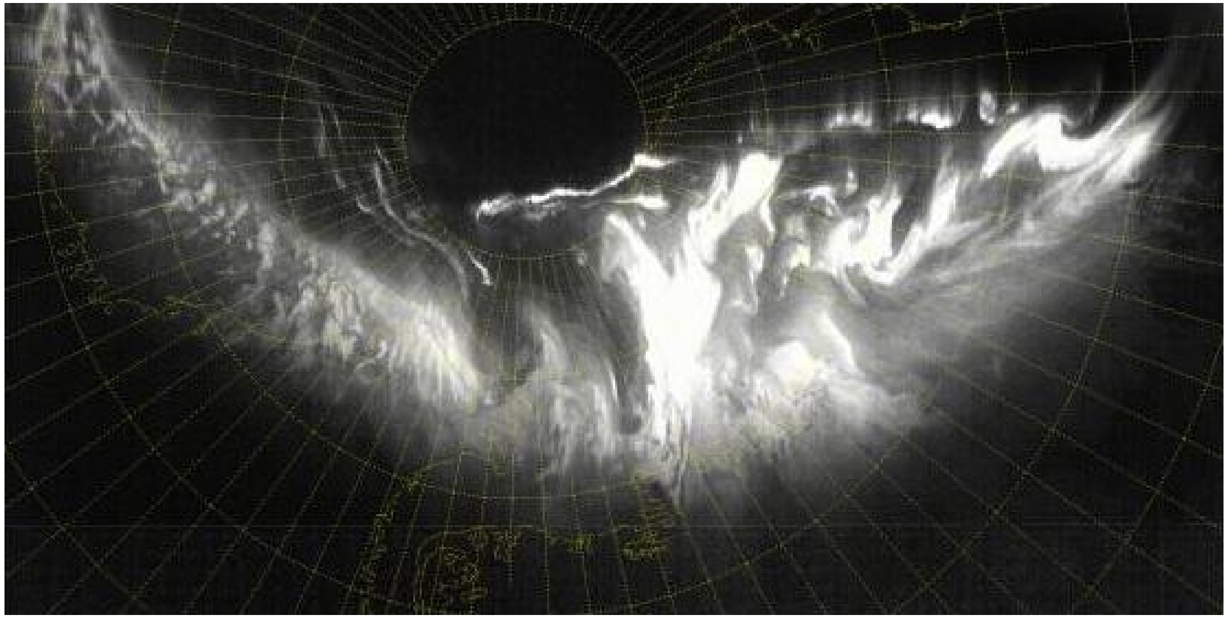
Can we solve the problem of substorms?

J.-A. Sauvaud

PNST, 13-14 octobre 2010

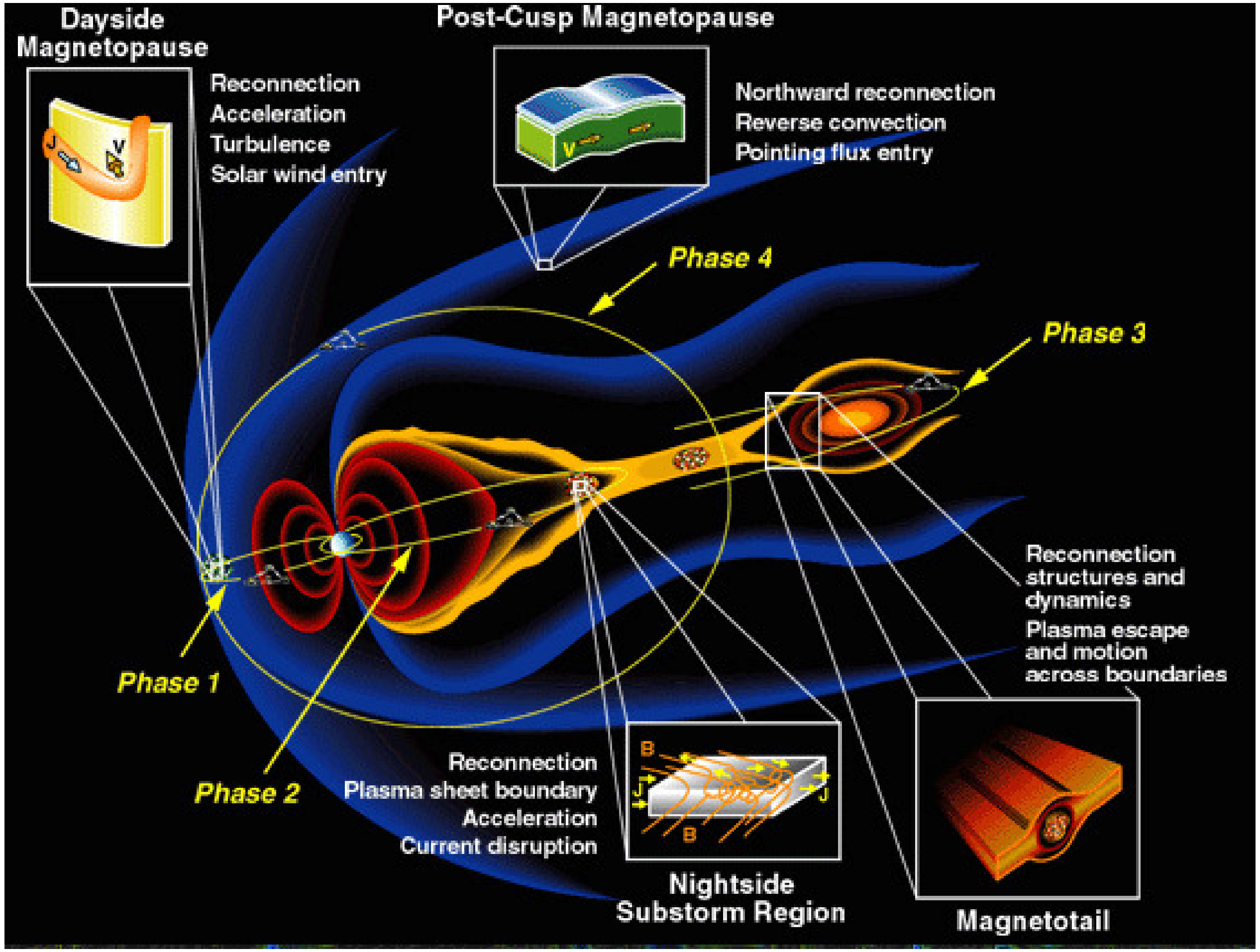


The FUV instrument on the IMAGE spacecraft observed more than 2400 substorm onsets.

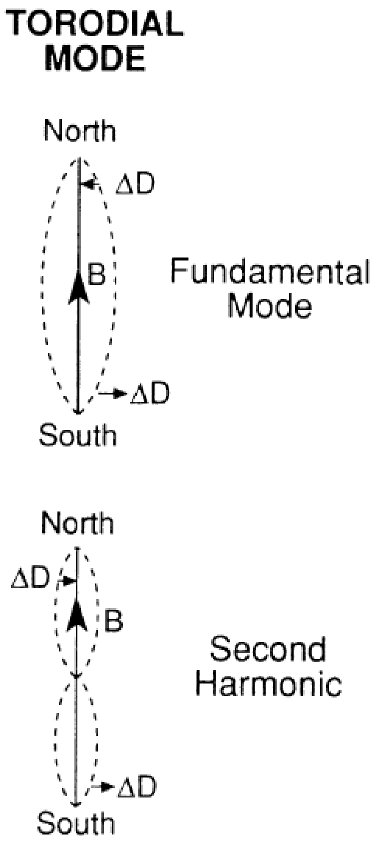
A median substorm onset location is 2300 hours MLT and 66.4 degrees magnetic latitude.

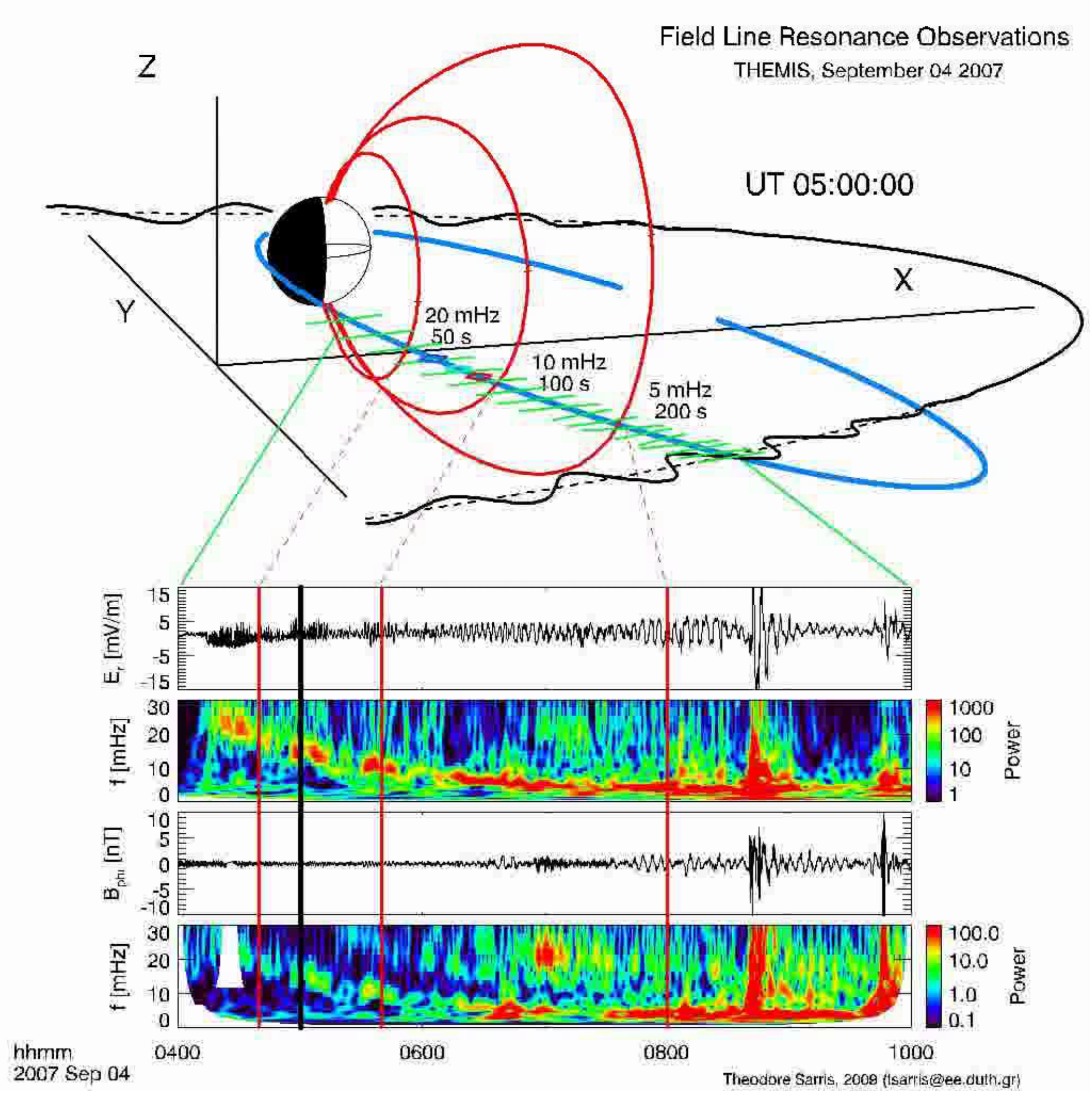
The problems

- (1) transformation of the solar wind kinetic energy into electromagnetic energy;
- (2) electromagnetic energy transfer into the magnetosphere;
- (3) organization of the system of currents, formation of field-aligned currents, and compatibility of these currents with the ionospheric current systems;
- (4) shape, value, and dynamics of the particle precipitation in auroral regions;
- (5) substorm expansion (auroral breakup)


Dayside Magnetopause
J
V
Reconnection
Acceleration
Turbulence
Solar wind entry
Post-Cusp Magnetopause
V
Northward reconnection
Reverse convection
Pointing flux entry
Phase 4
Phase 3
Phase 1
Phase 2
Reconnection structures and dynamics
Plasma escape and motion across boundaries
Reconnection
Plasma sheet boundary
Acceleration
Current disruption
B
J
J
B
Nightside Substorm Region
Magnetotail

Toroidal Mode Pulsations – Fundamental mode





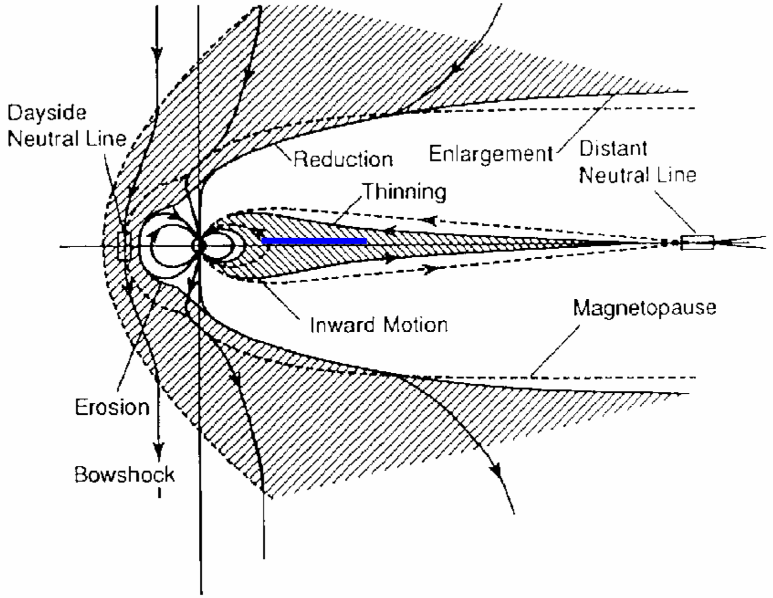
- *Southwood & Hughes, Space Sci Rev,1983*
- *Hughes, AGU Geophys. Monog. 81, 1994*
- *Hudson et al., Ann. Geophys., 2004*

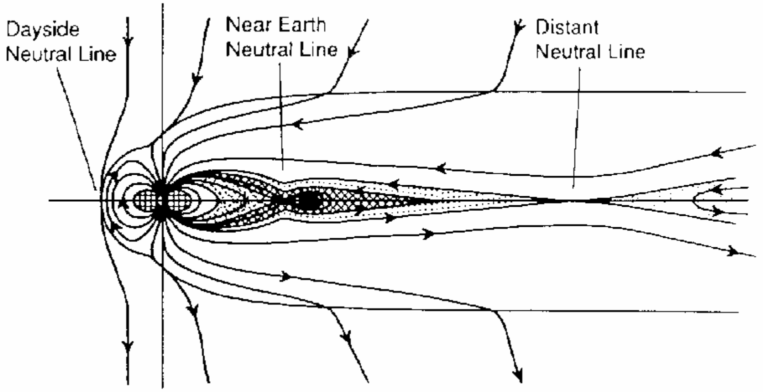
D'après Theodore SARRIS

Ideal substorm - Configuration changes

Substorm : A sequence of changes in the magnetosphere (loading/unloading) associated with explosive release of solar wind energy accumulated in the magnetotail

- Growth Phase
  - MF loading from dayside + depressed return flow (?),
  - tail current growth and B-field stretching, PS/CS thinning
- Transition to explosive instability
  - system catastrophe – loss of equilibrium
  - explosive growth of embedded TCS (?)
  - Instability onset
- Expansion phase
  - Explosive Magnetic Reconnection
  - Current disruption (MR or CInstability)
  - BBF, Dipolarization, plasma injection and flow braking, waves, turbulence
  - tailward progression
- Two basic strongly coupled tail processes :
  - Magnetic Reconnection
  - Interaction of closed plasma sheet tubes (controls and can stop convection and dissipation)





NENL model: Hones, Nishida, Baker et al. JGR 1996, 1998

Evolution of Closed Plasma Tube in the tail region

JGR special issue (role of entropy), reviews by Wolf et al. 2009, Birn et al.2009

MHD Entropy-based scenario (stability & dynamics, assume conservation of $S=PV^{5/3}$ in the moving closed plasma tube. S is violated in the inner tail (drifts))

○ average tail configuration – steep S(r) profile

Predictions:

– enforcing Earthward convection under strong SW driving, flat low S(r)

