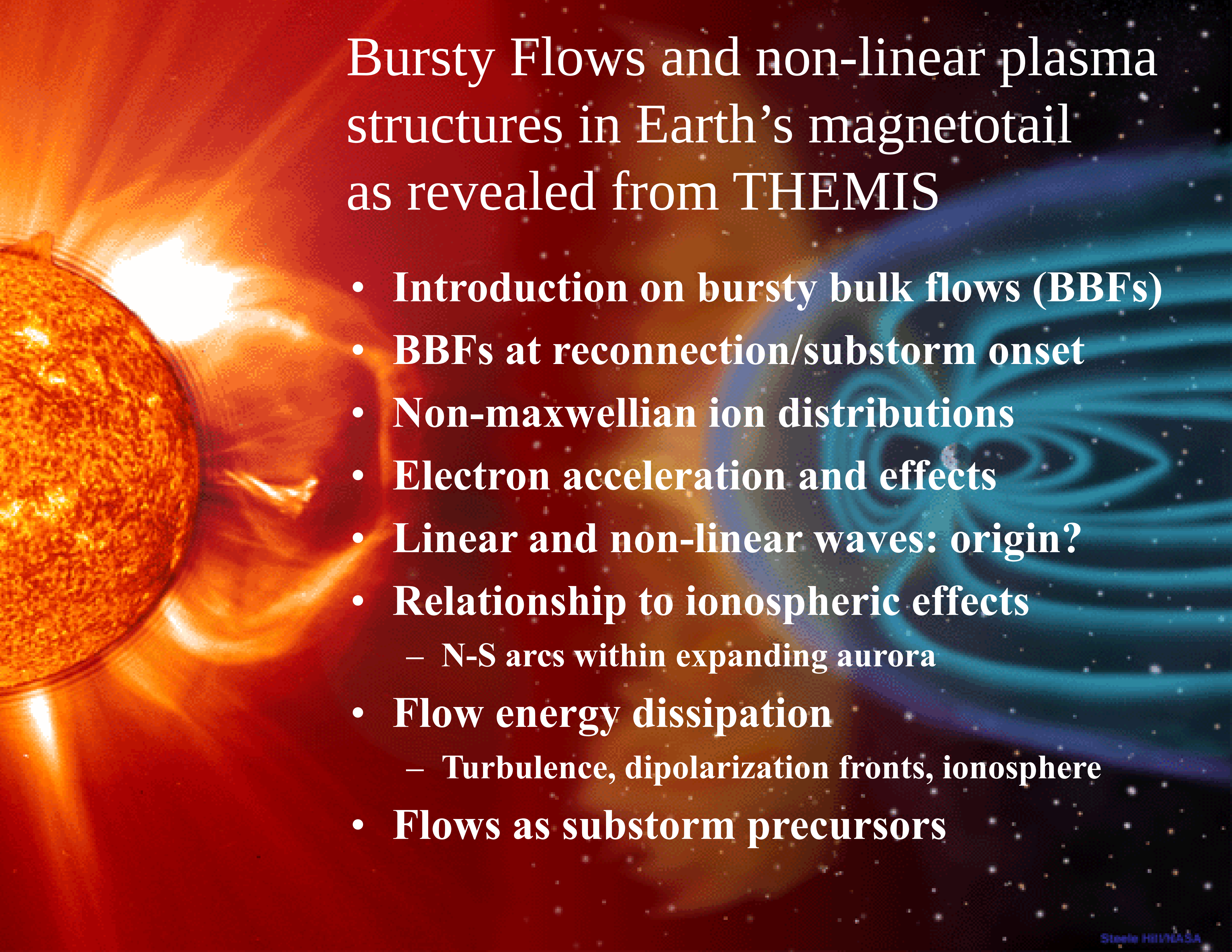


Bursty Flows and non-linear plasma structures in Earth's magnetotail as revealed from THEMIS

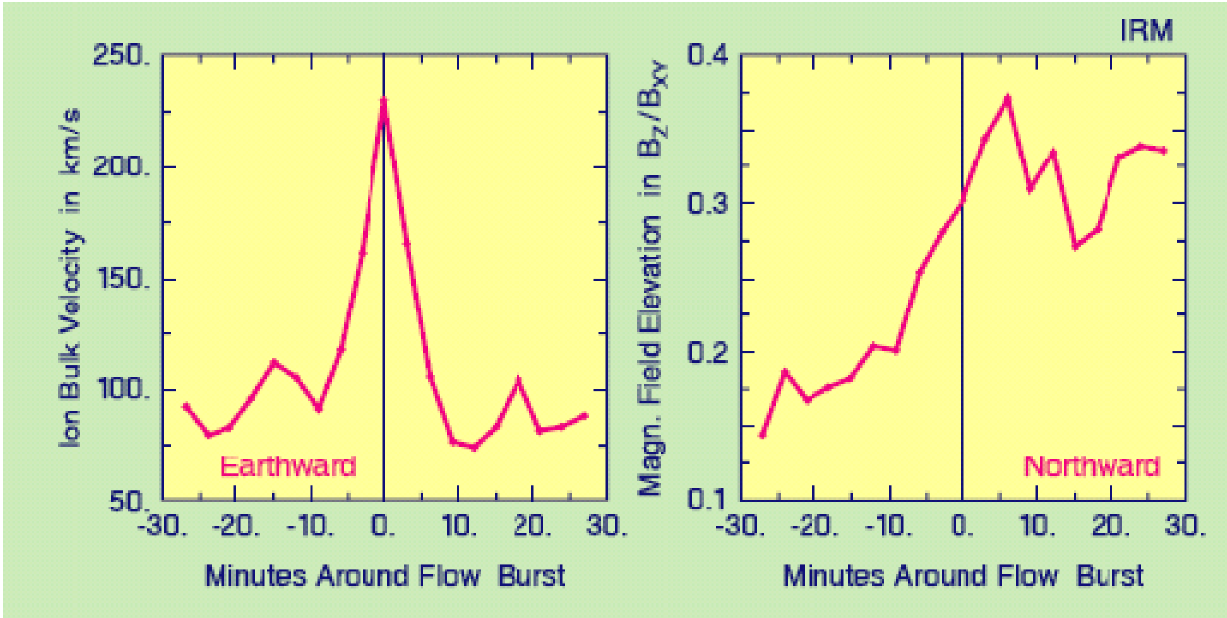
- **Introduction on bursty bulk flows (BBFs)**
- **BBFs at reconnection/substorm onset**
- **Non-maxwellian ion distributions**
- **Electron acceleration and effects**
- **Linear and non-linear waves: origin?**
- **Relationship to ionospheric effects**
  - **N-S arcs within expanding aurora**
- **Flow energy dissipation**
  - **Turbulence, dipolarization fronts, ionosphere**
- **Flows as substorm precursors**

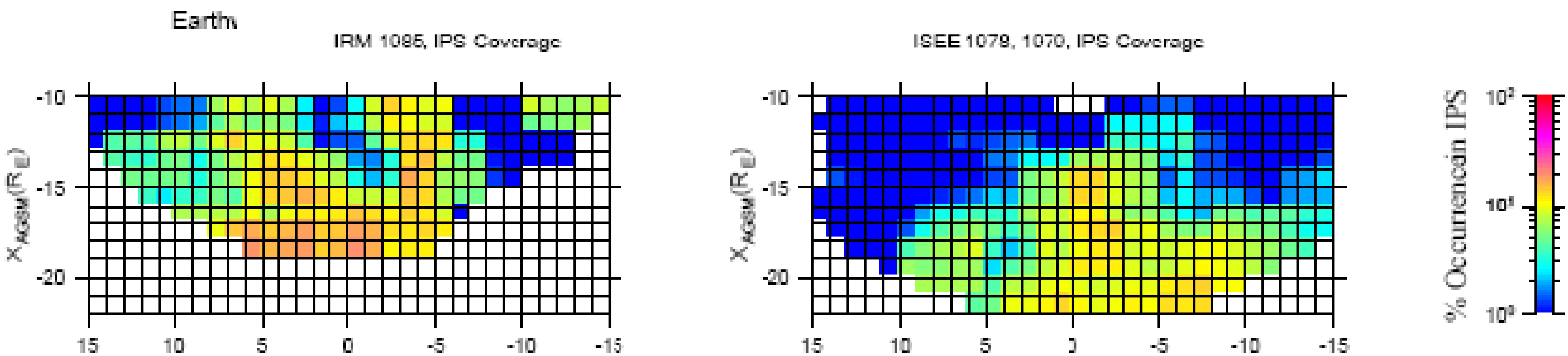
Early Observations

Baumjohann et al., 1990
Fast Vperp flow samples are rare and bursty

Angelopoulos et al., 1992
Coherence time ~ few min
Dipolarization, Low density, High Temperature, P~const.

Angelopoulos et al., 1994
Flow burst occurrence rate increases with distance.

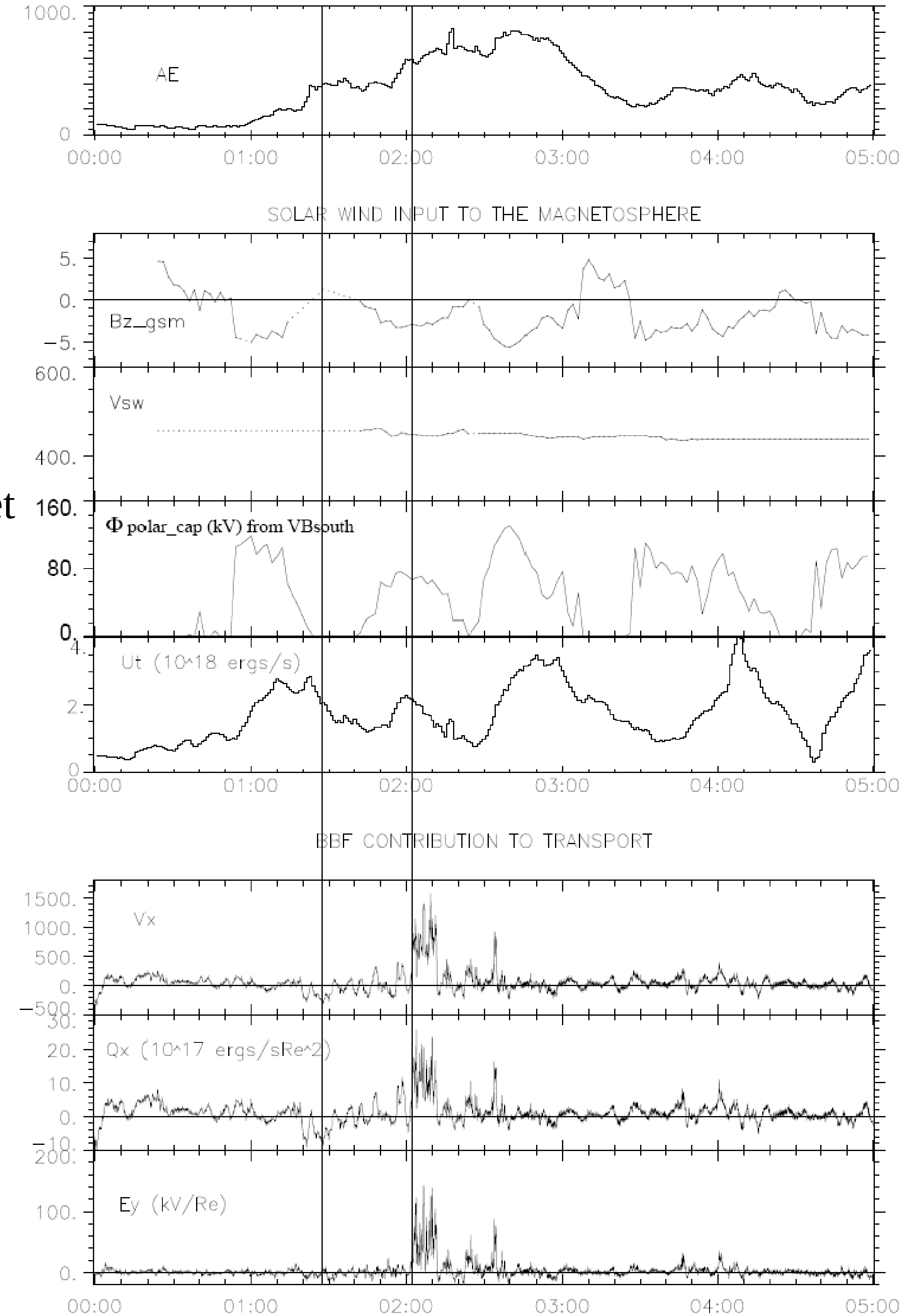




Early Observations: duration, scale properties

Angelopoulos et al., JGR 1995

- BBFs are 10min intervals of flow that encompass flow bursts
- Selection intends to pick near-neutral sheet events and near-perpendicular transport
- BBFs are important part of substorms, as they correlate with AE, though 1-to-1 correlation is more difficult to establish
- Can account for instantaneous transport rate if only $2R_E$ in width
- Need several to account for integrated substorm flux circulation
    - Spatially limited due to gradients
    - Temporally limited due to dissipation
        - Cross-scale coupling?
        - Ionospheric coupling?

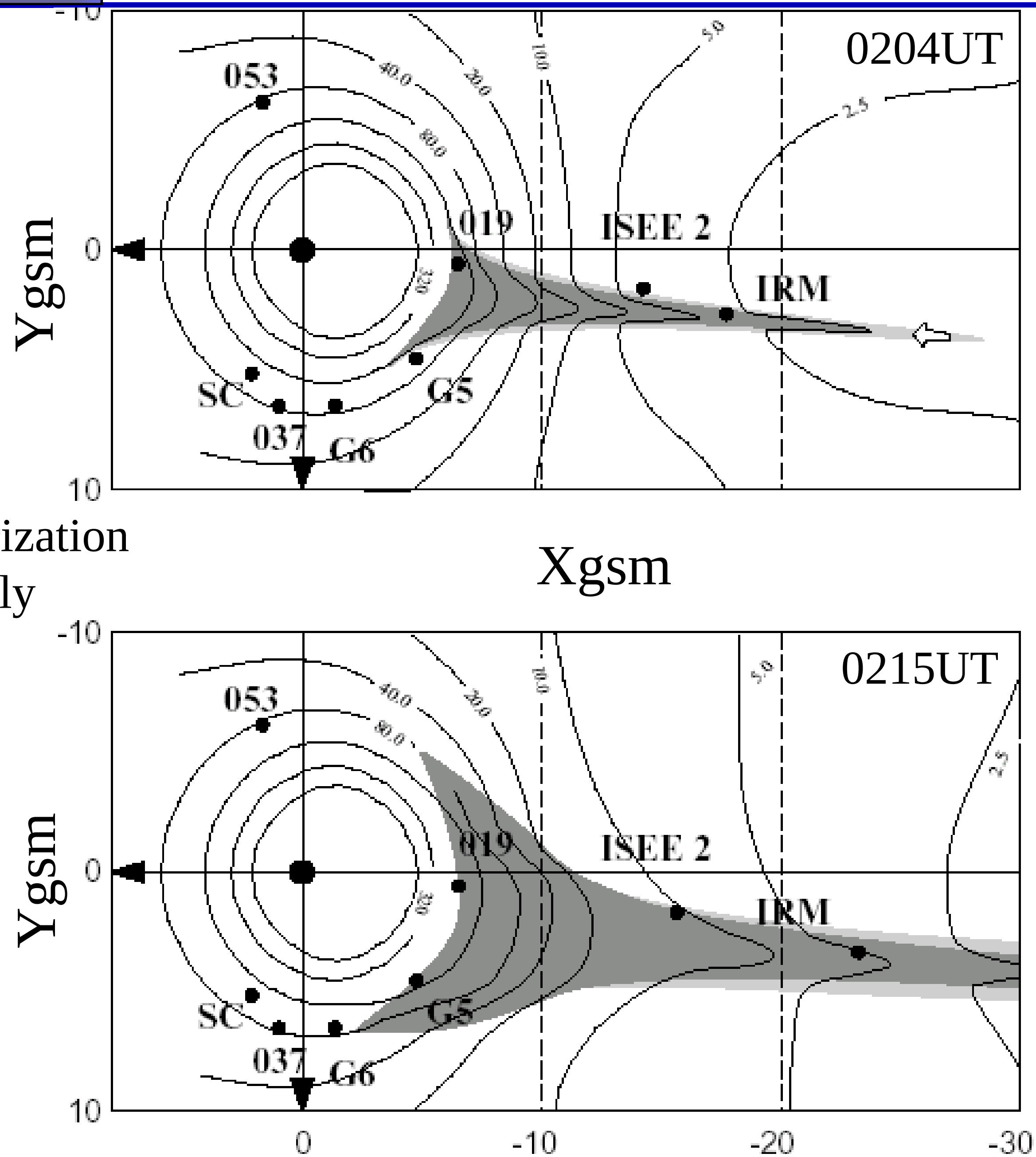


3D nature and relationship to substorm onset

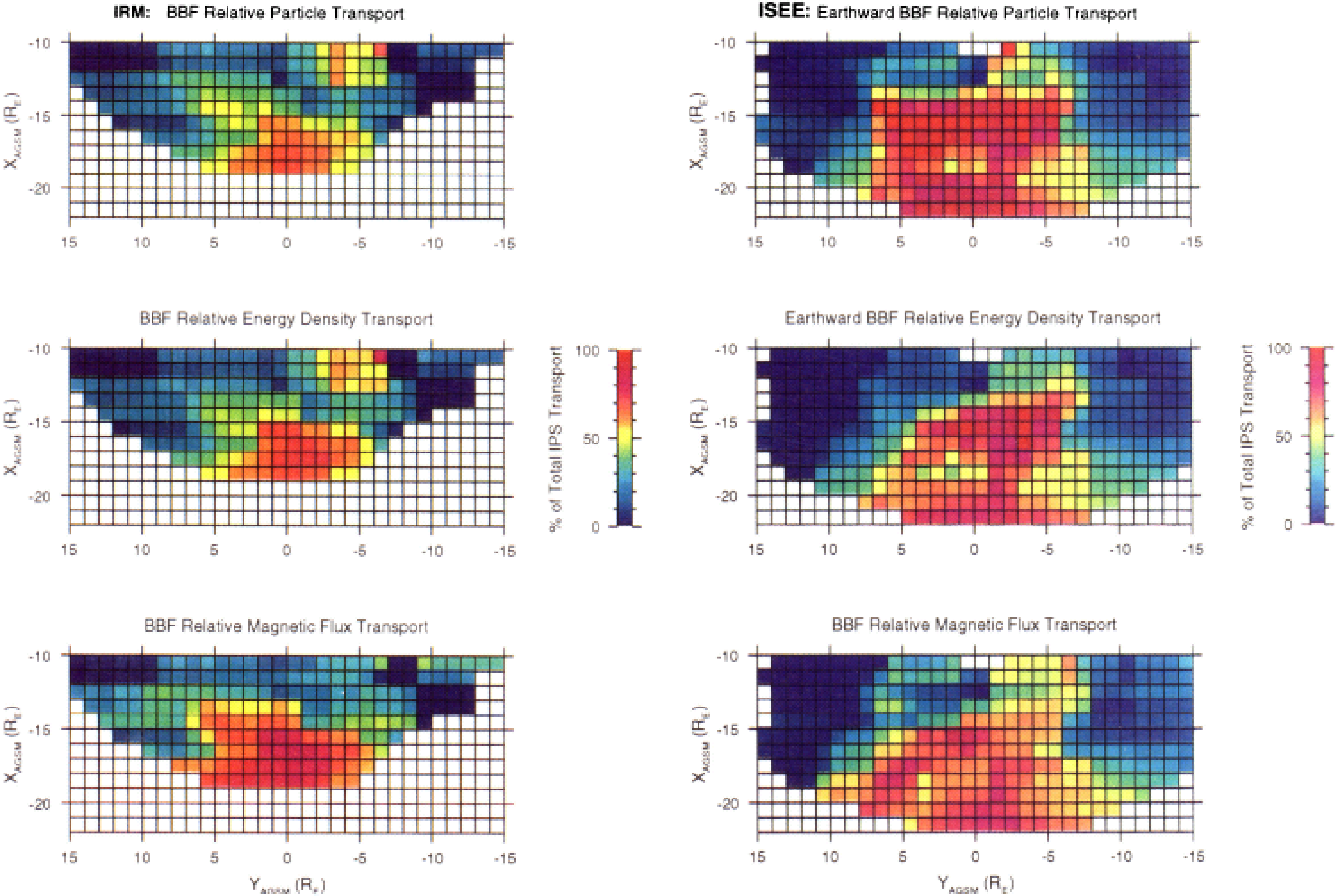
Substorm Onset: ~0202UT
In line with BBF onset

BBF lasts 10min because flow region is a shell enveloping dipolarization.

Both flow shell and dipolarization expand latterally and radially



Importance for Transport

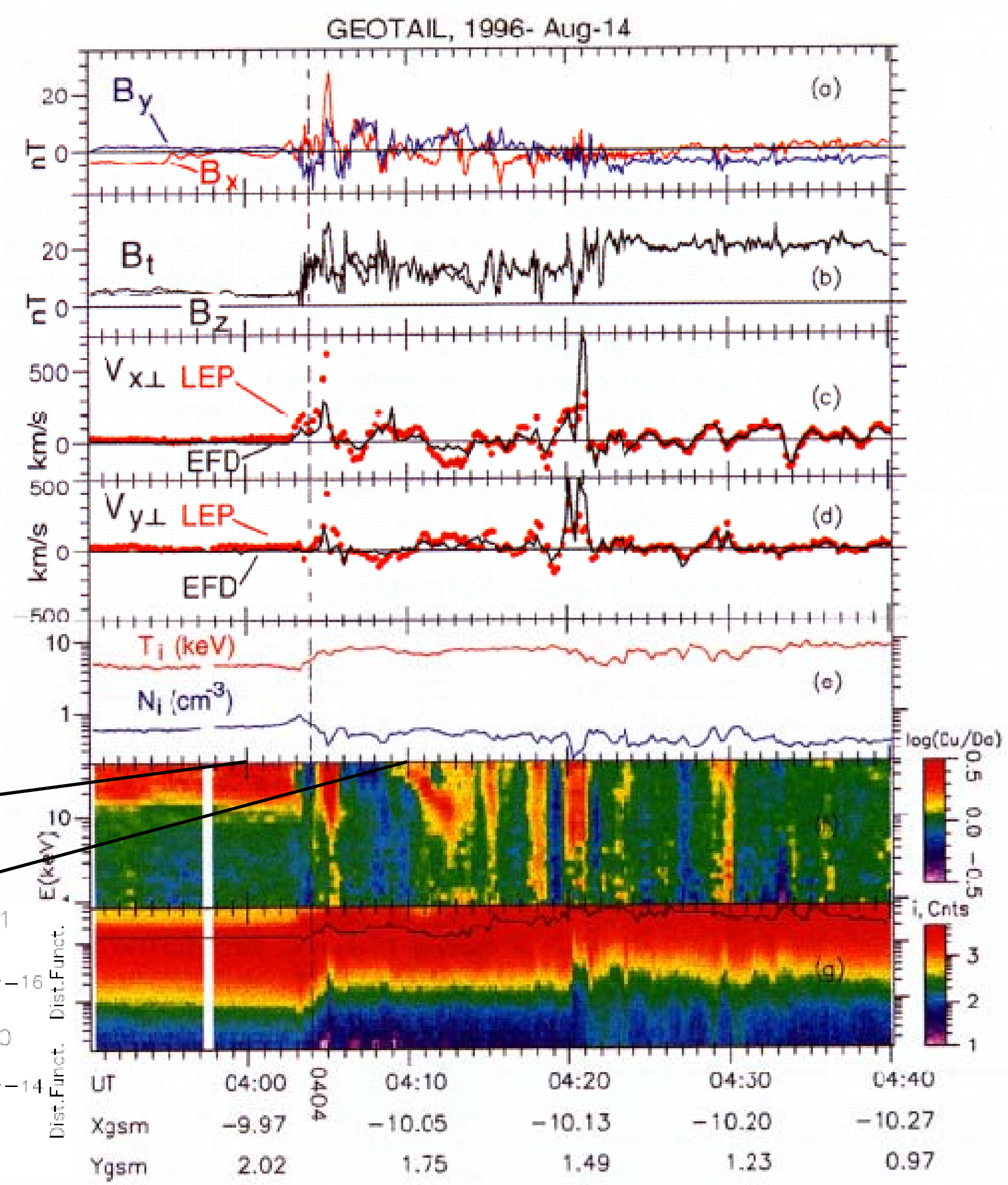


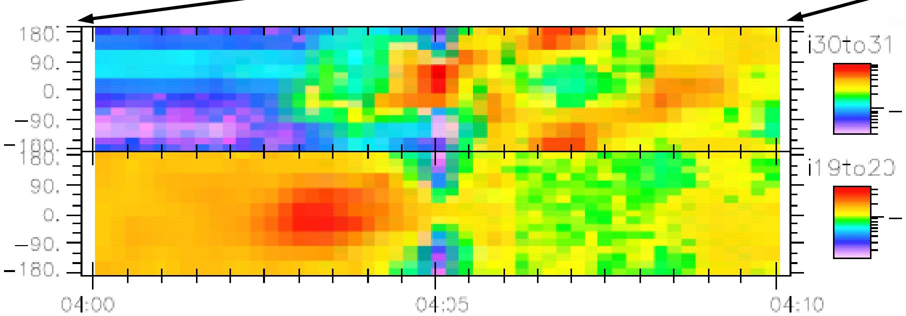
Near-Earth BBFs resemble current disruption, but move Earthward

Angelopoulos et al., GRL 1999

Earthward flows at $10R_E$ during a *small substorm* agree with (dawnward) gradient anisotropy. Dipolarization is moving Earthward.

(Awaited full resolution/confirmation by multiple spacecraft – THEMIS)

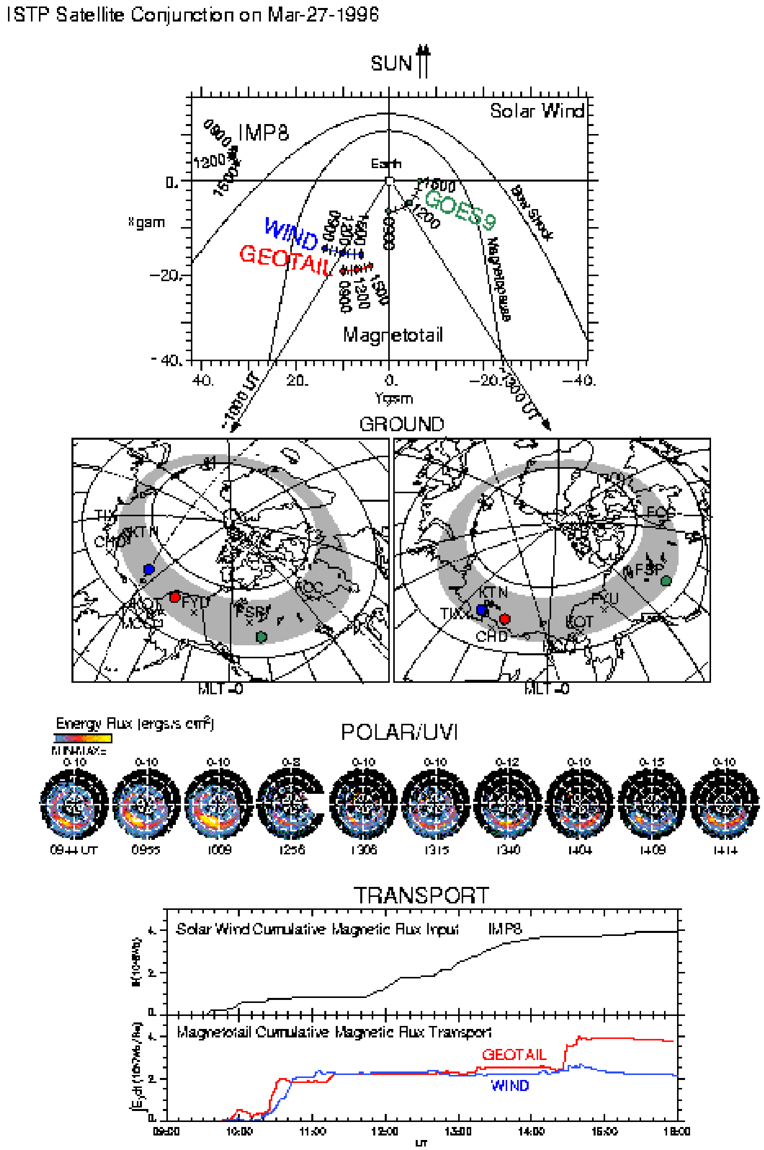




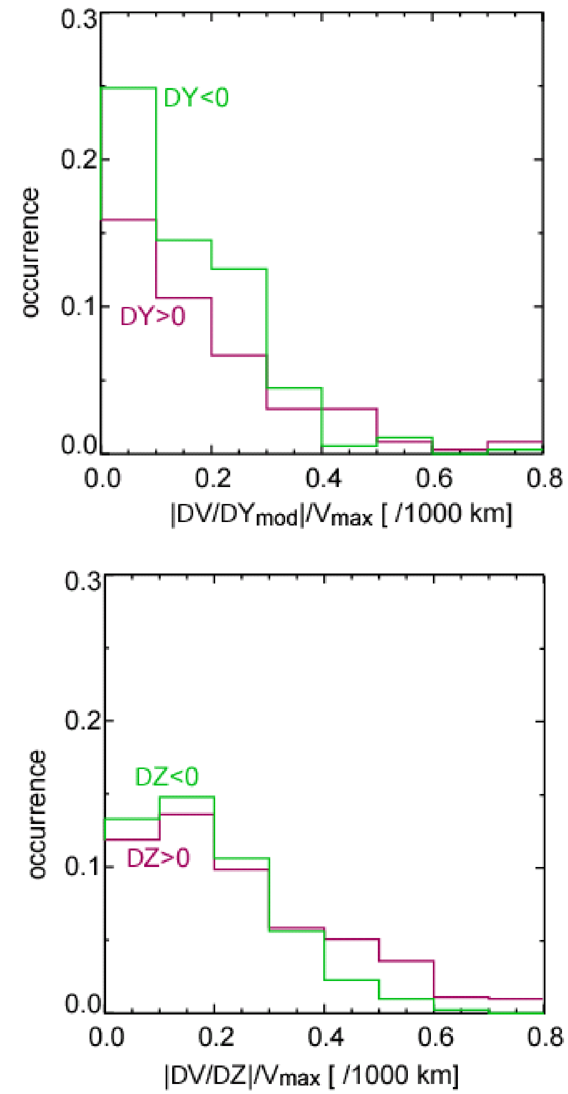
Near-Earth tail reconnection

Localization: the case for "point" reconnection

Angelopoulos et al., 1998 (Case study on localization)



