Substorms in Near-Earth Space

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■ Self-Introduction

- Yukinaga Miyashita
- Principal researcher at Korea Astronomy and Space Science Institute (KASI)
- Professor at Korea National University of Science and Technology (UST)
- Doctor, Kyoto University, Japan
- Worked at ISEE, Nagoya University, Japan; ISAS, JAXA, Japan; and UCLA, USA.
- Research interests:
  - space physics, solar-terrestrial physics, space weather, space environment, etc.
  - magnetospheric physics
    - magnetosphere, magnetotail
    - geomagnetic storm, substorm, aurora
    - space weather and its prediction

■ KASI

- **Korea Astronomy and Space Science Institute**
  https://www.kasi.re.kr/eng/index
- **Daejeon, South Korea**

- **Space science**
- **Optical astronomy**
- **Radio astronomy**
- **Theoretical astronomy**
- **Space situational awareness**

■ UST KASI School

- **Korea National University of Science and Technology**
  https://ust.ac.kr/eng/

- **KASI School: Astronomy and space science**
  https://www.kasi.re.kr/eng/pageView/338

- **Graduate School**
  - **Master course**
  - **PhD course**
  - **Integrated course (Master + PhD)**
- **Campuses: Government-funded research institutes in South Korea**
- **Admission: Twice a year (spring and fall)**
- **Internship (summer)**

■ Contents

- Space Science
  - Sun-Earth connection
  - What is the substorm?
- Substorm-associated phenomena
- Substorm triggering mechanism (models)
- To solve the substorm triggering mechanism

Space Science

Aurora: A Substorm Signature

- When substorms occur, active auroras appear in the polar regions near midnight.

Auroral breakup observed on the ground

(c) NASA

■ Aurora: A Substorm Signature

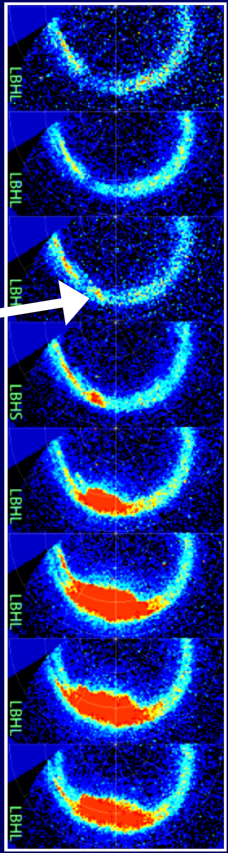
- When substorms occur, active auroras appear in the polar regions near midnight.

Aurora observed from a high-altitude satellite

(c) NASA

substorm onset

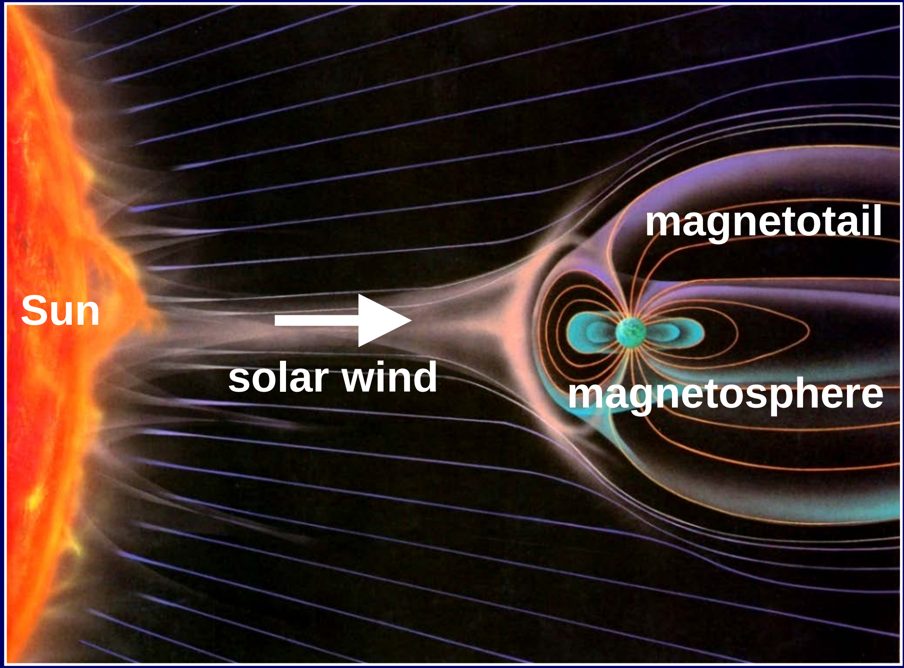
~10 min

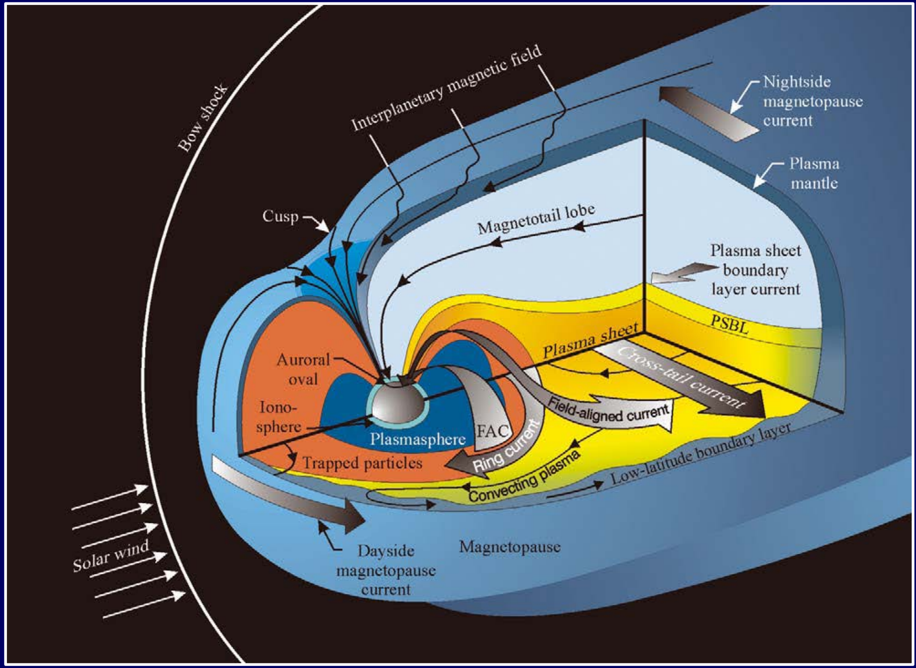


midnight

■ Sun-Earth System

- Space physics, Solar-terrestrial physics, ...
- Plasmas and energy are transported from the Sun to near-Earth space (magnetosphere and ionosphere).
- Severe solar activity can cause severe disturbances in near-Earth space, such as **geomagnetic (space) storms** and **substorms (active auroras)**.

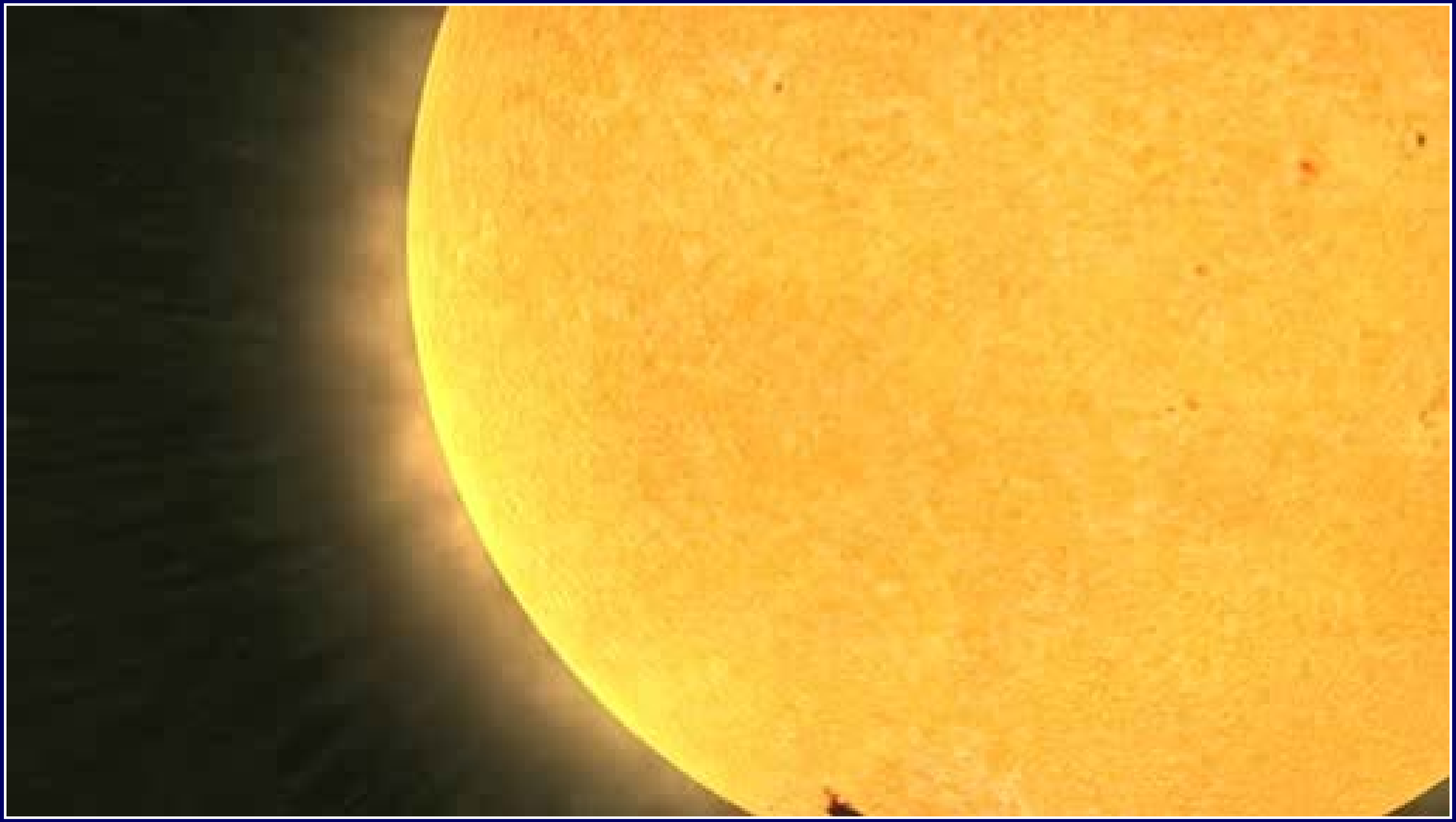




from Pollock et al. (2003)

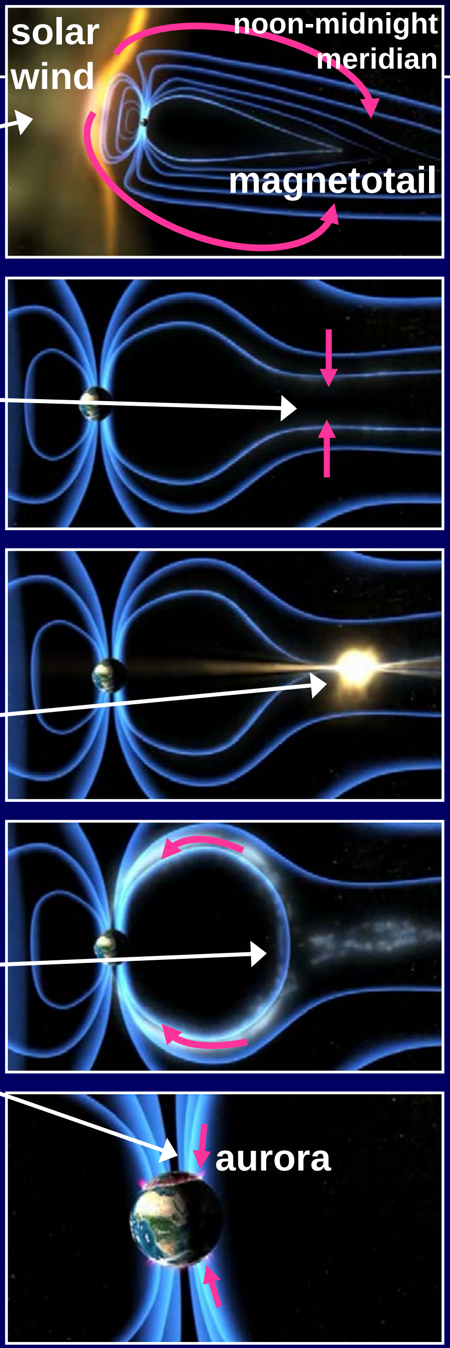
■ Substorm Generation Process

Energy for substorms comes from the sun.
It is accumulated in the magnetotail and then released.
→ Substorm and auroral breakup



(c) NASA

■ Substorm Generation Process



- **Interaction between the solar wind and the magnetosphere leads to energy accumulation in the magnetotail. The plasma/current sheet thins and magnetic field lines become stretched. (growth phase; typically for ~30-60 min)**

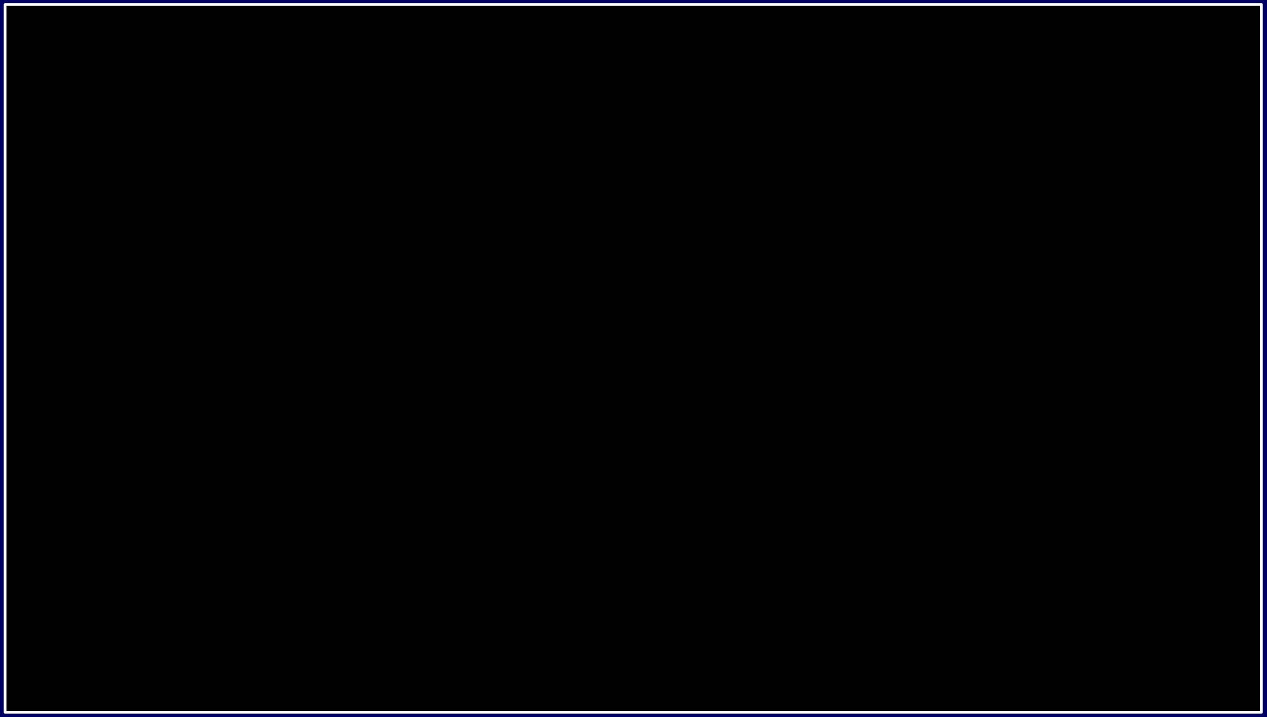
→ When the energy excessively accumulates, some process causes severe energy release and dissipation: substorm.

→ Various changes occur in the magnetosphere and the ionosphere and on the ground: dipolarization, auroral breakup, geomagnetic disturbances, etc. (expansion phase; typically for ~10-30 min)

- **What process causes a substorm?**

■ Geomagnetic (Space) Storms

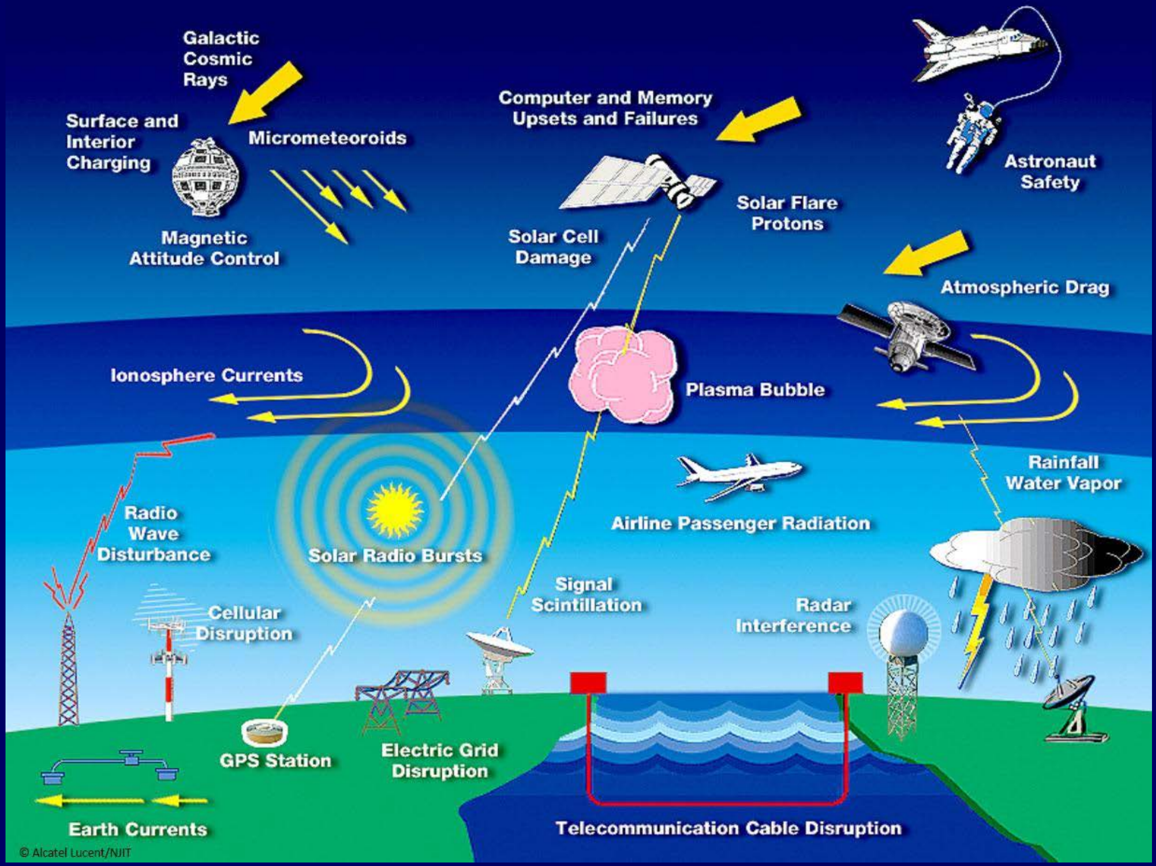
- Another major disturbance in near-Earth space.
- When a huge amount of energy from the Sun enters the magnetosphere, the ring current and the radiation belts in the inner magnetosphere highly develop, causing much severer disturbances called geomagnetic (space) storms.



■ Importance of Space Weather Research

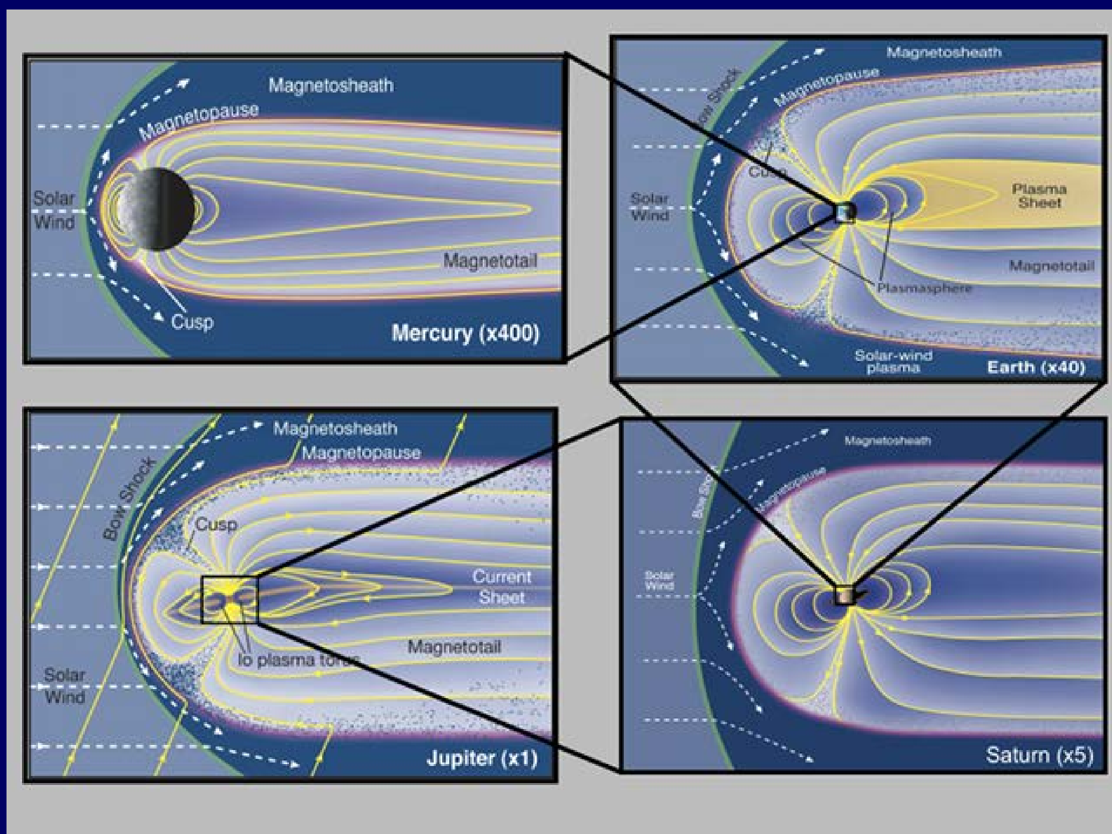
- Storms and substorms are fundamental in space weather and space plasma physics.
- It has become essential to utilize space for human life, and human activity is spreading to space more and more.
- Severe storms and substorms can cause damage to human activity.

→ Space weather research and forecast are essential to minimize damage.



■ Universality of Substorm Phenomena

- Substorms are explosive phenomena closely related to various plasma processes, such as instabilities, particle acceleration, and magnetic reconnection.
- They are common at planets, at the sun, and in the universe.

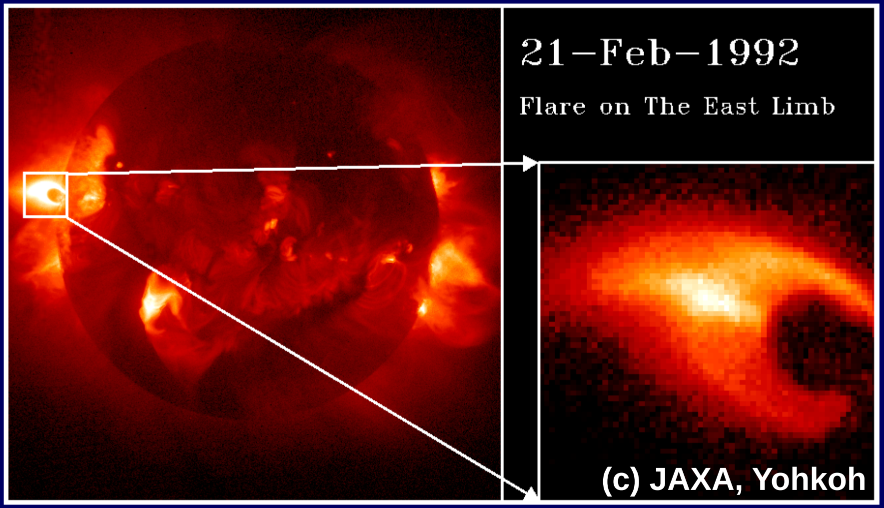


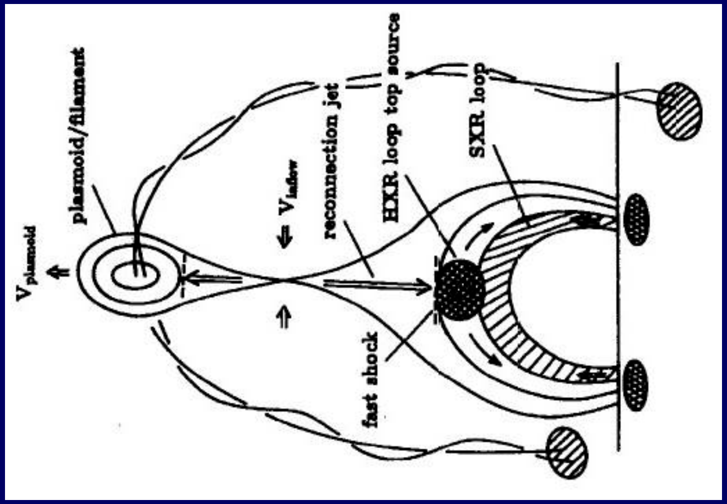
planetary aurora

(c) NASA

■ Universality of Substorm Phenomena

Solar flare



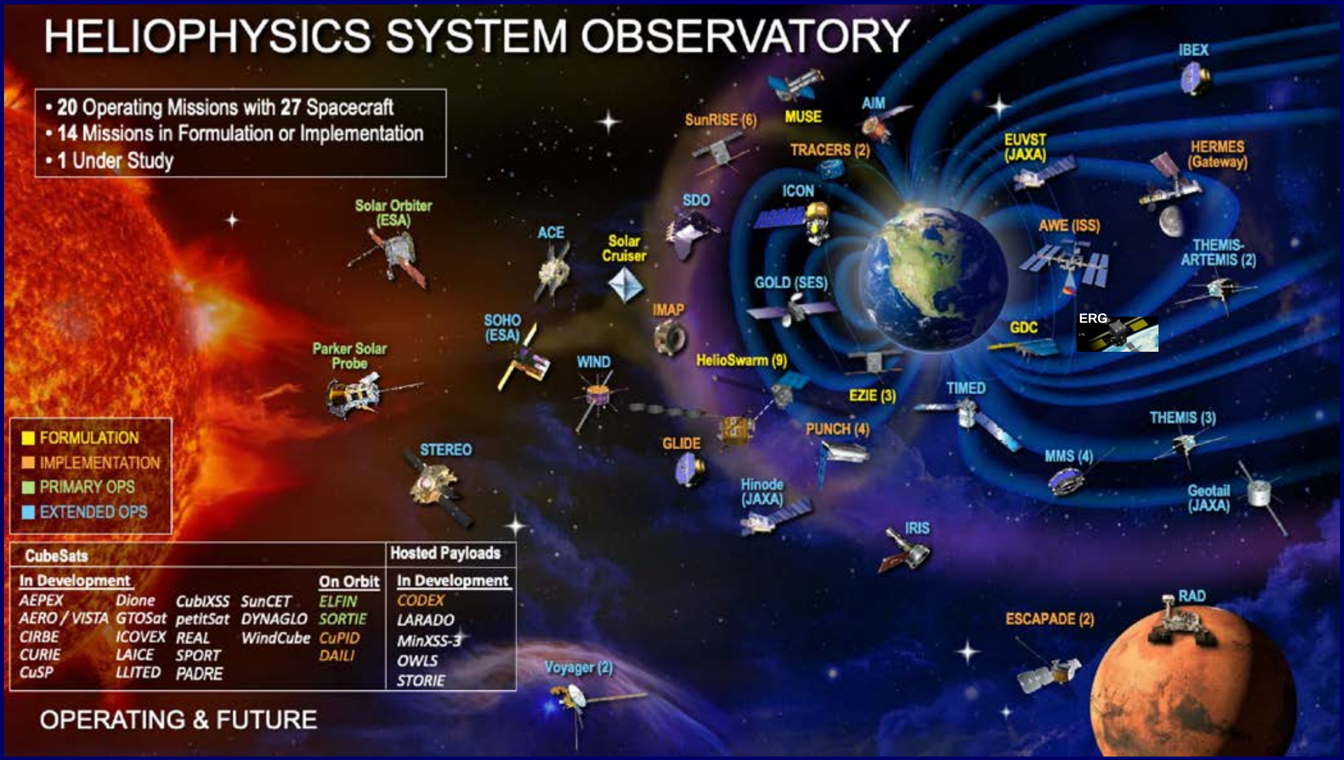


- Understanding of substorms will further promote that of universal space plasma physics at planets, the sun, and other celestial objects.
- Comparison will deepen not only our understandings of the near-Earth space environment itself and its universality and specialty but also those of other objects.

