Solar Wind –Magnetosphere Couplings

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Part – 1 : solar wind parameter dependence

- Solar Wind – Magnetosphere Interactions

- Substorms / Storms

- What solar wind parameters are important for substorms/storms/radiation belts?

Part – 2 : solar wind structure dependence

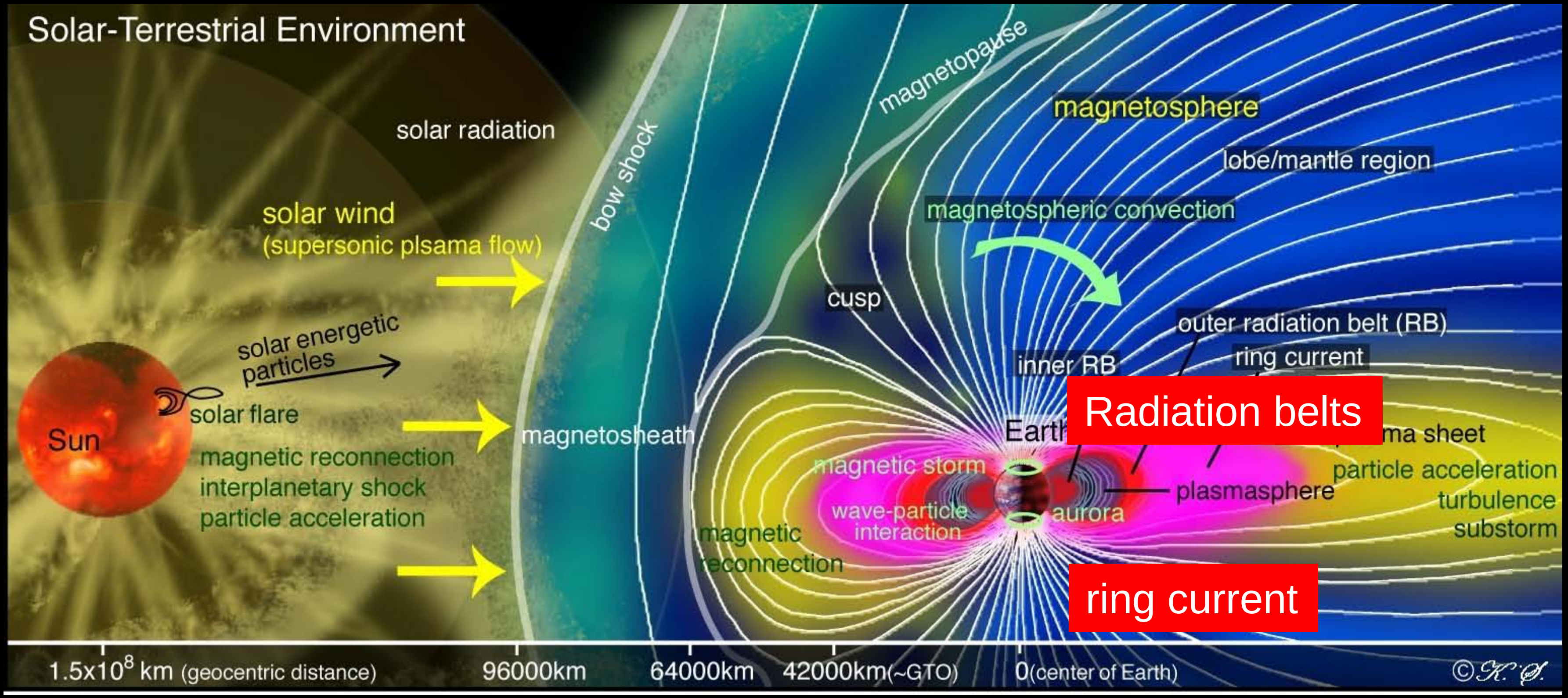
- Large scale structures (CME/CIRs) to produce storms
  - HILDCAAs
  - Russell-McPherron effect
  - calm before storm

- Differences of ring current / radiation belt evolutions between CME and CIR storms

- Solar cycle Variations of the radiation belts

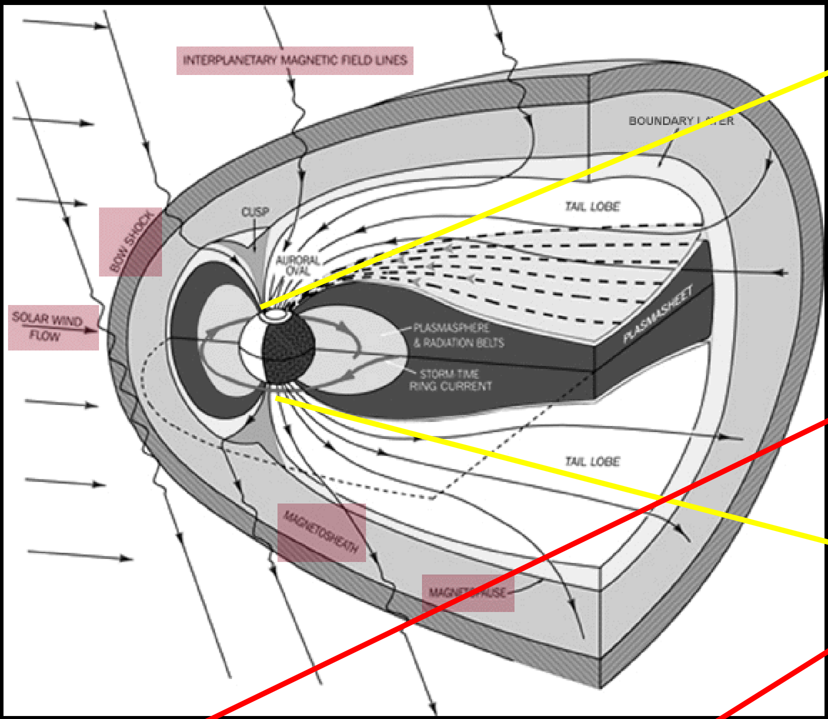
- Summary

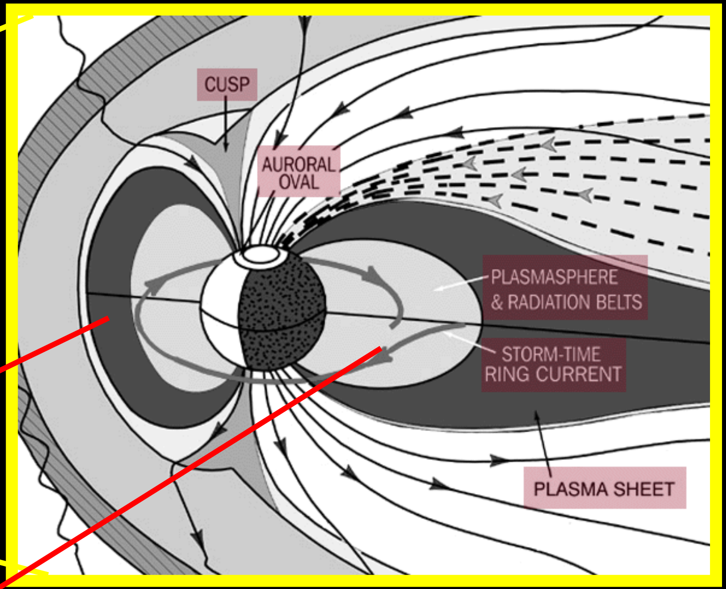
Introduction

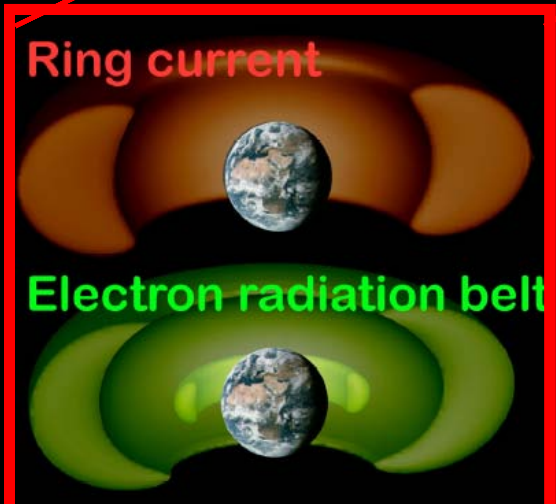


Sun -- Solar Wind – Magnetosphere

Magnetosphere







10-100 keV

~ MeV

- Topology:
  - Magnetopause,
  - Polar Cusps,
  - Tail,
  - Polar Caps,
  - Magnetosheath,
  - Bow shock.

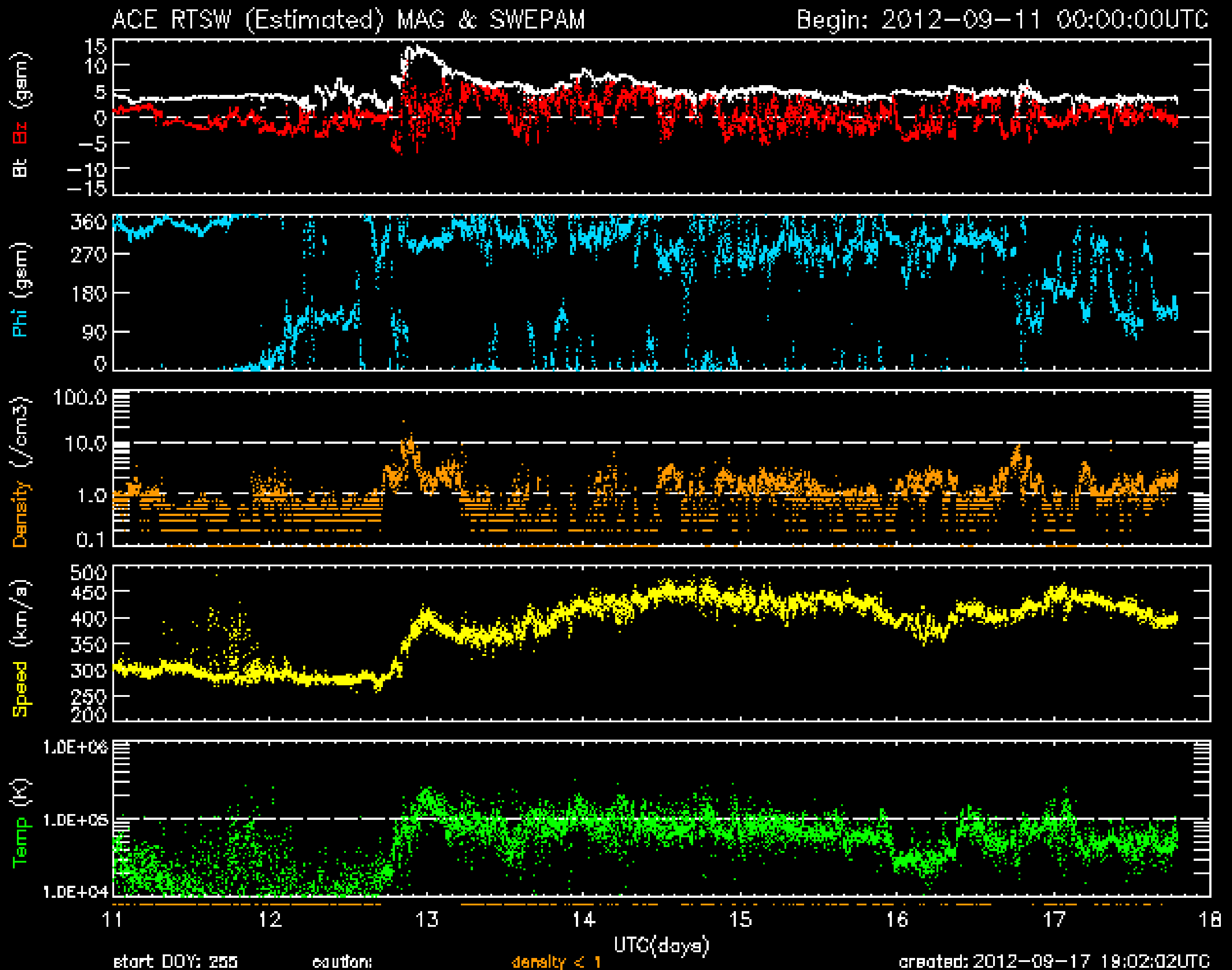
Characteristics of solar wind

Interplanetary Magnetic Field (IMF)

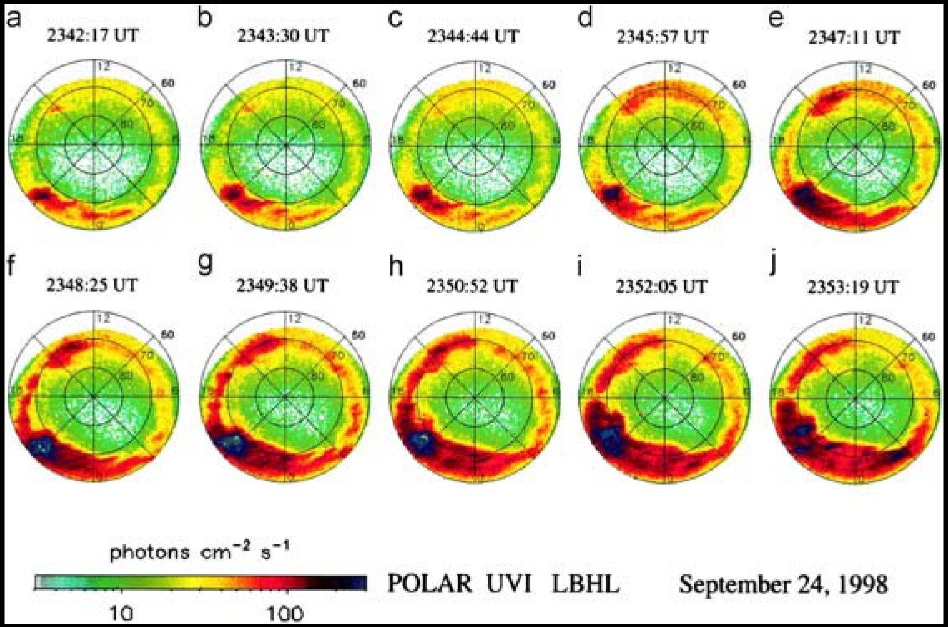
density

speed

temperature

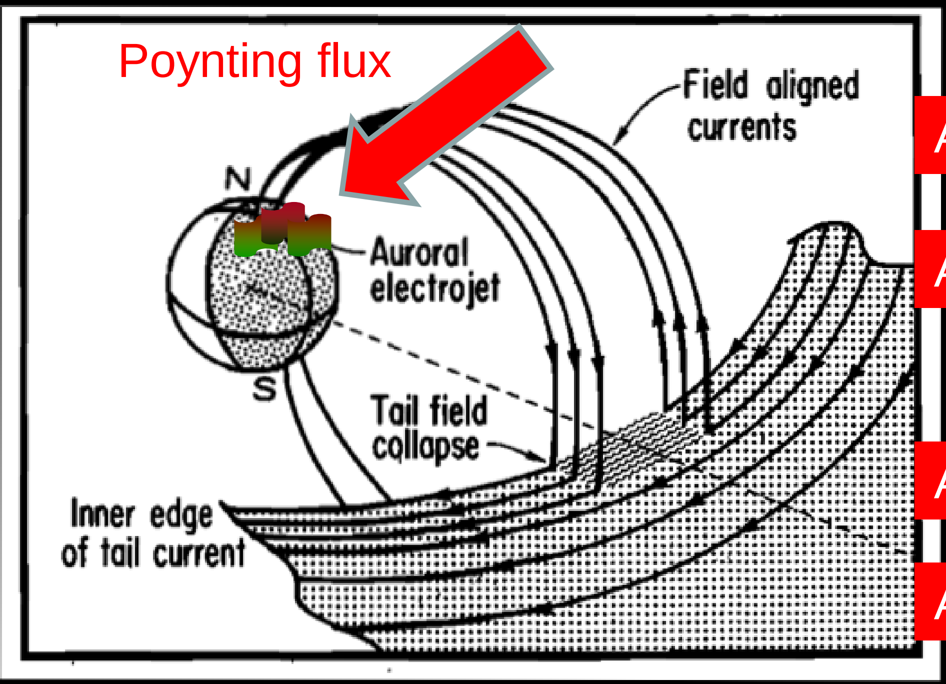


Substorms (1/2)

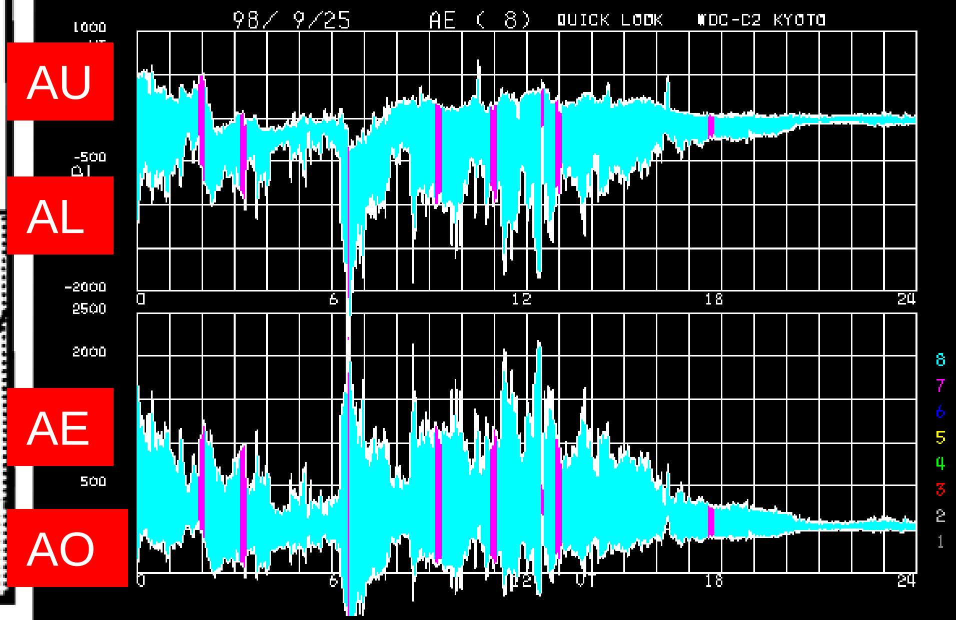


- Auroral expansions in the polar ionosphere
- Duration: ~1 -2 hours

Substorms (2/2)

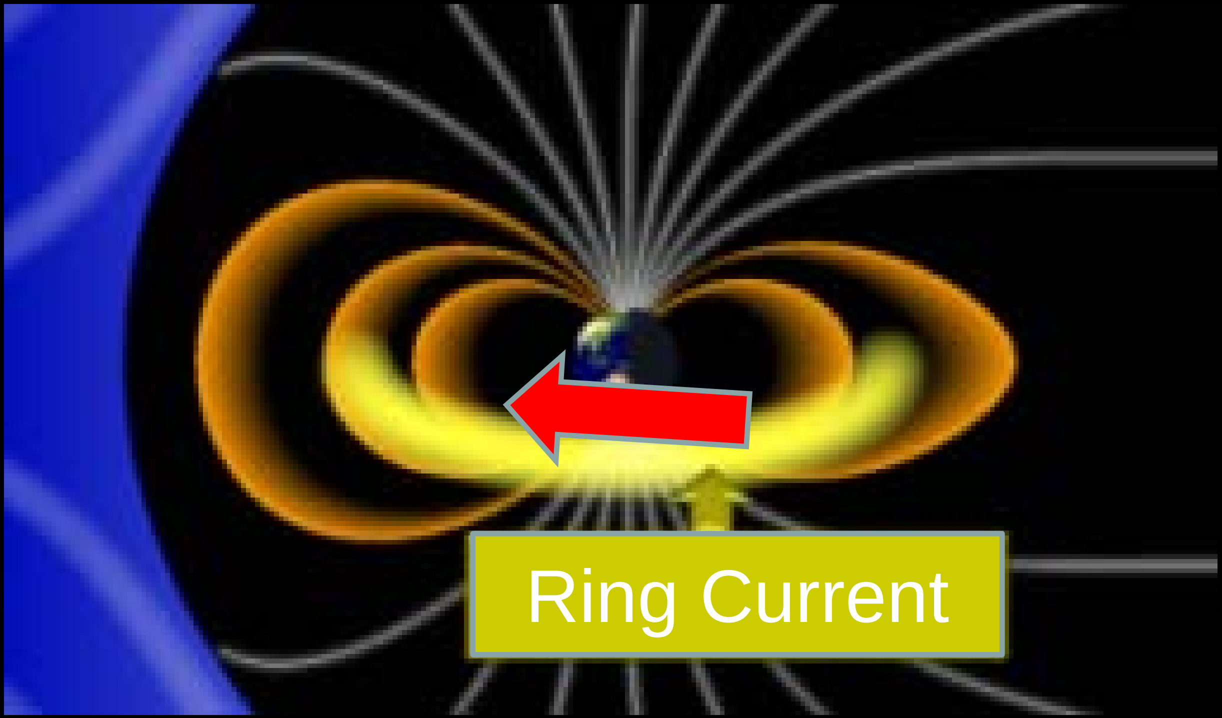


Auroral Electrojet (AE) index



- Formation of substorm current wedge
- Development of auroral electrojet as a result of enhancement of FAC
- Poynting flux goes from the magnetosphere to ionosphere.