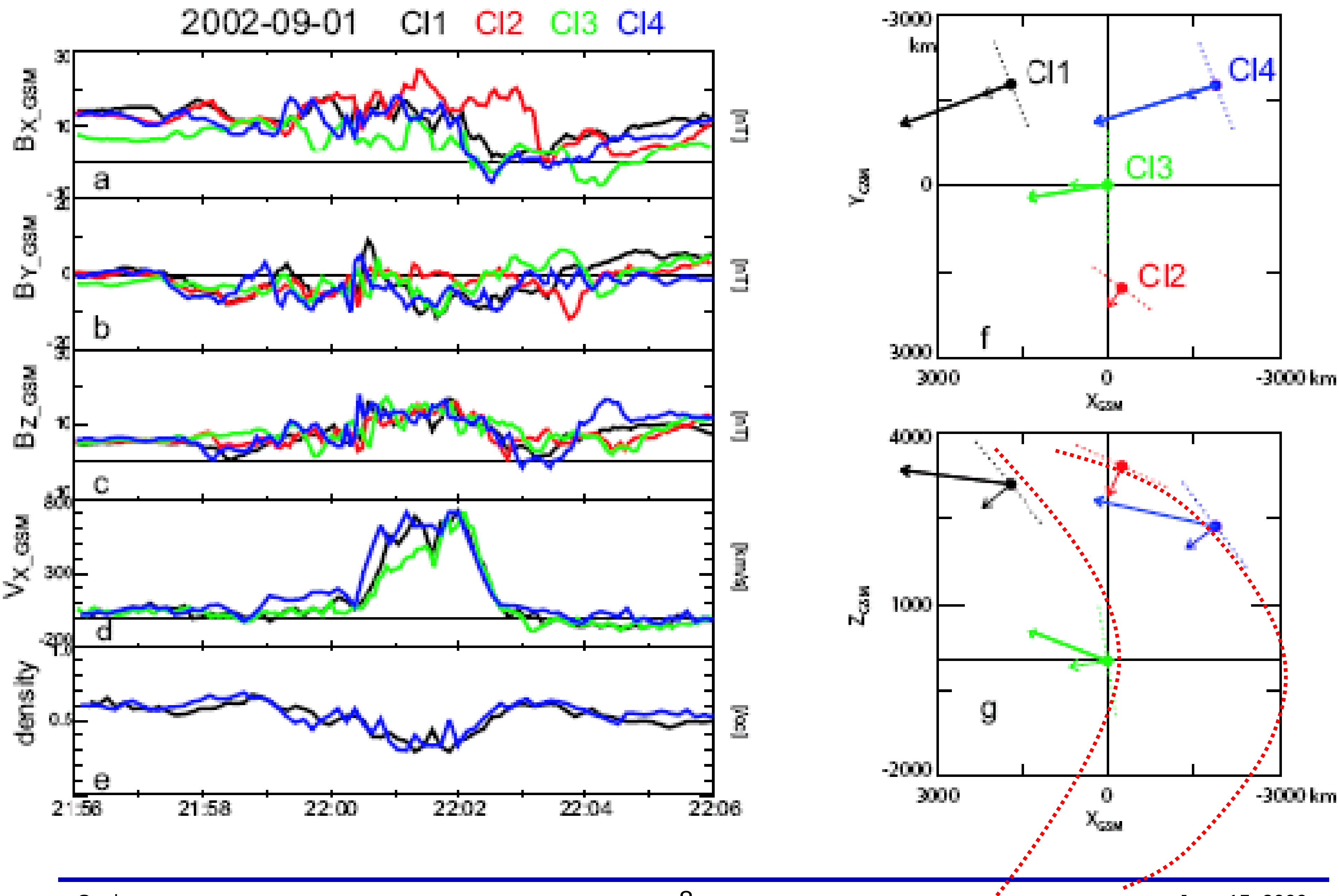
Nakamura et al., 2004 (Cluster statistics on localization)



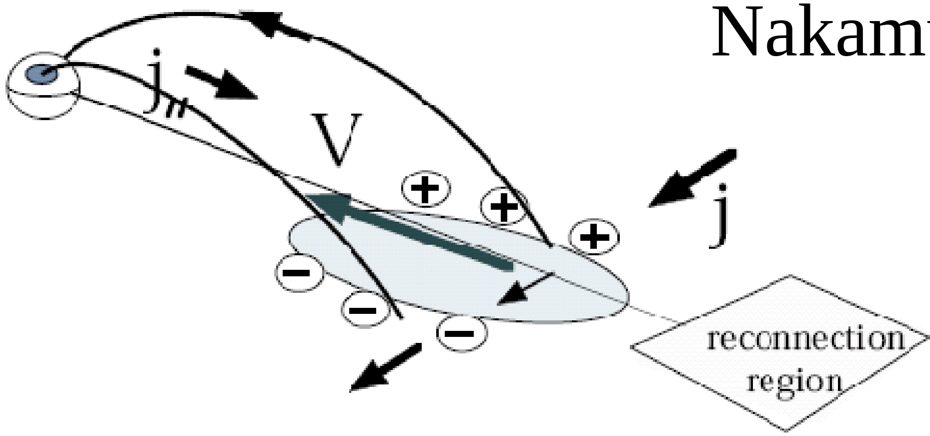
Scales: Vertical: 1.5-2 R_{E}, Azimuthal: 2-3 R_E

Sharper gradient on duskside flank

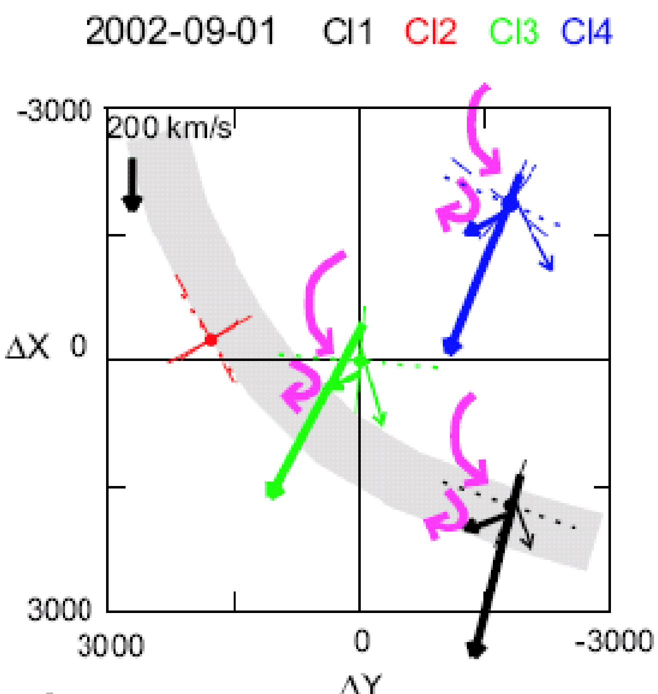
Nakamura et al., 2005



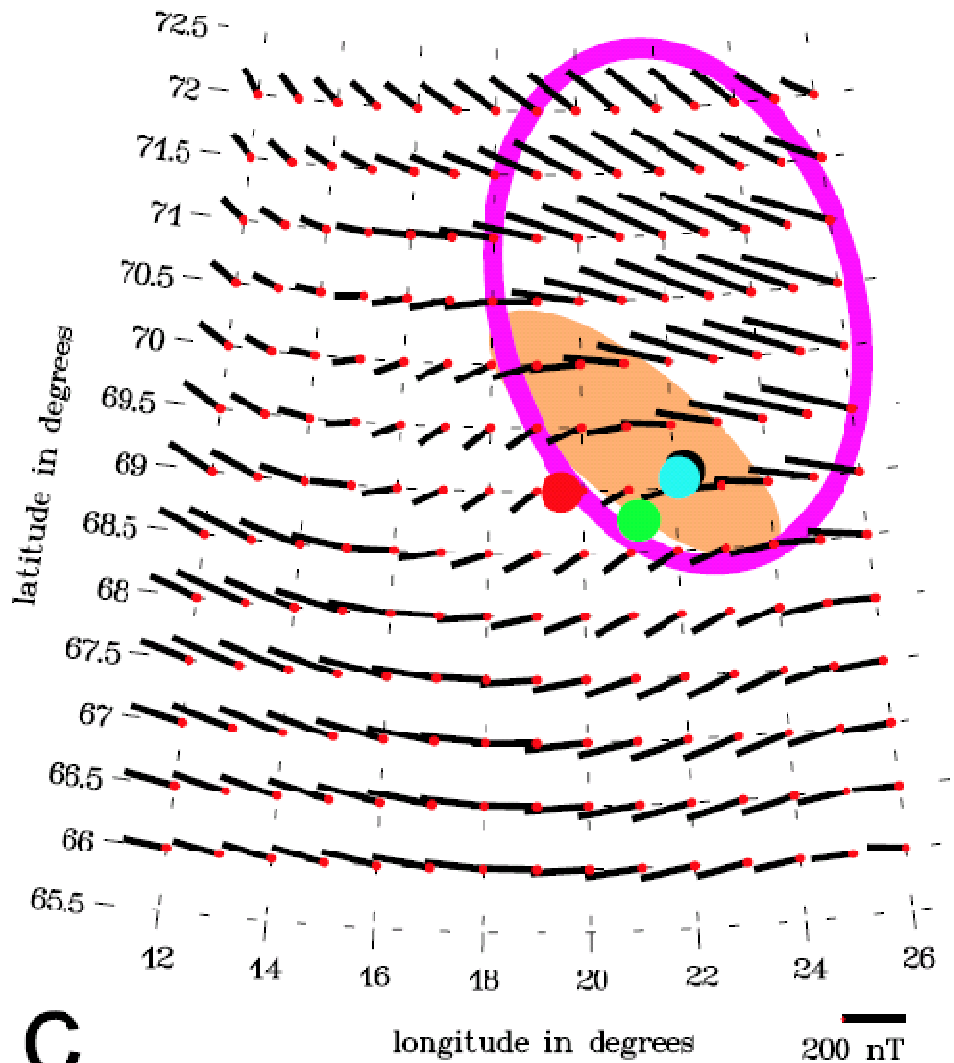
Nakamura et al 2004



a

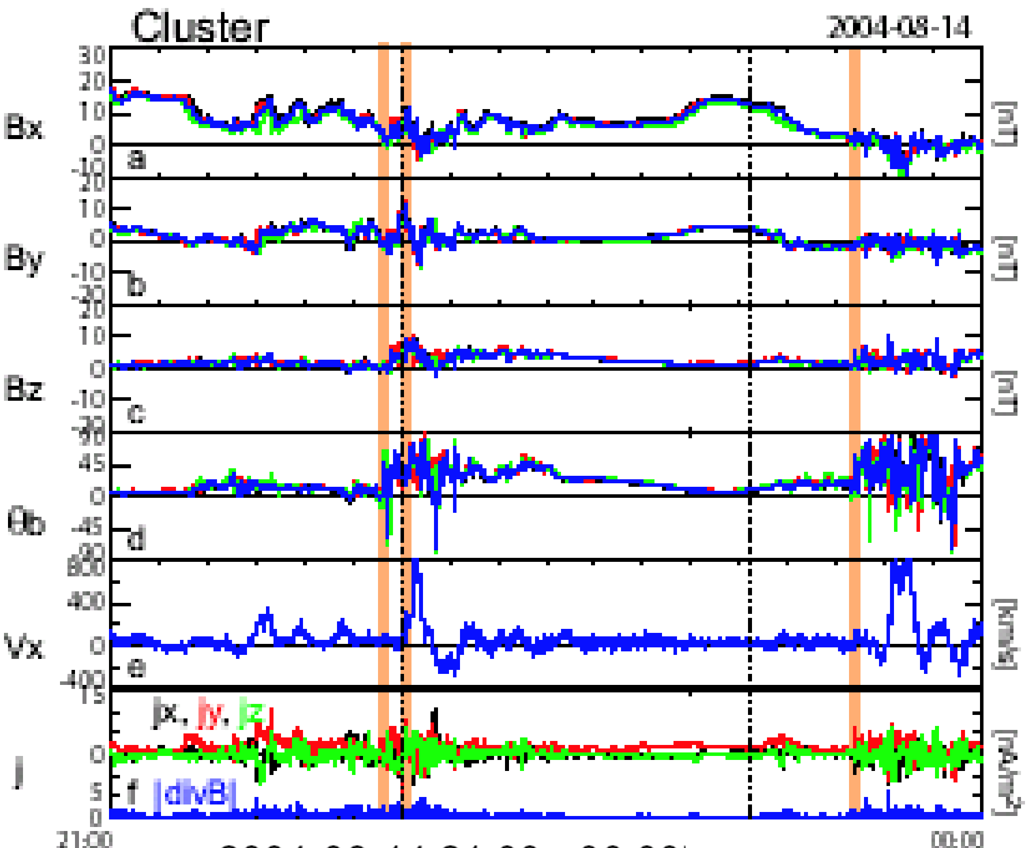


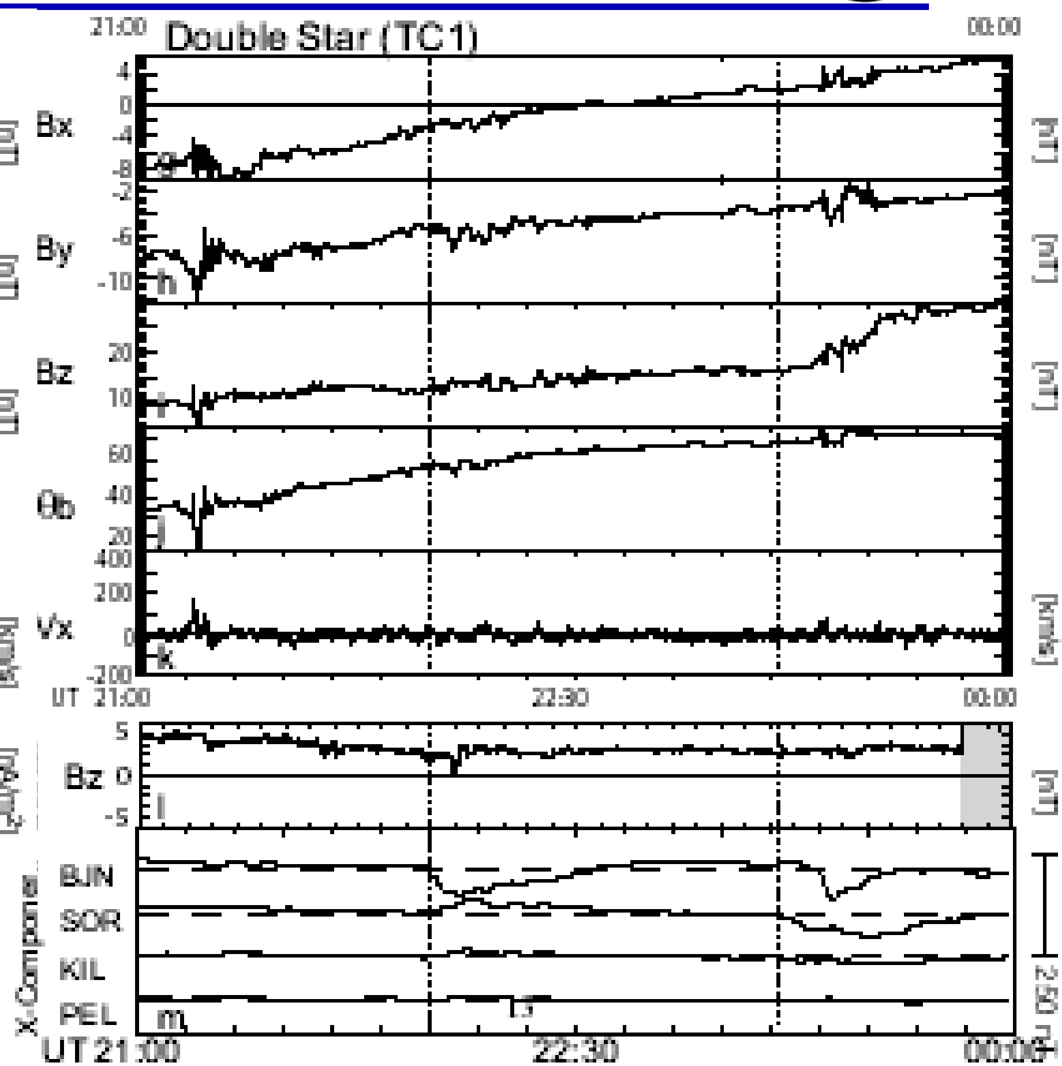
b

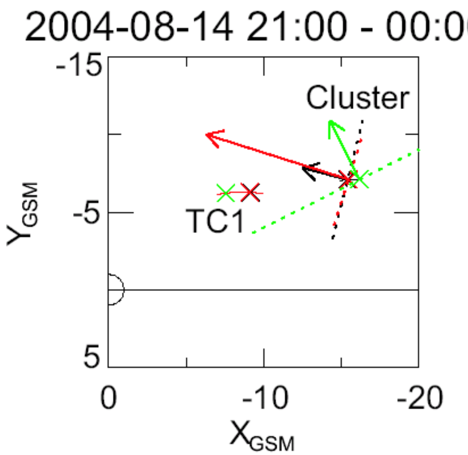


c

Nature is providing us a clue we need to follow:
Energy dissipated locally can be too fast.







Nakamura et al., 2004

Dissipation through turbulent latteral coupling?

Angelopoulos et al.,
Phys. Plasmas, 1999

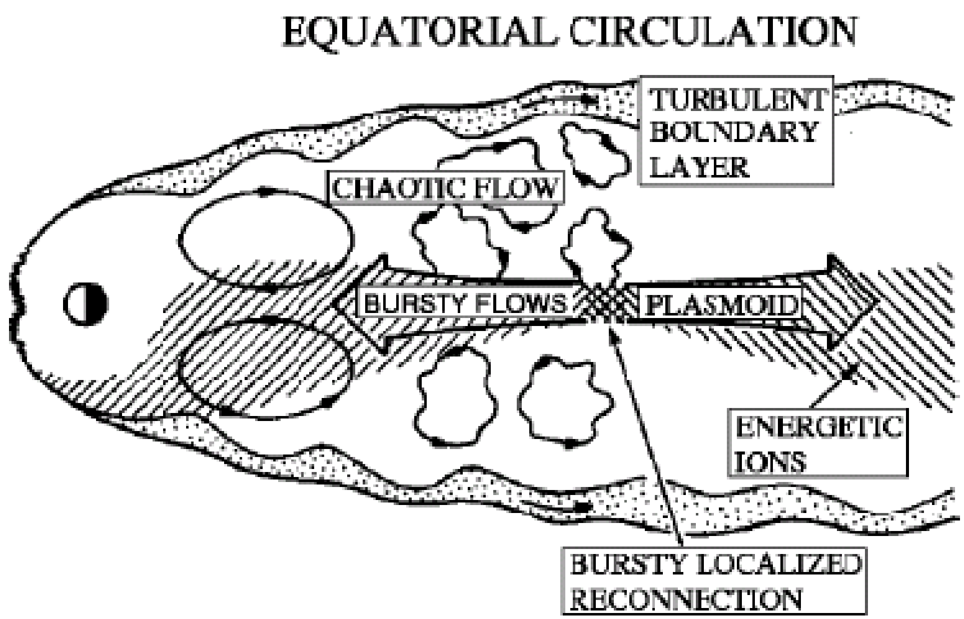
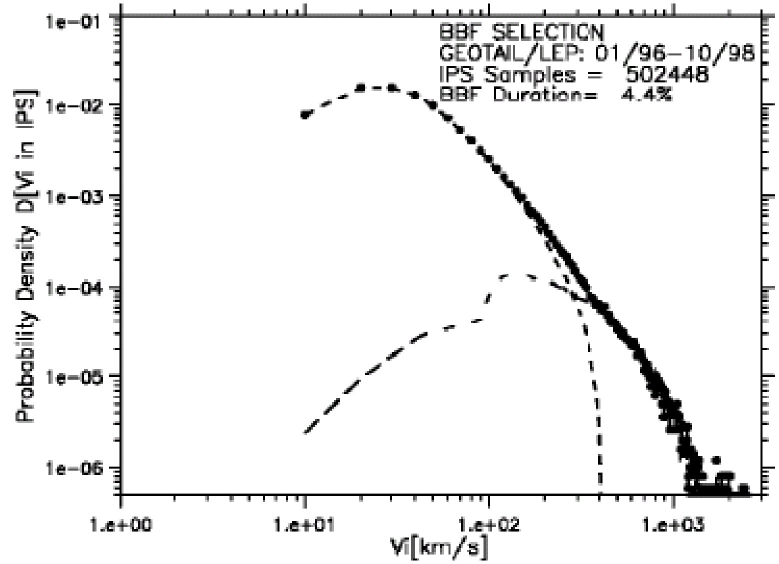
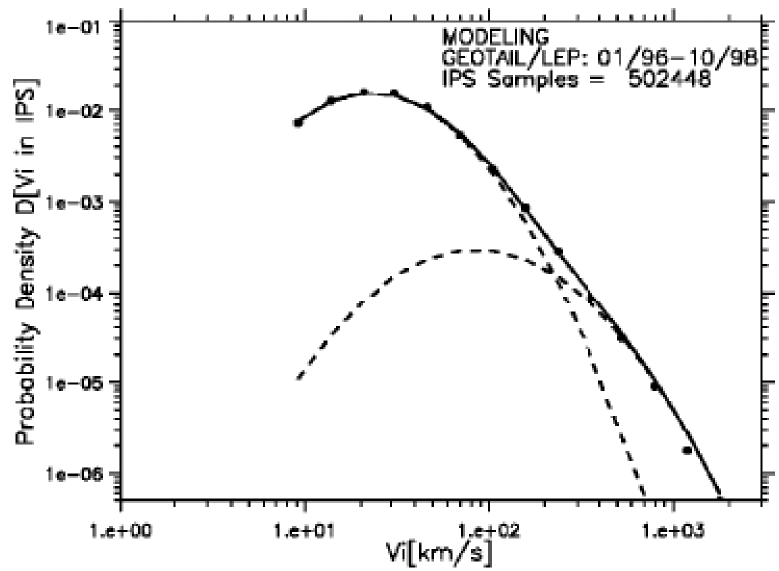


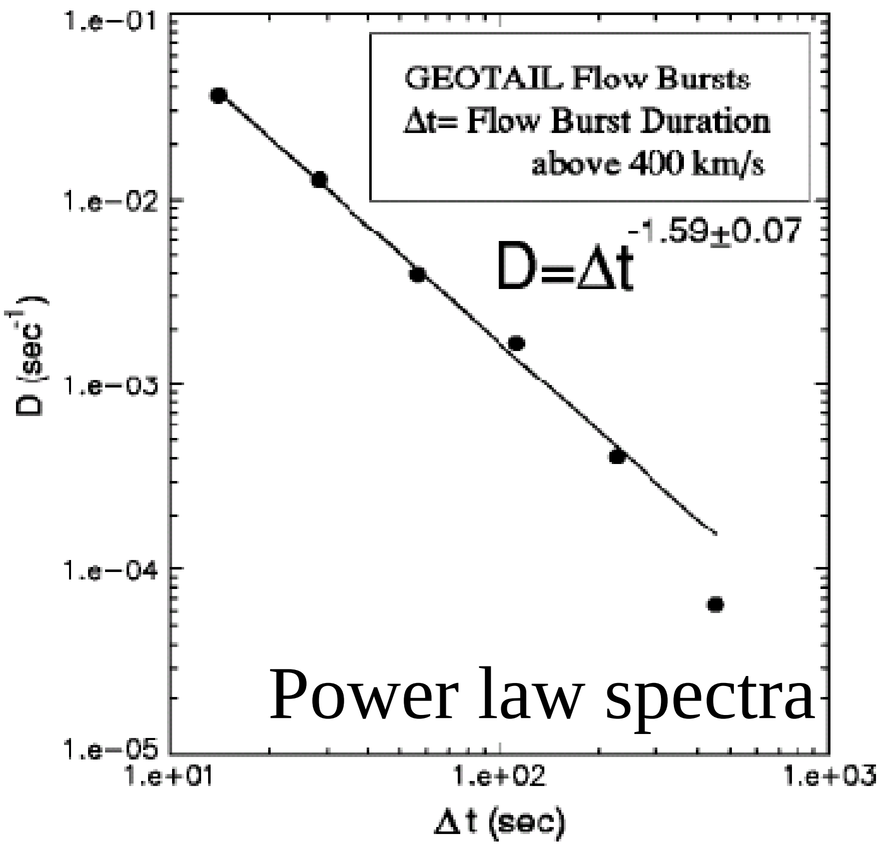
FIG. 3. Pictorial representation of magnetospheric circulation at the equatorial plane. Shown are localized bursty flows that drive vortical (turbulent) flows. [Adapted from Kennel (Ref. 10).]

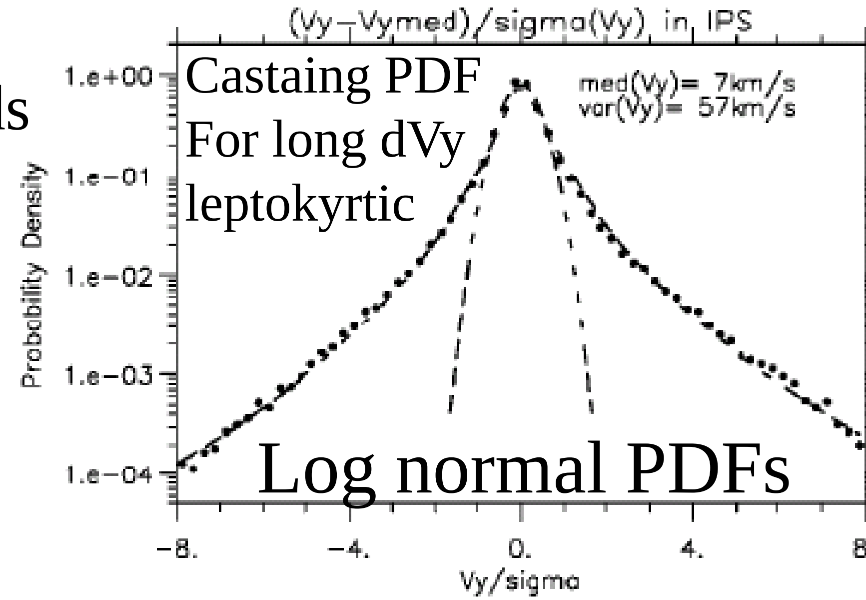


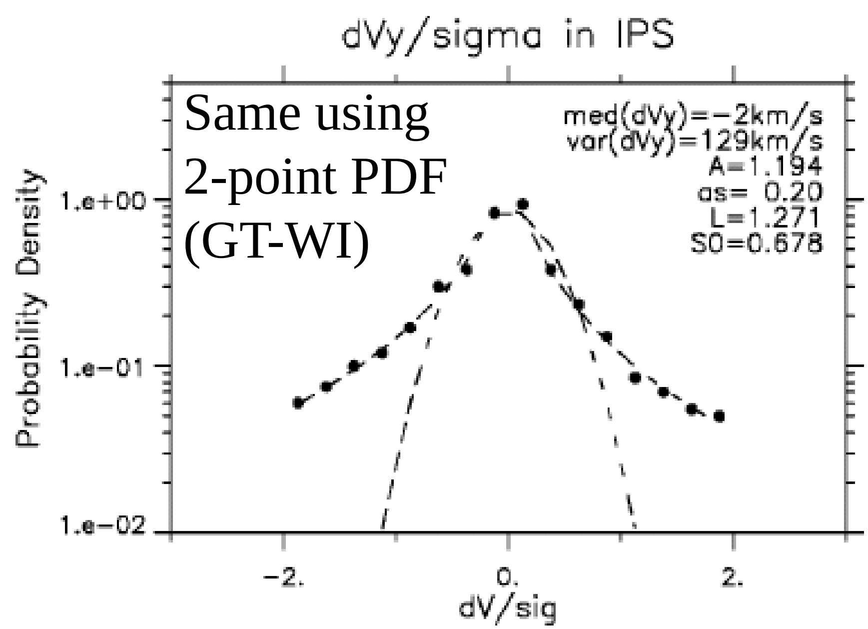


Intermittent turbulence established: effect on transport?

Angelopoulos et al., Phys. Plasmas, 1999 (intermittent turbulence) compute Reynolds numbers of fast flows using:
$\sigma=(N_i e^2/m_i)t_{scat}\sim10^6 s^{-1}$, if $t_{scat}\sim 10s\sim T_{ci}$
and $R_M=4\pi\sigma LV/c^6\sim 10\text{-}1000$







Dissipation scale of turbulence? Depends on speed…

τ_d decreases with V

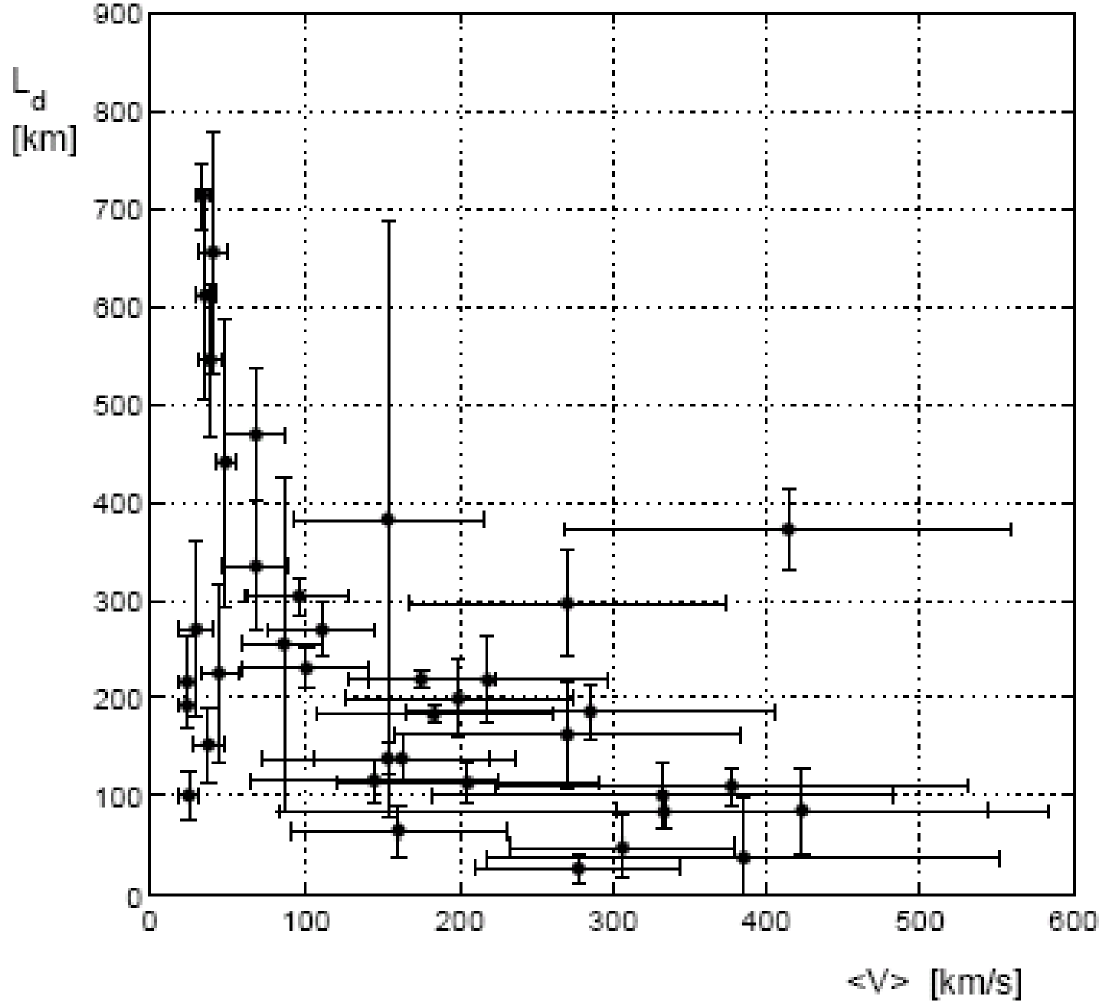
Assume $L_d \sim \langle V \rangle \tau_d$

$c/\omega_{pe} < L_d < c/\omega_{pi}$

Assuming $L \sim 2R_E$

$R \sim (L/L_d)^{4/3} \sim 1600$

Vöros, et al., 2005, 2006

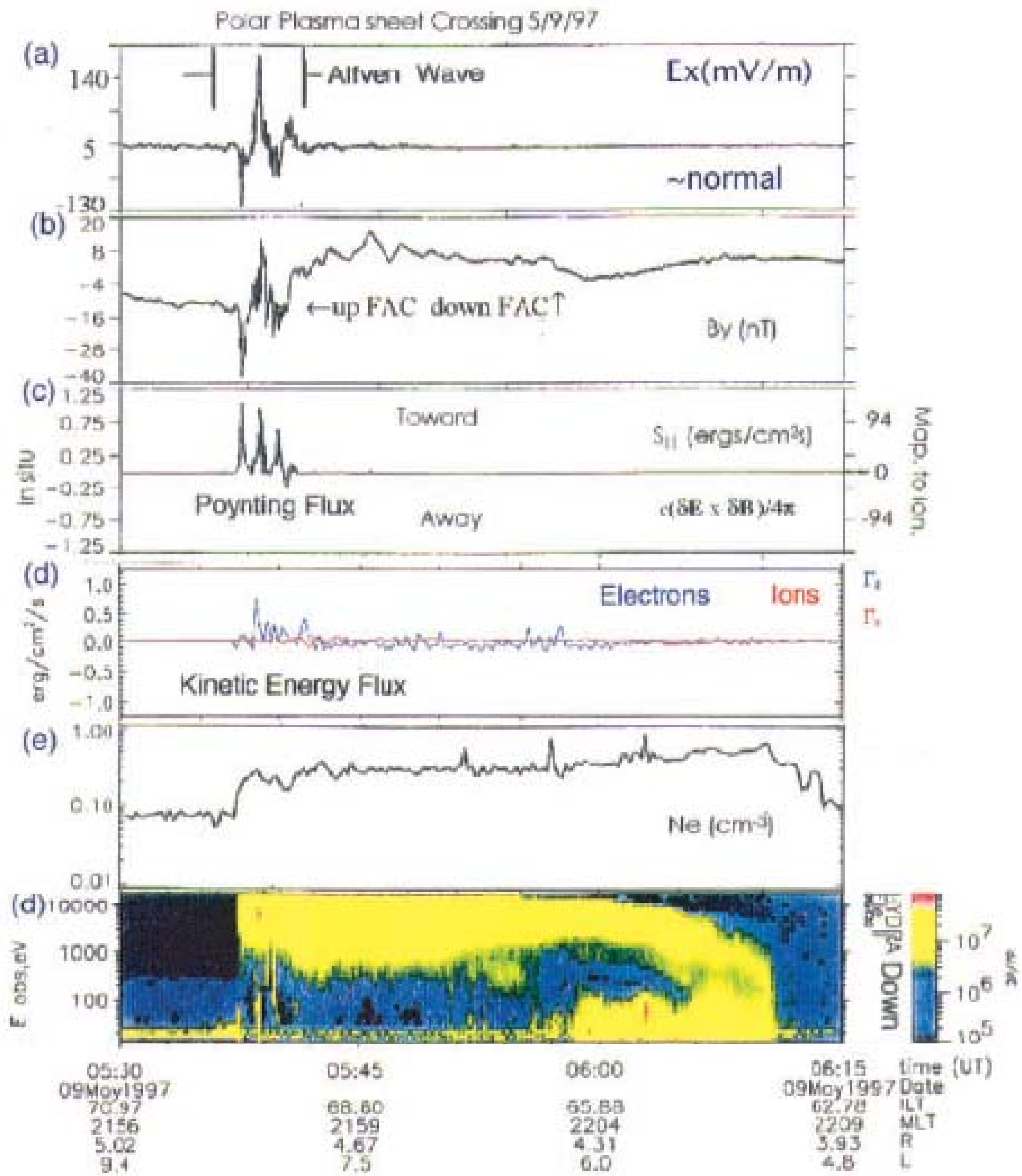


Dissipation through Alfven wave coupling?