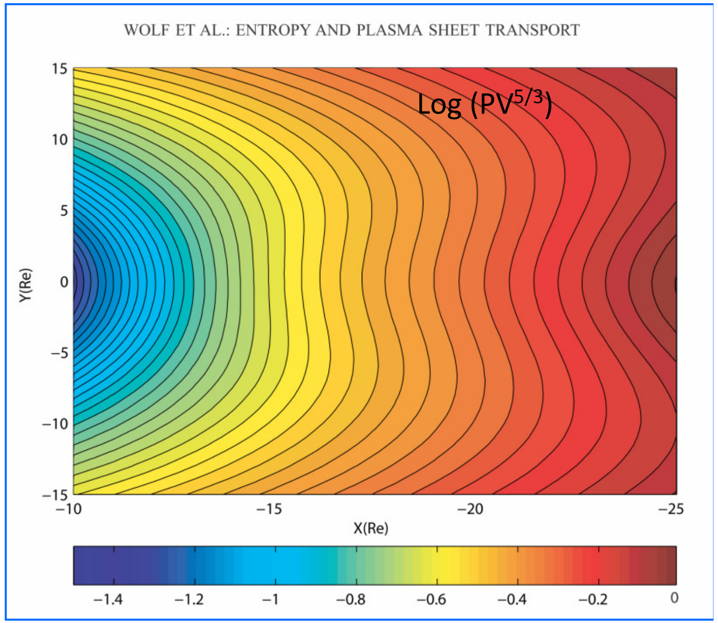
✓ Return convection, possible only in the narrow channel

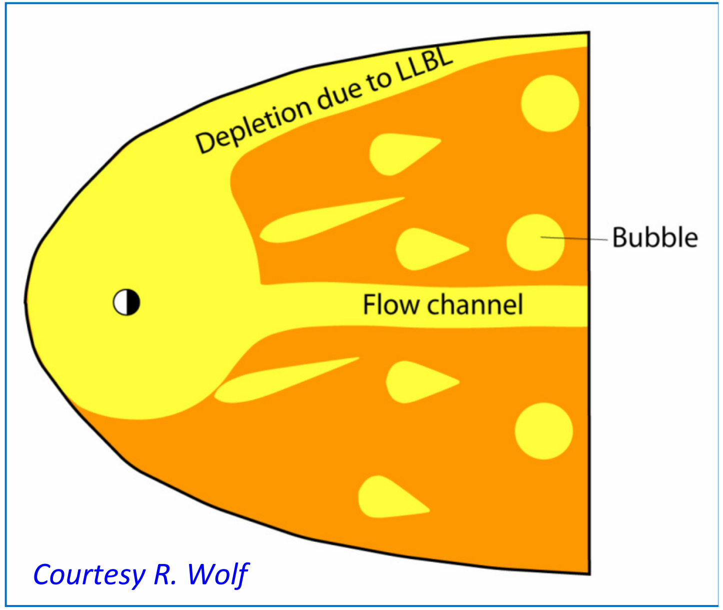
– …. , steep S(r) (*as in average tail*)

- depressed return PS convection, Ey~0 in the NS (pressure inconsistency)
- B and J grow in the tail, B tailward stretching
- Bz Min forms at near-Earth edge of tail CS
- Loss of equilibrium? But flux tubes with large $PV^{5/3}$ can not dipolarize (need MR, or ??)

– Localized region of low entropy (bubble)

- Bubbles forms (↑BZ ,↓n,P)
- Bubble penetrates inward until Sb=S





Courtesy R. Wolf

Depression of plasma sheet convection during the Growth Phase

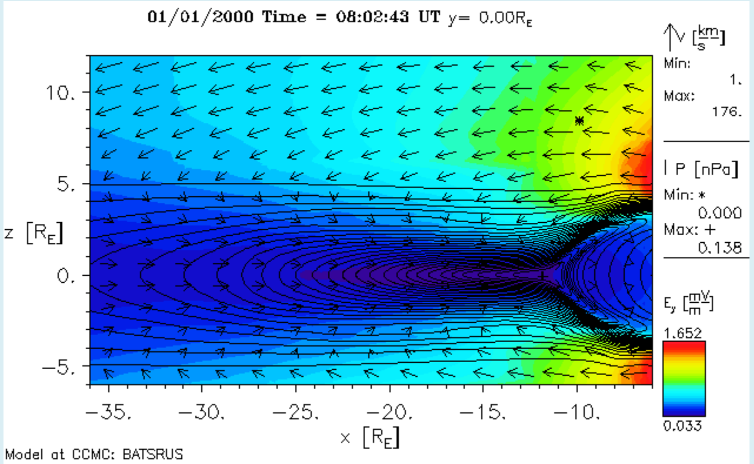
- **Neutral sheet ! Stable plasma. Weak flows**
- Averaging over 50min long

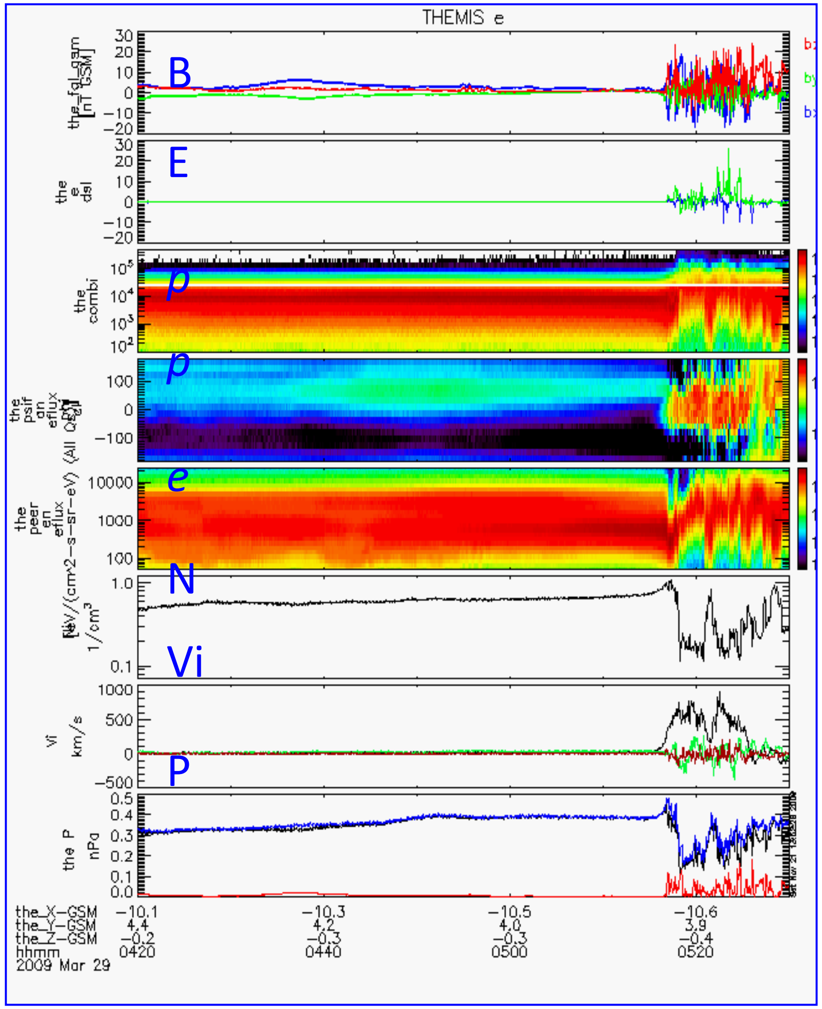
$E_y \approx \langle B \times V_i \rangle_y \approx 0.01\ \mathrm{mV/m}$

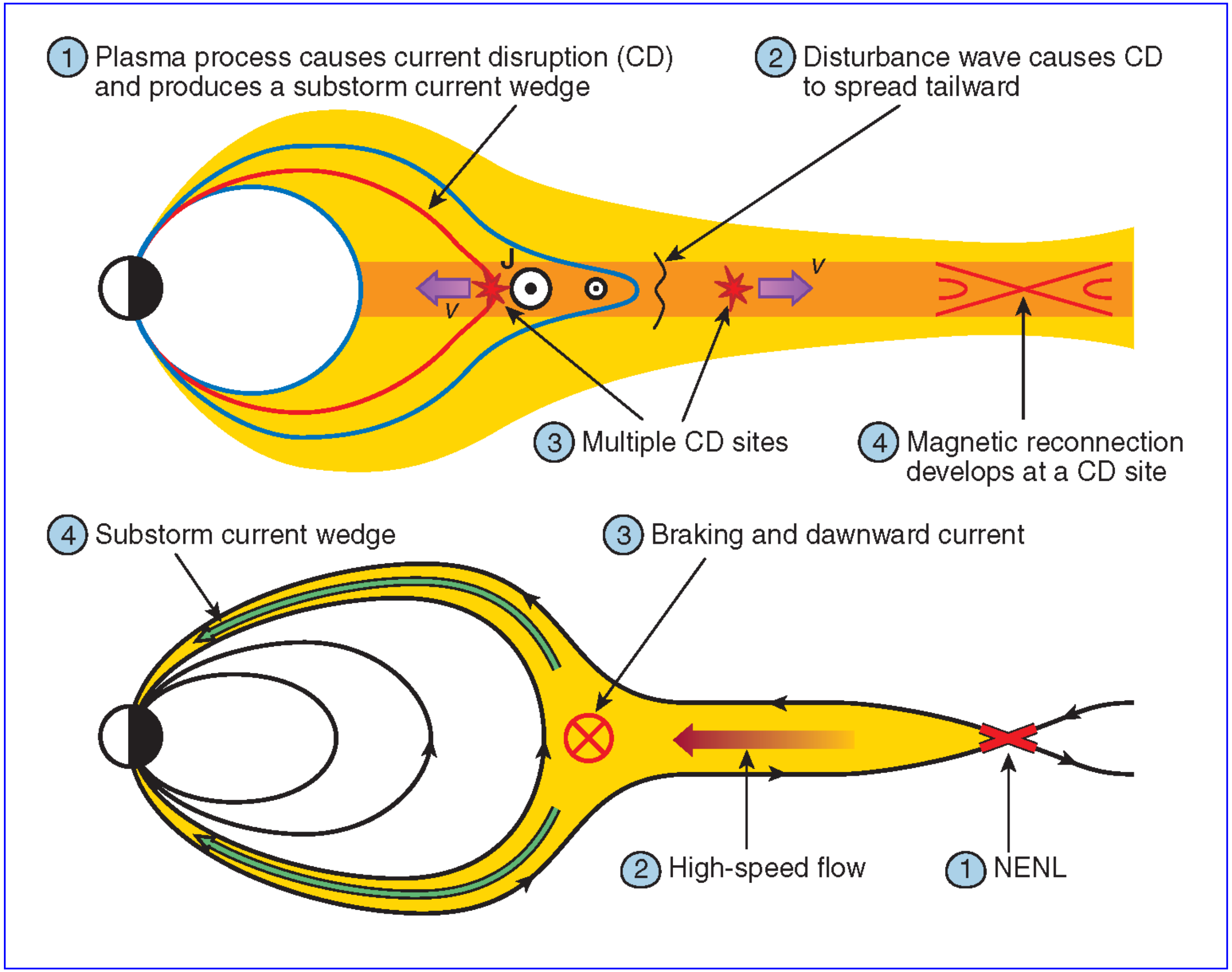
balanced convection rate would be

$\Delta\Phi / 2R_T \approx 50\mathrm{kV} / 50\mathrm{Re} \approx 0.15\ \mathrm{mV/m}$

$\Rightarrow$ ***' pressure inconsistency ' works***

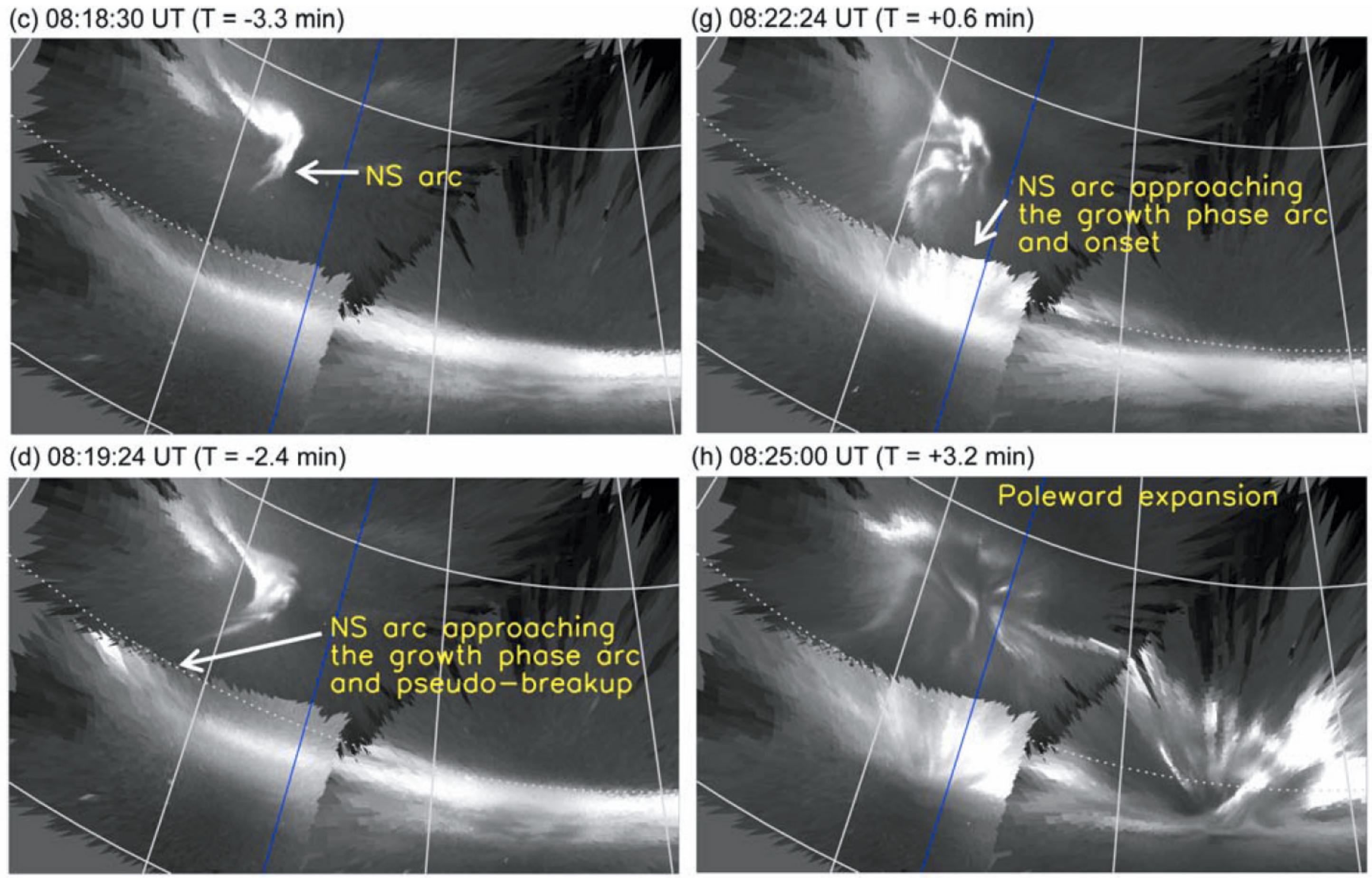





① Plasma process causes current disruption (CD) and produces a substorm current wedge
② Disturbance wave causes CD to spread tailward
J
v
v
③ Multiple CD sites
④ Magnetic reconnection develops at a CD site
④ Substorm current wedge
③ Braking and dawnward current
② High-speed flow
① NENL