Storms (Ring Current) (1/2)

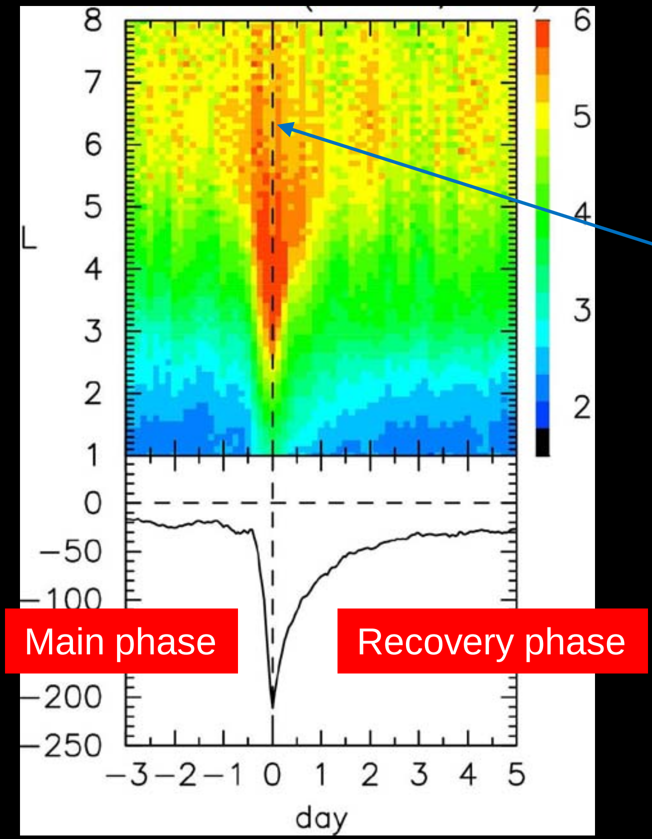


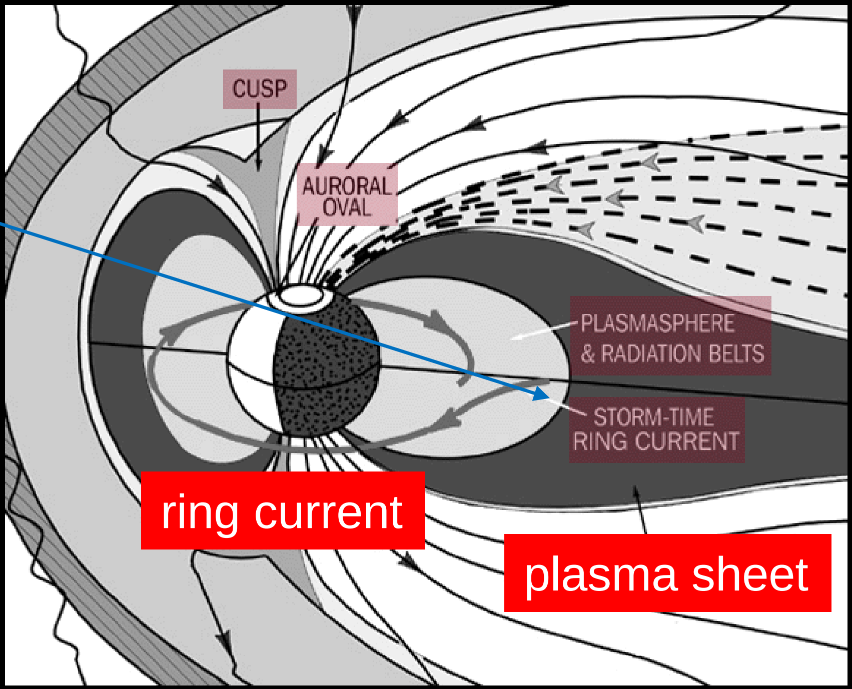
- Development of Ring Current that decreases the Earth’s magnetic field.
- Duration: 2~ 7 days

Storms (Ring Current) (2/2)

30 keV ion flux

Dst [nT]

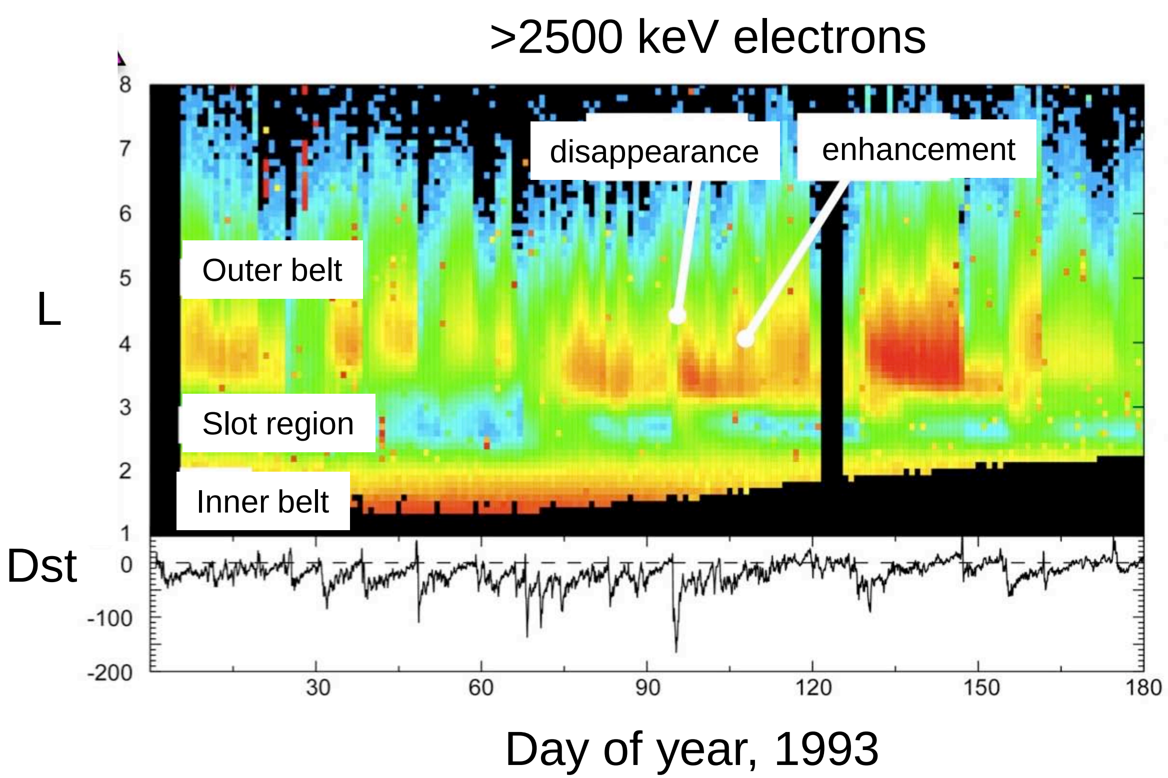


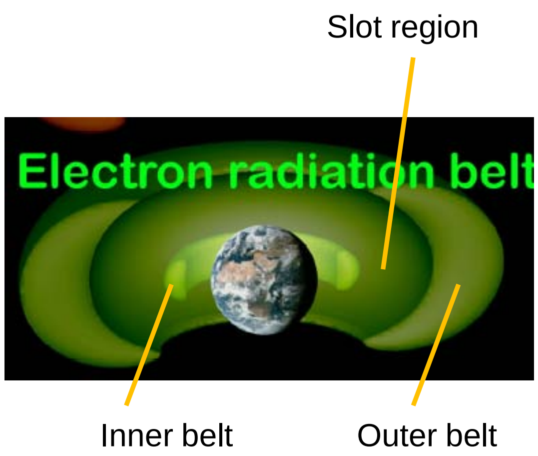


Miyoshi and Kataoka, 2005

- Deep penetration of plasma sheet ions into the inner magnetosphere.
- Dynamical variations occur everywhere in the magnetosphere.
 (ionosphere, inner magnetosphere, radiation belts, upper atmosphere)
- The Dst index is a proxy for development of storms.

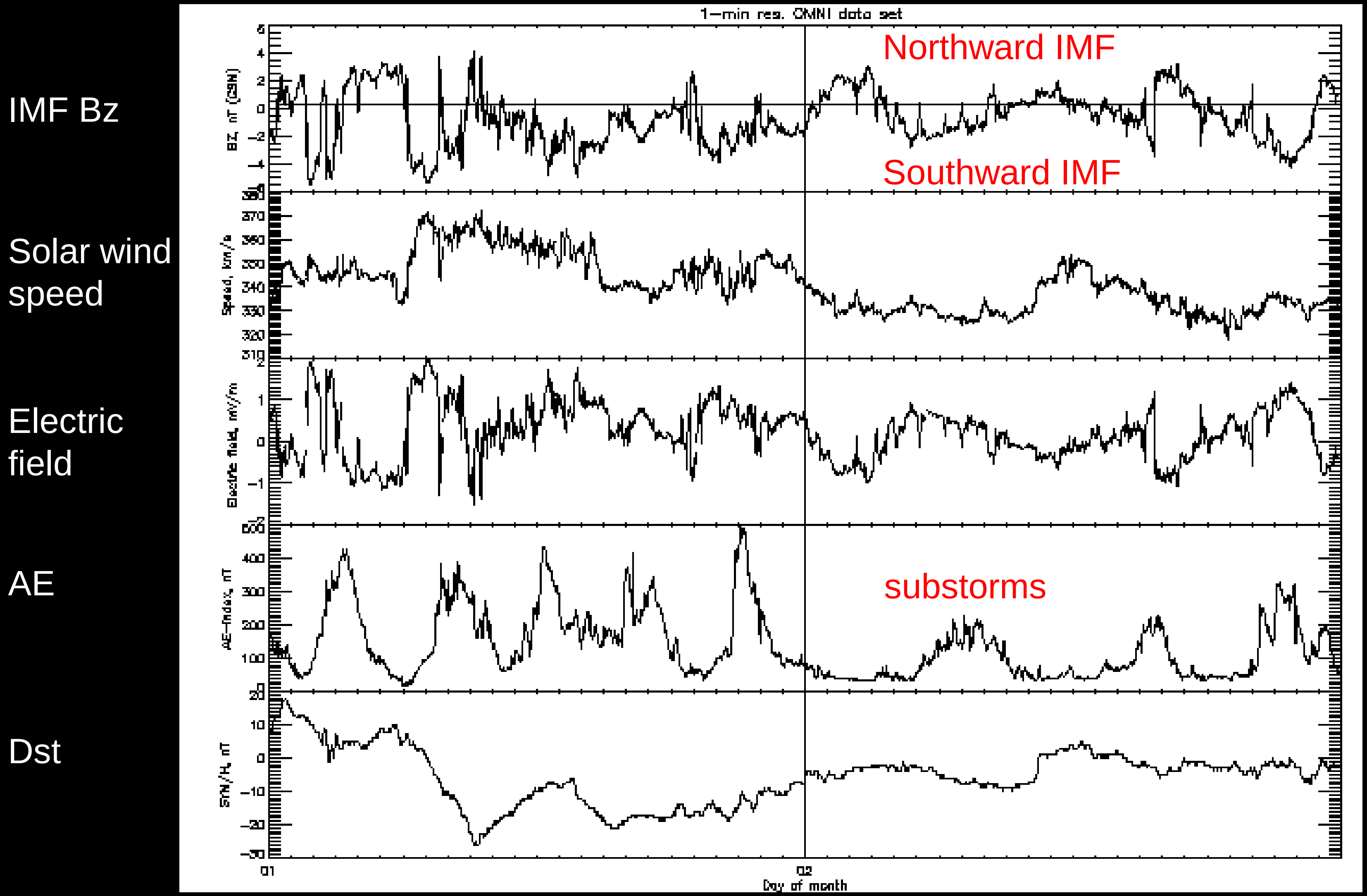
Radiation Belts





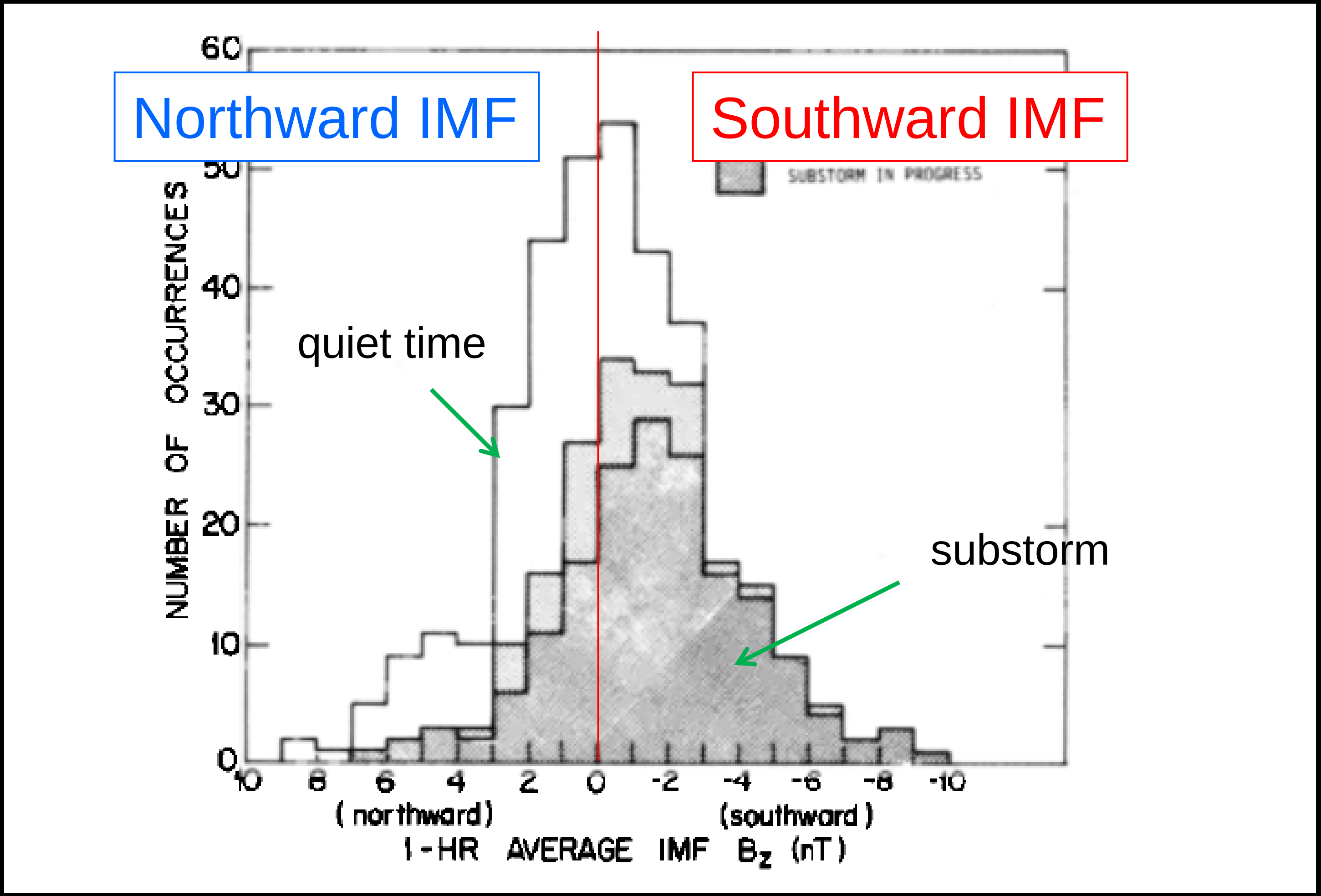
- Outer belt electrons decrease during the storm main phase, and then recovers and often increase more than pre-storm level.
- Even non-storm time, flux enhancements take place.

What solar wind parameter is important for substorms?



Aurora activity depends on IMF Bz

Occurrence of substorms as function of IMF Bz



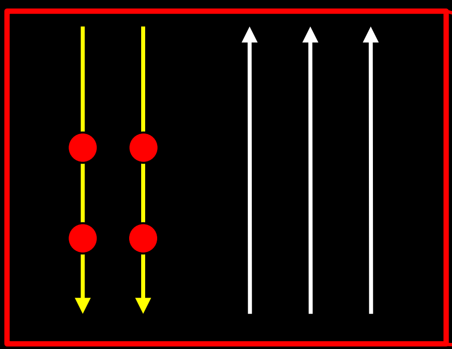
Kamide et al., 1977

IMF Bz controls substorms through reconnections

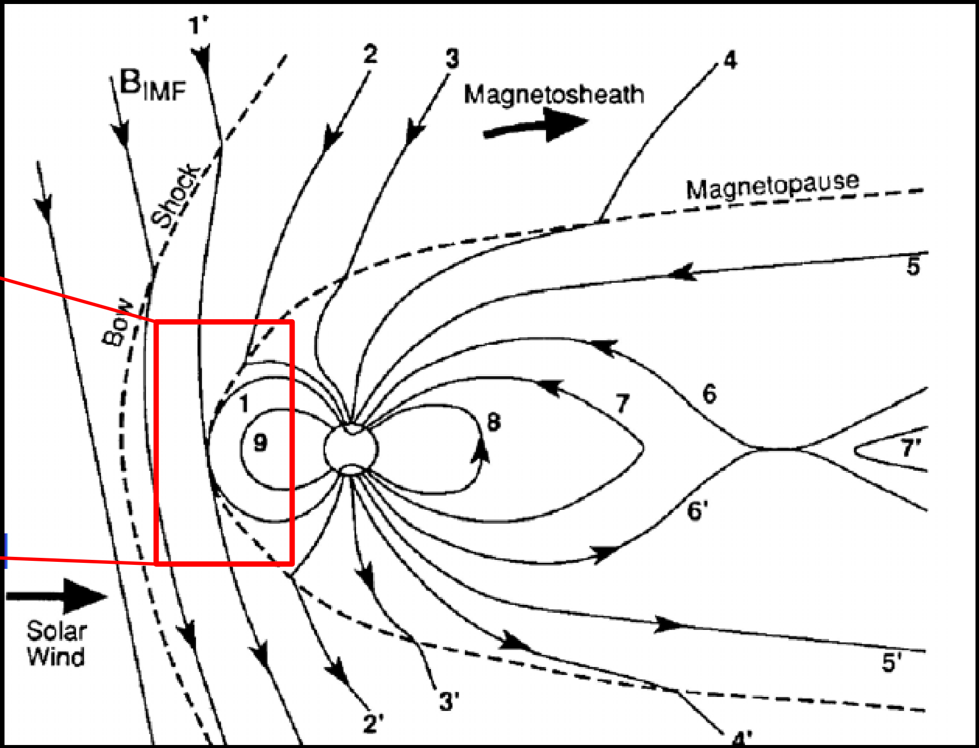
Transport of solar wind plasma into the tail

- Reconnection at the dayside

Southward IMF



Northward Earth magnetic field

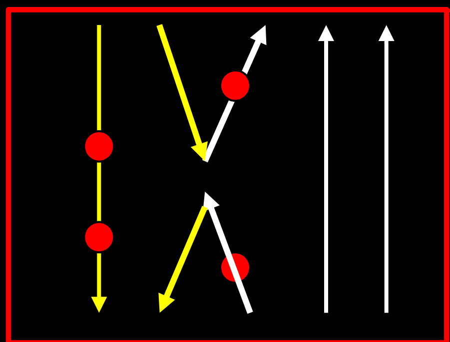


Energy storage phase

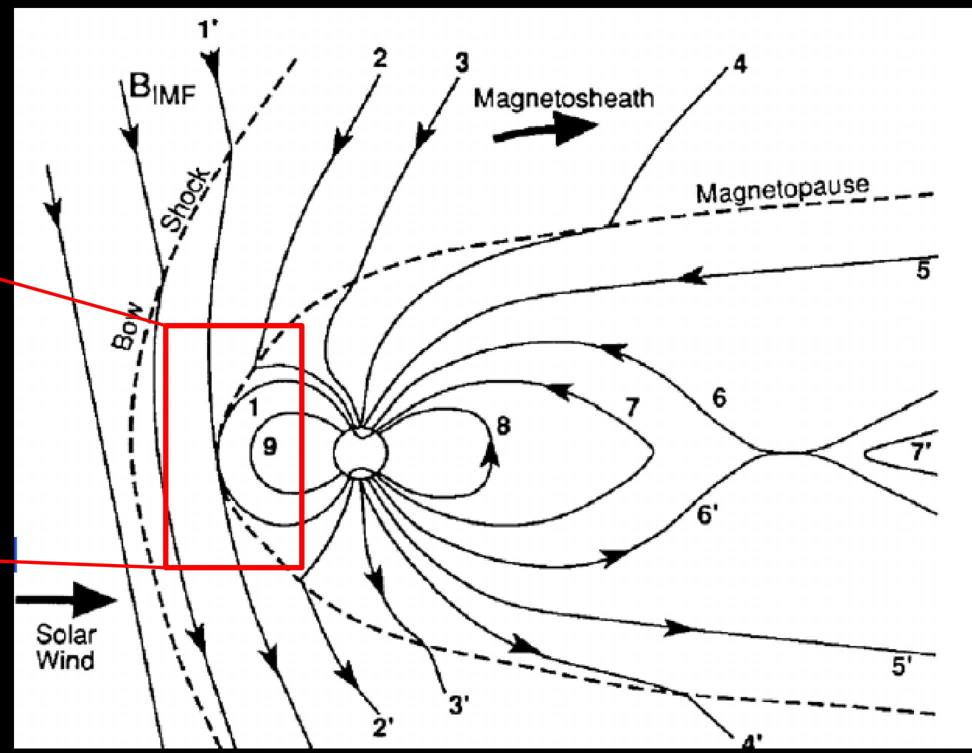
Transport of solar wind plasma into the tail

- Reconnection at the dayside

Southward IMF



Northward Earth magnetic field



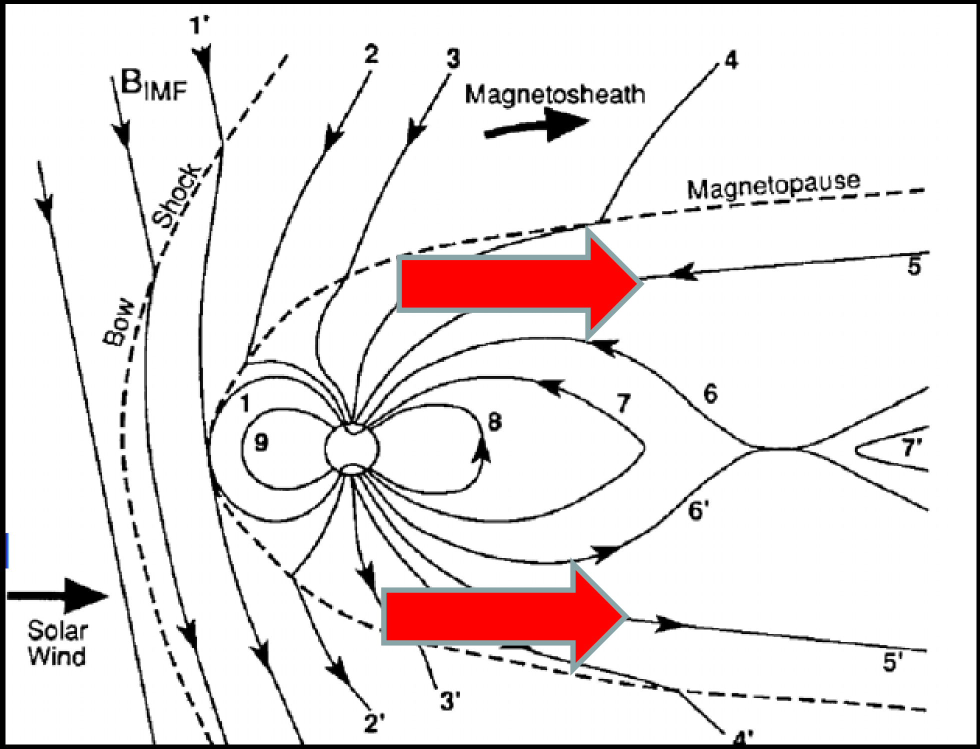
Energy storage phase

Transport of solar wind plasma into the tail

-Reconnection at the dayside

-Convection of the reconnected field line across the polar cap into the tail

[energy stored in the tail lobe]



