Minimum Massflow Residue) | ***YES*** | ***YES*** | ***NO*** |
| MLMR | (Minimum Linear Momentum Residue) | ***YES*** | ***YES*** | ***NO*** |
| MTER | (Minimum Total Energy Residue) | ***YES*** | ***YES*** | ***NO*** |
| MER | (Minimum Entropy Residue) | ***YES*** | ***YES*** | ***NO*** |
| COM | (Combination of above) | ***YES*** | ***YES*** | ***NO*** |

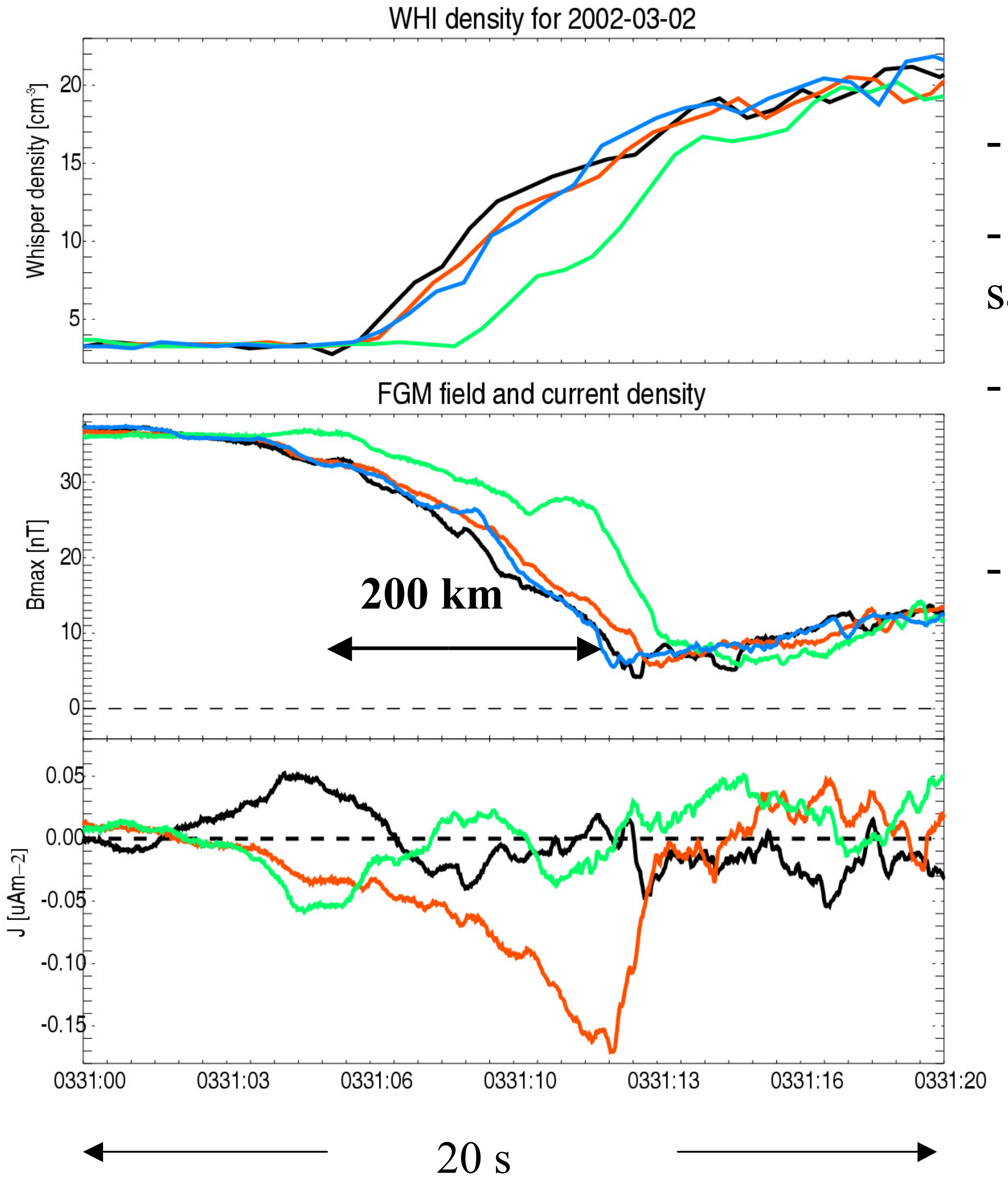
Sonnerup, Haaland et al.

# Normals for 5 Jul 2001 06:24 UT Magnetopause




(Sonnerup et al., 2006)

# Magnetopause: Thickness & Currents

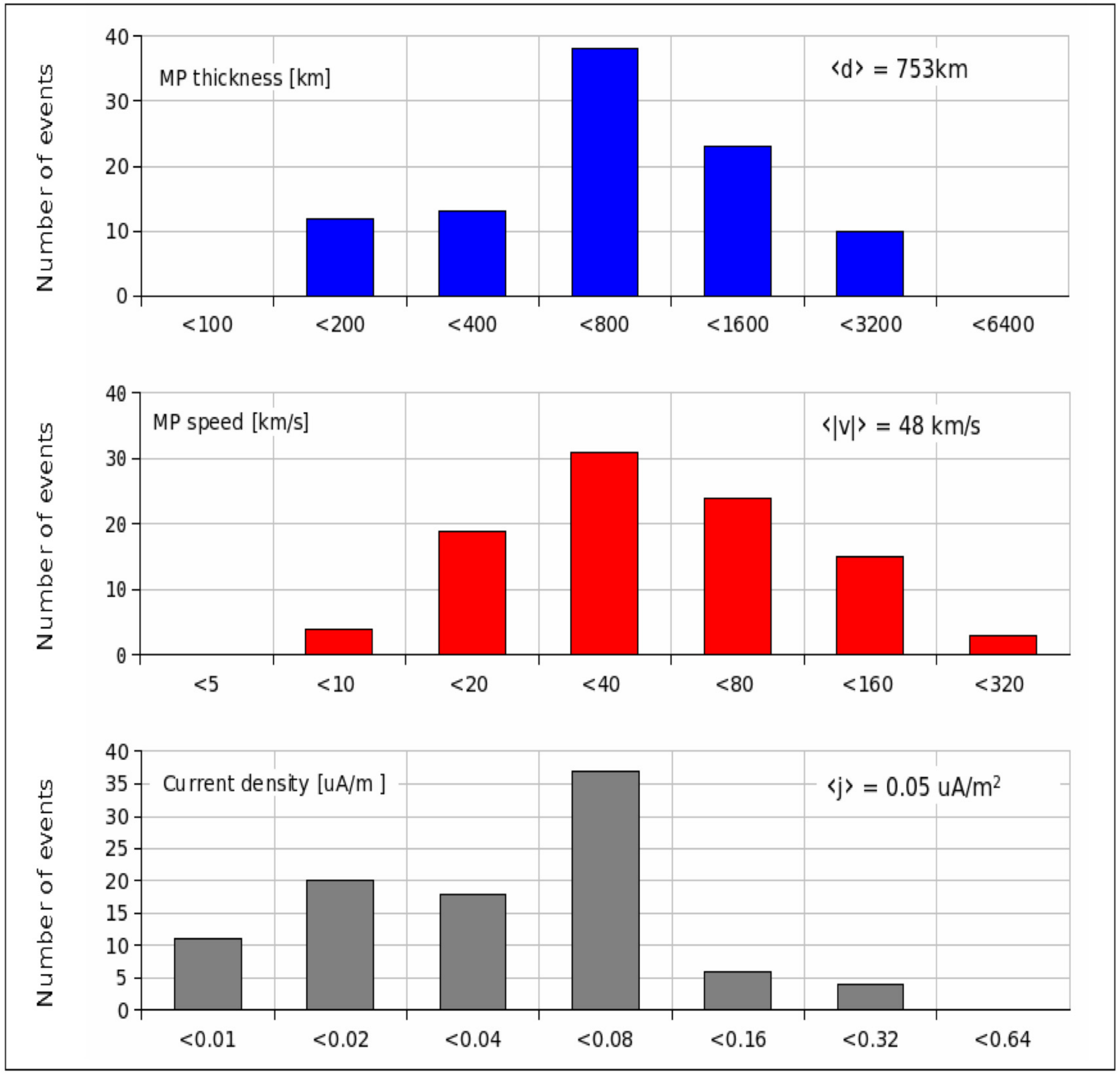



- Spacecraft separation: 100 km
- All 4 S/Cs in current layer at the same time
- currents from Ampere's law

  j = curl-**B**/mu0
- No Boundary Layer

[Haaland et al., 2004]