POLAR Poynting Flux:
Keiling et al., 2000
Wygant et al., 2000

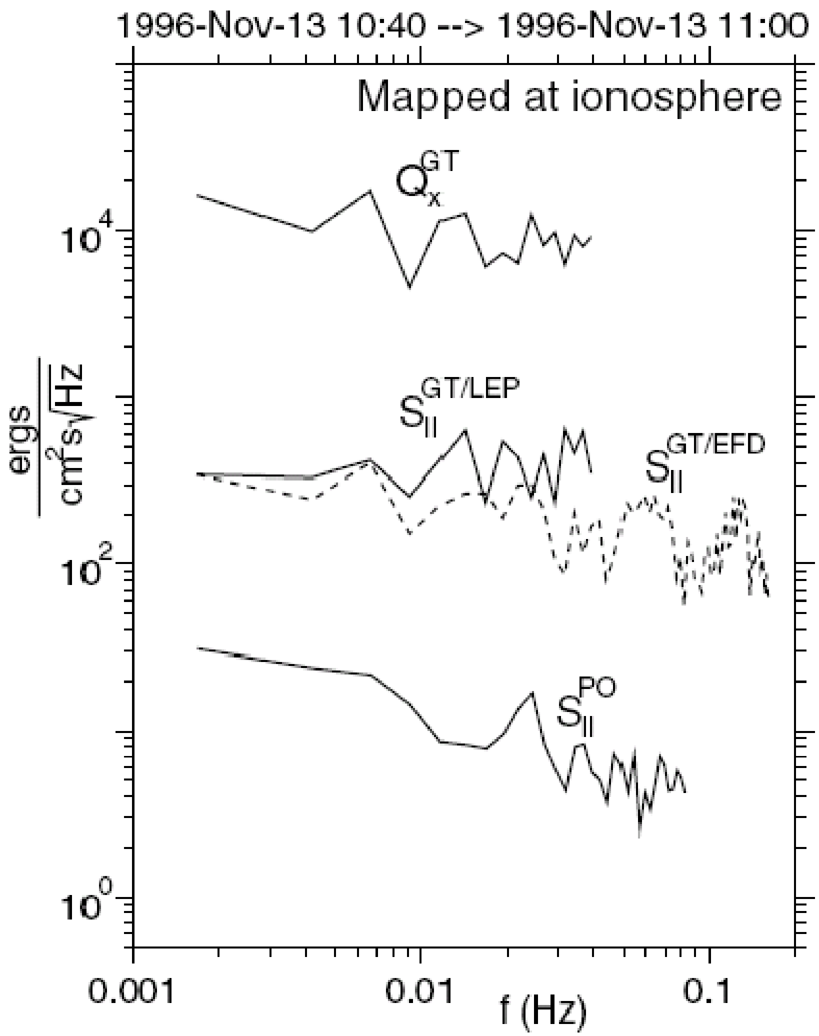
Important for ionospheric particle acceleration.

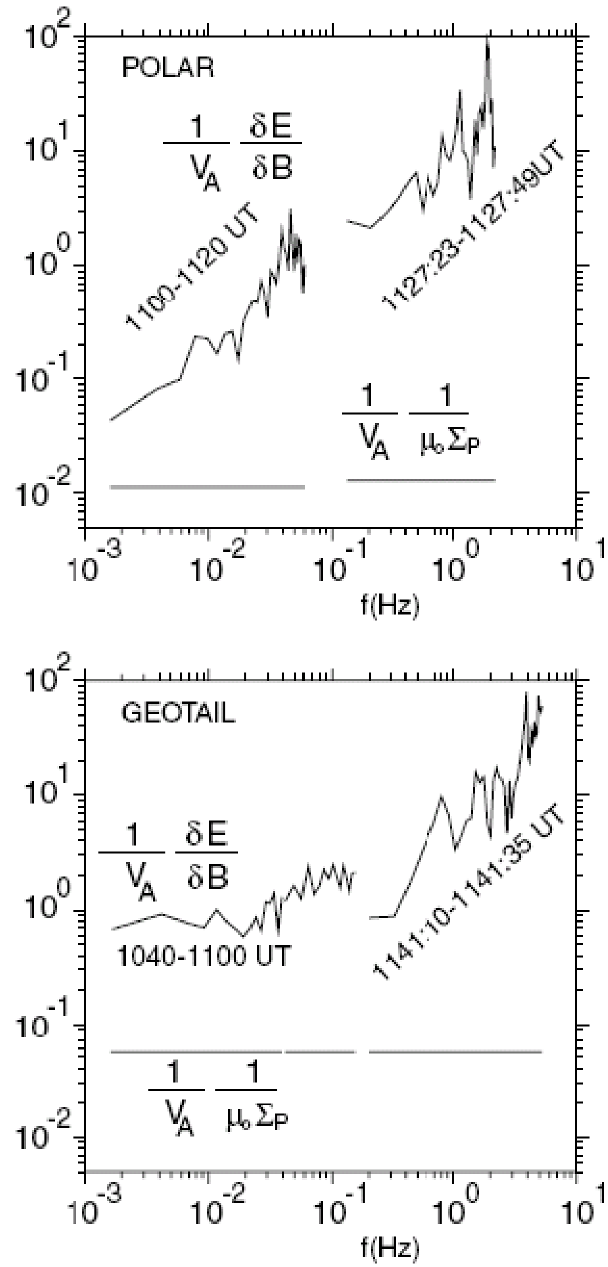
Kinetic at POLAR altitudes ($6R_E$), active-time (mostly substorm recovery), map to poleward auroral boundary.



Alfven waves: important energetically

Angelopoulos et al, 2002

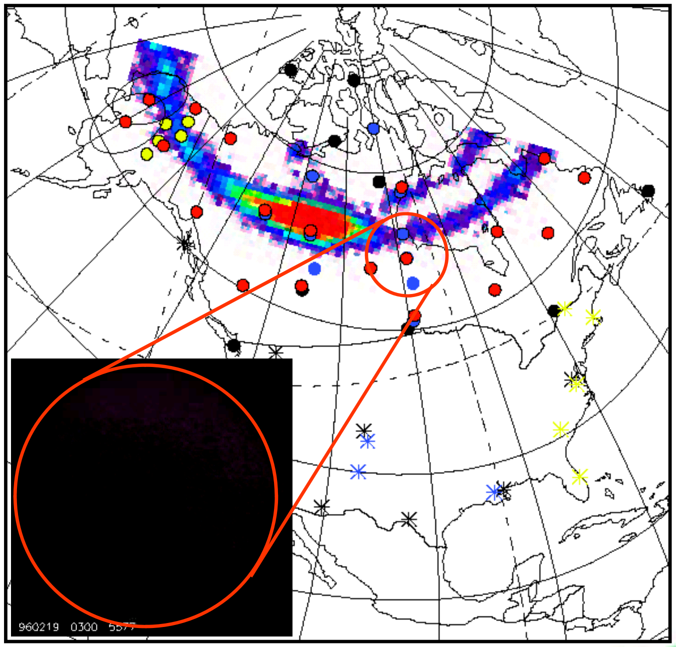




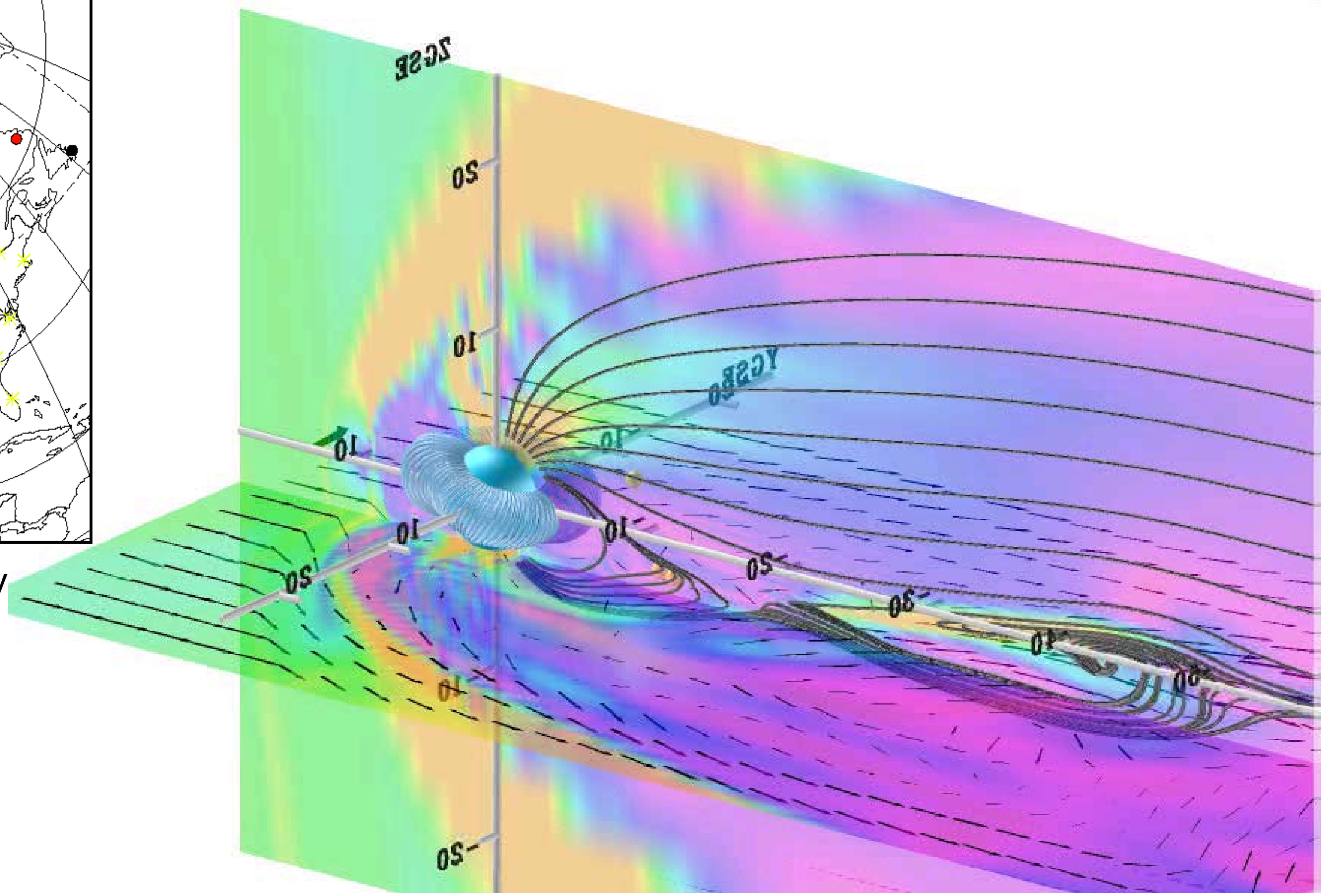
Probe conjunctions along Sun-Earth line recur once per 4 days over North America.

Ground based observatories completely cover North American sector; determine auroral breakup within 1-3s …

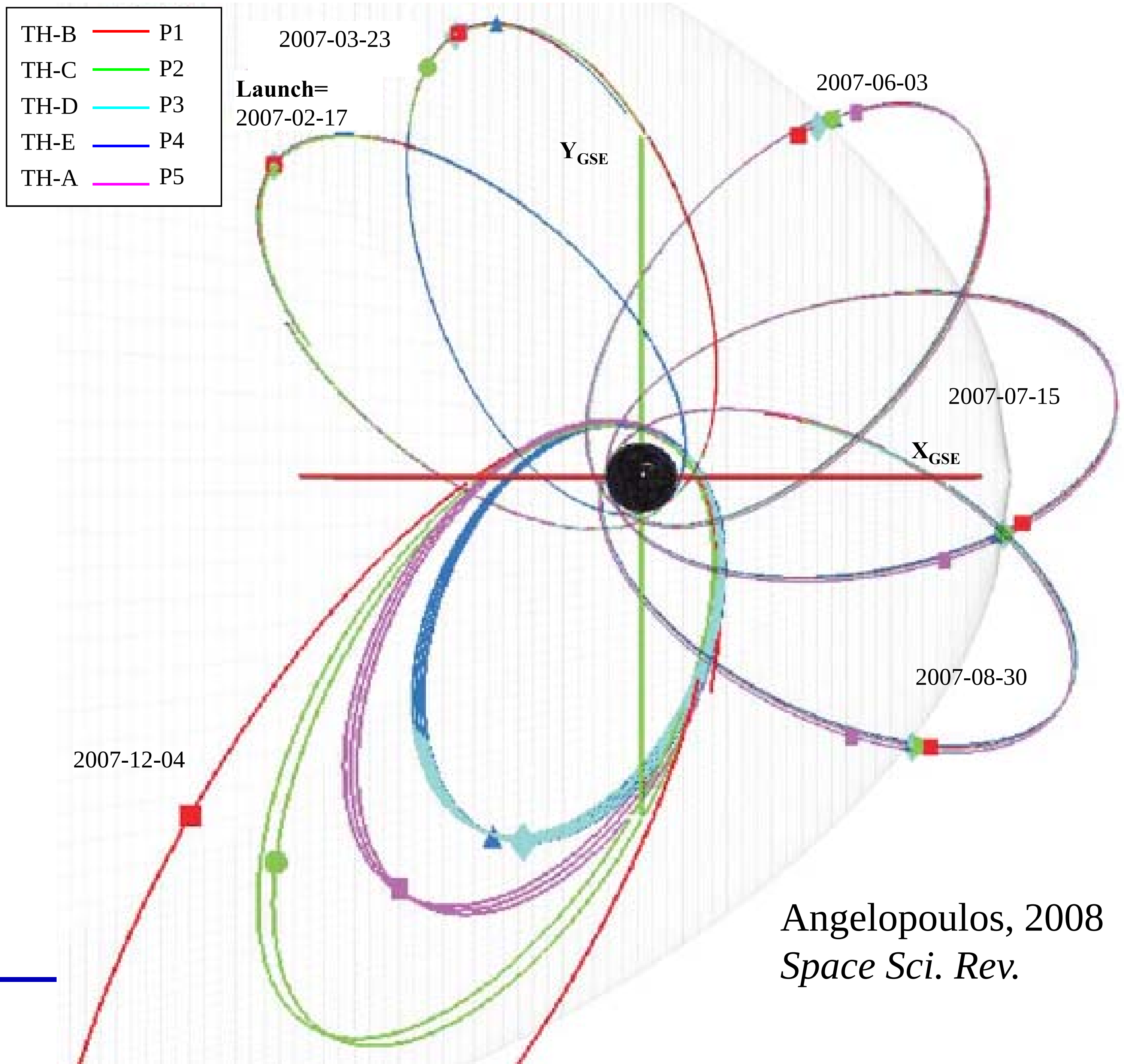
… while THEMIS's space-based probes determine onset of Current Disruption and Reconnection each within <10s.



•: Ground Based Observatory

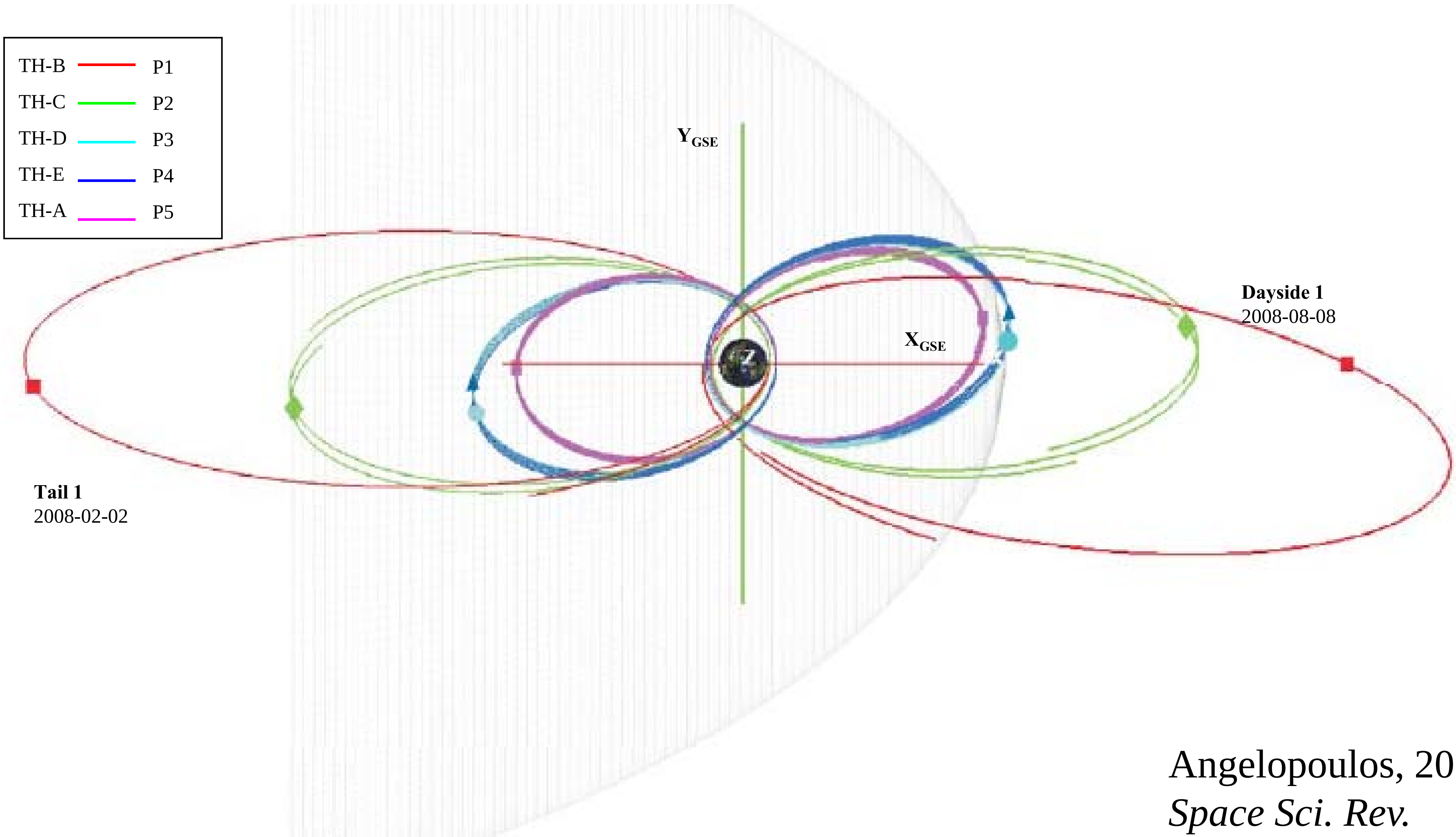


THEMIS: First 10 months



Angelopoulos, 2008
Space Sci. Rev.

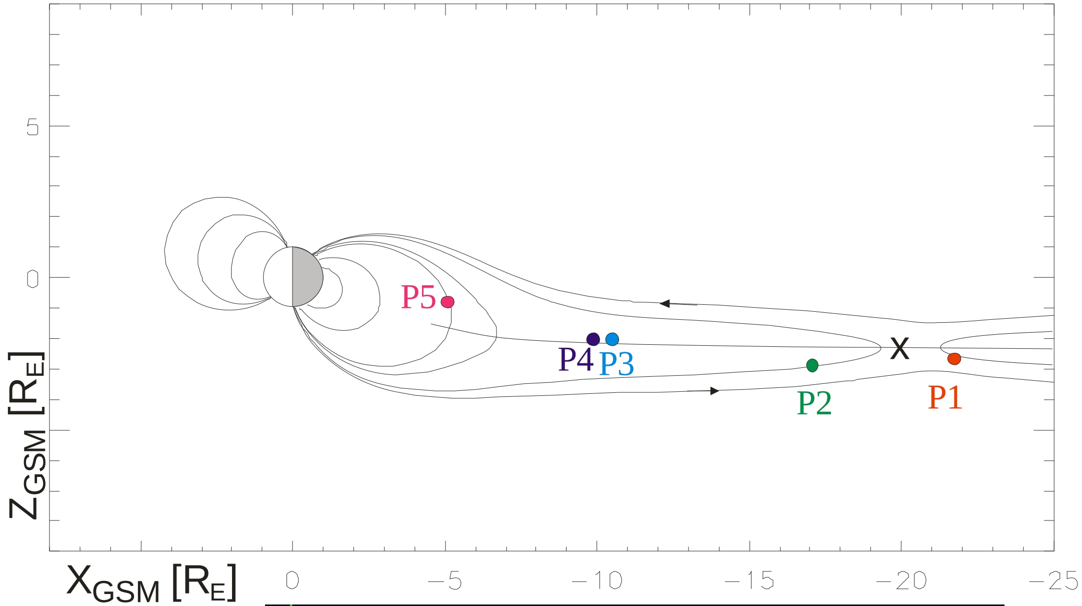
First year baseline orbit

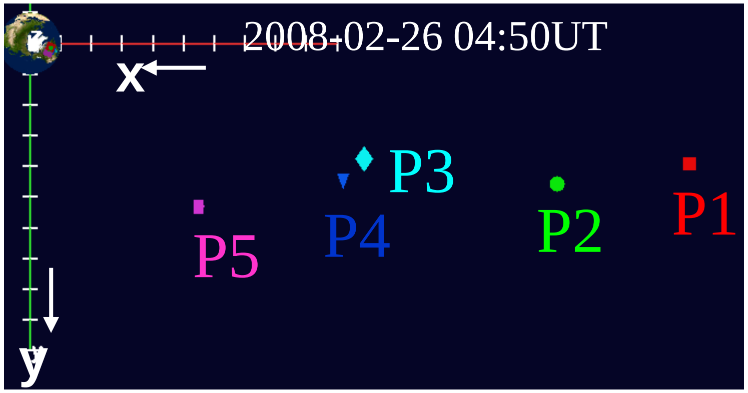


Angelopoulos, 2008
Space Sci. Rev.

Substorm study on Feb 26, 2008 (Angelopoulos et al., Science 2008)

Probe locations

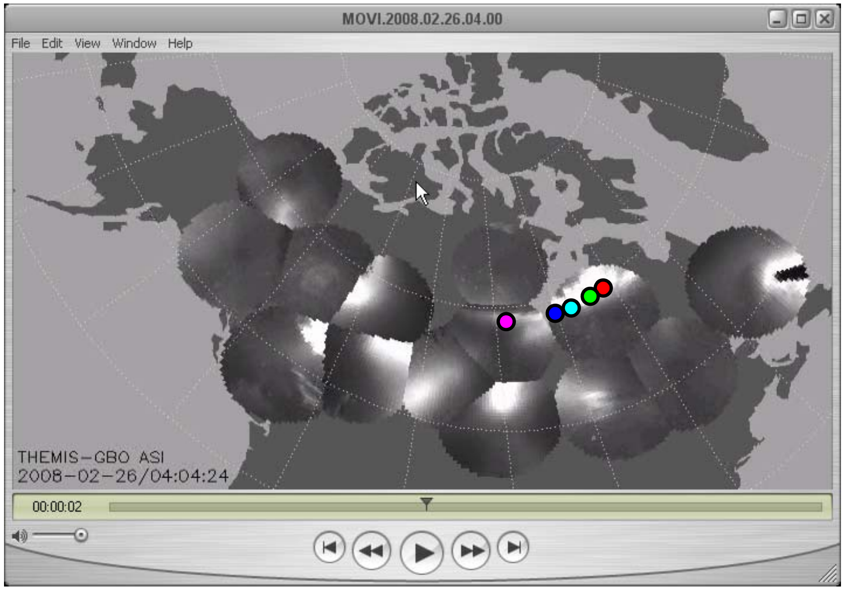




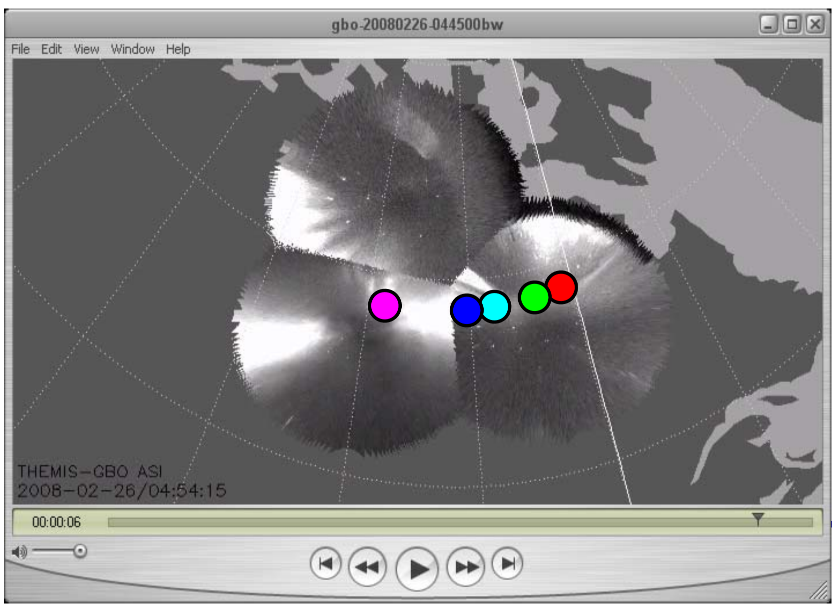
Satellite	Color	X	Y	Z	Neutral Sheet
THEMIS-A (P5)		-5.483	5.326	-0.623	0.6
THEMIS-B (P1)		-21.475	3.927	-2.806	-0.5
THEMIS-C (P2)		-17.165	4.573	-3.046	-0.8
THEMIS-D (P3)		-10.881	3.759	-2.086	0.2
THEMIS-E (P4)		-10.194	4.506	-1.913	0.2