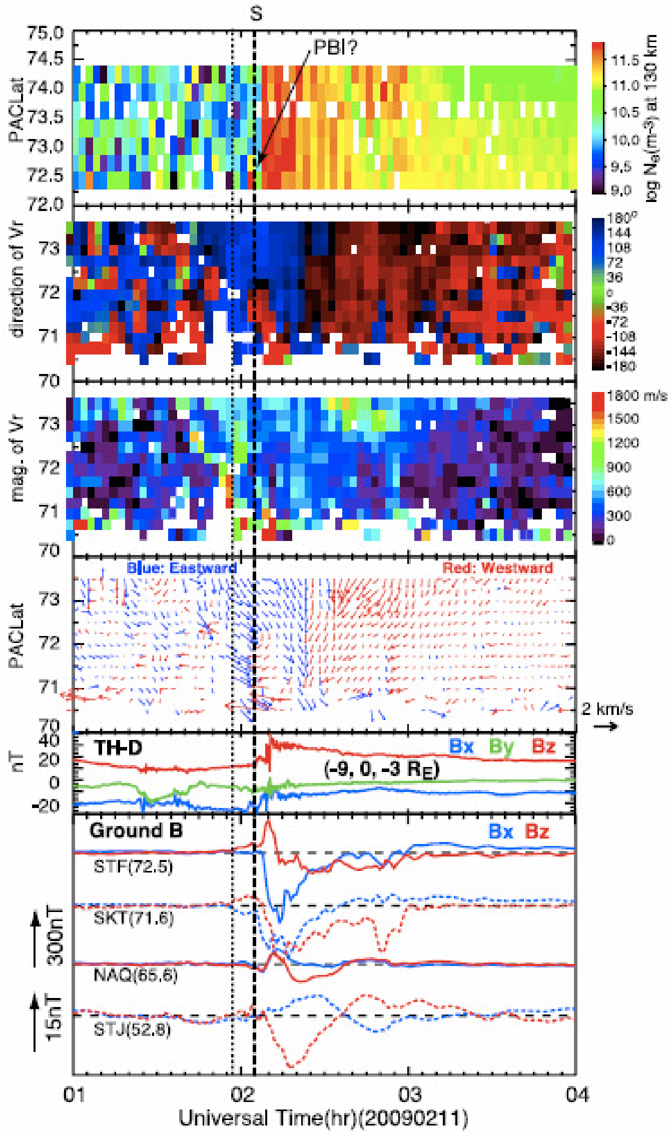
Substorm triggering by new plasma intrusion: THEMIS all-sky imager observations

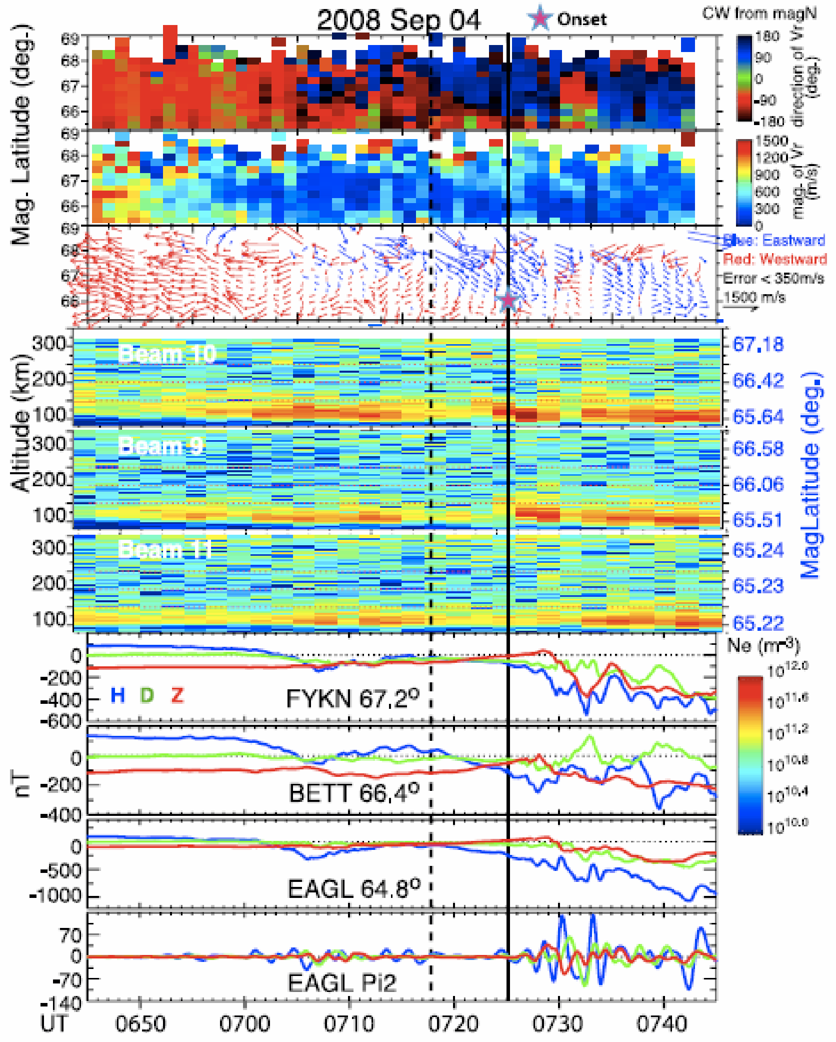
Y. Nishimura et al., 2010



Substorm triggering by new plasma intrusion: Incoherent-scatter radar observations

L. R. Lyons et al., JGR, 2010





Substorm triggering by new plasma intrusion: THEMIS all-sky imager observations

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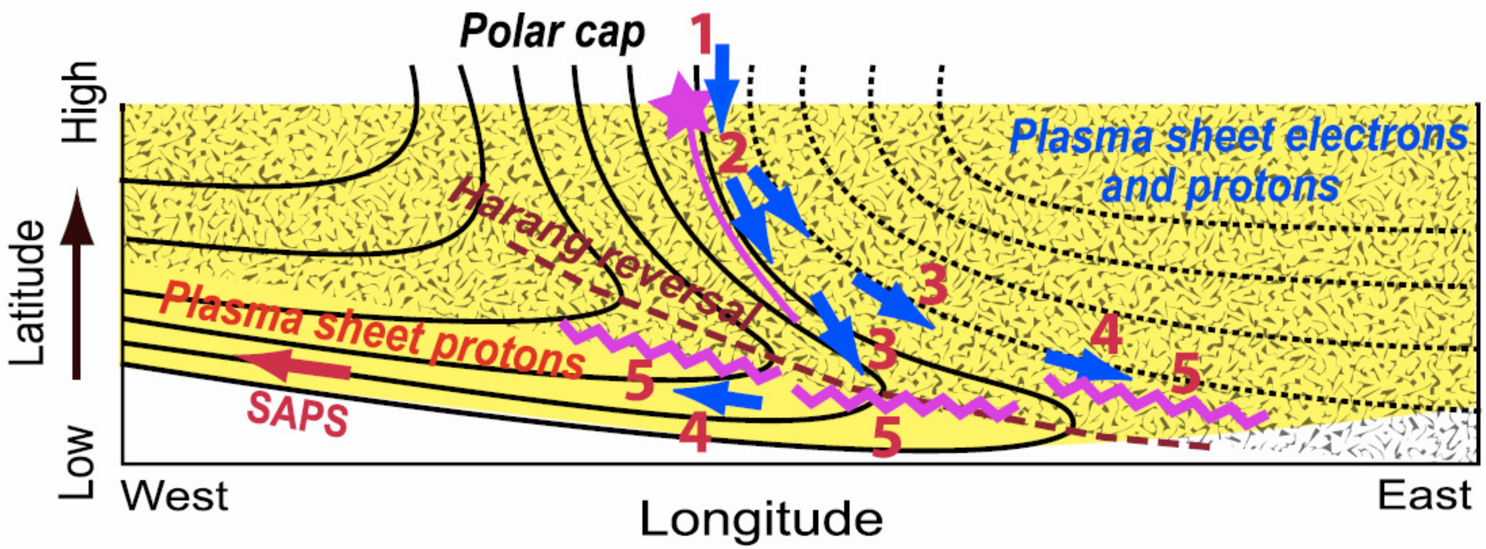
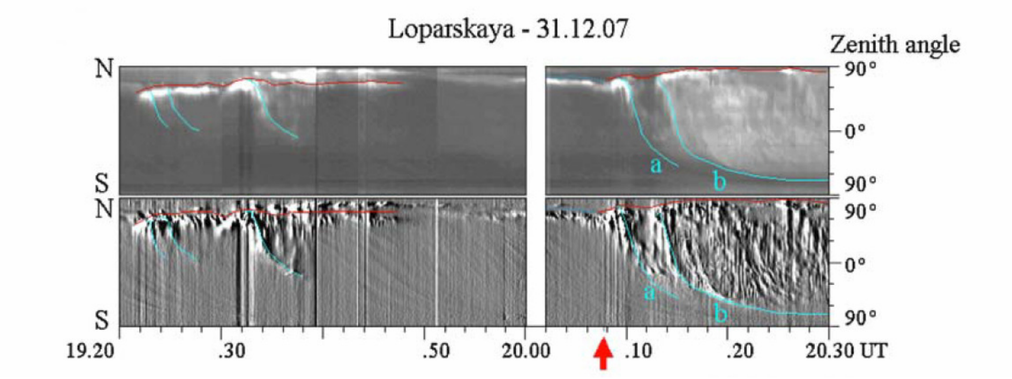
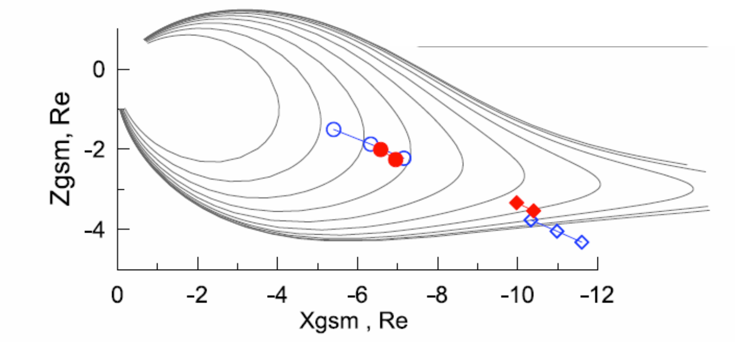


Schematic illustration of motion of pre-onset auroral forms and their relation to nightside ionospheric convection. The pink star, NS-oriented pink line, and azimuthally extended wavy lines indicate a PBI, NS-oriented arc and onset arcs, respectively. Blue arrows illustrate the plasma flow pattern inferred from pre-onset auroral motion. Numbers 1–5 show time evolution of pre-onset aurora (see text). Yellow and gray areas correspond to proton and electron precipitations.

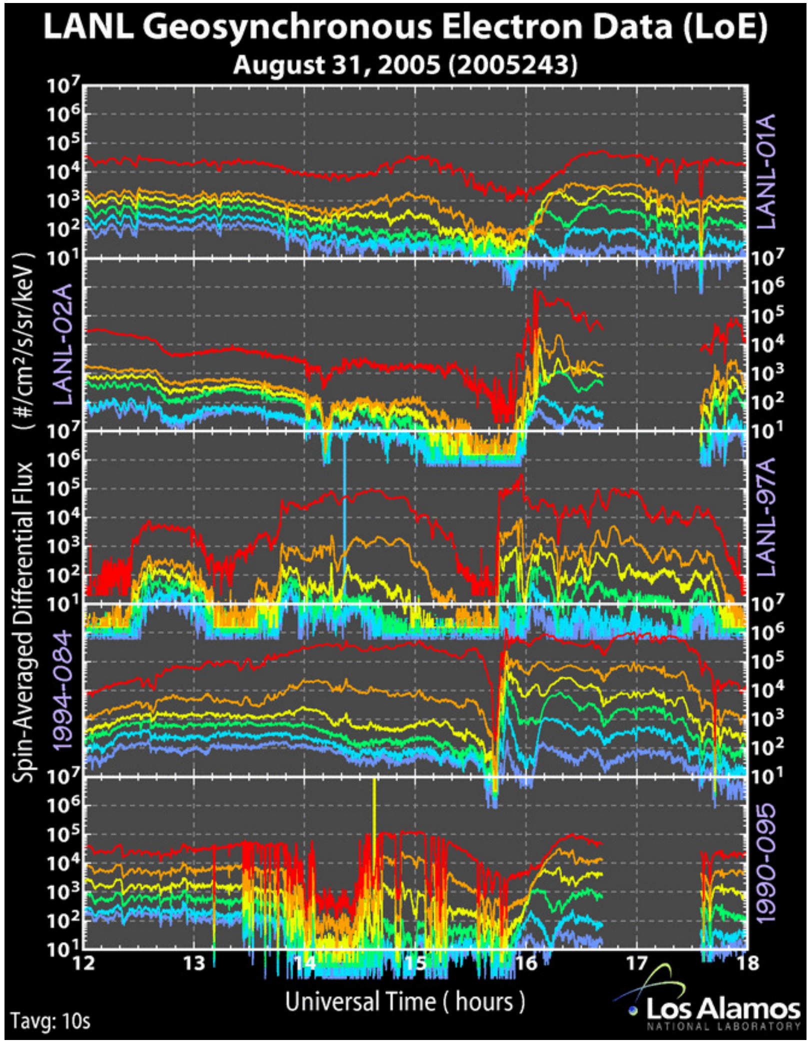
Auroral signatures of the plasma injection and dipolarization in the inner magnetosphere, V. A. Sergeev, JGR, 2010

- The equatorward edge of the auroral bulge corresponds to the innermost extent of earthward propagating dipolarization fronts in the magnetosphere,
- whereas individual equatorward moving auroral enhancements correspond to the motion of individual injection fronts reaching at times distances as close to Earth as 5.5 RE.
- The region of tail dipolarization corresponds to the auroral bulge, a broad spatial region of enhanced but structured auroral emissions, bounded on the poleward side by discrete auroral forms



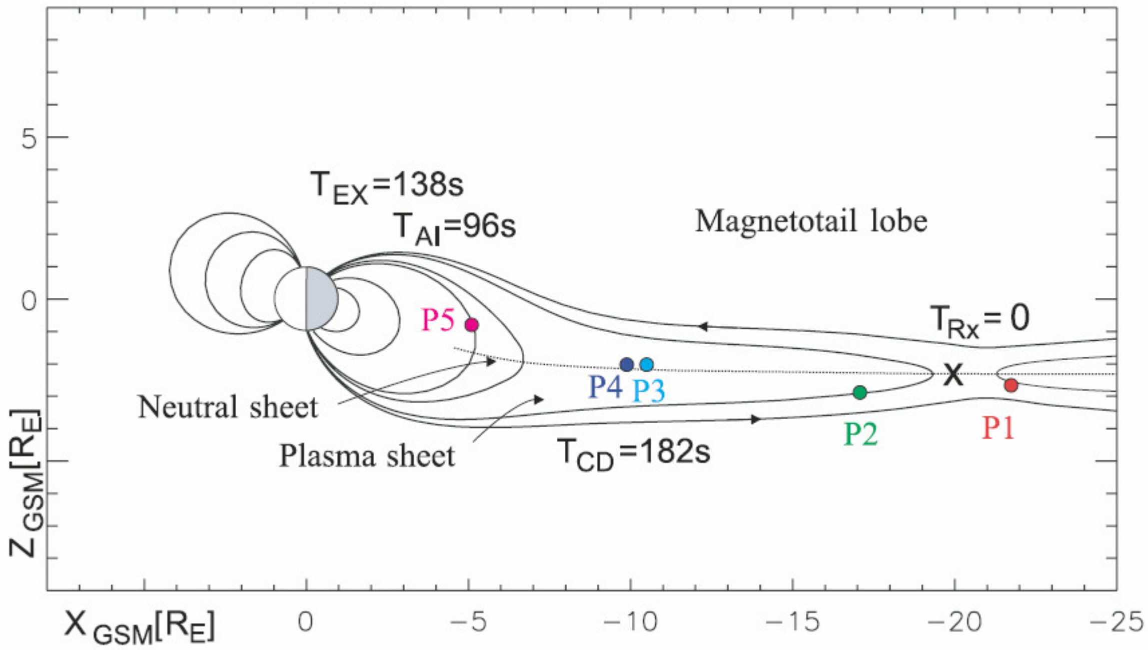


Auroral signatures of the plasma injection and dipolarization in the inner magnetosphere