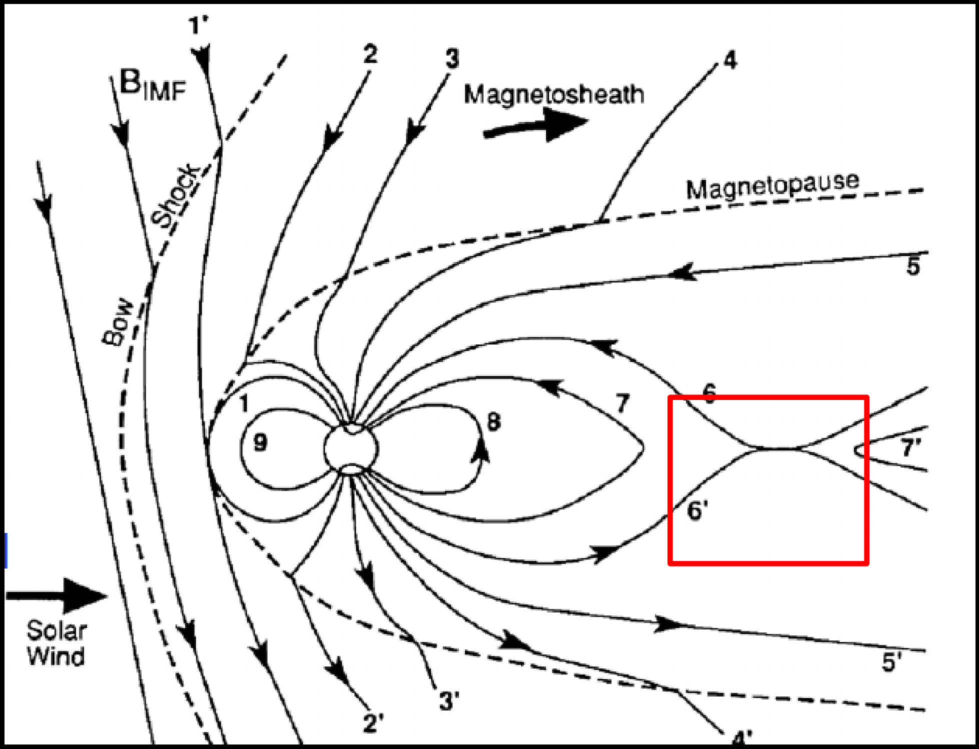
Energy storage phase

Transport of solar wind plasma into the tail

-Reconnection at the dayside

-Convection of the reconnected field line across the polar cap into the tail

-Formation of new closed field lines due to the reconnection



Energy release phase

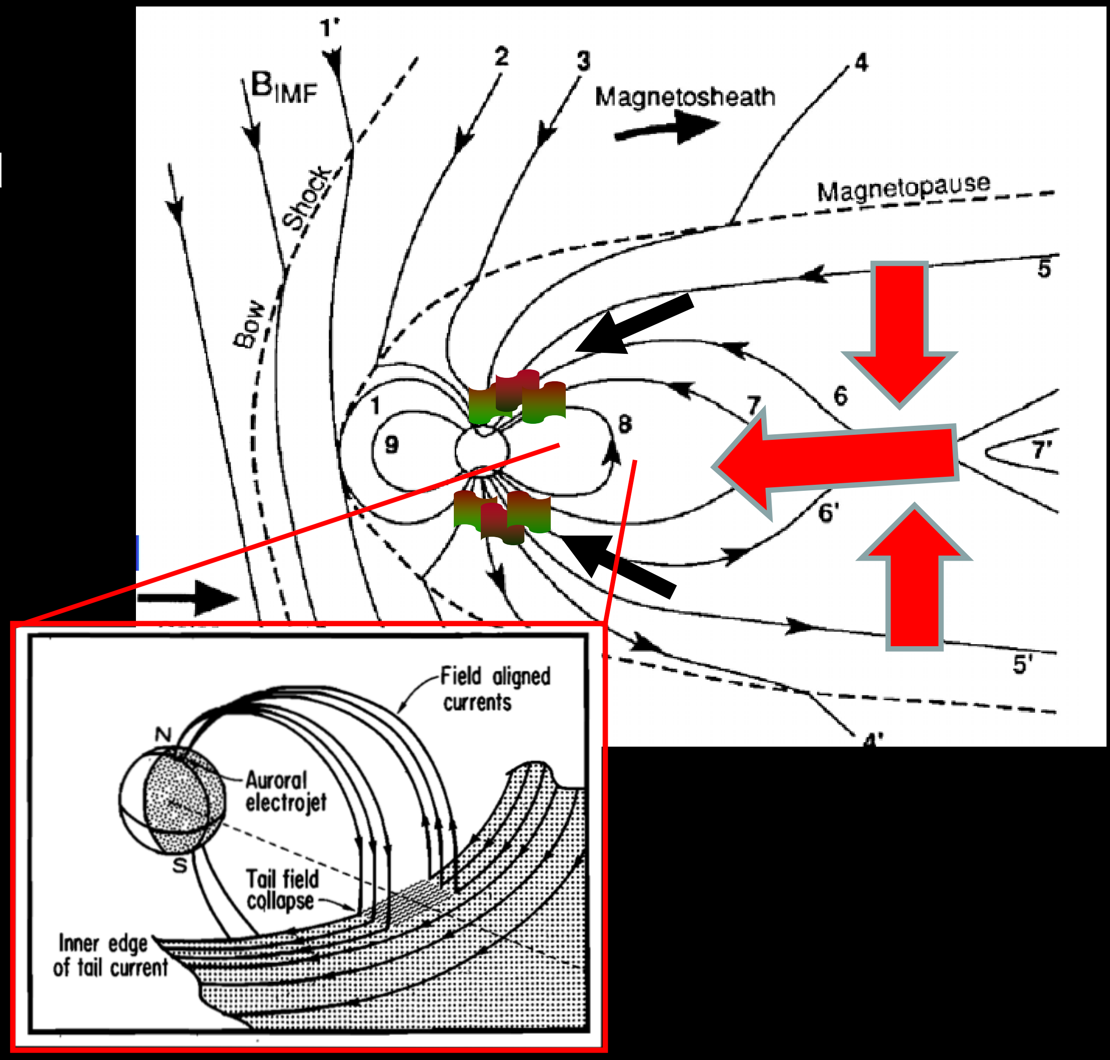
Transport of solar wind plasma into the tail

-Reconnection at the dayside

-Convection of the reconnected field line across the polar cap into the tail

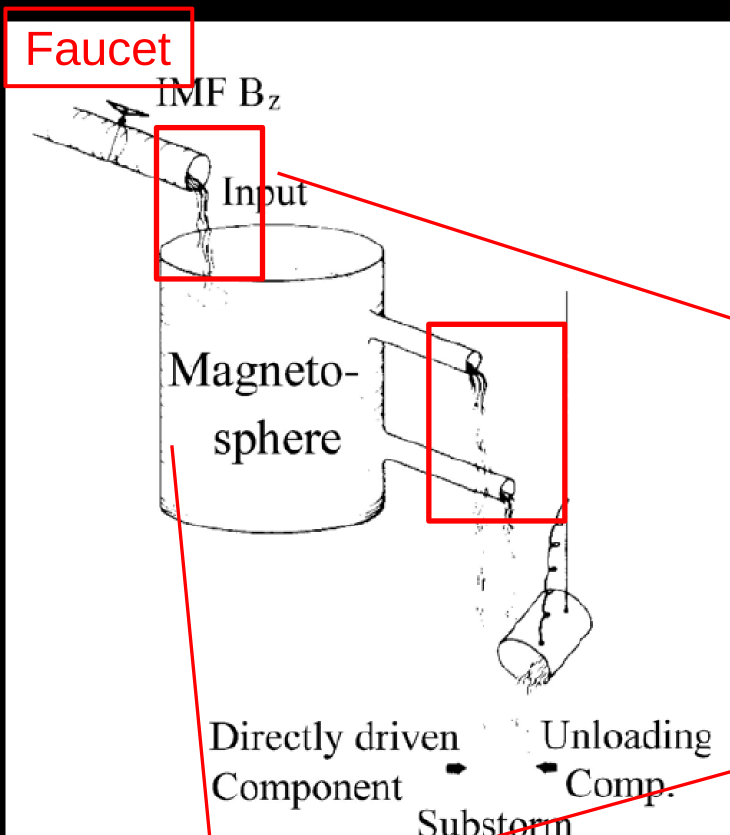
-Formation of new closed field lines due to the near-Earth reconnection

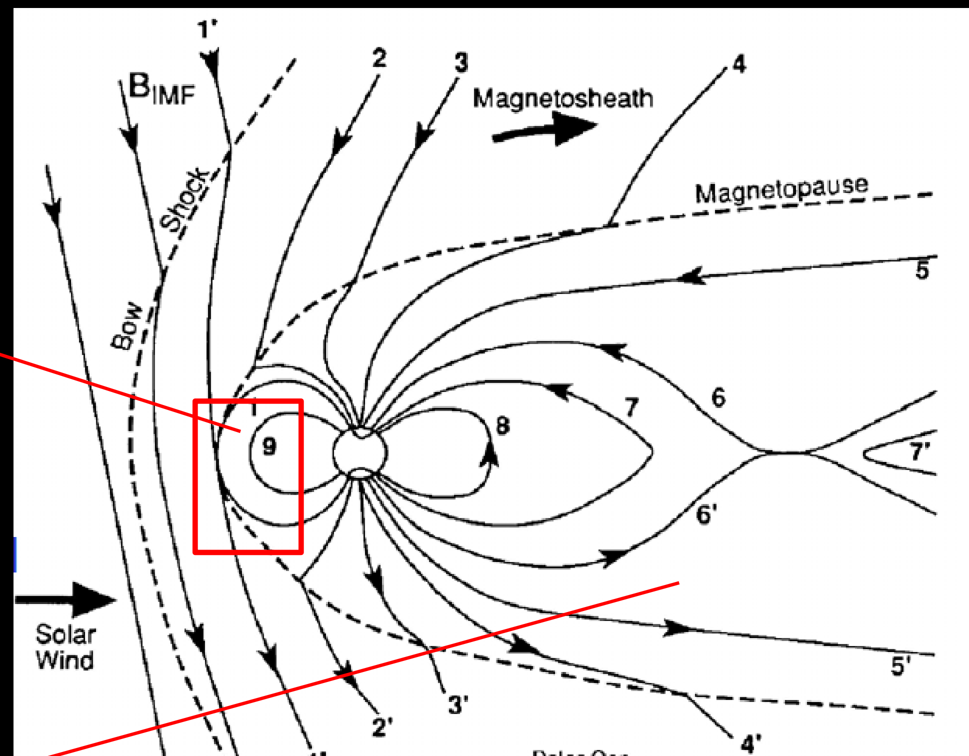
-Earthward plasma flow and formation of the substorm current wedge and aurora expansion.



Some threshold to drive substorm?

Bz controls energy input from solar wind into the magnetosphere, but substorm does not always occur during the southward IMF.





Is there any threshold to drive substorm?

Energy is stored in the tail lobe

Akasofu epsilon

Akasofu epsilon parameter is an empirical parameter to scale the stored energy in the magnetosphere.

$$\varepsilon = \frac{4\pi}{\mu_0} VB^2 \sin^4\left(\frac{\theta}{2}\right) l_0^2$$

$$VB^2 = (VB)B \propto E \times B$$

Akasofu, 1981

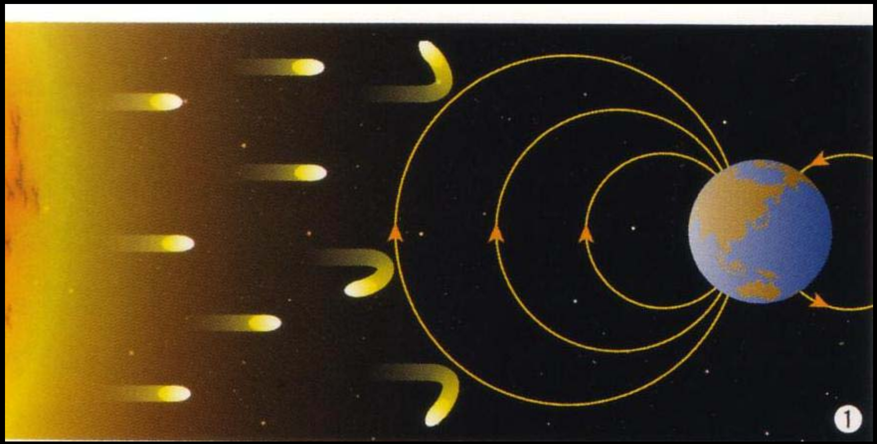
θ is the IMF clock angle in the YZ-plane

Akasofu epsilon is proportional to the Poynting flux of the solar wind.

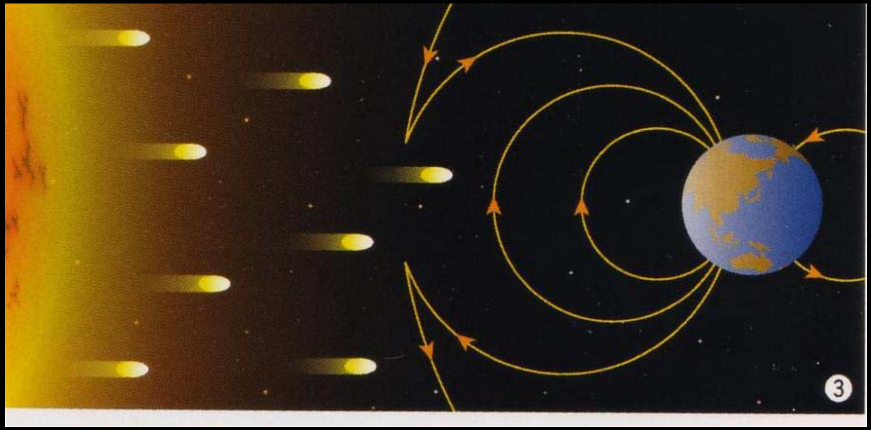
Akasofu epsilon exceeding 10^{11} W is likely to cause a substorm.

What parameter is important for substorms ?

Northward IMF: solar wind does not come into the magnetoshere.

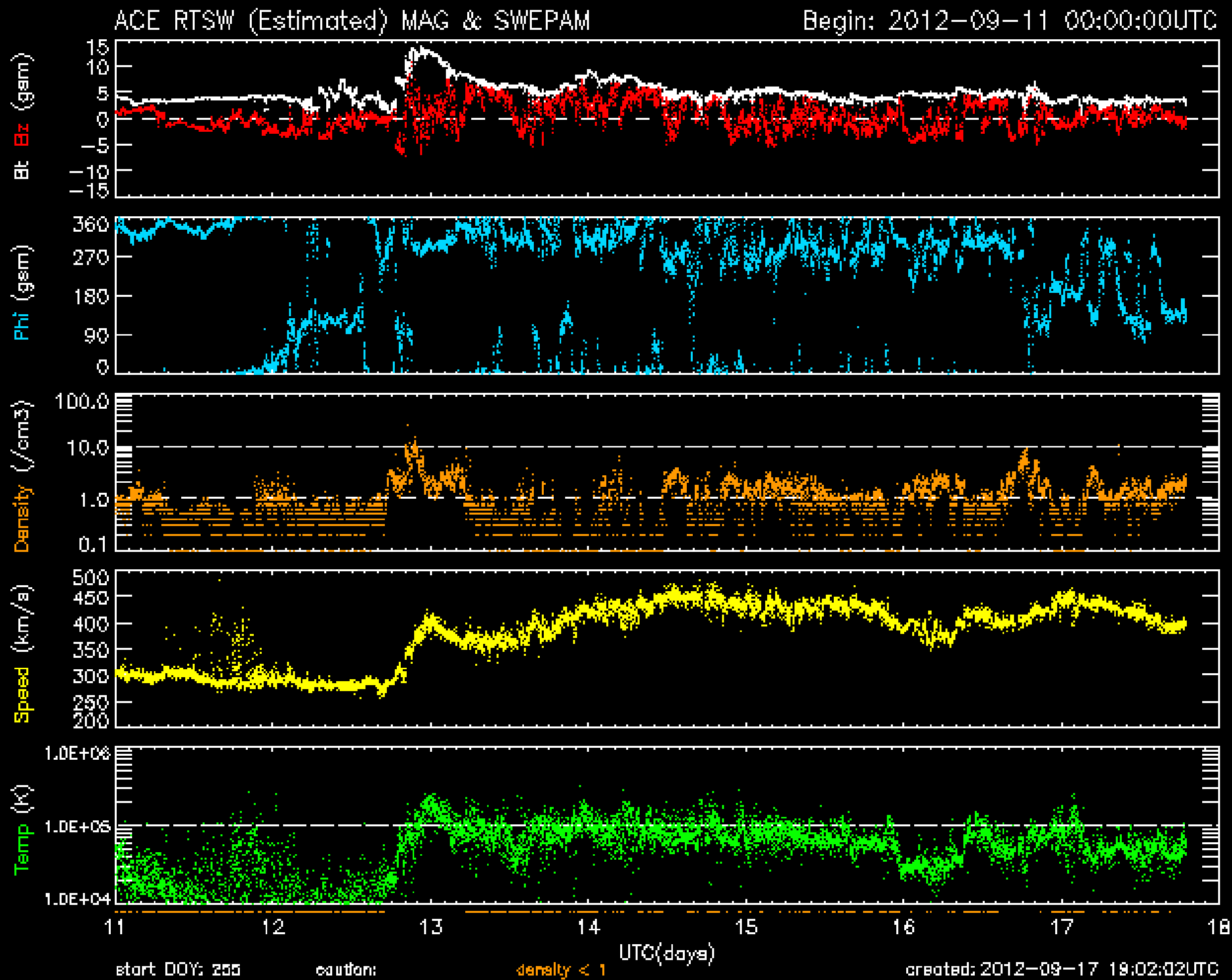


Southward IMF: solar wind energy can transfer to the magnetosphere.

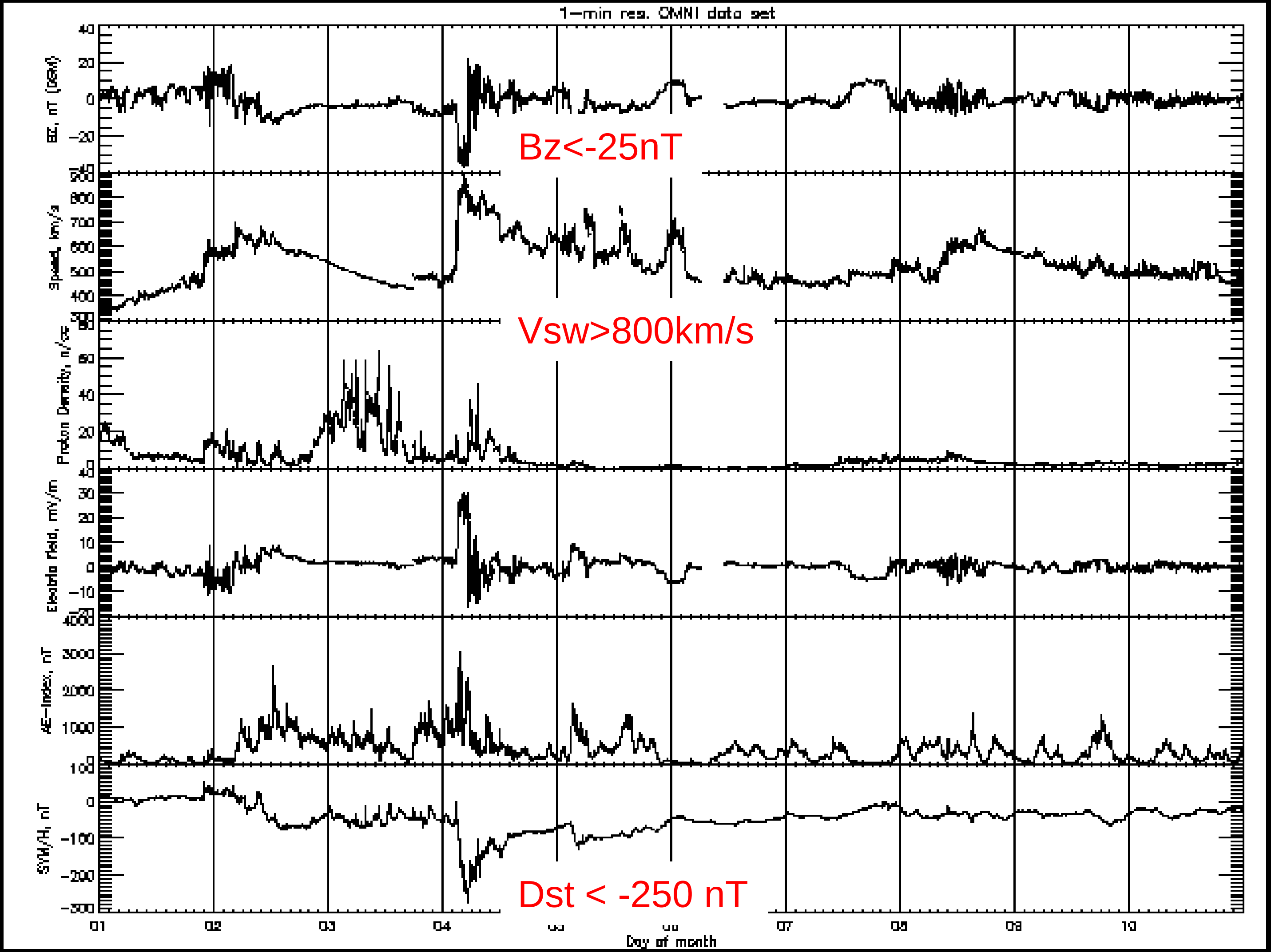


When we watch the aurora…..

We must check the IMF Bz condition.



What parameter is important for magnetic storm?