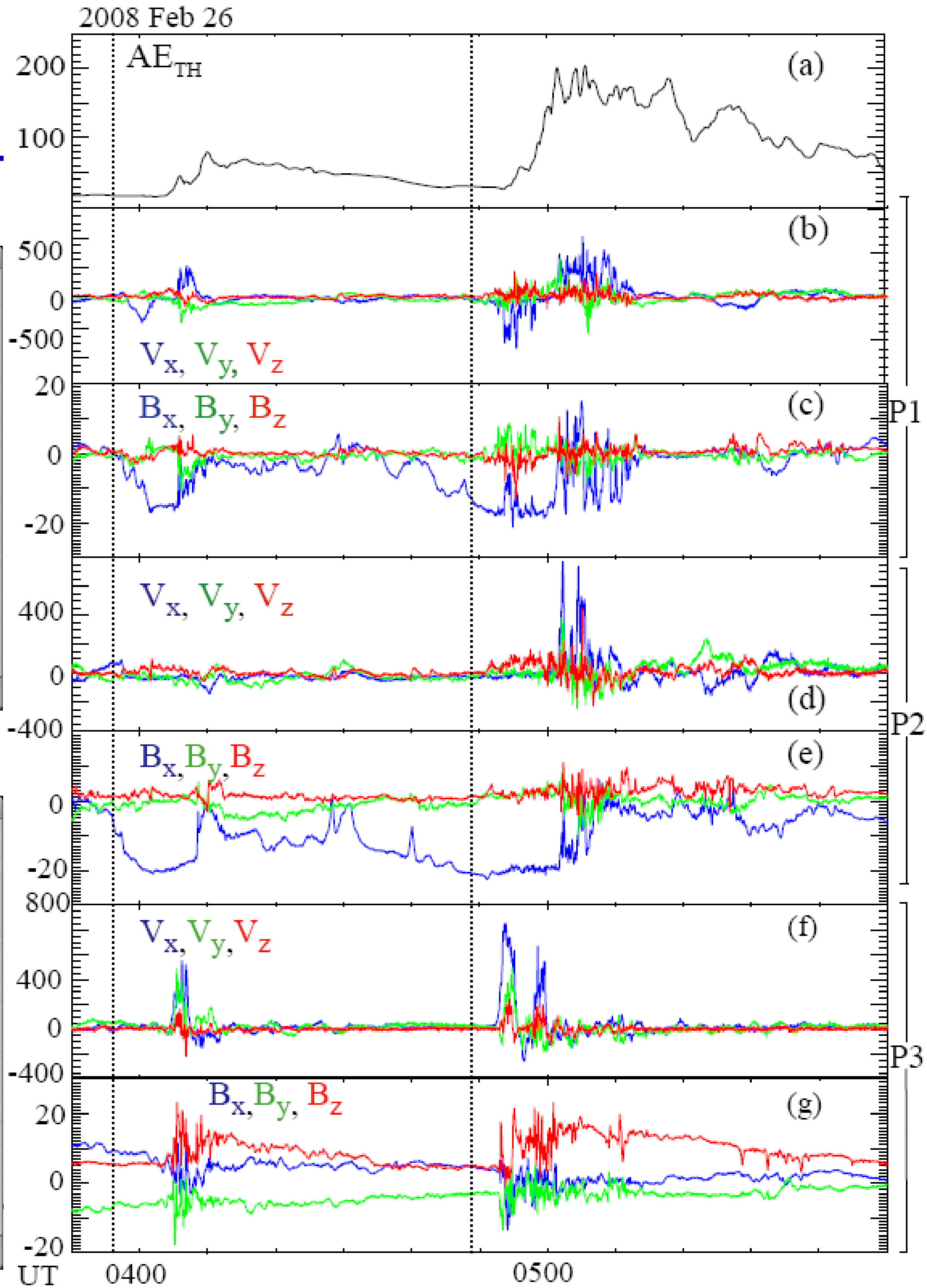
THEMIS

First Event

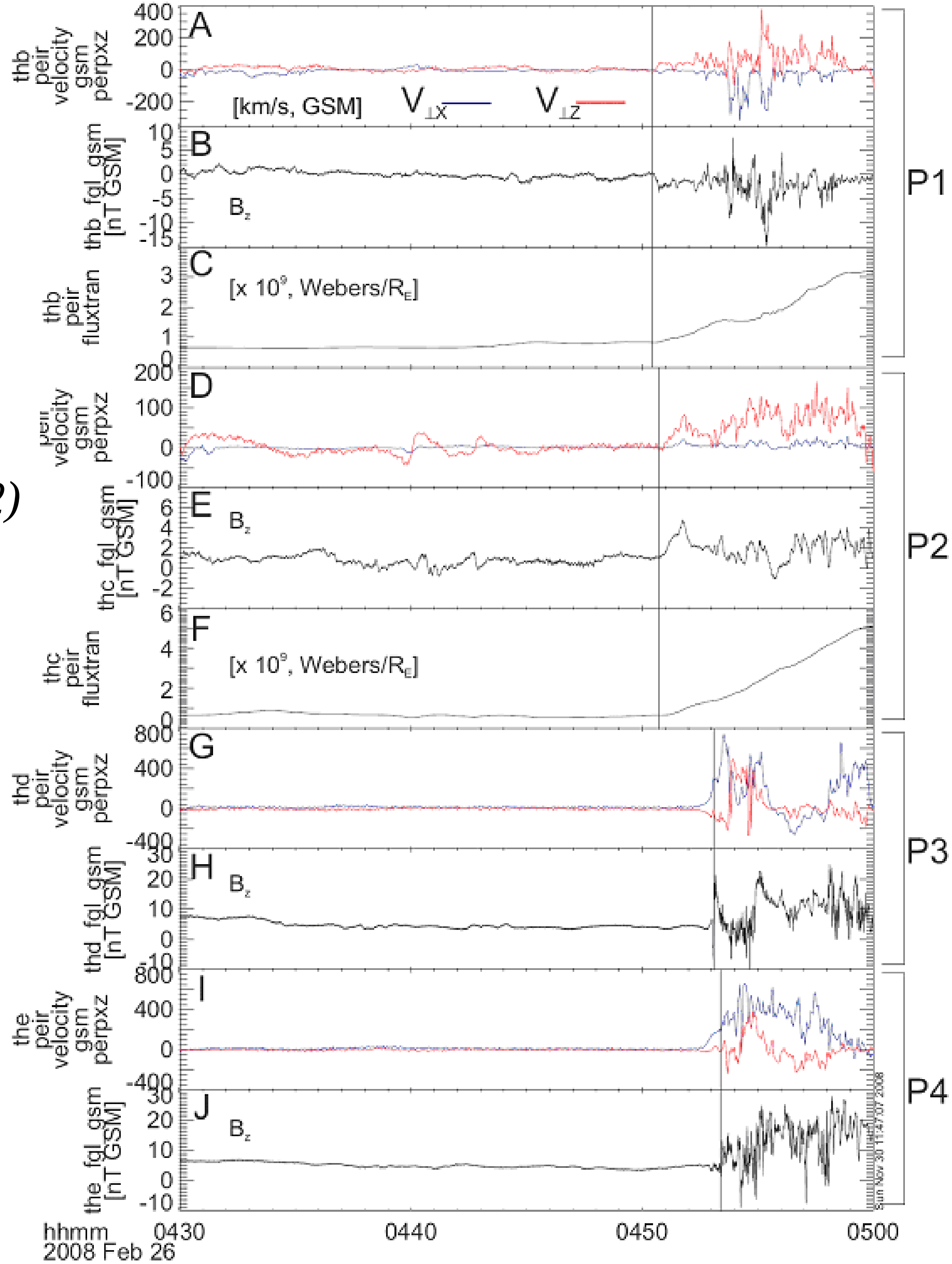


Second Event

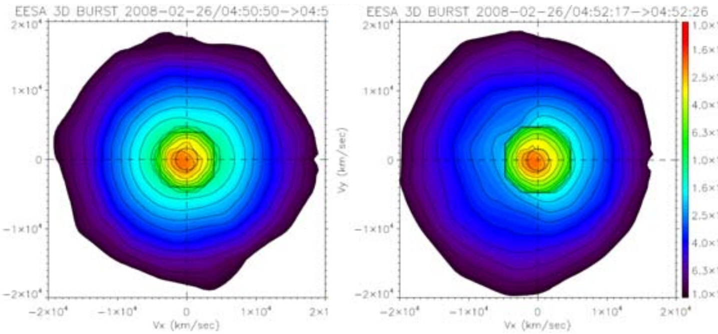


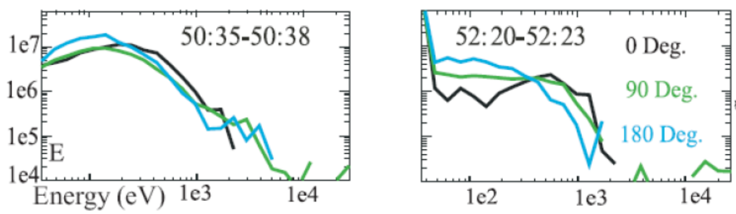


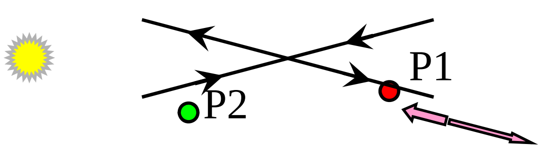
Reconnection onset associated with onset of large flux transport (inflow towards the Rx site at P1, P2)

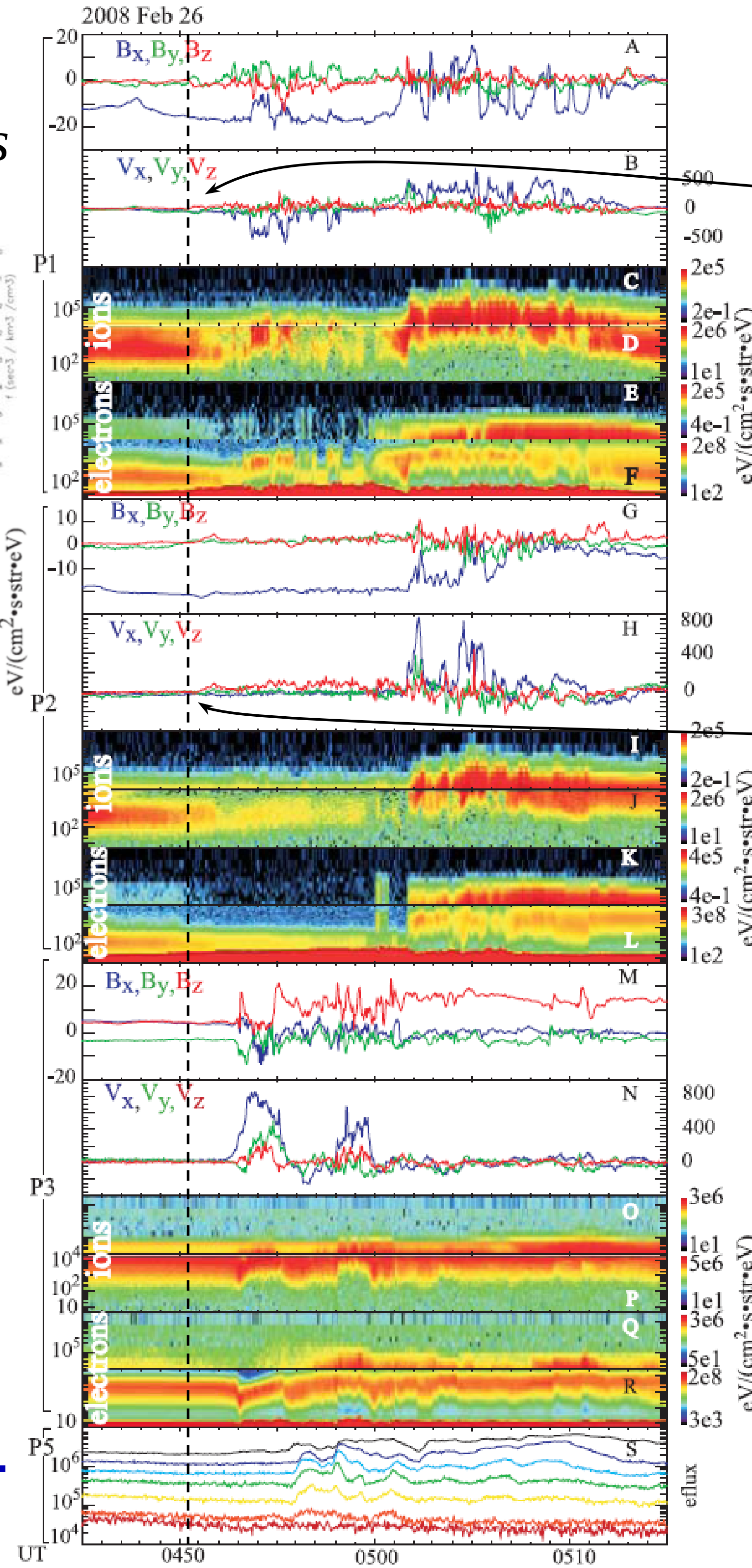


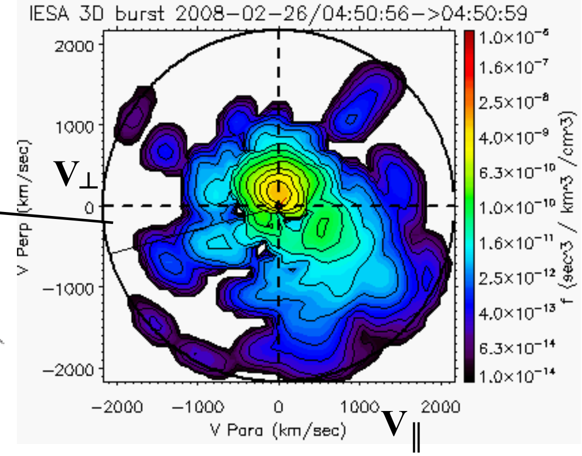
Tail substorm signatures: Fields, Flows, Distributions

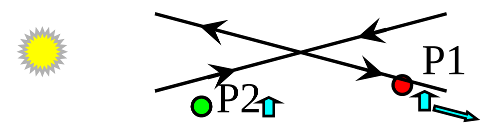


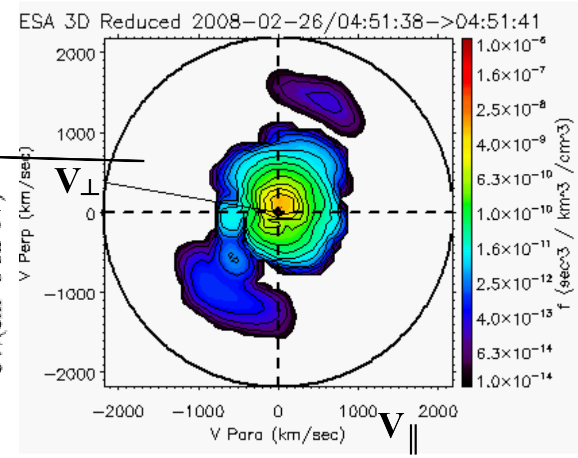












Similar to Nagai et al., 2001

Similar to Hoshino et al., 1998

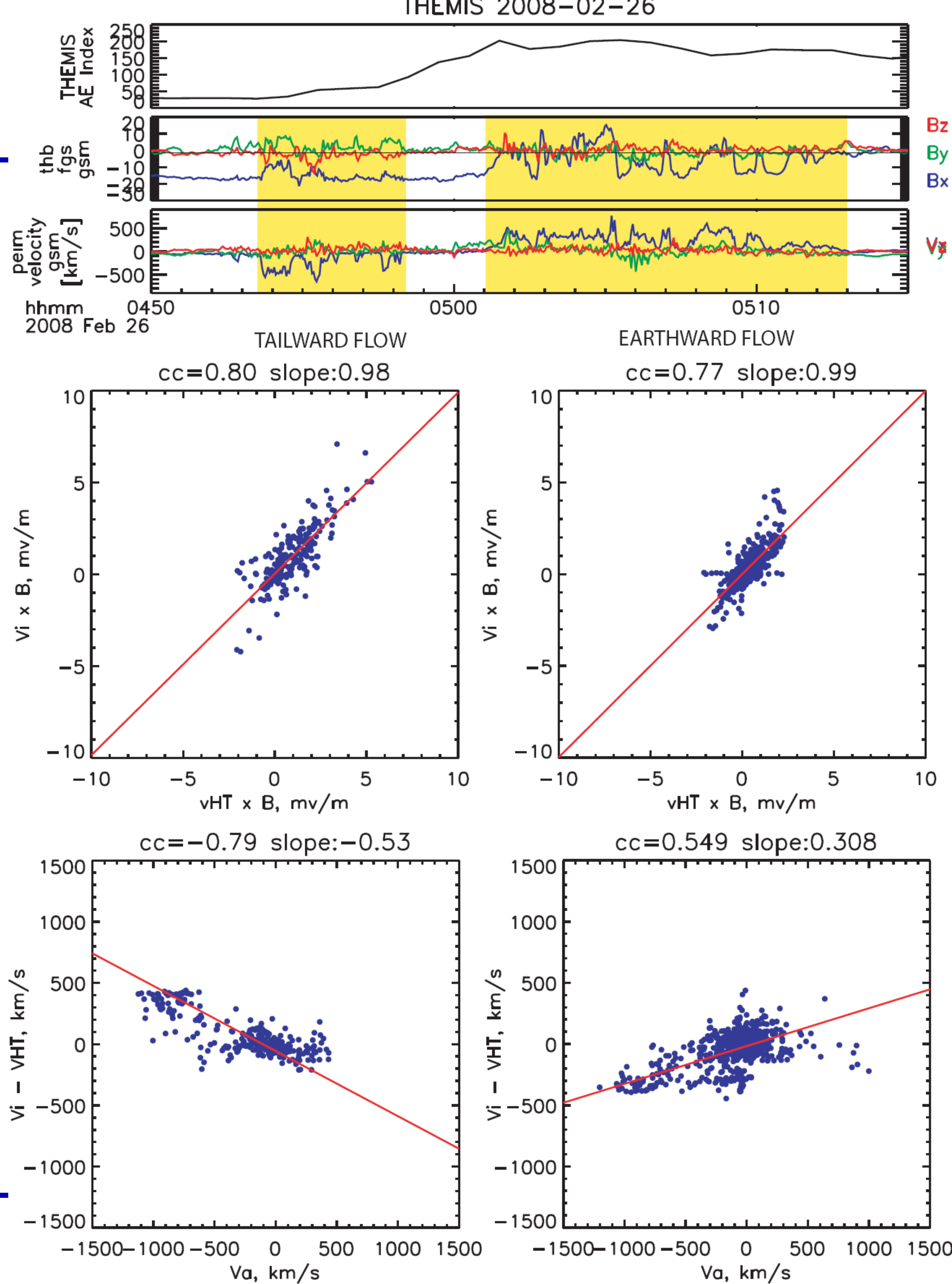
THEMIS

Middle Panels: Transformation to deHoffman-Teller frame

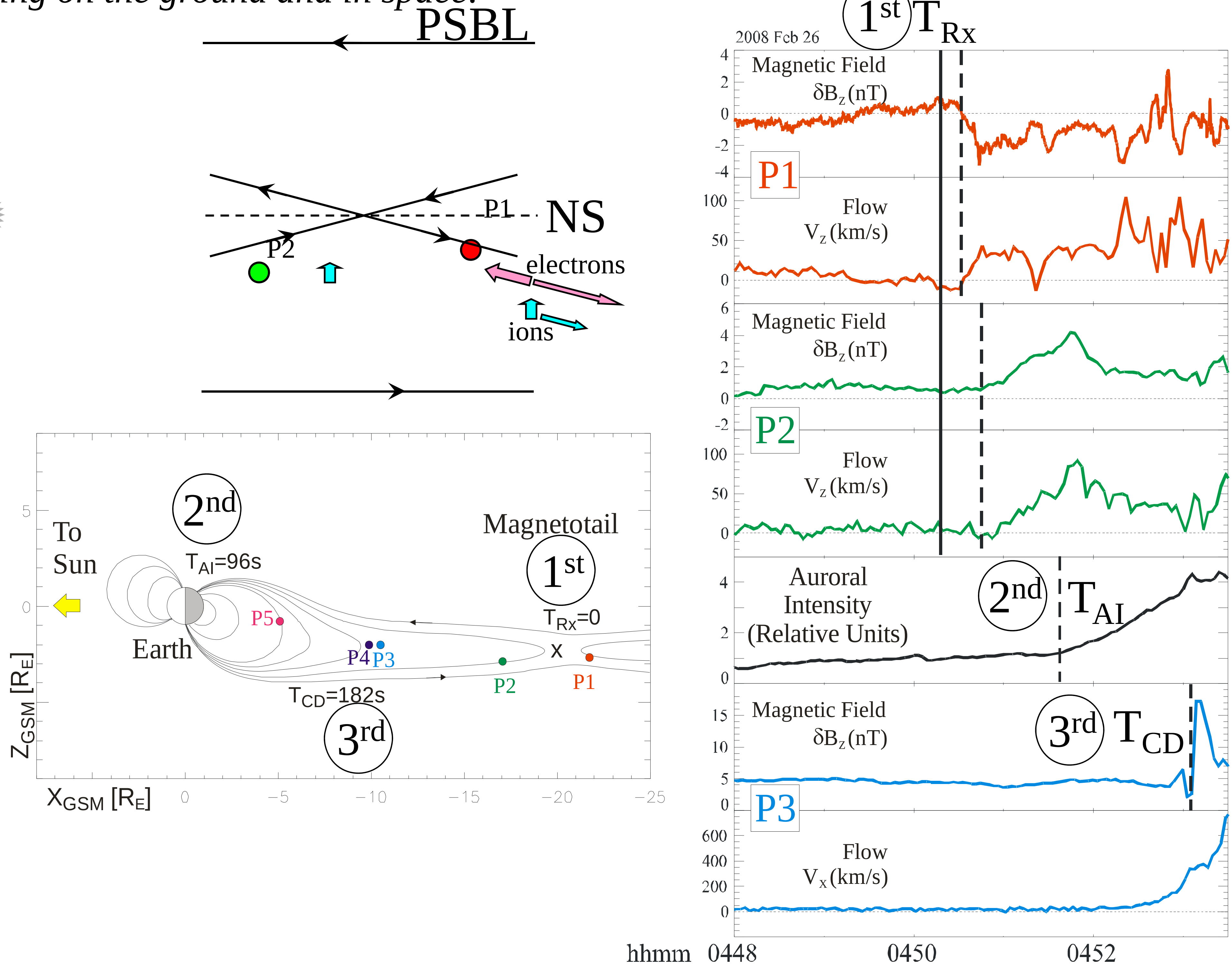
Bottom panels:
Walen test of stress balance

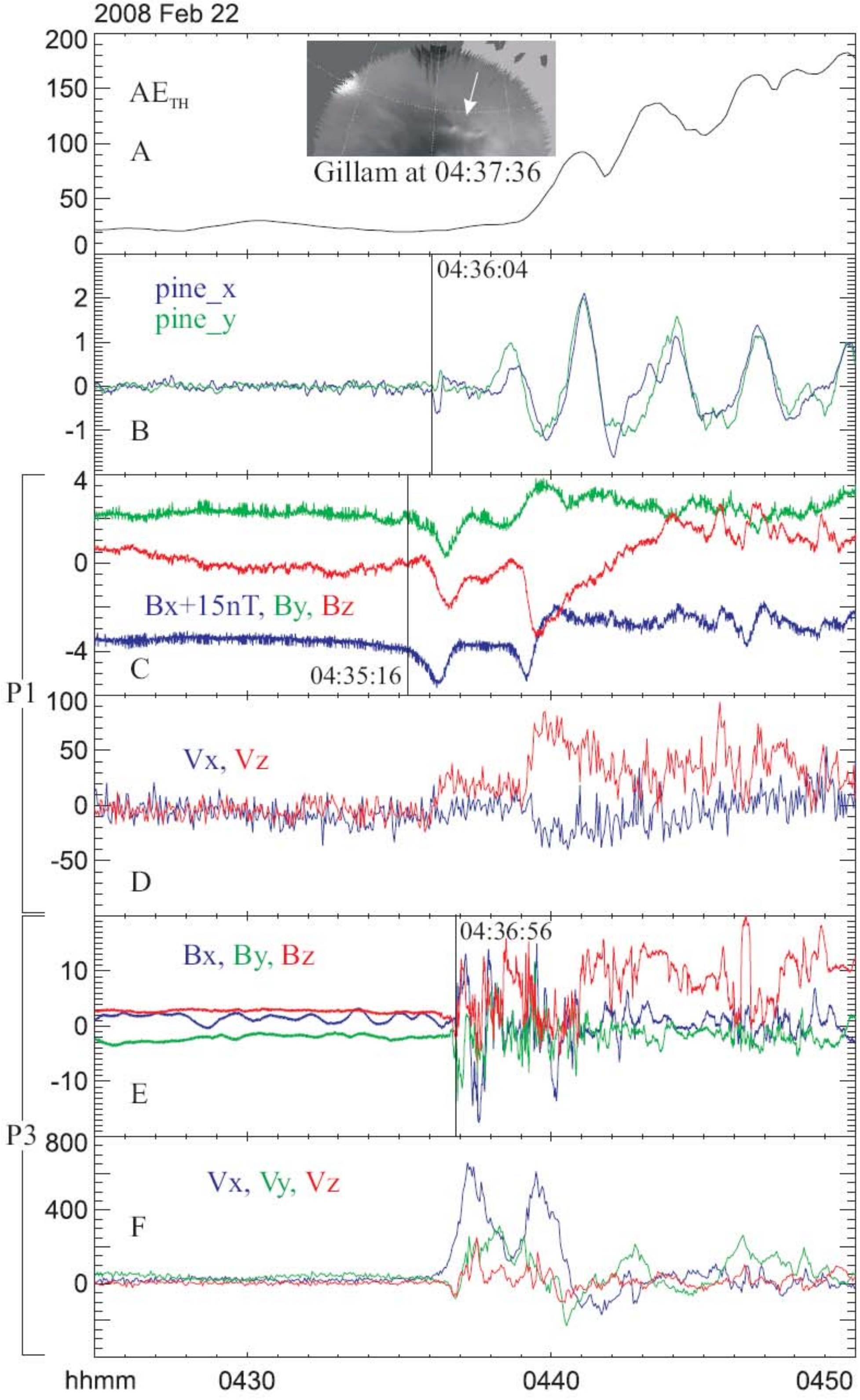
Caveats:
- Need to include energetic particle contribution to velocity
- Aliasing from temporal variations

Note: When peak velocity considered match to Alfven speed is better



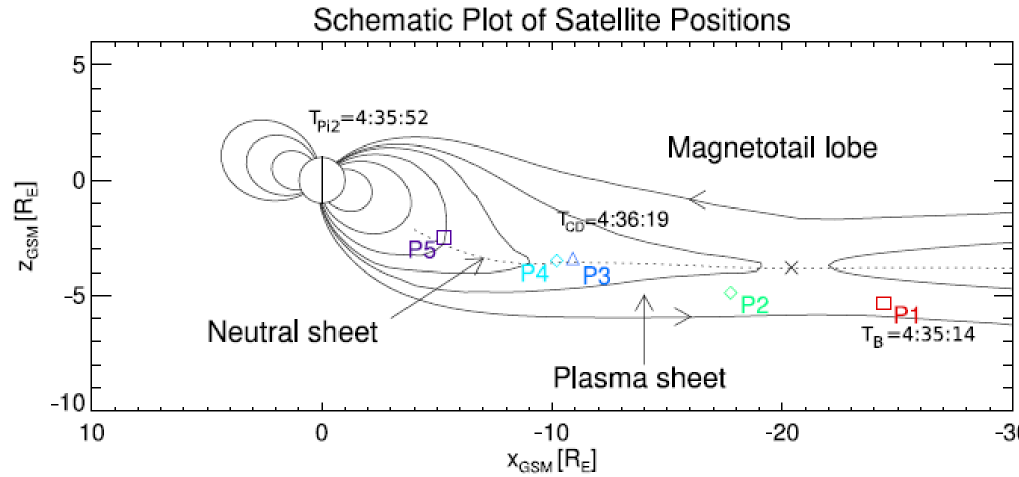
Timing on the ground and in space:





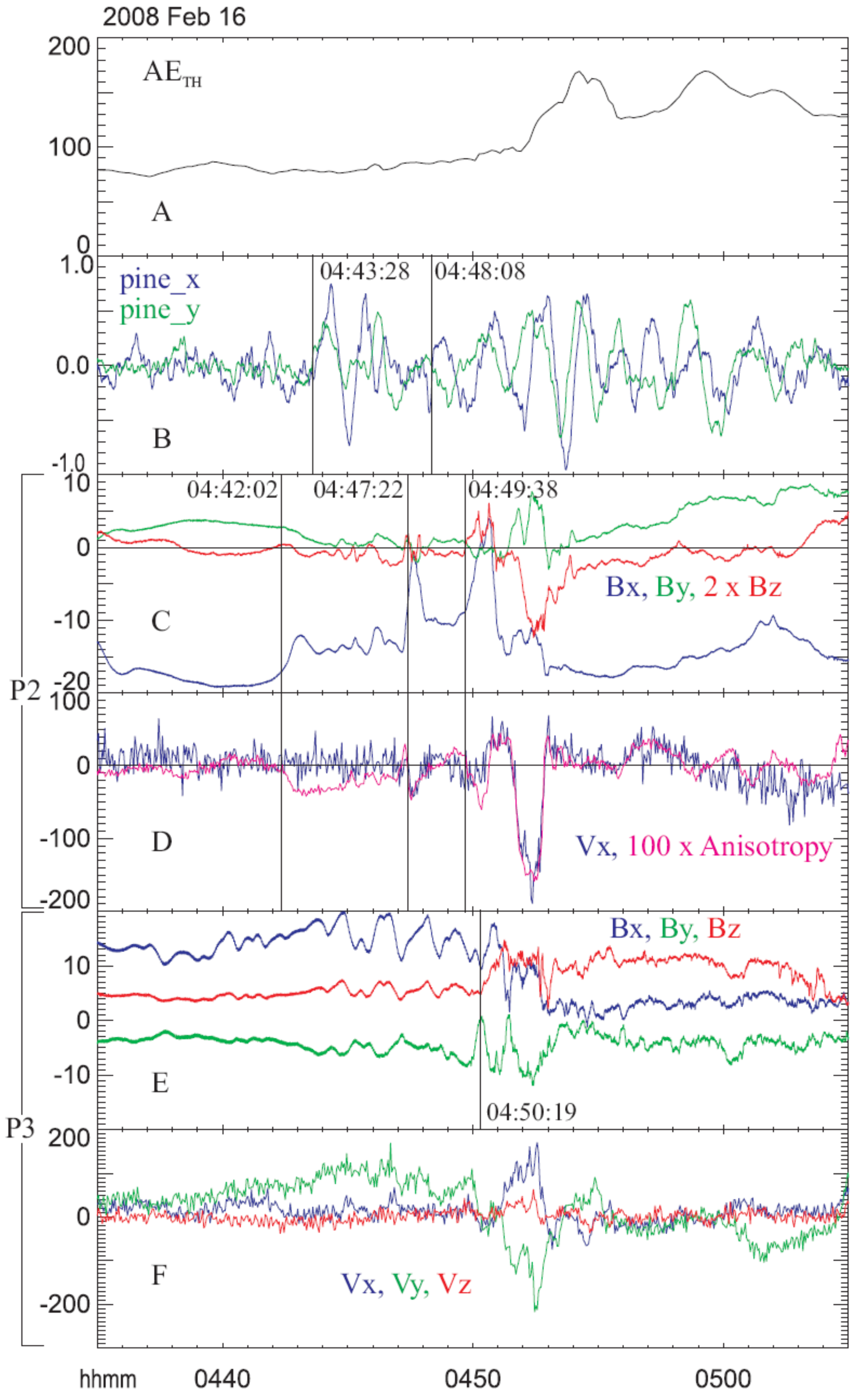
2008-Feb-22 event

Liu et al., 2008, Annales Geophys.