■ Comprehensive Studies of Space Physics

Comprehensive analyses are needed.

- **Multi-point satellites**
  ERG, MMS, THEMIS, Cluster, Geotail, GEO, etc.
- **Ground-based instruments**
  magnetometers, cameras, radars, etc.
- **Simulations**
  global MHD, local particle



(c) NASA

Substorm-Associated Phenomena

■ Substorm-Associated Phenomena

Various phenomena occurs, associated with substorms (at onset and in the expansion phase).

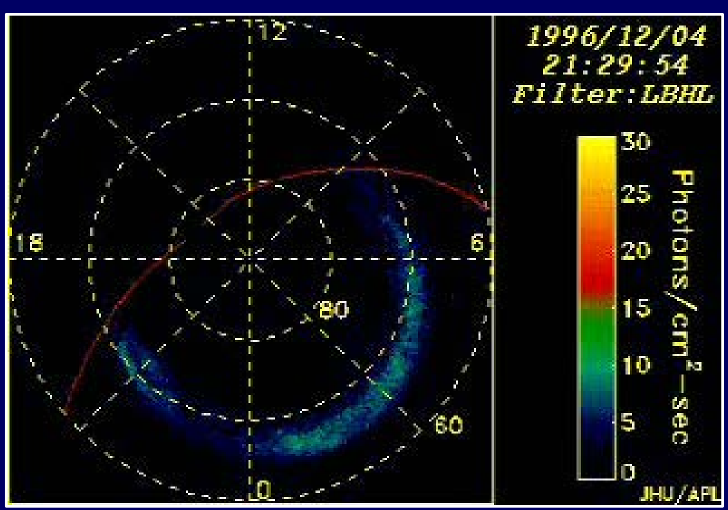
- Ionosphere
  - Auroral breakup (poleward expansion)
  - Intense westward auroral electrojet
- Magnetotail
  - Magnetic reconnection, fast flows, plasmoid
- Magnetotail and inner magnetosphere
  - Dipolarization, energetic particle injection
- Others
  - Auroral kilometric radiation
  - Pi2 and Pi1 pulsations (magnetosphere and ground)
  - Geomagnetic and ionospheric changes at middle and low latitudes on the ground

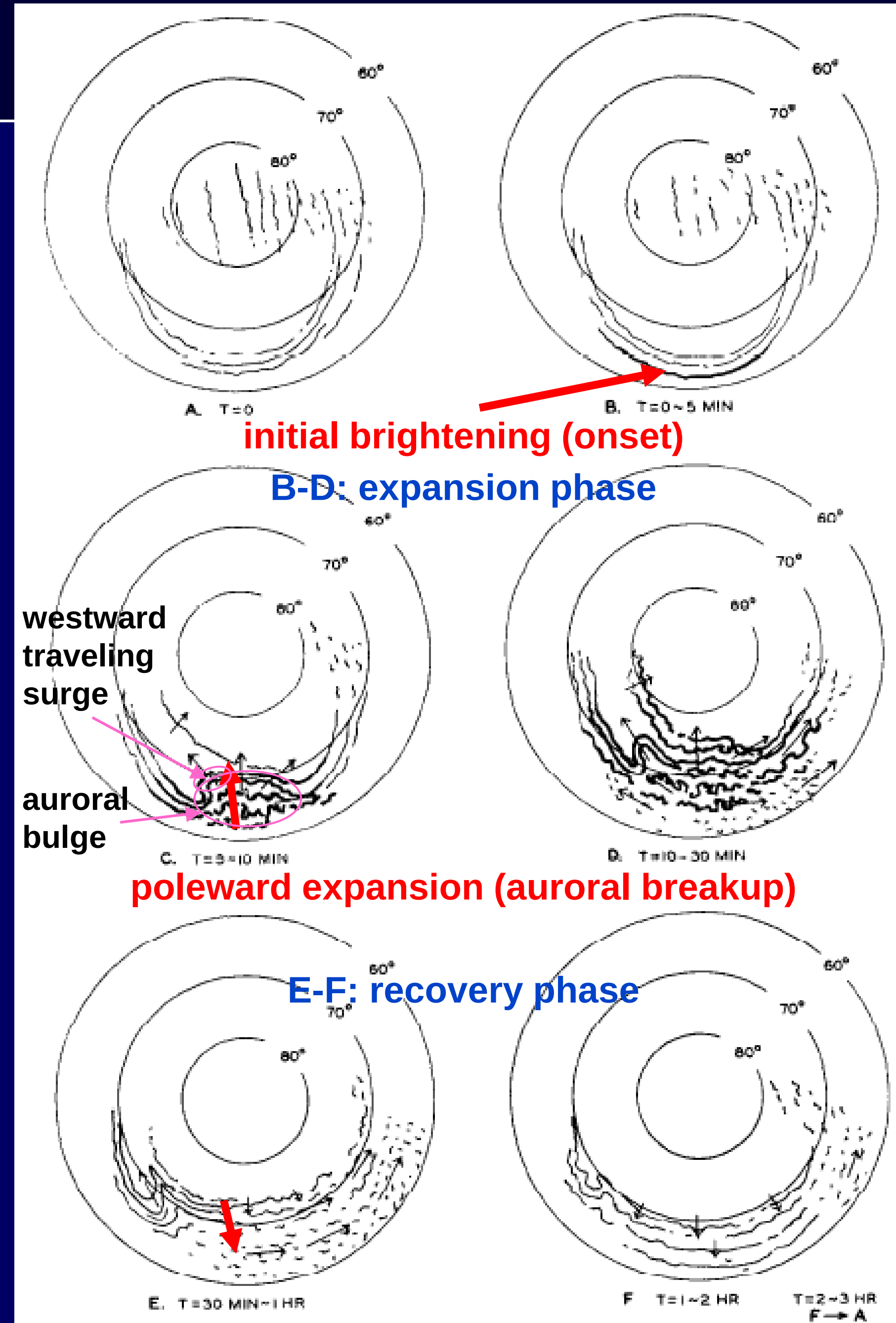
■ Auroral Breakup

Expansion phase

- **Initial auroral brightening** near the most equatorward part of the auroral oval (**substorm onset**)
- **poleward expansion** (**auroral breakup**)

Recovery phase: Subsiding

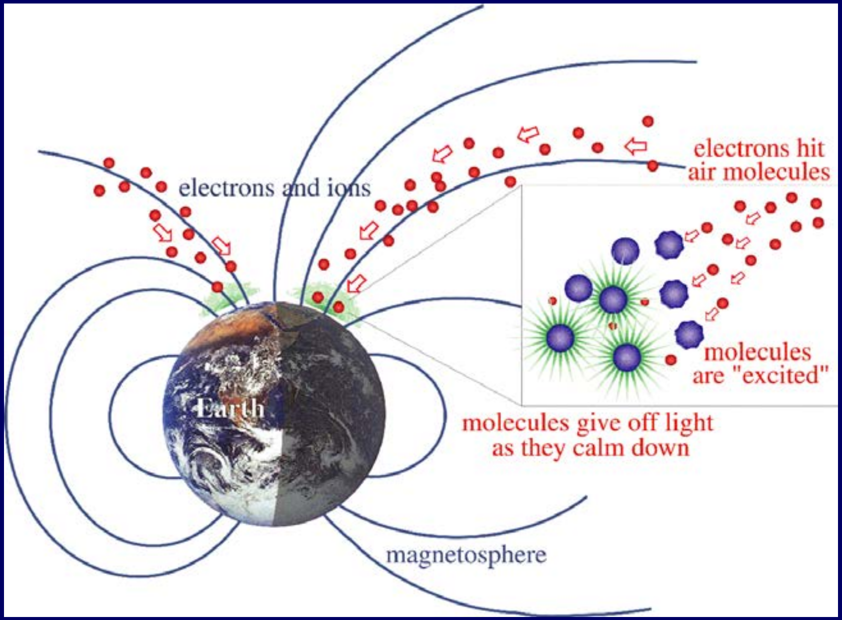




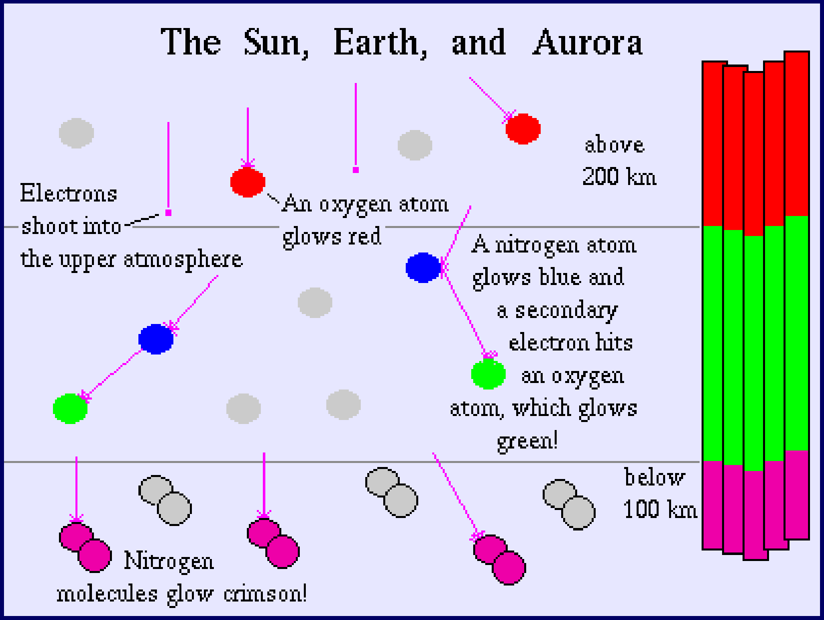
Akasofu (1964)

■ Mechanism of Aurora

- Auroral images are like television-screen view of magnetospheric processes.
- Precipitating particles collide with atoms and molecules, which are excited and emit radiation (aurora).
- The color and altitude of auroras depend on the species and altitudinal profile of the atoms and molecules and the energy of precipitating particles.



https://aurorawatch.lancs.ac.uk/alerts/

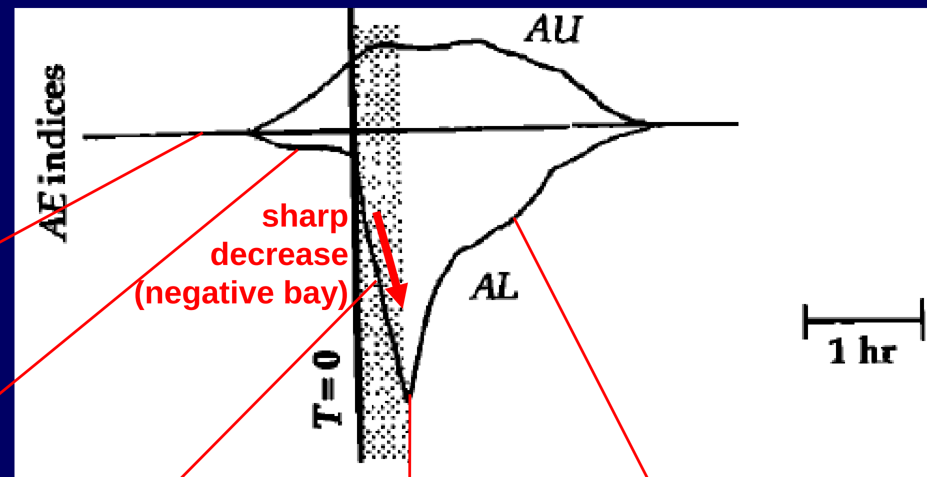


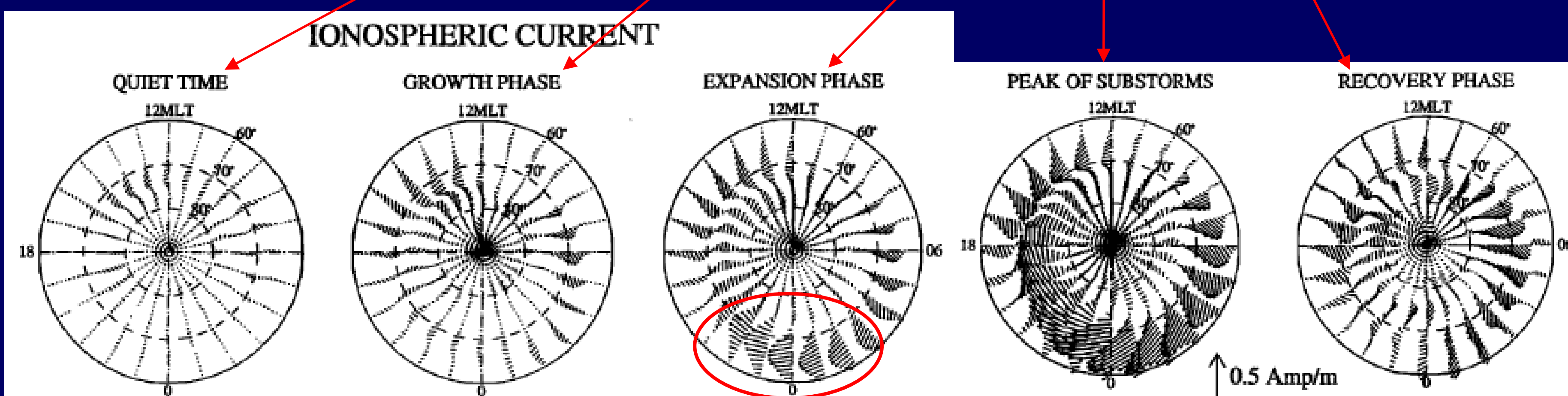
Univ. Alaska, Fairbanks

■ High-Latitude Ground & Substorm Phases

Intense westward ionospheric currents near midnight are associated with auroral breakup (poleward expanding intense aurora).

AU: maximum eastward electrojet
AL: maximum westward electrojet (poleward geomagnetic field perturbation)
AE=AU-AL





global convection (two cell)

global convection + substorm

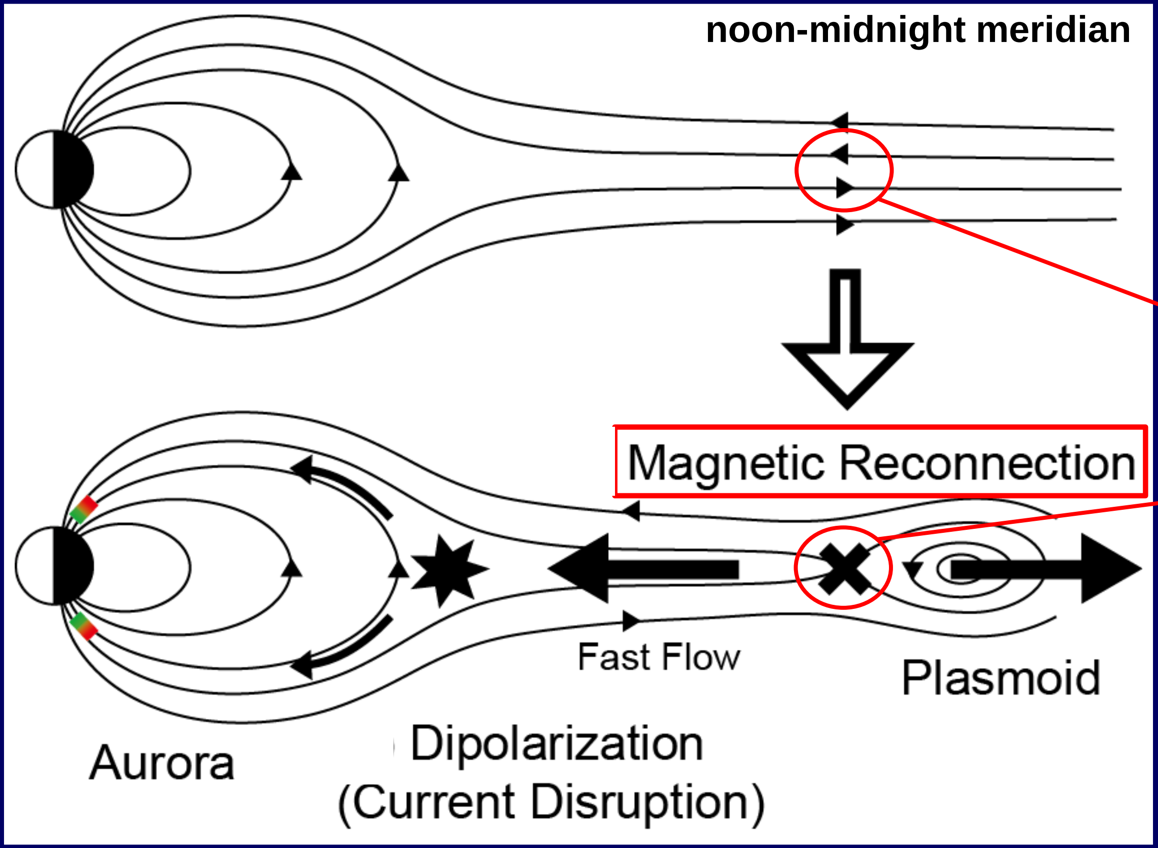
Kamide & Kokubun (1996)

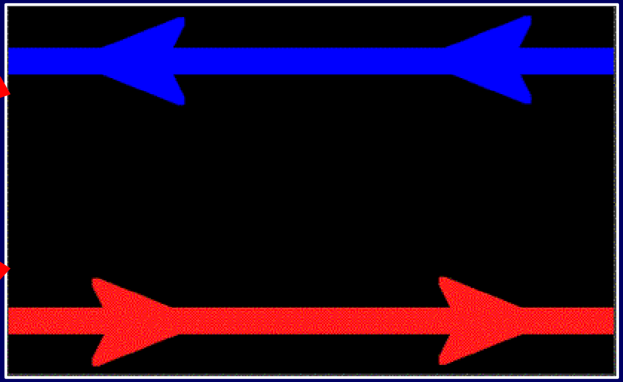
■ Substorm Phases

- **Growth phase** (typically for ~30-60 min)
  - Begins with southward interplanetary magnetic field.
  - The energy accumulates in the magnetotail (lobes). The auroral oval expands.
  - The plasma/current sheet thins, and magnetic field lines become stretched configuration.
- **Onset and expansion phase** (typically for ~10-30 min)
  - The accumulated energy releases.
  - Consequently, various severe changes occur in the magnetosphere and ionosphere and on the ground.
  - Multiple expansions often occur.
- **Recovery phase** (typically for ~30-60 min)
  - The activities subside.
  - The magnetosphere and the ionosphere return to quiet state.

■ Magnetic Reconnection in the Magnetotail

- **Magnetic reconnection** is disconnecting and connecting oppositely directed magnetic field lines.
- It converts magnetic energy into plasma energy i.e., energy release.



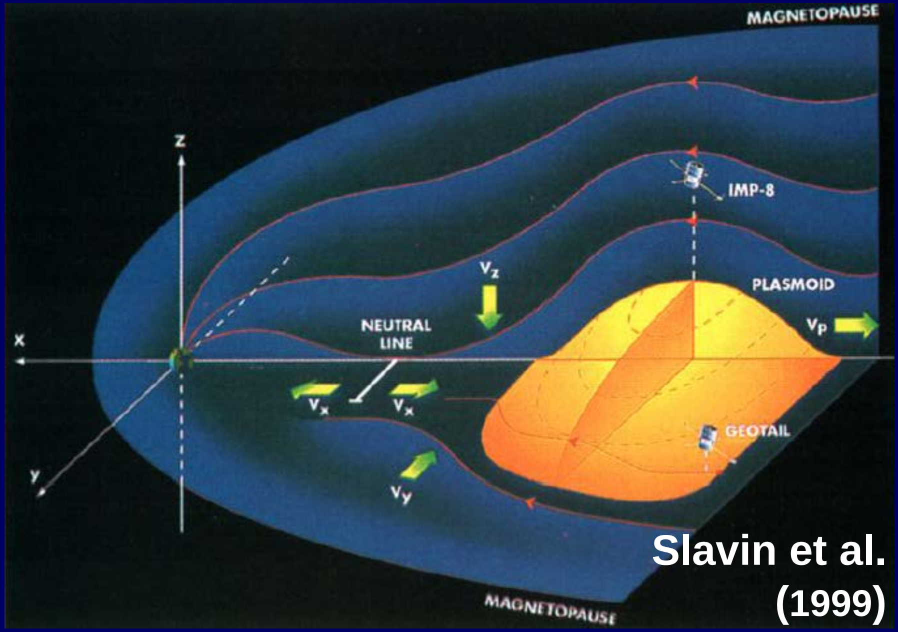


■ Magnetic Reconnection in the Magnetotail

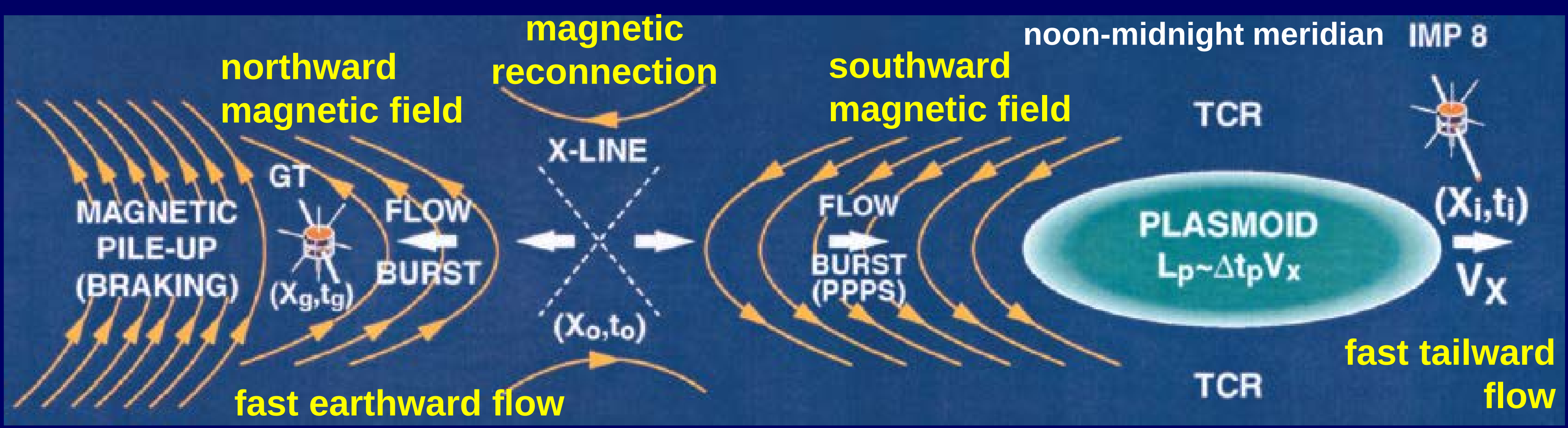
Magnetic reconnection in the near-Earth magnetotail at X ~ -20 Re (Re: Earth's radius)

→ - fast tailward flow with southward magnetic field (plasmoid)