# Magnetopause Statistics



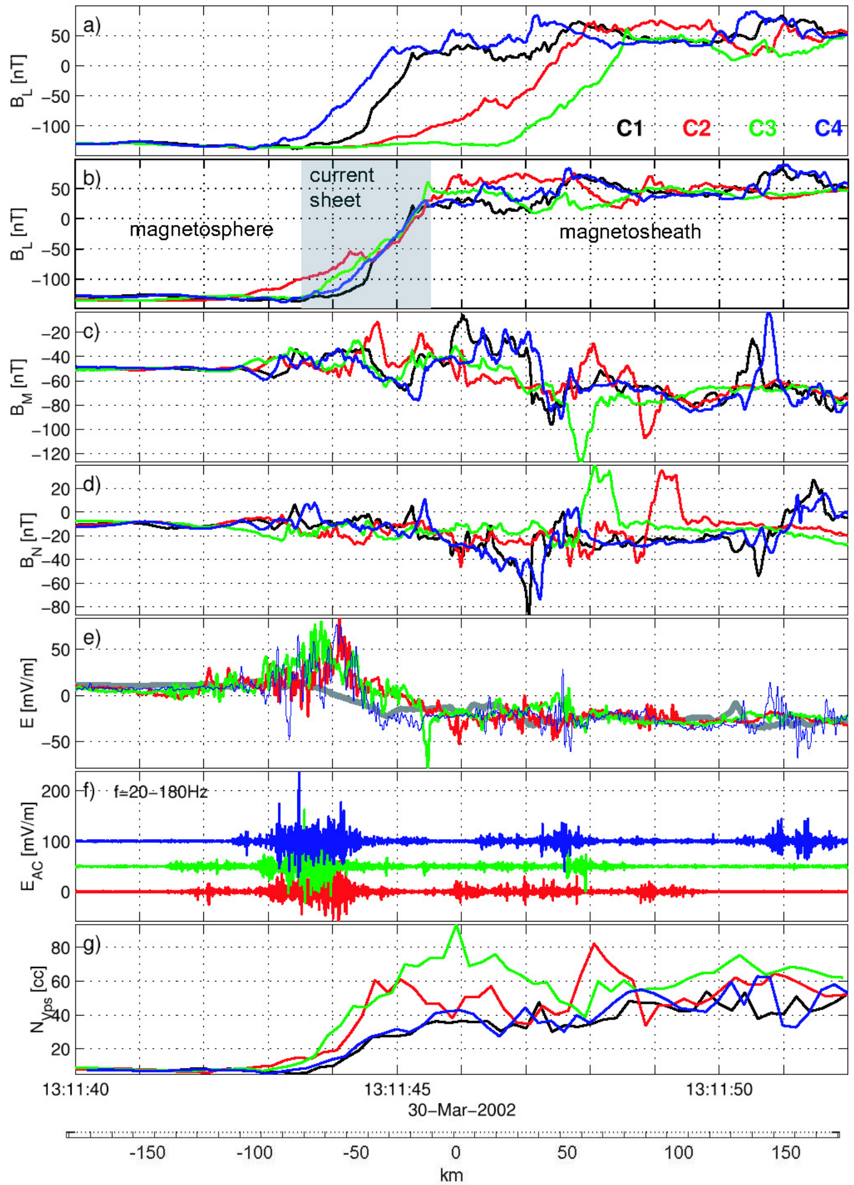

Thickness

Speed

Current Density

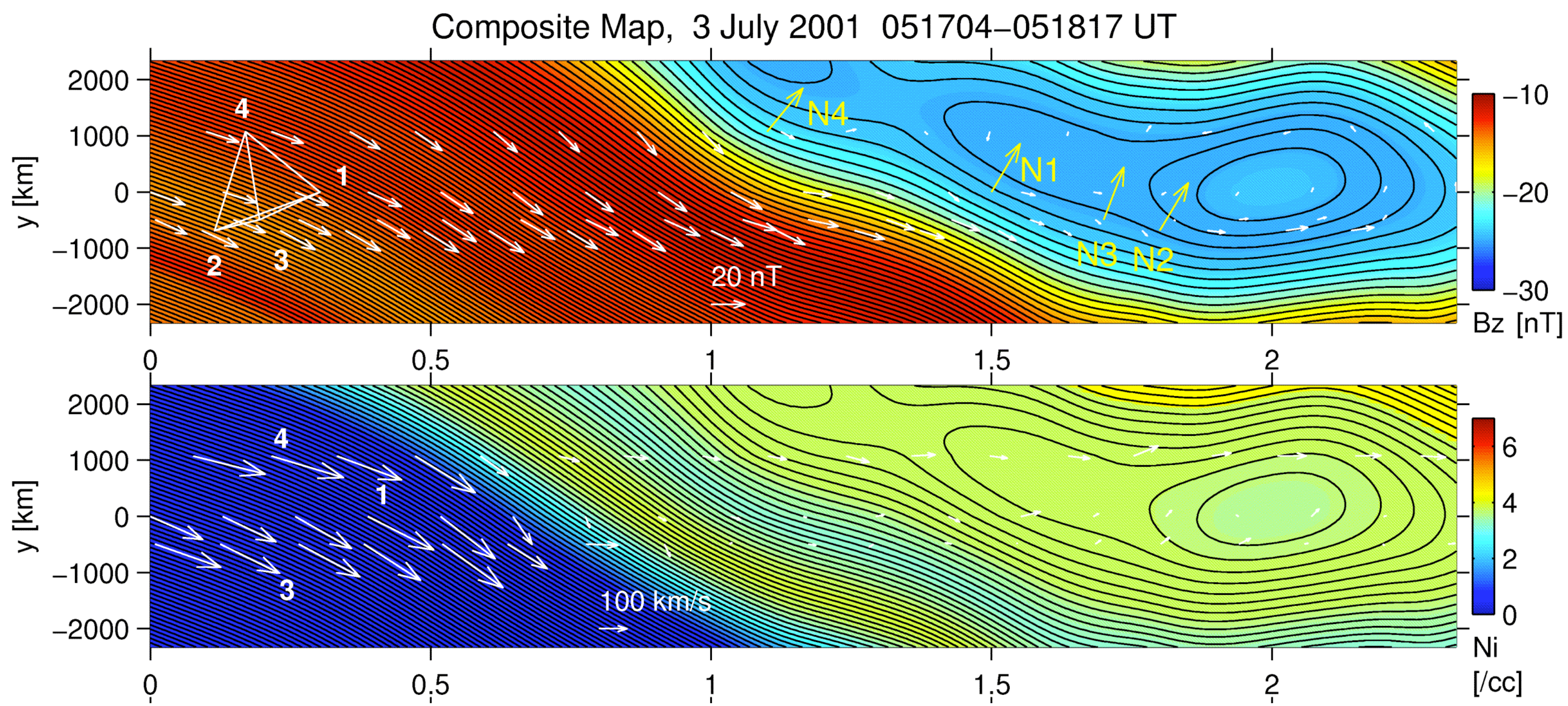
[Paschmann et al., 2005]

# Intrinsic Electric Field




[from A. Vaivads]

# Grad-Shafranov Reconstruction




$$\mathbf{j} \times \mathbf{B} = -\nabla p \longrightarrow \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{dP_t}{dA} = -\mu_0 j_z(A)$$ GS-Equ.

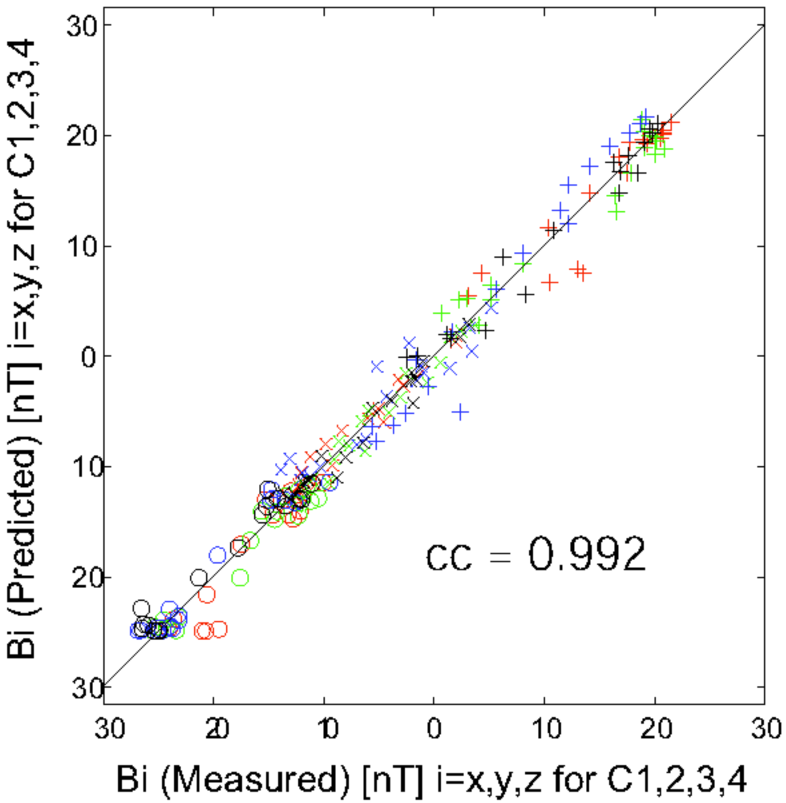
If 2D, time-stationary, no inertia forces

$A(x,y)\hat{\mathbf{z}}$ Vector Potential

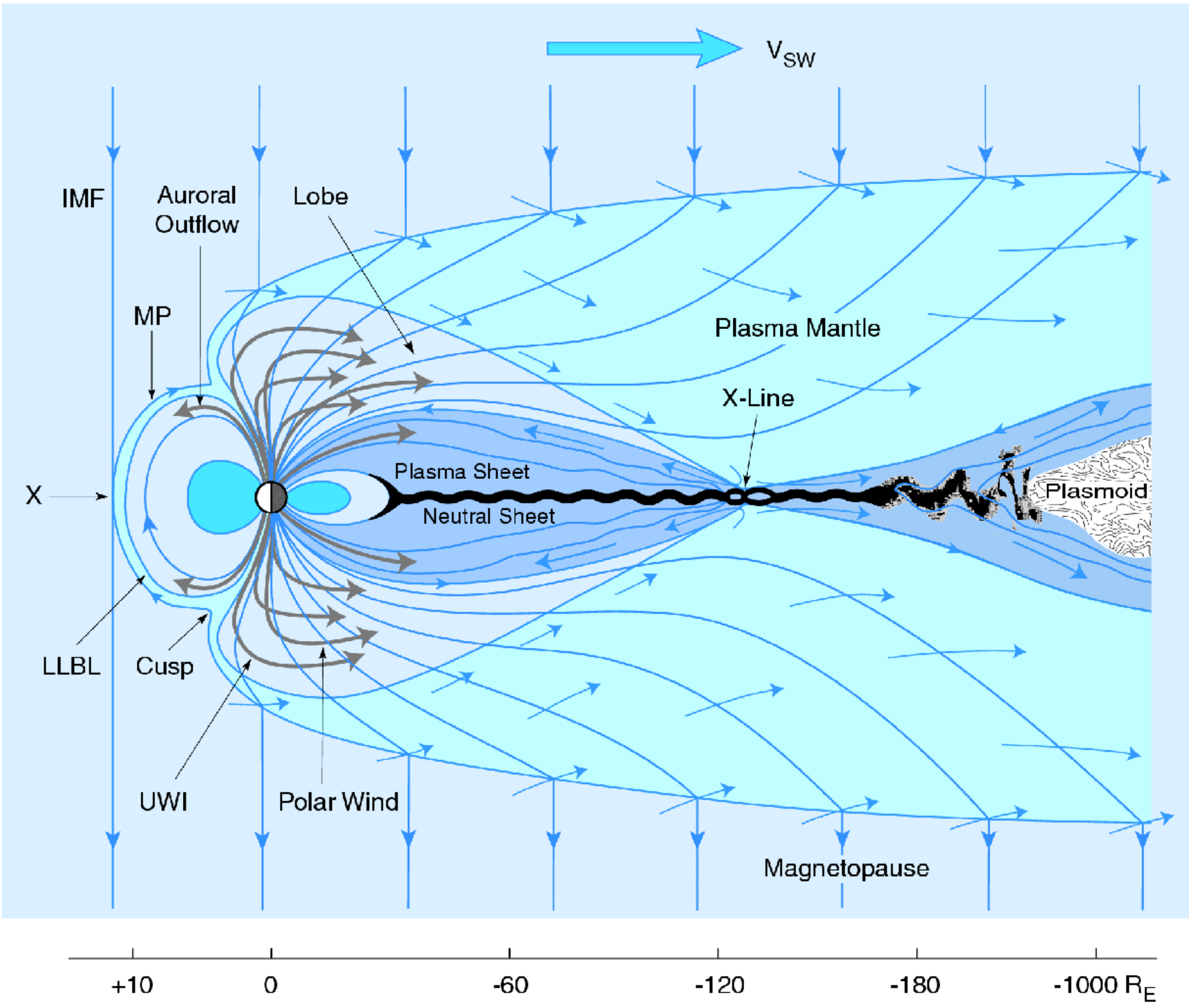
$$P_t = p + \frac{B_z^2}{2\mu_0}$$ Total Pressure