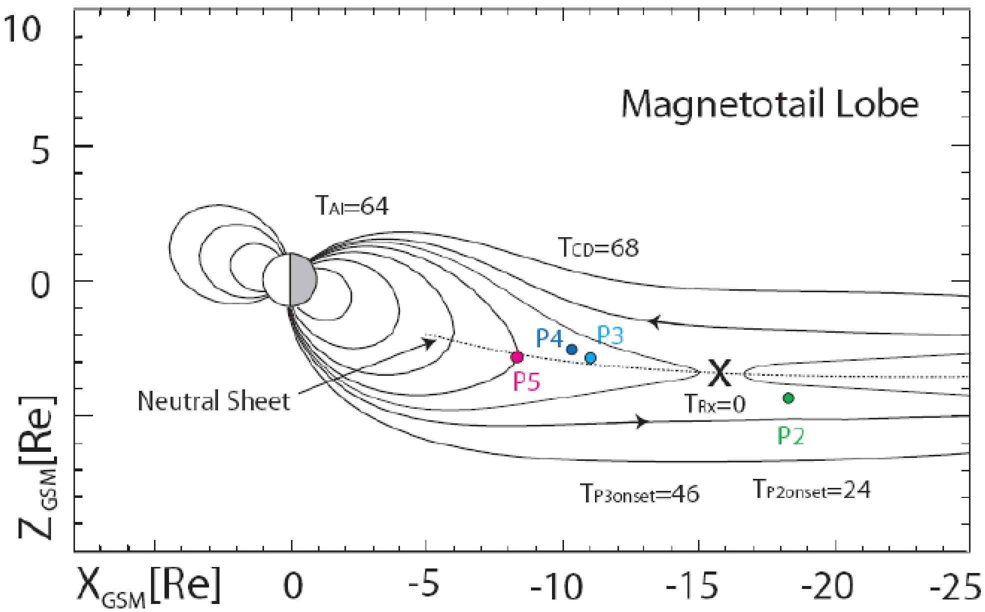
Probe	Time (UT)	X (R_E)
Reconnection onset	04:34:25~35:04	-19.5~-22.4
Reconnection effects at P2	04:35:14	-17.76
Tailward NFTE onset at P1	04:35:16	-24.4
Earthward flow onset at P3	04:36:03	-10.9
High-latitude Pi2 onset	04:36:10	-1
Aurora intensification	04:36:18	-1
Reconnection effects at P5	04:36:40	-5.3
Dipolarization on P3	04:36:49	-10.9
Dipolarization at P4	04:36:50	-10.2
Mid-latitude Pi2 onset	04:37:49	-1
Aurora Electrojet Increase	04:37:54	-1

74-113s



2008-Feb-16 event

Gabrielse et al., JGR, 2008



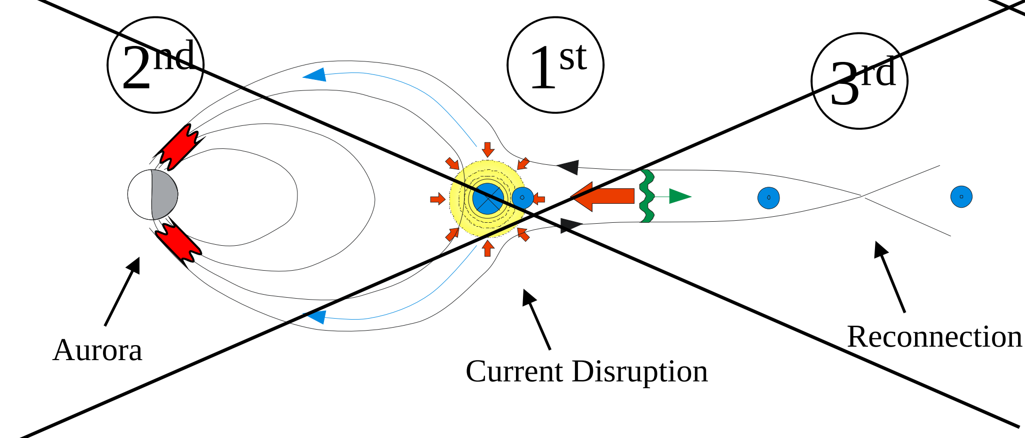
Event	Observed Timing (UT)	Inferred delay (seconds since 04:49:11 UT)
Reconnection (Timing analysis)	04:49:07-04:49:14	TRx=0
Reconnection effects at P3	4:49:57	46
Reconnection effects at P2	4:50:07	56
Auroral intensification (Integrated intensity)	4:50:15	TAI = 64
Dipolarization (obs. at P3)	4:50:19	TCD = 68
Auroral intensification (ASI)	4:50:21	70
Pi2 (SNKQ)	4:50:40	89
Pi2 (PINE)	4:51:30	139

64s

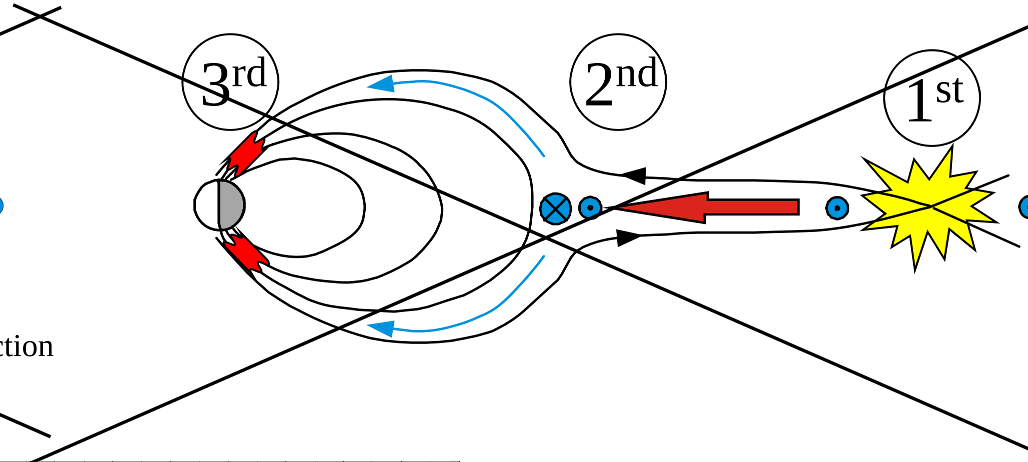
Summary of timing results

Note: what was observed was not the classical time sequence:
Aurora brightens before near Earth dipolarization
Moreover the time delay seems short for Alfven wave propagation

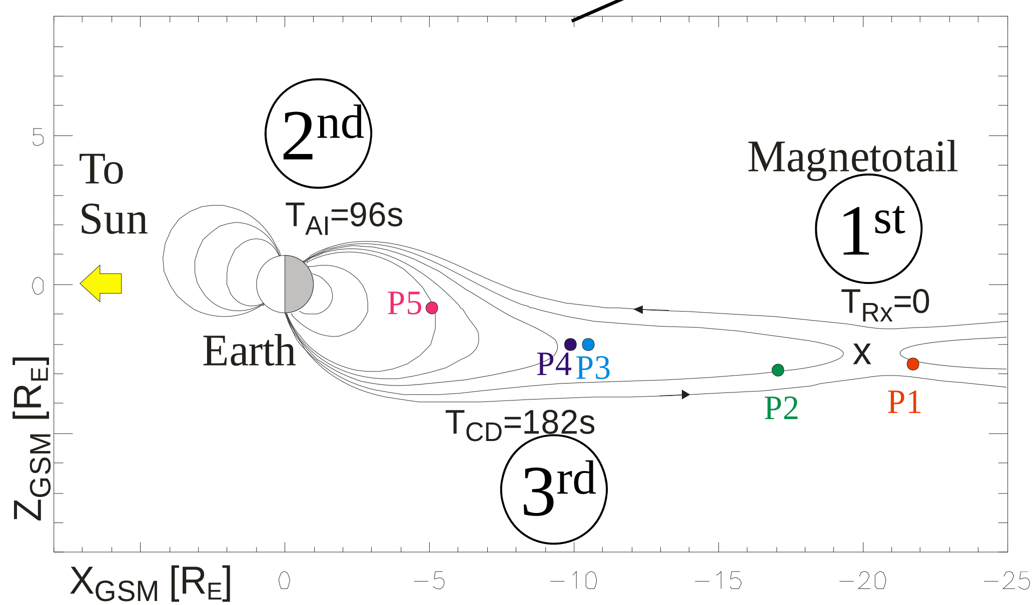
Inside out model



Outside-In model



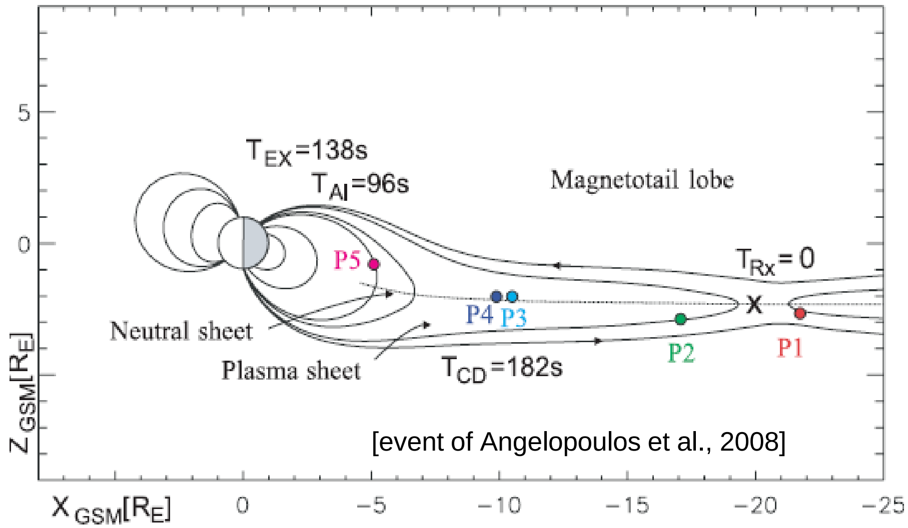
THEMIS finds:

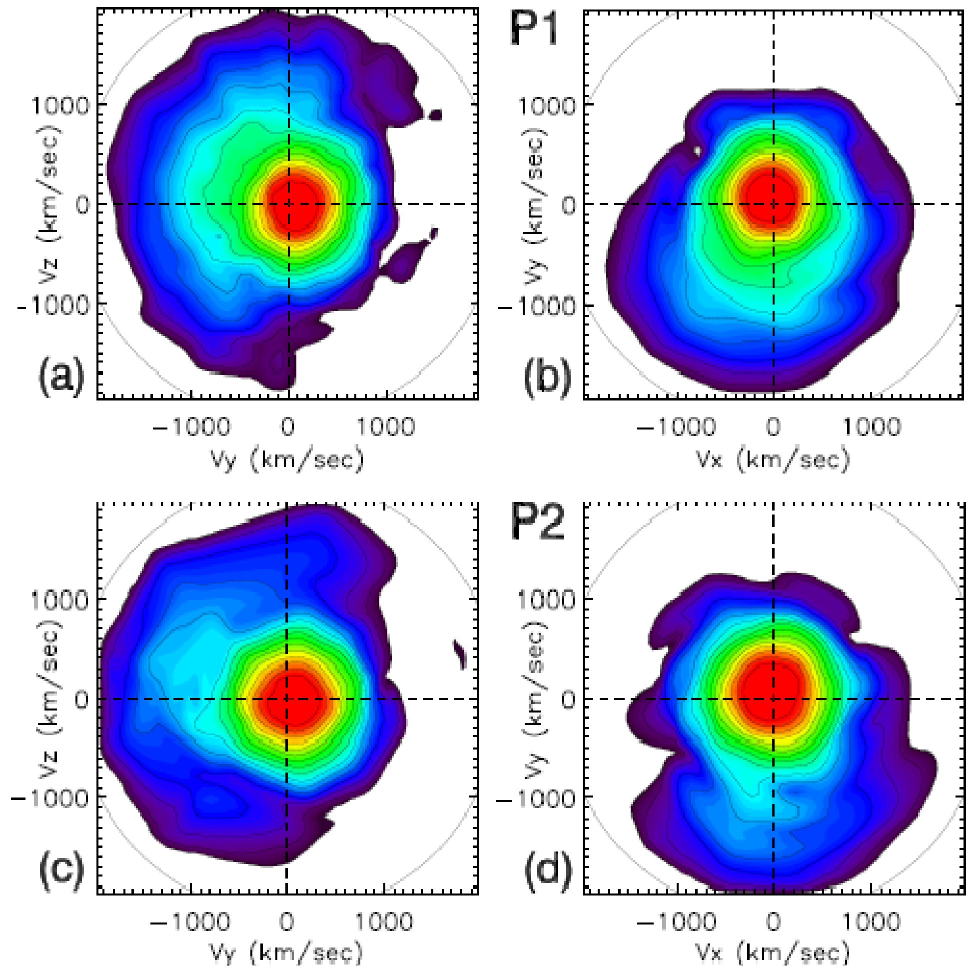


Open Questions from 2008 tail season:

- How does Rx communicate with and power aurora so fast (~96s)?
- What preconditions the tail to reconnect?
  - Spontaneous tearing?
- How can mapping be so distorted?
  - Need to model tail stretching using THEMIS for validation (MHD, Tsyganenko)
    - Consequences of tail stretching for tail stability, particle dynamics and wave growth?

X.-Z. Zhou et al., 2008, JGR



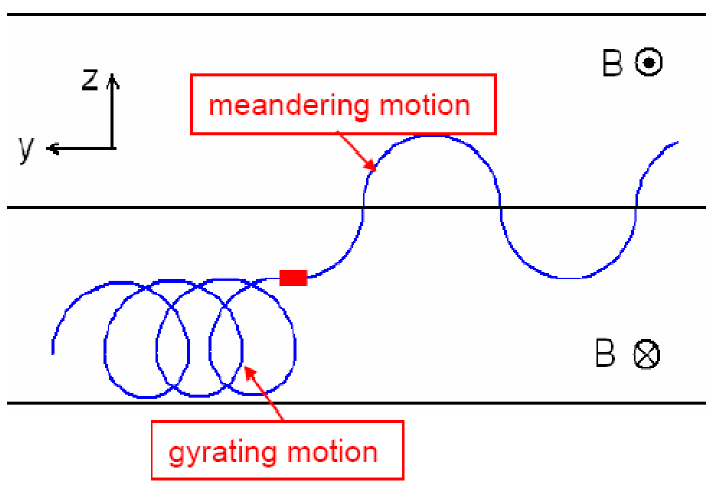


During the substorm late growth phase, the ion distribution functions observed by both P1 and P2 clearly showed anisotropic & non-gyrotropic features, which lasted a few minutes. The observations indicate a tail current sheet that is very thin, comparable to the thermal ion gyroradius.

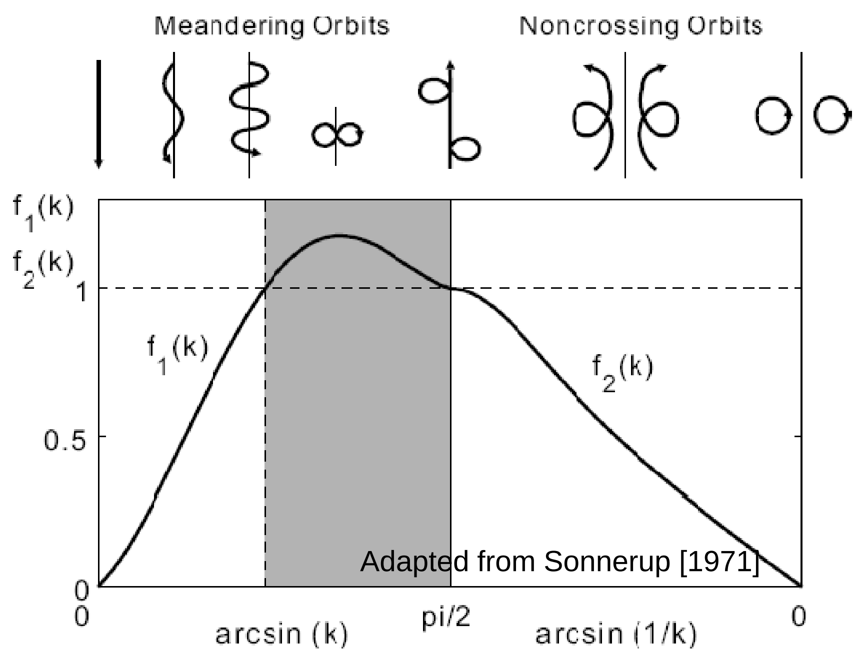
Note: $Y = -Y_{GSM}$

Modified Harris model with bifurcated current sheet

- Another invariant of motion, say, the sheet invariant $I = 1/2\pi \cdot \oint mV_z dz$ is used to contribute the distribution function (Sitnov et al., 2003, 2006).



Particles with the same energy but moving in different directions are following distinct orbits, and thus have very different I values.



- Now the distribution function can be modified from a Harris distribution:

$$f \propto \exp\left[-q\left(\phi + V_{D\alpha} A_y\right)/T_\alpha\right] \cdot \exp\left[-m\left(V - V_{D\alpha}\right)^2/2T_\alpha\right]$$

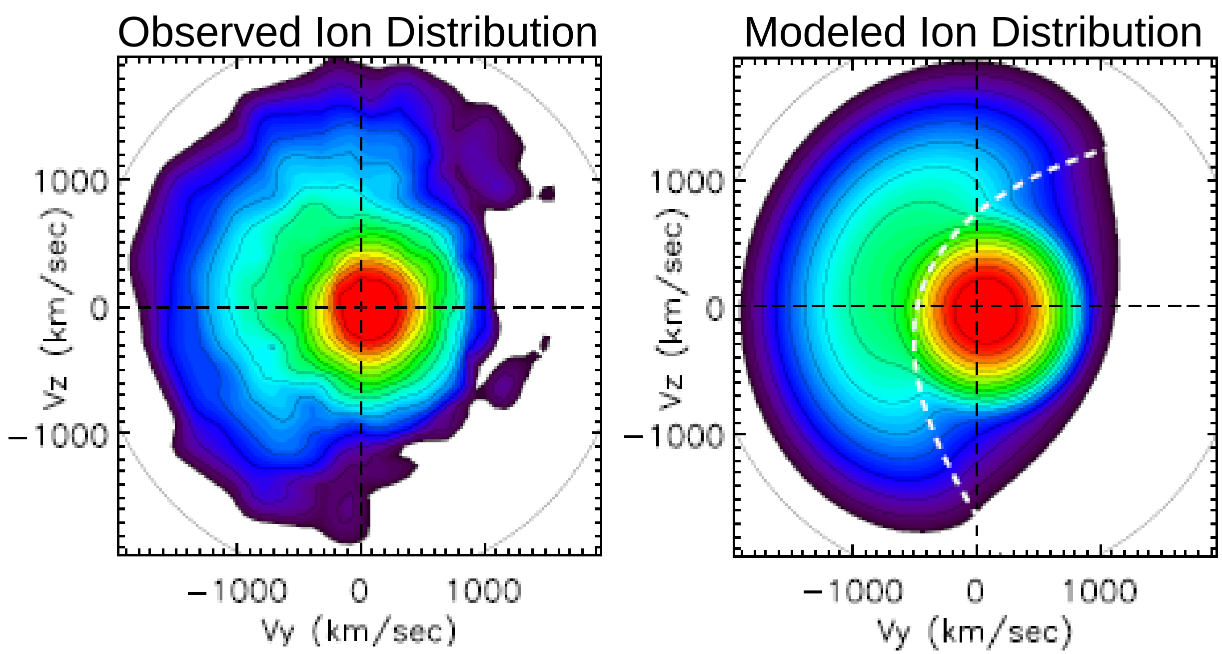
To: $$f_\alpha \propto \exp\left[-\left(W_\alpha - V_{D\alpha} P_{y\alpha}\right)/T_{//\alpha} + I_\alpha \left(T_{//\alpha}{}^{-1} - T_{\perp\alpha}{}^{-1}\right) \cdot \omega_\alpha / 2\right]$$

Adding a cold ion component

- To model the observations, the distribution function is written as the function of three invariants of motion [Sitnov et al., 2006]:

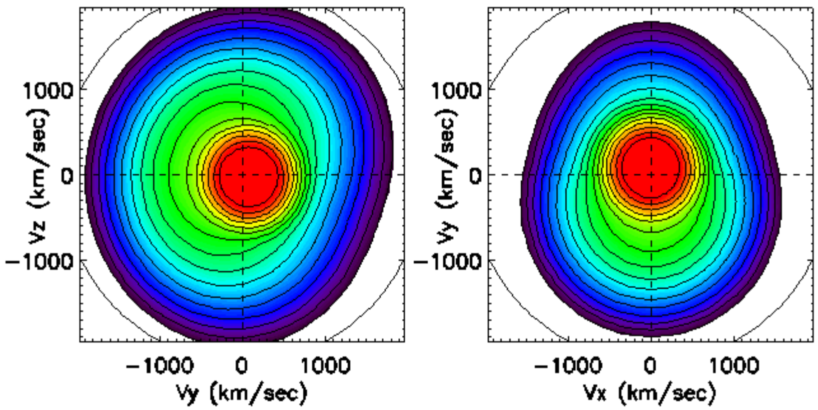
$$f_\alpha = A\exp\left[-\left(W_\alpha - V_{D\alpha w}P_{y\alpha}\right)/T_{//\alpha w} + I_\alpha\left(T_{//\alpha w}^{-1} - T_{\perp\alpha w}^{-1}\right)\cdot\omega_\alpha/2\right]$$
$$+ B\exp\left[-\left(W_\alpha - V_{D\alpha c}P_{y\alpha}\right)/T_{//\alpha c}\right]$$

and fitted with the observations to obtain the current sheet profiles

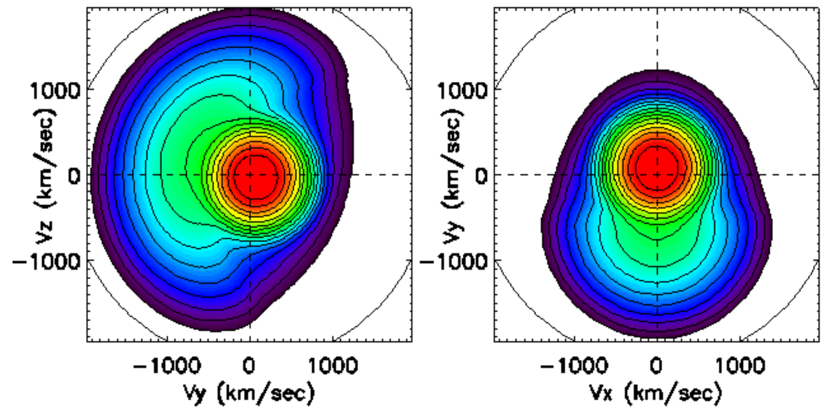


Remote sensing of current sheet

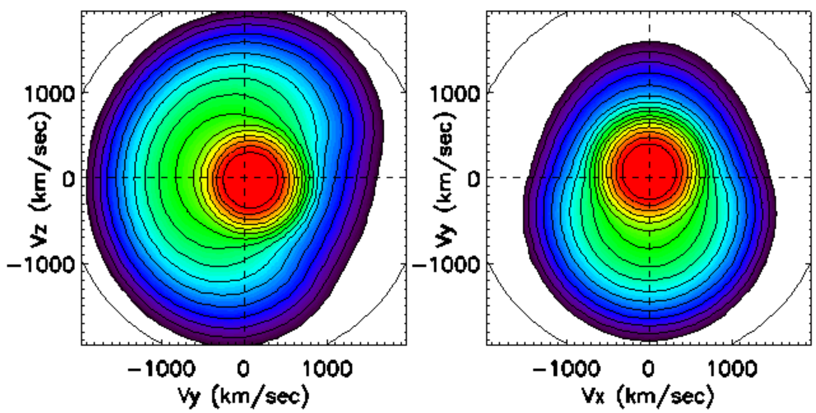
Distance = 0 km



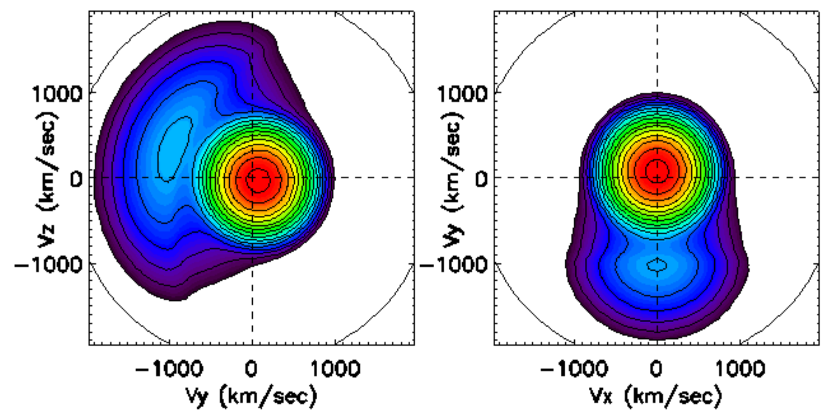
Distance = 1200 km



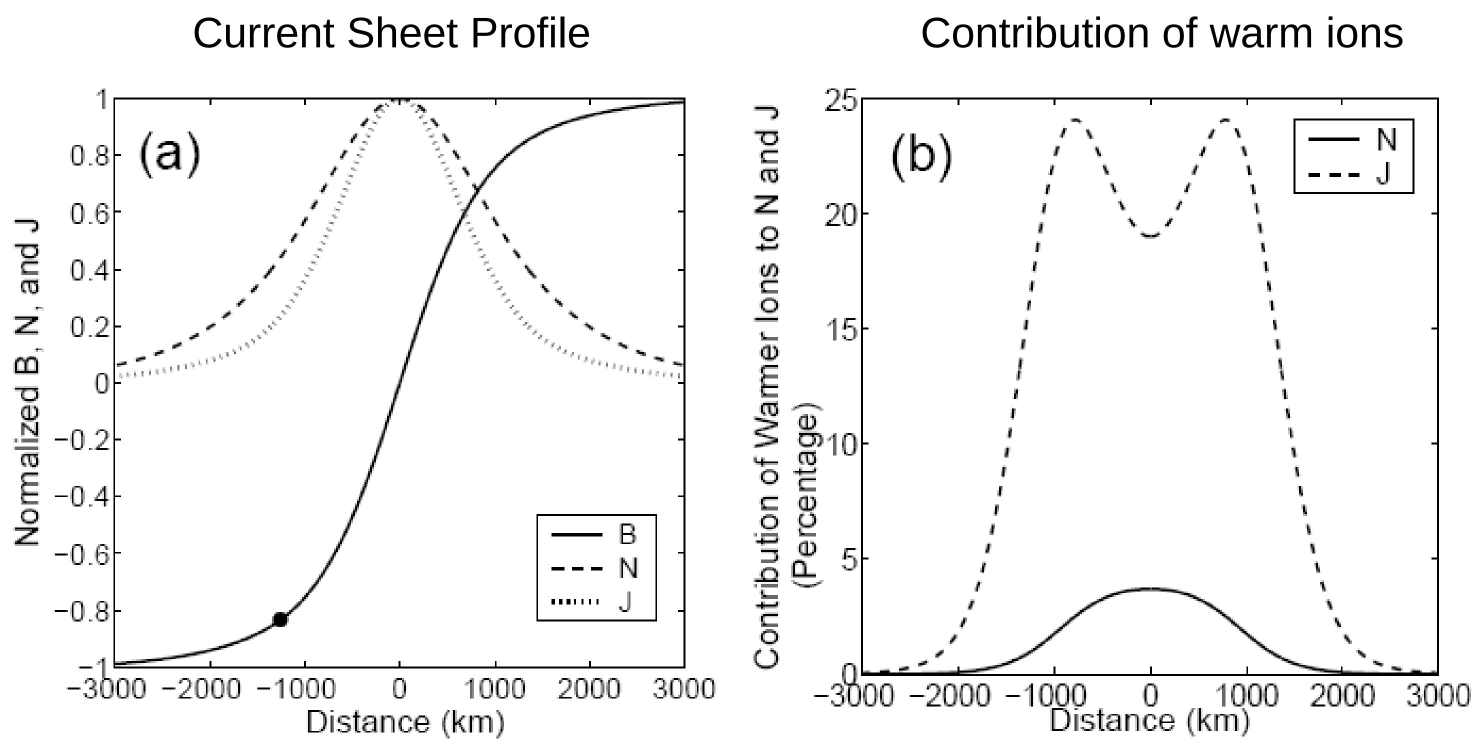
Distance = 600 km



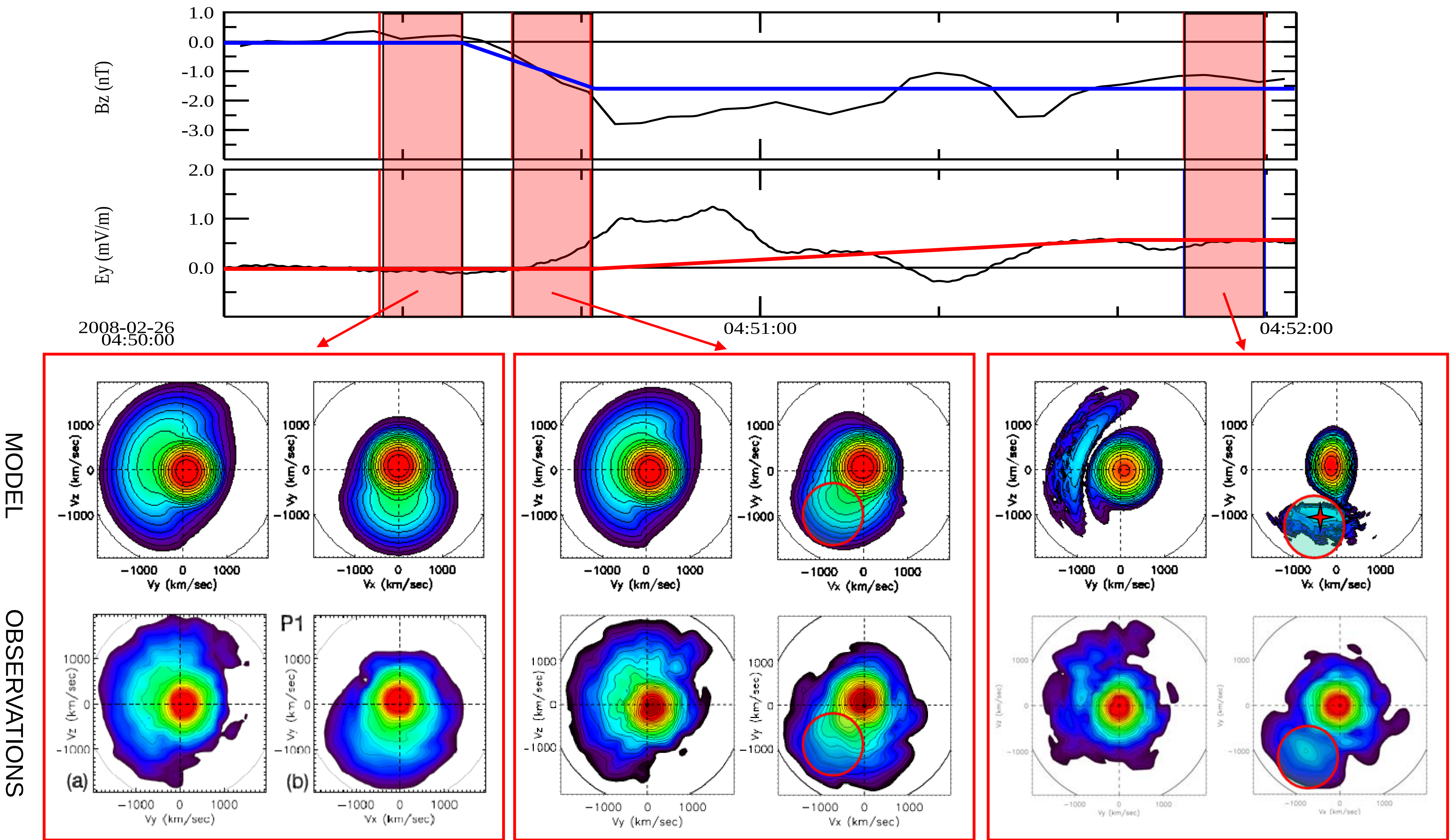
Distance = 1800 km



- The warm ions are a small (up to 5%) part of the density but contribute a significant portion of the (bifurcated) cross tail current.
  - The presence of the warm ions is critical to the stability of the current

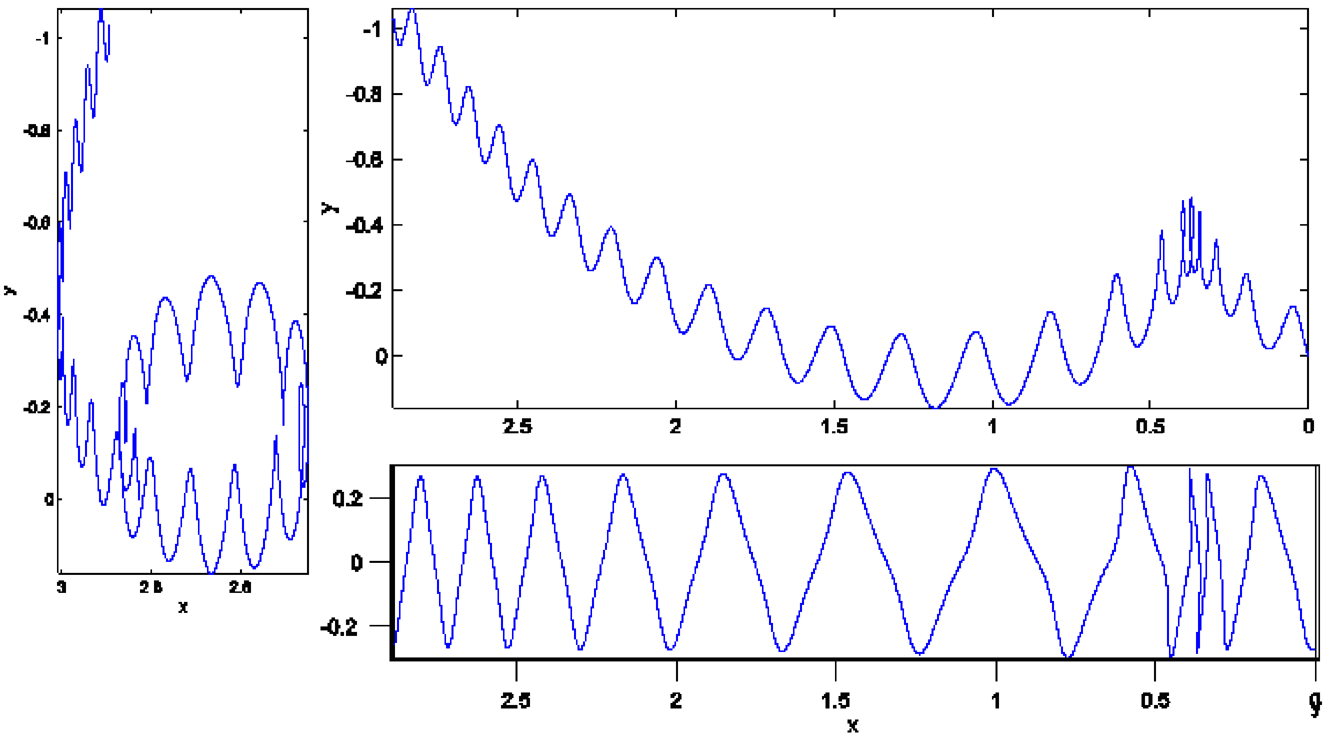


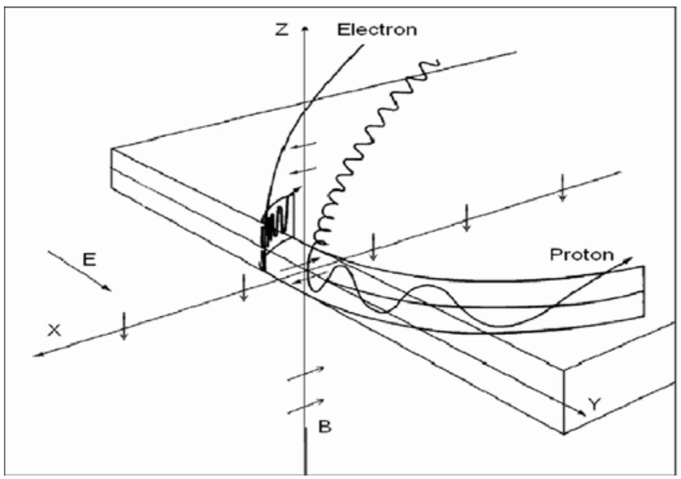
… and time history of its evolution



Orbits can be readily understood

- The most clear feature of the observed particle distribution 15 sec later than the onset of a negative Bz is the tailward motion of the warmer ion component, which can be understood by the Speiser orbit [Speiser, 1965] with negative Bz.