Strong interplanetary electric field is necessary

Gonzalez and Tsurutani [1987]

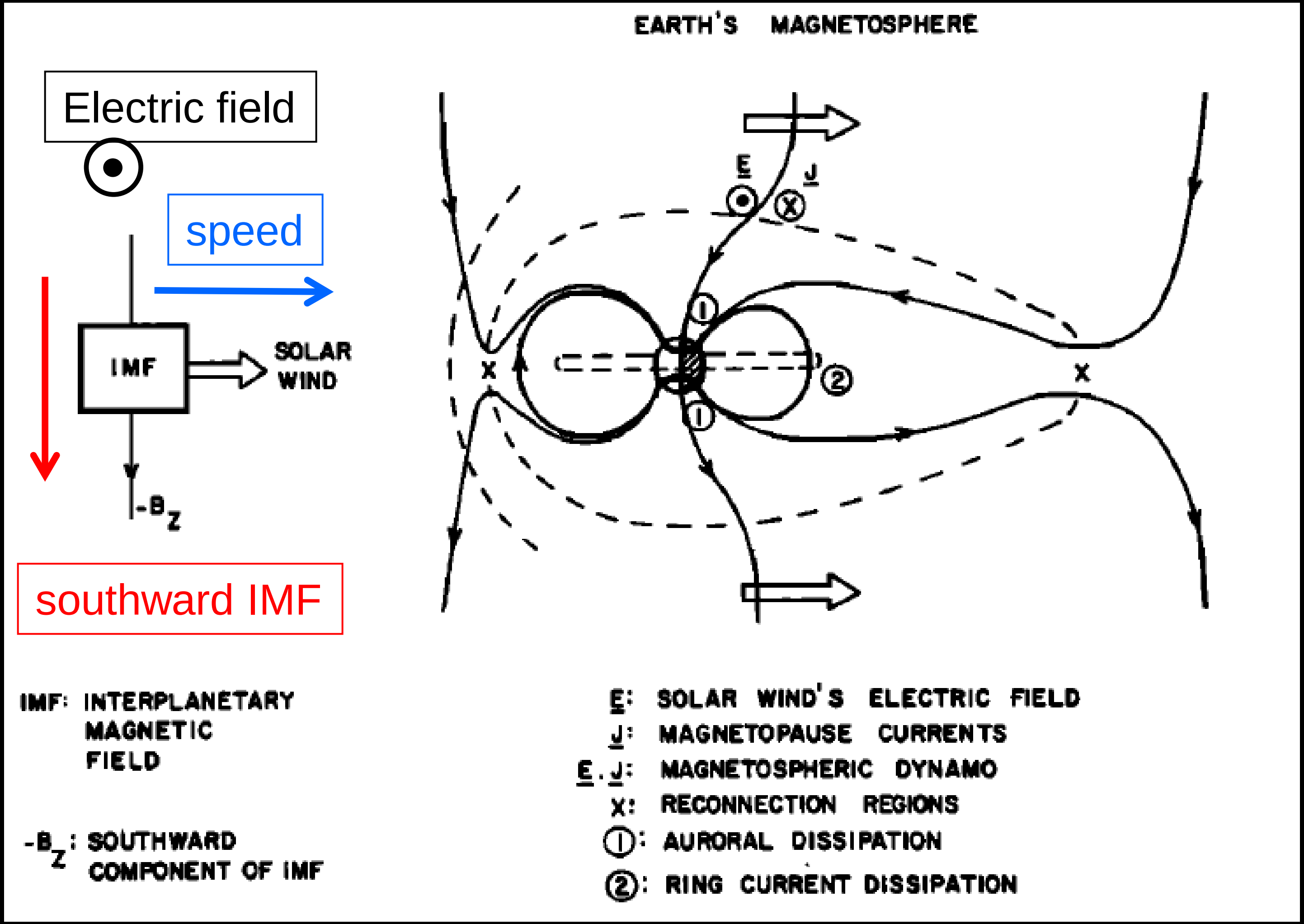
: IMF must have a long-duration (more than 3 hours),
large negative (<-10 nT) southward component
associated with duskward electric field (>5 mV/m).

	Dst, nT	B_z, nT	ΔT, hours
Intense	−100	−10	3
Moderate	−50	−5	2
Small (typical substorm)	−30	−3	1

Gonzalez et al., 1994

Interplanetary electric field is essential to drive storms

The electric field of the solar wind $E = v \times B_s$ is important to drive magnetic storms.



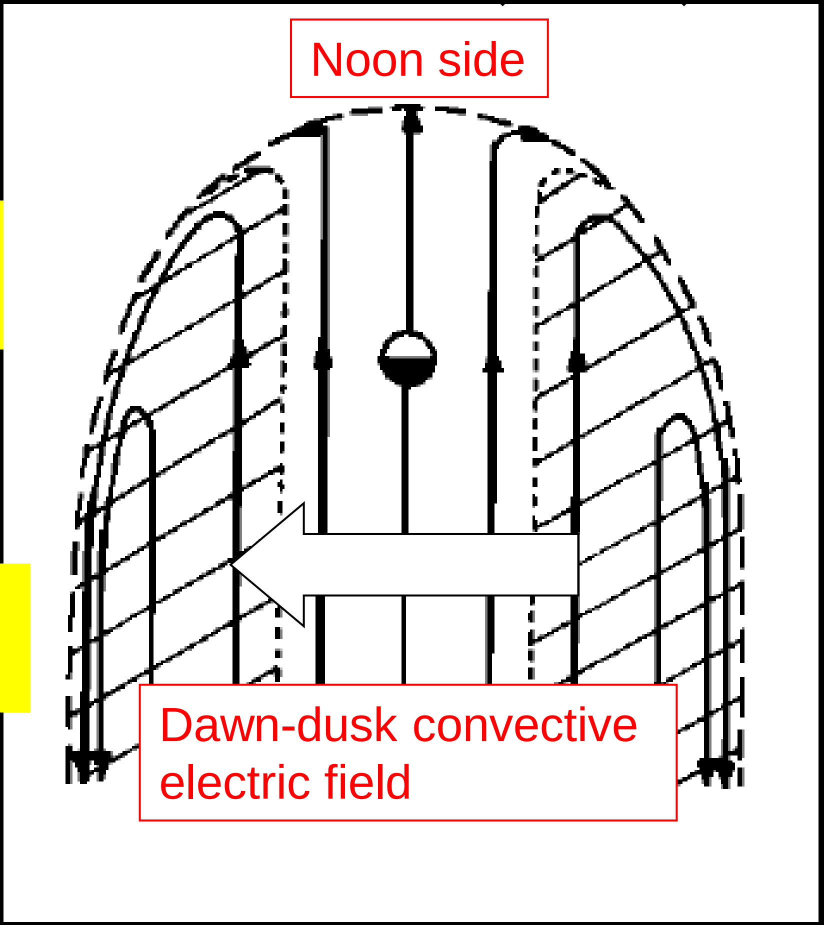
Gonzalez et al., 1994

Interplanetary electric field is essential to drive storms

Enhacement of interplanetary electric fields

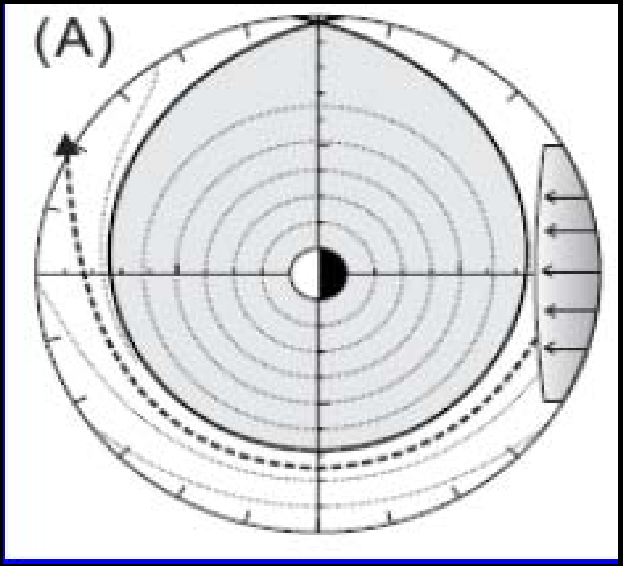
Enhanced dawn-dusk convective electric Field in the magnetospehre

Enhanced convection causes movement of particles into the inner magnetosphere



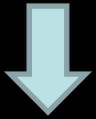
Cowley, 1982

Why strong electric field is important?



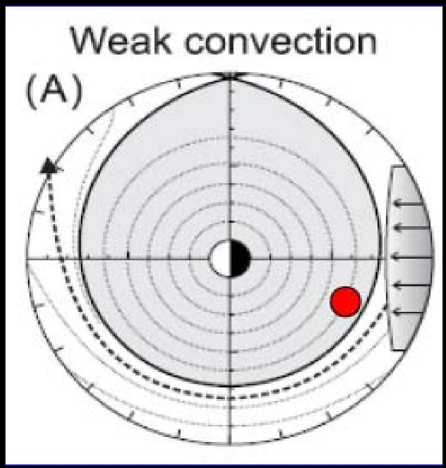
Ebihara and Ejiri, 2002

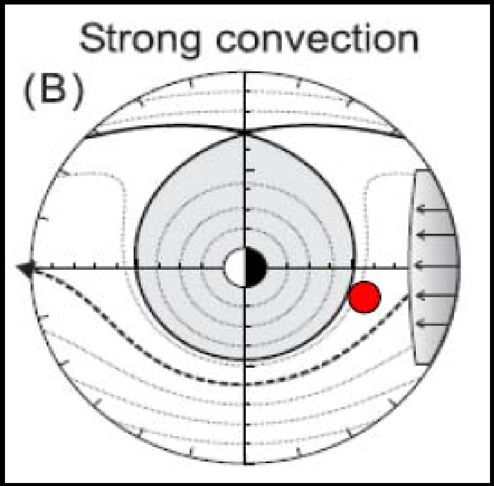
Energetic particle (ring current particle, radiation belt particles) drifts around the Earth due to gradient/curvature drifts.



Not access to the inner magnetosphere without E x B drift.

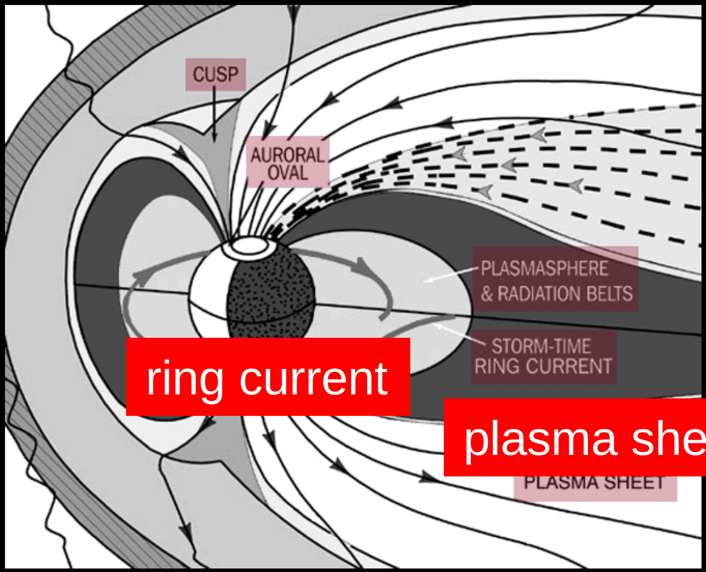
Why strong electric field is important?





magnetic drift > convection
not access to the inner magnetosphere

convection > magnetic drifts
access to the inner magnetosphere



To build up ring current in the inner magnetosphere, strong convective electric fields are essential.

Interplanetary electric field is essential to drive storms

Energy balance equation to describe the time evolution of Dst

$$\frac{d\left(Dst\right)}{dt} = Q\left(vB_s\right) - \frac{Dst}{\tau}$$

Burton et al., 1975

INPUT: solar wind electric field

$$vB_s$$

Solar wind speed

Southward IMF

What parameter is important for magnetic storm?

Intense southward IMF (electric field):

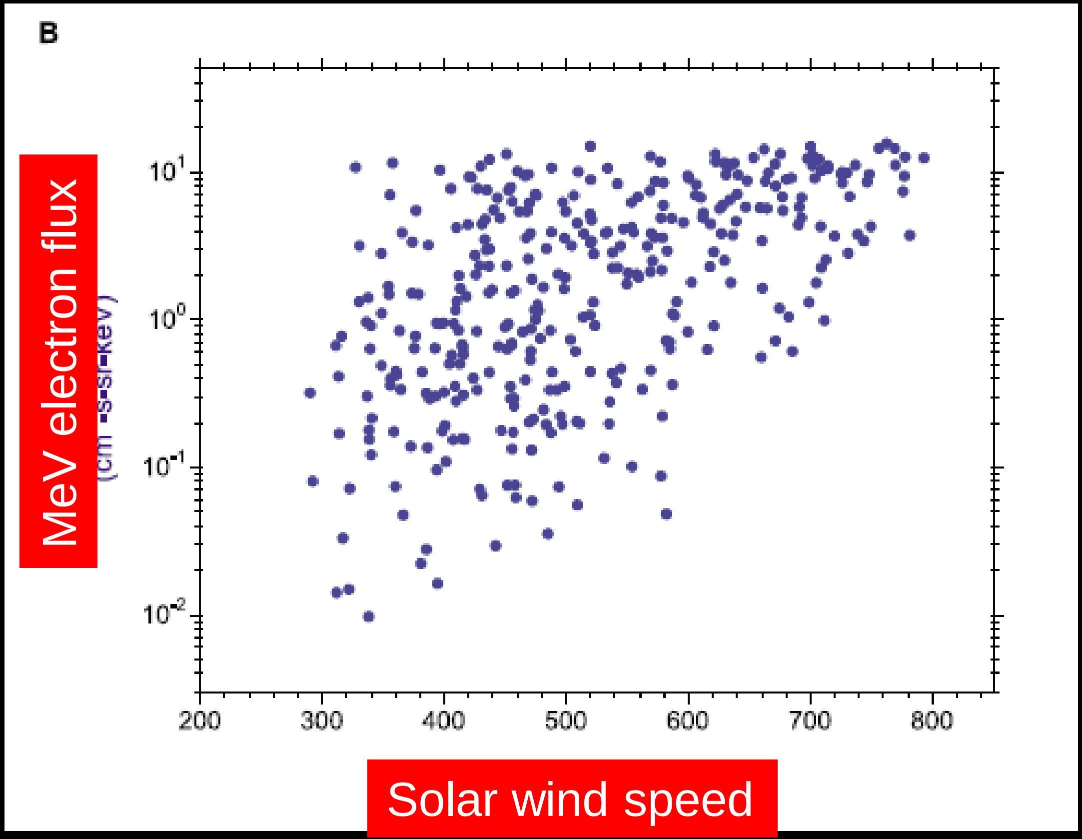
To build up the ring current in the inner magnetosphere, intense southward IMF (electric fields) is essential.

Where the intense southward IMF is found?

--- topics in Part II

What parameter is important for radiation belts?

It has been believed that the solar wind speed is a primary parameter to produce the large flux enhancement.

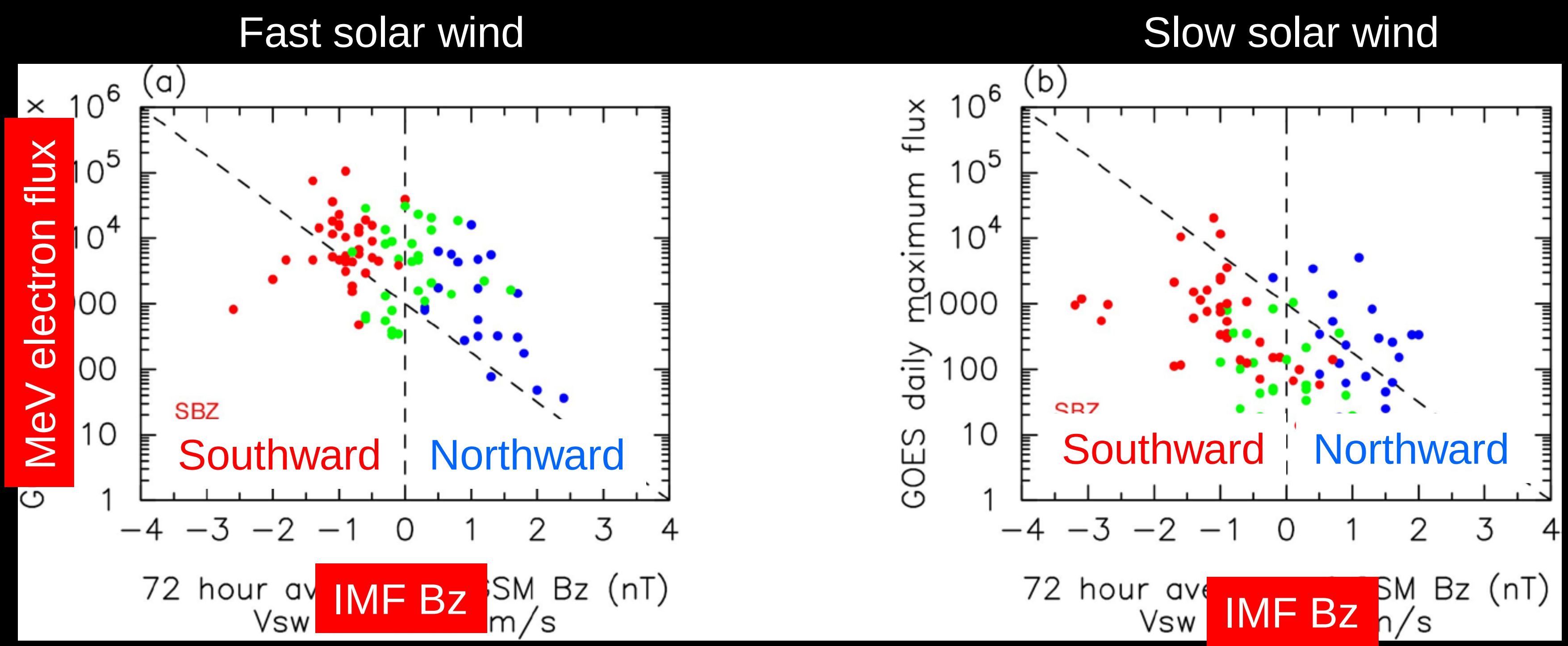


Reeves et al., [2011]

Solar wind speed dependence may indicate that MHD waves are important for the accelerations.

What parameter is important for radiation belts?

Other studies indicated that the southward IMF is also important for the large flux enhancement.



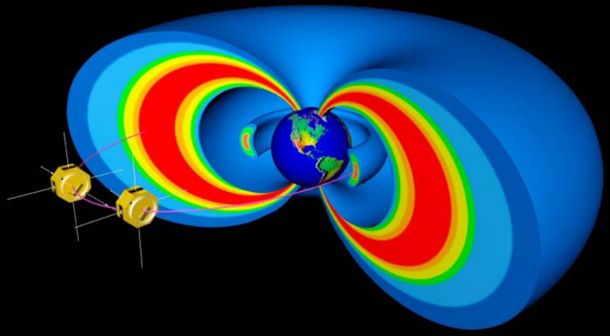
Miyoshi and Kataoka [2008]

IMF Bz dependence may indicate that VLF whistler mode waves are important for the accelerations via substorms.

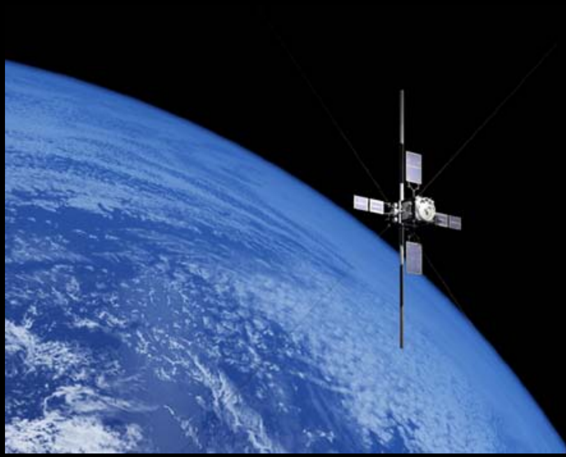
What parameter is important for radiation belts?

Still outstanding problem!

US/RBSP (launch 2012/08/30)



Japan/***ERG*** (launch 2015/12)



New missions will elucidate what solar wind parameter is important.