Tail Reconnection Triggering Substorm Onset

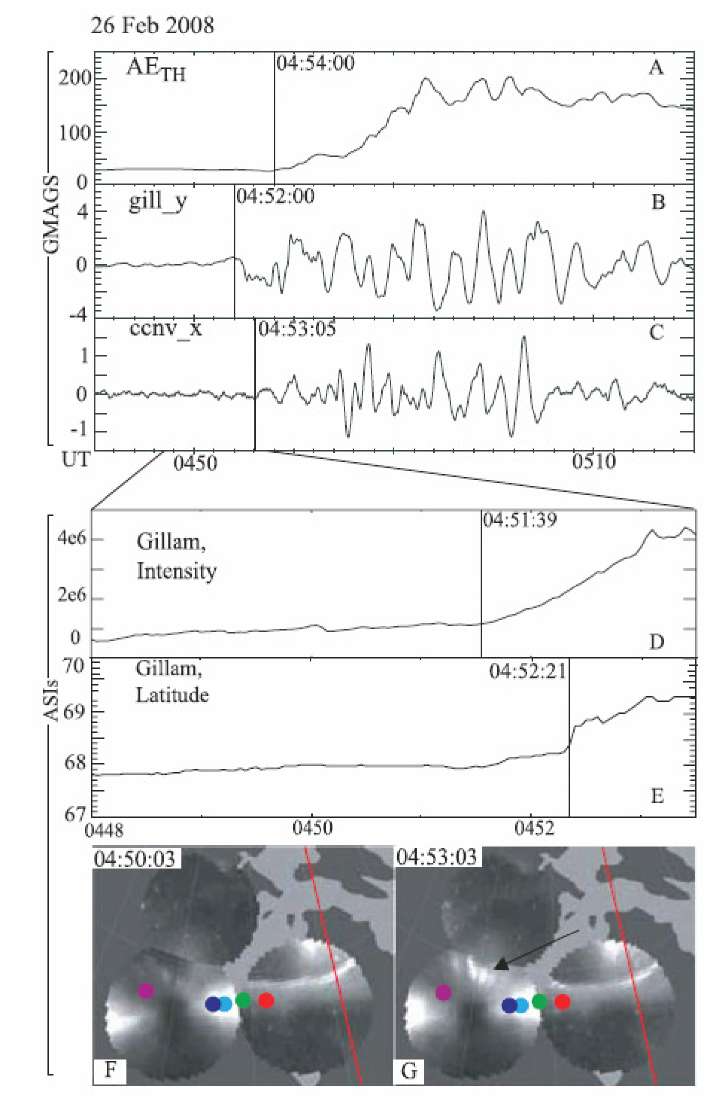
Angelopoulos et al., Science, 2009

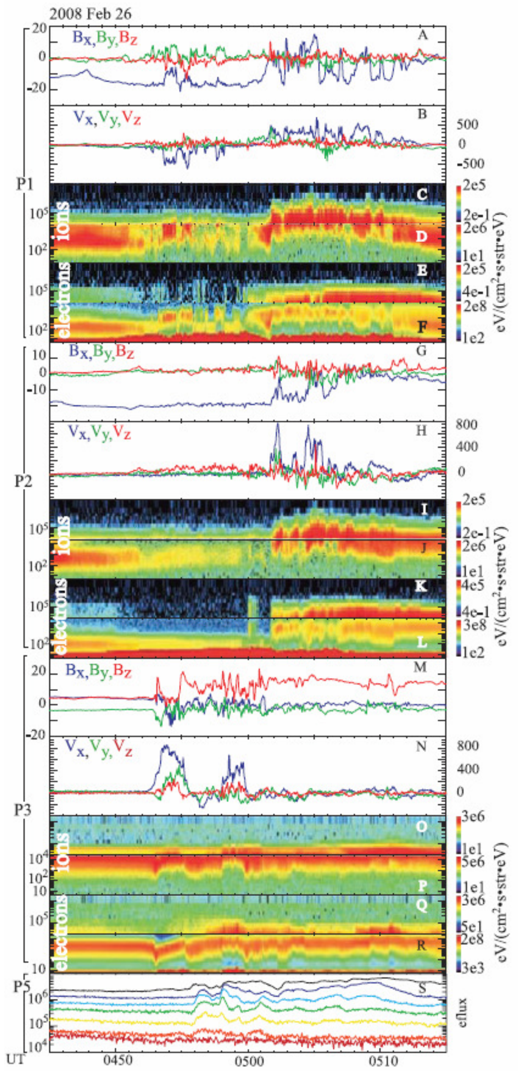


Satellite	Color	X	Y	Z	Neutral Sheet
THEMIS-A (P5)	🟪	-5.483	5.326	-0.623	0.6
THEMIS-B (P1)	🟥	-21.475	3.927	-2.806	-0.5
THEMIS-C (P2)	🟩	-17.165	4.573	-3.046	-0.8
THEMIS-D (P3)	🟦	-10.881	3.759	-2.086	0.2
THEMIS-E (P4)	🟦	-10.194	4.506	-1.913	0.2

Tail Reconnection Triggering Substorm Onset

Angelopoulos et al., Science, 2009





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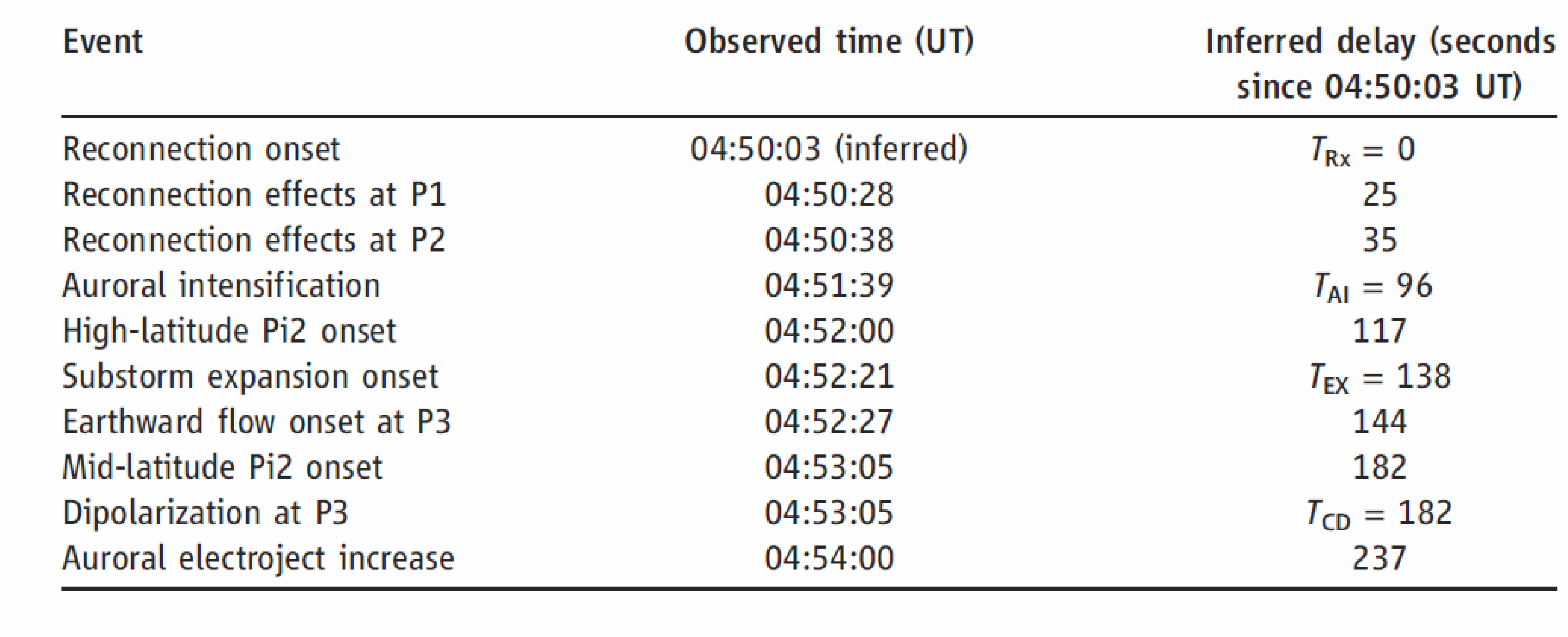


Event	Observed time (UT)	Inferred delay (seconds since 04:50:03 UT)
Reconnection onset	04:50:03 (inferred)	$T_{Rx} = 0$
Reconnection effects at P1	04:50:28	25
Reconnection effects at P2	04:50:38	35
Auroral intensification	04:51:39	$T_{AI} = 96$
High-latitude Pi2 onset	04:52:00	117
Substorm expansion onset	04:52:21	$T_{EX} = 138$
Earthward flow onset at P3	04:52:27	144
Mid-latitude Pi2 onset	04:53:05	182
Dipolarization at P3	04:53:05	$T_{CD} = 182$
Auroral electroject increase	04:54:00	237

Near-Earth XNL

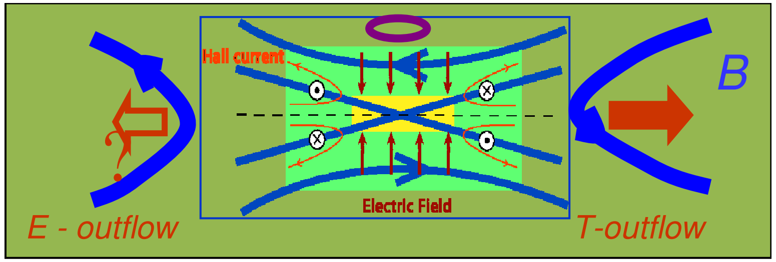
- A set of 5 critical signatures of reconnection process have been identified in 3 events on 26.09.2005 at ~15Re (Cluster):
  - Fast Tailward plasma outflow + southward magnetic flux , ideally – observations of both T and E outflows ;
  - Frozen-in magnetic field (E + [VxB] ≈0) in the outflow
  - Hall-related quadrupole By - spatial distribution
  - Deceleration of incoming electrons crossing the separatrix.
  - Ionospheric signature – accelerated particles+poleward expansion

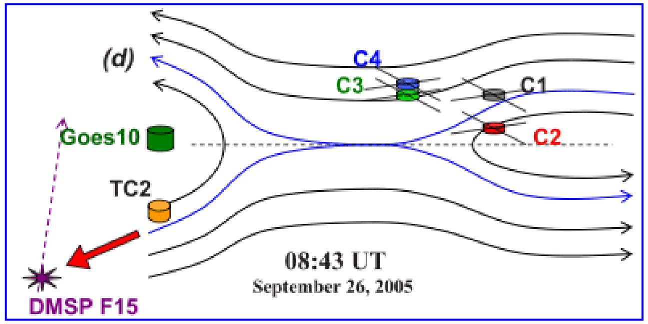
14-16Re – tailward Alfvenic outflows + Turbulent dipolarizations and ion injections at 6.6Re in events *a, b, c*

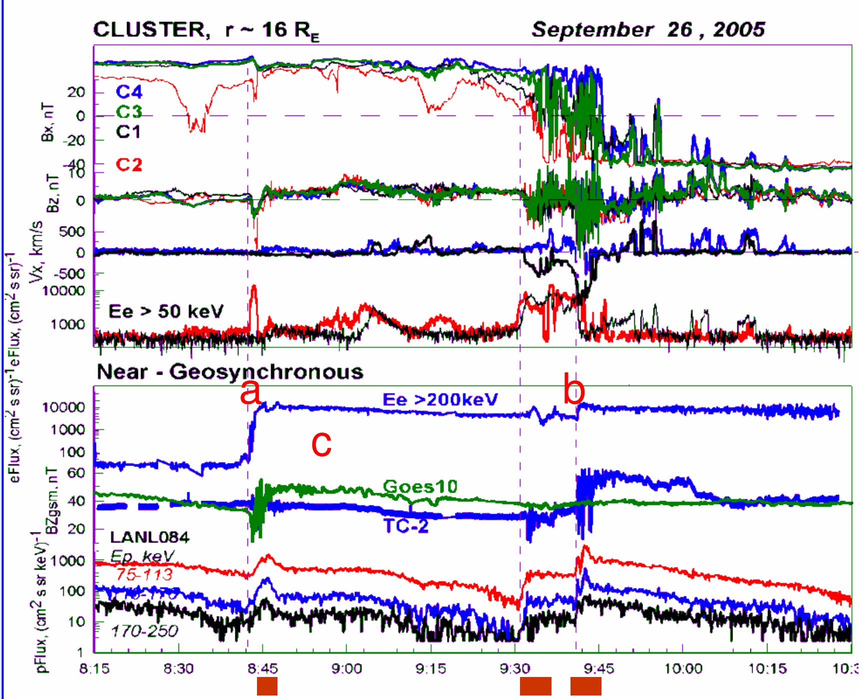
XNL signatures confirmed by other authors *(Petrukovich , Eastwood,..)*, interpretation with XNL at ~12Re confirmed by MHD modeling *(Ivanova et al.,2007)*

- Previous observations of NENL at
  - <13Re strong SBS (*Paschmann et al.,1985, ISEE-1,2*)
  - <15Re weak SBS (*Sergeev et al.,1995, ISEE-1,2*)
  - <14Re (*Miyashita et al., 2005 ,GT*)

- Near-Earth reconnection (<15Re) on closed FL
  is possible,
  Not necessarily during disturbed times (?)

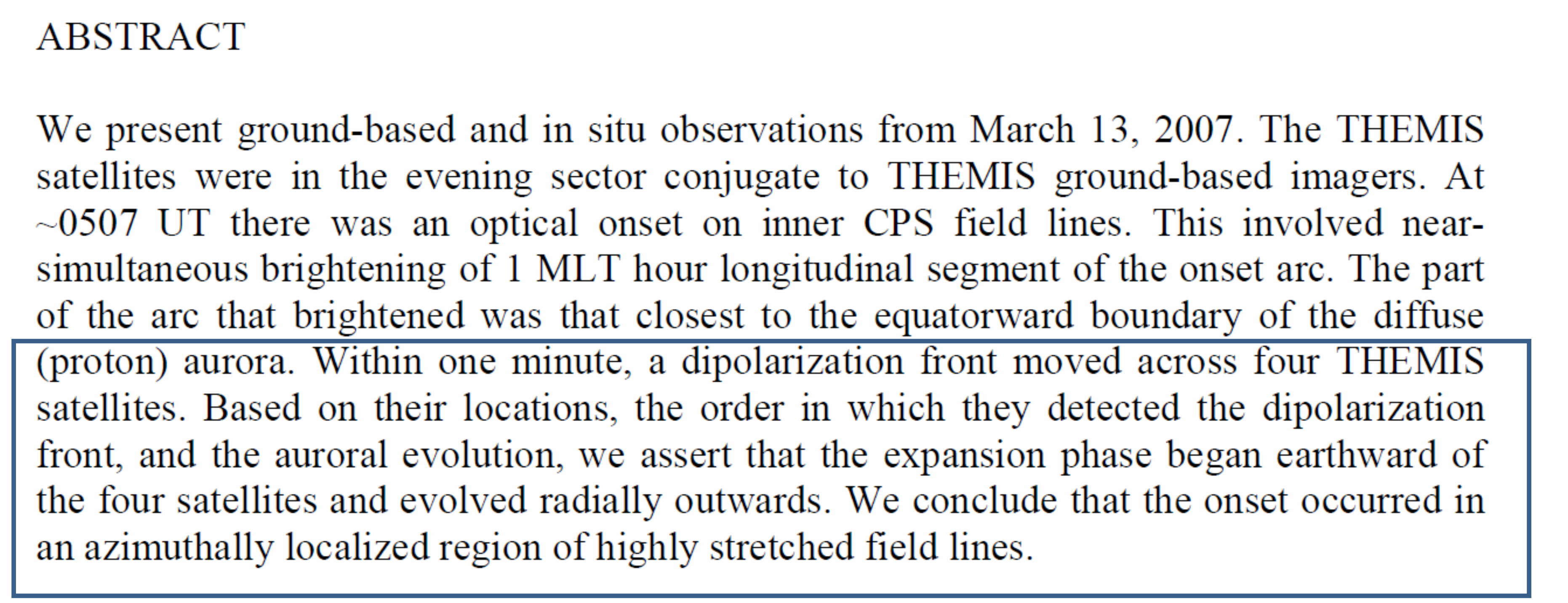






Sergeev et al. (GRL 2007, JGR 2008)