- fast earthward flow with northward magnetic field



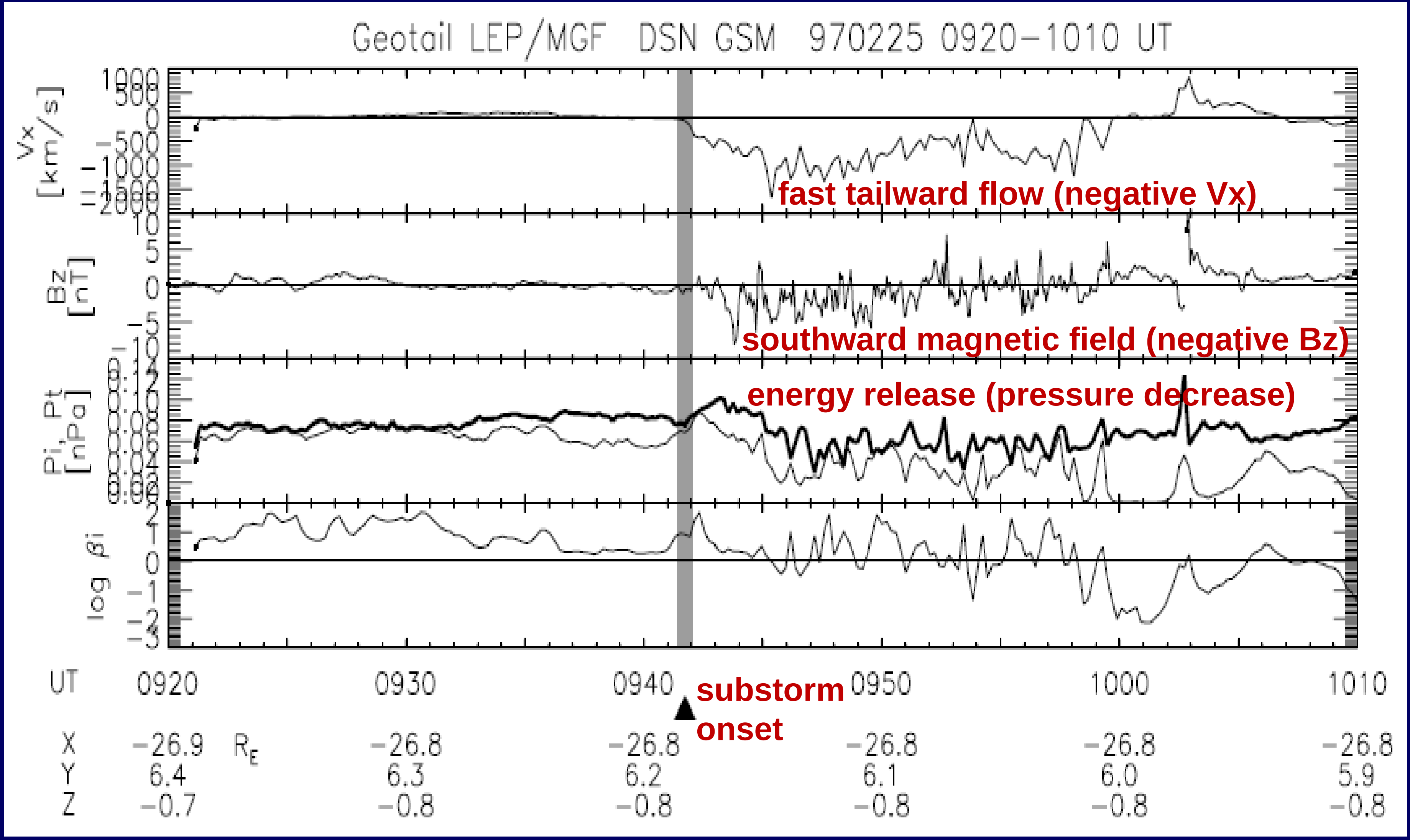
Slavin et al. (1999)



Slavin et al. (2002)

■ Magnetic Reconnection in the Magnetotail

An example of the plasmoid

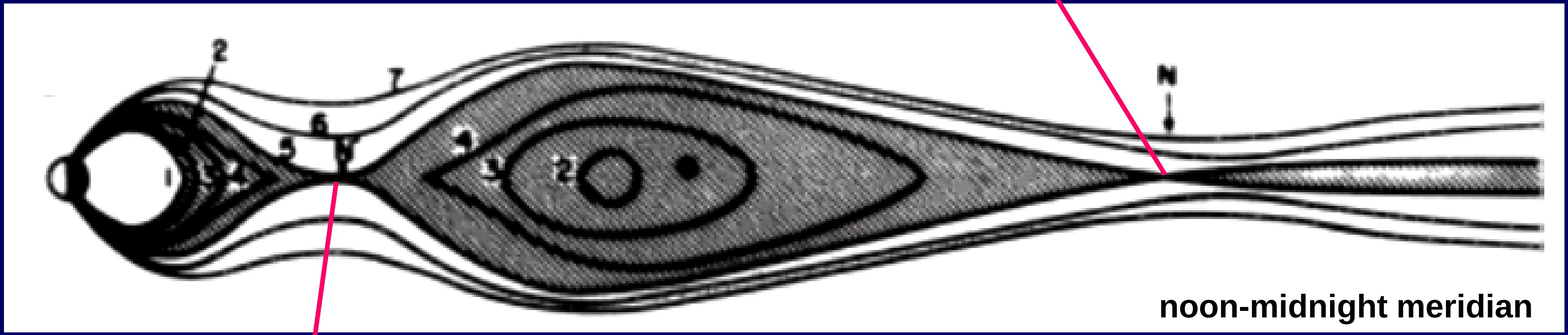


Miyashita et al. (2009)

■ Two Reconnection Sites: NENL and DNL

- There are two magnetic reconnection sites in the magnetotail (in a macroscopic view).

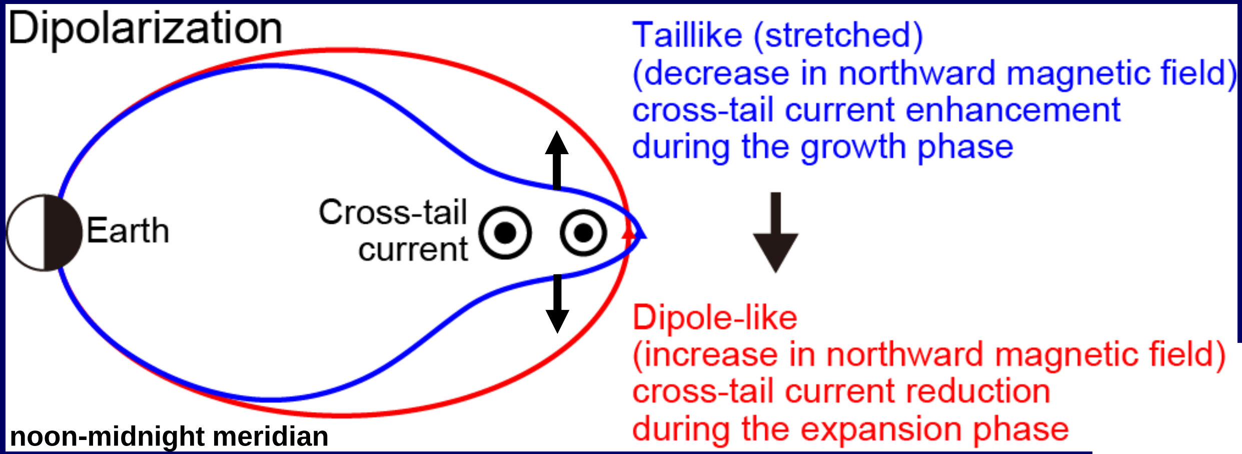
Distant Neutral Line (DNL or DXL) associated with global convection
X ~ -100 Re

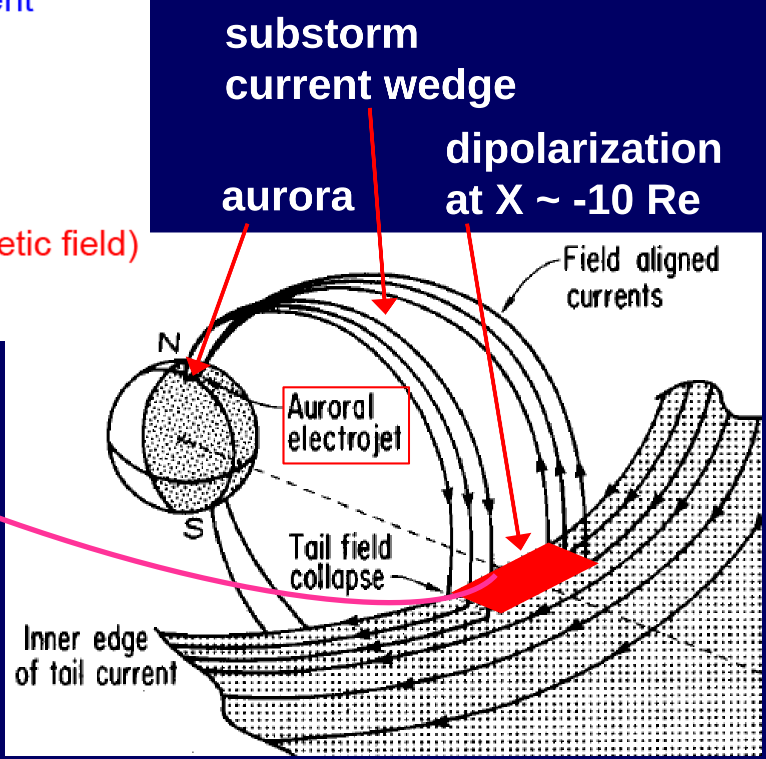


Near-Earth Neutral Line (NENL or NEXL) associated with substorm onset
X ~ -20 Re

■ Dipolarization in the Magnetotail

- During the growth phase, magnetic field lines become **taillike** (stretched) configuration.
- In the expansion phase, they return **to dipole-like** configuration: dipolarization.



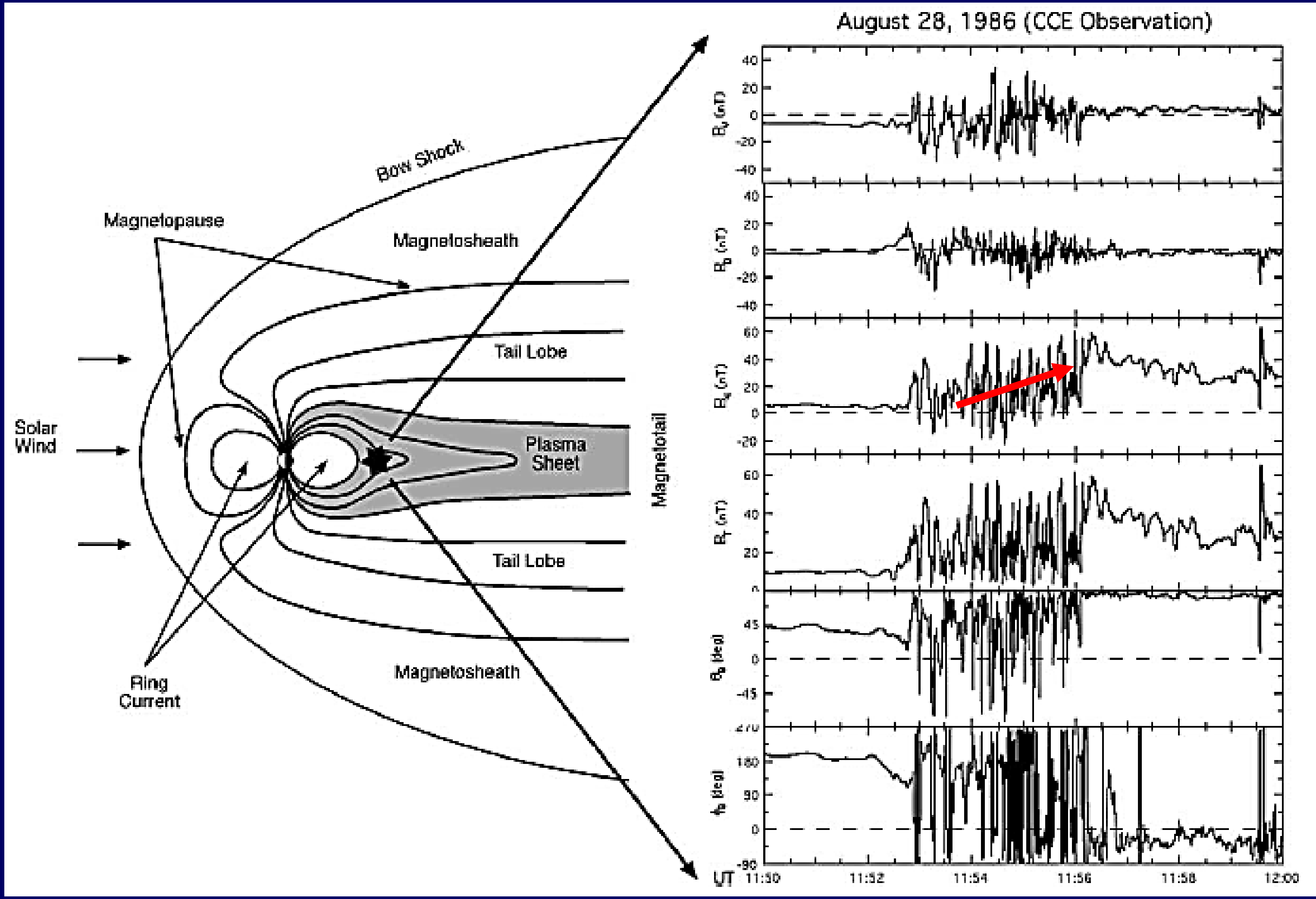


McPherron et al. (1973)

- Dipolarization occurs in the substorm current wedges.
- Directly connected with auroral poleward expansion.

■ Dipolarization in the Magnetotail

An example



Dipolarization: Net increase in northward magnetic field

Accompanied by rapid fluctuation

from Lui [2004]

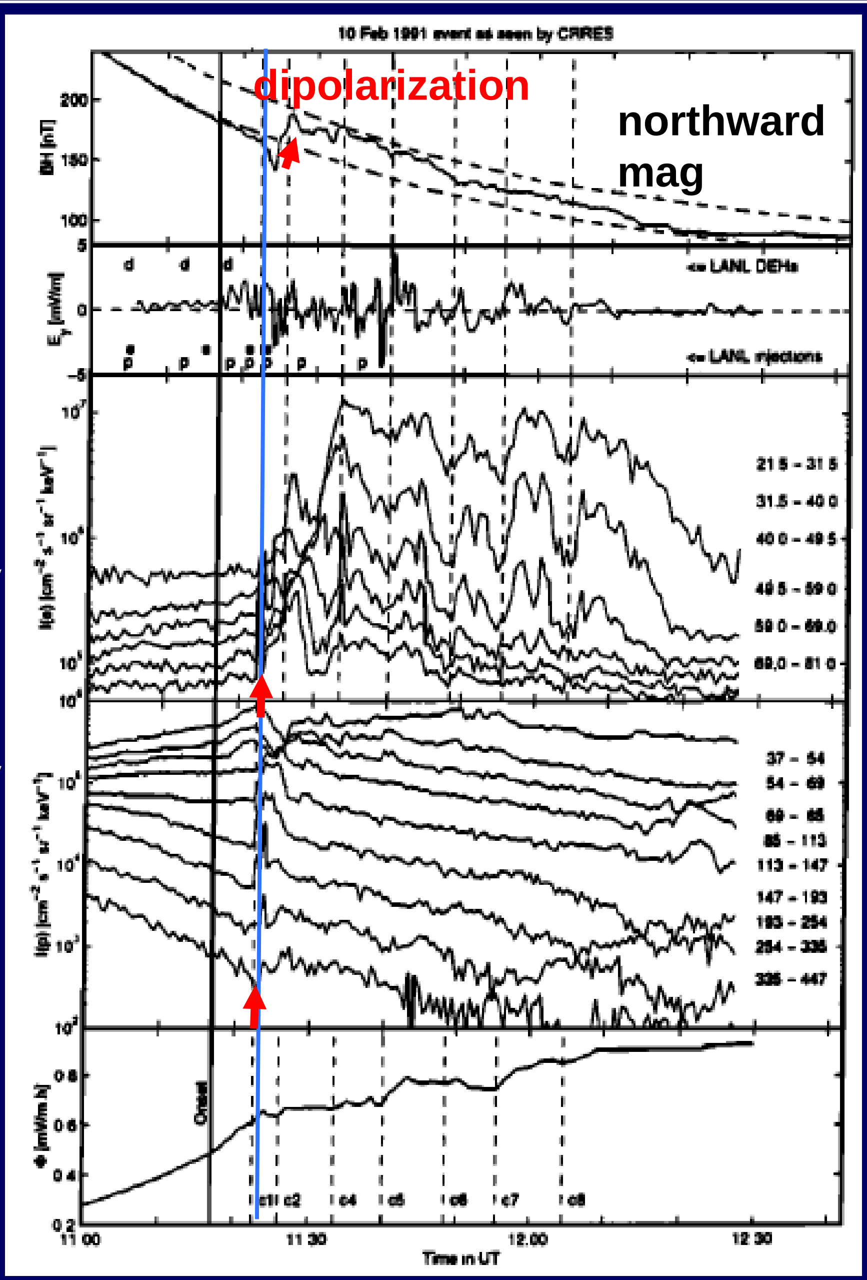
■ Energetic Particle Injection

- Energetic particles are generated, associated with dipolarization.
- Then the particles drift around Earth.

- Increase in energetic particle fluxes: "injection"

high-energy electron fluxes

high-energy proton fluxes



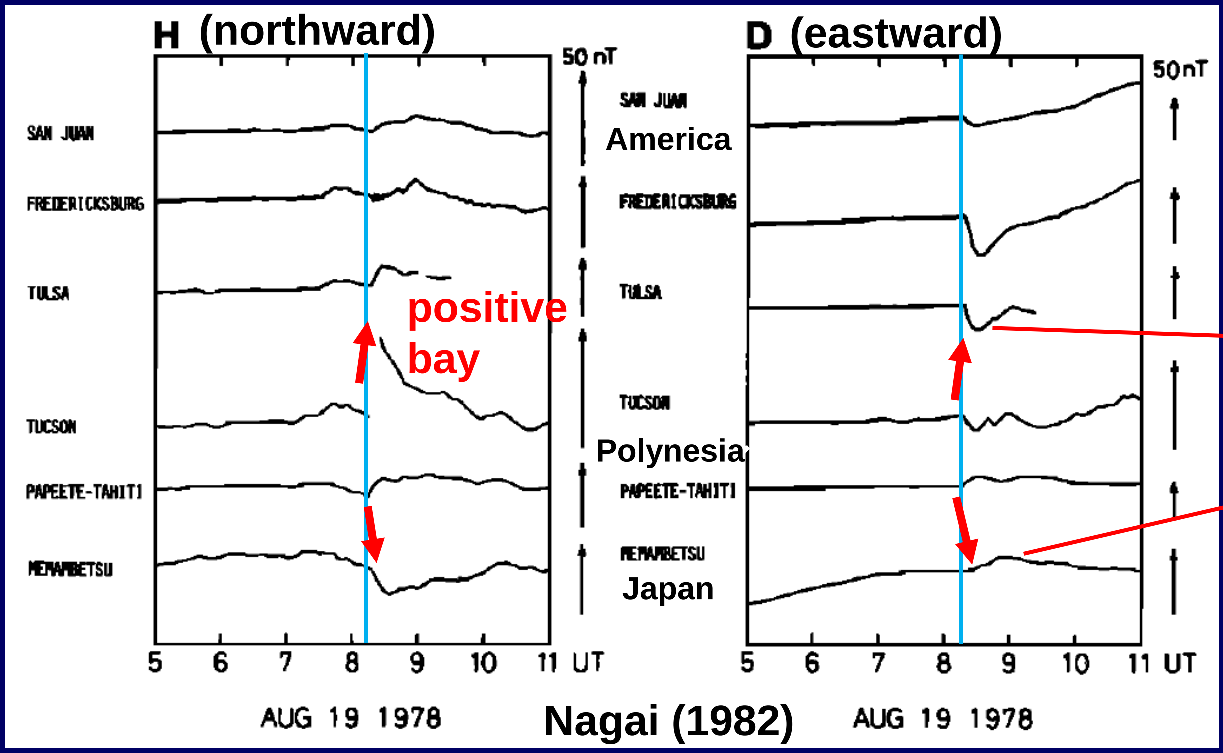
at L~5

Sergeev et al. (1998)

■ Substorm Current Wedges & Positive Bay

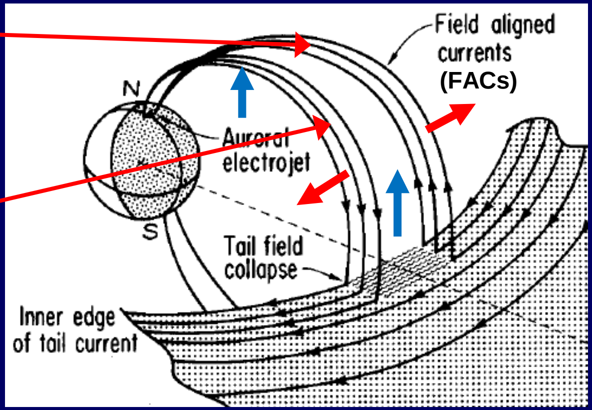
- **Positive bay** perturbation is increase in northward mag at low latitudes inside the SCWs by a few to 10 nT, due to FACs and cross-tail current reduction.
- Eastward and westward mag deflect due to FACs of the SCWs. → The SCWs expands longitudinally.

ground mag from longitudinally-aligned low-latitude stations



Nagai (1982)

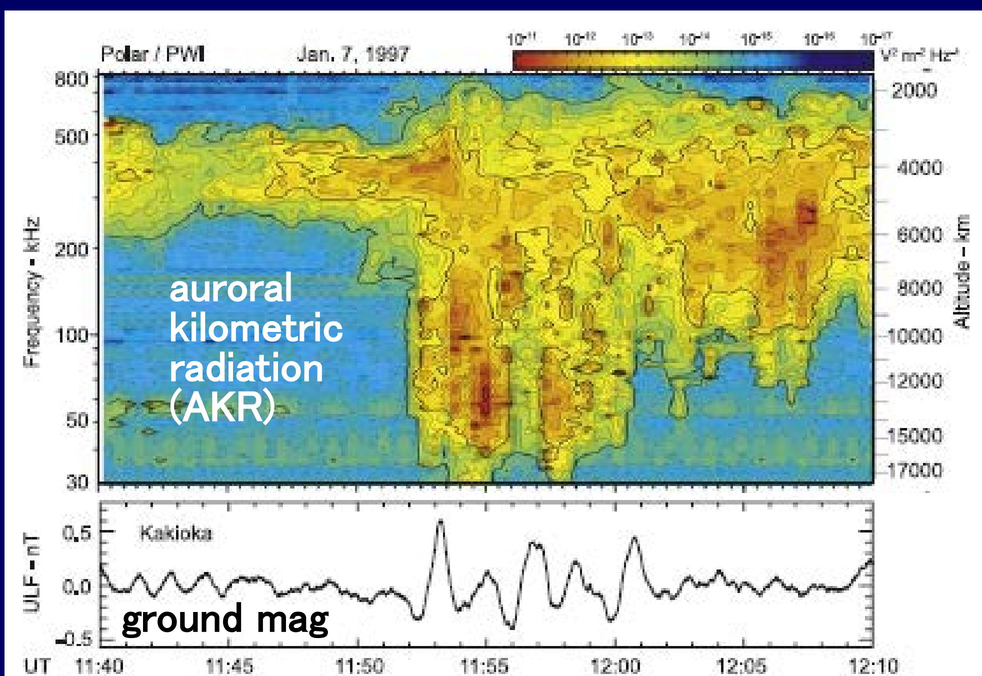
substorm current wedge (SCW)



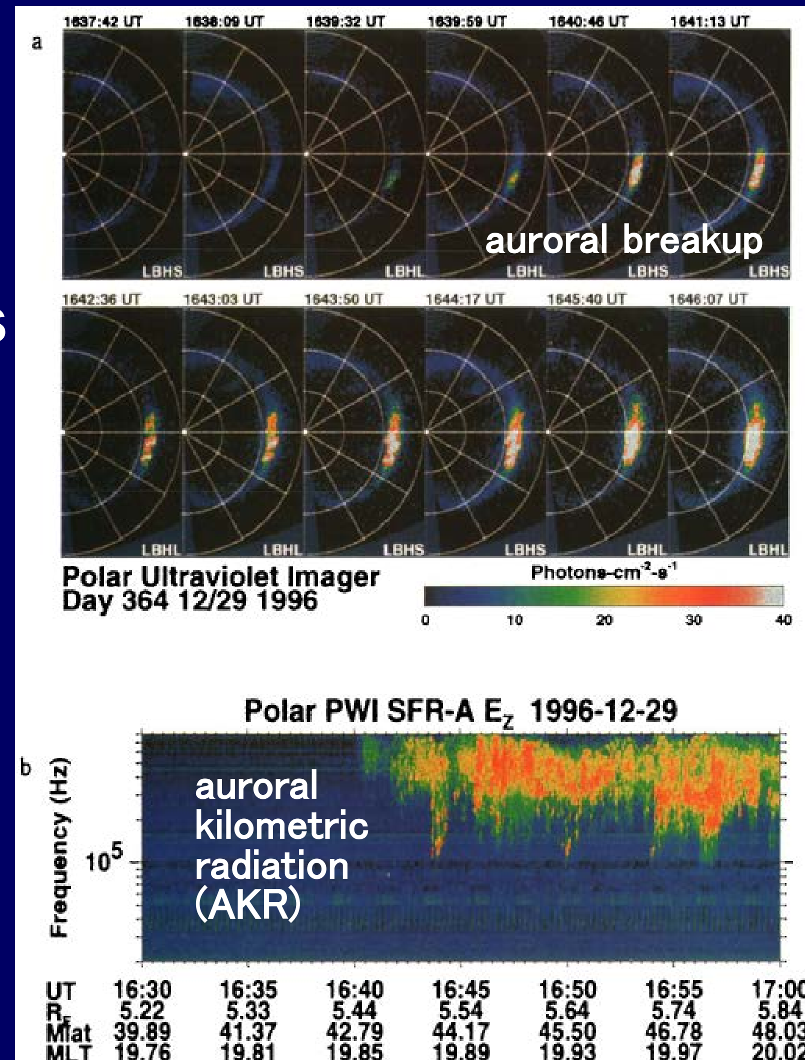
McPherron et al. (1973)

■ Auroral Kilometric Radiation

- Related to **acceleration of auroral particles** at ~2000-20,000 km altitude.
- Observed in a wide area of near-Earth space
- Good correlation with auroral breakup and geomagnetic waves



Morioka et al. (2007)