Part – 2 : solar wind structure dependence

- Large scale structures (CME/CIRs) to produce storms
  - HILDCAAs
  - Russell-McPherron effect
  - calm before storm

- Differences of ring current / radiation belt evolutions between CME and CIR storms

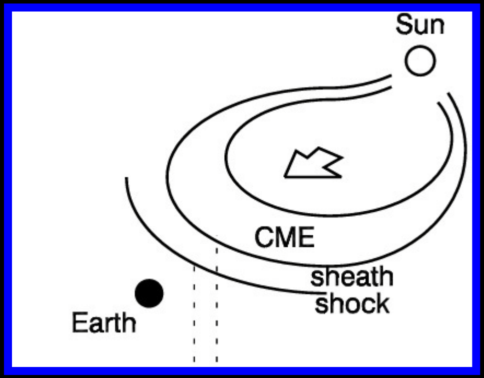
- Solar cycle Variations of the radiation belts

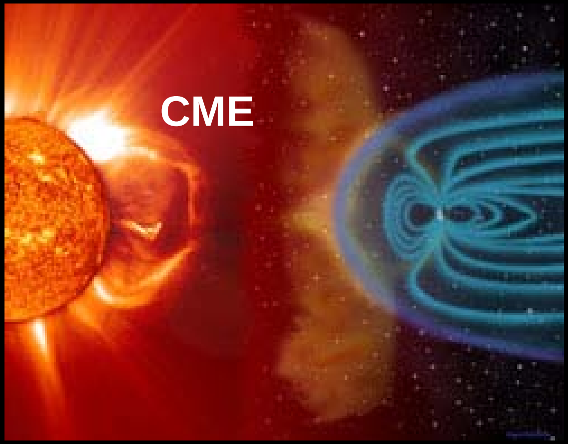
- Summary

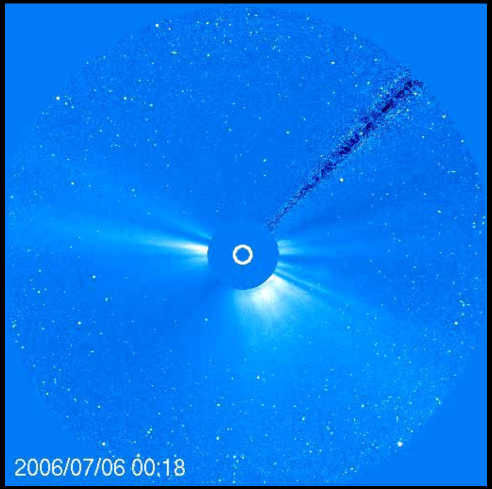
Large Scale Structures to cause storms

Two drivers for magnetic storms:

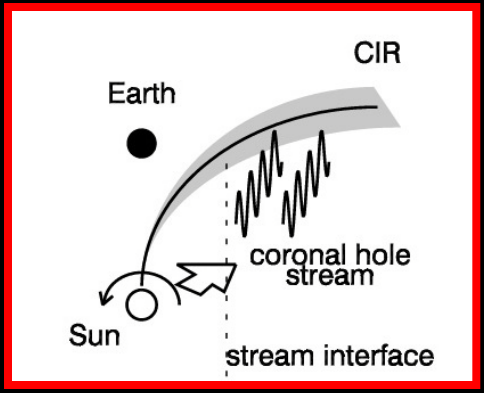
CME







CIR



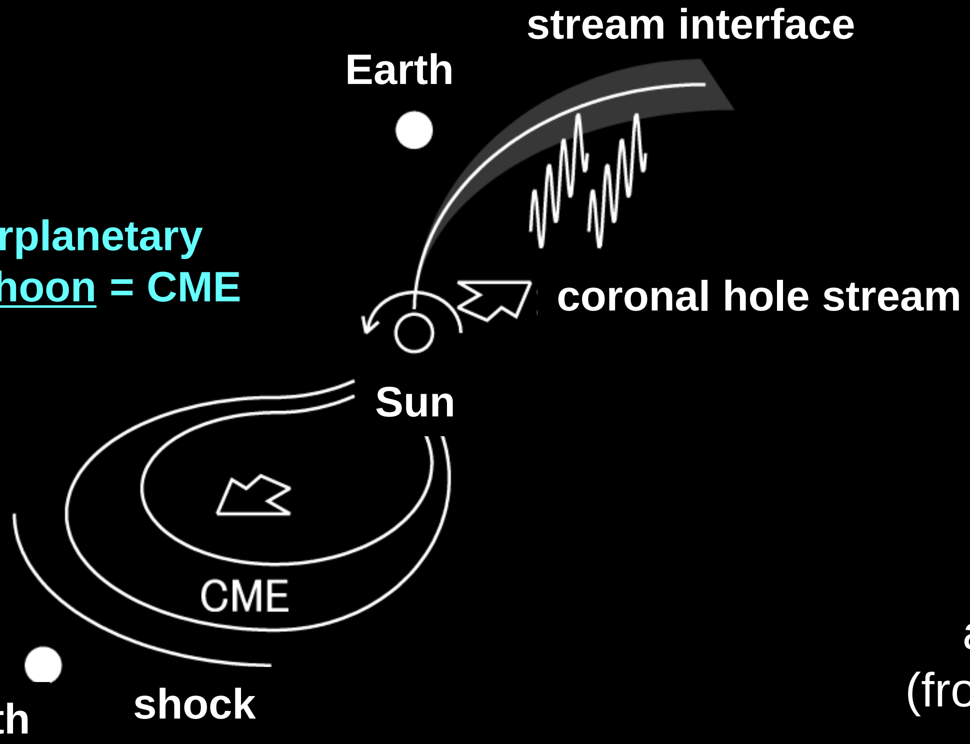
Tsurutani et al. [2006]

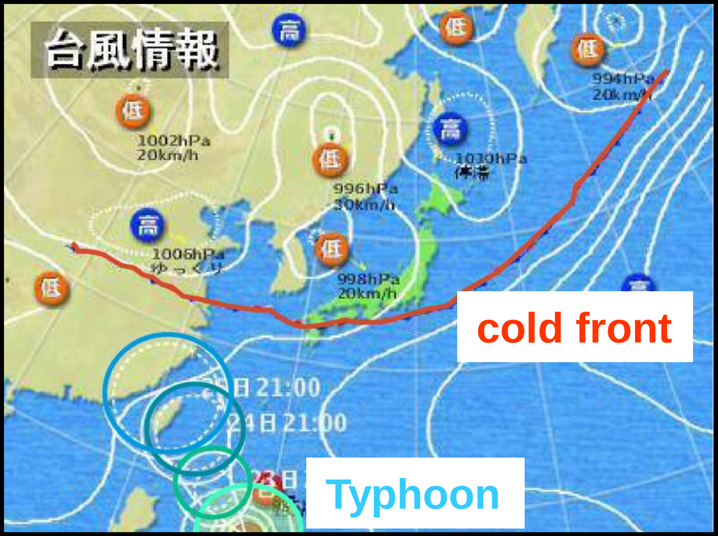
CME and CIRs as interplanetary Air Mass

Analogy between atmospheric pattern and CIRs/CMEs.

Interplanetary Cold Front = CIR

Interplanetary
Typhoon = CME



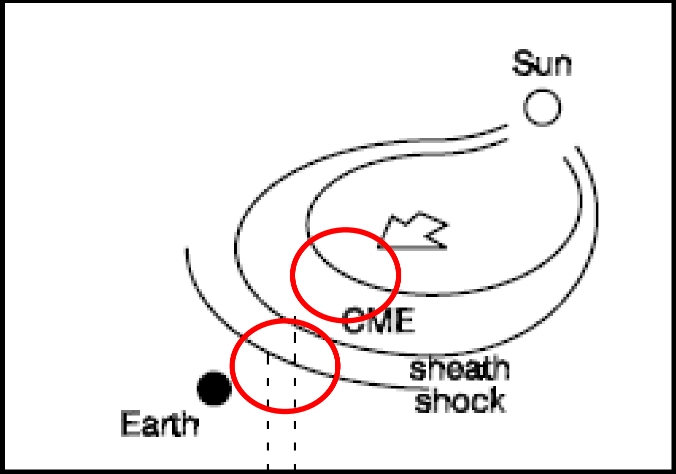


atmospheric pattern around Japan
(from Japanese Meteorological Agency)

CME-driven storms

CME (Coronal Mass Ejections):

Driver of main phase
: sheath
magnetic clouds



density

speed

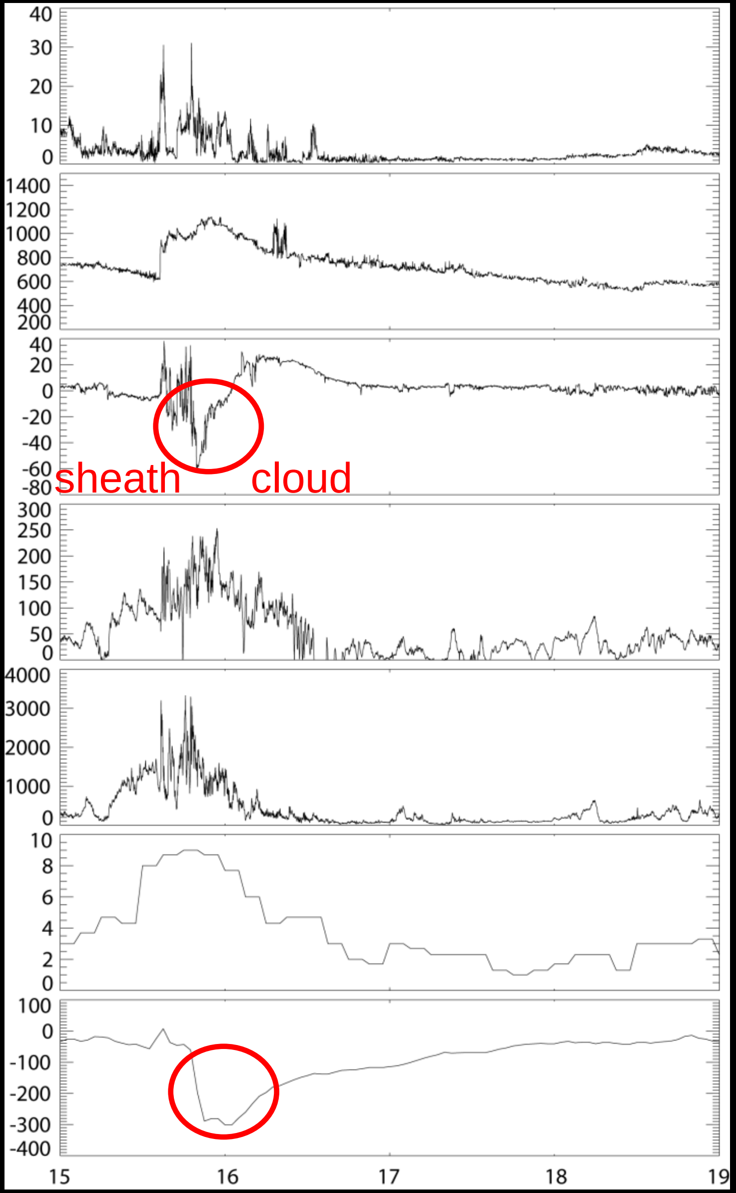
IMF Bz

Polarcap potential

AE

Kp

Dst

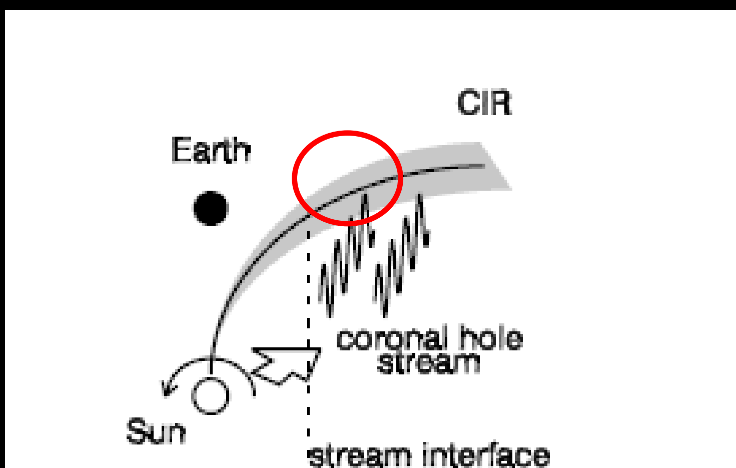


CIR and High Speed Coronal Hole Streams

CIR (Corotating Interaction Regions)

Driver of main phase

: corotating interaction region



density

speed

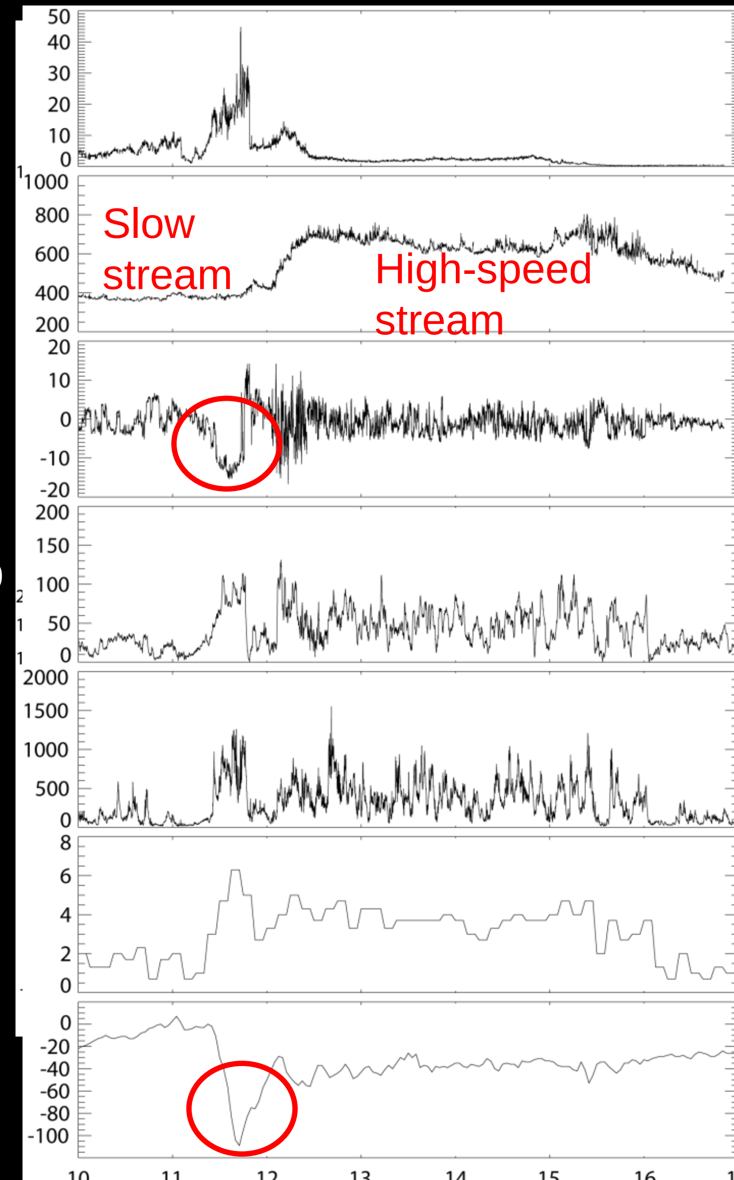
IMF Bz

Polarcap potential

AE

Kp

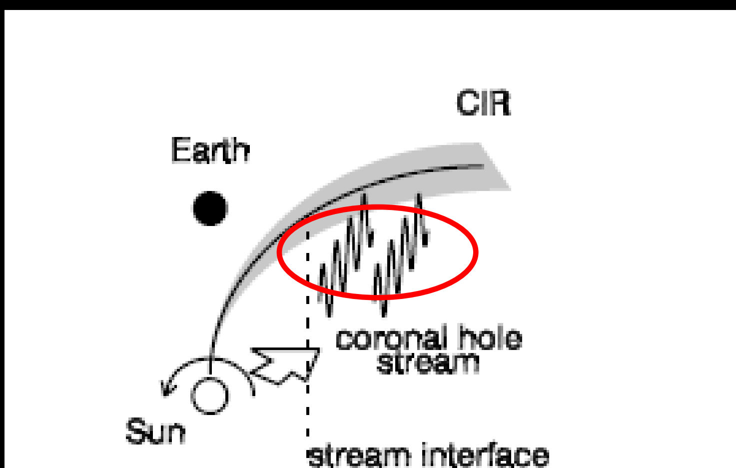
Dst



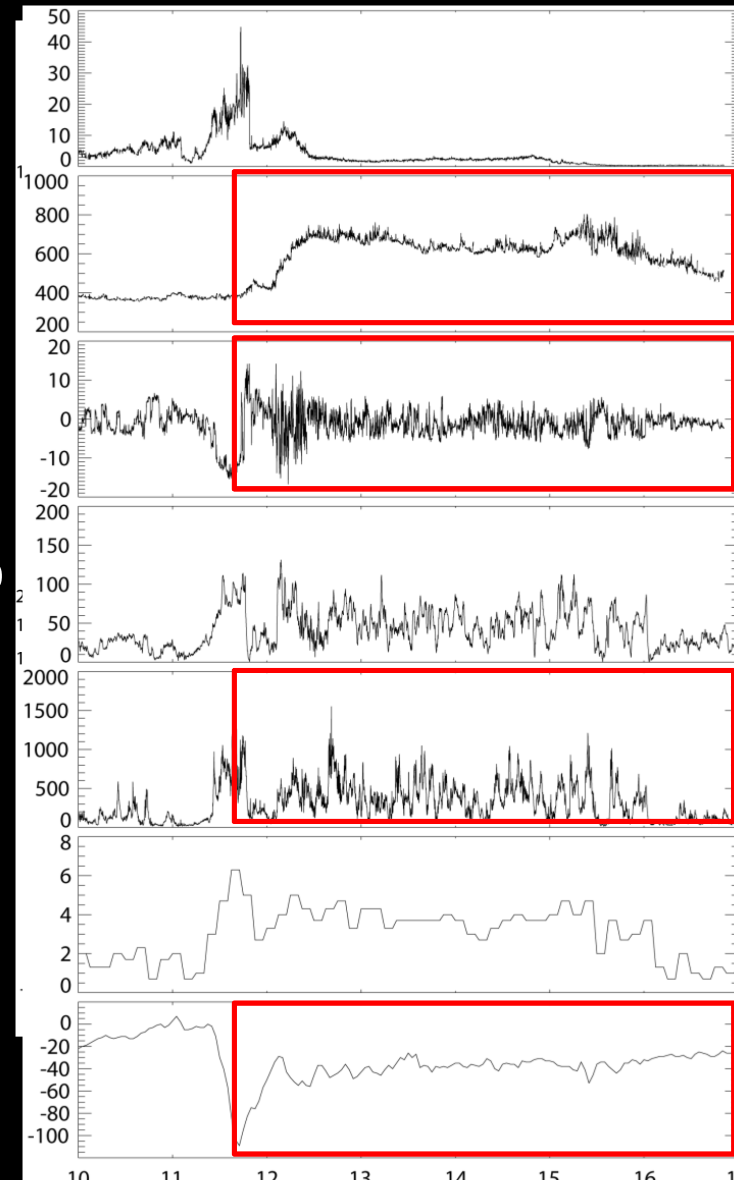
CIR and High Speed Coronal Hole Streams

High speed coronal hole streams
(recovery phase of CIR storms)

Alfvenic fluctuations are embedded
in high-speed coronal hole streams.

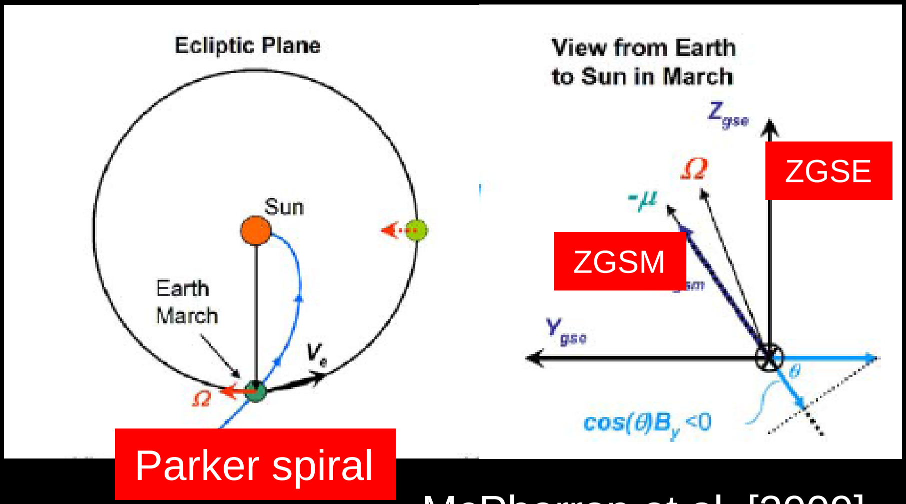


density
speed
IMF Bz
Polarcap
potential
AE
Kp
Dst



Russell-McPherron Effect

Spring-Toward Fall-Away rule

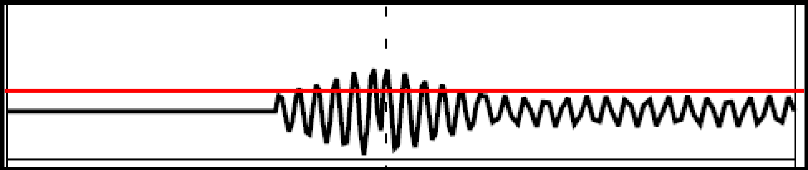


McPherron et al. [2009]

Toward sector polarity in Spring
→ southward IMF Bz

Away sector polarity in Fall
-> southward IMF Bz

Russell and McPherron [1973]



IMF By (GSE) projects to IMF Bz (GSM).

Geomagnetic activity tends to enhance in spring and fall.
(semi-annual variations)

If the coming coronal hole has toward (away) sector in spring (fall),
it is the best period to watch aurora.

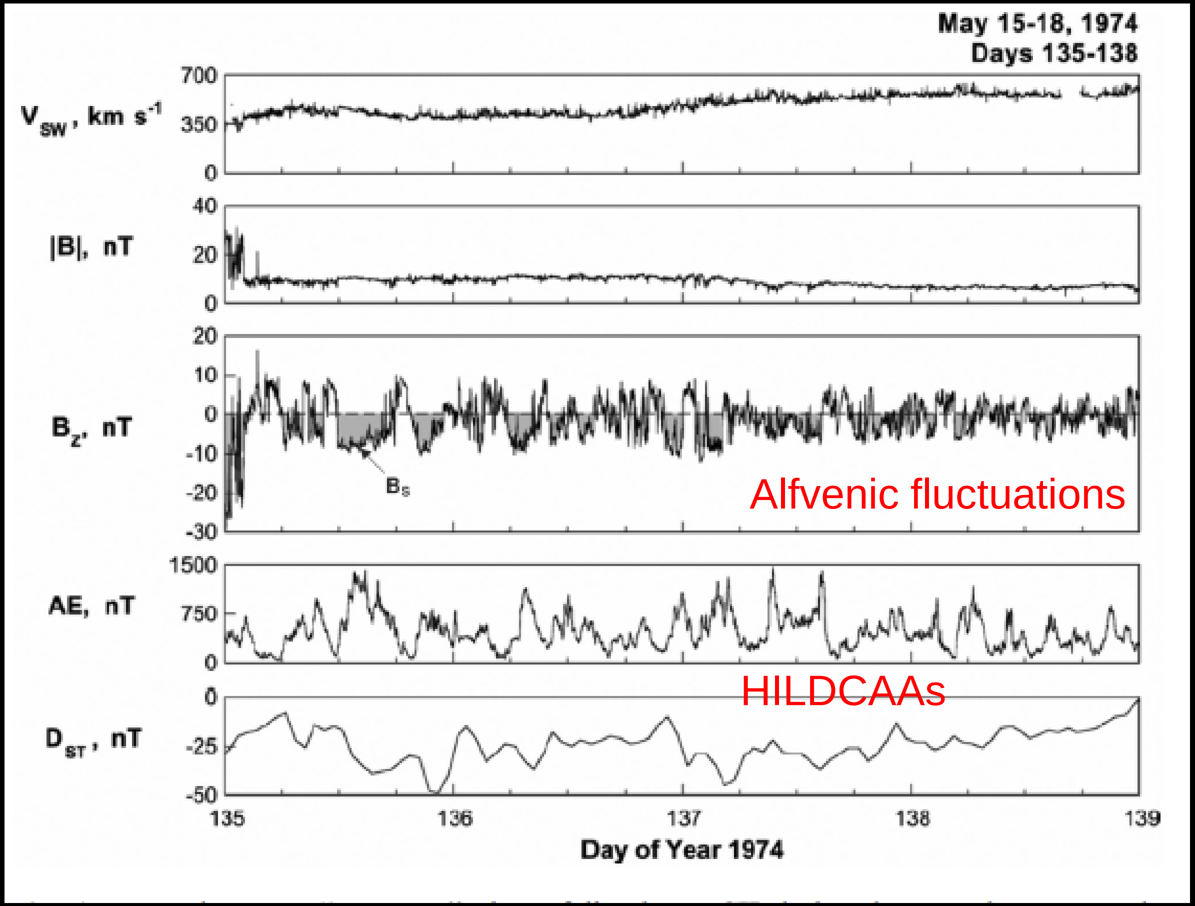
HILDCAAs (recovery phase of CIR-storms)

Solar wind speed

Bz

AE

Dst



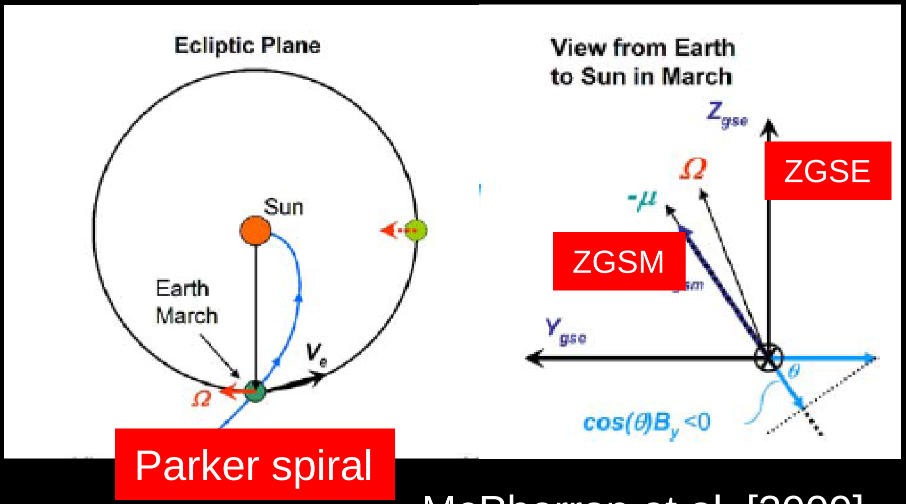
Tsurutani et al. [2006]

Alfvenic fluctuations cause continuous AE activity.