[Hasegawa et al., 2003]

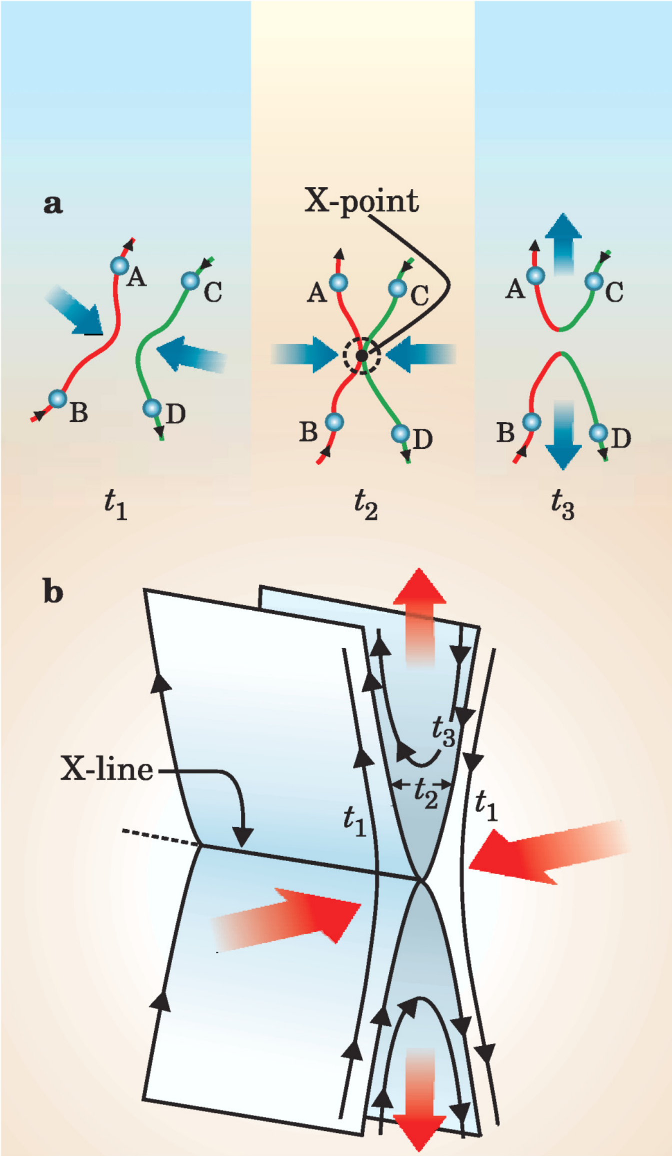
# Measured vs. Predicted Fields



# Magnetosphere Topology & Flows



# Magnetic Reconnection: "Breaking through the lines"




*Magnetic reconnection:*

1) *Occurs at thin current sheets.*
2) *Is a process that converts magnetic energy to bulk flow energy and plasma heating.*
3) *Changes the field topology.*
4) *Requires breakdown of the frozen-in condition of MHD in small region around the x-line*

(Nature, News&Views, 2006)

# Cluster Magnetic Reconnection Obervations

- Magnetopause
- Magnetotail
- Solar Wind
- (Magnetosheath)

# Walén Relation

For an ideal MHD RD, the following relation holds:

$$\mathbf{V'} = \pm \mathbf{V_A}$$

where $\mathbf{V'} = (\mathbf{V} - \mathbf{V}_{HT})$ is the (field-aligned) plasma velocity in the deHoffmann-Teller (HT) frame, and $\mathbf{V_A} = [(1 - \alpha)/\mu_o \rho]^{1/2}\mathbf{B}$ is the intermediate mode wave speed, and $\alpha = (p_{ll} - p_\perp)\mu_o/B^2$ is the pressure anisotropy factor. The + and – signs correspond to waves propagating anti-parallel and parallel to $\mathbf{B}$ respectively, $\rho$ is the mass density, $\mu_o$ is the permeability of free space,

In the spacecraft frame, the vector change in velocity ($\Delta\mathbf{V}$) experienced by plasma passing through an RD is

$$\Delta\mathbf{V} = \pm \Delta\mathbf{V_A} = \pm[(1 - \alpha_2)/\mu_o \rho_2]^{1/2}\mathbf{B}_2 - [(1 - \alpha_1)/\mu_o \rho_1]^{1/2}\mathbf{B}_1$$

$$= \pm[(1 - \alpha_1)/\mu_o \rho_1]^{1/2}(\mathbf{B}_2 \rho_1/\rho_2 - \mathbf{B}_1)$$

Where $\Delta$ refers to changes between points up and downstream from the RD.

# deHoffmann-Teller (HT) Frame

- Frame of reference in which the plasma flow is field-aligned
  (or, equivalently, the electric field vanishes)
  on both sides of the discontinuity.

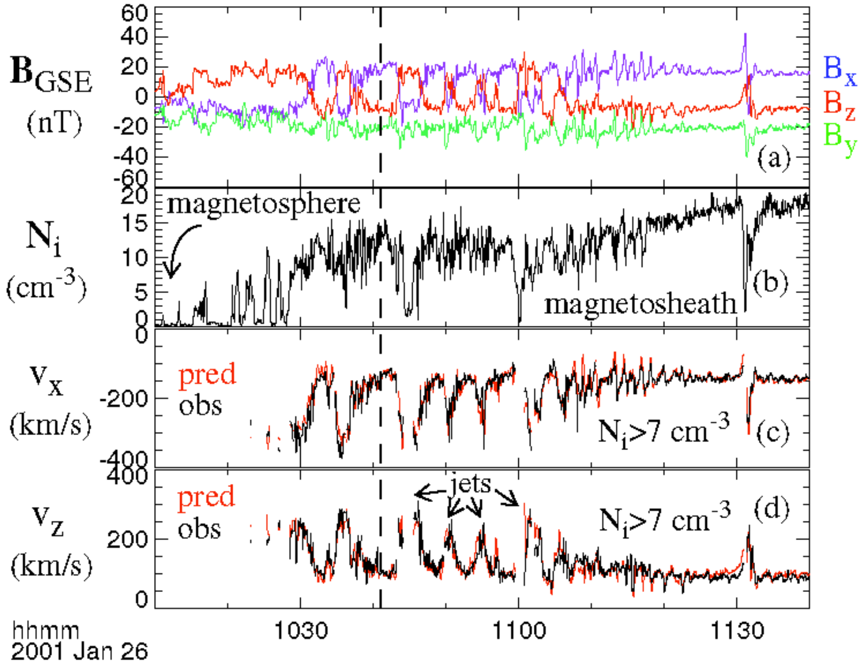
- Introduced for shocks by deHoffmann and Teller (1951).

- The transformation velocity $\mathbf{V}_{\mathbf{HT}}$ from spacecraft to HT frame is determined from least-squares fitting of $-\mathbf{V}_{\mathbf{HT}} \times \mathbf{B}_{\mathbf{i}}$ to the directly measured electric field vectors $\mathbf{E}_{\mathbf{i}}$, or $-\mathbf{V}_{\mathbf{i}} \times \mathbf{B}_{\mathbf{i}}$, if only plasma measurements $\mathbf{V}_{\mathbf{i}}$ are available (Sonnerup et al., 1987).

- The HT frame participates in boundary motion. Thus $\mathbf{V}_{\mathbf{HT}} \cdot \mathbf{n} = u$ is the boundary speed

- Existence of HT frame is a necessary but not sufficient condition for ongoing reconnection

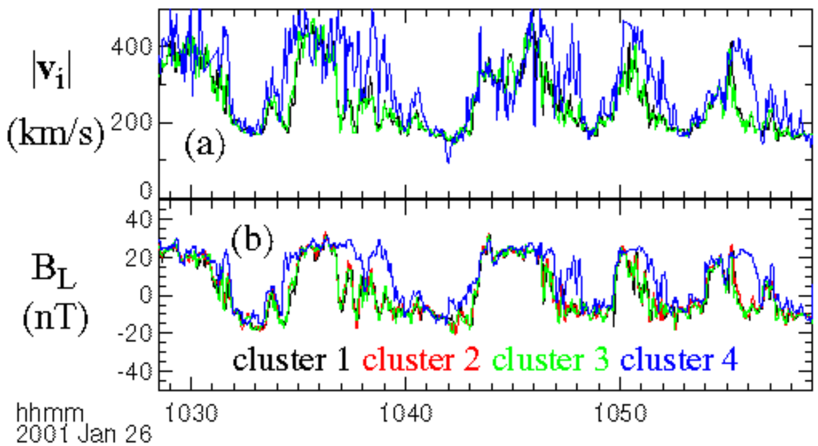
# Plasma Jetting: Evidence for Reconnection