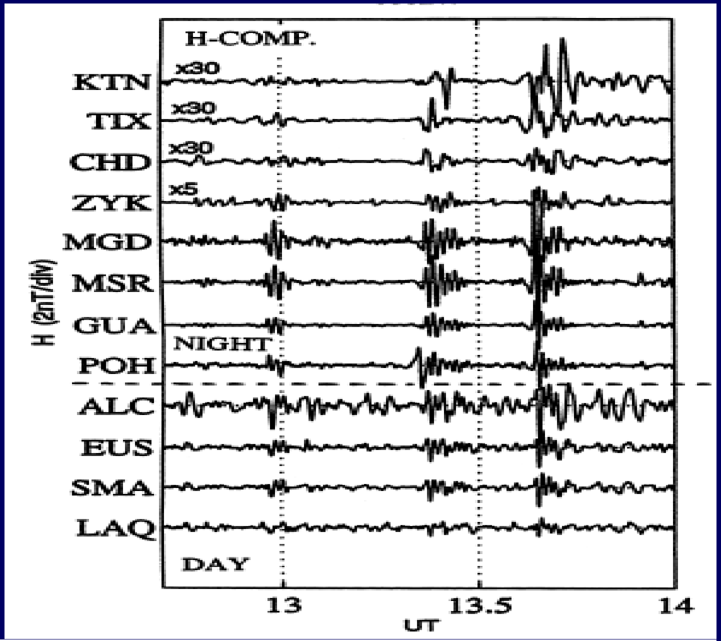


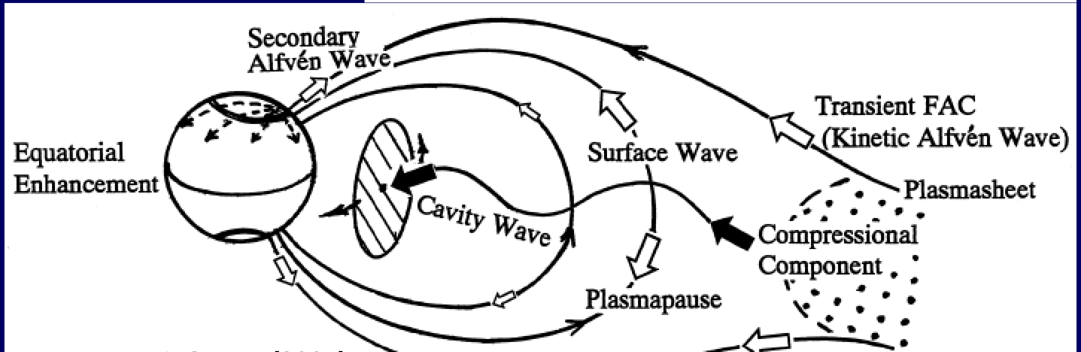
Liou et al. (2000)

■ Pi2 and Pi1 Pulsations

- **Pi2 pulsation (period: 40-150 s)**
- **Pi1 pulsation (period: 1-40 s)**
  - Geomagnetic waves
  - Generated by reconnection and dipolarization in the near-Earth magnetotail at substorm onsets
  - Propagates in the magnetosphere to the ground
  - Amplitude: <1 to ~10 nT on the ground

Pi2 pulsations



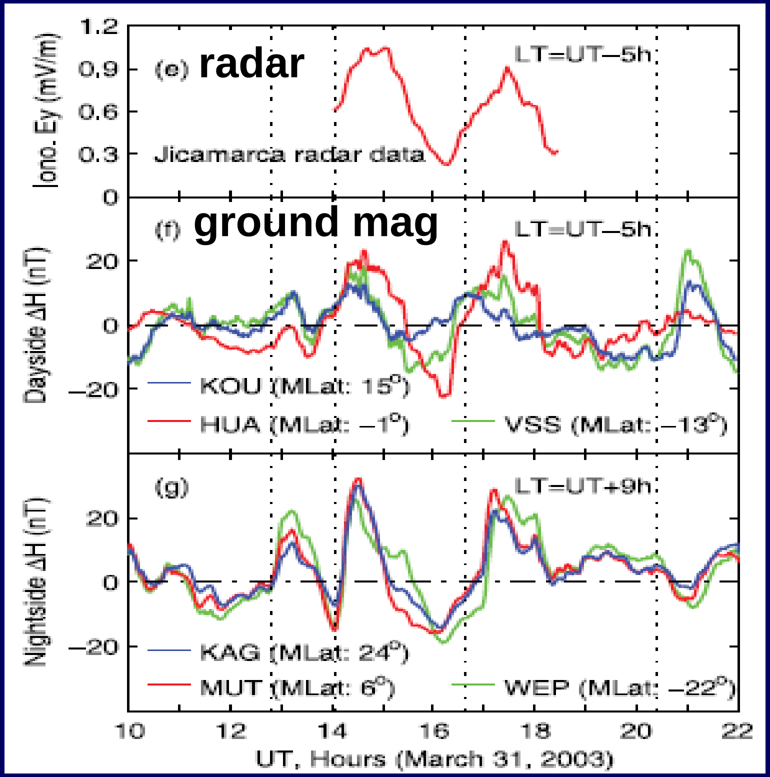


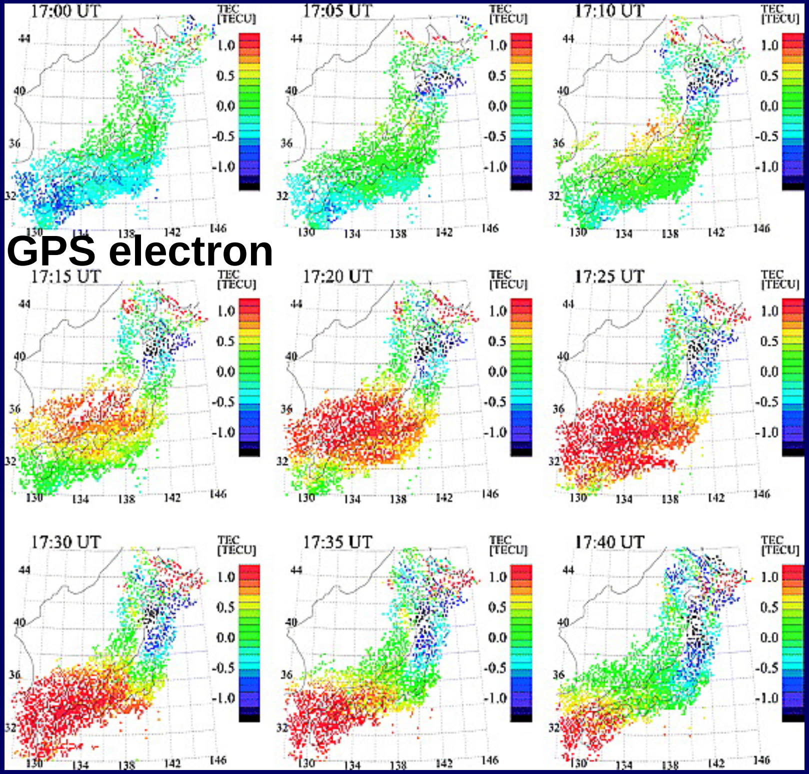
Yumoto & CPMN (2001)

■ Low-Latitude Ionosphere

Substorm phenomena at low-latitudes

- **Electric field (convection) enhances even on the dayside.**
- **Large-scale traveling ionospheric disturbances**
  - **Propagate equatorward from the auroral region.**
  - **Cameras, radars, GPS-TEC, ionosondes, etc.**





Huang (2009) **Shiokawa et al. (2003)**

Substorm Triggering Mechanism (Models)

■ Substorm Triggering Mechanism

The substorm triggering mechanism has been a major issue for more than half a century.

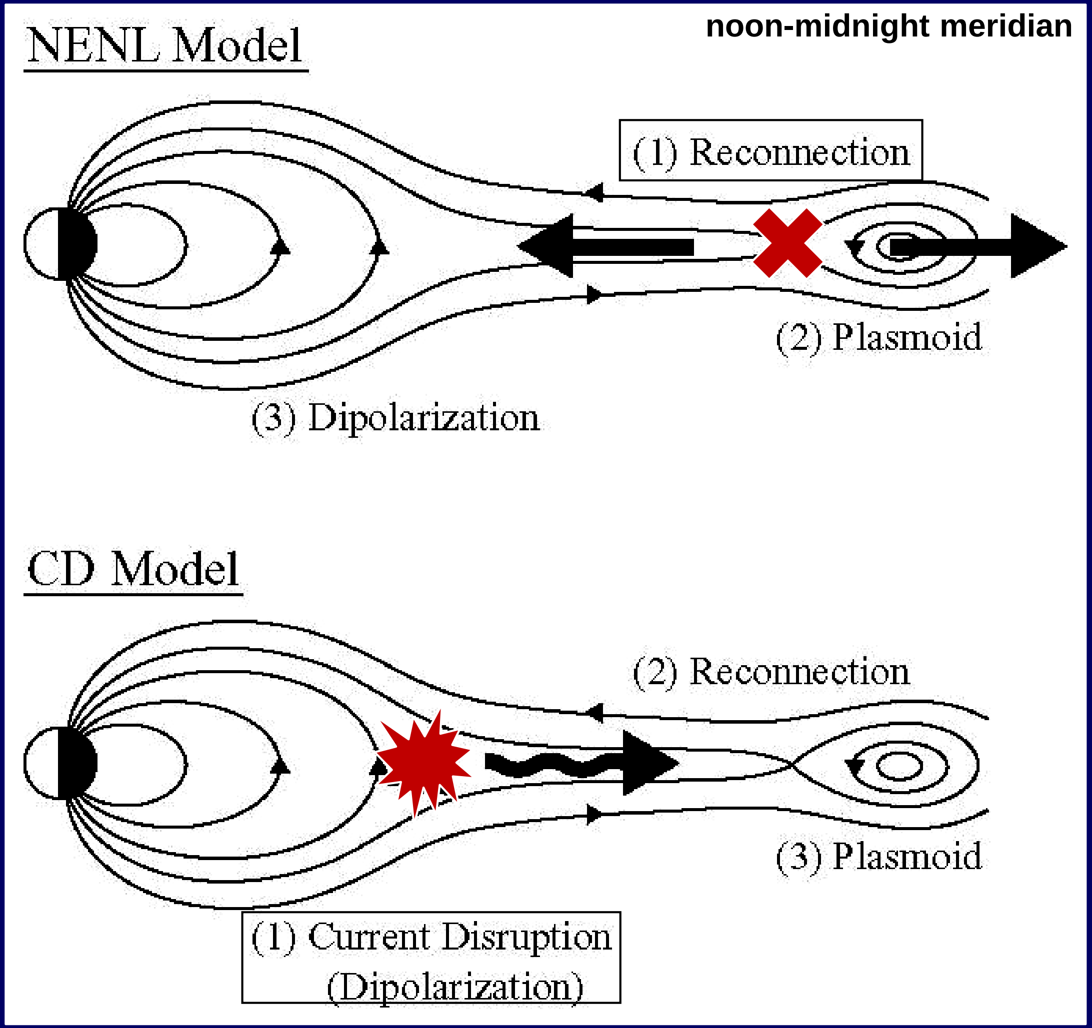
Various substorm models have been proposed:

- Near-Earth Neutral Line Model (“Outside-In”) [e.g., Baker et al., 1996]
- Current Disruption Model (“Inside-Out”) [e.g., Lui, 1996]
- Magnetosphere-Ionosphere Coupling [e.g., Kan et al., 1988]
- Convection Reduction Model [Lyons, 1995]
- Boundary Layer Dynamics Model [Rostoker and Eastman, 1987]
- Thermal Catastrophe Model [Smith et al., 1986]
- Catapult Current-Sheet Relaxation Model (Middle → In & Out) [Machida et al., 2009]
- New plasma intrusion (preonset streamer) model [Nishimura et al., 2010]
- etc.

■ Two Leading Substorm Models

Near-Earth Neutral Line (NENL) Model "**Outside-In**"

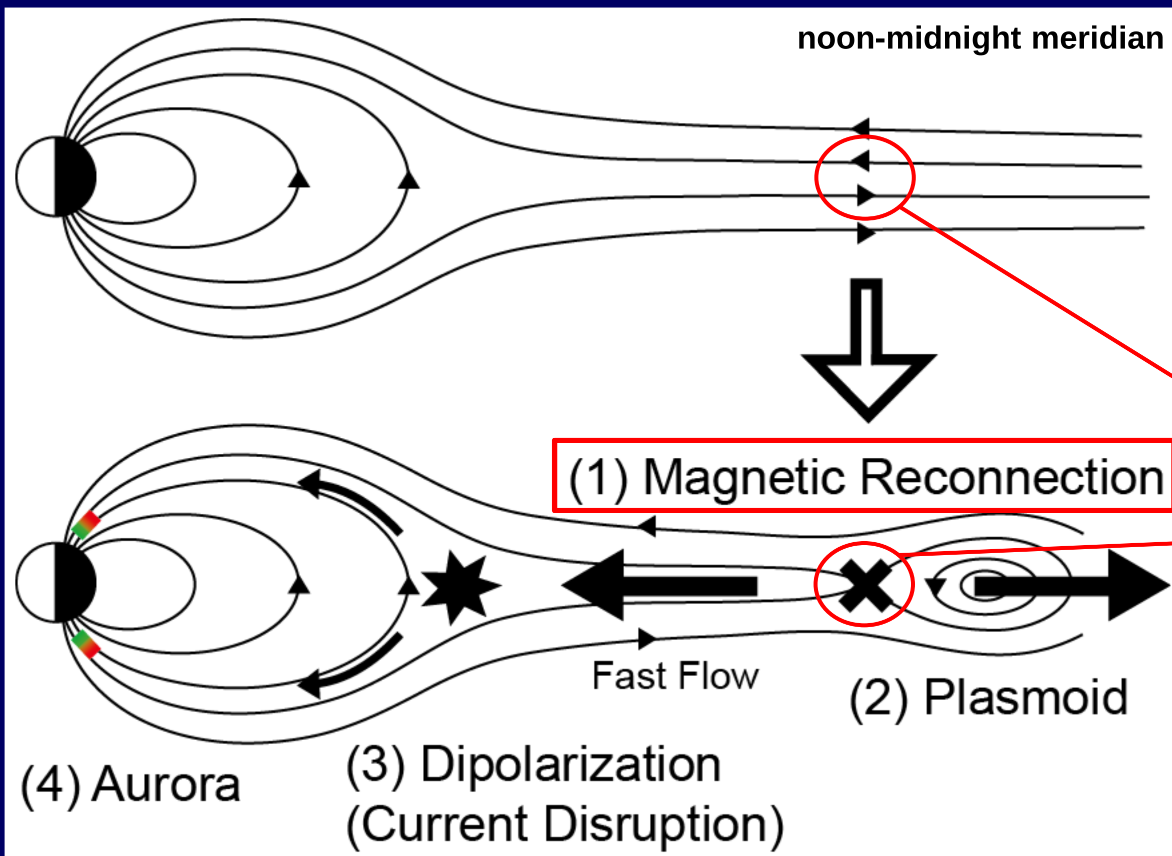
Current Disruption (CD) Model "**Inside-out**"



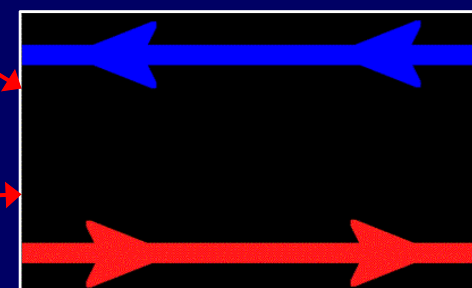
The substorm triggering mechanism has been a major issue for more than half a century.

■ Near-Earth Neutral Line Model

- **Magnetic reconnection in the magnetotail drives energy release and a substorm.**



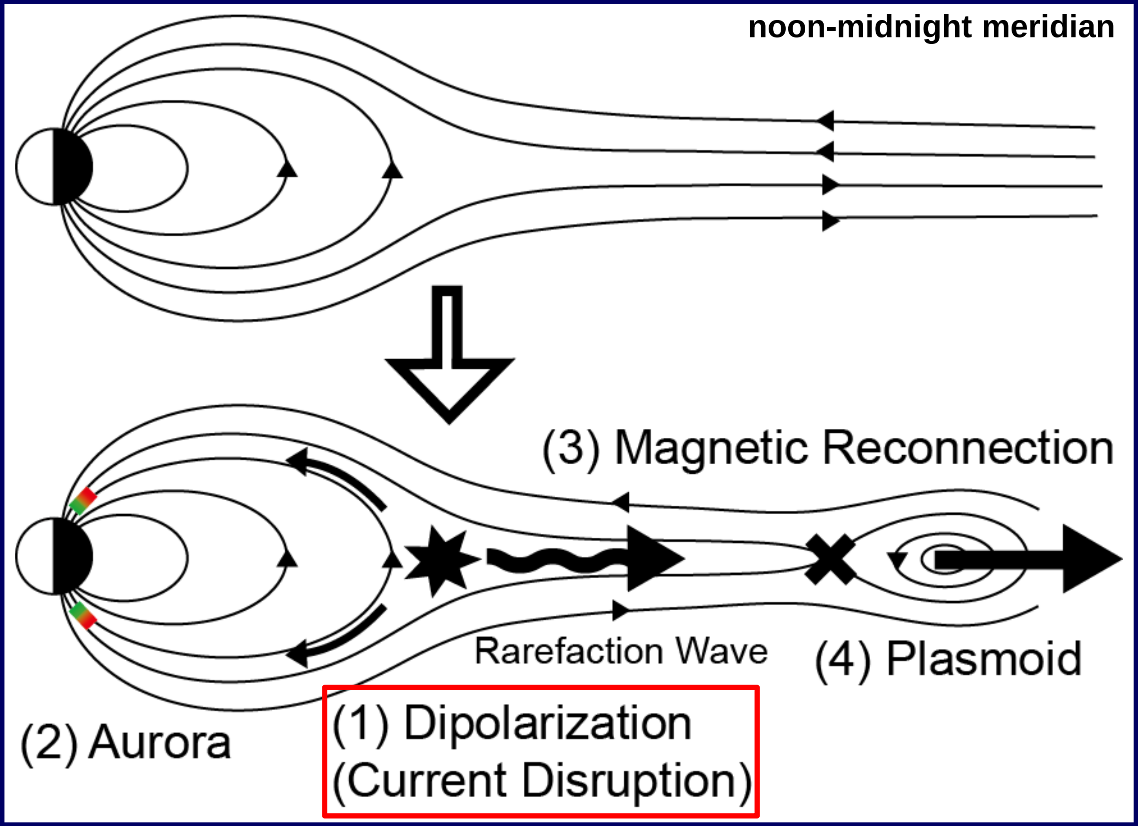
Magnetic reconnection: disconnecting and connecting oppositely directed magnetic field lines



Converts magnetic energy into plasma energy.

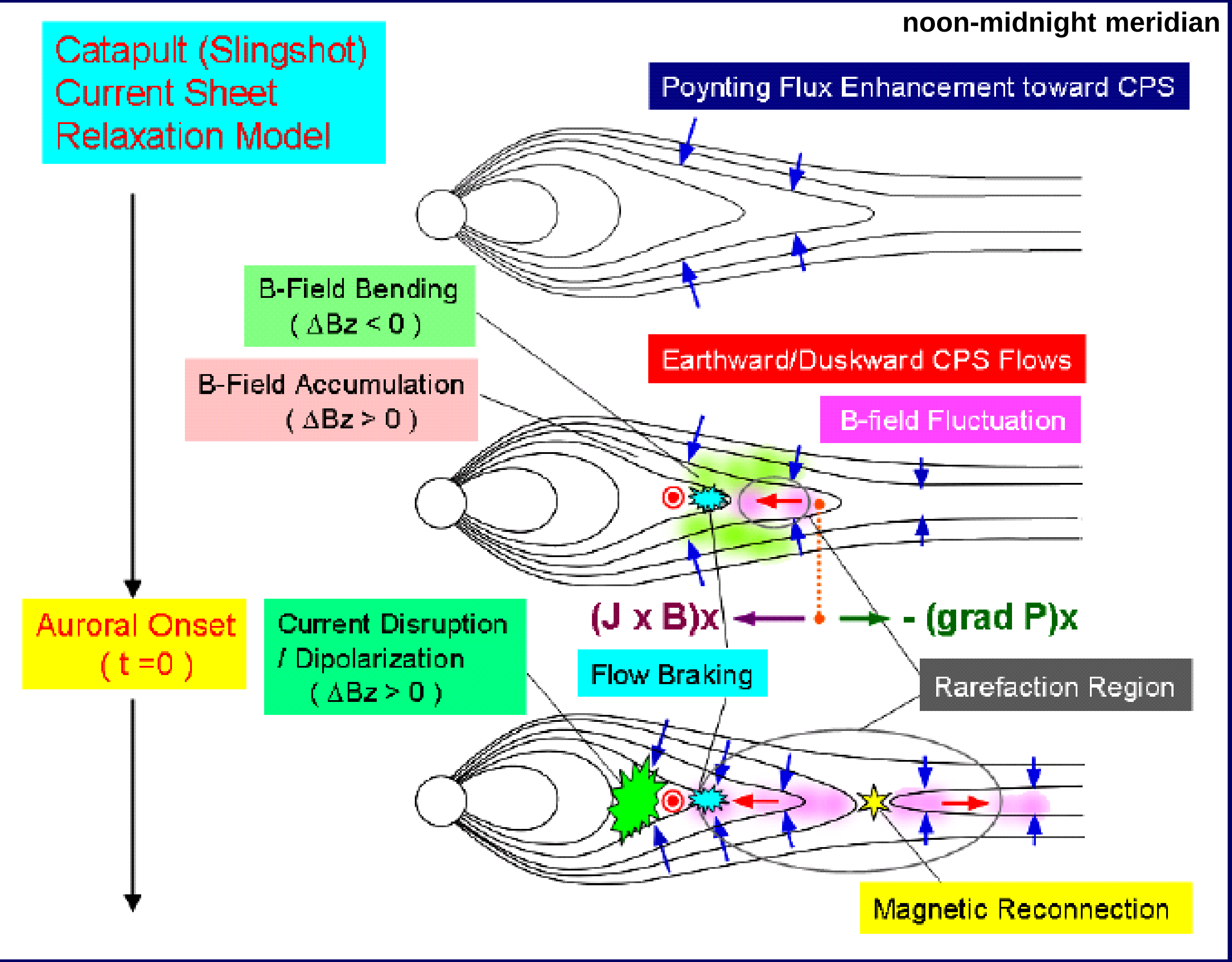
■ Current Disruption Model

- The time sequence is different.
- Current disruption drives energy release and a substorm.



→ Relative timing and causal relationship between reconnection and current disruption?

■ Catapult Current-Sheet Relaxation Model

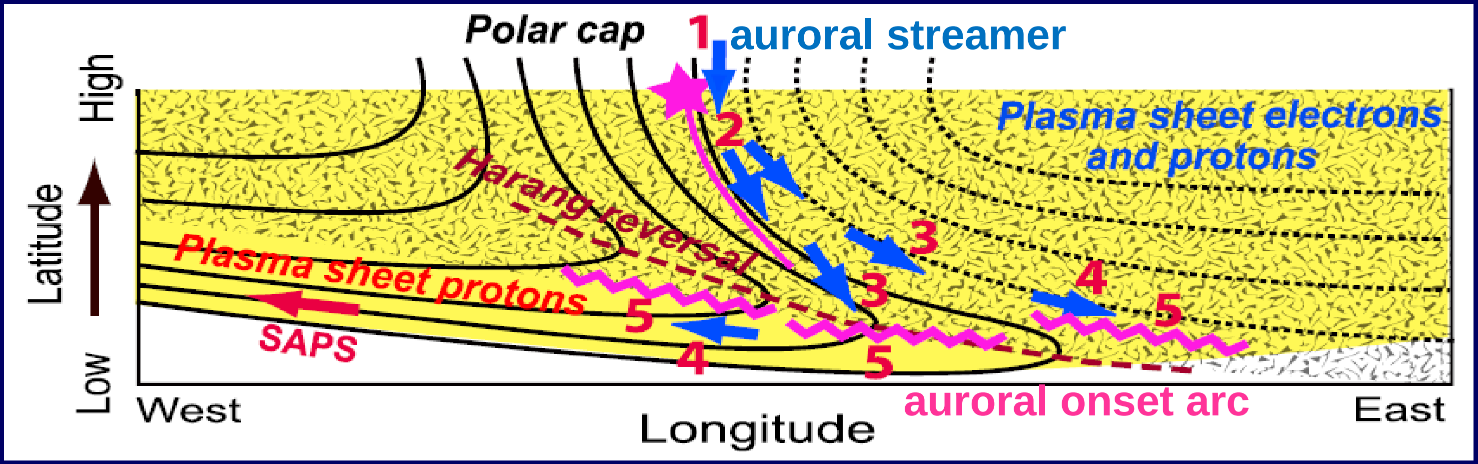


Middle → In & Out

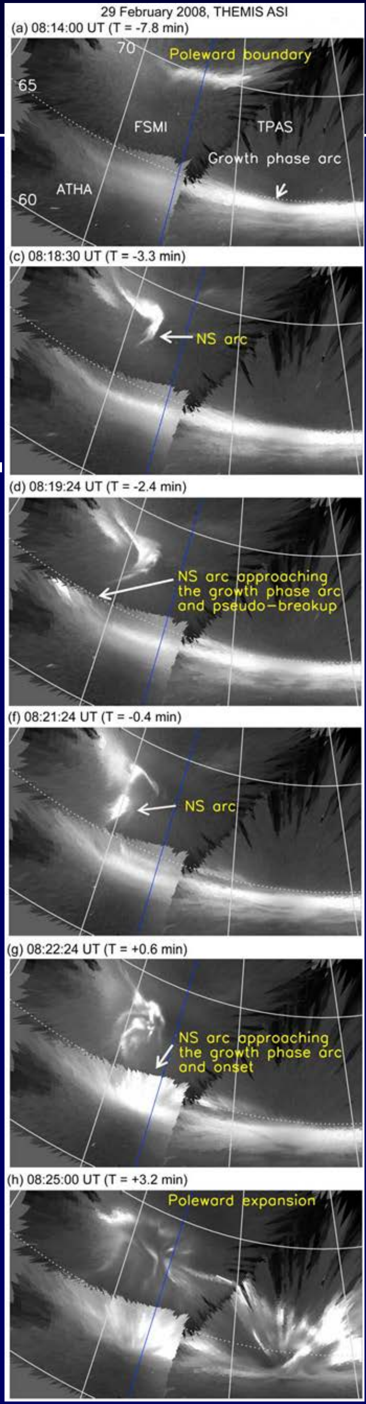
Machida et al. (2009)

■ New Plasma Intrusion Model

- An auroral streamer or arc ("preonset aurora") moving equatorward from the auroral poleward boundary corresponds to a fast earthward flow from the DNL in the magnetotail.
- This flow triggers the substorm in the near-Earth magnetotail at X~-10 Re.