HILDCAA: (High Intensity Long Duration Continuous AE Activities)

many substorms occur; good period to watch aurora!

Russell-McPherron Effect



McPherron et al. [2009]

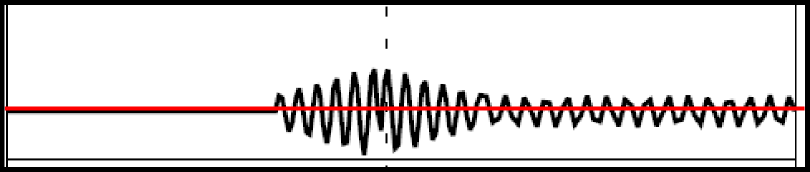
IMF By (GSE) projects to IMF Bz (GSM).

Spring-Toward Fall-Away rule

Toward sector polarity in Spring
→ southward IMF Bz

Away sector polarity in Fall
-> southward IMF Bz

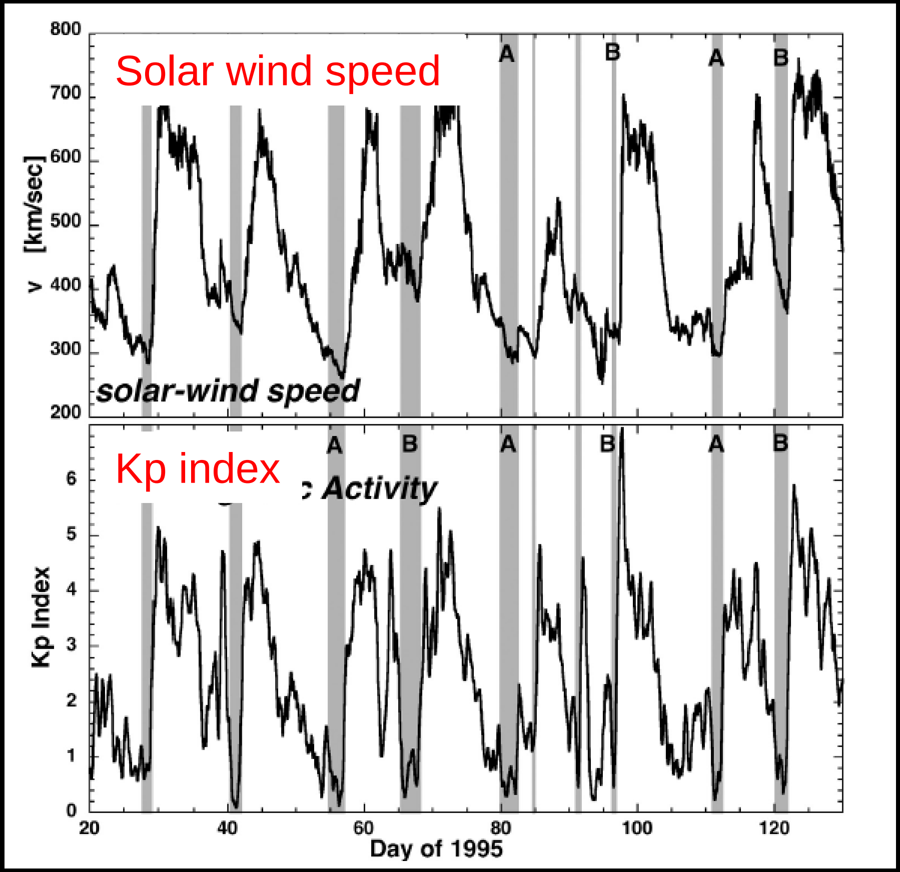
Russell and McPherron [1973]



Geomagnetic activity tends to enhance in spring and fall.
(semi-annual variations)

If the coming coronal hole has toward (away) sector in spring (fall),
it is the best period to watch aurora.

Calm-before-storms



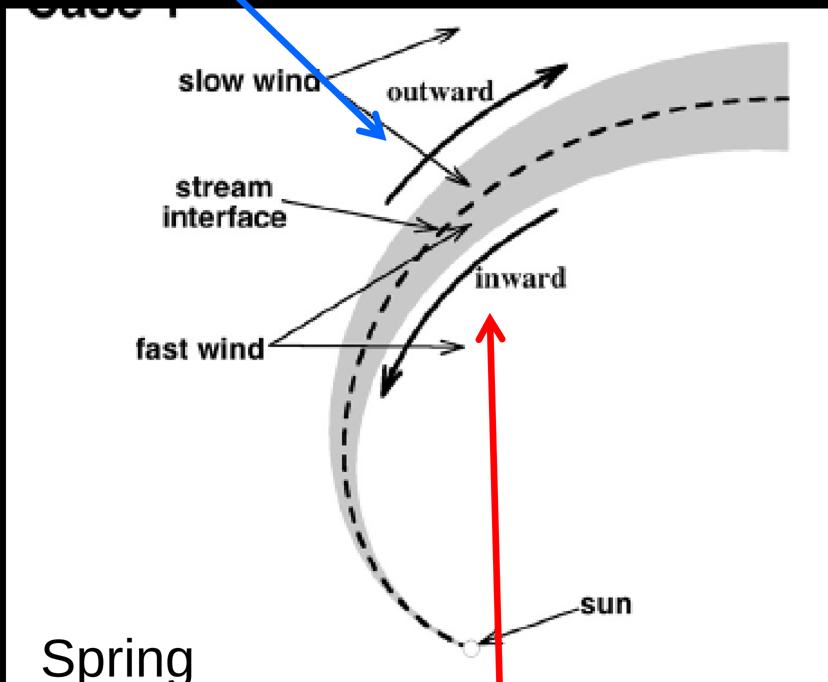
Borovsky and Steinberg, 2006

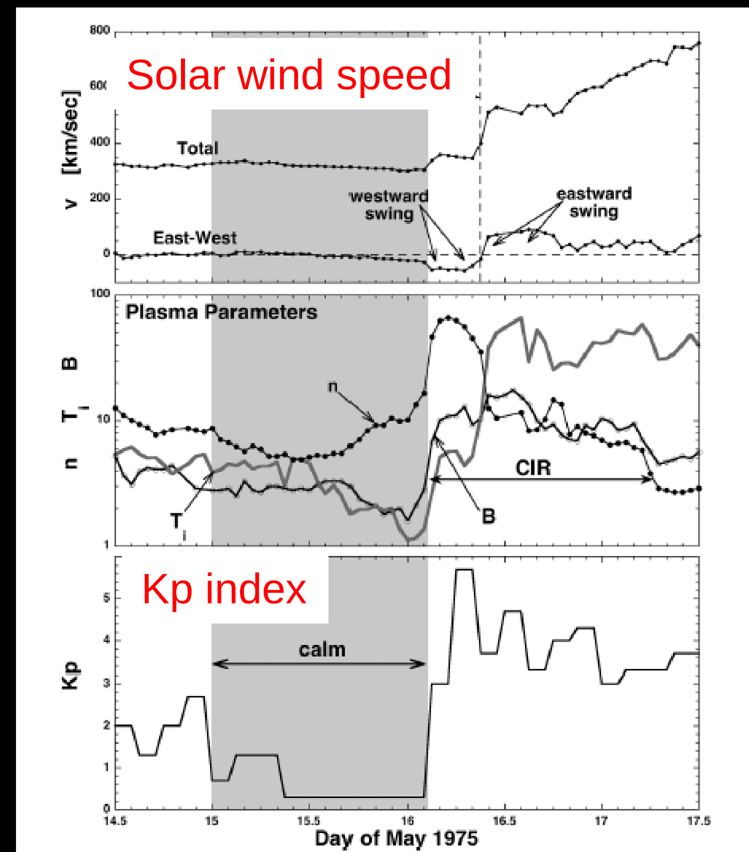
Just before CIR arrival, geomagnetic activity significantly becomes quiet (Kp < 1).

Calm before storms

Calm-before-storms

Russell-McPherron effect
supreses geomagnetic activity.

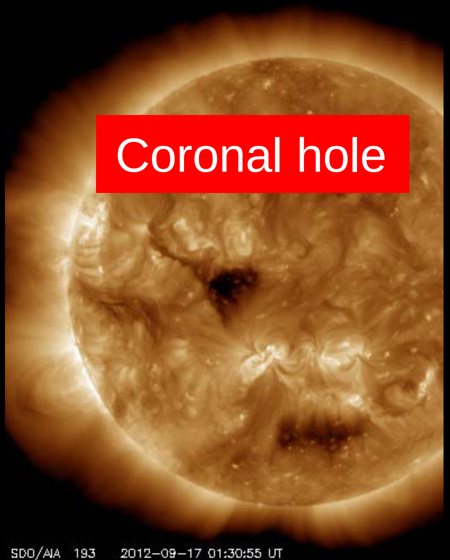


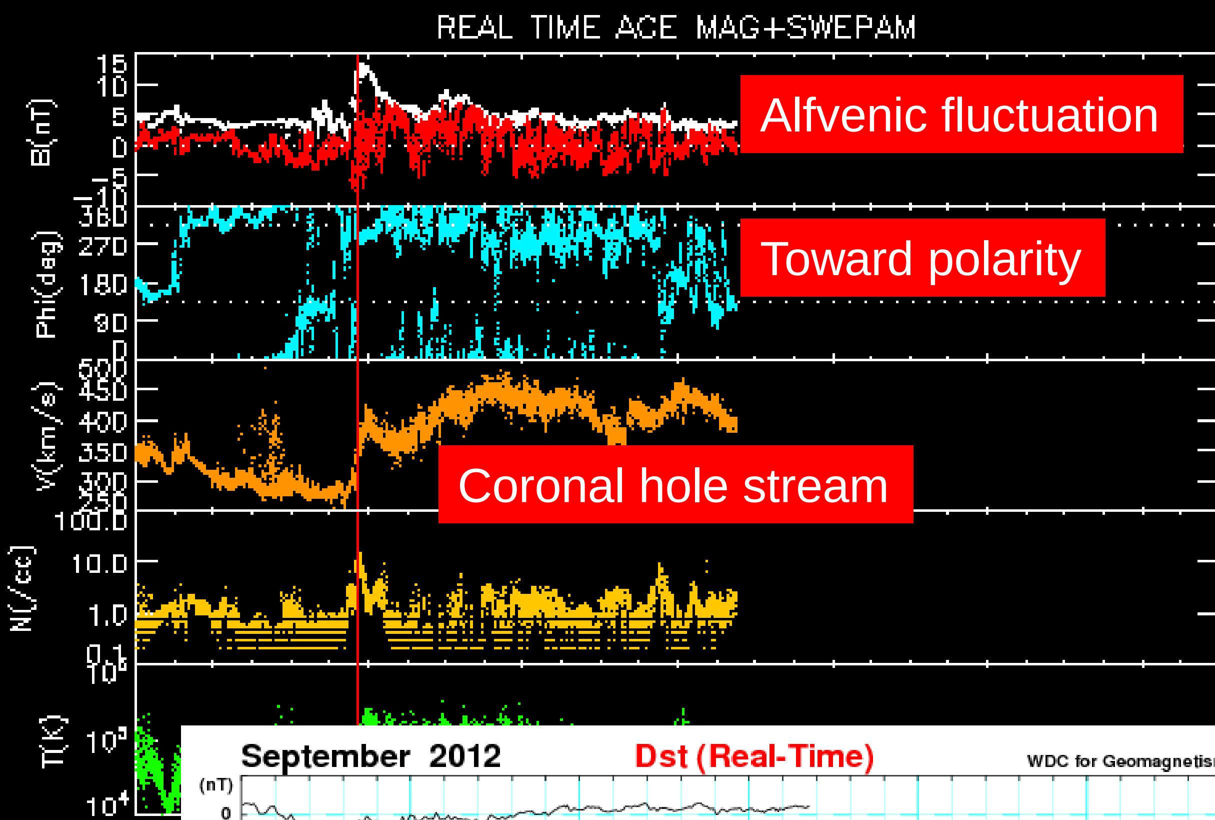


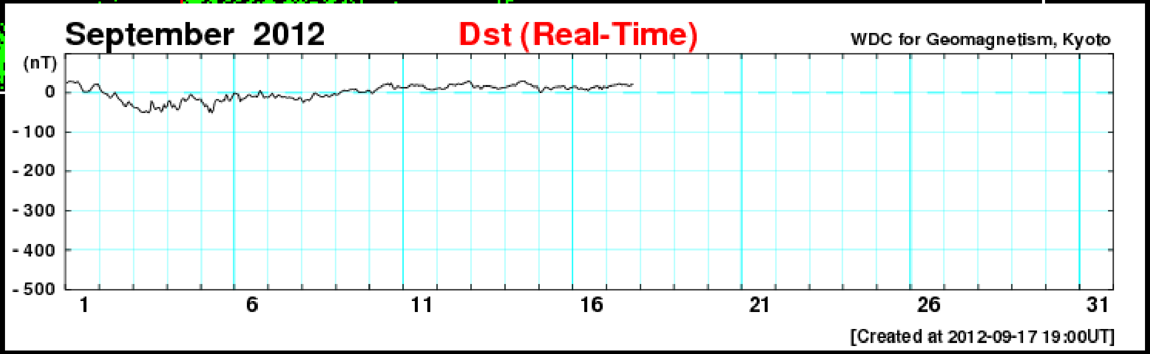
Russell-McPherron effect
 enhances geomagnetic activity.

Borovsky and Steinberg, 2006

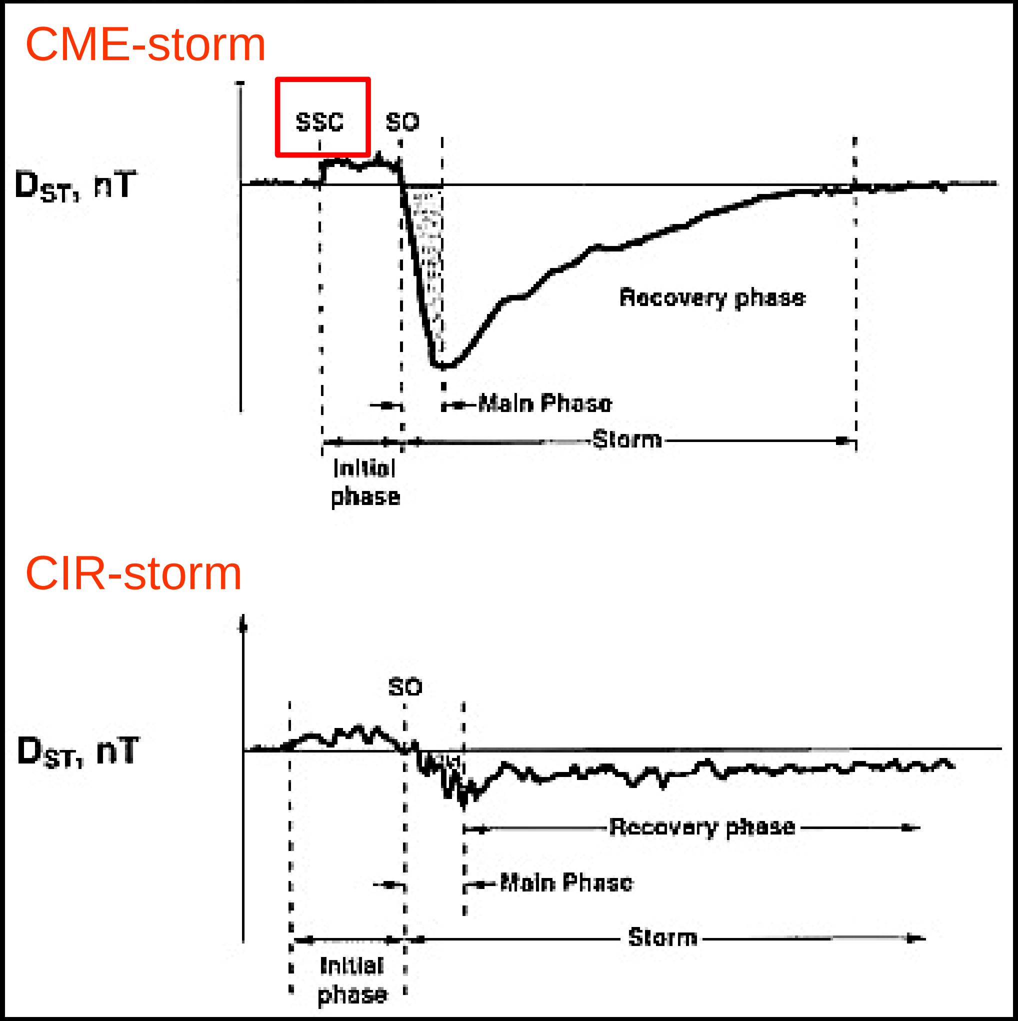
Today's solar wind







Different evolutions of CME/CIR storms

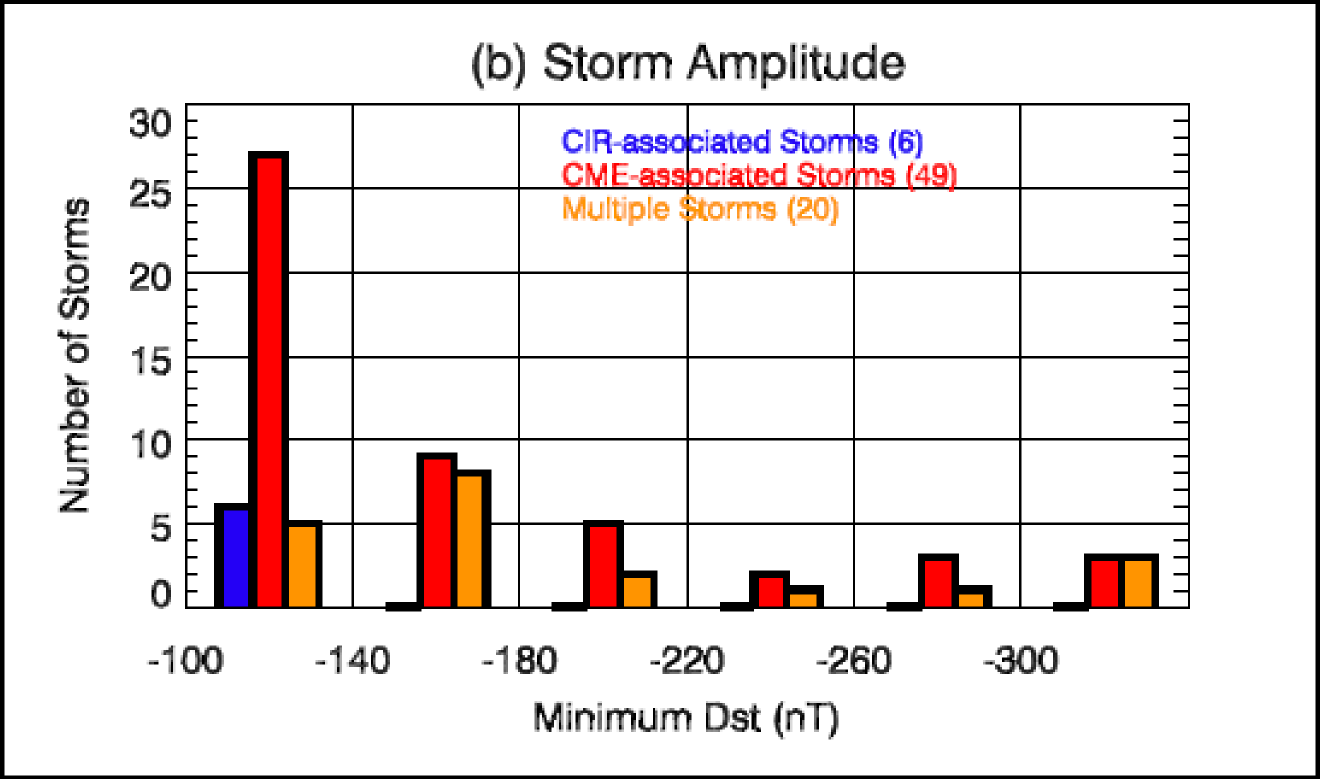


-Intense main phase
-Recovery phase has
a decay time of ~10 hours

-Weak/moderate main phase
-Recovery phase has
a long decay time accompanied
with HILDCAAs

Tsurutani et al. [2006]