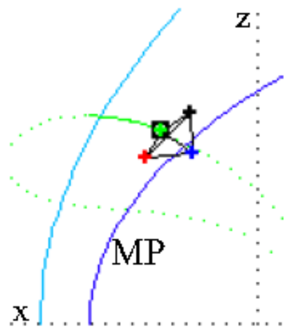



Jump relation for an RD with isotropic pressure:

$$\Delta V = \Delta V_A = \Delta B\ (\mu_0 \rho)^{-0.5}$$

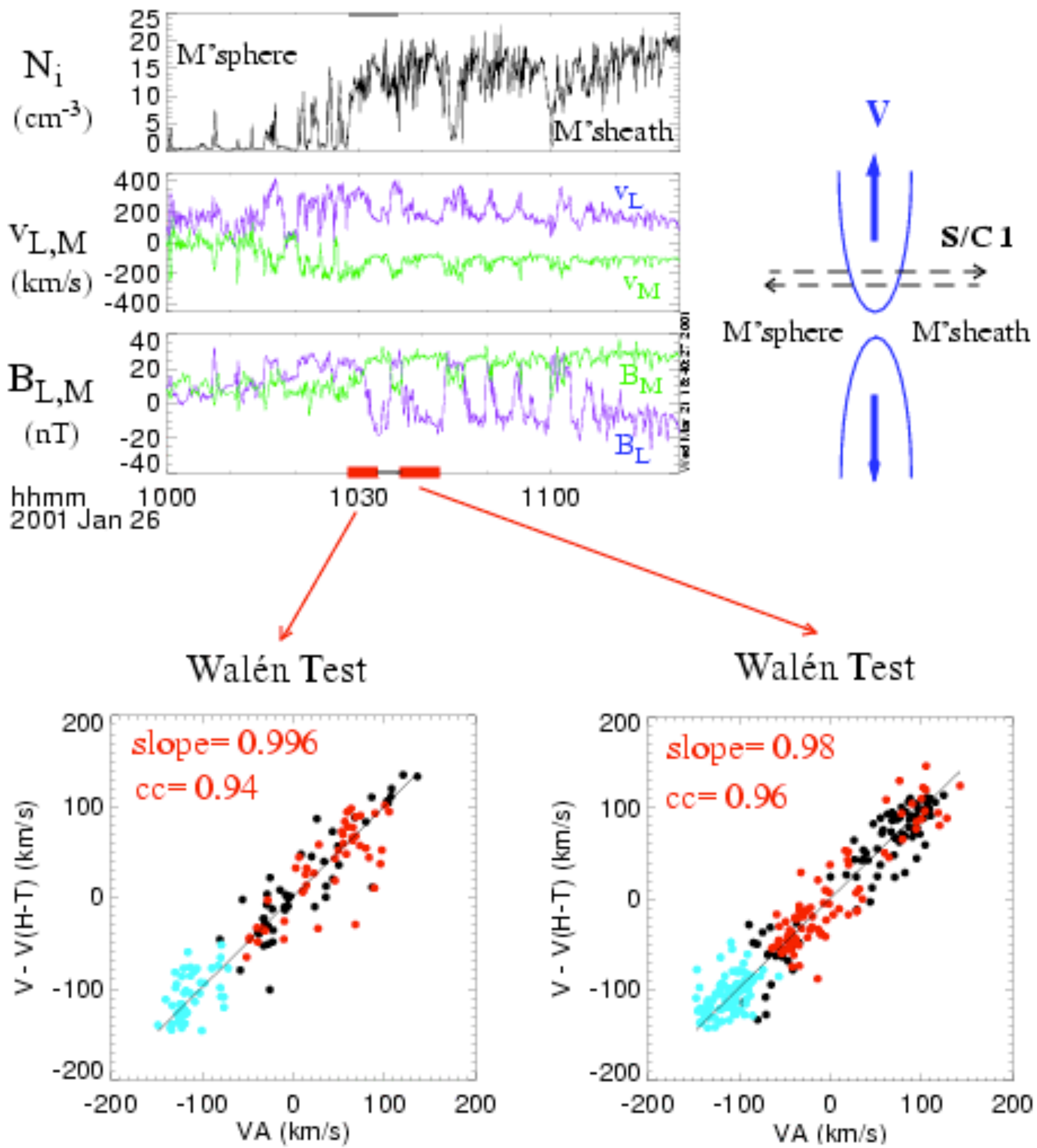
Acceleration is due to $\mathbf{j} \times \mathbf{B}_n$ force



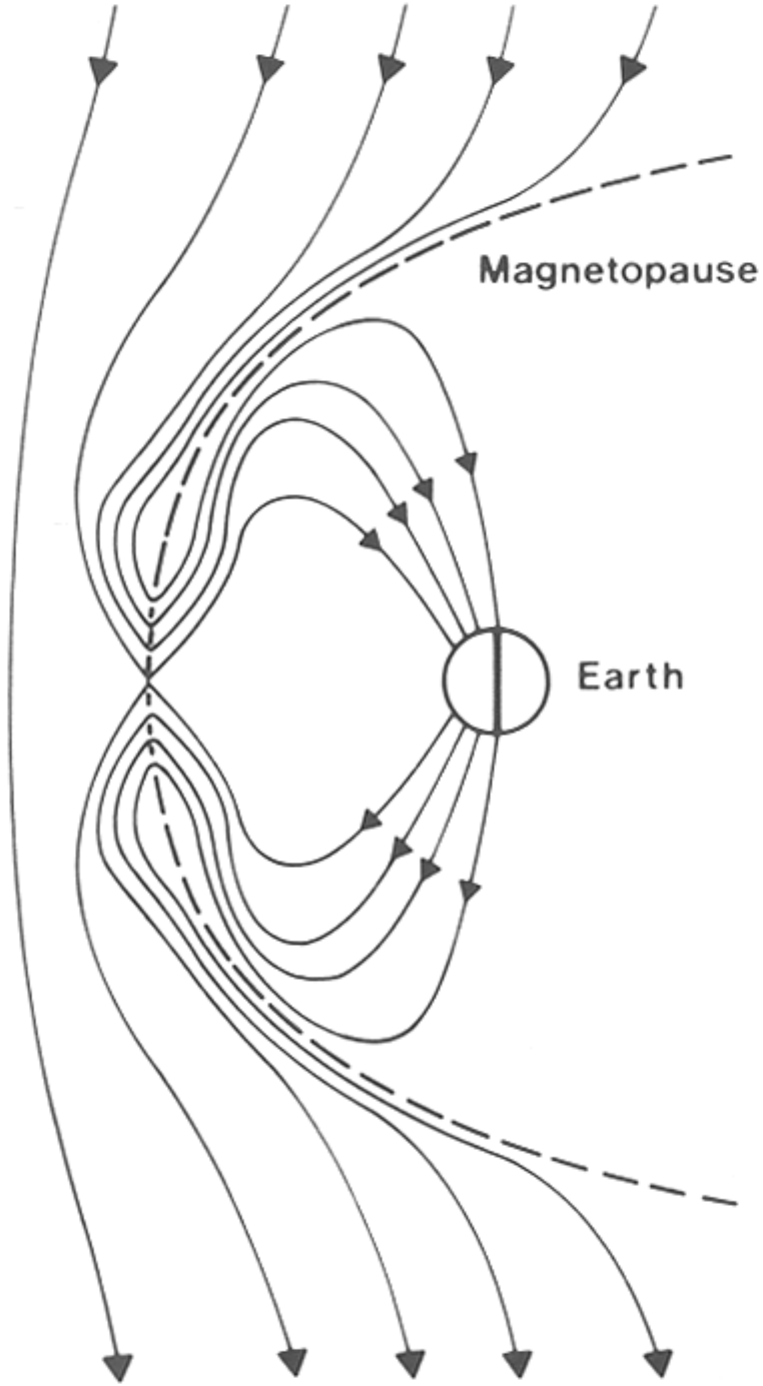




[Phan et al., 2004]