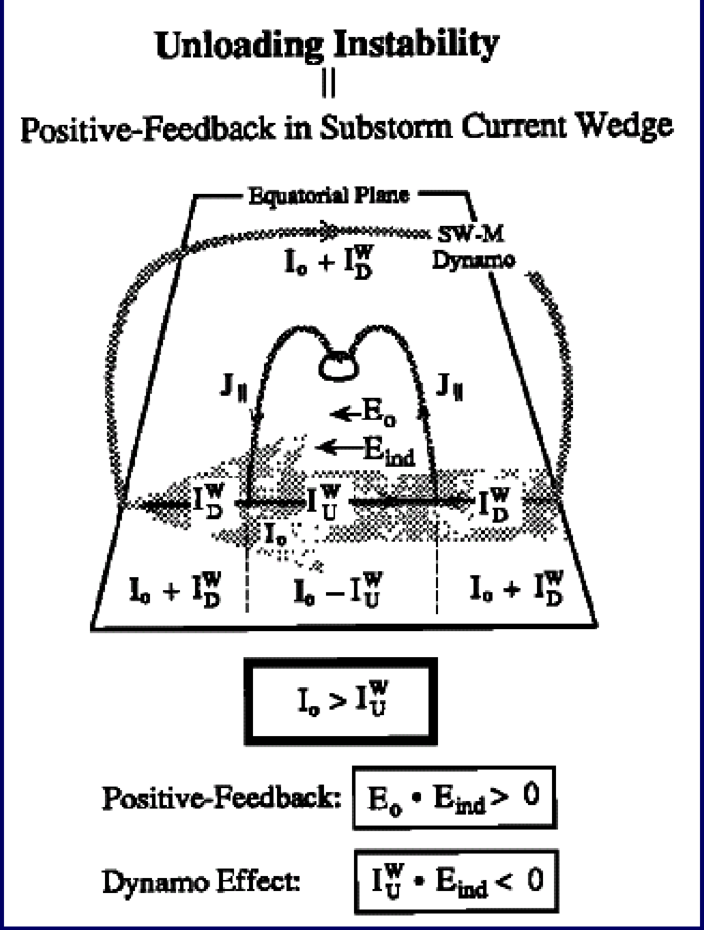


Nishimura et al. (2010)

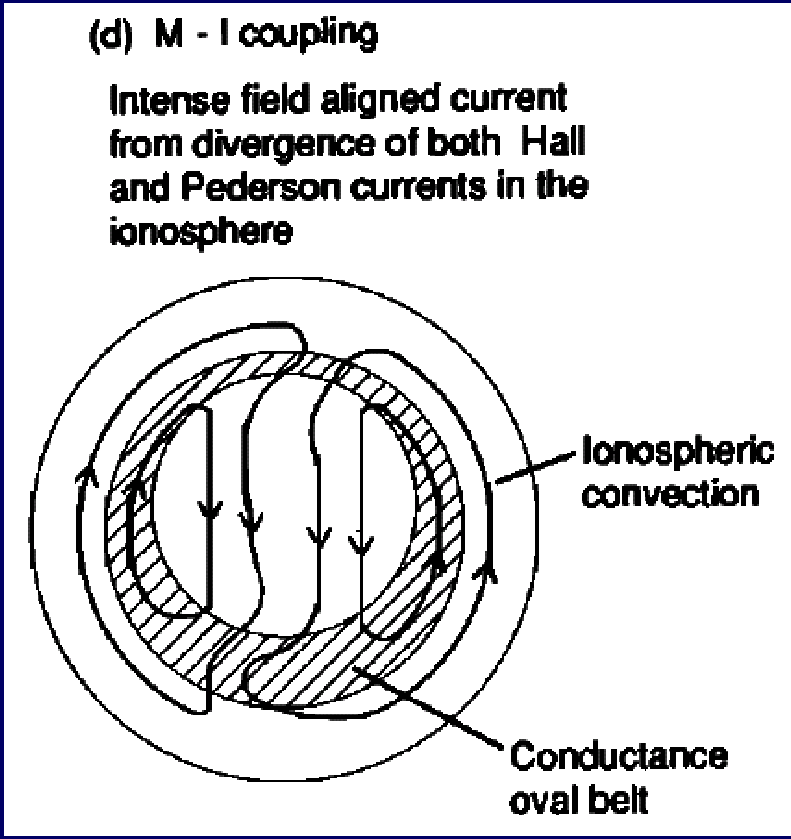


■ Magnetosphere-Ionosphere Coupling Model

- **Field-aligned current and convection enhance by positive feedback by Alfvén waves.**
  (Kan et al., 1988; Kan, 1993; Kan and Sun, 1996; Wang and Lyu, 2021)



Kan (1993)

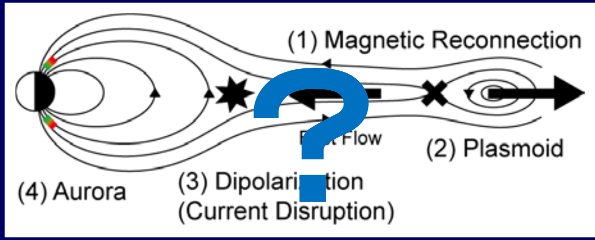


from Lui (1991)

To Solve the Substorm Triggering Mechanism

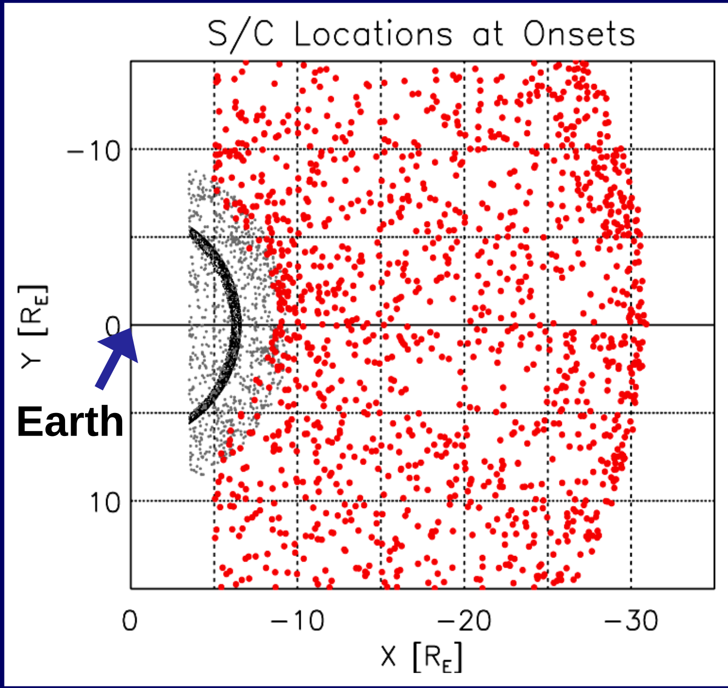
■ To Solve the Triggering Mechanism

- **What drives the substorm (auroral breakup)?**
  — When and where in the magnetotail does the first change occur, associated with substorm onset?



- **Miyashita et al. (2009):**
  3787 substorm events from auroral breakups observed by Polar and IMAGE

→ statistical analysis (superposed epoch analysis) using ~10 years of ion and electric and magnetic field data from Geotail, GOES, and Polar



Miyashita et al. (2009)

■ The Geotail Satellite

(c) JAXA

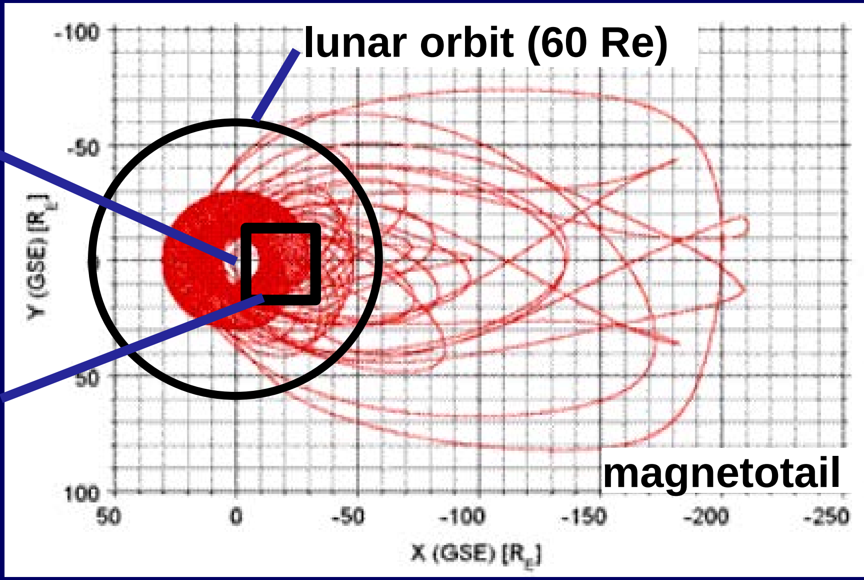
- The first satellite that observed Earth's magnetotail thoroughly.
- Launched on 24 July 1992 in collaboration with Japan (ISAS) and NASA.
- Ended on 28 November 2022.
- **In situ** observations of plasma (flow, pressure, etc.), electric and magnetic fields, and waves.

  — characteristics of solar-terrestrial physics

Earth

← the sun

region of the present study

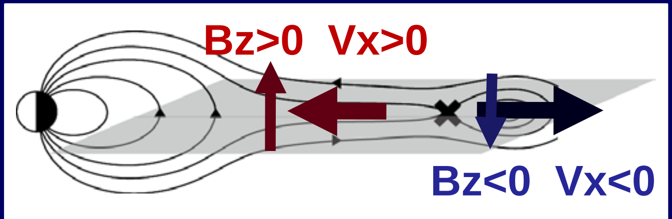


Geotail orbit in view from the north

Re: Earth's radius

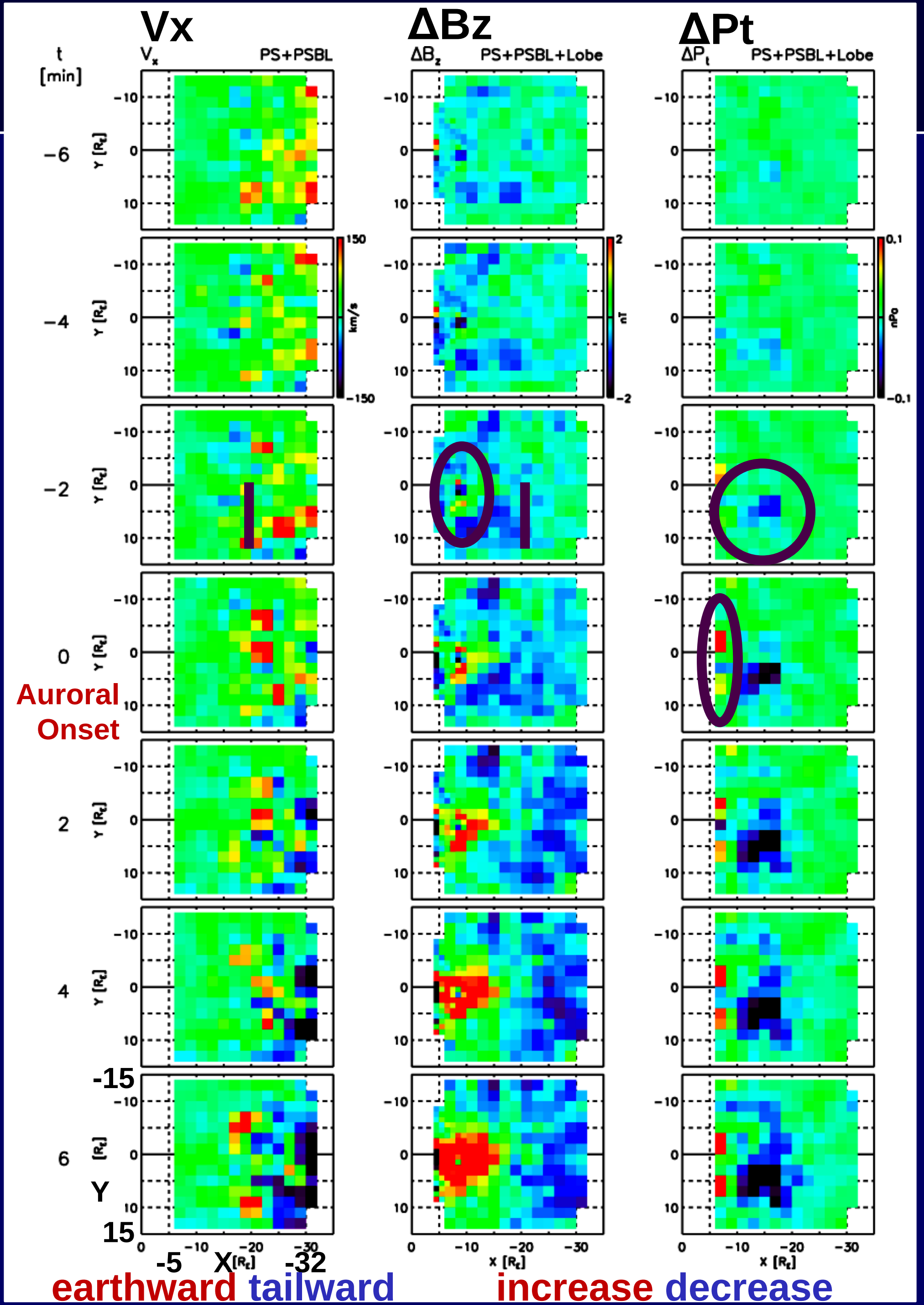
■ Statistical Study

- **Magnetic reconnection**
  -16 > X > -20 Re, tailward edge of the thin current sheet
- **Dipolarization**
  -7 > X > -10 Re
  2 min before onset.

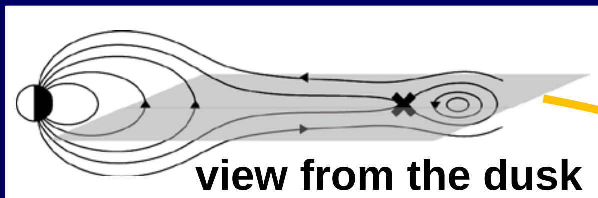


- **Total pressure** (Pi + Pb)
  - largely decreases at -10> X > -18 Re (between NENL and CD)
  - increases at X > -10 Re (dipolarization)

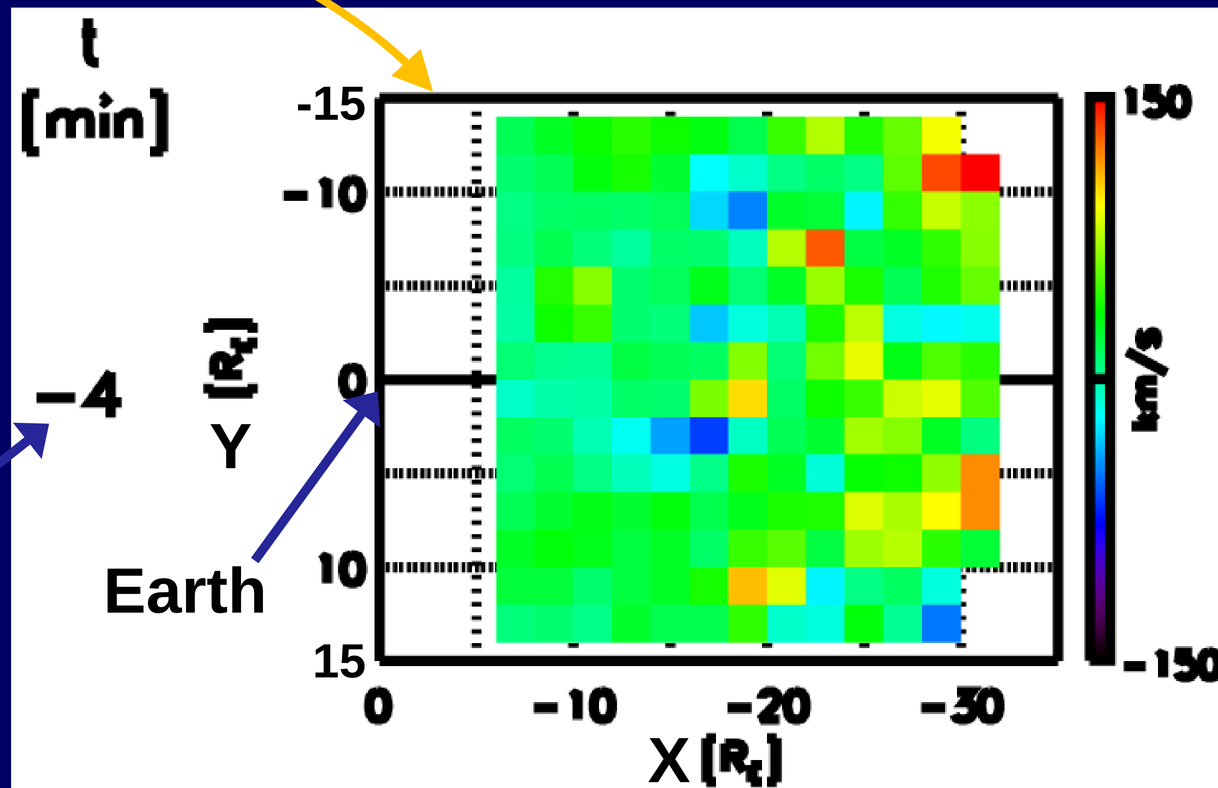
Miyashita et al. (2009)



■ Format of Panel



Equatorial plane
in view from the north



← Sun

Earth

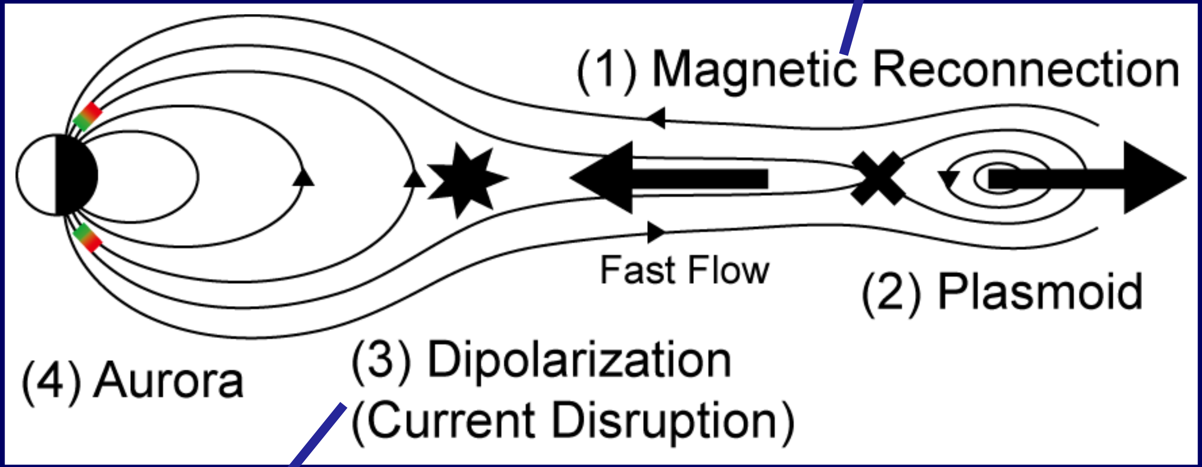
Time [min] from substorm onset (t=0: initial auroral brightening)

|Y|<15 Re, -5 > X > -32 Re
Re: Earth’s radius

■ Conclusions from Our Statistical Studies

- A series of our statistical studies
  - Established **the overall morphological picture of magnetotail evolution and energy transport associated with substorm onsets.**
  - Clarified that near-Earth reconnection plays an important role in triggering a substorm, energy release, and reconfiguration.

at X ~ -18 Re at t = -4 or -2 min

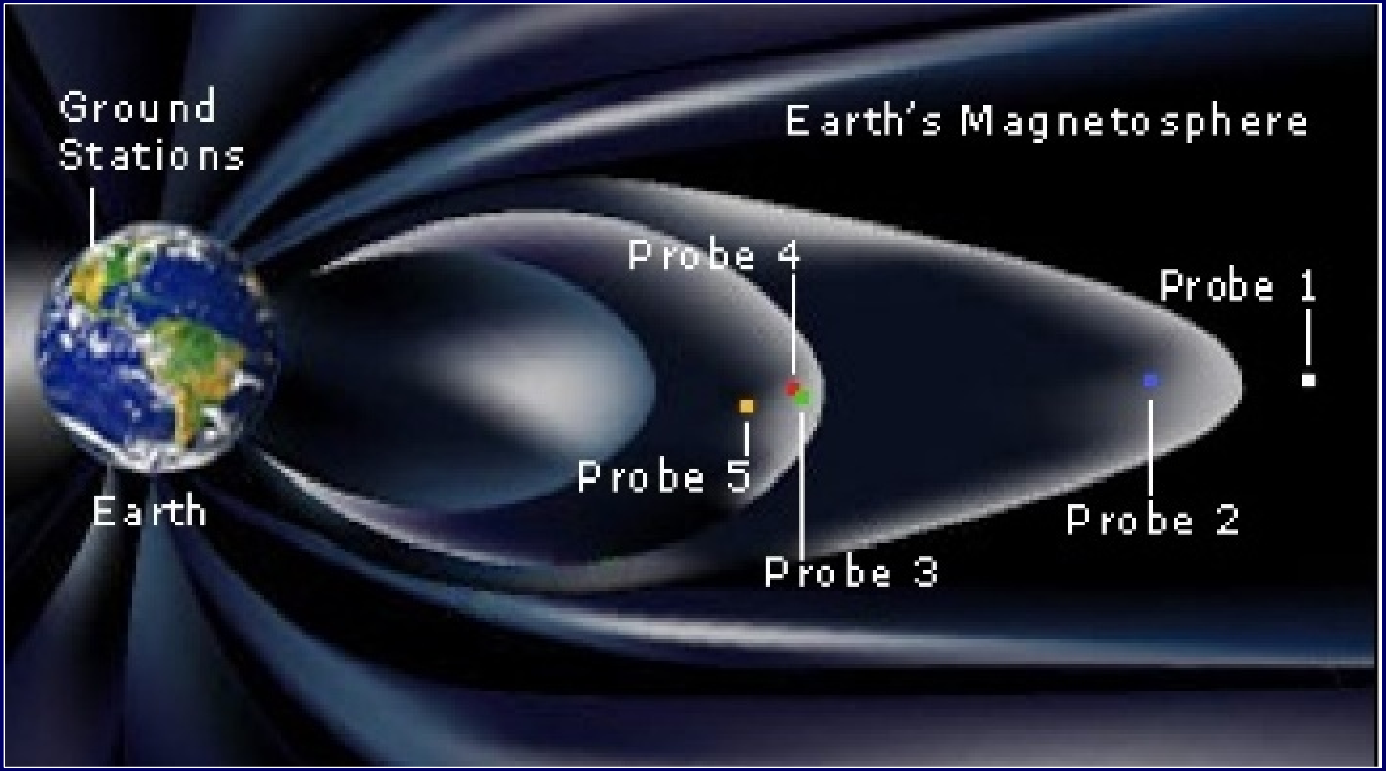


There is no evidence that current disruption causes reconnection.

at X ~ -8 Re at t = -2 min → Expands in all directions

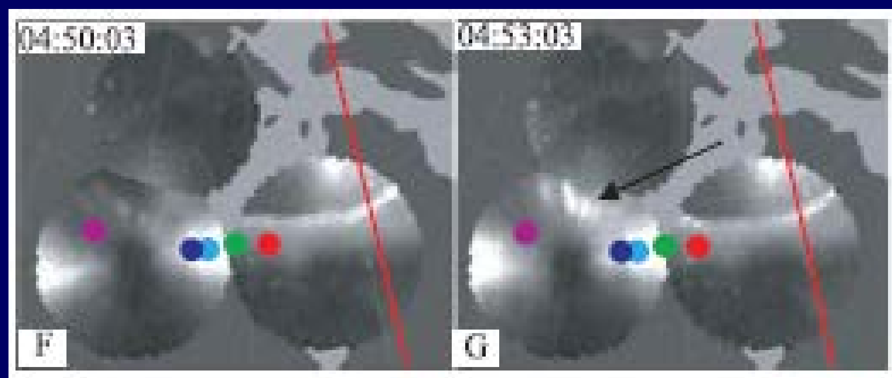
■ Multi-Point Simultaneous Observations

- Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission (2007-, USA)
- 5 spacecraft in the magnetotail
  + ground-based auroral cameras and magnetometers
- To solve the substorm triggering mechanism

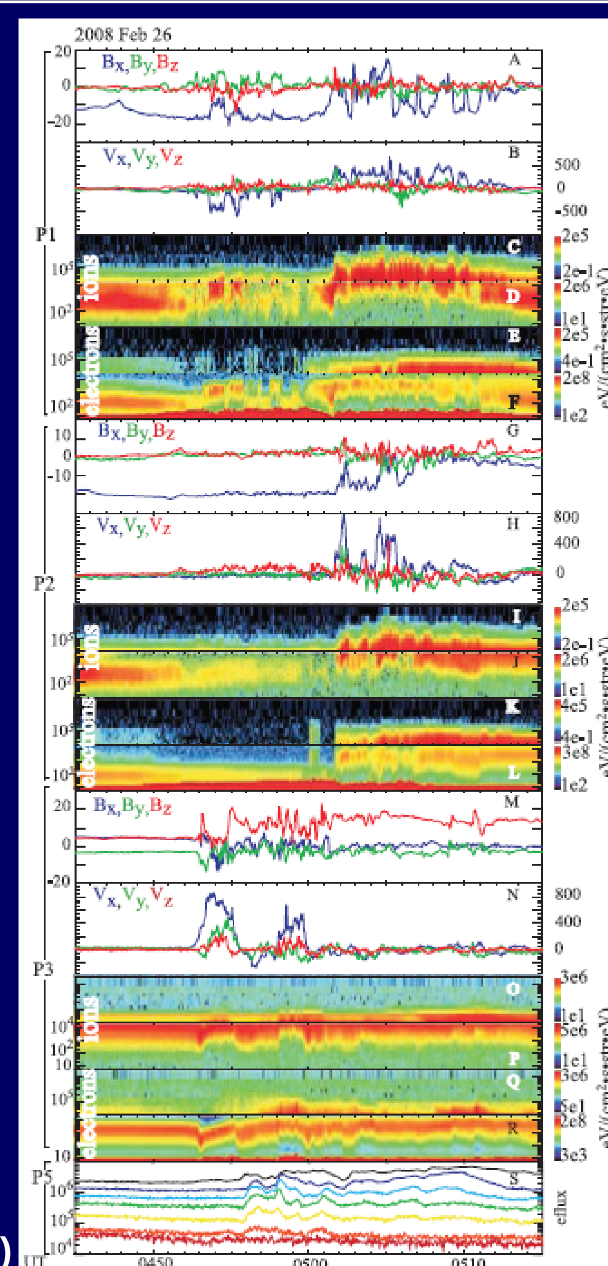


■ Multi-Point Simultaneous Observations

- **Reconnection signatures, such as plasmoid and fast earthward flow, were observed before dipolarization.**