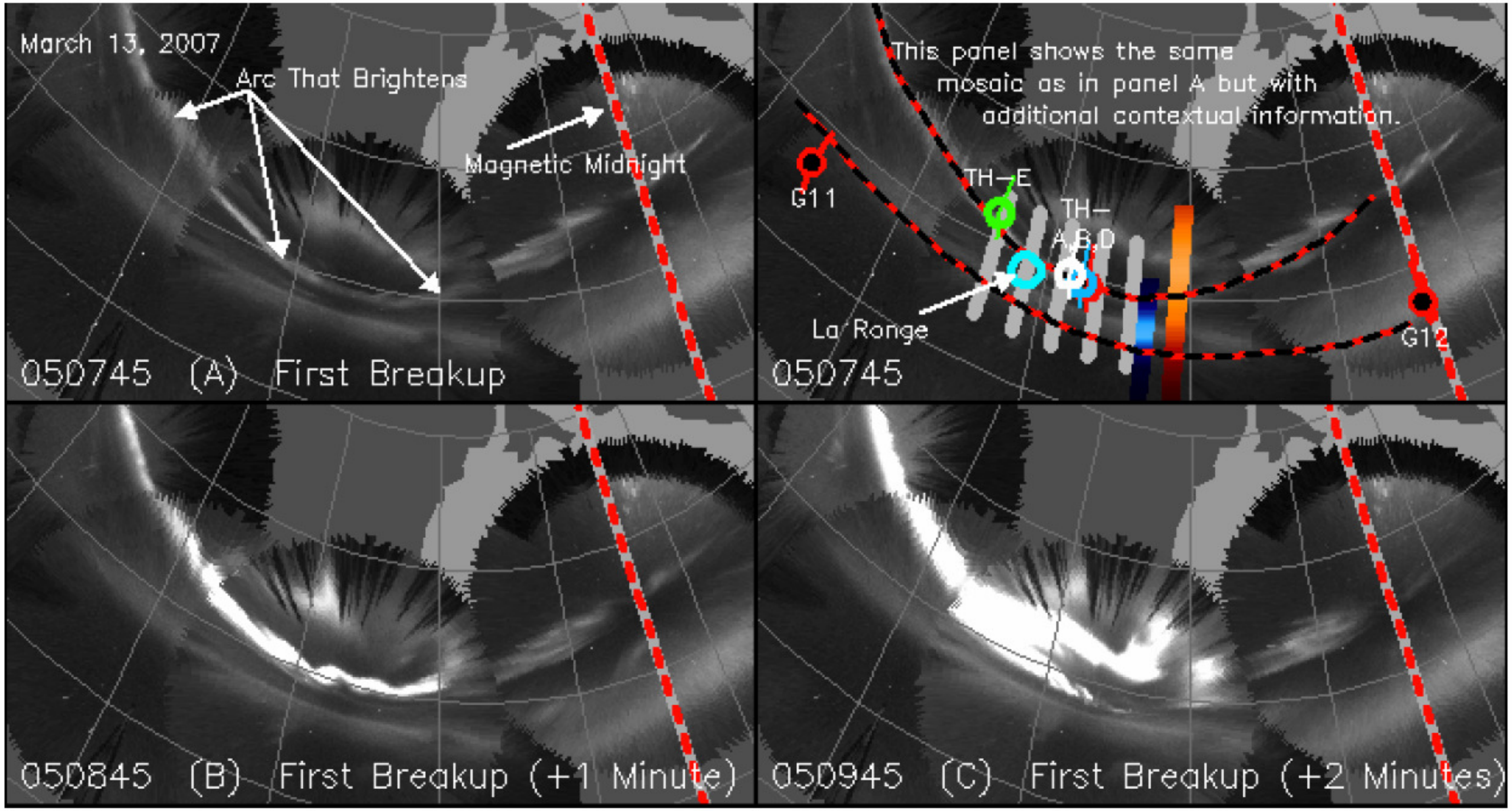
Simultaneous THEMIS in situ and auroral observations of a small substorm, Donovan et al., 2010 GRL

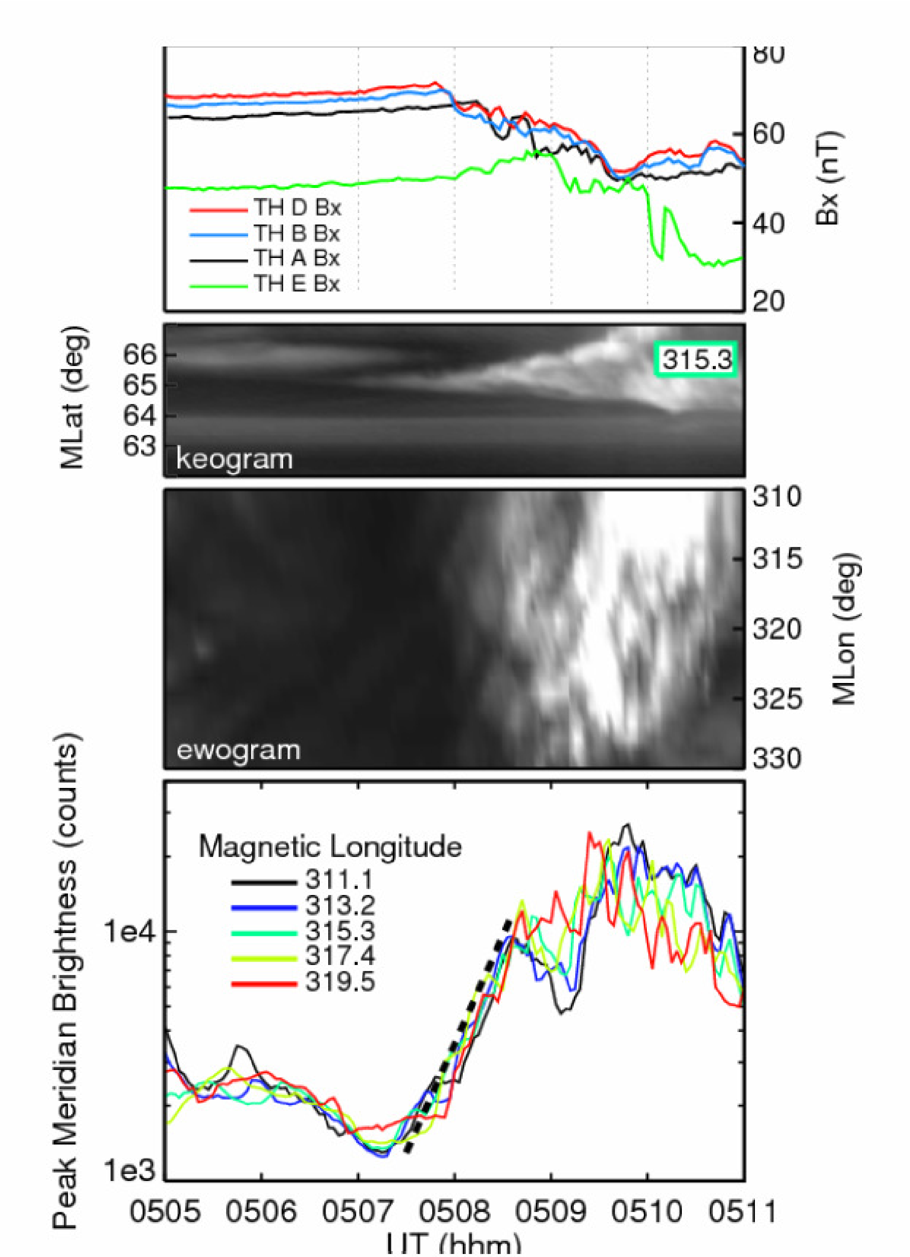


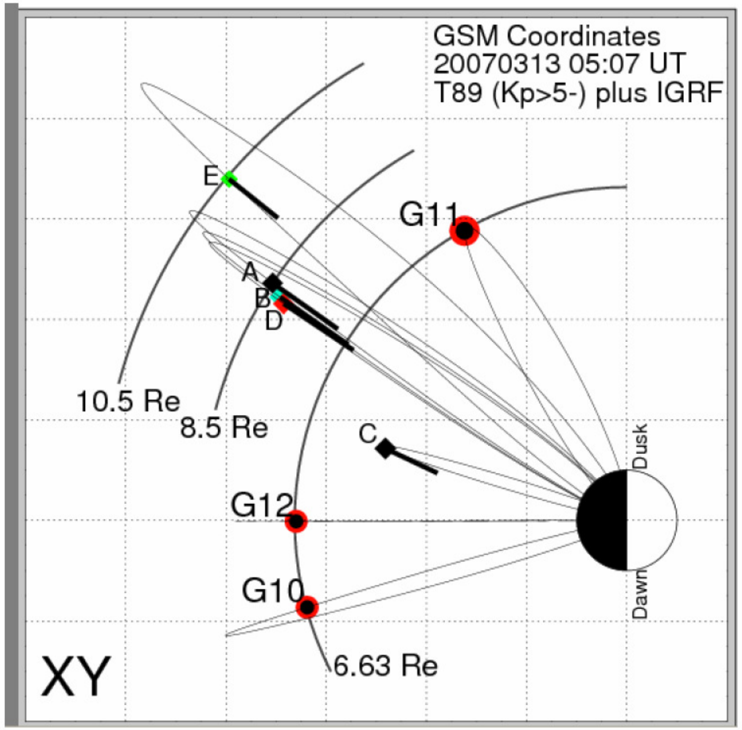
ABSTRACT

We present ground-based and in situ observations from March 13, 2007. The THEMIS satellites were in the evening sector conjugate to THEMIS ground-based imagers. At ~0507 UT there was an optical onset on inner CPS field lines. This involved near-simultaneous brightening of 1 MLT hour longitudinal segment of the onset arc. The part of the arc that brightened was that closest to the equatorward boundary of the diffuse (proton) aurora. Within one minute, a dipolarization front moved across four THEMIS satellites. Based on their locations, the order in which they detected the dipolarization front, and the auroral evolution, we assert that the expansion phase began earthward of the four satellites and evolved radially outwards. We conclude that the onset occurred in an azimuthally localized region of highly stretched field lines.

Simultaneous THEMIS in situ and auroral observations of a small substorm, Donovan et al., 2010 GRL

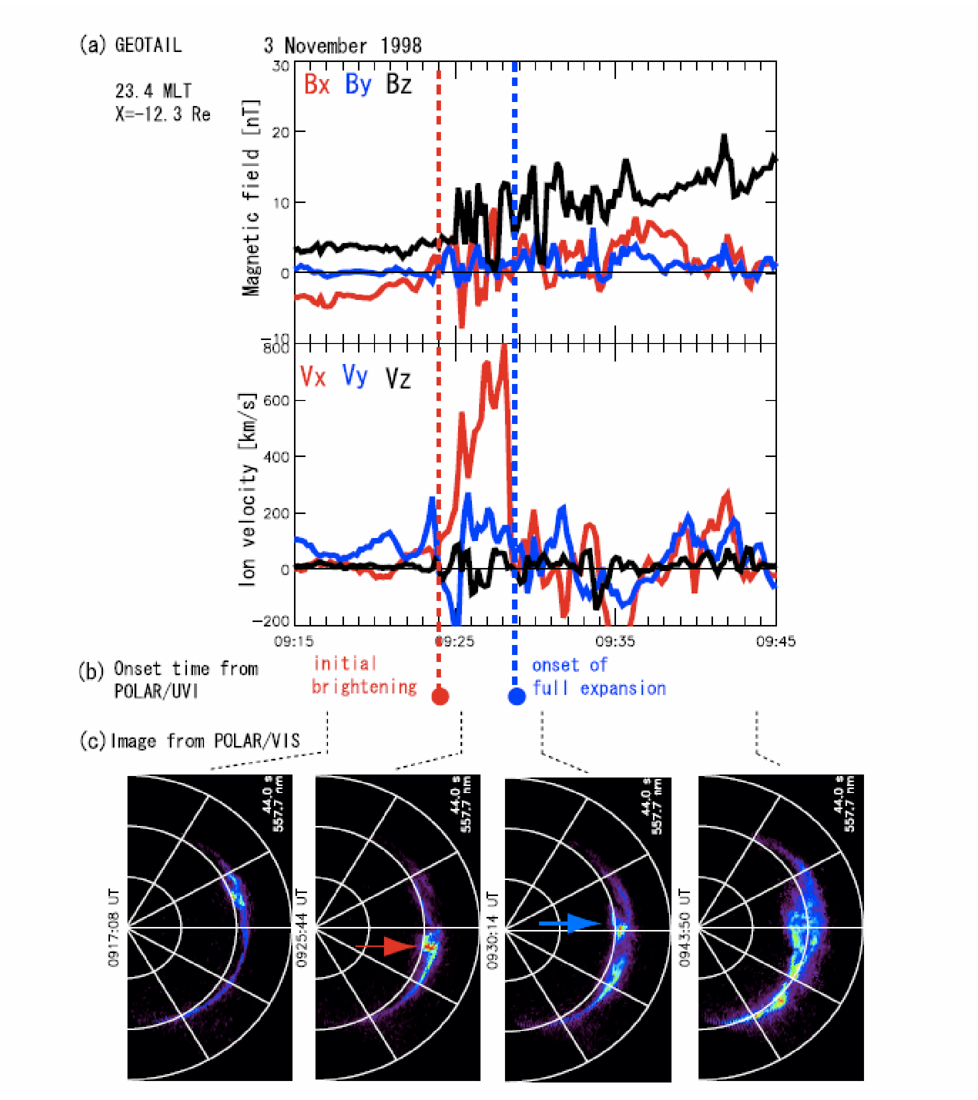



80
60
40
20
Bx (nT)
TH D Bx
TH B Bx
TH A Bx
TH E Bx
MLat (deg)
66
65
64
63
315.3
keogram
310
315
320
325
330
MLon (deg)
ewogram
Peak Meridian Brightness (counts)
Magnetic Longitude
311.1
313.2
315.3
317.4
319.5
1e4
1e3
0505
0506
0507
0508
0509
0510
0511
UT (hhm)

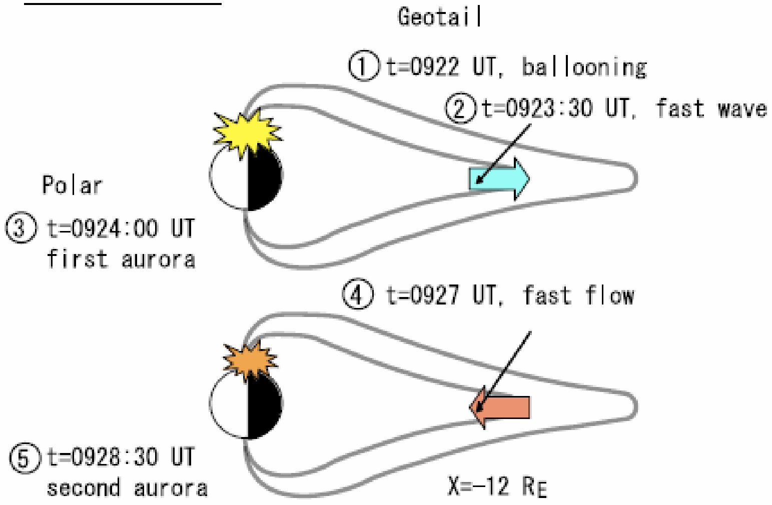

GSM Coordinates
20070313 05:07 UT
T89 (Kp>5-) plus IGRF
E
A
B
D
C
G11
G12
G10
10.5 Re
8.5 Re
6.63 Re
Dusk
Dawn
XY

Stepwise feature of aurora during substorm expansion compared with the near-Earth tail dipolarization: Possible types of substorm dynamics,