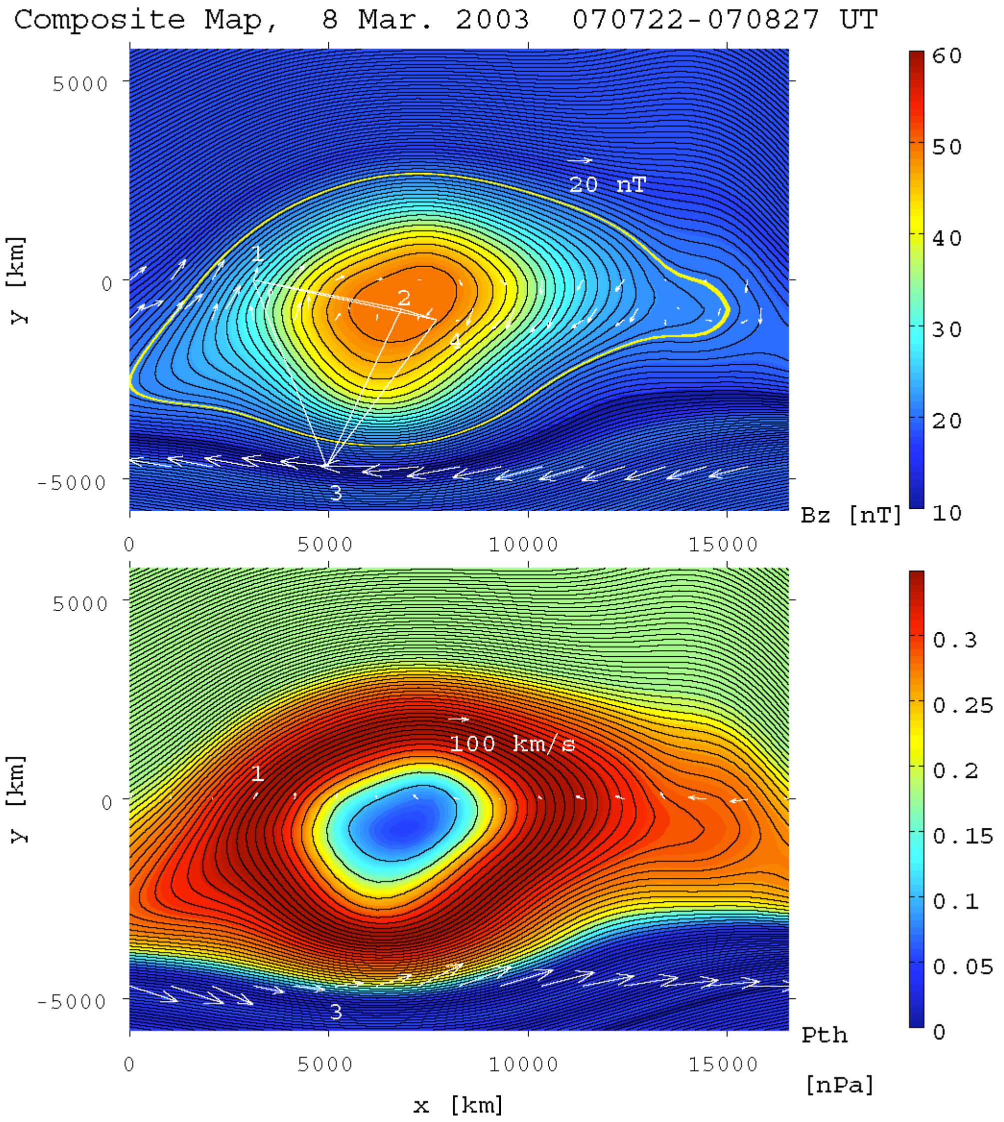
# Walén Test at MP

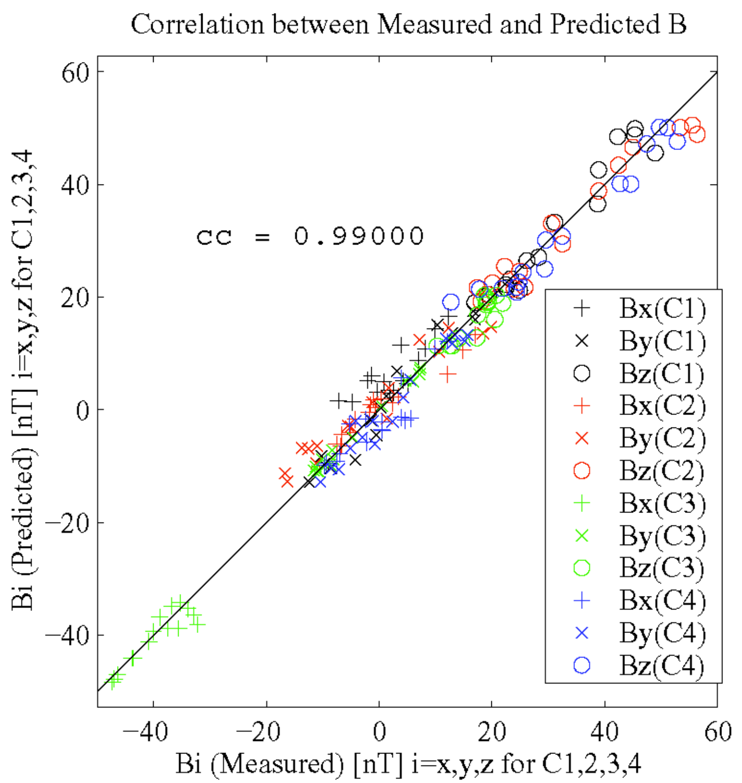


# Temporally Modulated Reconnection Rate



# Reconstruction of an FTE

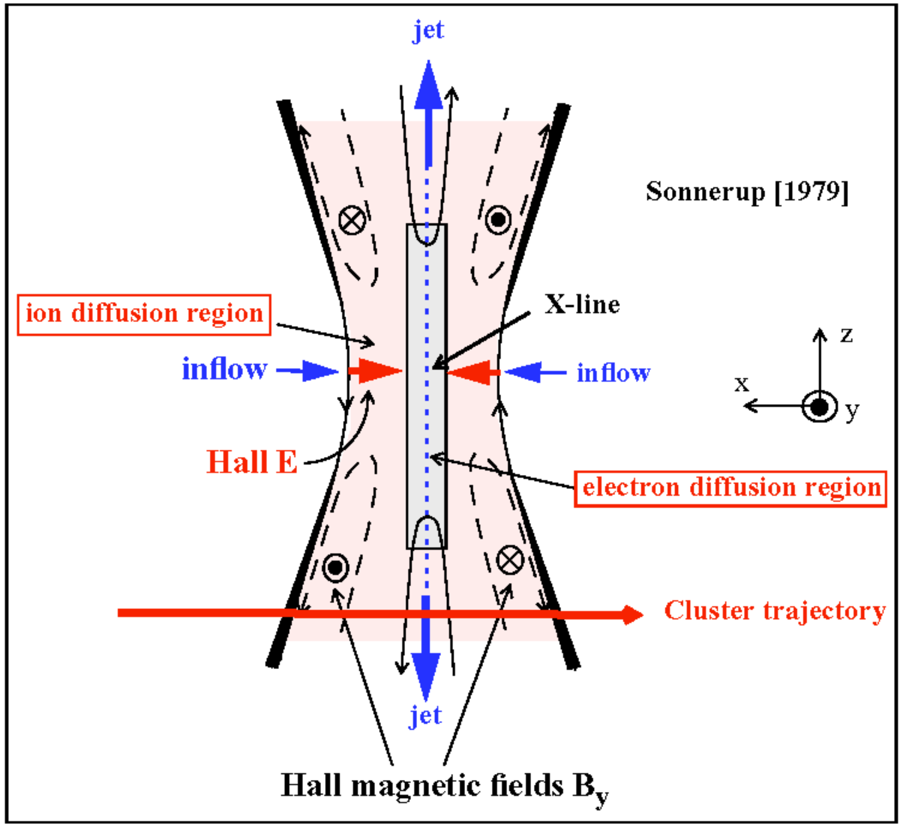



[Sonnerup et al., 2004]

# Hall Magnetic Field: Ion Diffusion Region

**Magnetic Reconnection Diffusion Region**

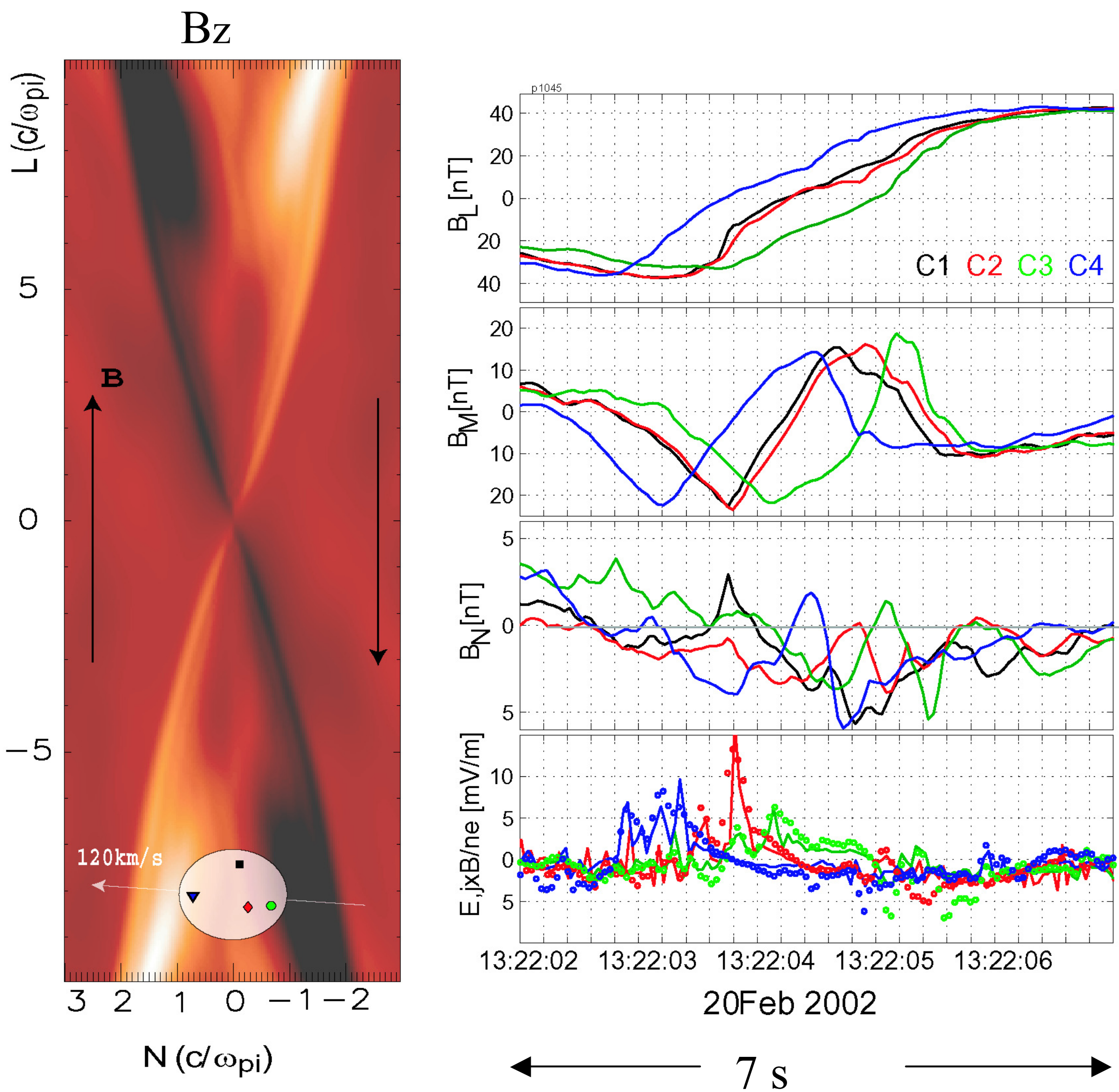



ion scale        electron scale

$$\mathbf{E} + \mathbf{v_i} \times \mathbf{B} = (\mathbf{j} \times \mathbf{B})/ne - \nabla \cdot \underline{\underline{\mathbf{P}}}_e/ne^2 + (1/\varepsilon_0 \omega_{pe}^{\ 2}) d\mathbf{j}/dt + \eta \mathbf{j}$$

Hall    electron pressure    electron inertia    resistive

# Hall Magnetic Field & E-Field Balance




Current sheet

Ion diffusion region

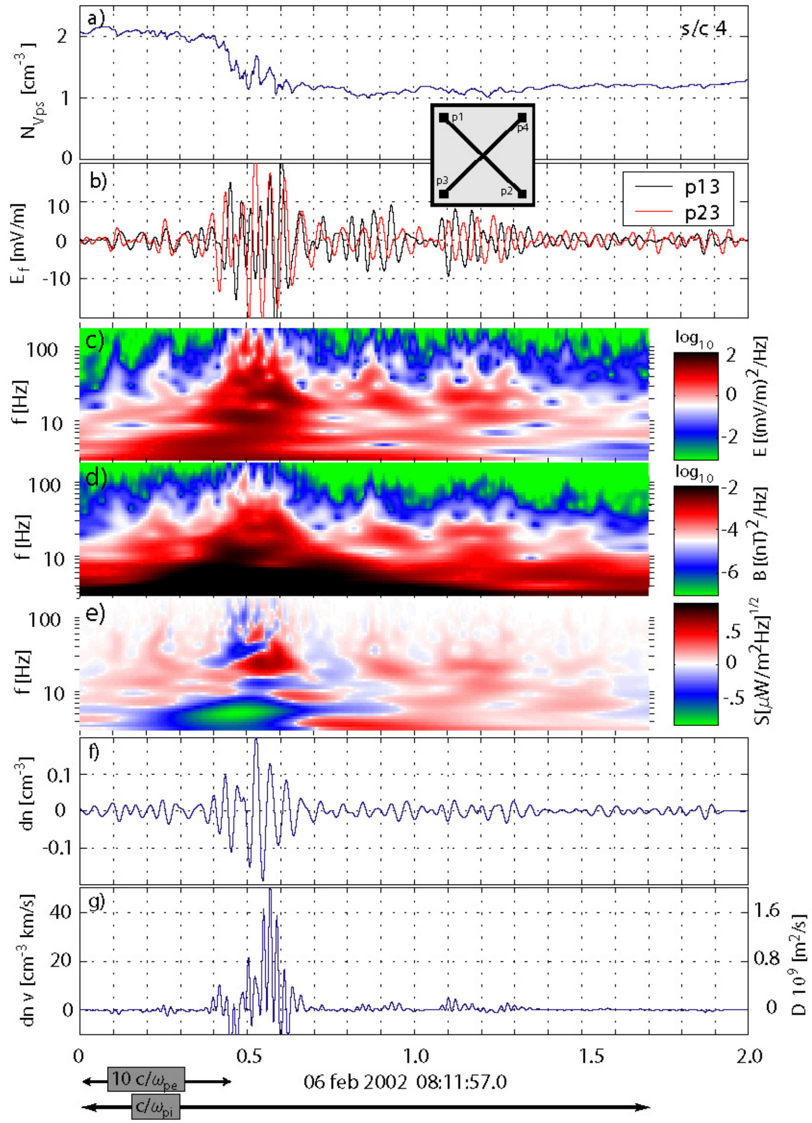
Reconnection !