Significance of Zhou's results

Particle ejection (tailward/earthward motion) can:

- help monitor current sheet :
  - Effect must be observable also at high energies if $L_{xy,thinning} > \rho_L$
  - Predominant energy of streaming tells us about both $L_{z,\ cs}$ and $L_{xy,\ thinning}$
- affect current sheet structure:
  - If leaking particle energy is ~ thermal energy then plasma beta is lowered
  - Loss of current carriers may result in explosive destabilization of current
  - Tailward streaming particles exert tailward pressure on B-field
- destabilize tail as close as the near-Earth plasma sheet
  - In Y-type neutral line can result in leakage of ring-current particles

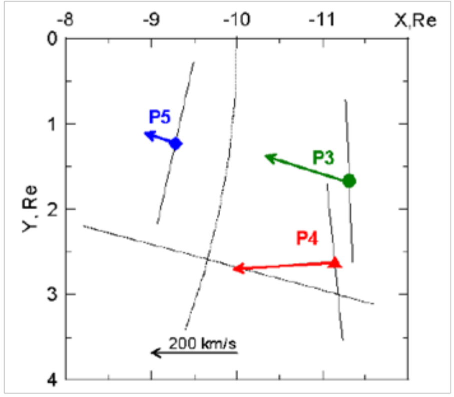
Beyond the driver: fate of the fast flows?

- Earthward flows contain a significant part of the energy from the reconnection process. Yet their dissipation process is unclear.

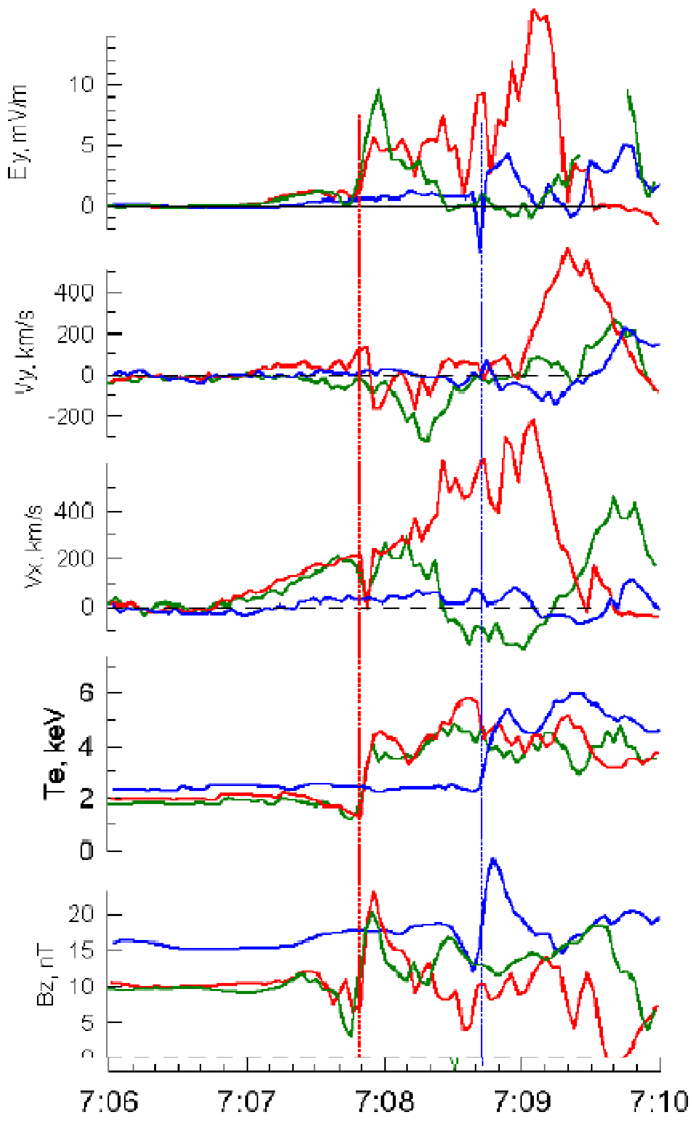
- Recent studies of the interface between the fast flows and the surrounding medium confirms earlier results, leads to new appreciation of a non-linear (steepened, self-similar, kinetic) interaction of the flows with the ambient medium, a tangential discontinuity. The Earthward moving tangential discontinuity is host to interesting Hall physics.

- Recent multipoint studies by THEMIS reveal that the injection of plasma to the near-Earth environment is composed of localized (1-2R_E) dipolarization fronts that set up vortical structures [Keiling et al., 2008] but may also result in turbulent mixing and current filamentation and heating.

Sergeev et al., 2009, in preparation
(also Runov et al., 2009 GRL, in press)



February 23, 2008 Themis P3 & P4 & P5



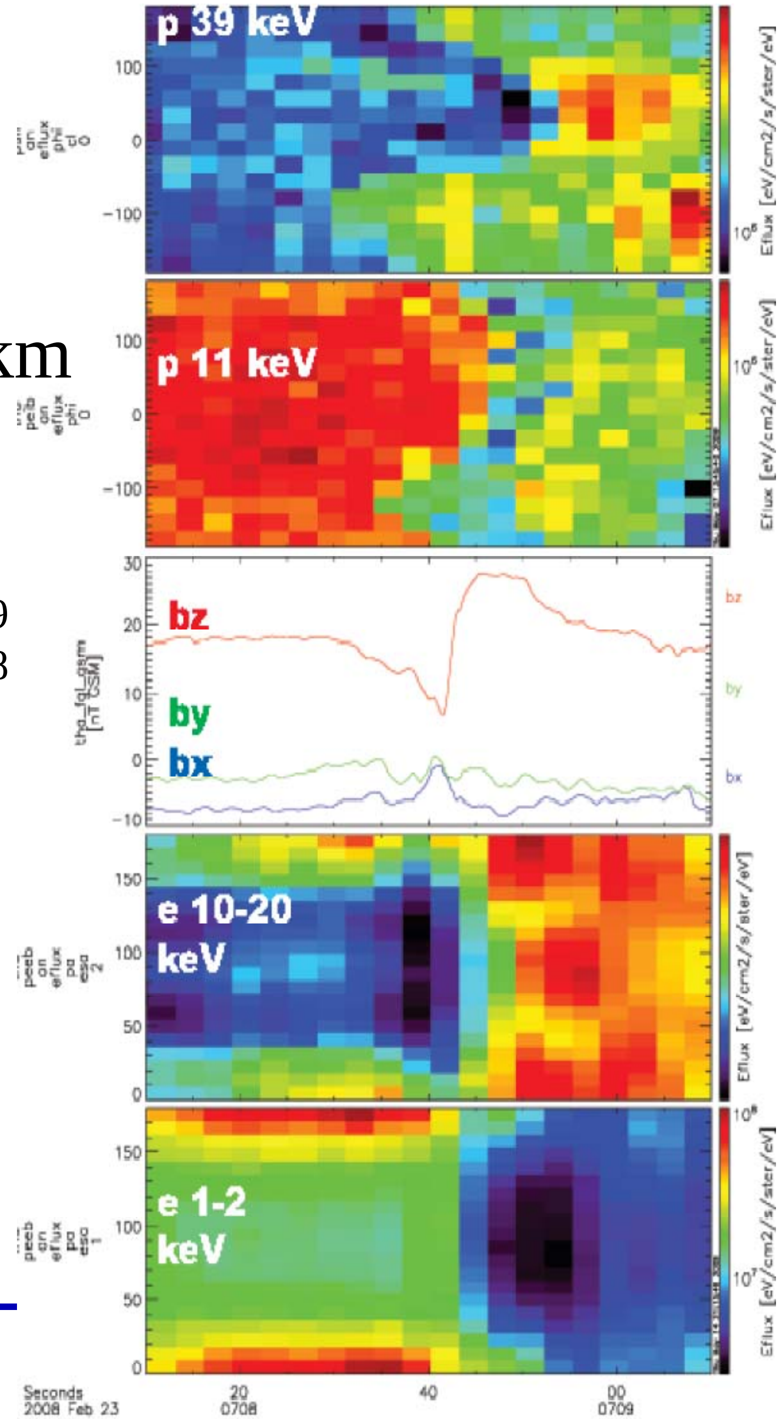
ρ_L=1400km

V=150km/s

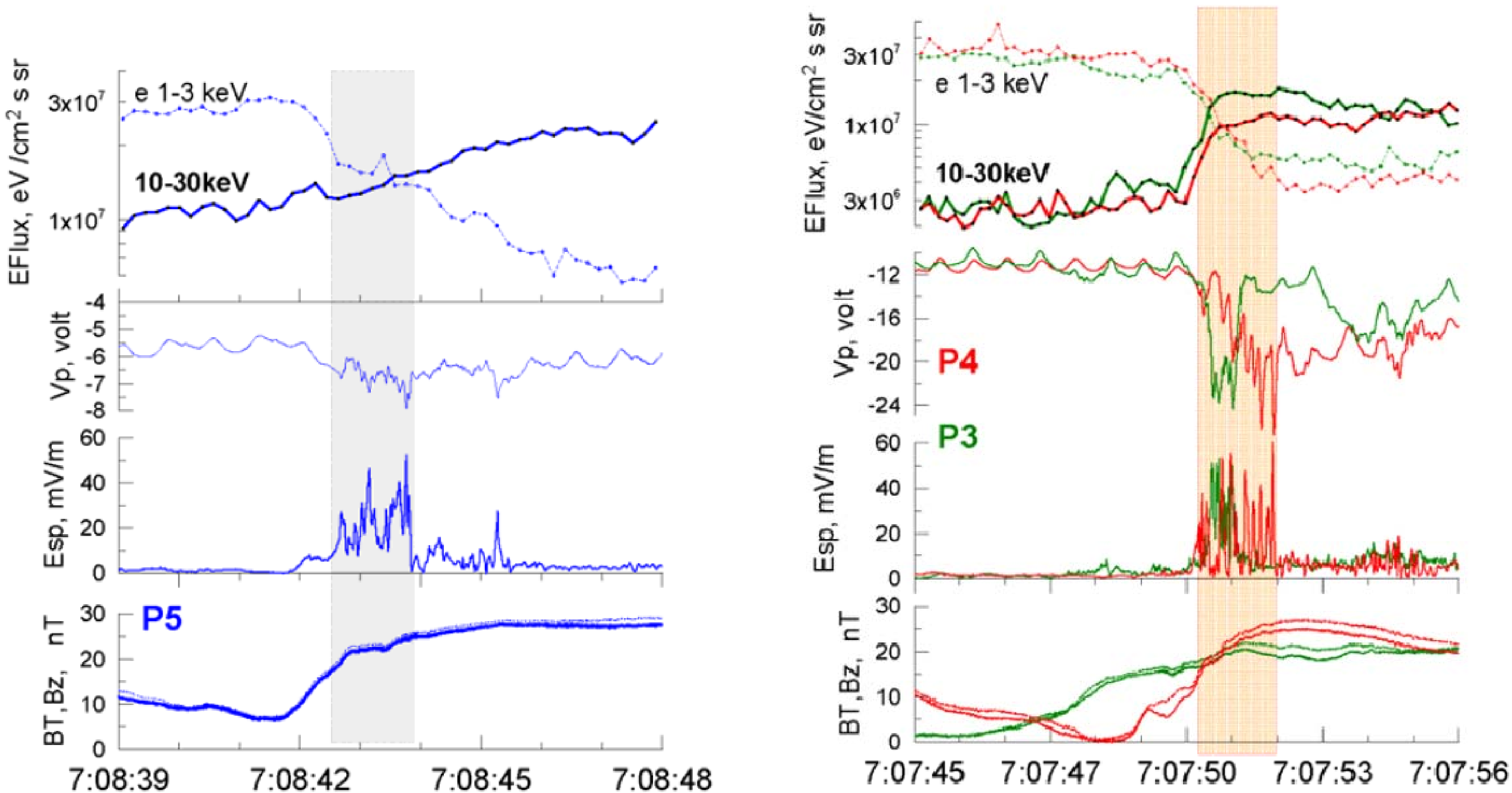
δt=2.5s

D=V*δt~400km

Remote sensing
similar to:
Angelopoulos et al. 1999
Angelopoulos et al. 2008



Sergeev et al, 2009

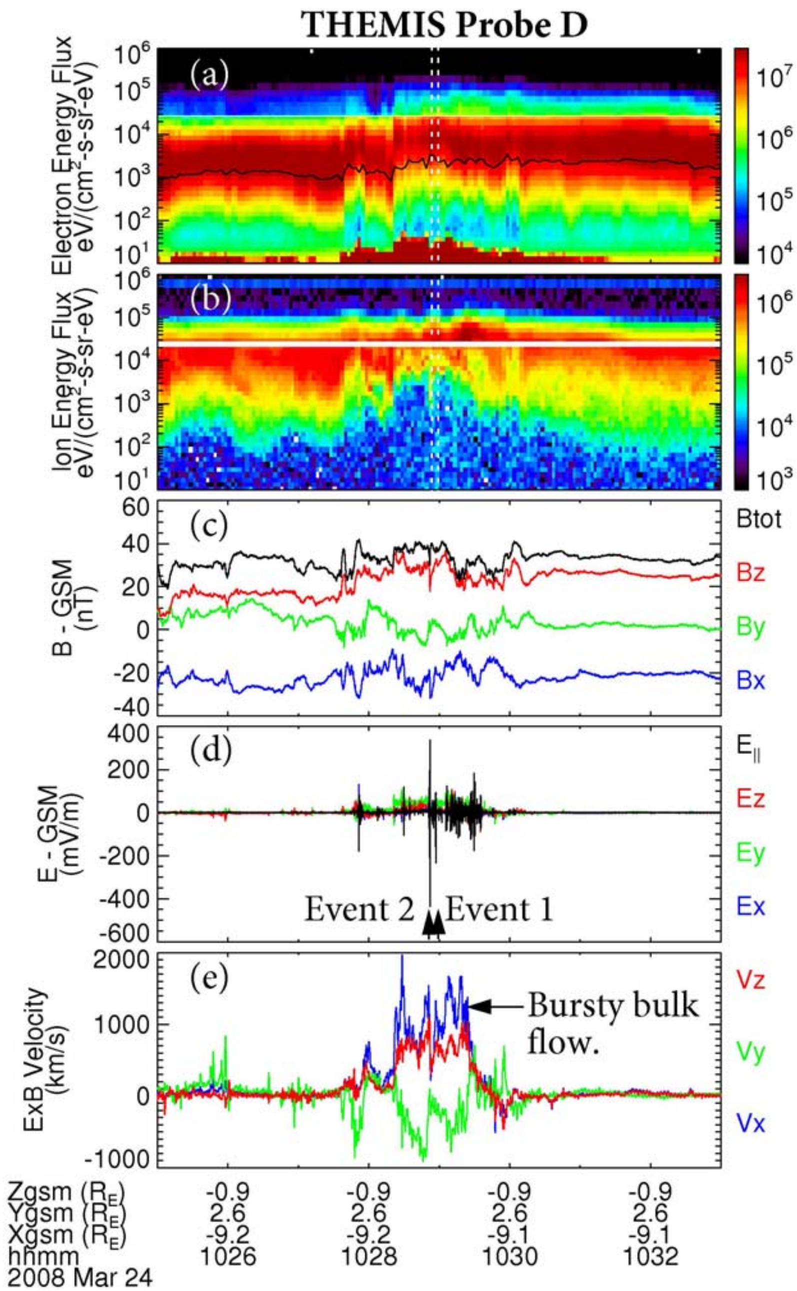


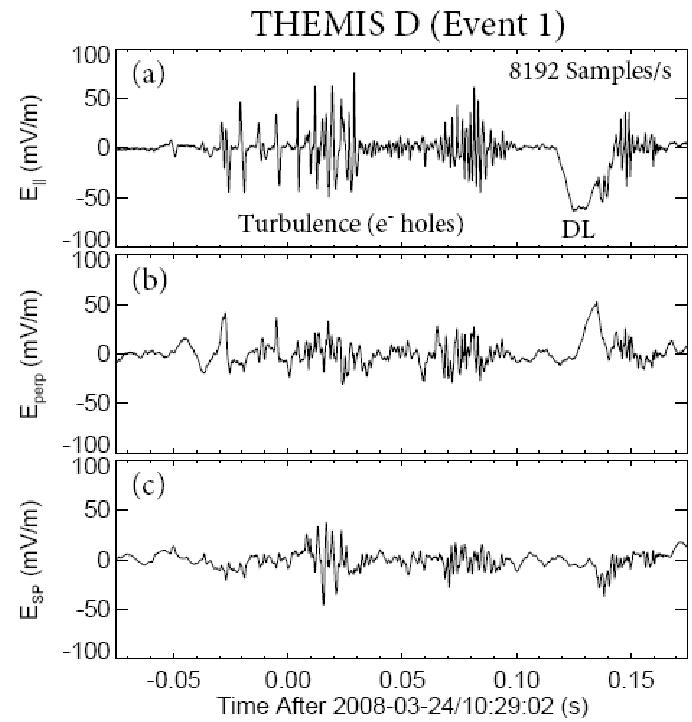
Inward dipolarization: results

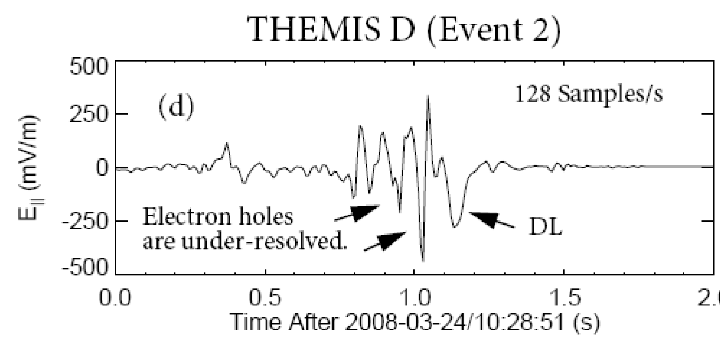
- Sharp dipolarization fronts:
  - Have scale size L~400km, i.e., sub-gyroradius, yet they:
  - Retain their structure/coherence as they travel through stationary plasma
  - Host a variety of waves, in low hybrid range resembling low hybrid cavities in the ionosphere and plasma sheet observed by Cattell et al
- Electron heating is observed:
  - in conjunction with those waves
  - in conjunction with density depletions at the interface of cold/hot plasma
- Ion heating is observed:
  - In conjunction with the approaching structure, but is more gradual
- Flow acceleration/deceleration can be understood as:
  - imbalance between pressure/tension [Shanshan Li, 2009, in preparation]
- Ion heating can be traced to:
  - dissipation at the interfaces [Xiaojia Zhang, 2009, in preparation]

Non-linear phenomena within the BBFs/dipolarization

Ergun et al, PRL, 2009



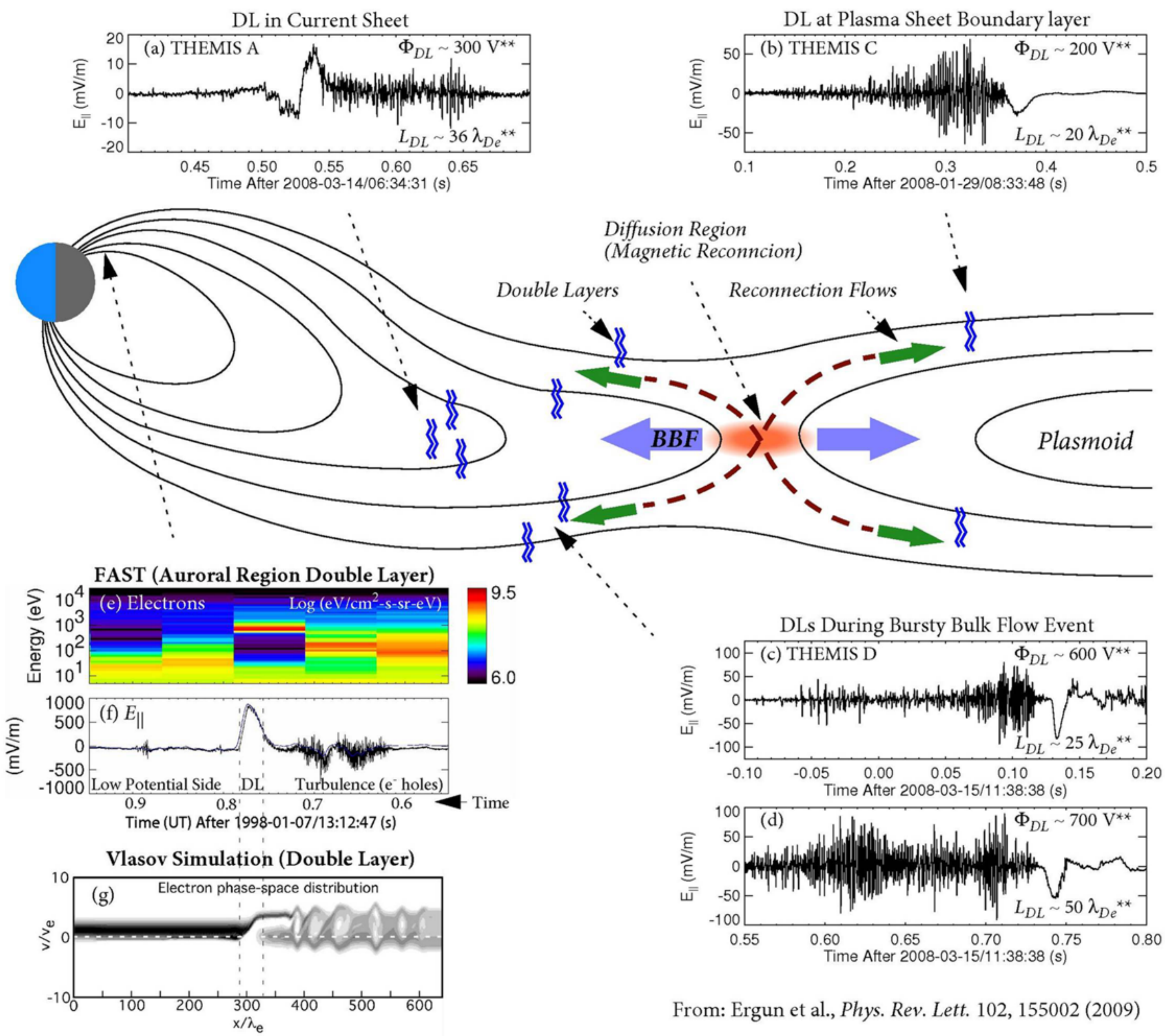




Assuming 250km/s<V_{DL}<$V_{i,s}$ (1400km/s) then:

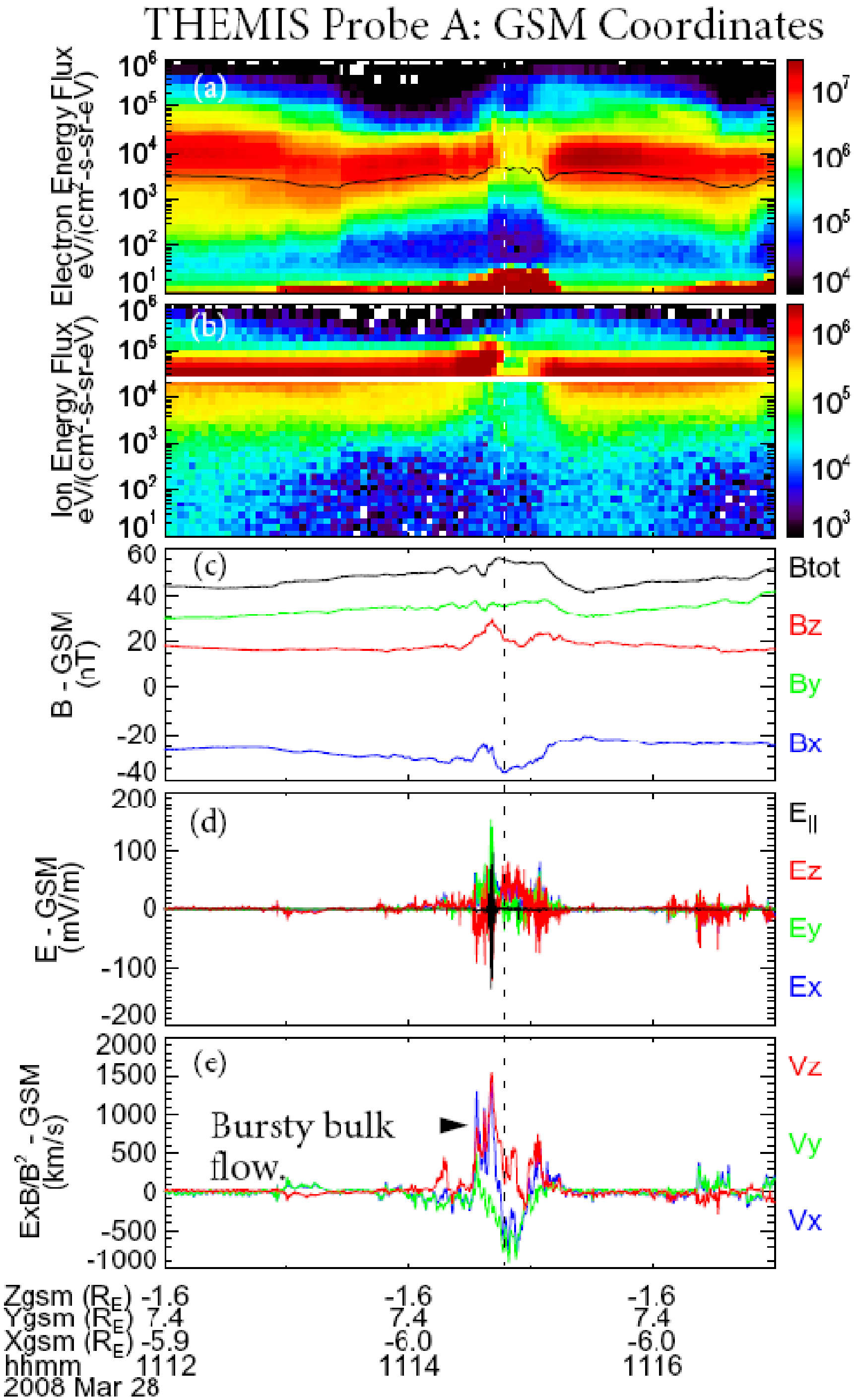
- L_{II}~5-30km~5-30λ_D
- Φ_{DL}~ 0.25-14keV ~ kTe

THEMIS Observations of Double Layers in the Plasma Sheet



From: Ergun et al., *Phys. Rev. Lett.* 102, 155002 (2009)

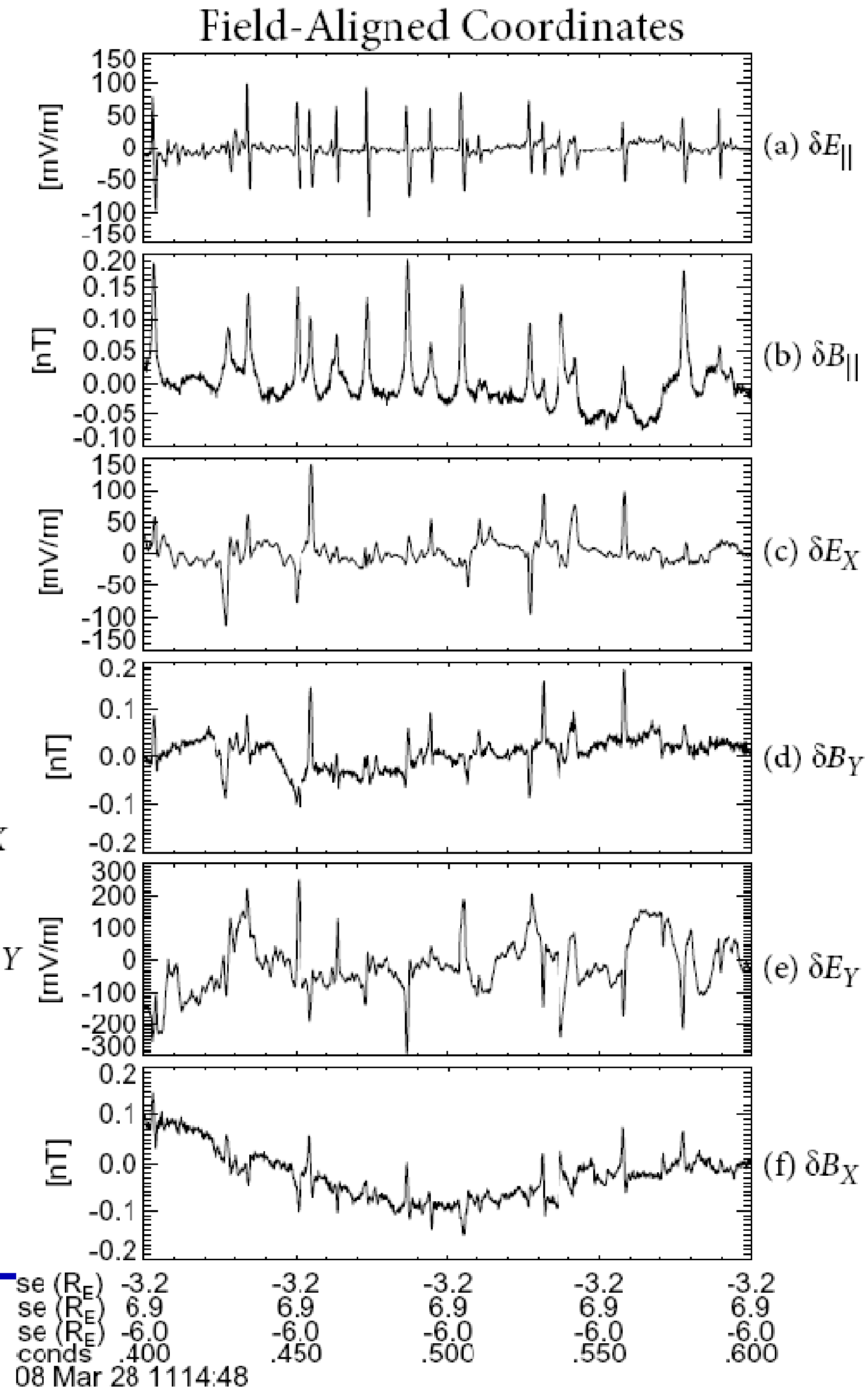
Electron Hole Properties
(Anderson et al., PRL 2009)