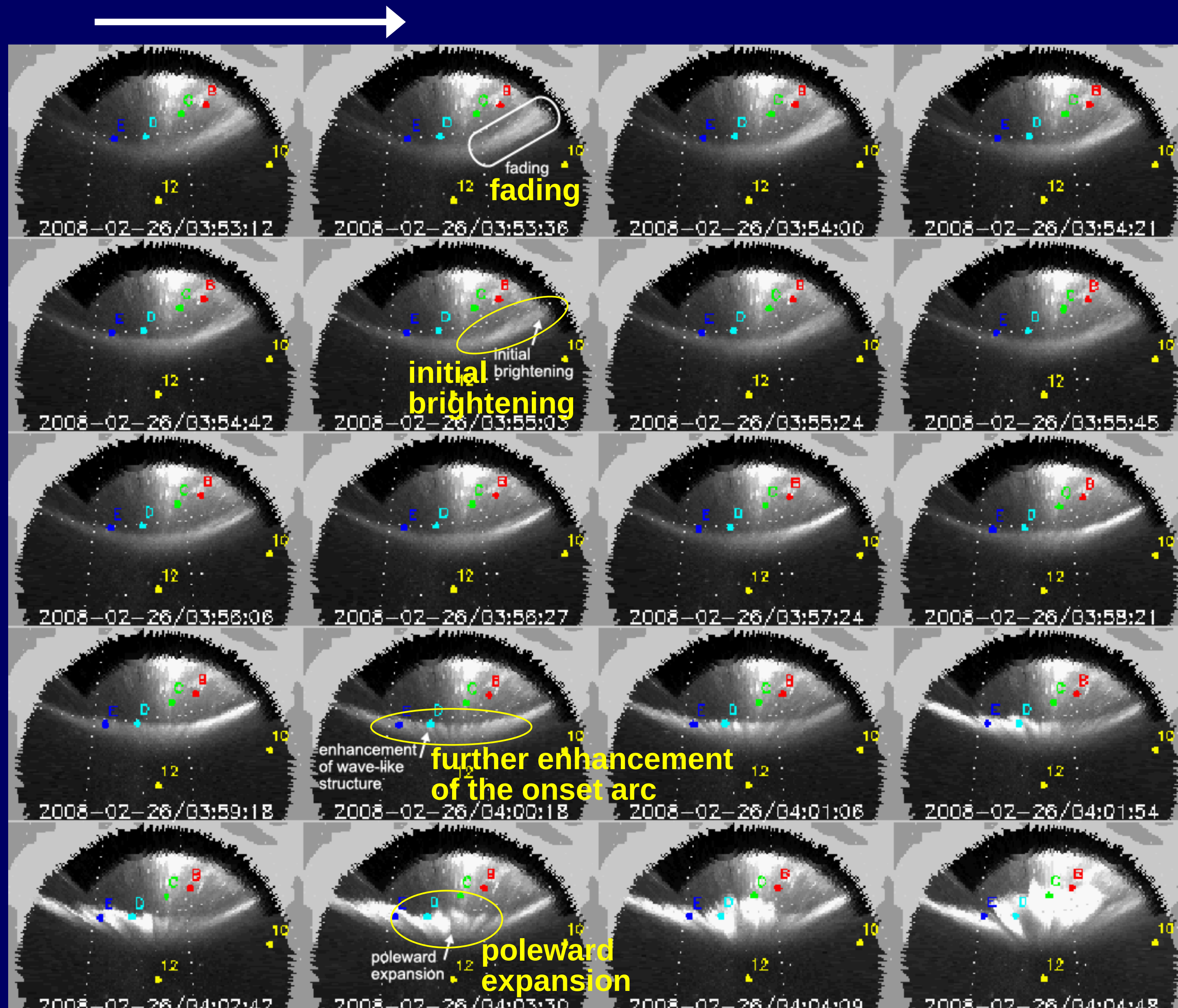
Event	Observed time (UT)	Inferred delay (seconds since 04:50:03 UT)
Reconnection onset	04:50:03 (inferred)	$T_{Rx} = 0$
Reconnection effects at P1	04:50:28	25
Reconnection effects at P2	04:50:38	35
Auroral intensification	04:51:39	$T_{AI} = 96$
High-latitude Pi2 onset	04:52:00	117
Substorm expansion 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



Angelopoulos et al. (2008)

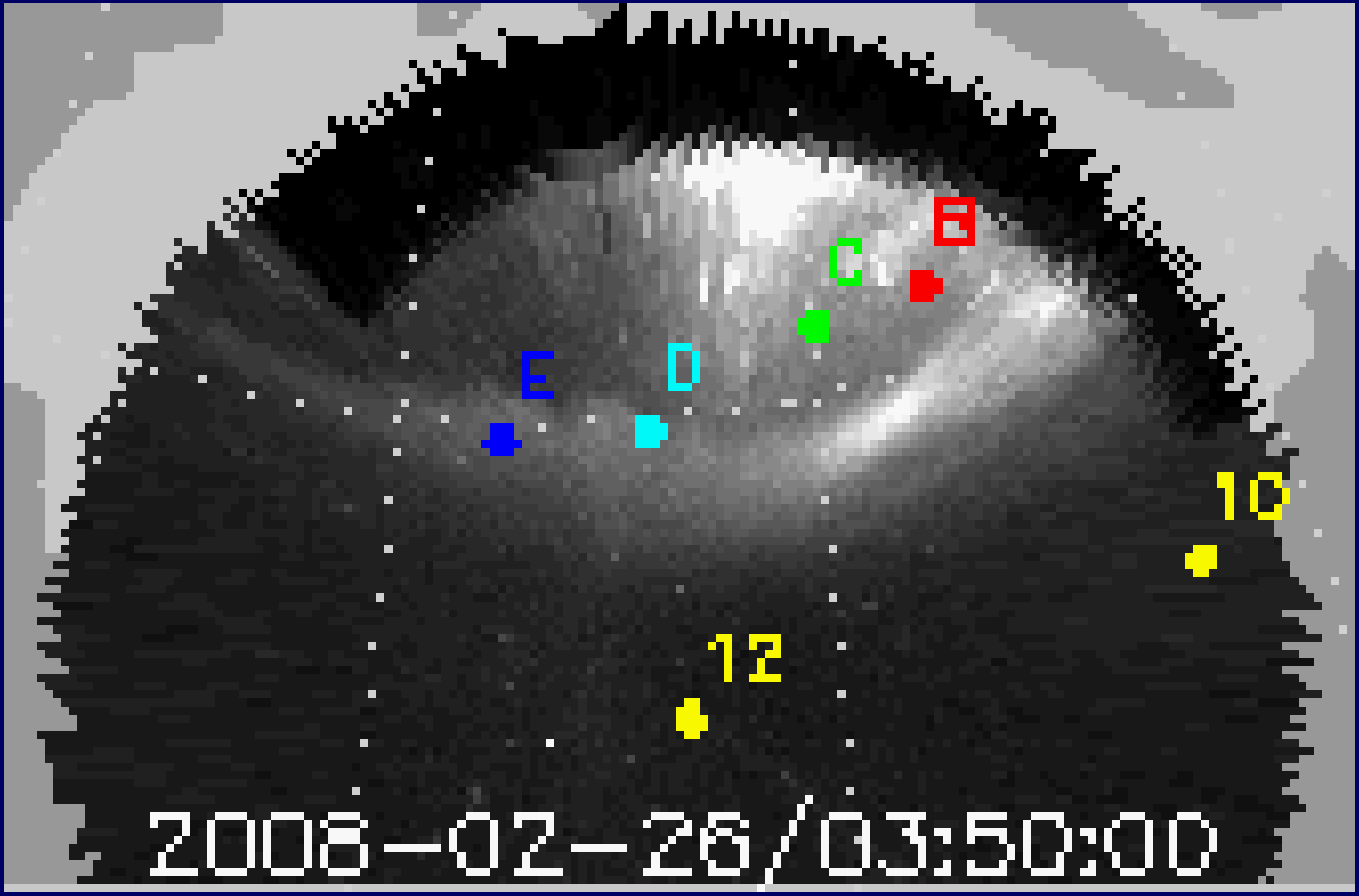
■ Stepwise Development of Onset Aurora

Auroral arc development associated with a substorm onset observed by a THEMIS ground-based camera



Miyashita et al. (2018)

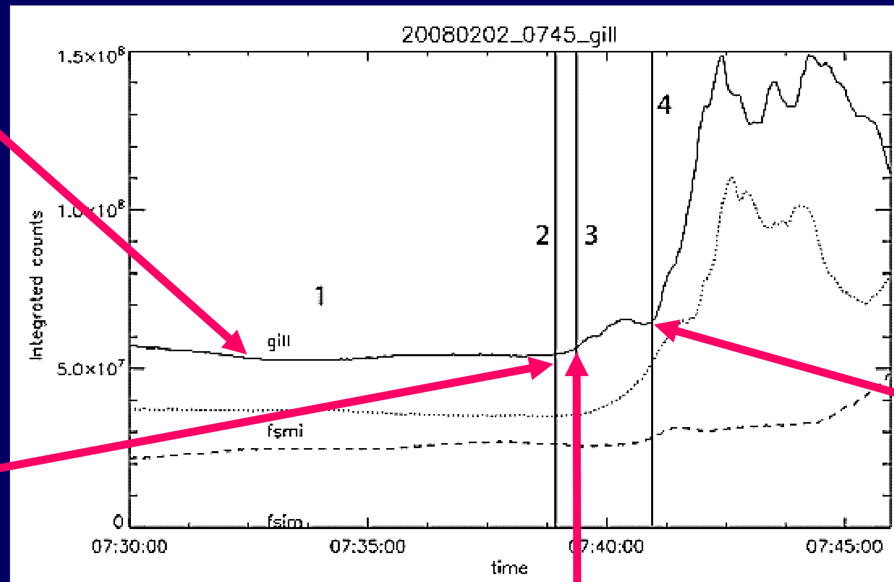
■ Stepwise Development of Onset Aurora



Miyashita et al. (2018)

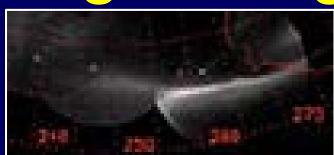
■ Stepwise Development of Onset Aurora

(1) fading

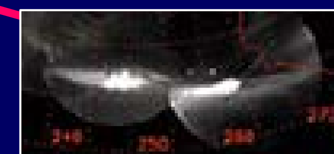


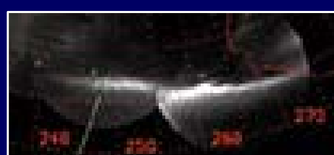
Mende et al. (2009)

(2) initial brightening



(4) poleward expansion





(3) further enhancement of the onset arc

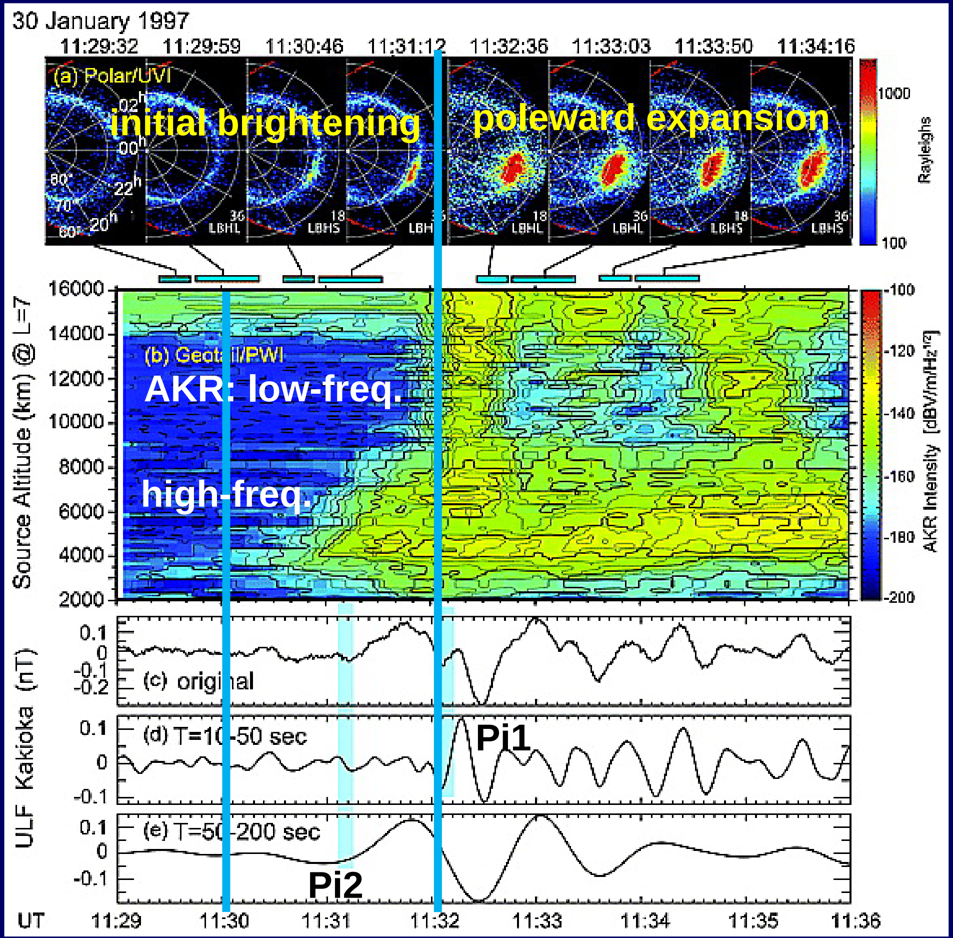
See Miyashita & Ieda (2018)

- Most studies mark only one or two timings and choose one as the substorm onset time.
- Each step corresponds to tail substorm signatures.

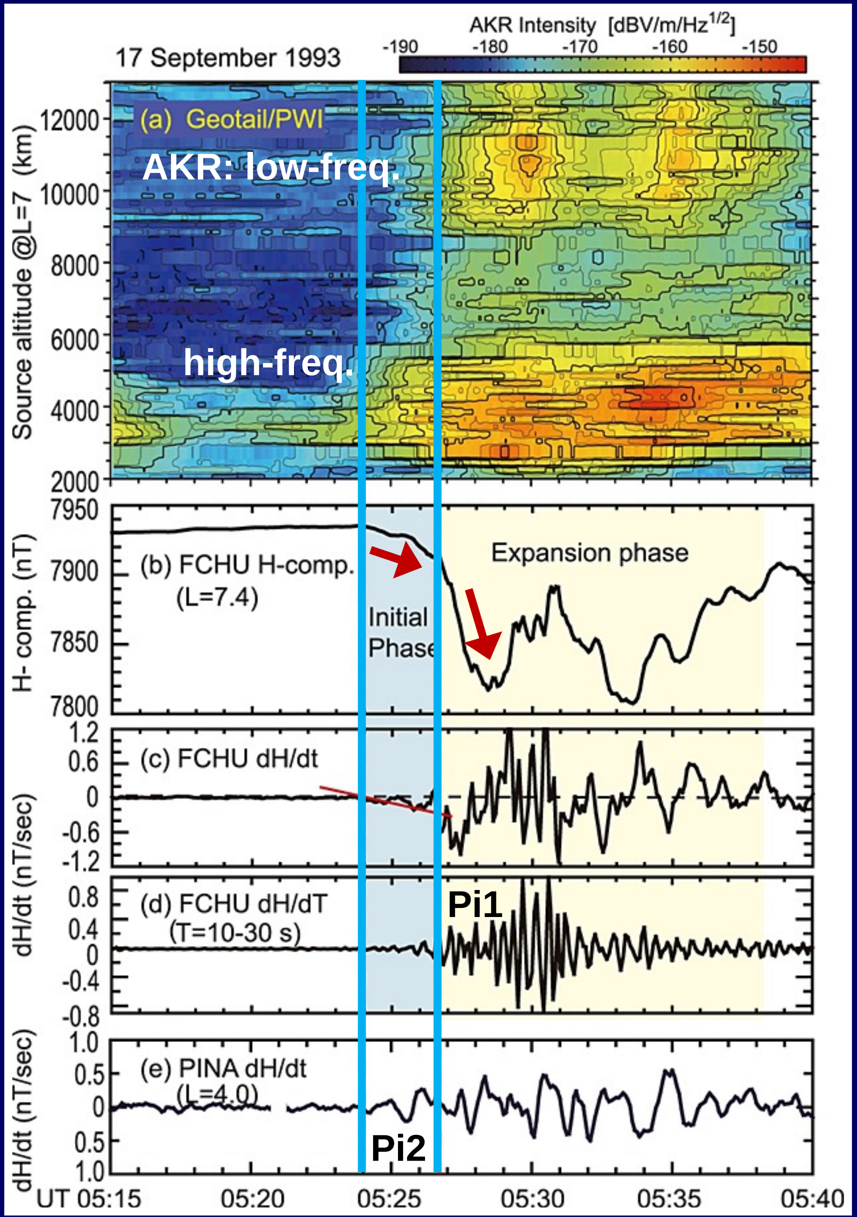
→ It is important to determine these auroral steps, when we discuss the timing issue and magnetotail changes.

■ Multi-Step Development of Substorm Onset

- **Auroral breakup, AKR, Pi2/1, and geomagnetic negative bay develop in two steps.**



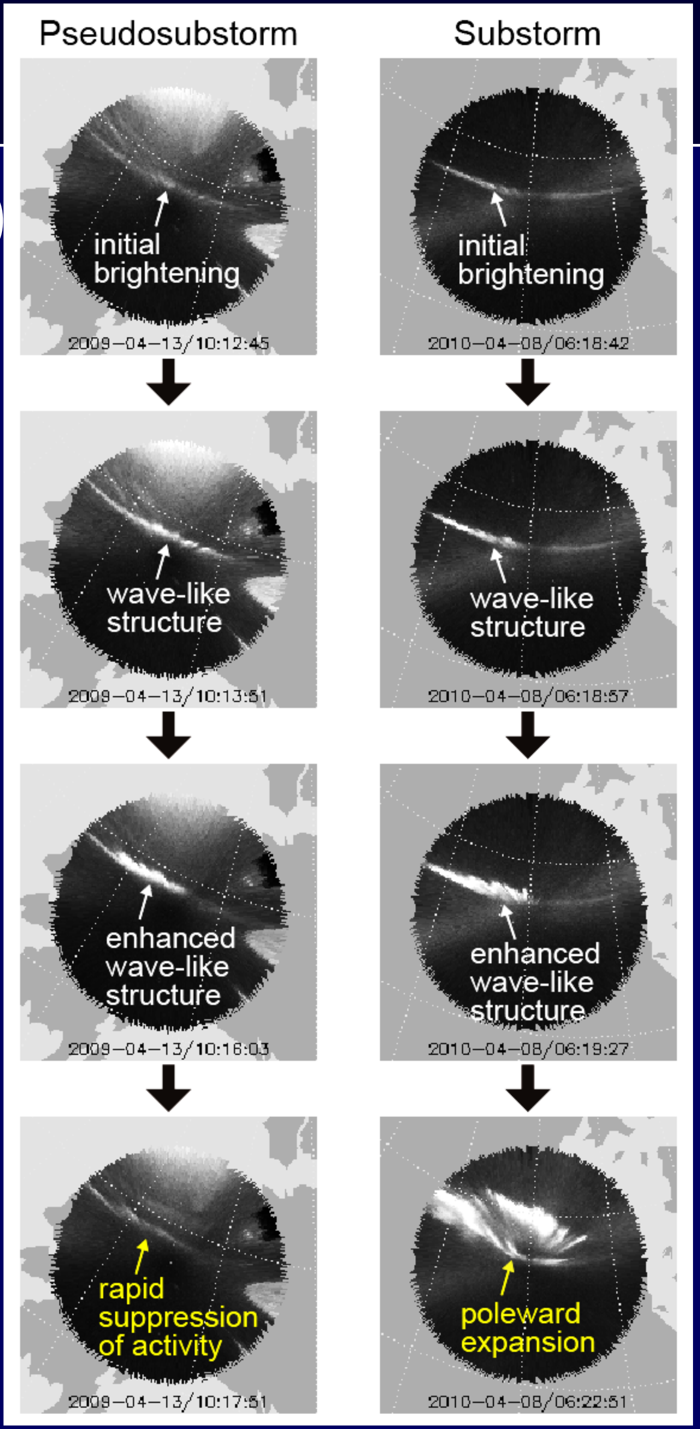
Morioka et al. (2010)



Morioka et al. (2014)

■ Pseudosubstorm

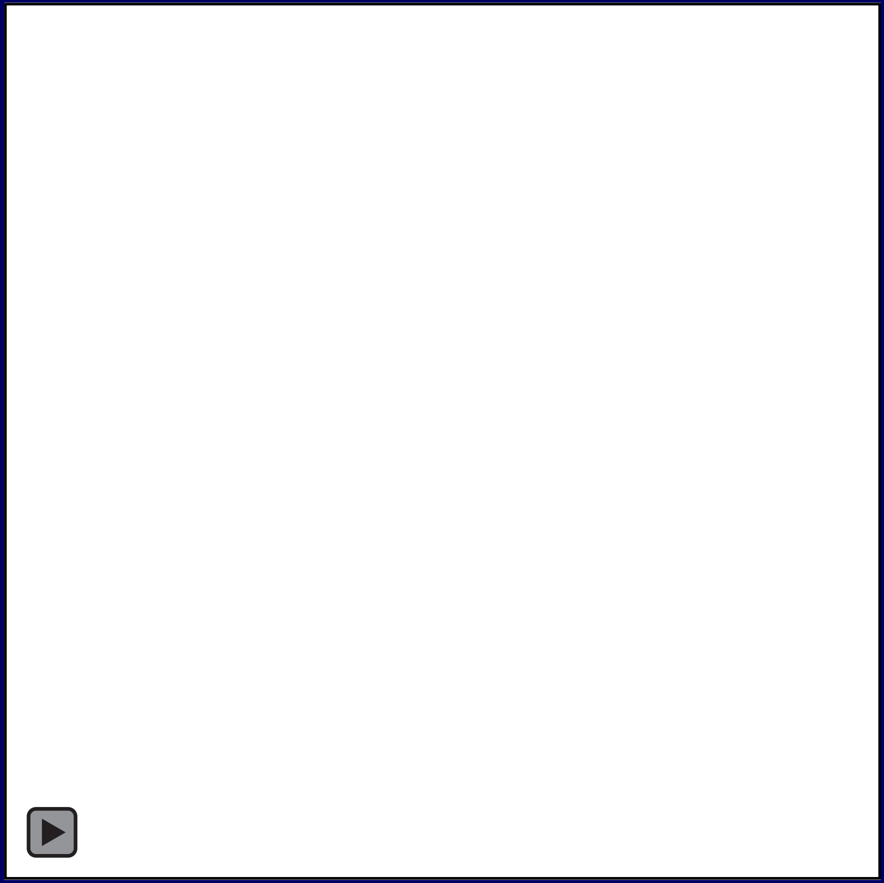
- Pseudosubstorms (pseudobreakups) are similar to substorms in magnetotail processes and the early stage of auroral onset arc development.
- However, they differ in the subsequent auroral development. For the pseudosubstorm, the onset arc is suppressed without progressing to poleward expansion.
- Comparison between substorms and pseudosubstorms helps us understand the substorm triggering mechanism.