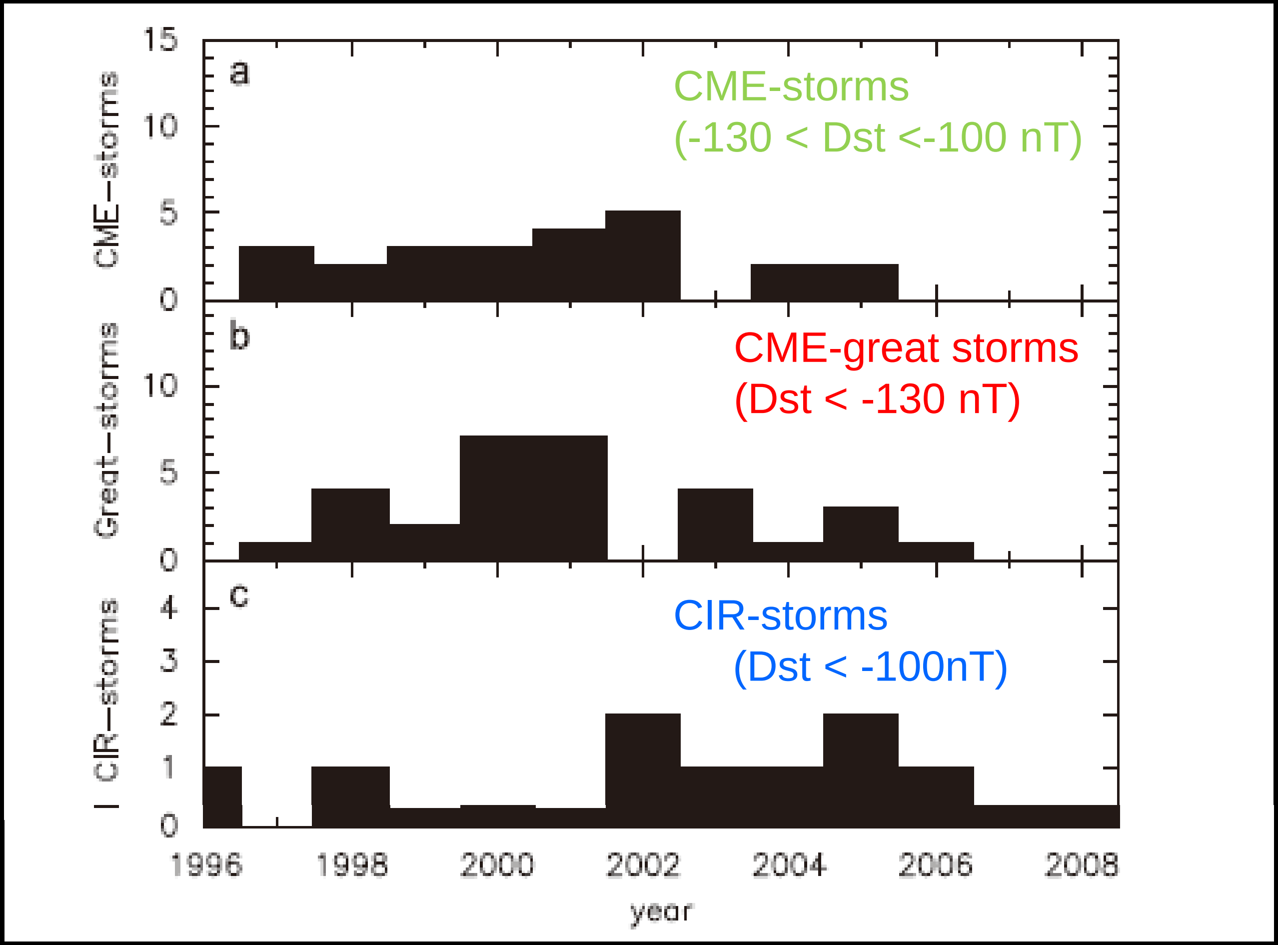
Differences on storm amplitude



Kataoka and Miyoshi [2006]

All magnetic storms less than -150 nT are driven by CME-storms.

Different occurrence during solar cycle



Miyoshi and Kataoka [2011]

CME storms tend to occur during solar maximum,
while CIR storms tend to occur during solar declining phase.

How different evolutions of RC/RB between CME and CIRs?

our recent studies

superposed epoch analysis on solar wind

ring current

radiation belts

Average solar wind profile of CIR/CME storms

✱ CIR storms –

The solar wind speed is the fastest during the recovery phase, i.e., coronal hole streams.

Large amplitude Alfvenic fluctuations within CHS cause HILDCAAs in the magnetosphere.

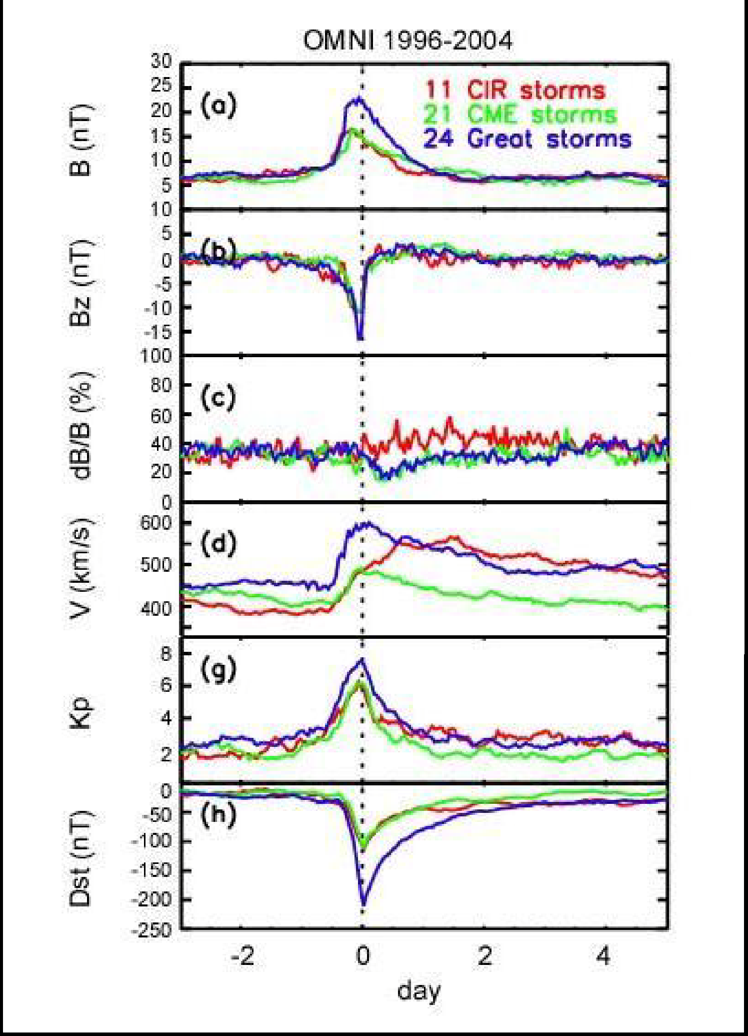
The Dst index remains small during the recovery phase.

✱ CME storms/Great storms –

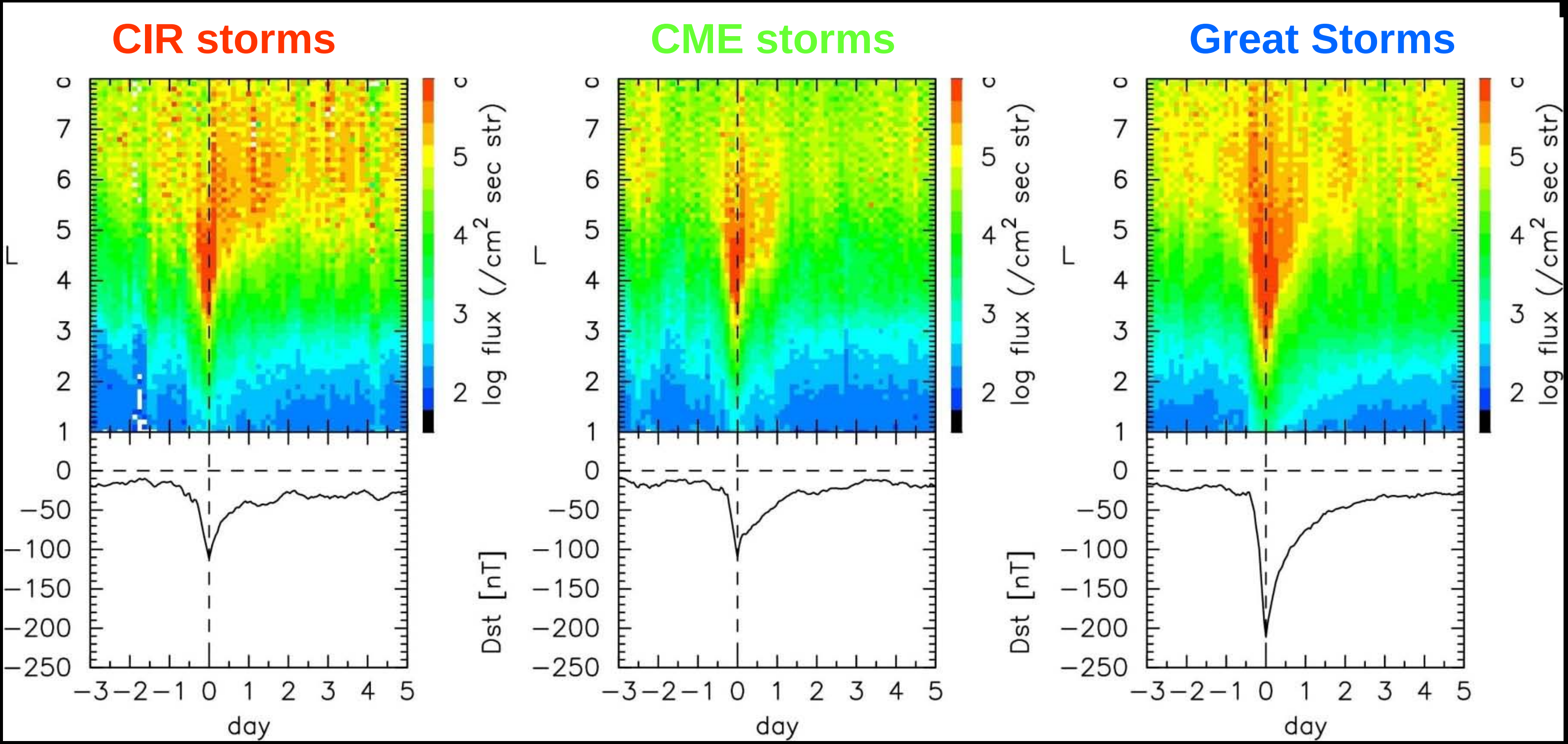
The solar wind speed is the fastest during the main phase.

The amplitude of southward Bz is the strongest during the great-storms.

The Dst index recovers uniformly during the recovery phase.



Differences on ring current evolution (30 keV ions)



Miyoshi and Kataoka [2005]

- During the main phase, hot ions come from the plasma sheet and the flux increases at L=3 to 5.
- The most intense flux enhancement occurs during CME-driven great storms.
- During the recovery phase of CIR-storms, hot ions are continuously injected from the plasma sheet, suppressing the Dst index. These injections are associated with HILDCAAs driven by Alfvenic fluctuations.

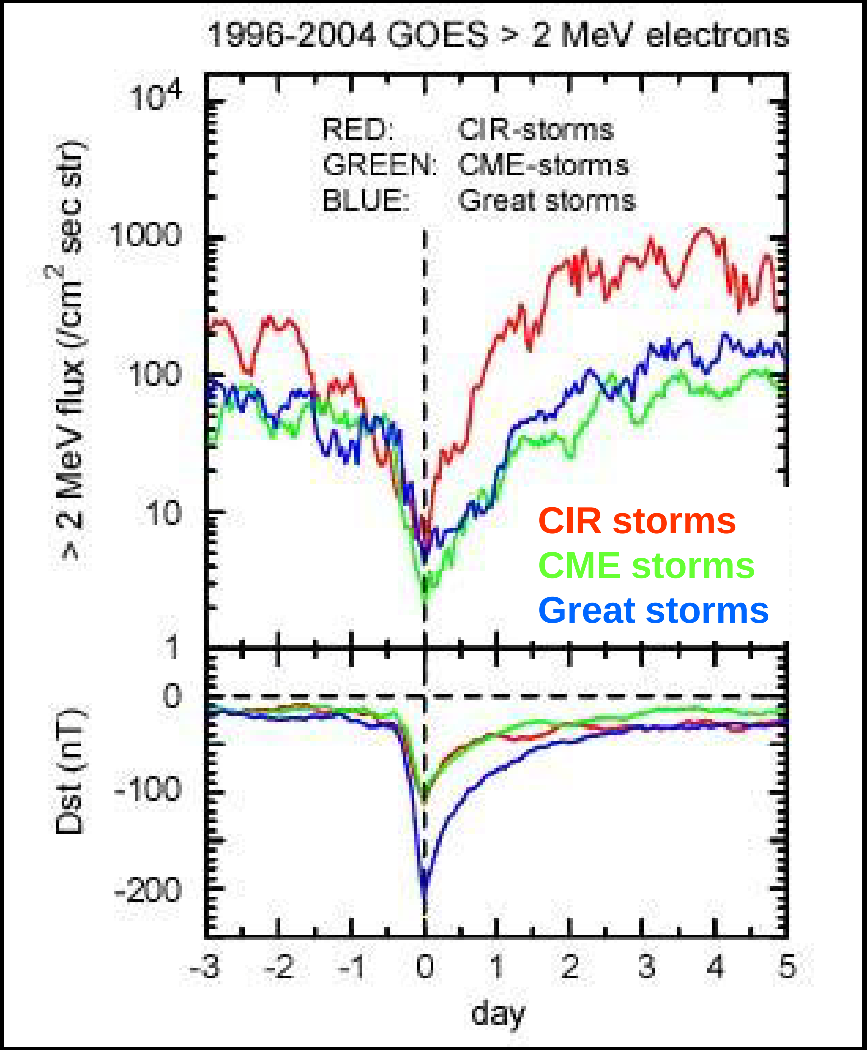
Differences on radiation belt electrons at geosynchronous orbit

In CIR-storms
The recovery and enhancement are faster and stronger than in both CME- and great-storms.

In CME-storms
The flux recovers gradually and reaches to the pre-storm level at t=2.0days.

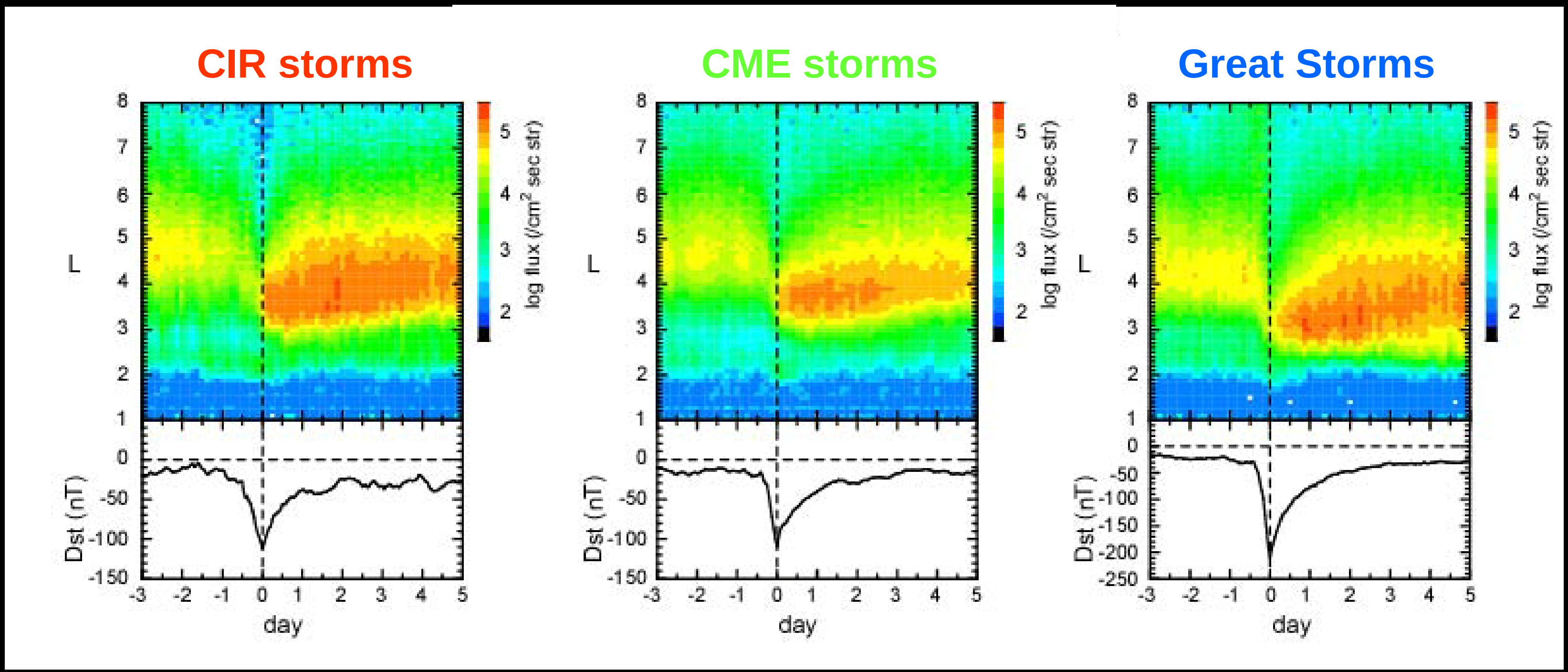
The most effective structure for the flux enhancement at GEO is
not CMEs but CIRs.
The flux increases at GEO are
not correlated with the storm size.

GOES > 2 MeV electron



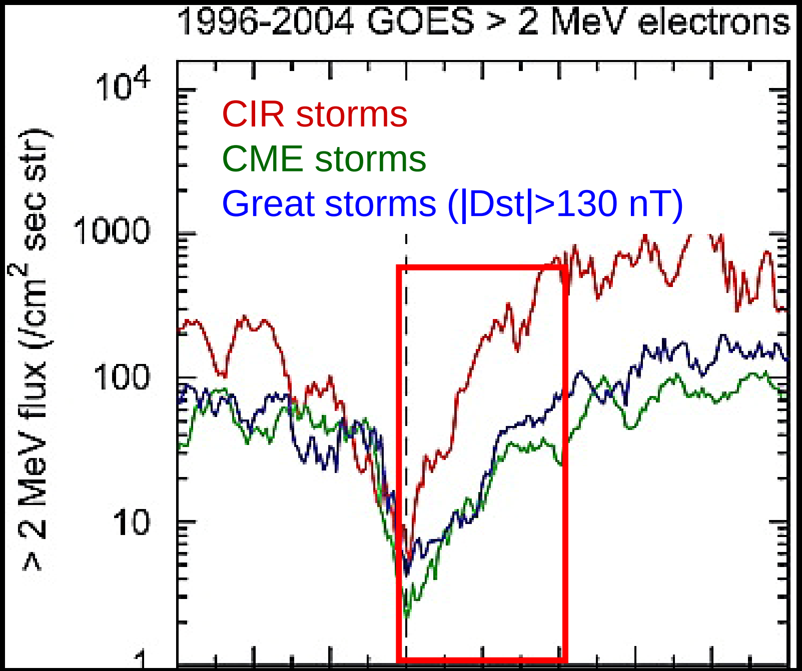
Miyoshi and Kataoka [2005]

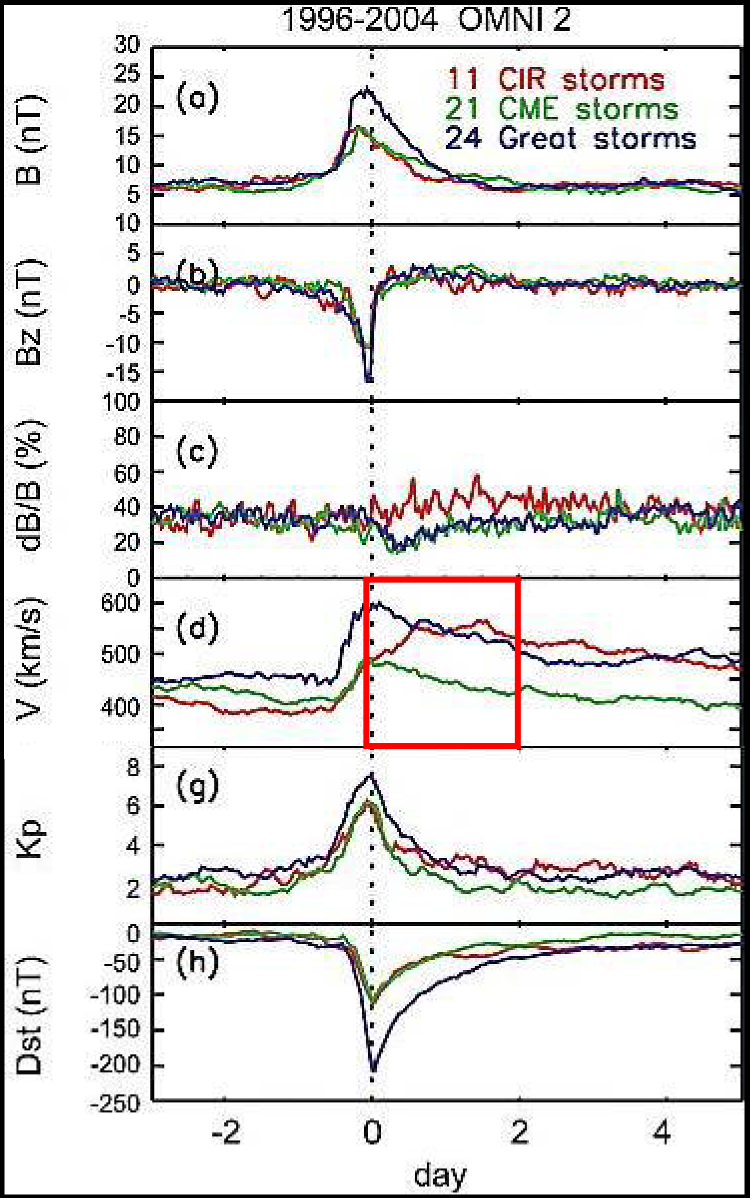
Differences on radiation belt electrons (300 keV electrons)



- The outer region (L>3.5) – CIR-storms cause the most intense flux enhancement.
- The inner region (L<3.5) – CME-driven great storms cause the most intense flux enhancement.
  The outer radiation belt moves toward the earth.