Lorenz:

$$\delta B_Y = \frac{v_{EH}}{c^2}\delta E_X$$

$$\delta B_X = -\frac{v_{EH}}{c^2}\delta E_Y$$



Electron Hole Properties

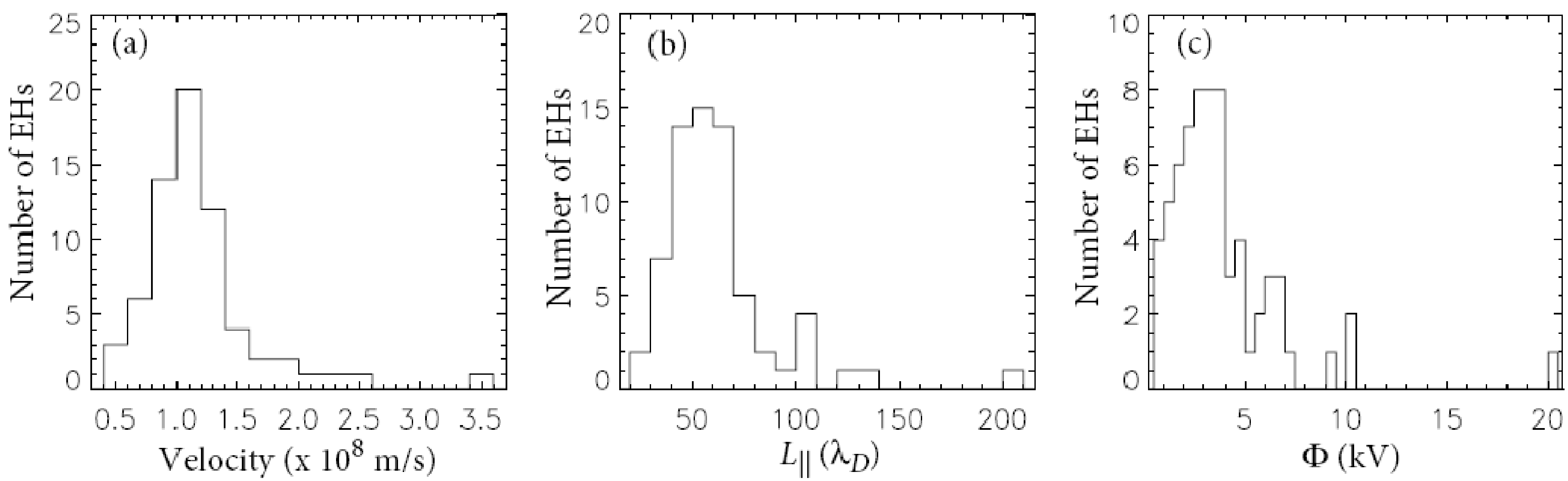
First observations of "fast" electron holes:

$V_{EH} \sim 100{,}000$ km/s $> V_{e,th} \sim 40{,}000$ km/s

$L_{II} \sim 60 km \sim 50 \lambda_D$

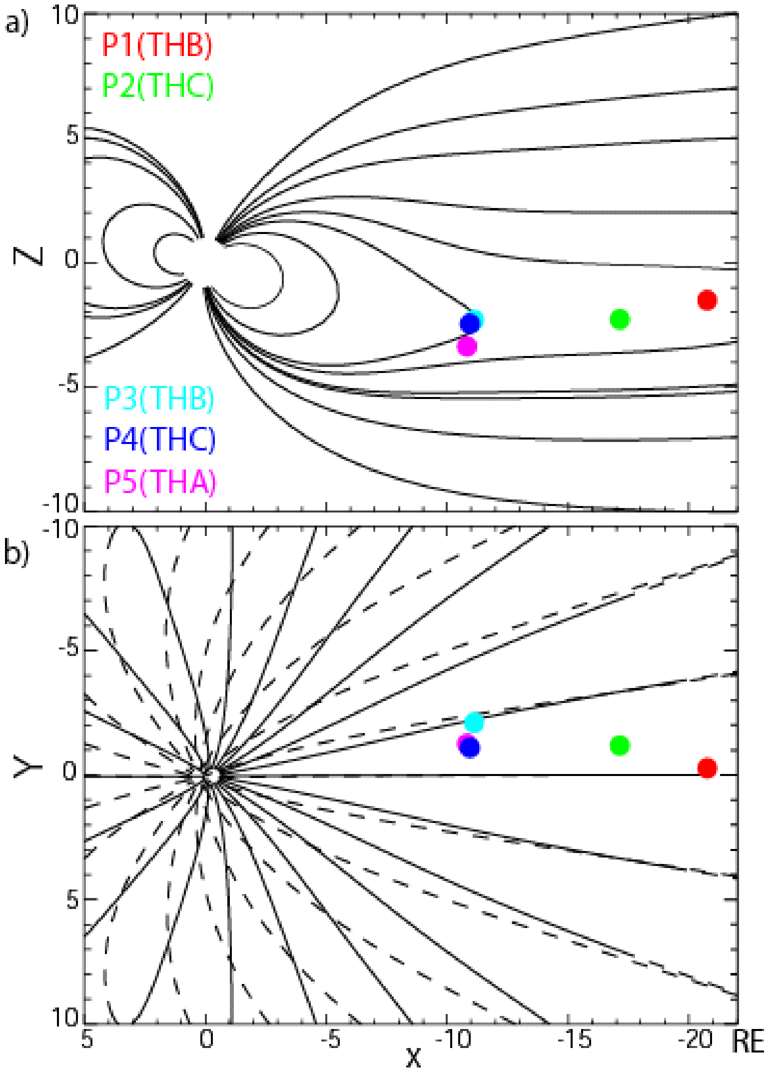
$\Phi \sim 4 keV \sim 0.5\, kT_e$

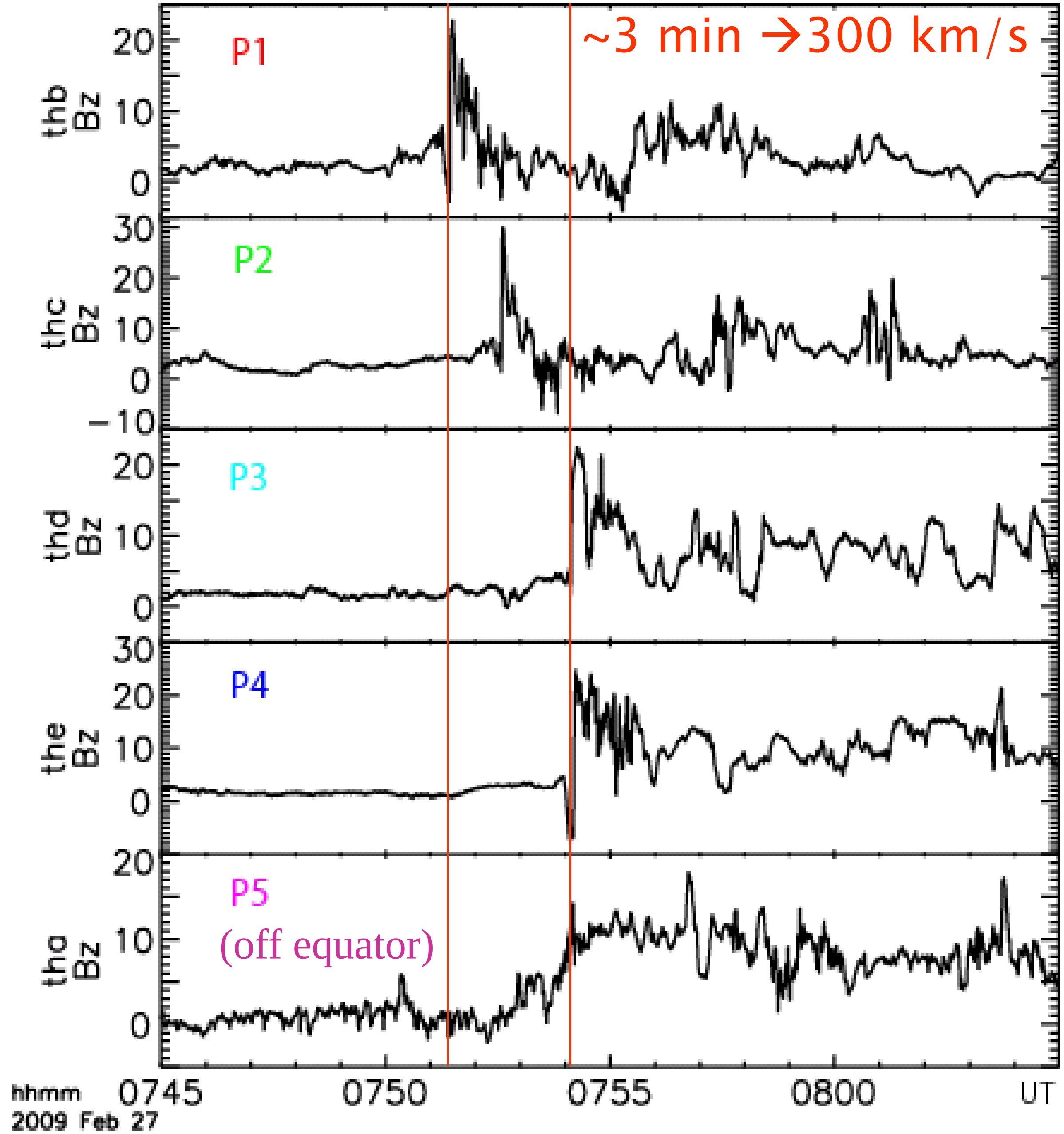
Remote sensing of presence of DL's on that field line

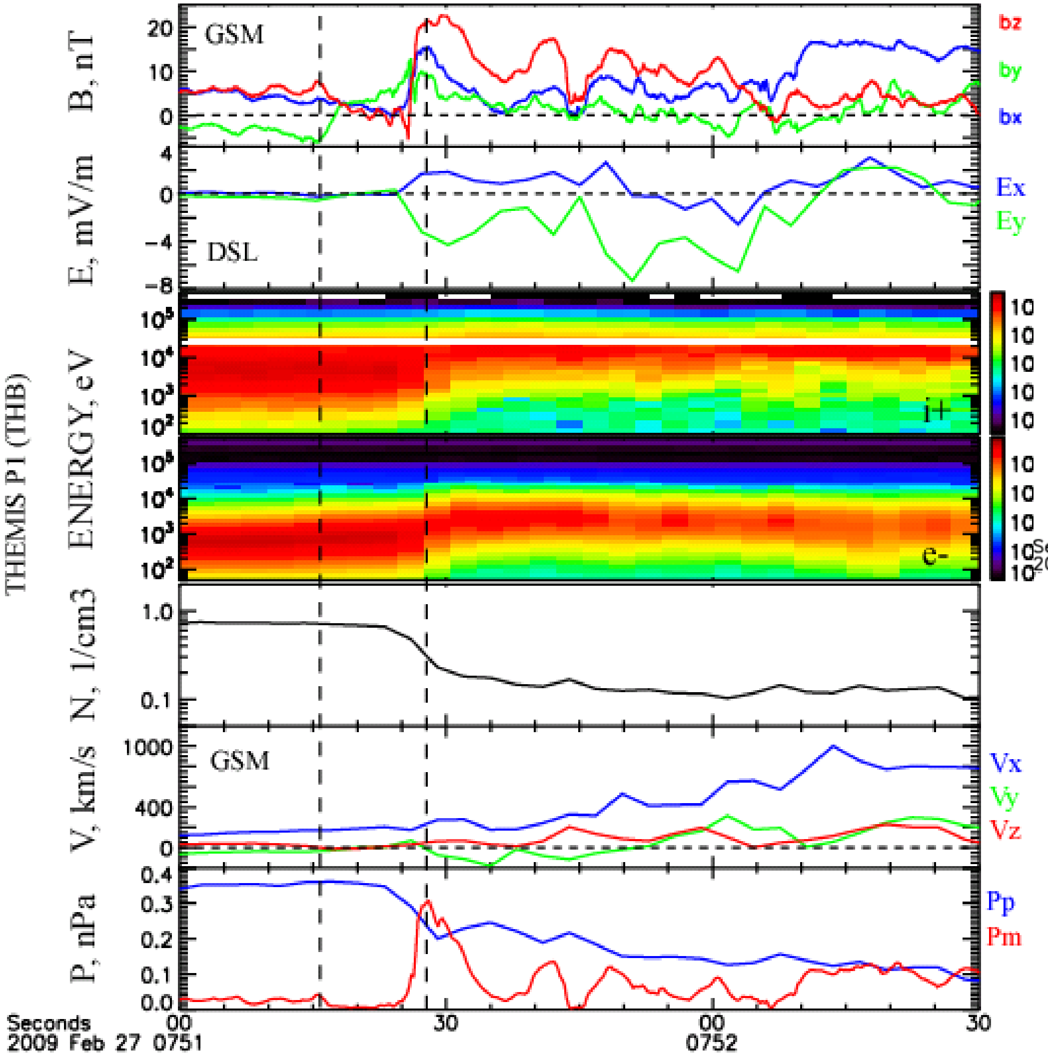


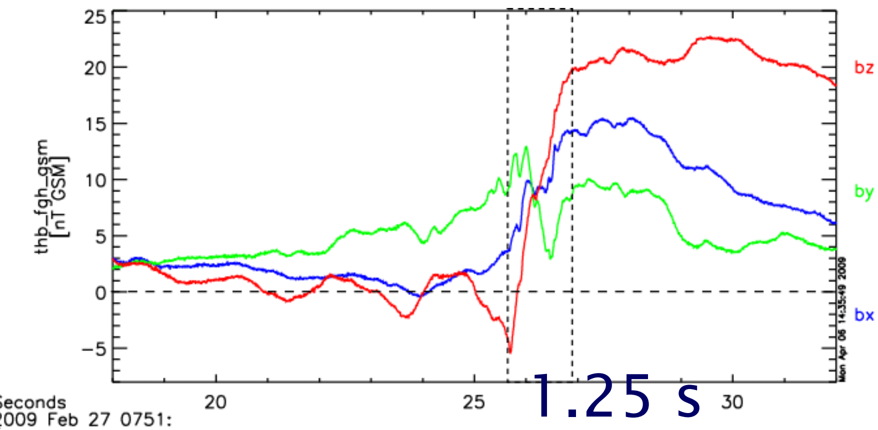
How far? THEMIS configuration and Bz time series during 0745-0805 UT

Runov et al., GRL 2009



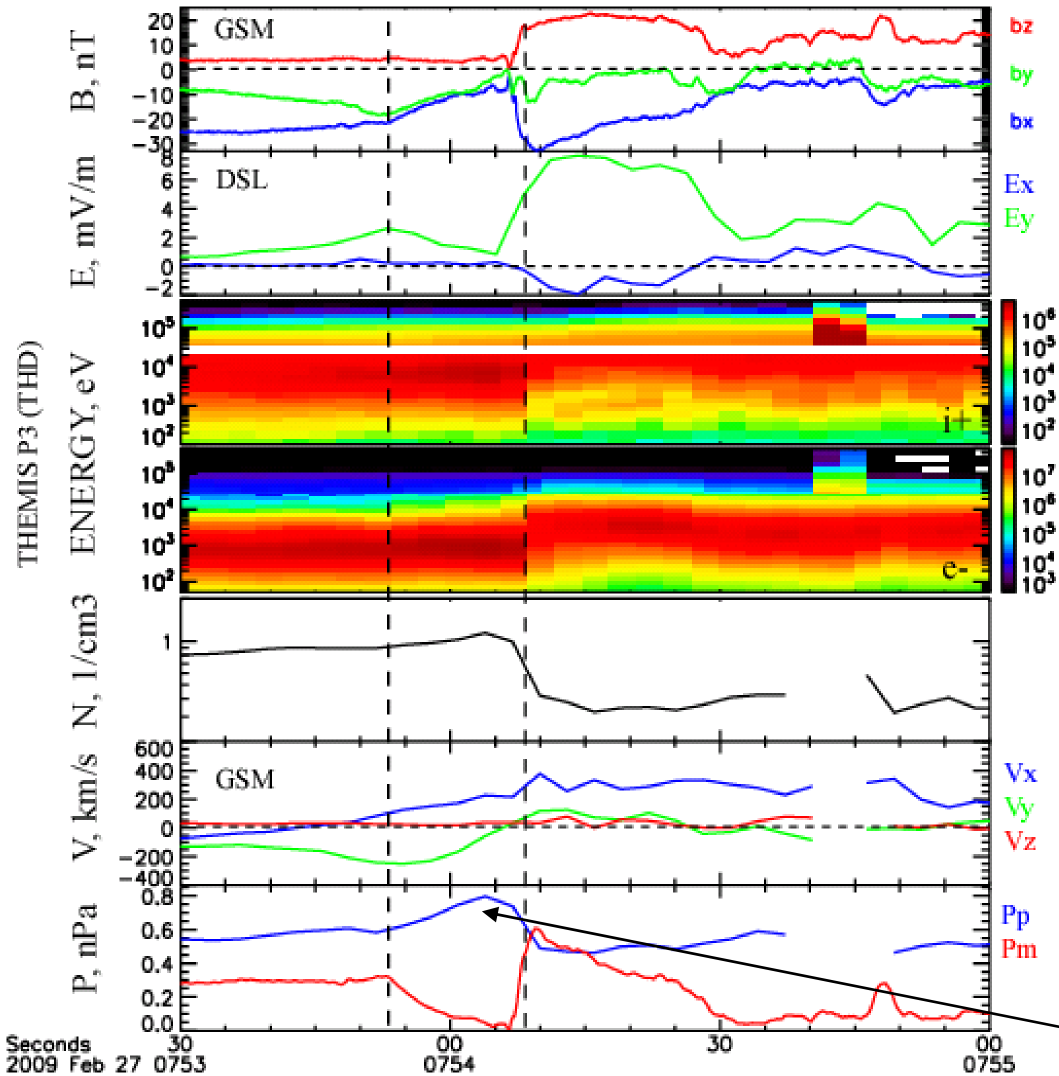




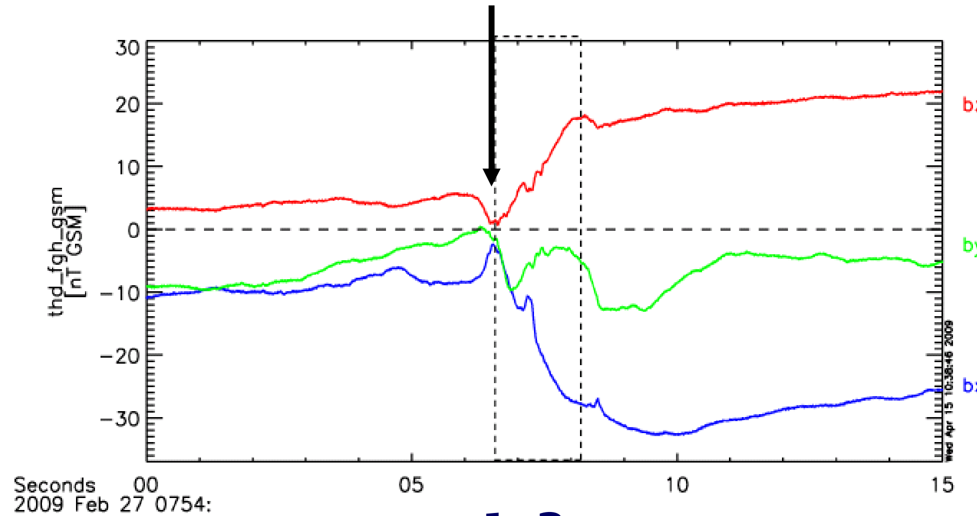


Assuming 300 km/s propagation velocity, the DF thickness is ~400 km < ion thermal gyroradius in the upstream field; comparable to the ion skin depth.

P3 @ [-11.1, -2.8, -2.1]



Bz decrease



1.3 s

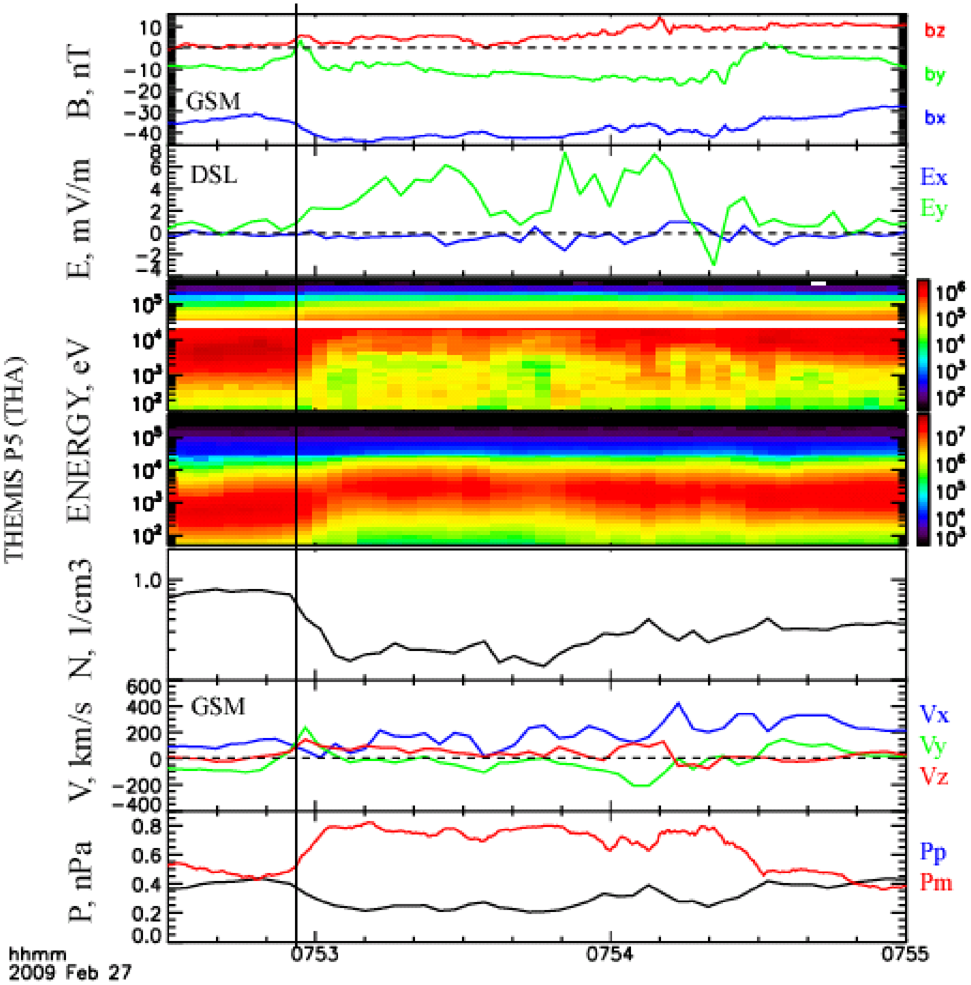
~400 km

A short decrease (~1 s -> 300 km) in Bz (and occasionally other components as well as Bt) prior to the dipolarization front: due to the approaching current layer.

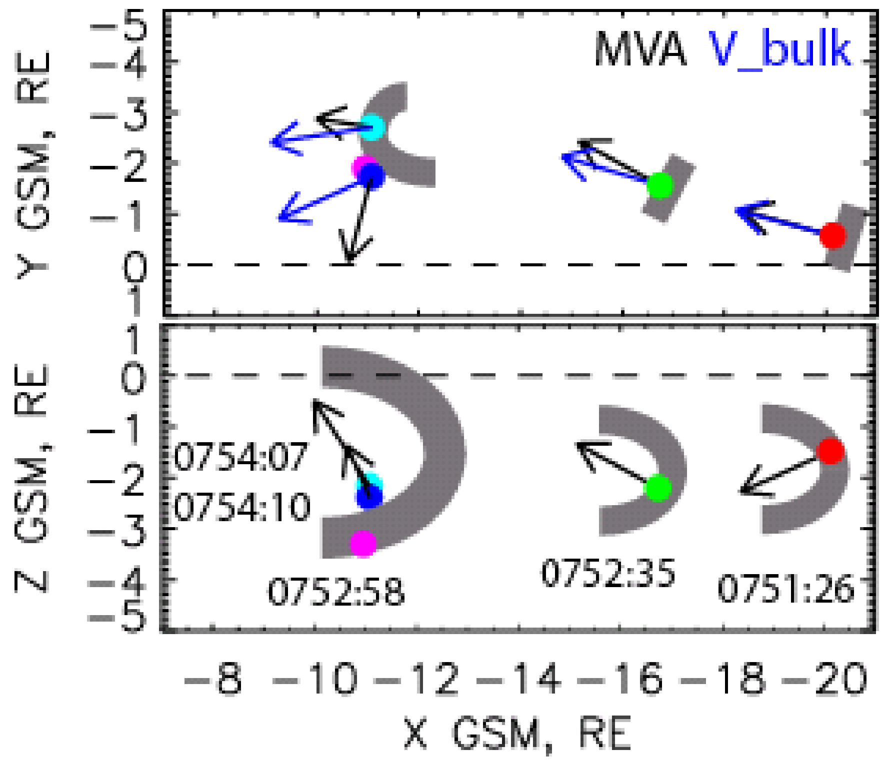
Diamagnetic effect (30sec ->2R_E)

P5 @ [-11.0, -1.9, -3.3]