$E_N \sim jxB/ne$

← 7 s →

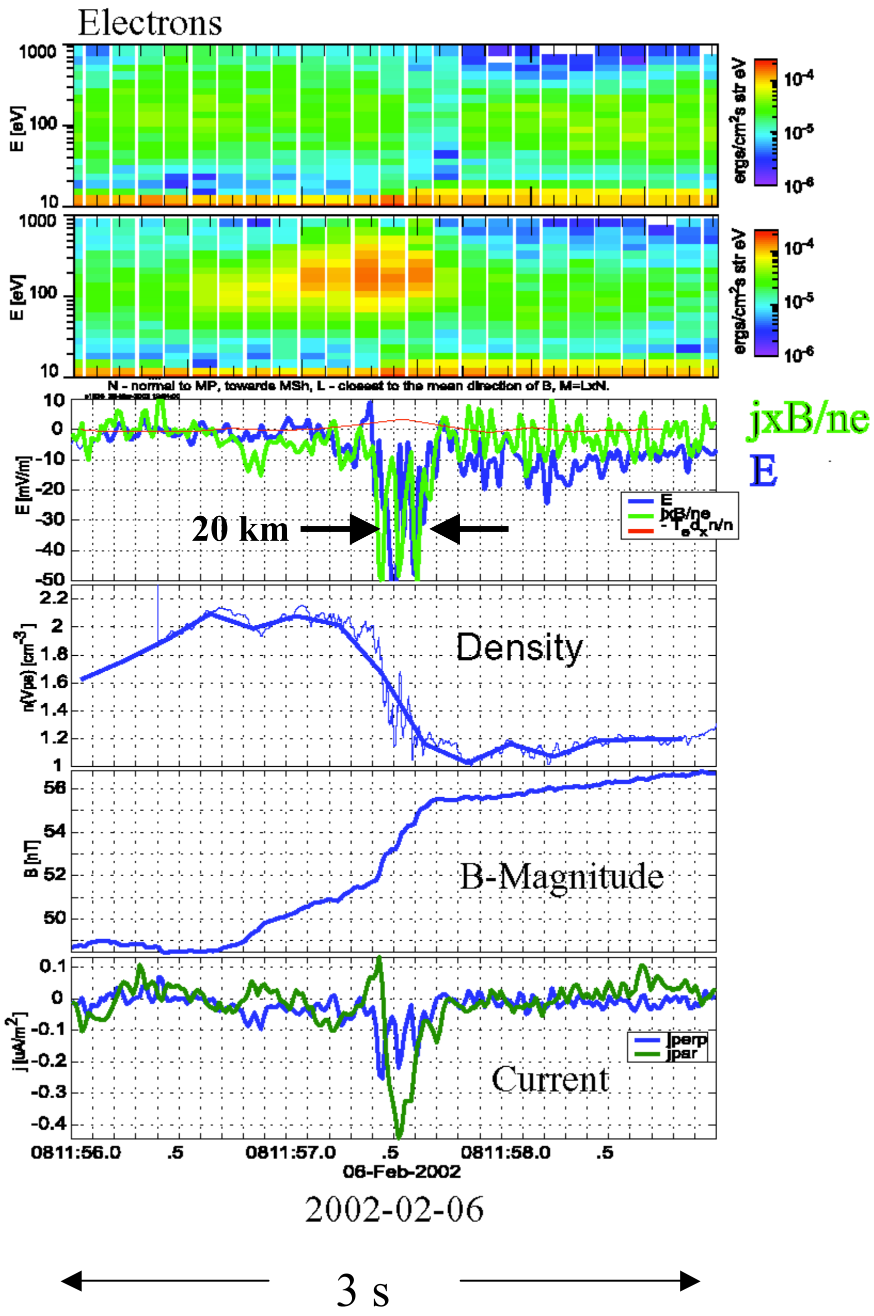
[Vaivads et al., 2003]

# Lower-Hybrid Waves




[Vaivads et al., 2004]

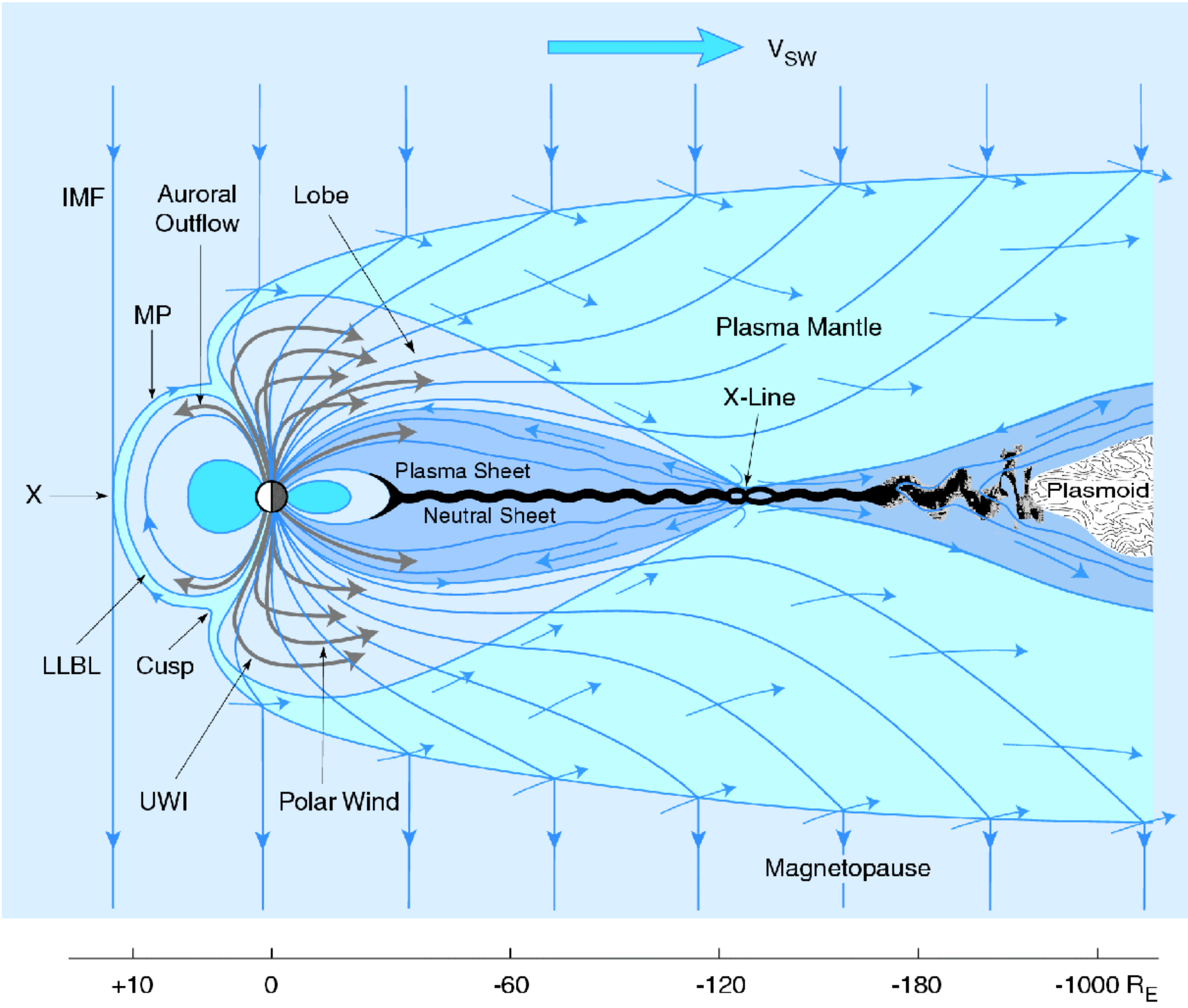
# Electron-Scale Layer at Separatrix




[Andre et al., 2003]