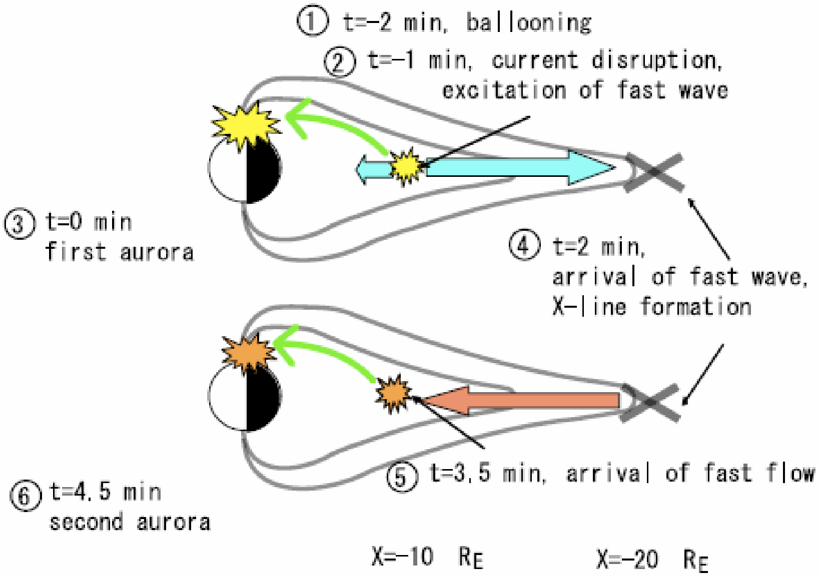
Saito et al., JGR, 2010



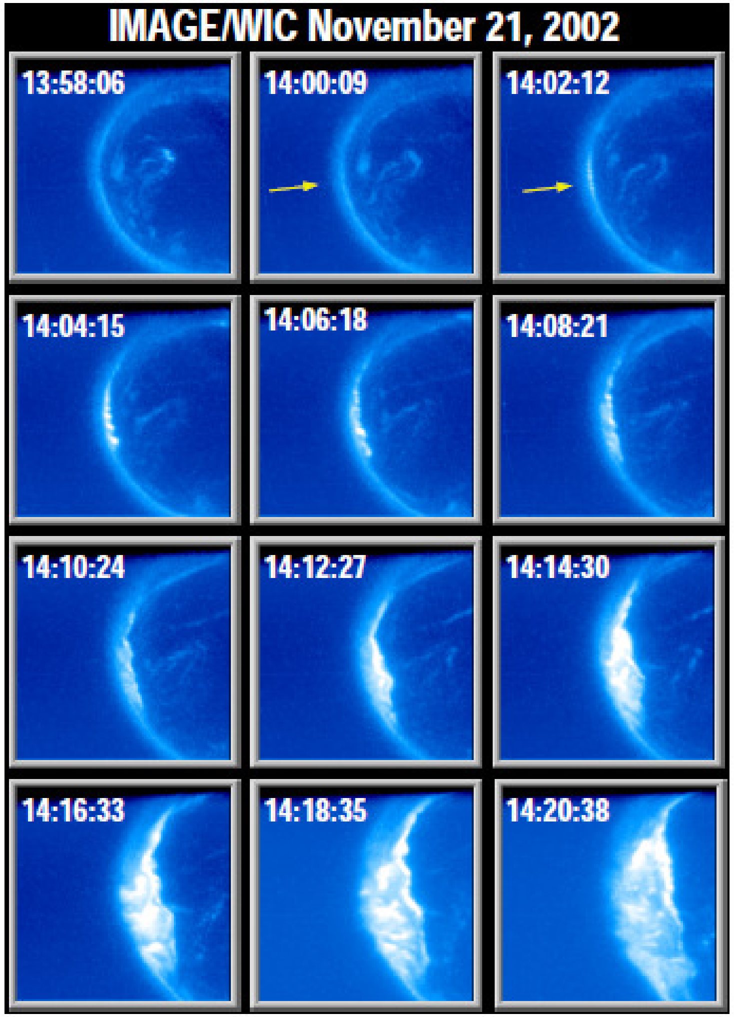
Observation



Synthesis



Observational evidence for an inside-out substorm onset scenario, Henderson, Ann. Geophys., 2009



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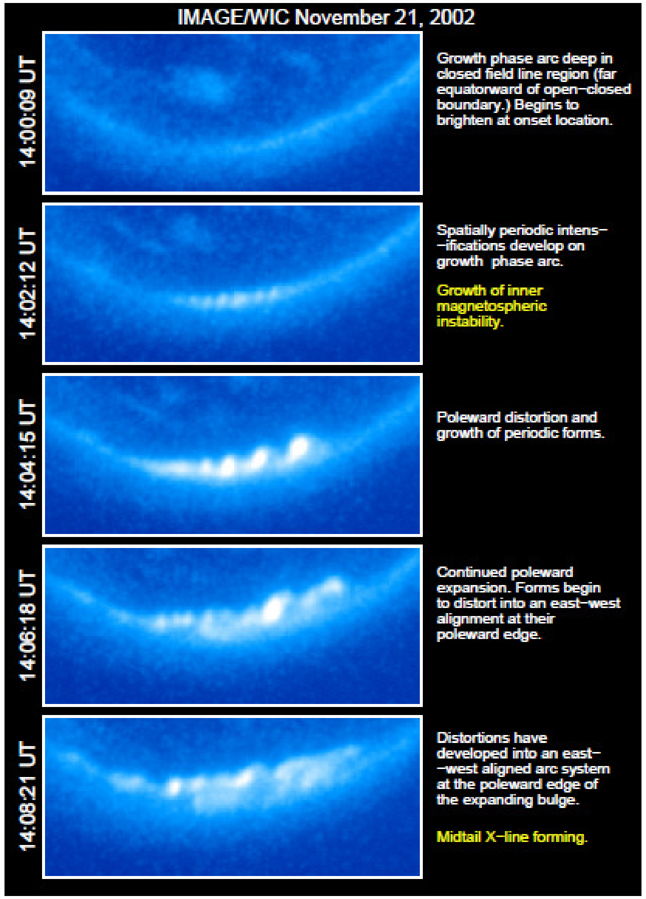


Growth phase arc deep in closed field line region (far equatorward of open–closed boundary.) Begins to brighten at onset location.

Spatially periodic intensifications develop on growth phase arc.

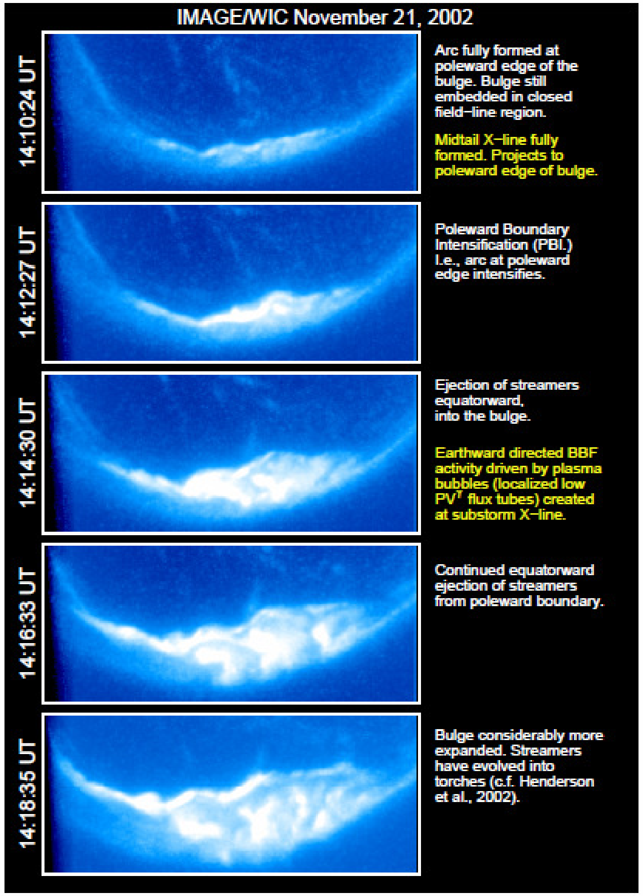
Growth of inner magnetospheric instability.

Poleward distortion and growth of periodic forms.

Continued poleward expansion. Forms begin to distort into an east–west alignment at their poleward edge.

Distortions have developed into an east–west aligned arc system at the poleward edge of the expanding bulge.

Midtail X–line forming.



Arc fully formed at poleward edge of the bulge. Bulge still embedded in closed field–line region.

Midtail X–line fully formed. Projects to poleward edge of bulge.

Poleward Boundary Intensification (PBI.) I.e., arc at poleward edge intensifies.

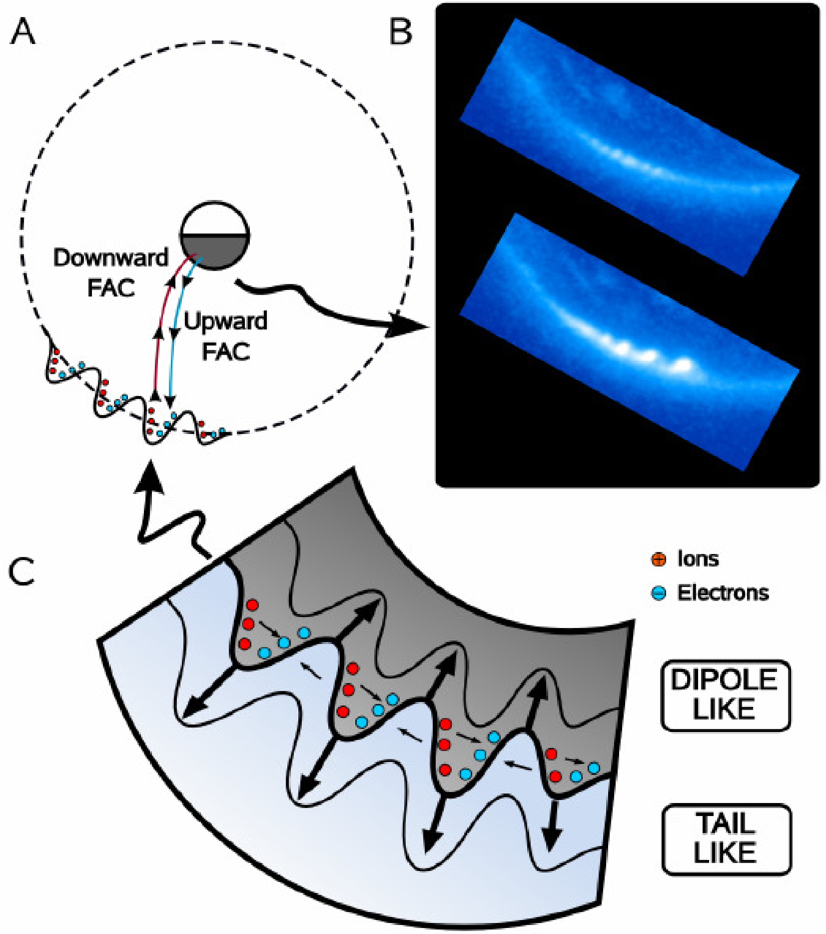
Ejection of streamers equatorward, into the bulge.

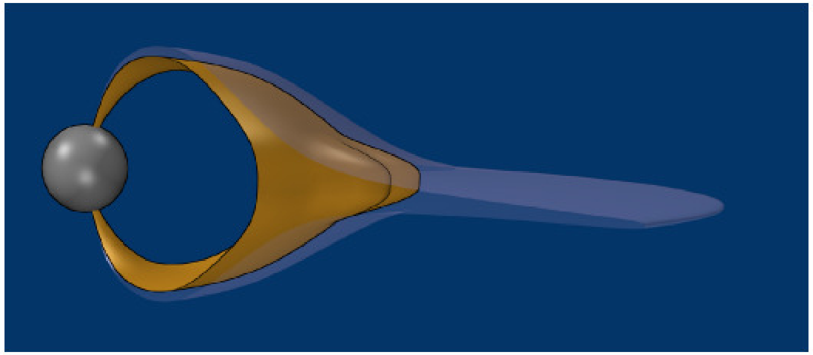
Earthward directed BBF activity driven by plasma bubbles (localized low PV^{γ} flux tubes) created at substorm X–line.

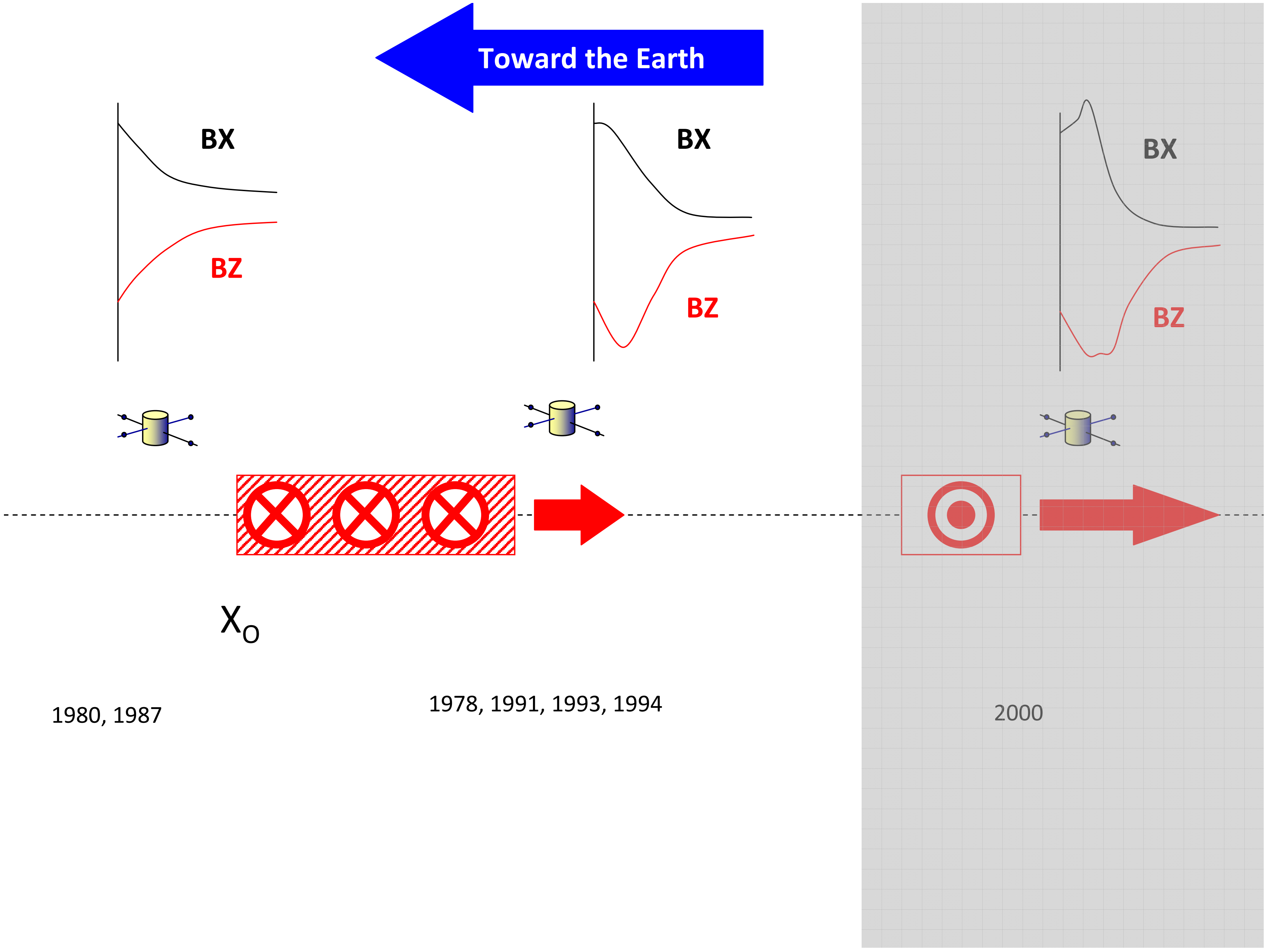
Continued equatorward ejection of streamers from poleward boundary.

Bulge considerably more expanded. Streamers have evolved into torches (c.f. Henderson et al., 2002).