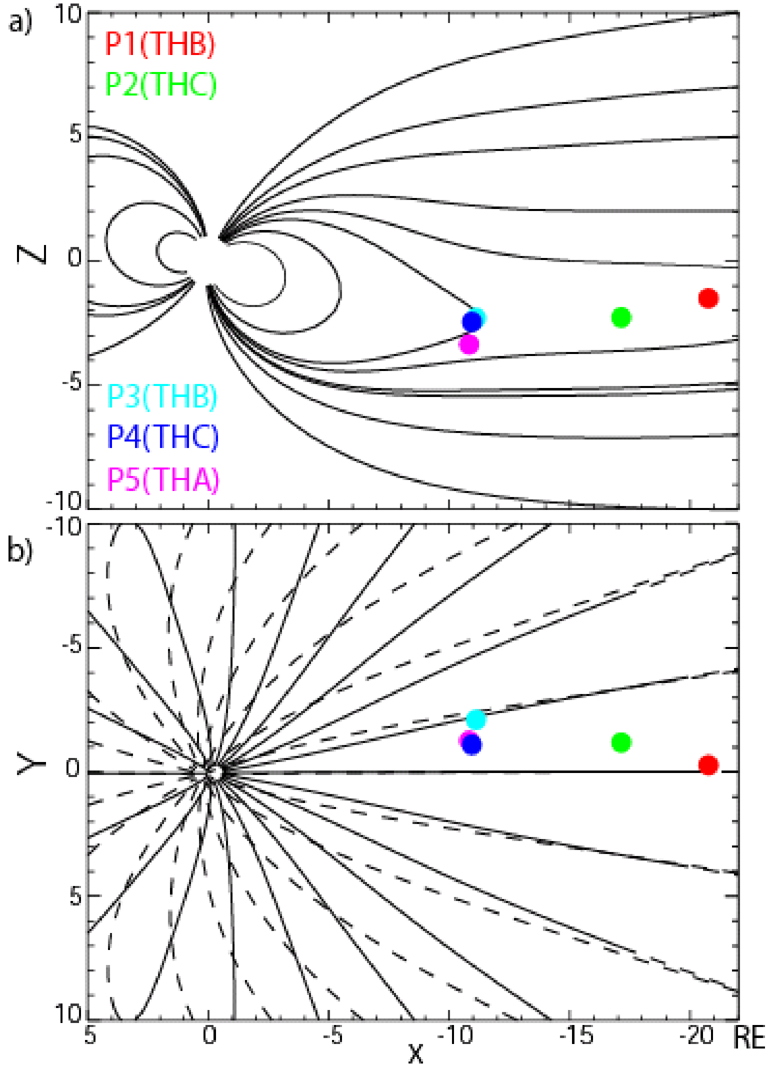
Increase of Pm
Earlier than P3/P4

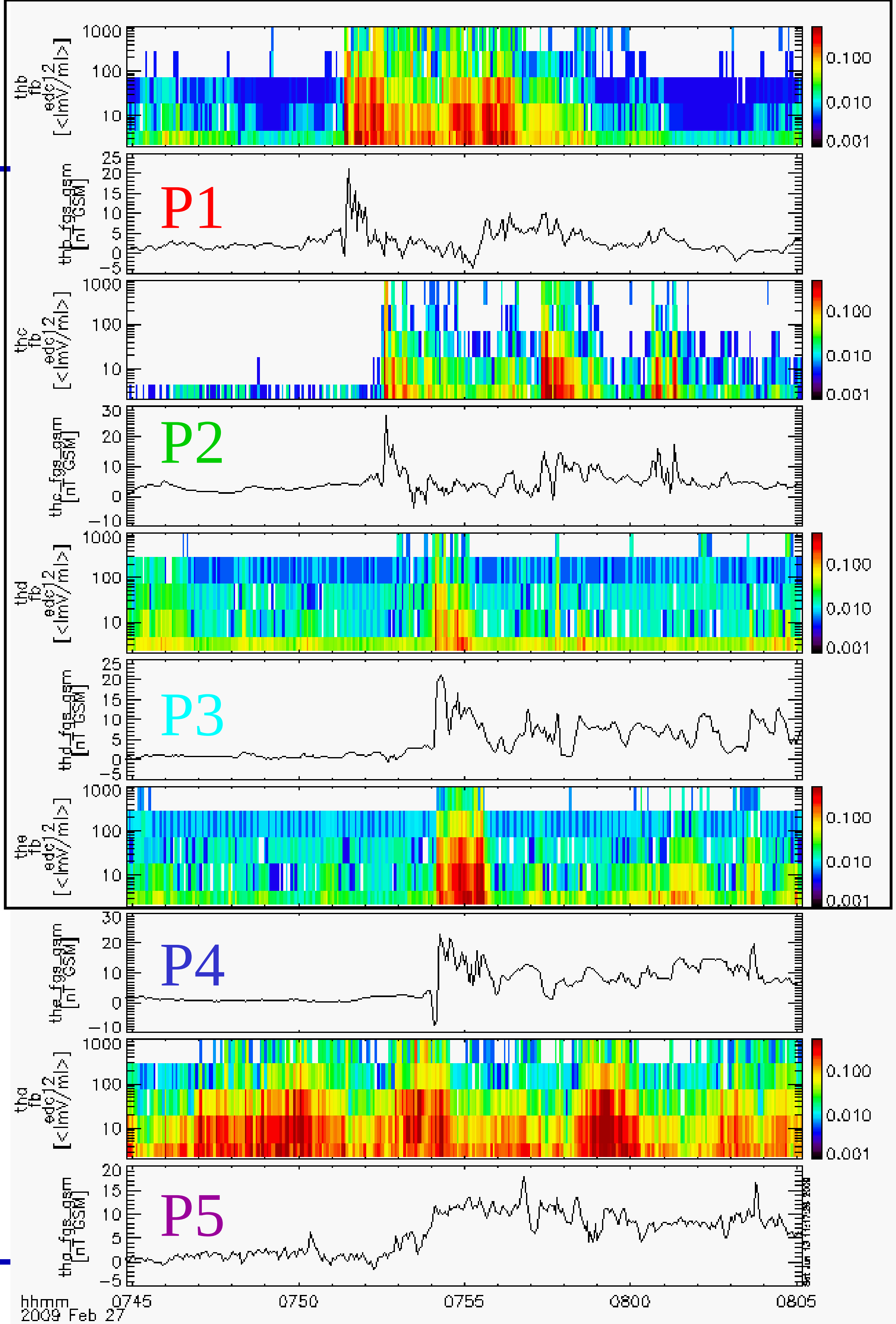


Interpretation scheme

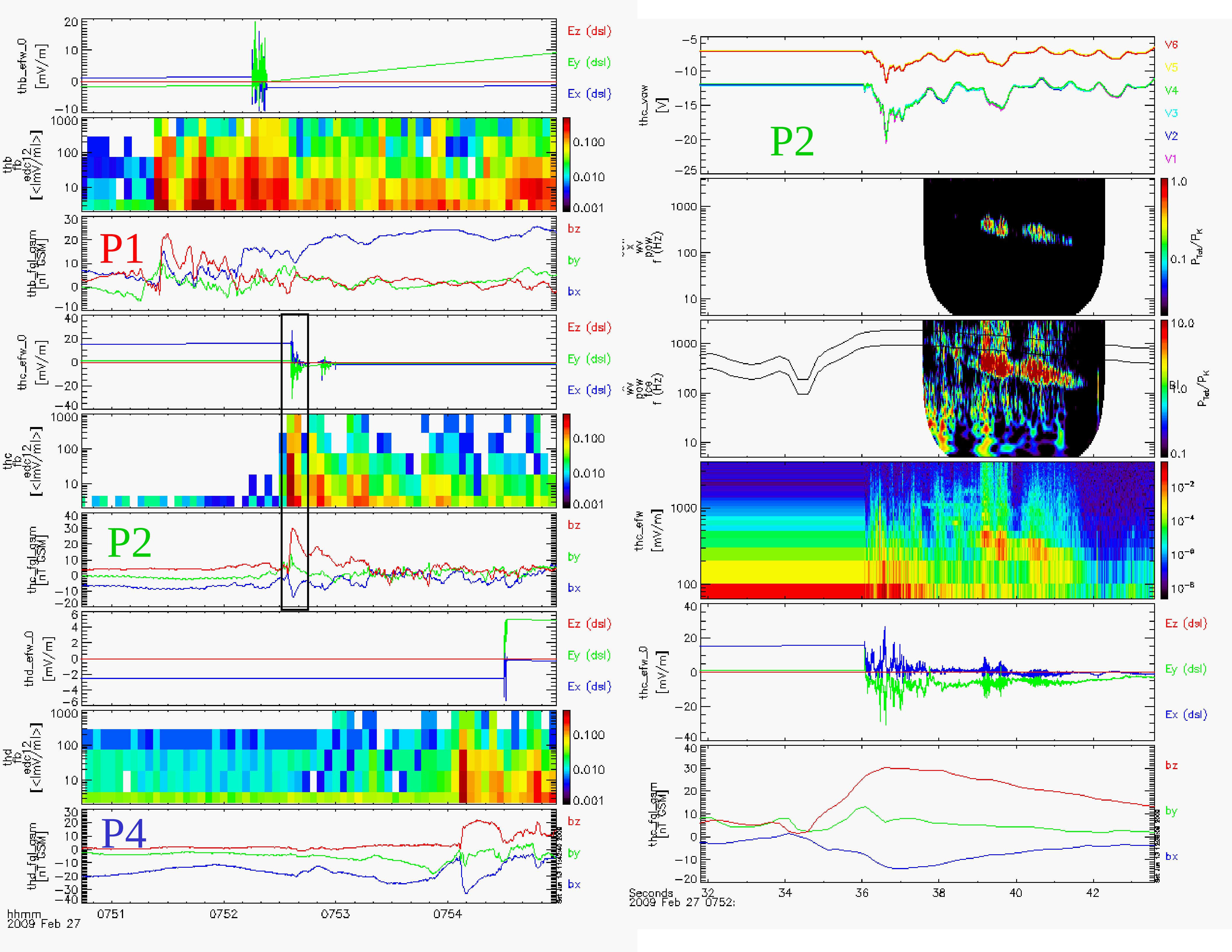


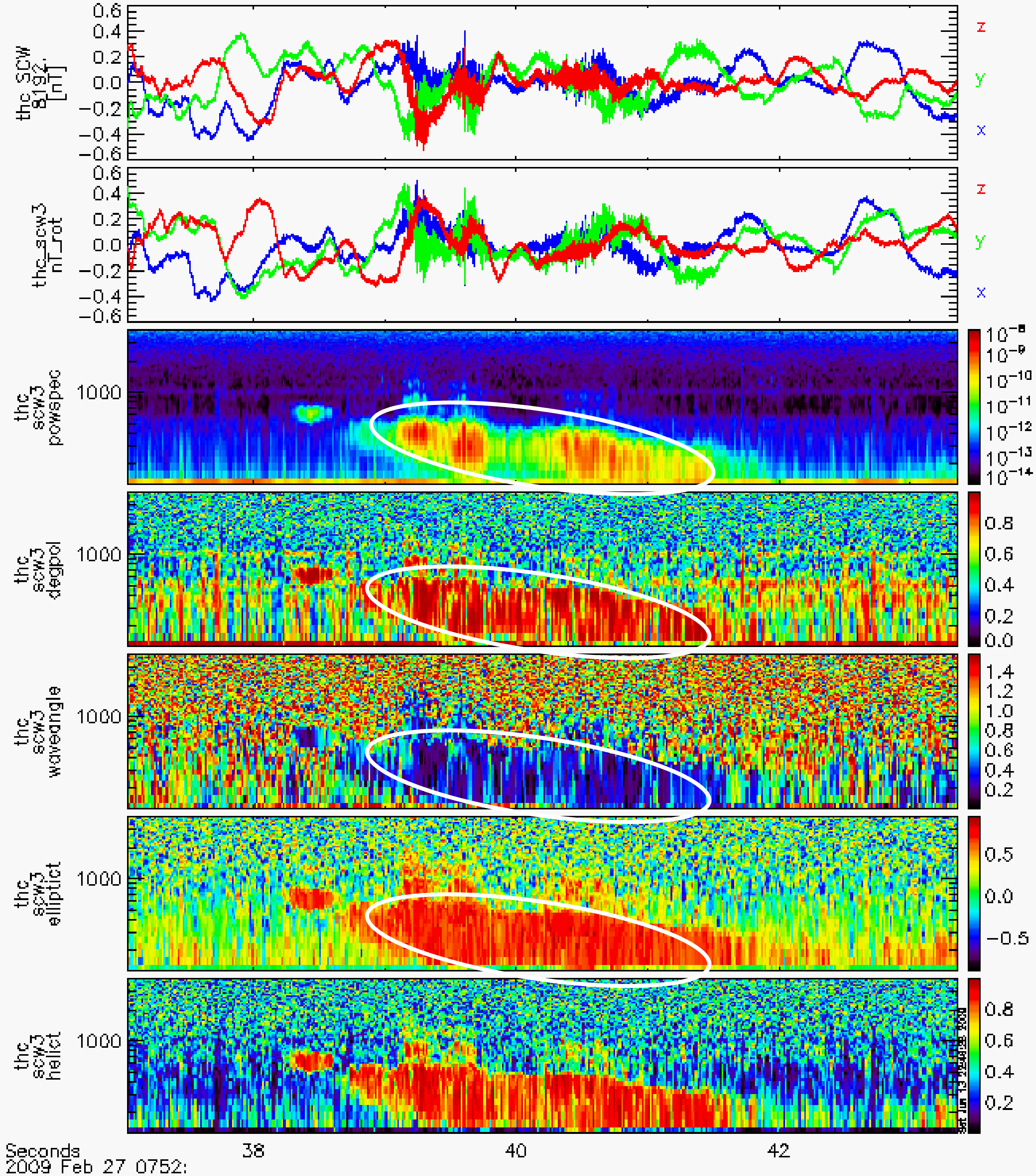
THEMIS





Angelopoulos et al., 2009


P1
P2
P4
P2
thb_efw_0 [mV/m]
Ez (dsl)
Ey (dsl)
Ex (dsl)
thb fb edc12 [<|mV/m|>]
thb_fgl_gsm [nT GSM]
bz
by
bx
thc_efw_0 [mV/m]
thc fb edc12 [<|mV/m|>]
thc_fgl_gsm [nT GSM]
thd_efw_0 [mV/m]
thd fb edc12 [<|mV/m|>]
thd_fgl_gsm [nT GSM]
hhmm
2009 Feb 27
0751
0752
0753
0754
thc_vaw [V]
V6
V5
V4
V3
V2
V1
f (Hz)
thc_efw [mV/m]
Seconds
2009 Feb 27 0752:
32
34
36
38
40
42

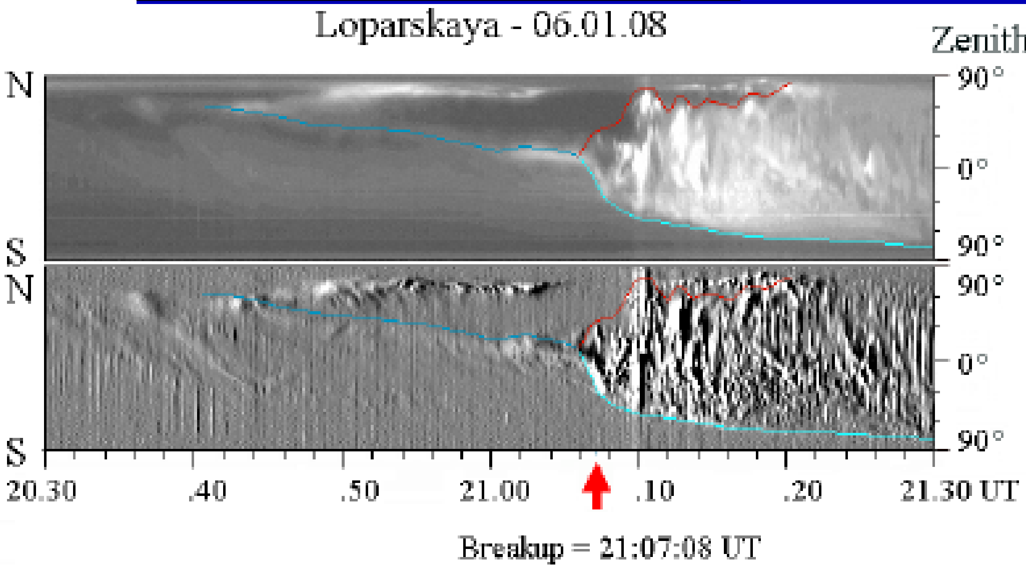


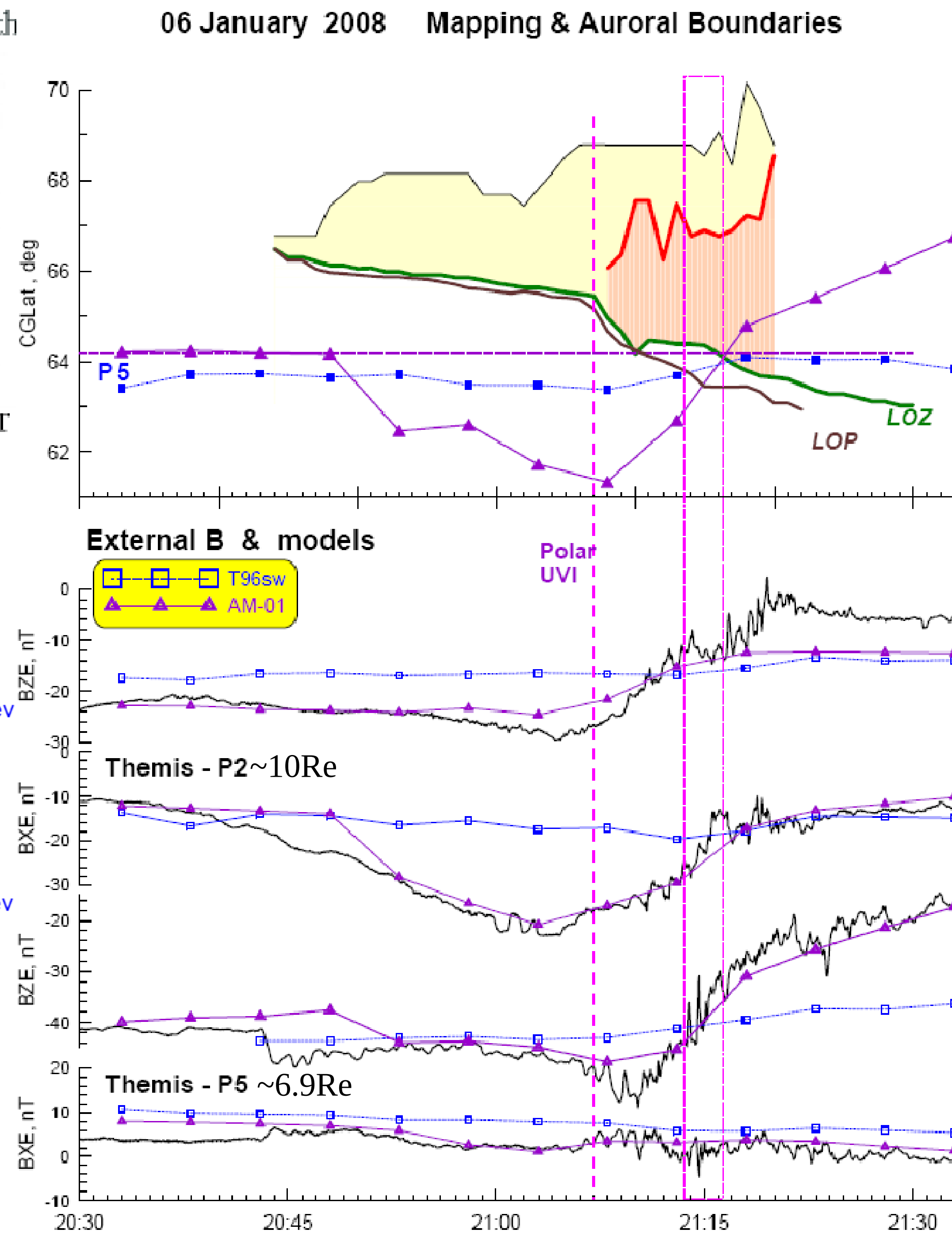
thc_scw 8192' [nT]
thc_scw3 nT_rot
thc scw3 powspec
thc scw3 degpol
thc scw3 waveangle
thc scw3 elliptict
thc scw3 helict
z
y
x
1000
Seconds
2009 Feb 27 0752:
38
40
42

Importance of non-linear waves at Bursty Flows

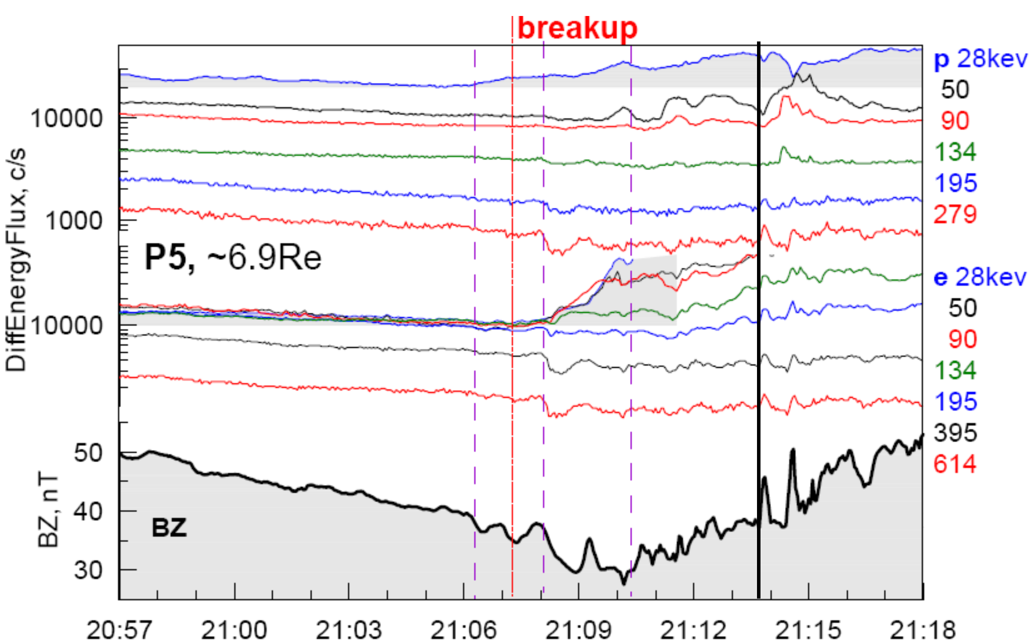
- Low hybrid waves may provide free energy for electron heating at the dipolarization interface
- Fermi and betatron acceleration may contribute to electron heating ahead and behind interface
- Resultant whistlers may contribute to electron scattering into loss-cone; non-linear behaviour may be related to wave saturation.
- Electron energy density has been observed - on occasion - to exceed 1 erg/cm^2/s and may result in:
  - First signature of aurora at onset
  - Increased local conductivity in the ionosphere, allowing flow of bursty flow-related currents through the ionosphere and convection.
- BBF double layers provide missing link between magnetotail and ionospheric potential acceleration – an important first step in understanding global substorm arc electrodynamics

Expansion phase bursty flows in connection to auroral bulge



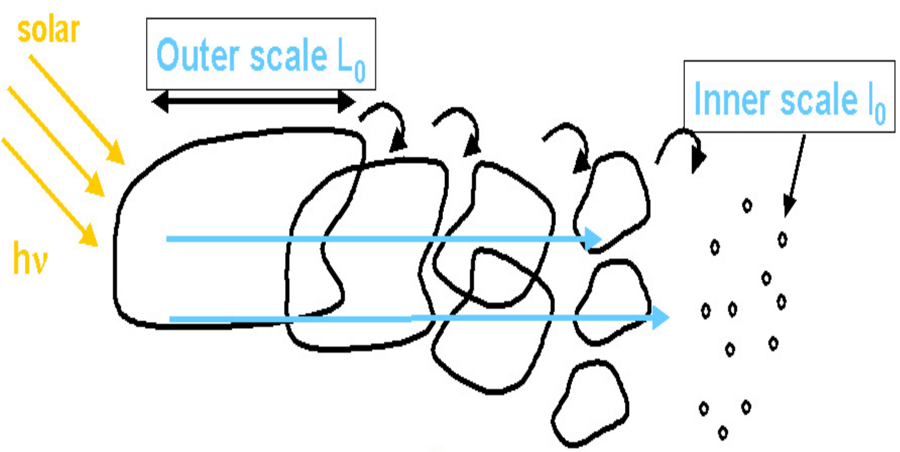


Sergeev et al., 2009, submitted



Turbulent cascade

In the atmosphere, using regular hydrodynamics, turbulence is a primary means of enery dissipation



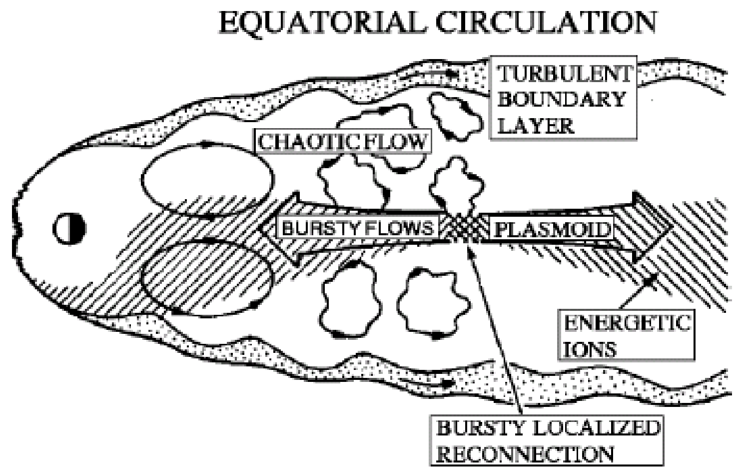


FIG. 3. Pictorial representation of magnetospheric circulation at the equatorial plane. Shown are localized busty flows that drive vortical (turbulent) flows. [Adapted from Kennel (Ref. 10).]

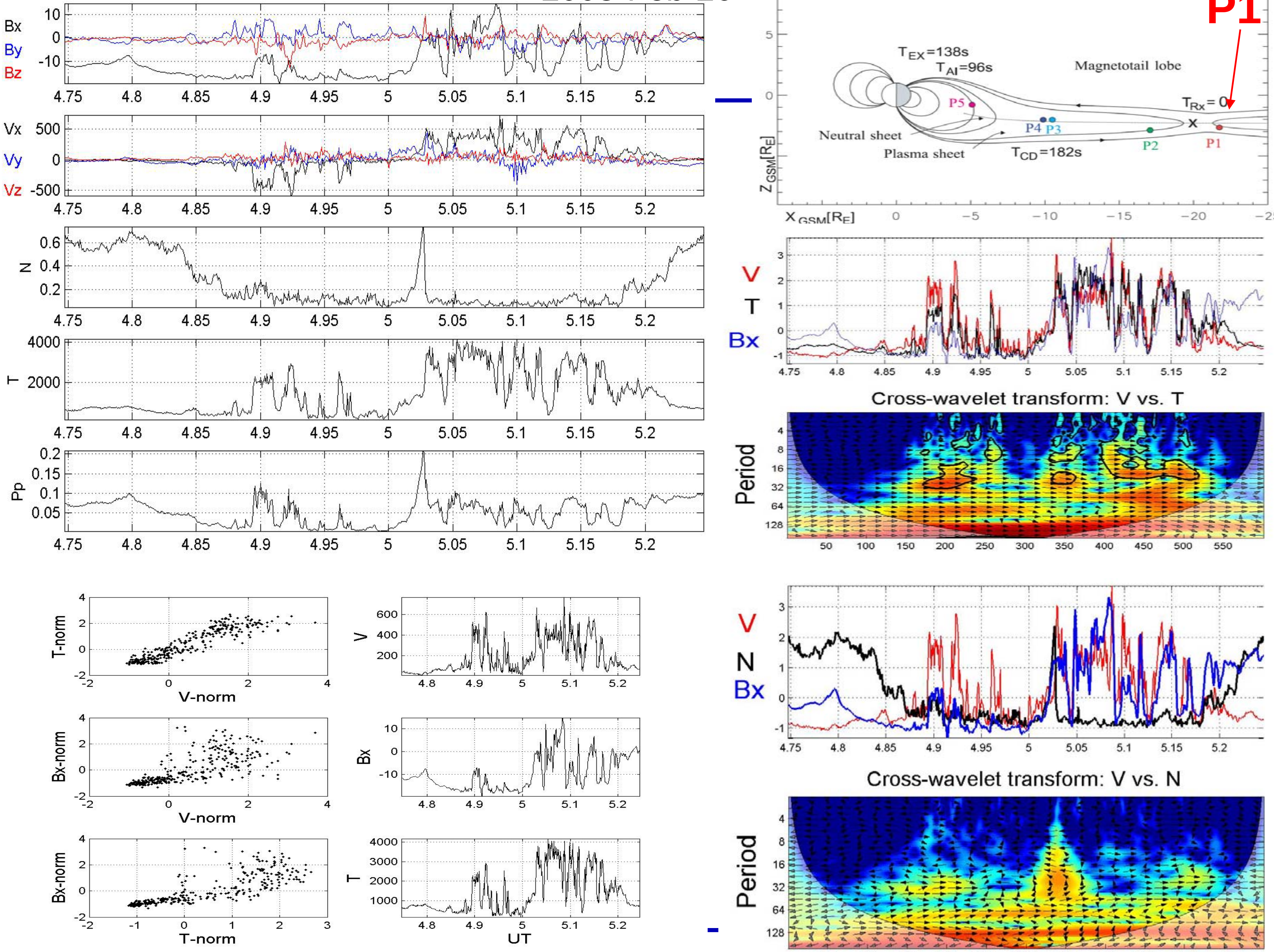
In the magnetotail, two main questions regarding dissipation are:

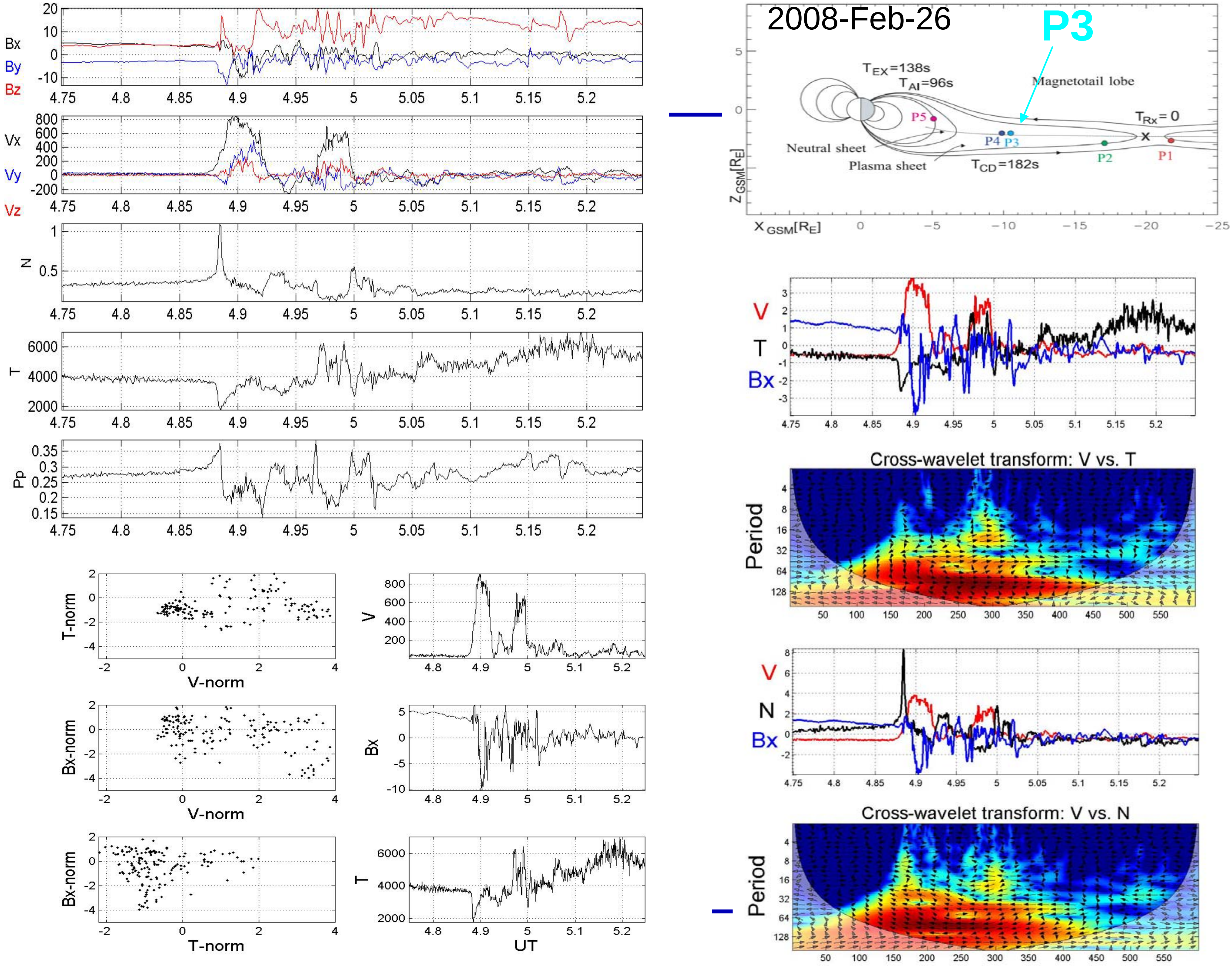
– To understand the mechanism by which the energy contained in large-scale drivers (BBFs) is transferred to smaller scales or higher frequencies
– If sufficient energy is contained in high frequency/small scales, then how is this energy the eventually deposited as thermal energy in the plasma

- It is unclear how to determine spatial correlations from time series data with single spacecraft in the plasma sheet. Use of the Taylor hypothesis, as in the solar wind, is not always warranted. Single spacecraft time-series are representative of spatial scales for fast flows, but not for slow flows [Voros et al., 2007].

- THEMIS provides the opportunity to understand how the fluctuations evolve in space

2008-Feb-26


Bx
By
Bz
Vx
Vy
Vz
N
T
Pp
UT
P1
P2
P3
P4
P5
T_EX=138s
T_AI=96s
T_Rx= 0
T_CD=182s
Magnetotail lobe
Neutral sheet
Plasma sheet
Z_GSM[R_E]
X_GSM[R_E]
V
T
Bx
Cross-wavelet transform: V vs. T
Period
N
Cross-wavelet transform: V vs. N
T-norm
V-norm
Bx-norm



2008-Feb-26
P3
T_{EX}=138s
T_{AI}=96s
Magnetotail lobe
T_{Rx}= 0
P5
P4 P3
P2
P1
Neutral sheet
Plasma sheet
T_{CD}=182s
$Z_{GSM}[R_E]$
$X_{GSM}[R_E]$
Bx
By
Bz
Vx
Vy
Vz
N
T
Pp
T-norm
V-norm
Bx-norm
T-norm
V
Bx
T
UT
V
T
Bx
Cross-wavelet transform: V vs. T
Period
V
N
Bx
Cross-wavelet transform: V vs. N
Period

- It is unclear how to separate with single spacecraft space from time. Use of the Taylor hypothesis, as in the solar wind, is not always warranted in the tail. Single spacecraft time-series are representative of spatial scales for fast flows, but not for slow flows [Voros et al., 2007].

- THEMIS provides the opportunity to understand how the fluctuations evolve in space (Voros et al., 2009)
  - Near the source, there is a strong correlation with distance to the neutral sheet. The moment correlations suggest Taylor hypothesis is not valid due to encounters of different plasma parcels and different flow structures within.
  - Away from the source, moments do not exhibit similar correlations suggesting that Taylor-hypothesis may be more valid. The leptokyrtic nature of the PDFs there is a good indicator of turbulence.

- Future: Emphasis has to be placed on interaction of BBFs with ambient plasma, far from Rx site, and closer to the inner edge of the plasma sheet. This is expected to happen at decreasing distances in the extended mission phase.

Synthesis: BBFs are kinetic, non-linear phenomena with global effects

- Reconnection (likely at multiple sites) takes hold spontaneously in thin current sheets – possibly in response to an instability related to ion escape.
- In the absence of significant ionospheric conductivity current closure is prohibited, convection quenched. Rapid flow dissipation may occur through turbulence and Poynting flux radiation.
- Electron heating by LH waves, betatron/Fermi, and scattering by whistlers can create “first light” and enhance conductivity either in substorm precursors or during early substorm expansion phase onset.
- At the ensuing stage of substorm expansion, double layers/electron holes link the evolving aurora to the BBFs emanating from the reconnection site.
- Equatorward moving arcs within the auroral bulge move through the high conductance region efficiently; correspond to Earthward moving dipolarization.
- Further dissipation occurs at the sharp dipolarization fronts at the inner edge of the plasma sheet. Dissipation there is likely a combination of wave-particle interactions in thin layers and turbulent cascade within flow vortices.

10th INTERNATIONAL CONFERENCE ON SUBSTORMS

San Luis Obispo, California

March 22 - 26, 2010

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- Transportation (Coastal, between San Francisco and Los Angeles)

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Connecting via Los Angeles, San Francisco, Salt Lake City and Phoenix
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Twenty miles to Cambria and Paso Robles

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Activities: *Kayaking, Golf Course, Hiking, Hearst Castle, Wineries*

Links:
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San Luis Obispo
Pismo Beach (*meeting location*)

Pado Robles Wine Area, in San Luis Obispo County (*Larry's favorite California wine area*)
San Luis Obispo Wine Area