# Reconnection in the Magnetotail

# Magnetosphere Topology & Flows

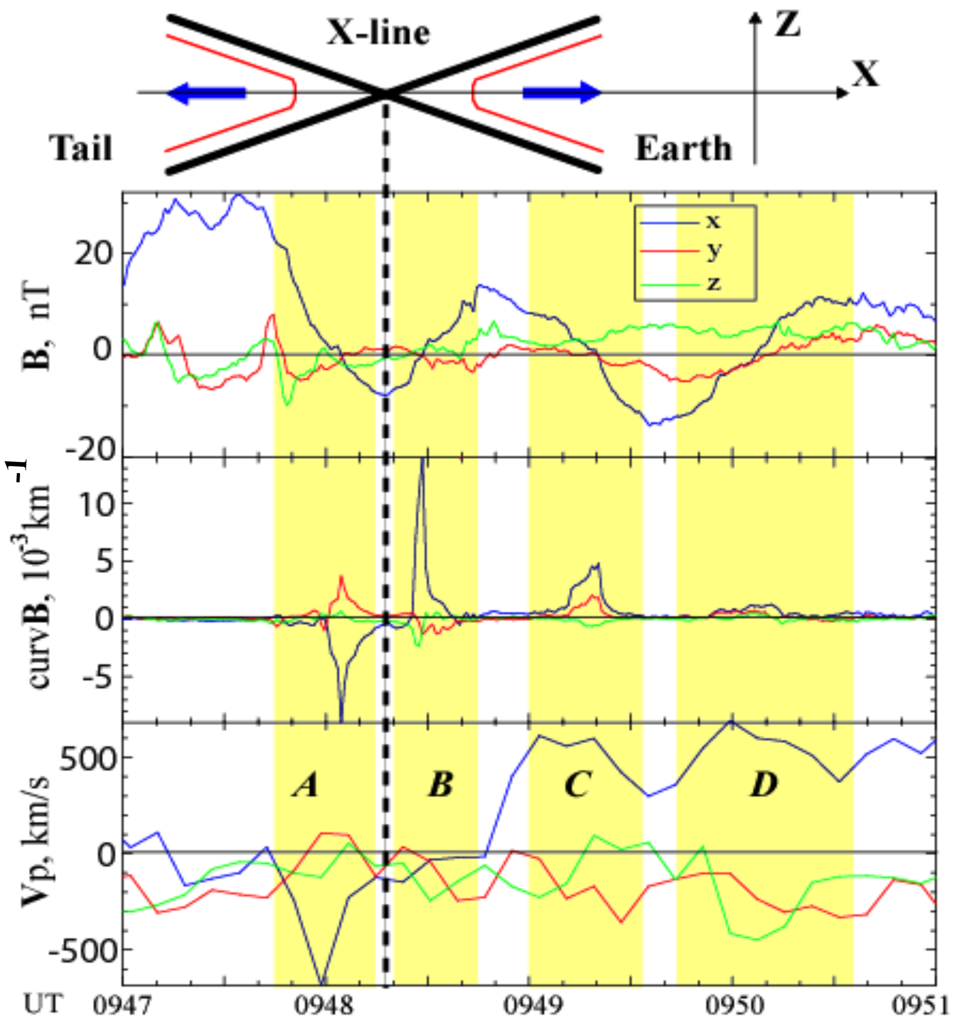


# Flow & Field Curvature Reversals

- Magnetic field components in the Cluster barycentre: 4 current sheet traversals
- Field line curvature:

  curv B = (b.grad)b

- Flow and field line curvature reversal
- X-line moves tailward over Cluster



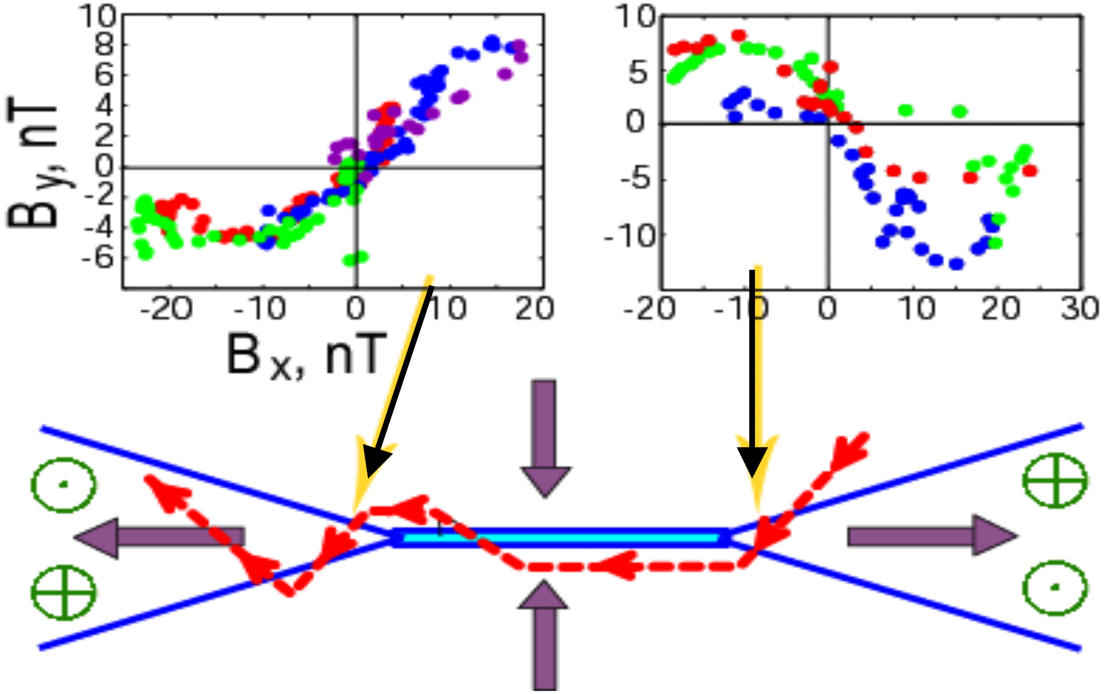

[Runov et al, GRL, 2003b]

1 Oct 2001

# Reconnection & Hall Effect at the Tail Current Sheet

- 500 km thin current sheet around X-line
- Bifurcated current sheet on both sides of X-line
- Hall effect ($\Delta B_y$) during ‘outer’ crossings shows ion decoupling

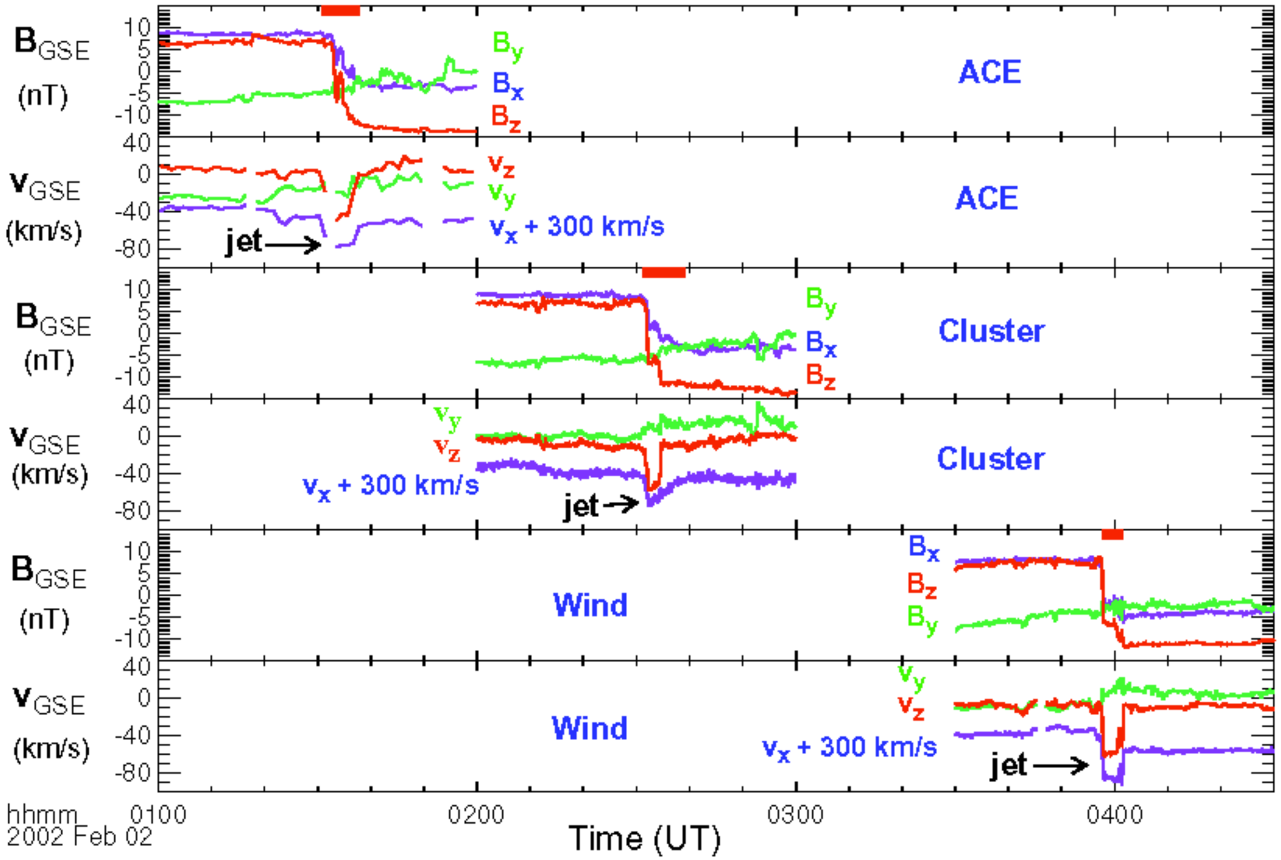
1 Oct 2001

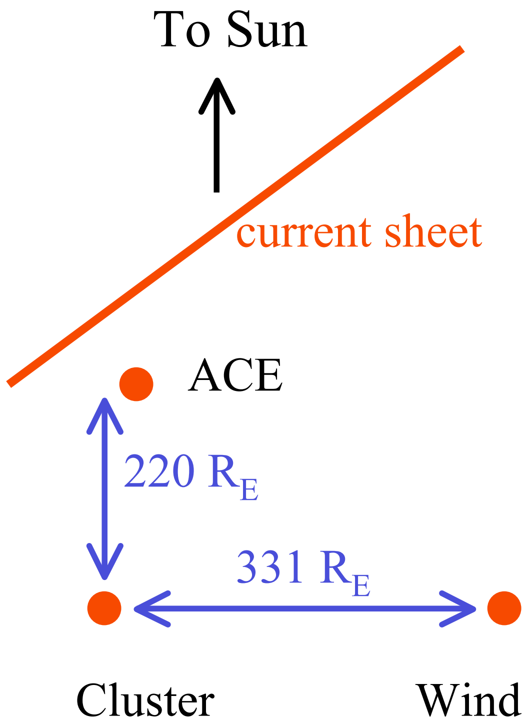



[Runov et al., GRL, 2003b]