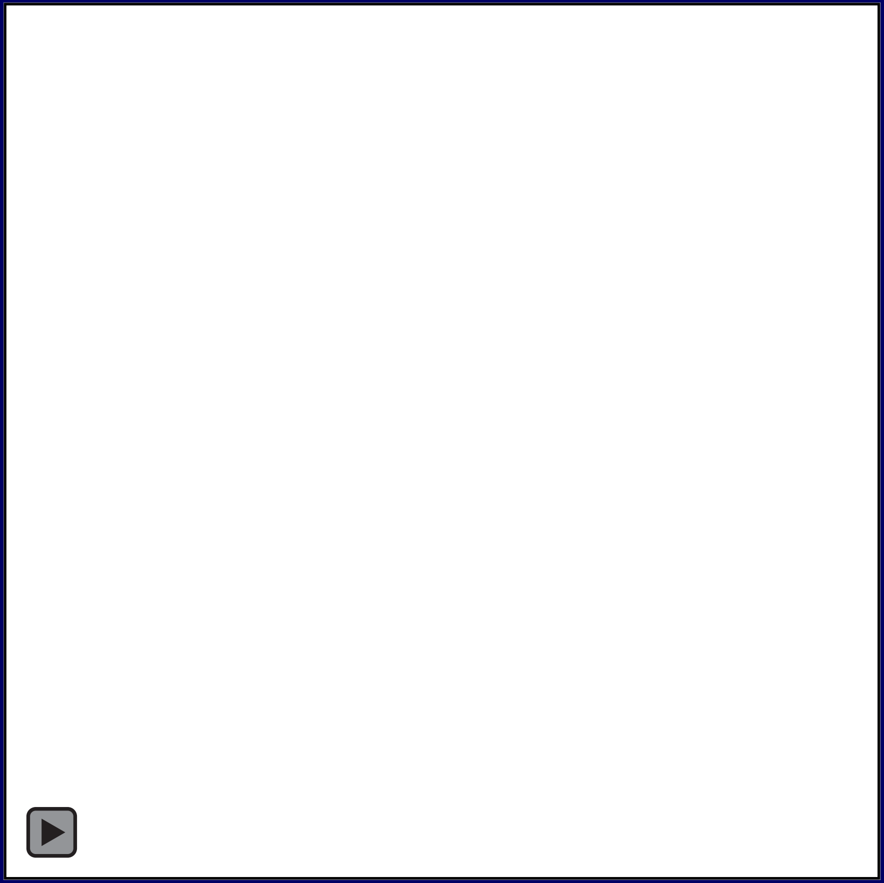
Fukui, Miyashita et al. (2020)

Pseudosubstorm

Pseudosubstorm (Pseudobreakup)



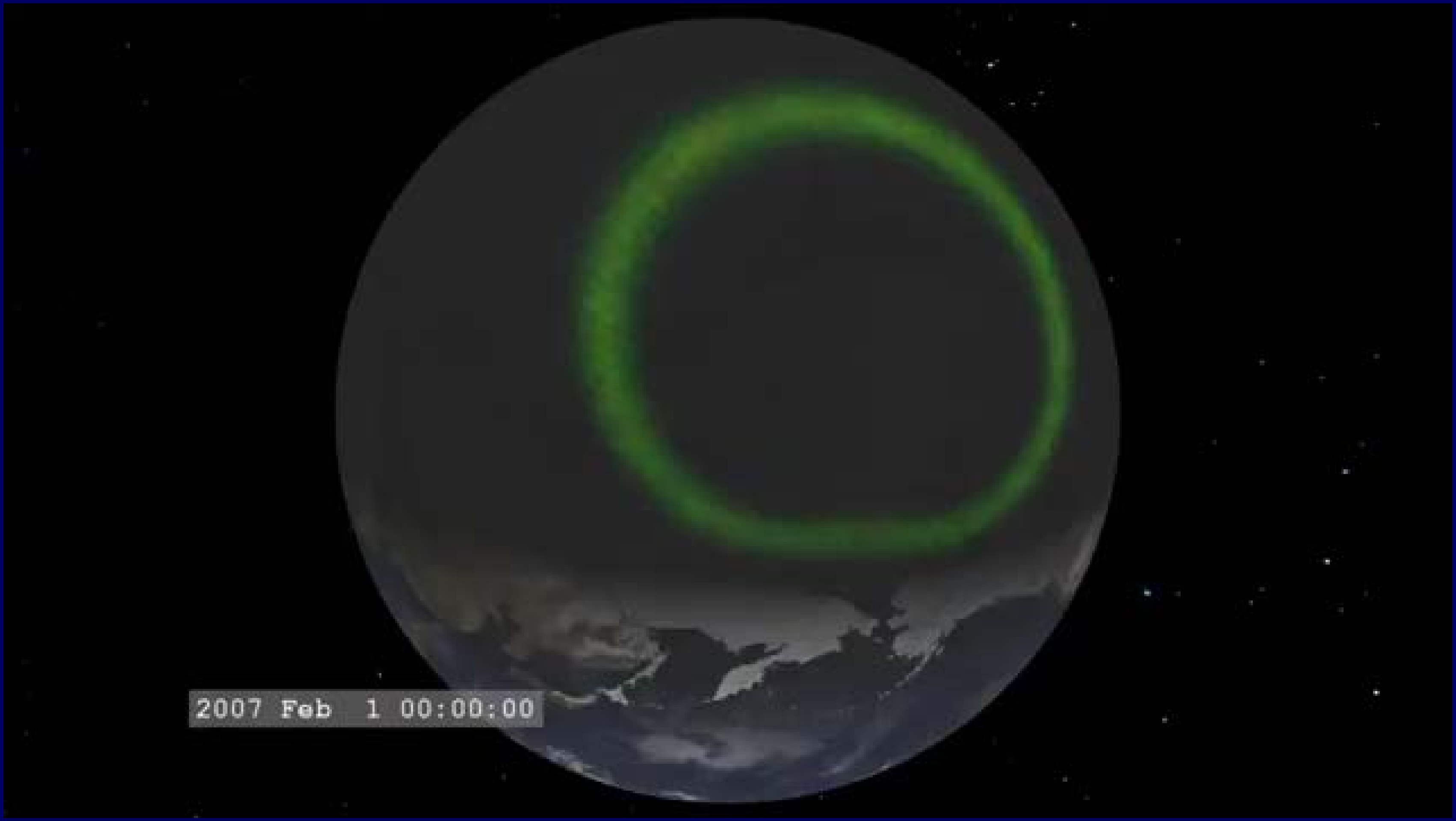
Substorm



Fukui, Miyashita et al. (2020)

■ Simulation Studies (1)

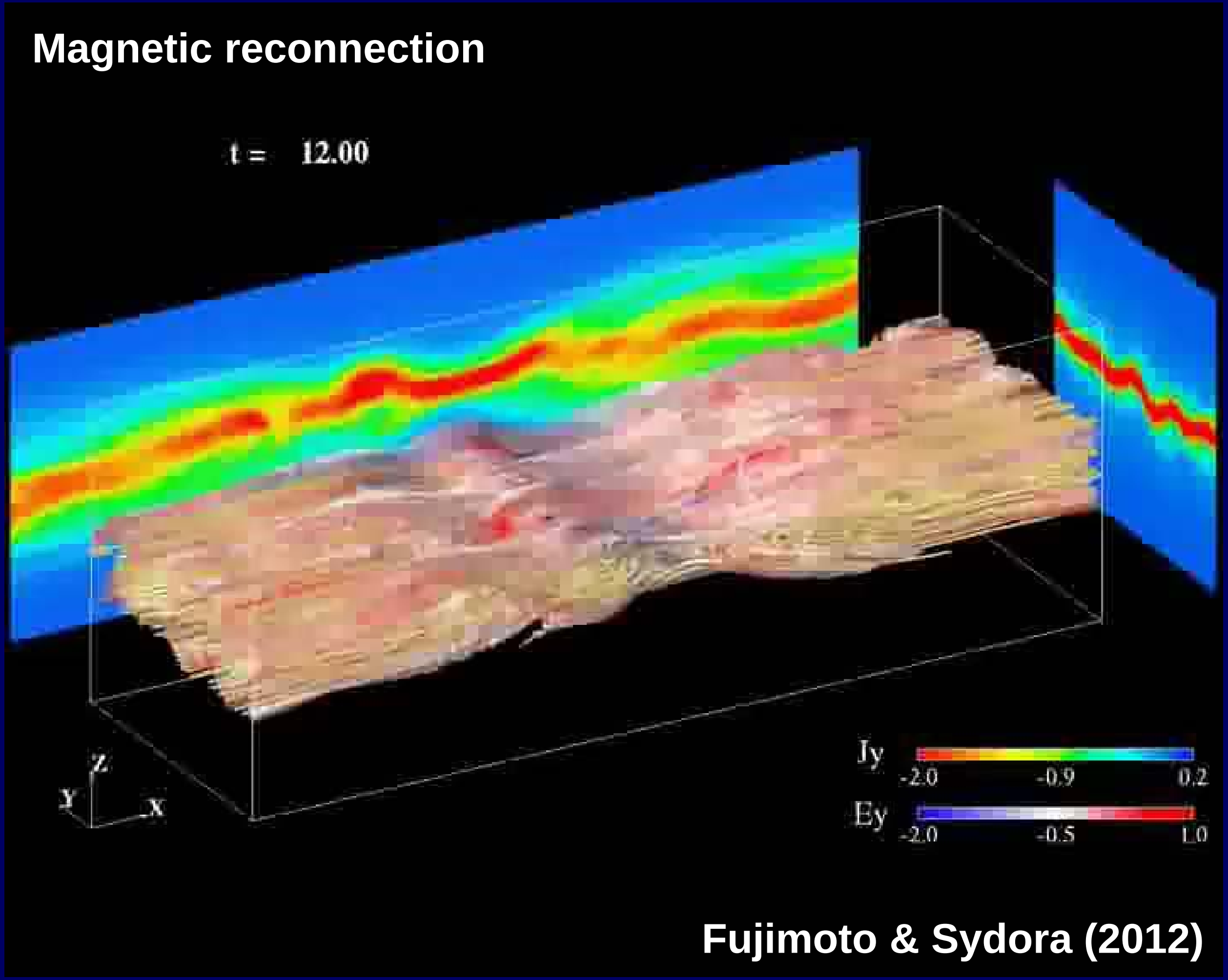
- **Global magnetohydrodynamic (MHD) simulation for understanding the global context**



(c) NASA THEMIS

Simulation Studies (2)

- **Local particle (kinetic) simulation**
  for understanding the detailed mechanisms



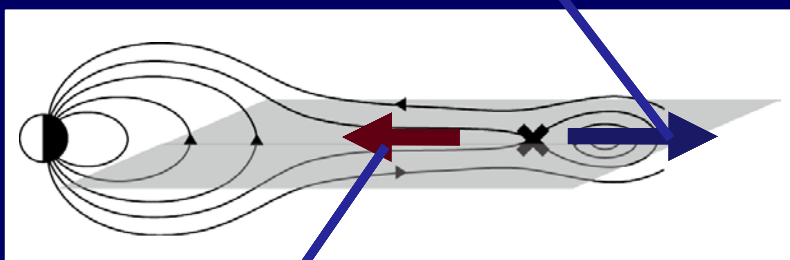
■ Summary

- The substorm is a process of **energy release and dissipation** in the magnetotail possibly triggered by magnetic reconnection.
- It causes various plasma and electromagnetic disturbances in the magnetosphere and the ionosphere and on the ground, such as active **auroral breakup** and geomagnetic changes.
- **The triggering mechanism** of substorms is still an open question, although various models have been proposed.
- To understand the mechanism, **multi-point simultaneous observations** by **spacecraft** and **ground-based instruments** are important.
- **Simulation** studies are also needed to understand the global context and the detailed mechanisms.
- **Substorms at other planets** and **the solar flare** would be helpful for understanding the mechanisms.

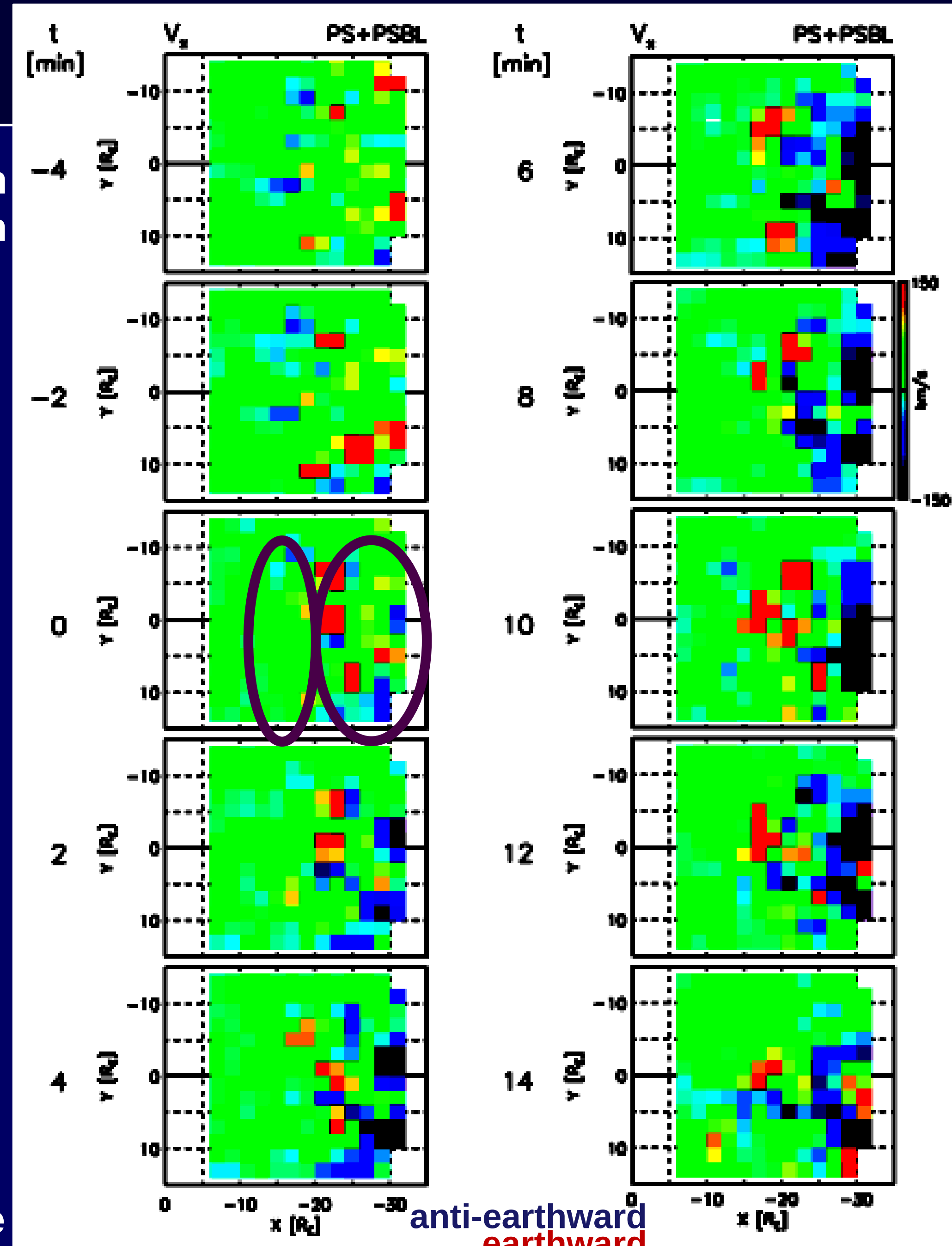
■ Plasma Flow

- **Anti-earthward fast plasma flows**: at X < -20 Re after onset

View from the north



- **Earthward fast plasma flows**: only a few flows at -15 > X > -20 Re around onset



|Y|<15 Re

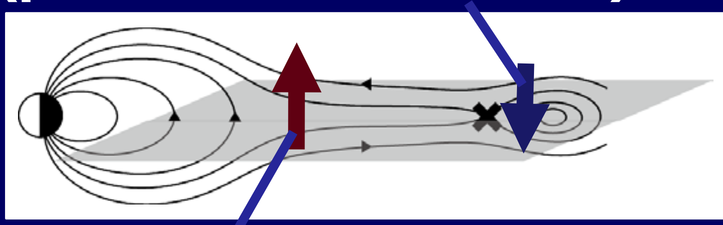
← the sun

-5 > X > -32 Re

Miyashita et al. [2009]

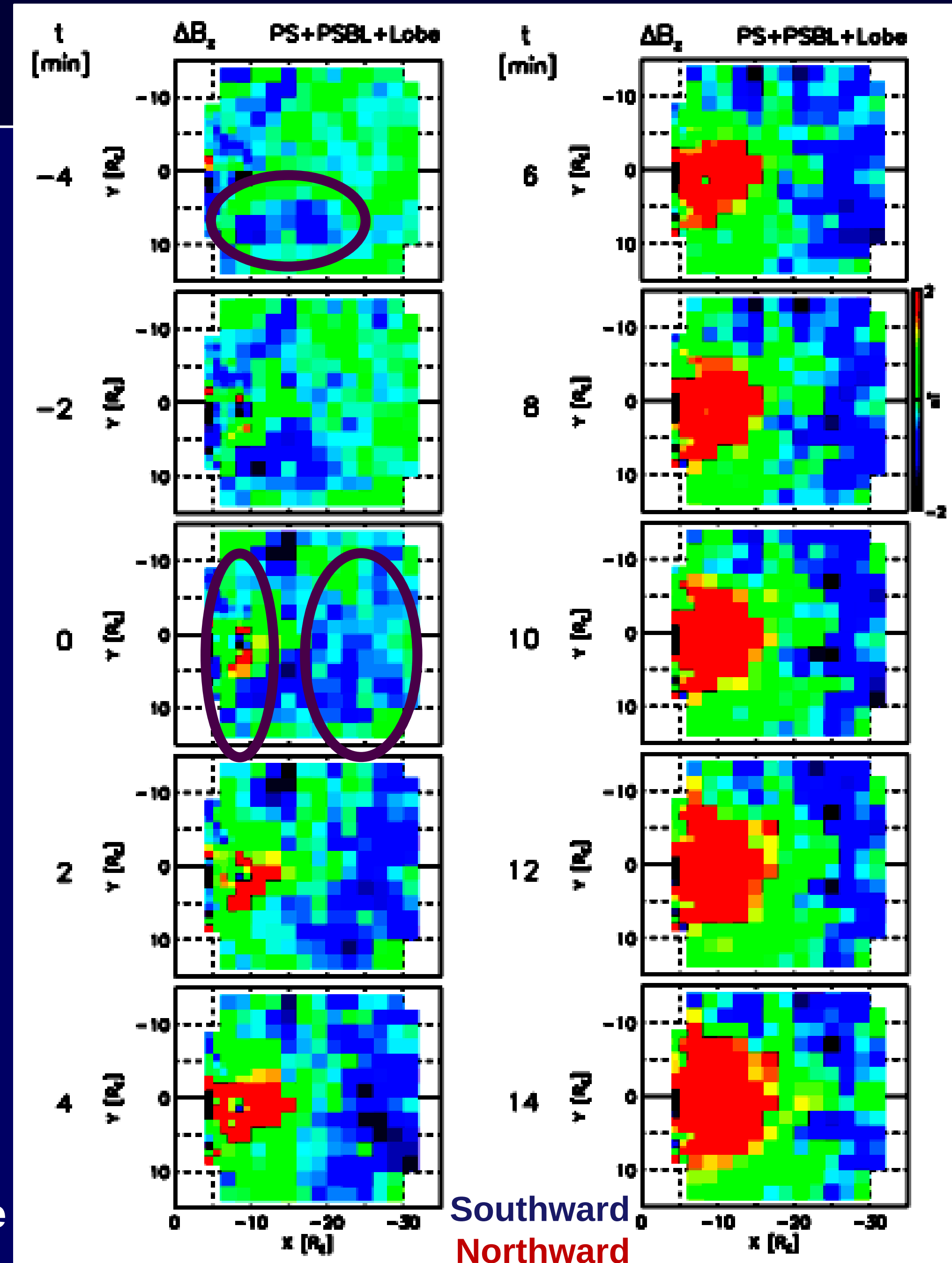
■ North-South Bz

- $\Delta Bz<0$ (southward increase) at X < -20 Re at onset (plasmoid formation)



- $\Delta Bz>0$ (northward increase): at X ~ -8 Re at the same time as plasmoid (dipolarization) Expands in all directions.

- At -5 > X > -20 Re, highly stretched before onset



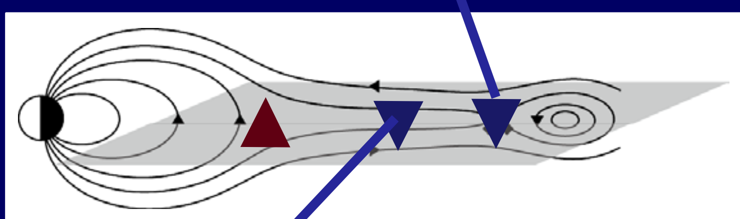
|Y|<15 Re

← the sun　　-3 > X > -32 Re　　Miyashita et al. [2009]

■ Total Pressure

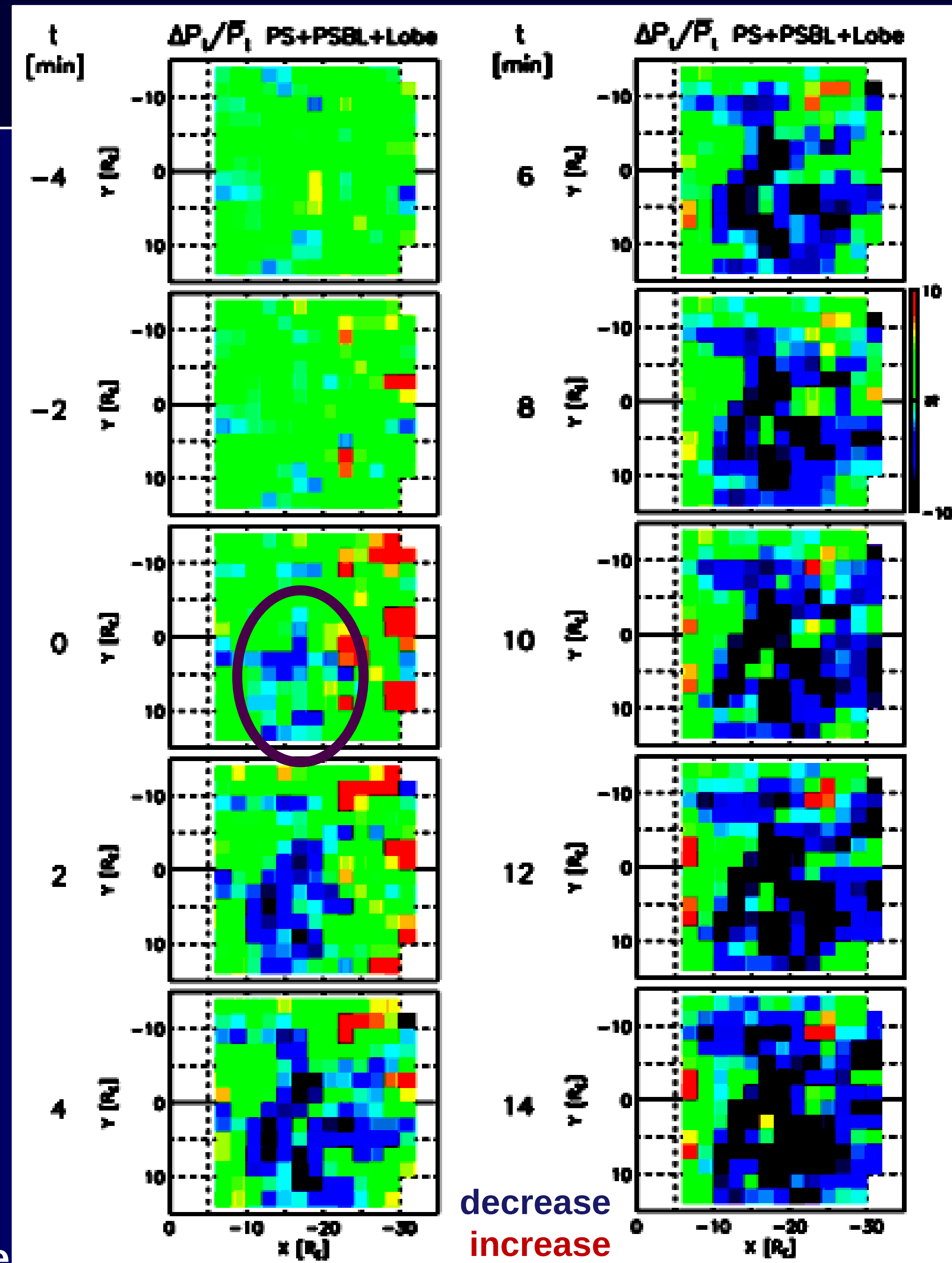
Pt = Pi + Pb, a measure of energy density

・At X ~ -18 Re at t=-2 min Pt begins to **decrease** and then in the surrounding regions successively.



・Largely decrease at -10 > X > -18 Re.