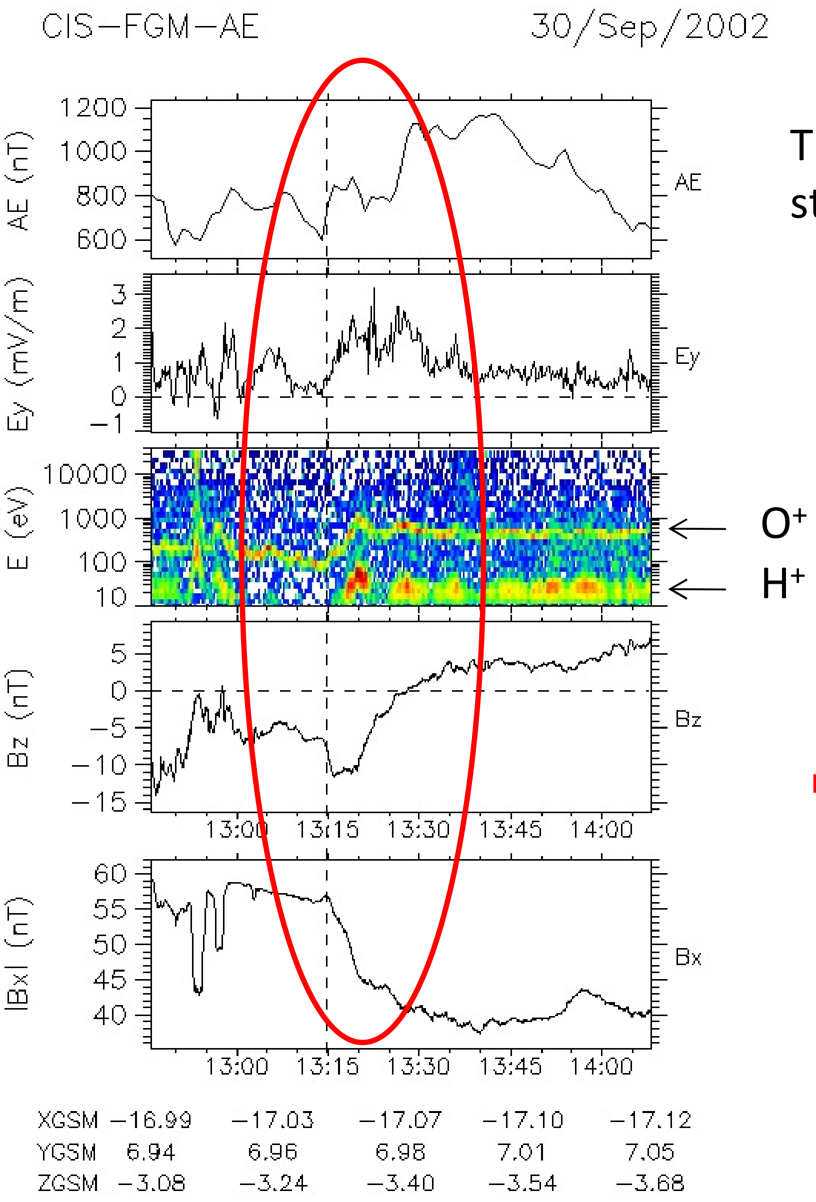
Observational evidence for an inside-out substorm onset scenario, Henderson, Ann. Geophys., 2009






Toward the Earth
BX
BZ
BX
BZ
BX
BZ
X_O
1980, 1987
1978, 1991, 1993, 1994
2000

DIPOLARIZATION + OXYGEN



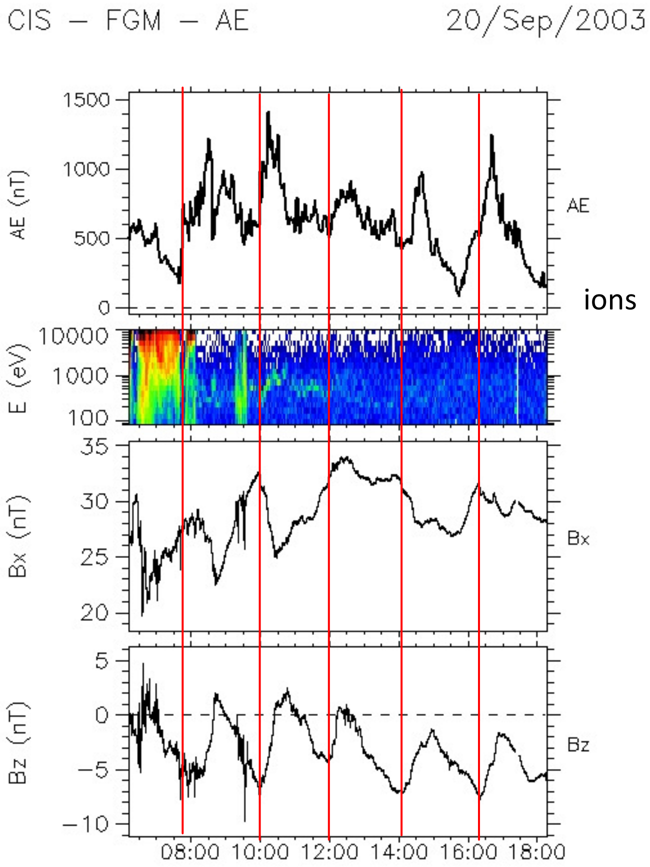
Traveling Dipolarization associated with a strong impulsive electric field (-**v**x**B**)

$E/L = B/T$

➡ $L = 15\ R_E$

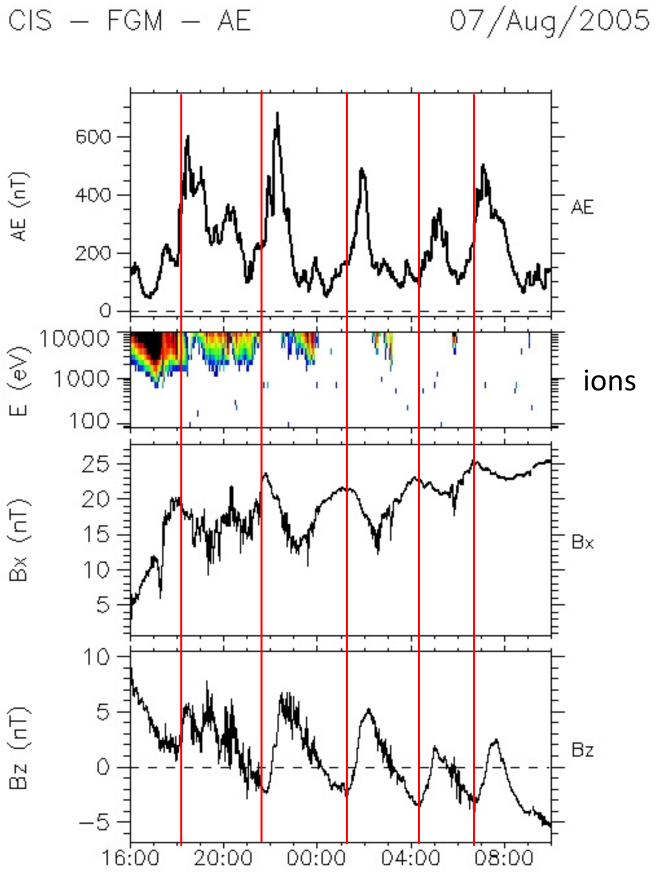
Sauvaud et al., en préparation, 2010

MULTIPLE DIPOLARIZATIONS IN THE LOBE



ions

XGSM	−18.19	−17.74	−16.83	−15.49	−13.69
YGSM	3.56	2.67	2.21	2.66	3.68
ZGSM	−4.87	−6.97	−8.57	−9.72	−10.44

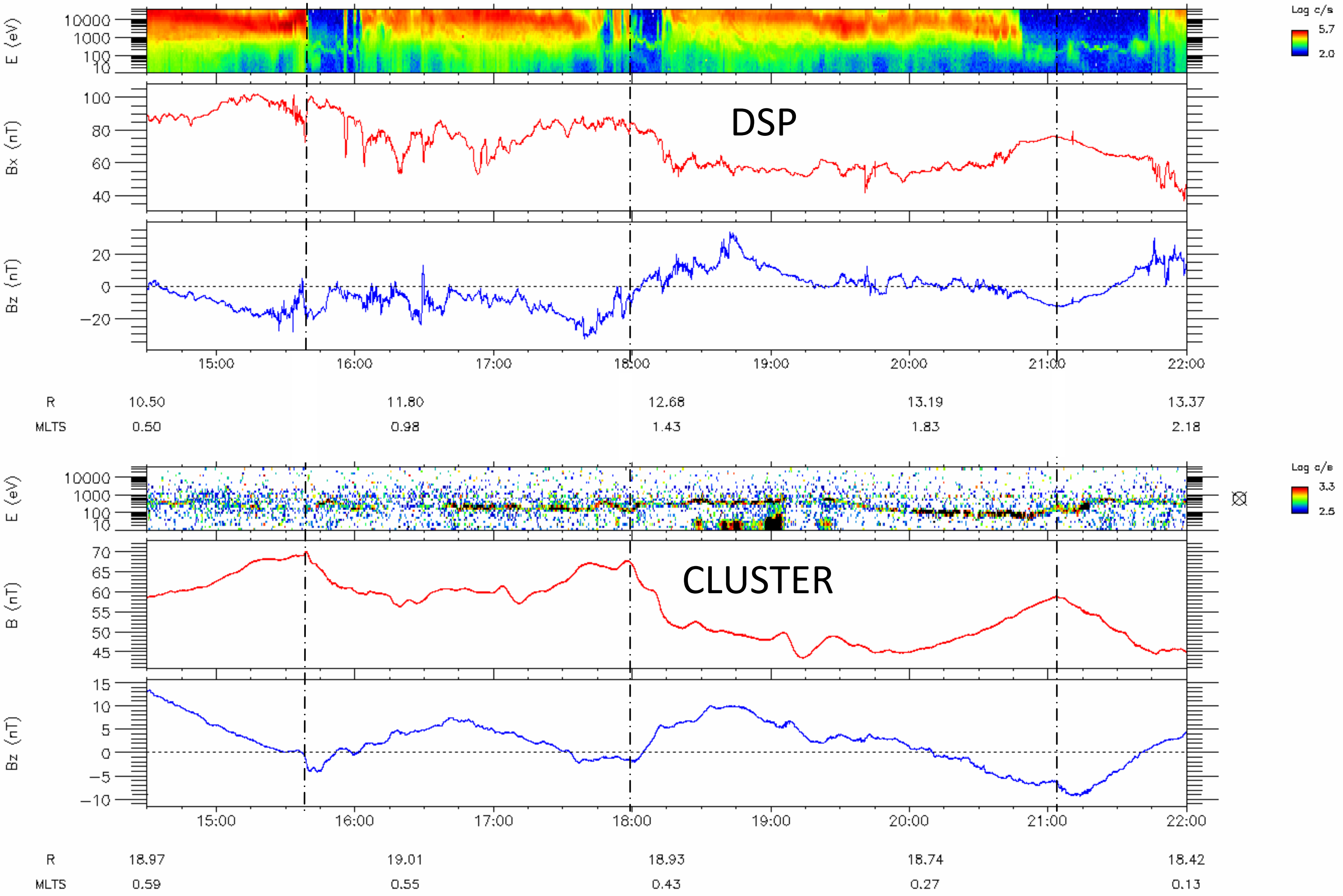


ions

XGSM	−15.22	−16.21	−16.17	−15.14	−13.12
YGSM	−8.82	−8.32	−7.26	−7.26	−7.13
ZGSM	1.18	−3.59	−6.35	−7.54	−8.70

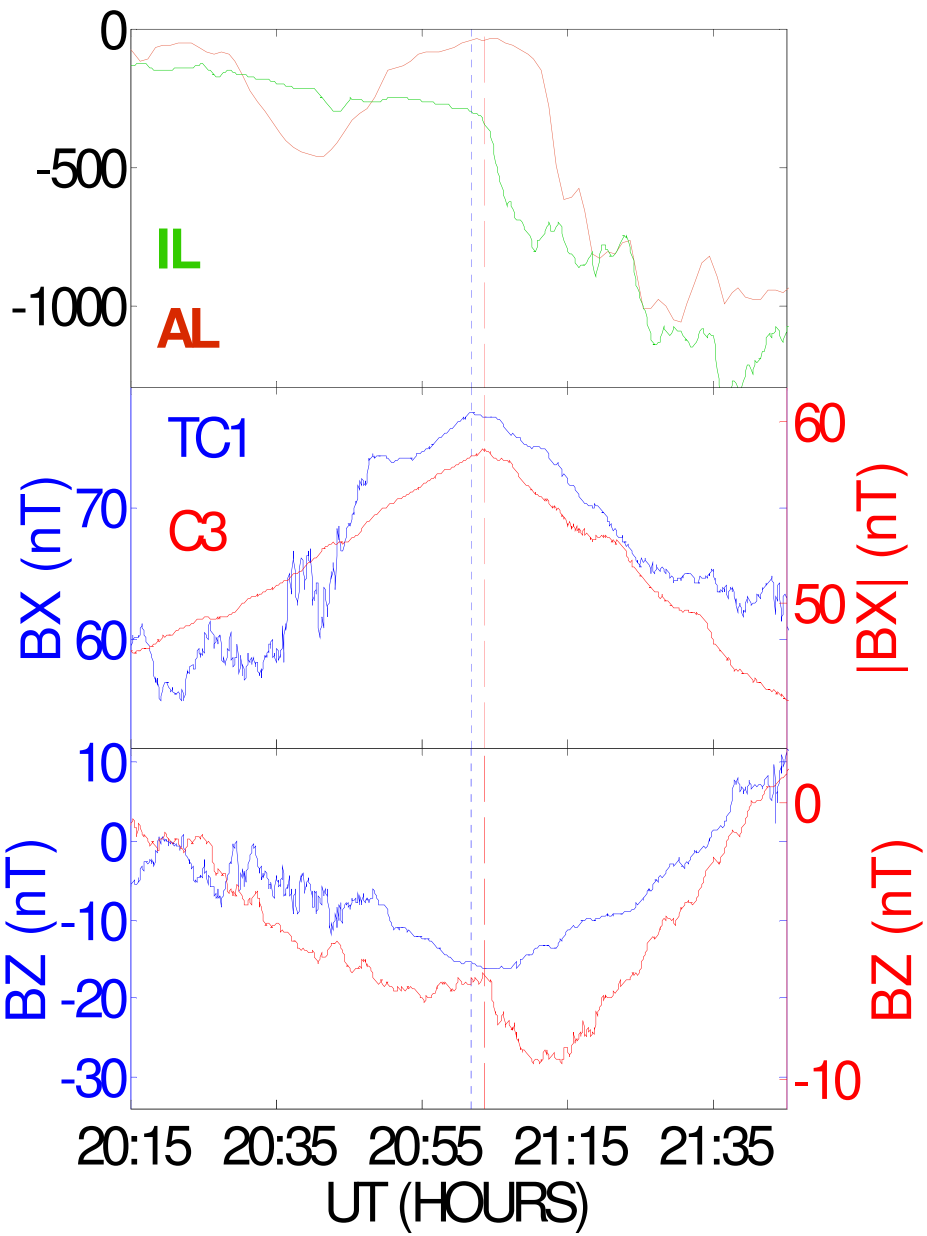
Sauvaud et al., en préparation, 2010

AUGUST 31, 2005 Double STAR - CLUSTER



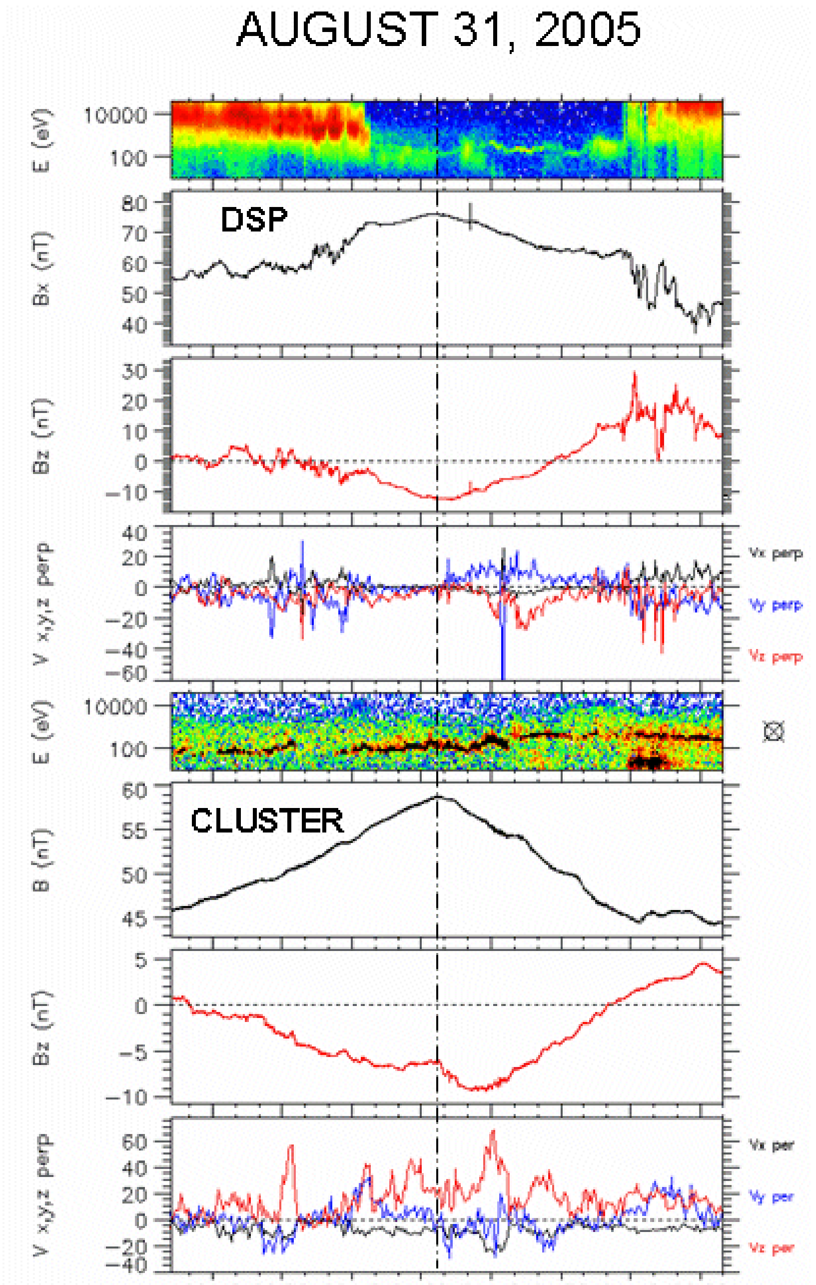
Cluster is in the south lobe (Bx <0)