# Reconnection in the Solar Wind

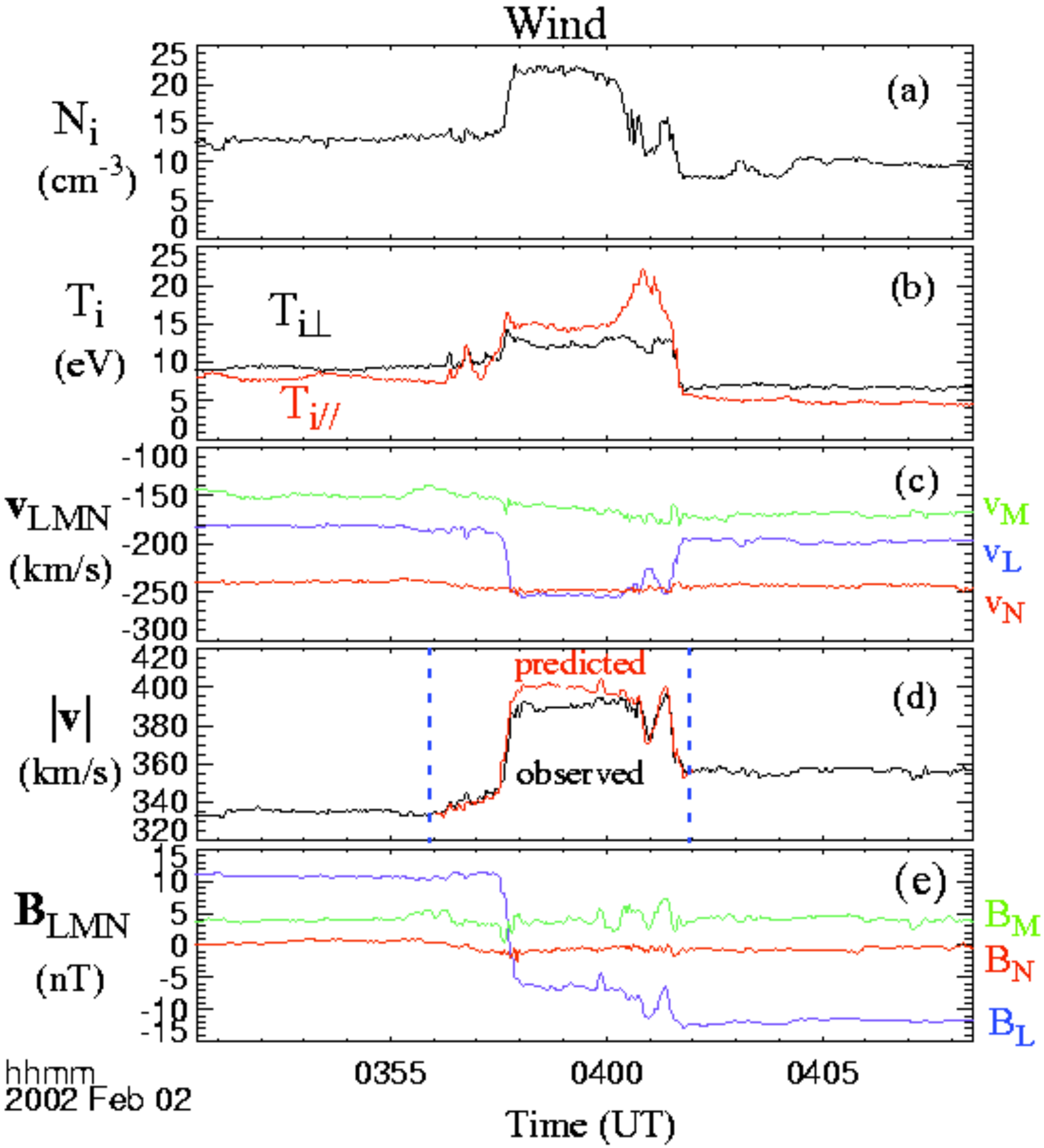
# Overview 2002-02-02 Event




(Phan et al., Nature 2006)

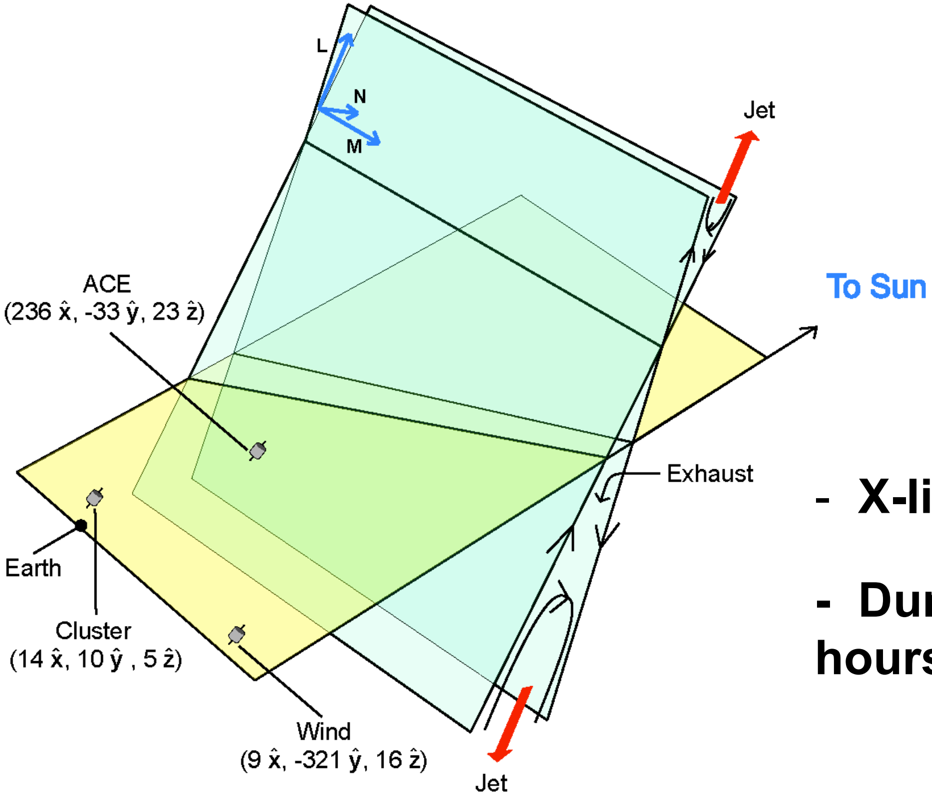
# The 2002-02-02 Reconnection Event at Wind




Flow speed change agreed with Walen condition.

Change in normal speed ~5 km/s. Implies $V_{an}$ ~ 2.5 km/s and low reconnection rate.

# Geometry of 2002-02-02 Event



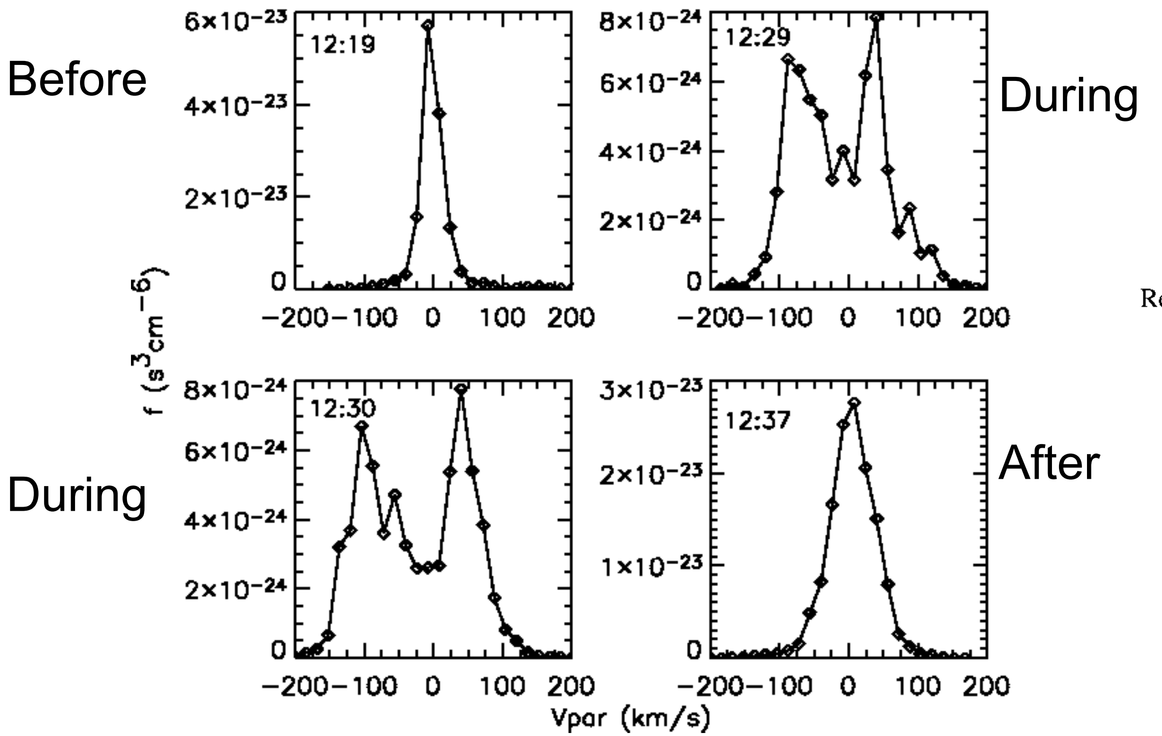

- **X-line Extent: At least 390 $R_E$**

- **Duration of Reconnection: At least 2.5 hours**

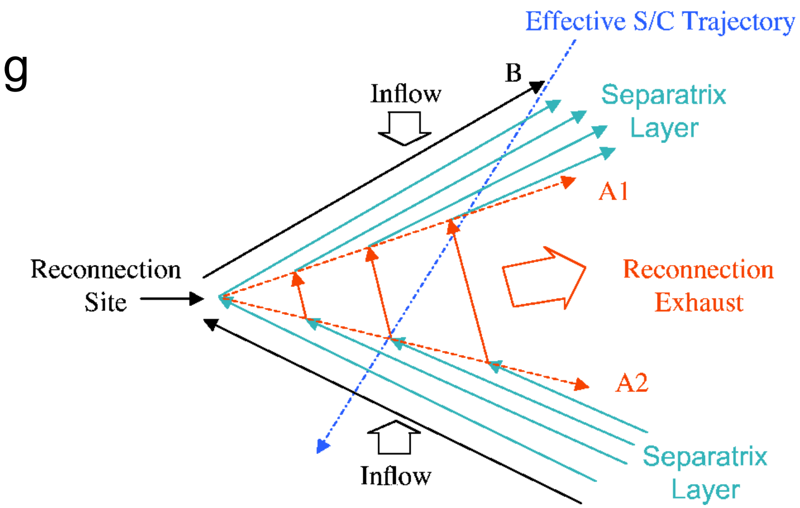
Current Sheet Normal**:** (0.71**x**, 0.60**y**, -0.37**z**) in GSE (MVAB)
Current Sheet Tilt: > $40^o$ with respect to $y_{GSE}$

# Reconnection Signatures: Interpenetrating Ion Beams

Solar Wind Frame




11/23/1997




(Gosling et al., 2005a)

The End