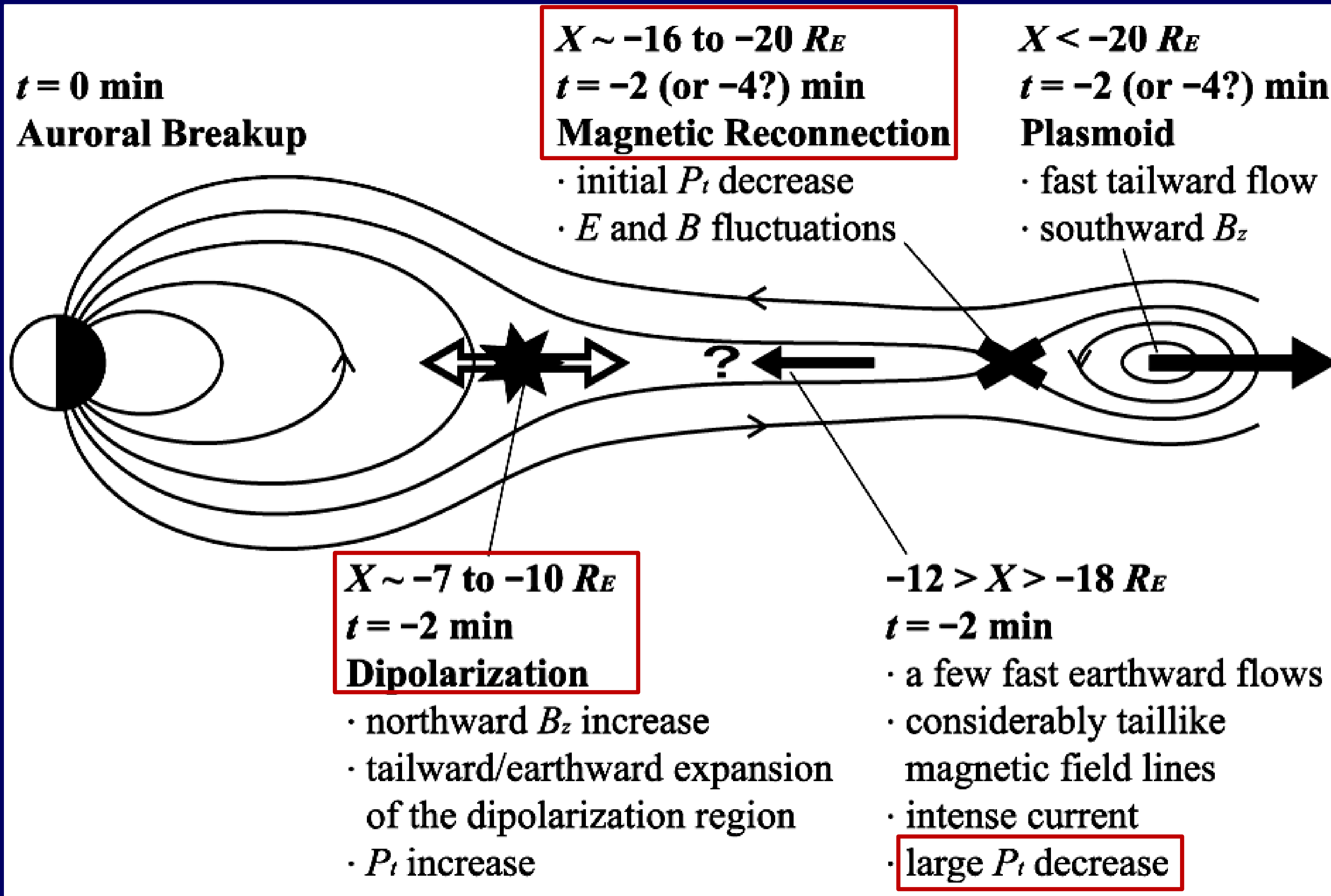
・At X ～ -8 Re, Pt **increases** associated with **dipolarization**.



|Y|<15 Re

← the sun -5 > X > -32 Re Miyashita et al. [2009]

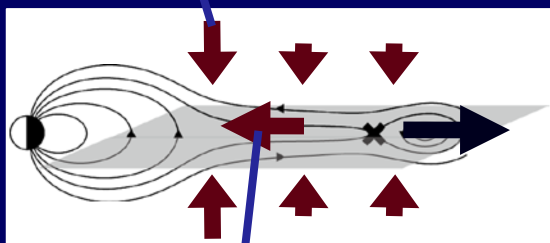
■ Overall Picture of Magnetotail Evolution



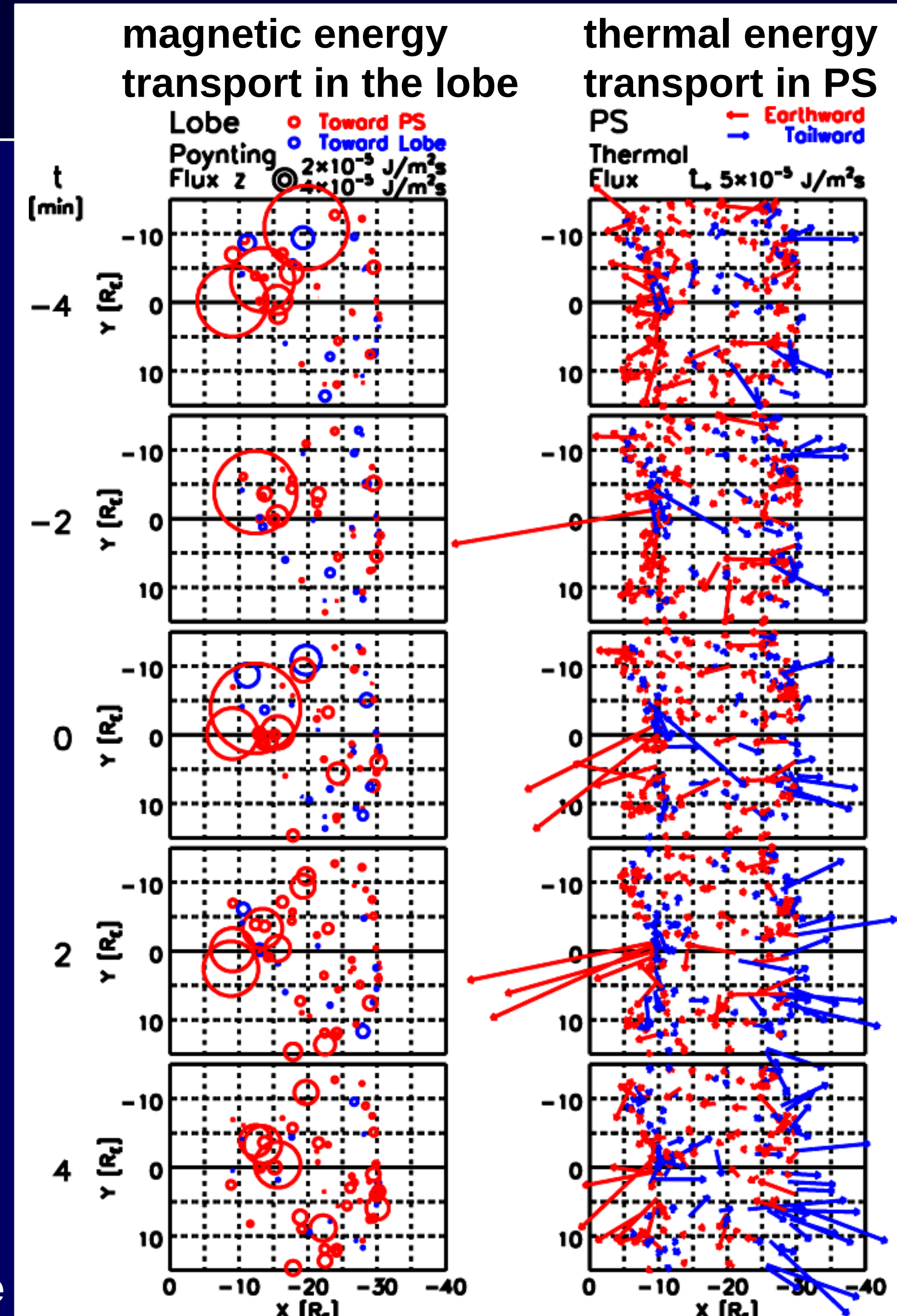
Miyashita et al. [JGR, 2009]

■ Energy Transport

- **From the lobe to the plasma sheet**, magnetic energy is transported in the form of the Poynting flux.



- In the plasma sheet, thermal energy is transported from the reconnection site earthward and anti-earthward from t=-2 min. (Magnetic energy is converted into thermal energy.)

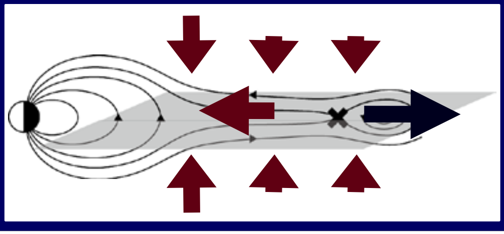


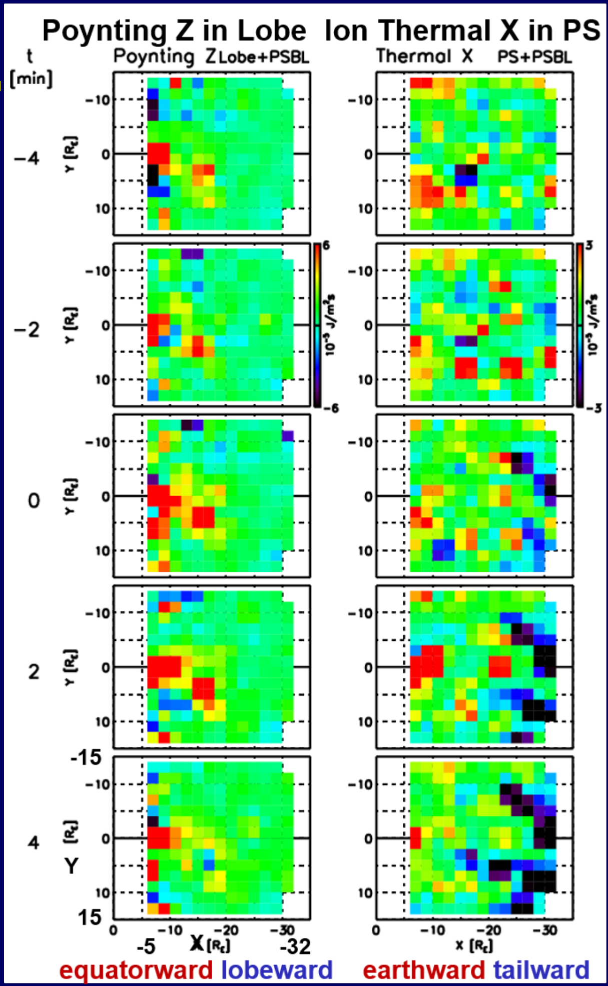
|Y|<15 Re

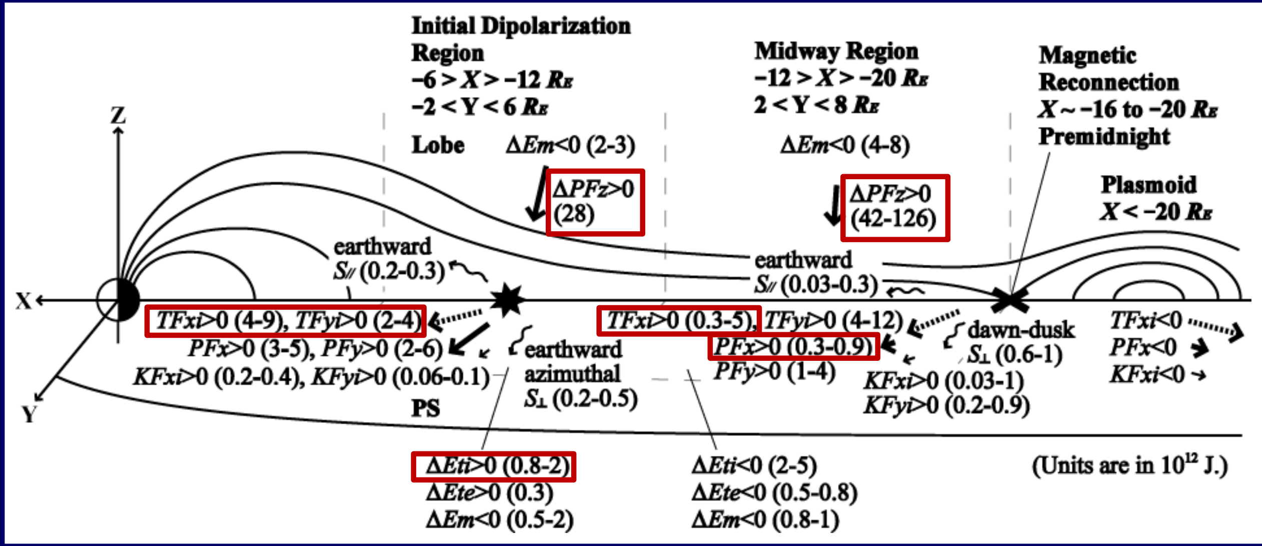
← the sun -5 > X > -32 Re Miyashita et al. [2003]

■ Energy Transport and Changes

- Energy related to dipolarization is transported by **Poynting fluxes from the lobes, rather than fast flows generated by near-Earth reconnection.**
- Near-Earth reconnection enhances large-scale convection (Poynting flux), associated with substorm onset.





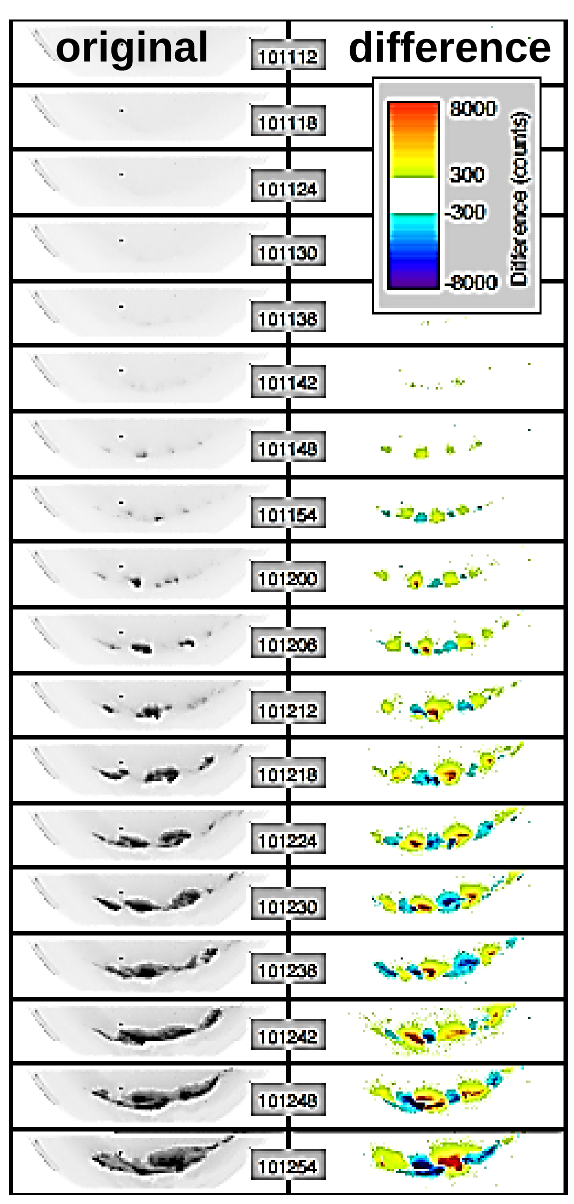


Miyashita et al. [JGR, 2012]

■ Auroral Beads at Substorm Onset

- A bead-like (wave-like) structure appears during the early stage of the development of an onset arc and extends in the azimuthal direction (Elphinstone et al.,1995; Donovan et al., 2007).
- Spatial scale: <~10 km x ~1-2 h MLT
- Wavelength: ~100 km (m=100-300)
- The forms may correspond to ballooning instability in the near-Earth magnetotail.

1 min 42 s

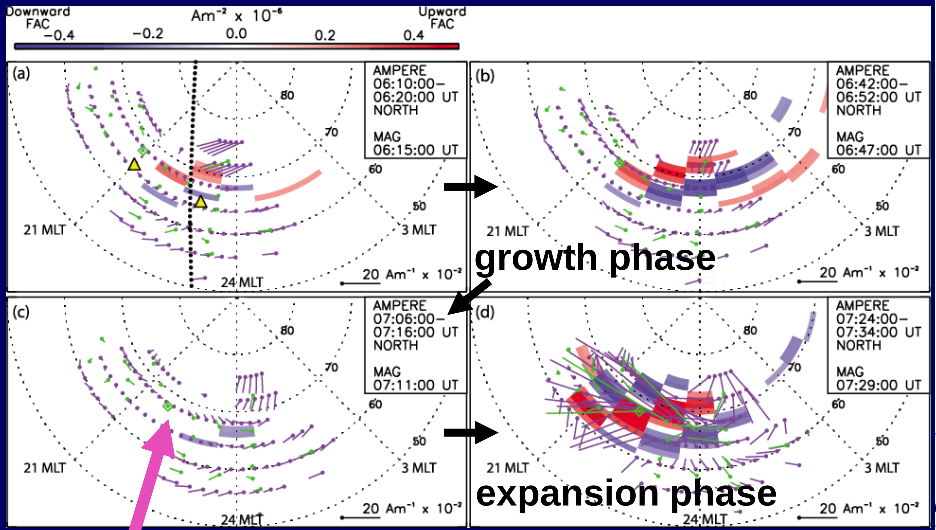


Donovan et al. (2007)

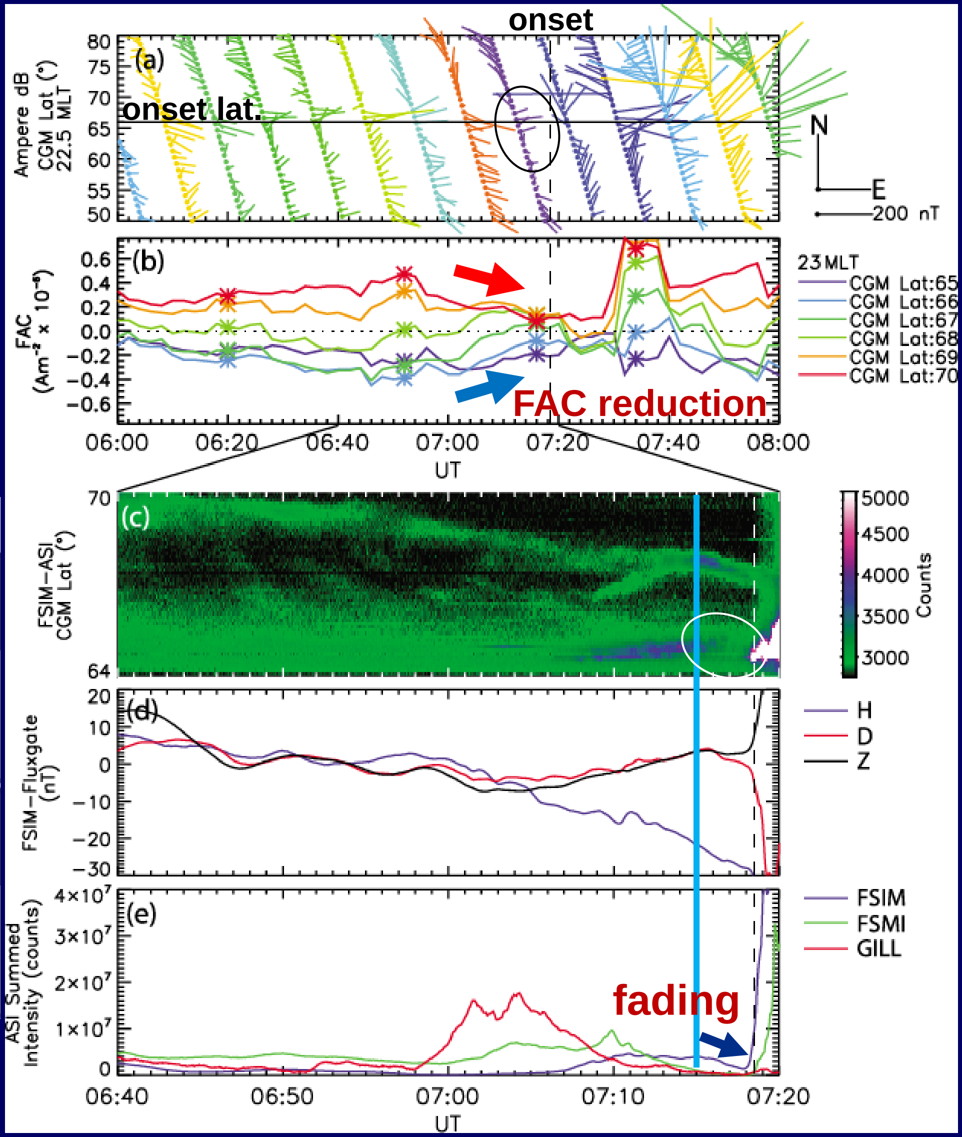
■ Auroral Fading and FAC Reduction

- **FAC deduced, associated with auroral fading (dimming) before initial auroral brightening.**

FAC and equivalent currents (EC)



FAC & EC reduction during fading

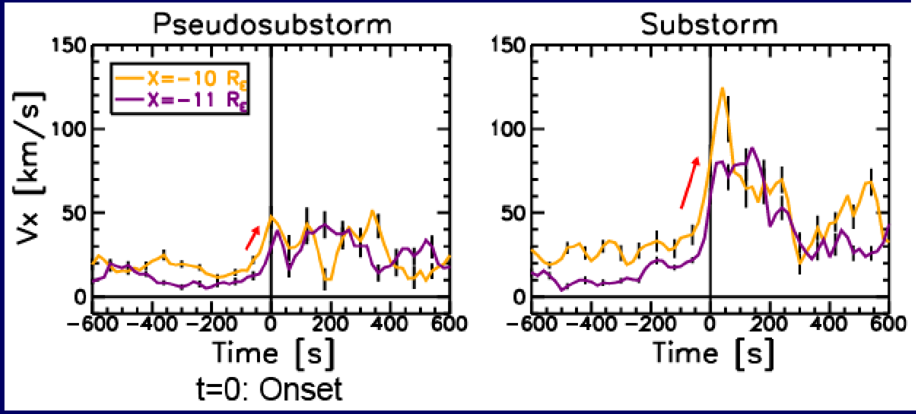


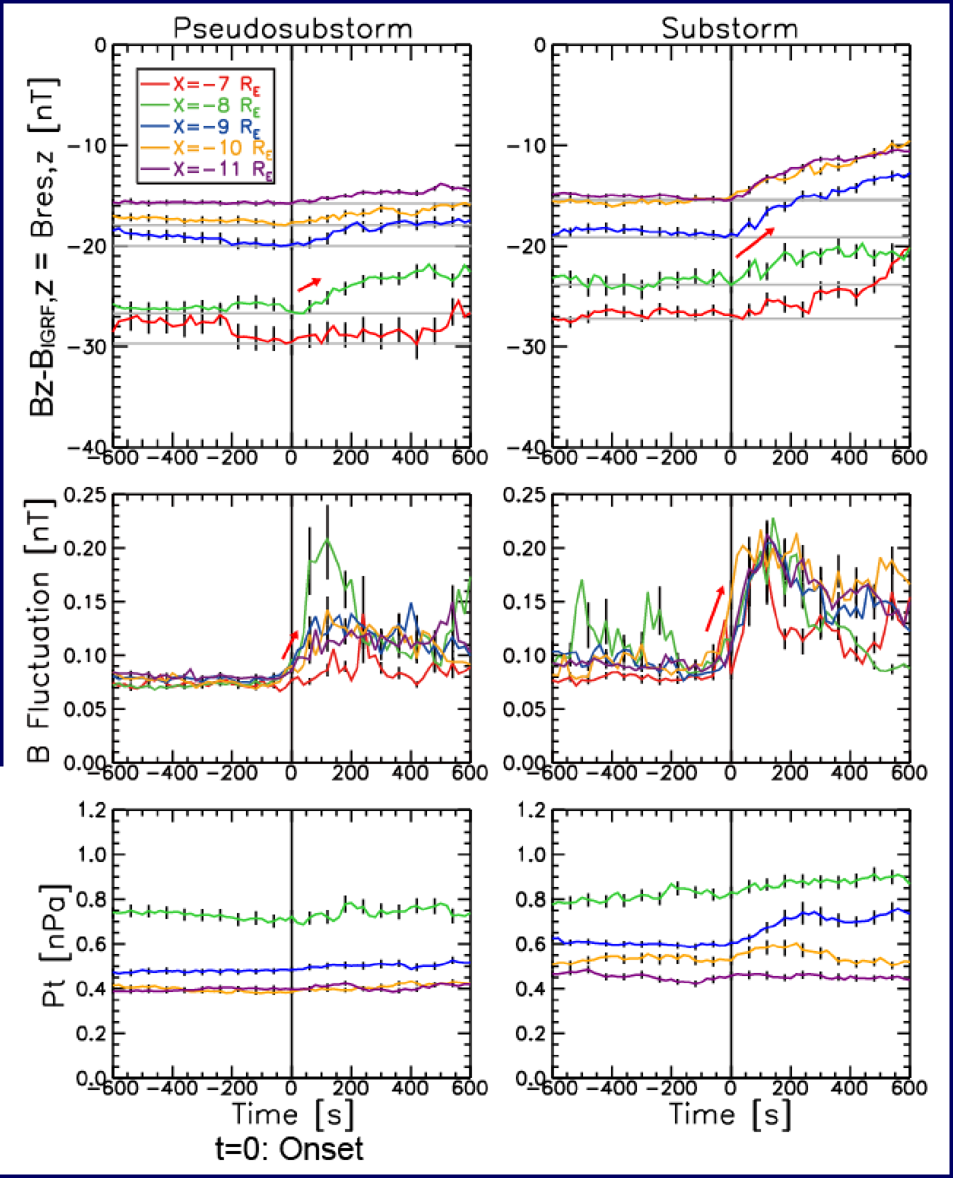
Murphy et al. (2012)

■ Magnetotail Statistics

For pseudosubstorms:

- **Dipolarization and δB are weaker, except for X=-8 Re.**
- **Pt before onset is lower.**
- **Vx at X=-10 to -11 Re at onset is slower.**



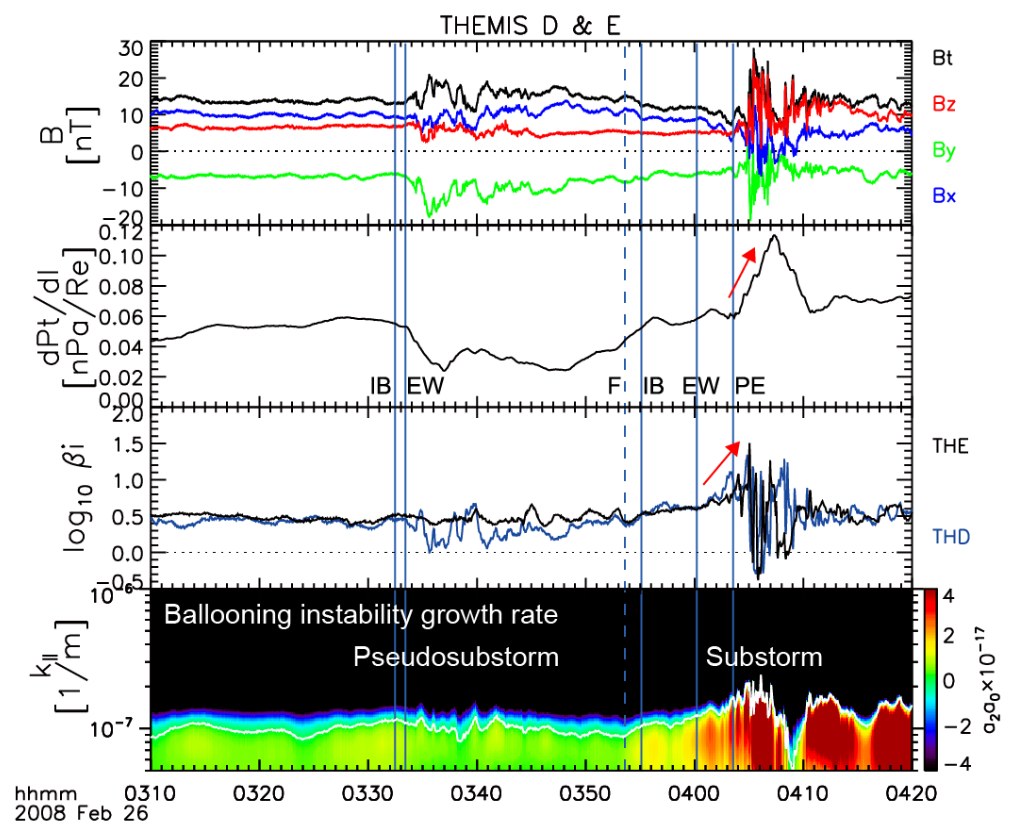


Fukui, Miyashita et al. (2020)

■ Case Study / Conclusion

• ∇P and β increased more after the substorm onset.

• The growth rate of ballooning instability was small for the pseudosubstorm but increased more and more after the substorm initial brightening.



Miyashita et al. (2018)

Conclusion

• We suggest that near-Earth magnetotail conditions, such as P, ∇P, and β, affect whether ballooning instability grows in a wide area, that is, whether the initial action develops into a substorm or subsides as a pseudosubstorm.

Planetary Missions

- Mercury
  - MESSENGER
    (Launched 2004,
    Observed 2011-2015, NASA)
  - BepiColombo
    (2018, 2026-2027, JAXA-ESA)
- Jupiter
  - JUNO
    (2011, 2016-2018, NASA)
  - JUICE
    (2022, 2030-, ESA)
- Saturn
  - Cassini
    (1997, 2004-2017, ESA)