Sauvaud et al., en préparation, 2010

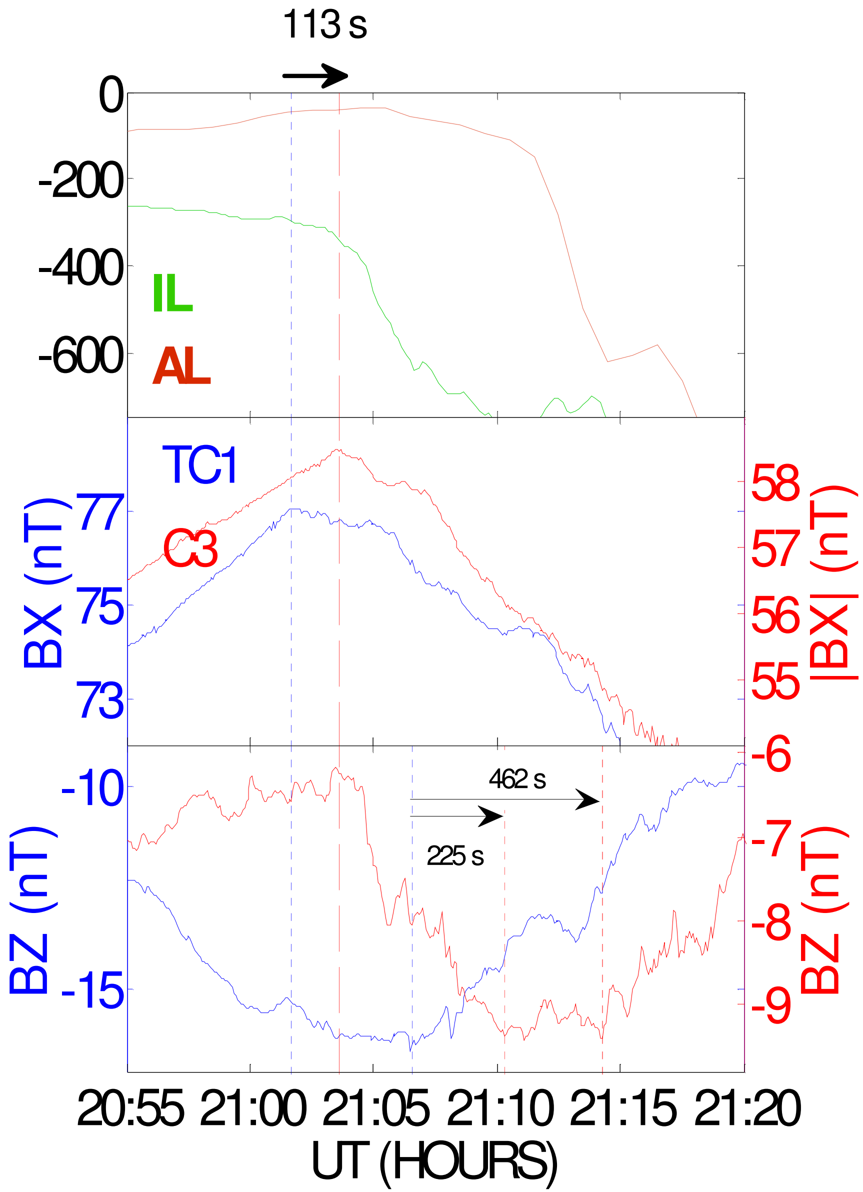


X= -10

X= -17



Sauvaud et al., en préparation, 2010



- Current reduction front (BZ min):

  Δt = 225 ~462 s
  Assuming a propagation purely along X
  □ V = 90~190 km/s

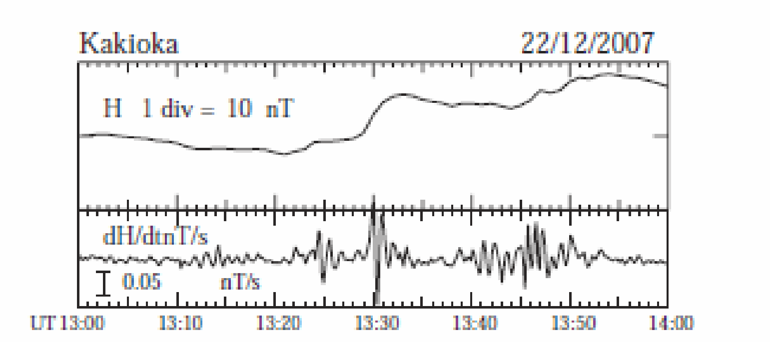
- Start of the current reduction (BX max):

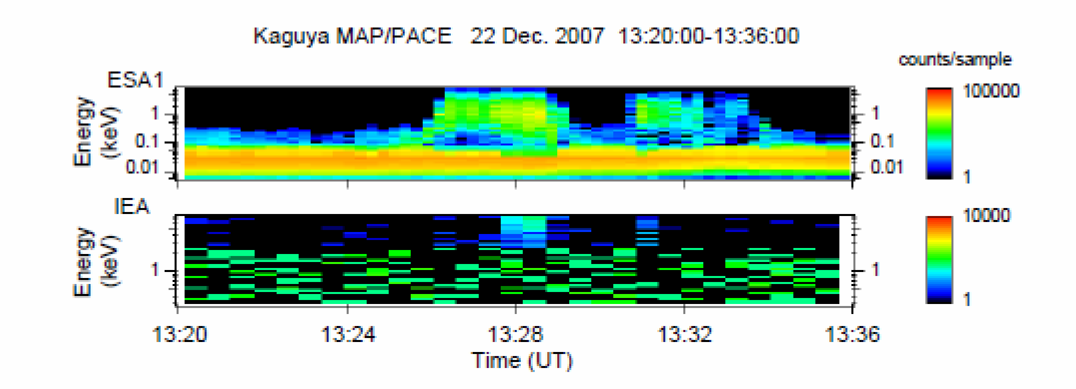
  Dt = 113 s □ V ~ 380 km/s

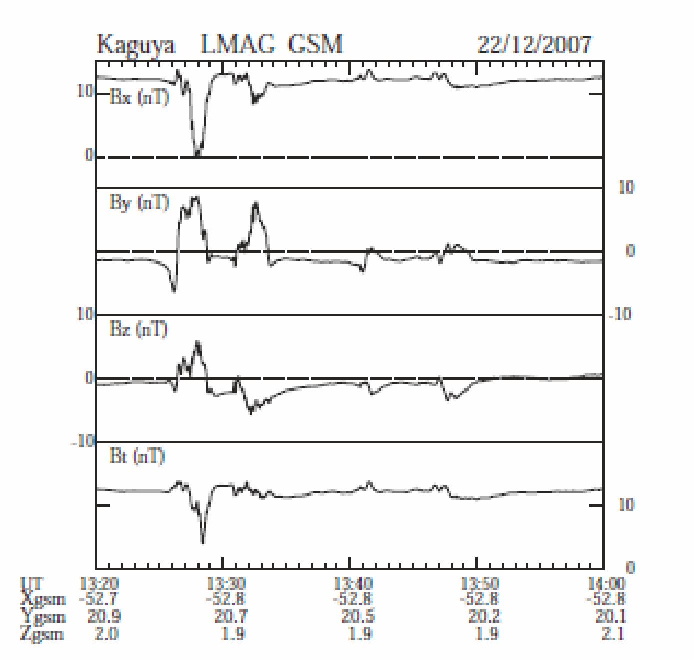
- During the ~5 first minutes, BZ is roughly constant at TC1.

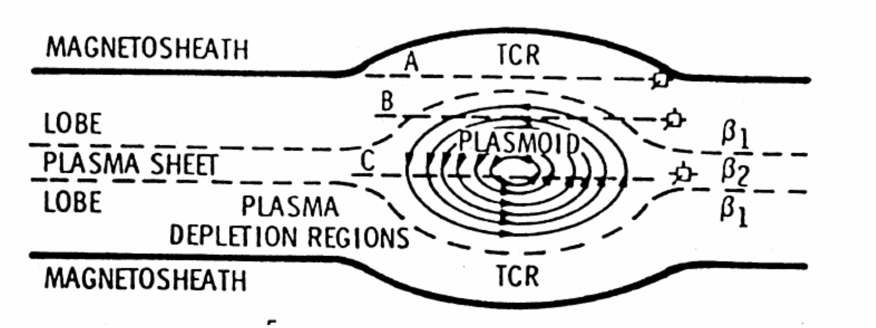
  (i) The current reduction is at the TC1 location and does not propagate immediately
  (ii) TC1 is initially out (dawnward) of the current wedge

Plasmoid formation for multiple onset substorms: observations of the Japanese Lunar Mission “Kaguya”, T. Nagai, Ann. Geophys., 2009

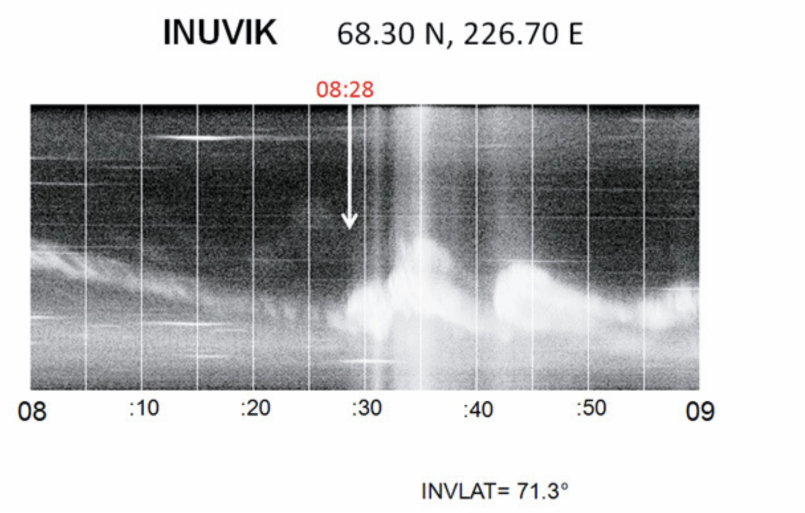


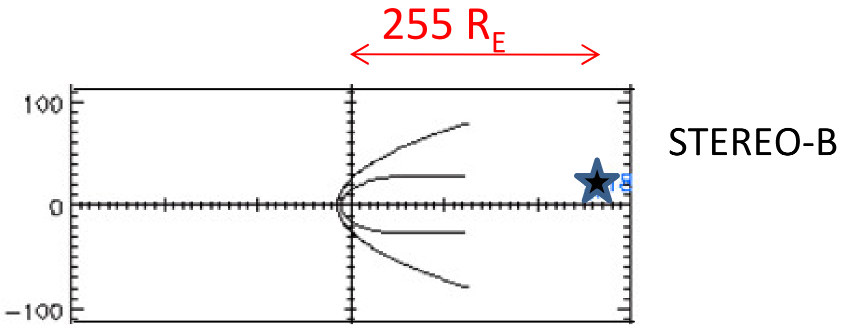






Substorm associated wave propagation over 255 RE

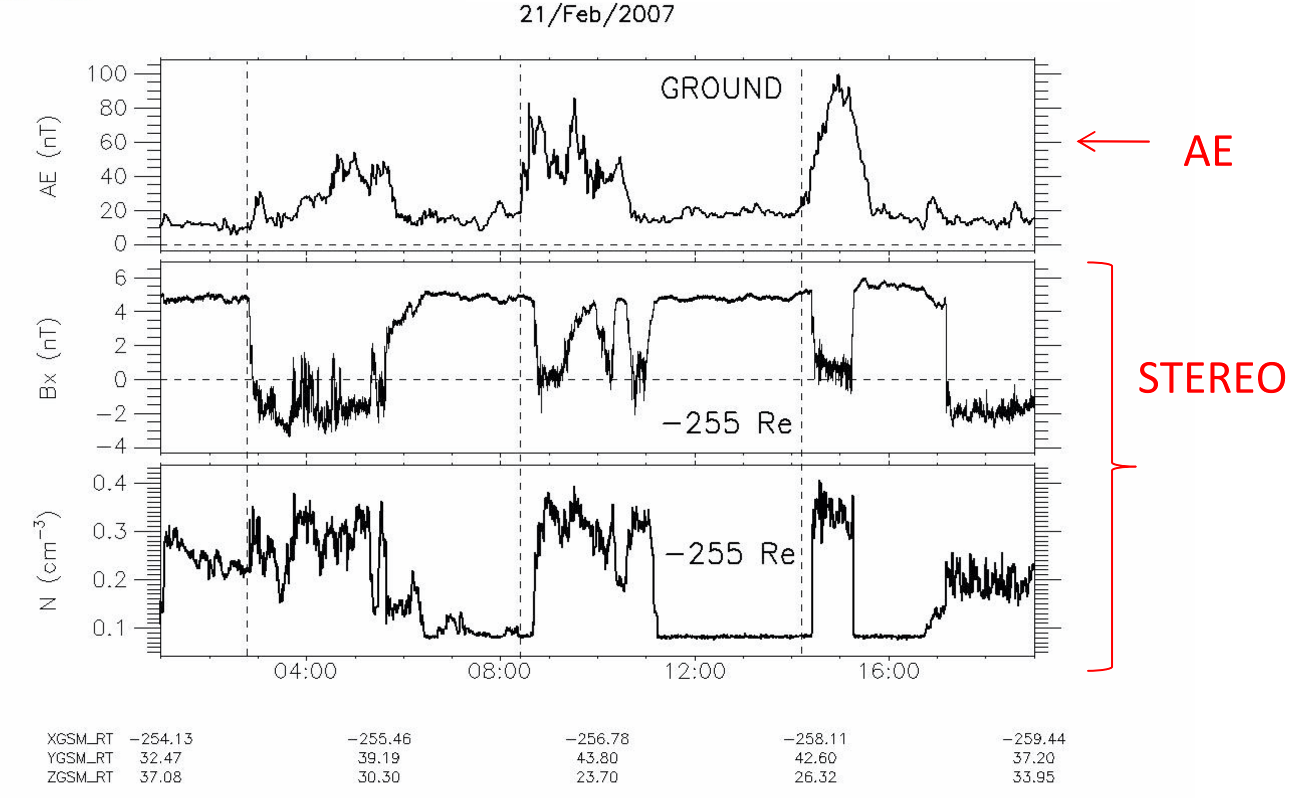




Time delay

➡ V=1800 km/s

→ wave



Sauvaud et al., 2010

Il existe des observations “sures”:
-Amincissement de la couche de courant “cross-tail” pendant la phase de croissance,
-Injections de particules énergétiques à 6-8 Rt et reconfiguration de la magnétosphère.
-Ejection de plasmoïdes en direction anti-terestre, depuis la queue de la magnétosphère
-Apparition de flots rapides de plasma associés aux substorms: earthward et tailward.

Des progrès significatifs sont faits grâce aux stations au sol associées au projet THEMIS (dont ne peut pas bénéficier Cluster en aout-septembre de chaque année) et aux radars au sol .

Cependant
-La séquence temporelle d’évènements associés au début du sous-orage n’a pas encore été clairement établie; elles fait l’objet d’articles très contradictoires:
- In – out (Donovan, Lui,…)
- Out-in (Angelopoulos, …)

Par ailleurs:
-La physique de la reconnection est mal comprise et déclenchée dans les codes MHD par une résistivité numérique.

-Les instabilités de courant “cross-tail” (et leur conséquences globales) pouvant conduire à sa fragmentation/diversion ne sont pas fermement établies. La séquence de processus physiques et leur relation de cause à effet reste obscure.

Une difficulté majeure provient du couplage des échelles, depuis les échelles électroniques jusqu’à la très grande échelle (>10 R_t),

FUTUR

-Il est indispensable de coordonner les mesures au sol et en satellite, l’effort autour de THEMIS est remarquable!

-La résolution en temps des mesures au sol et en radar est souvent insuffisante,

--L’imagerie aurorale dans diverses longueur d’ondes (énergies des électrons différentes) est indispensable,

-Les mesures en satellites montrent que la gamme d’énergie des analyseurs électrostiques est trop limitée; les particules de grande énergie portant une part significative de la pression du plasma.

-Les corrélations inter-missions et sol-espace sont trop négligées. Cluster dans la queue de la magnétosphère en été n’apporte quasiment rien à Themis.

Concertation inter-agence indispensable