What is the main driver for the evolution of the outer belt?

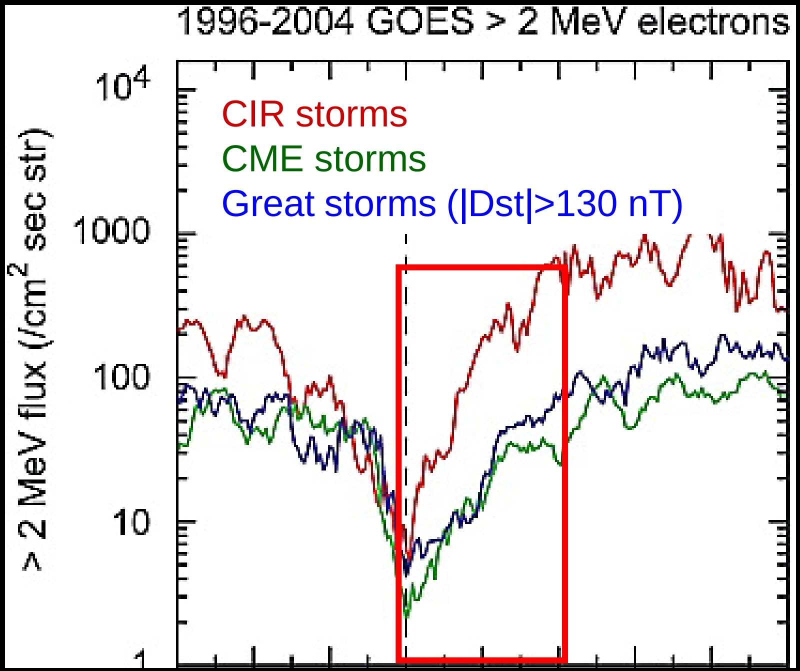


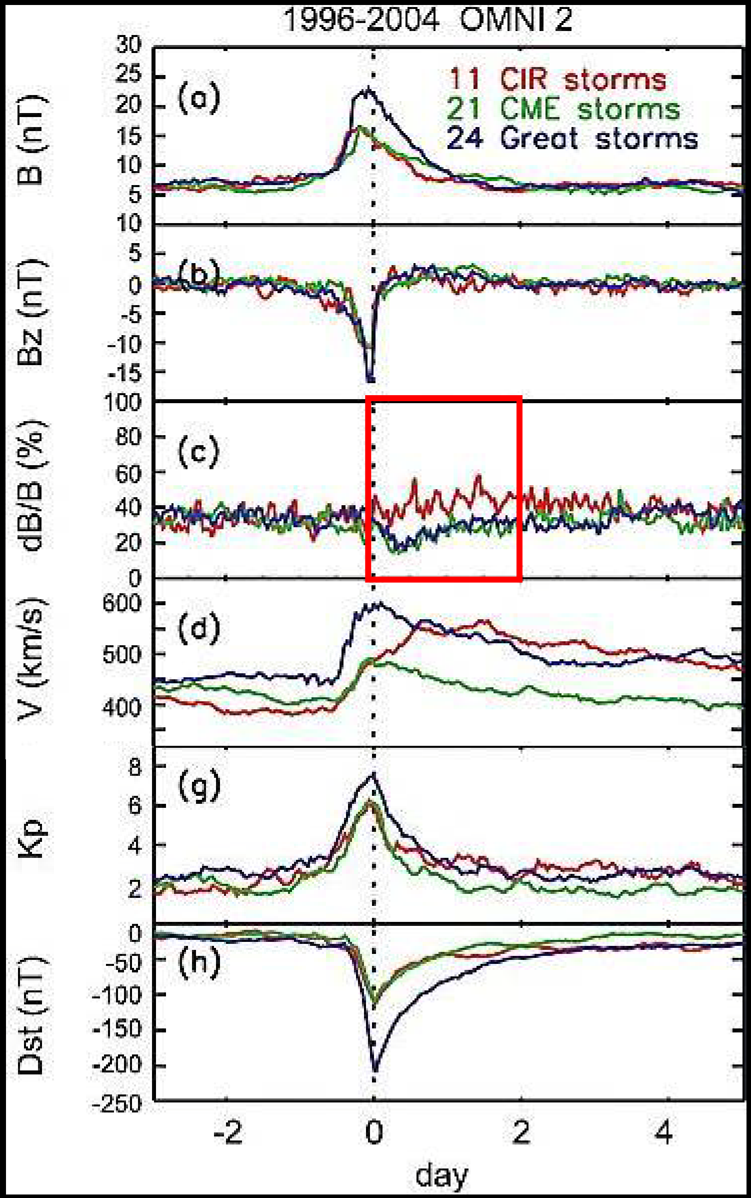


The solar wind speed of CIR storms is smaller than or comparable to that of great storms, but the greatest flux enhancement is found in CIR storms.

Only the high-speed solar wind is not a sufficient condition for the flux enhancement.

What is the main driver for the evolution of the outer belt?





The fluctuation level of IMF is small in CME-storms, while is about twice in CIR-storms.

Such fluctuation is effective for the evolution of the outer belt through HILDCAAs in the magnetosphere.

The flux enhancement of the outer belt associated with CIRs

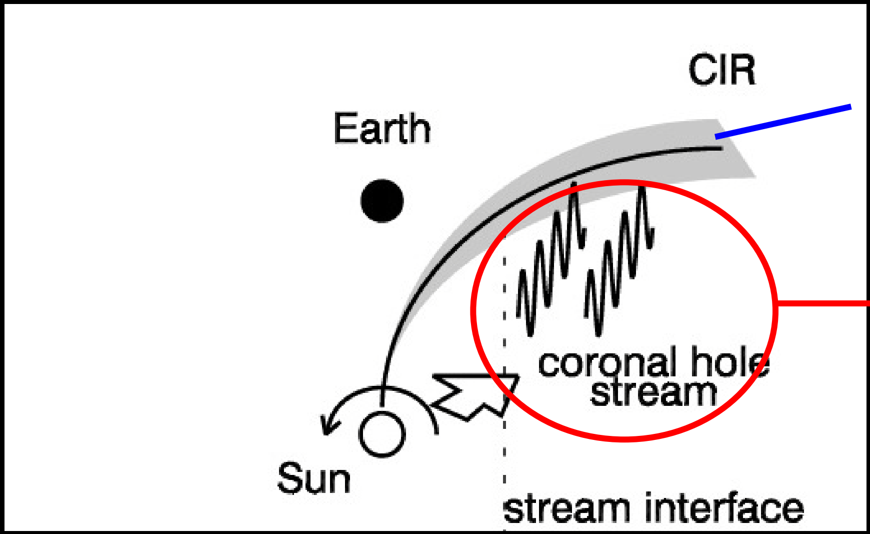
<solar wind>
Alfvenic fluctuation within CHS

<magnetosphere>
HILDCAAs (substorms)

<inner magnetosphere>
outer belt enhancement

The evolution of the outer belt strongly depends on the Russell-McPherron effect.

Alfvenic fluctuations with small southward offset given by Russell-McPherron effect control the HILDCAAs activity

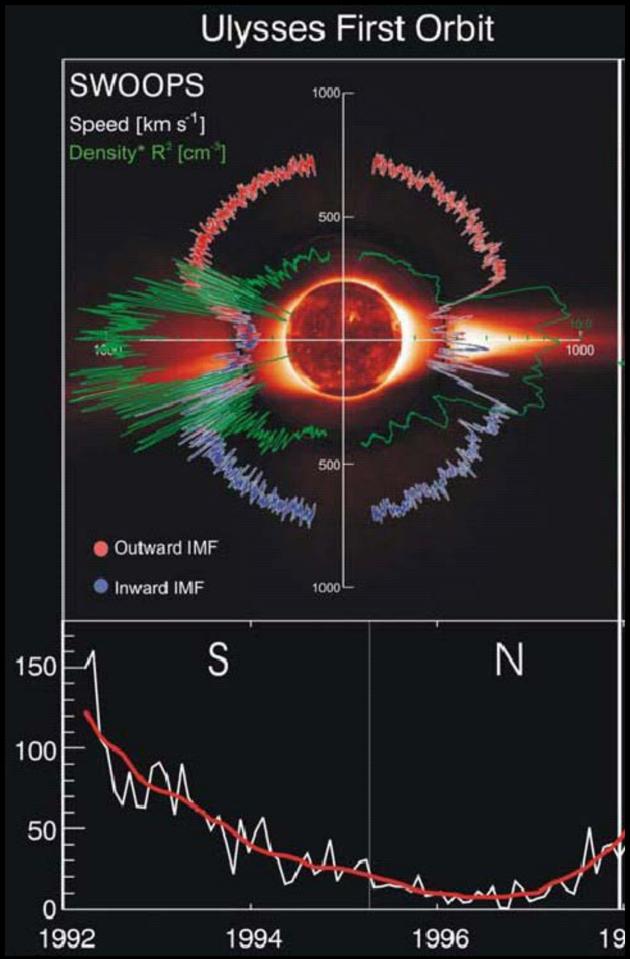


Intense southward IMF
Driver for storm main phase

Effective for
outer belt enhancement

Miyoshi et al.[2007], Miyoshi and Kataoka [2008, 2011]

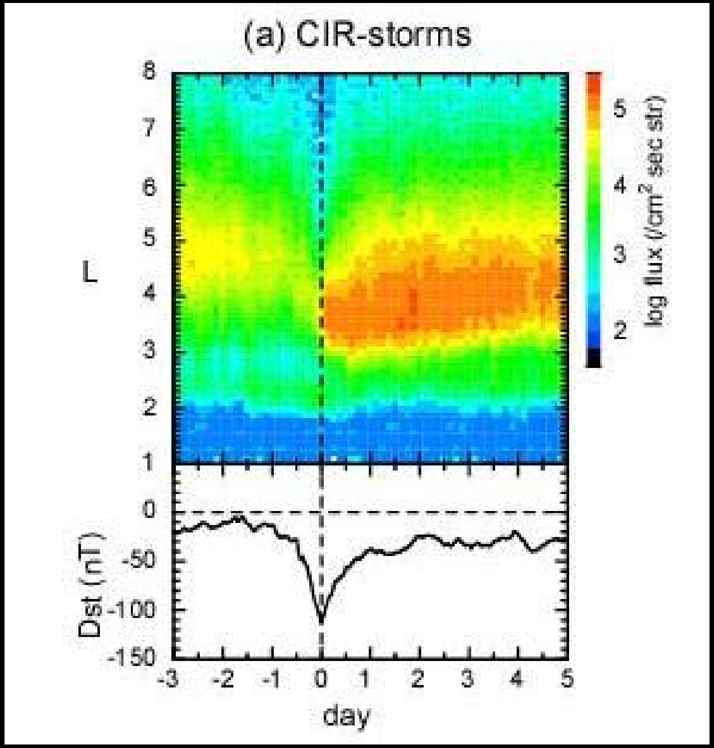
Solar Cycle Variation of the Radiation Belts

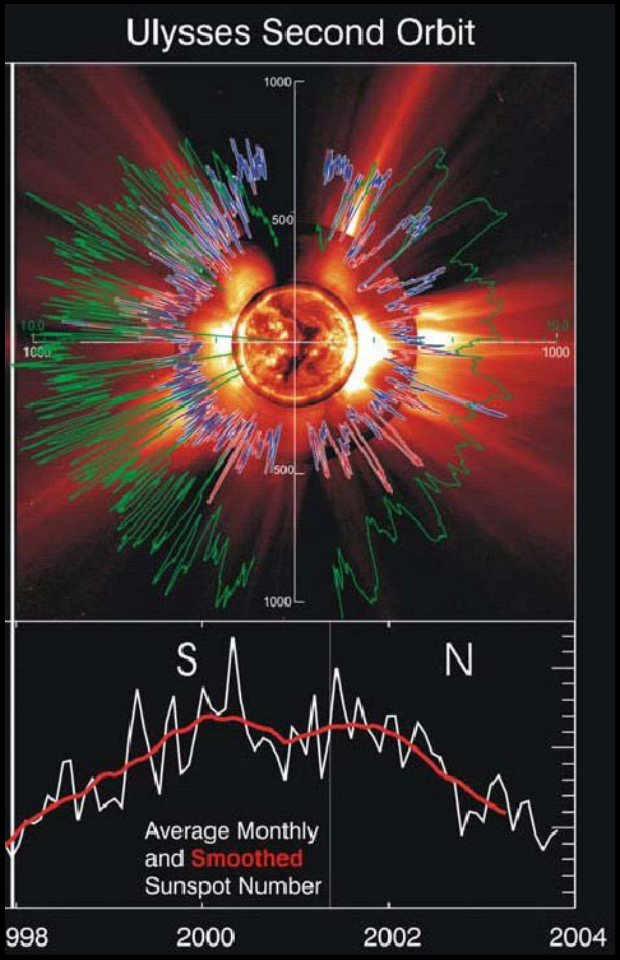


Zhang et al. [2005]

solar- declining phase ~ minimum

There are number of CIR-storms which cause strong flux enhancement in the outer belt.

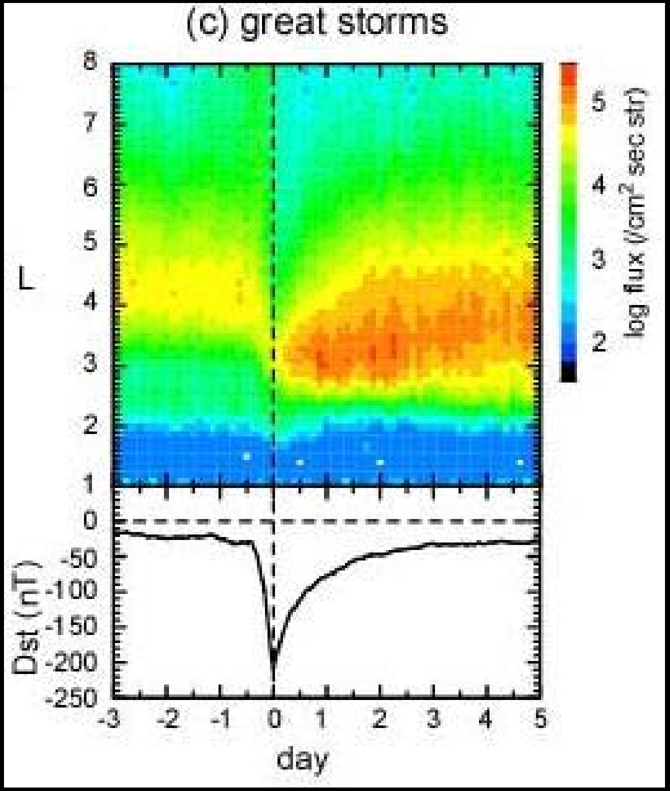




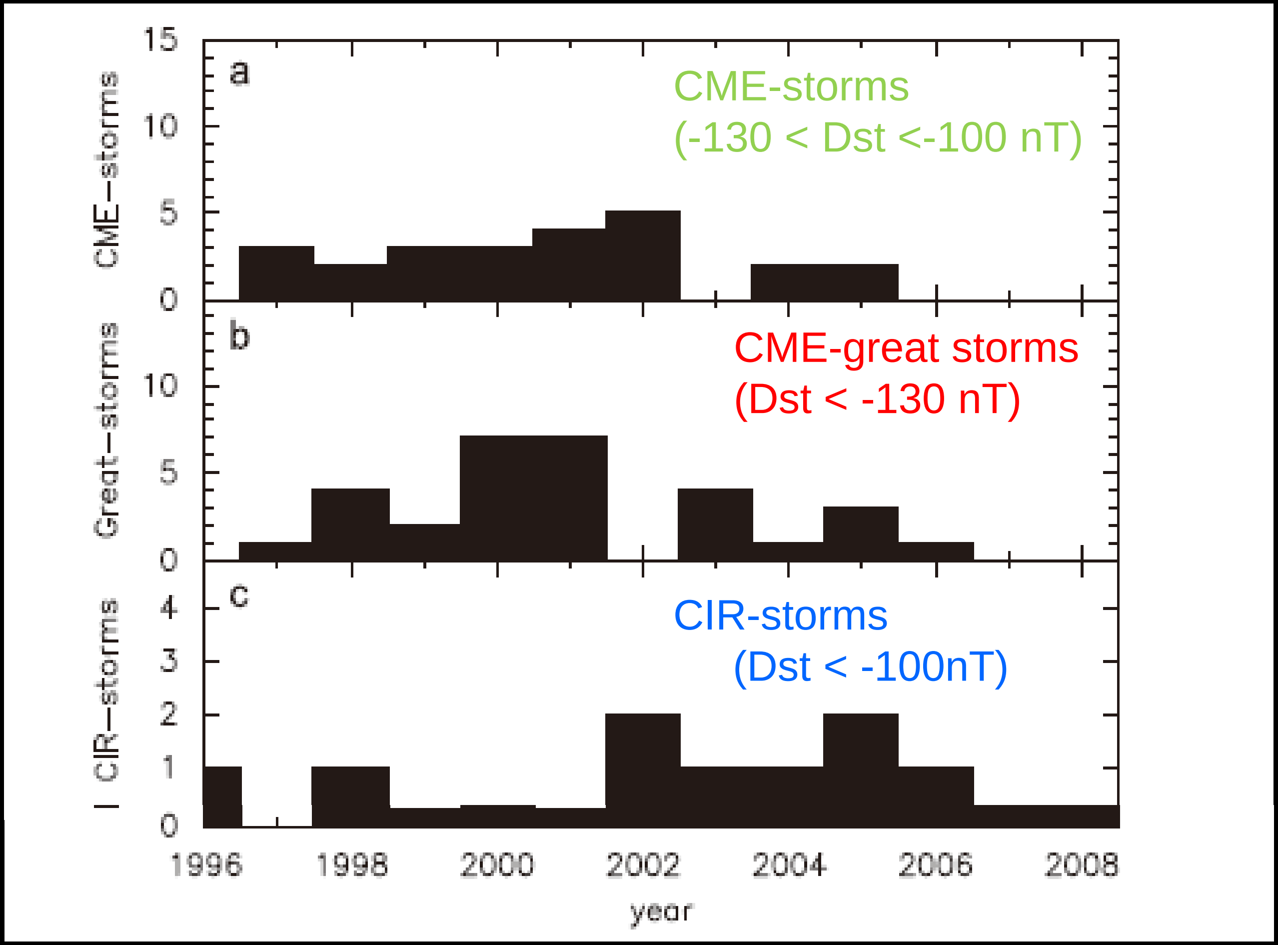
Zhang et al. [2005]

solar-maximum

There are number of CME-storms which cause flux enhancement at the inner portion.



Different occurrence during solar cycle



Miyoshi and Kataoka [2011]

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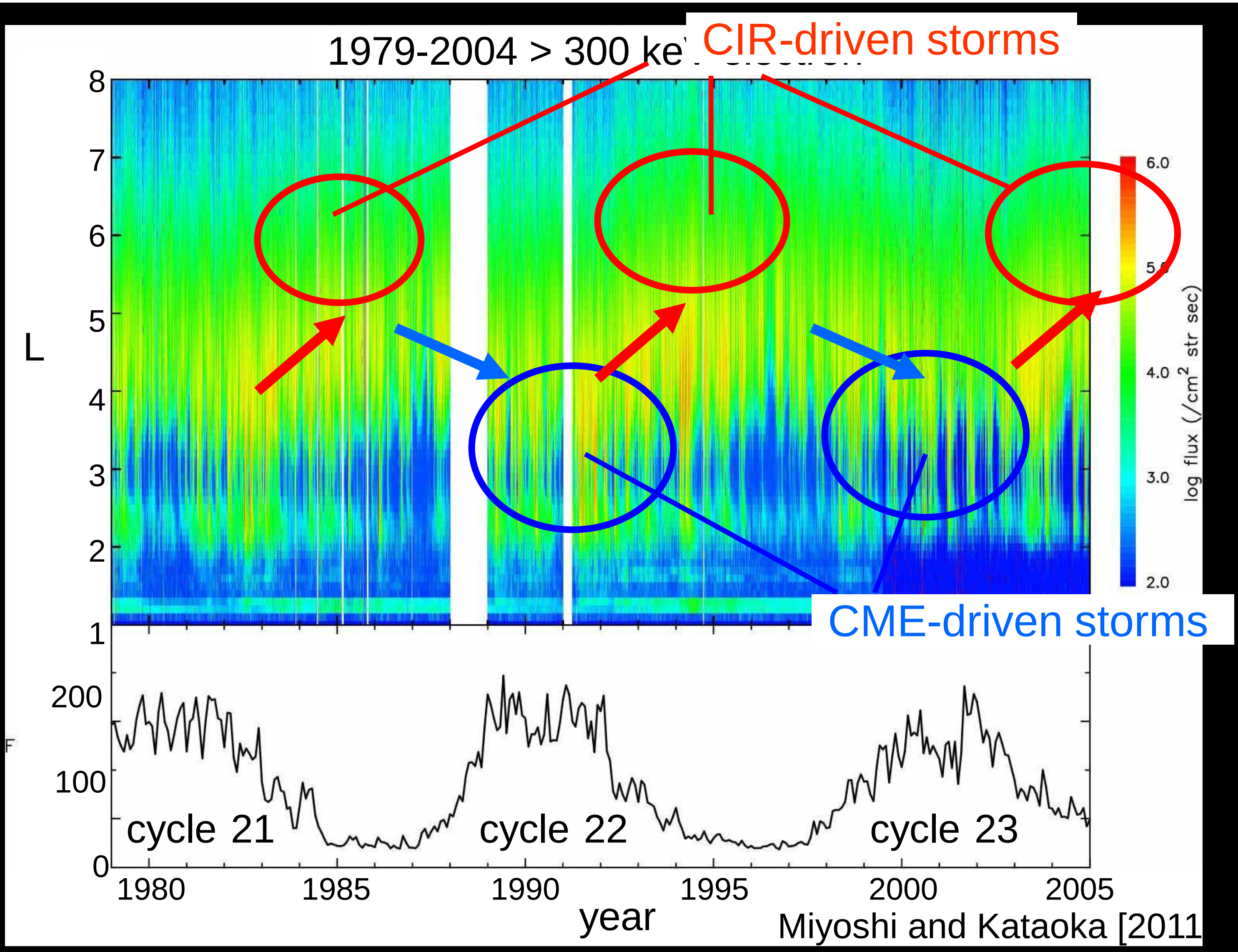


Difference of storm-driver sources during solar cycle produces the long-term variation of the radiation belt structures.

Unusual solar wind / radiation belts of cycle 24

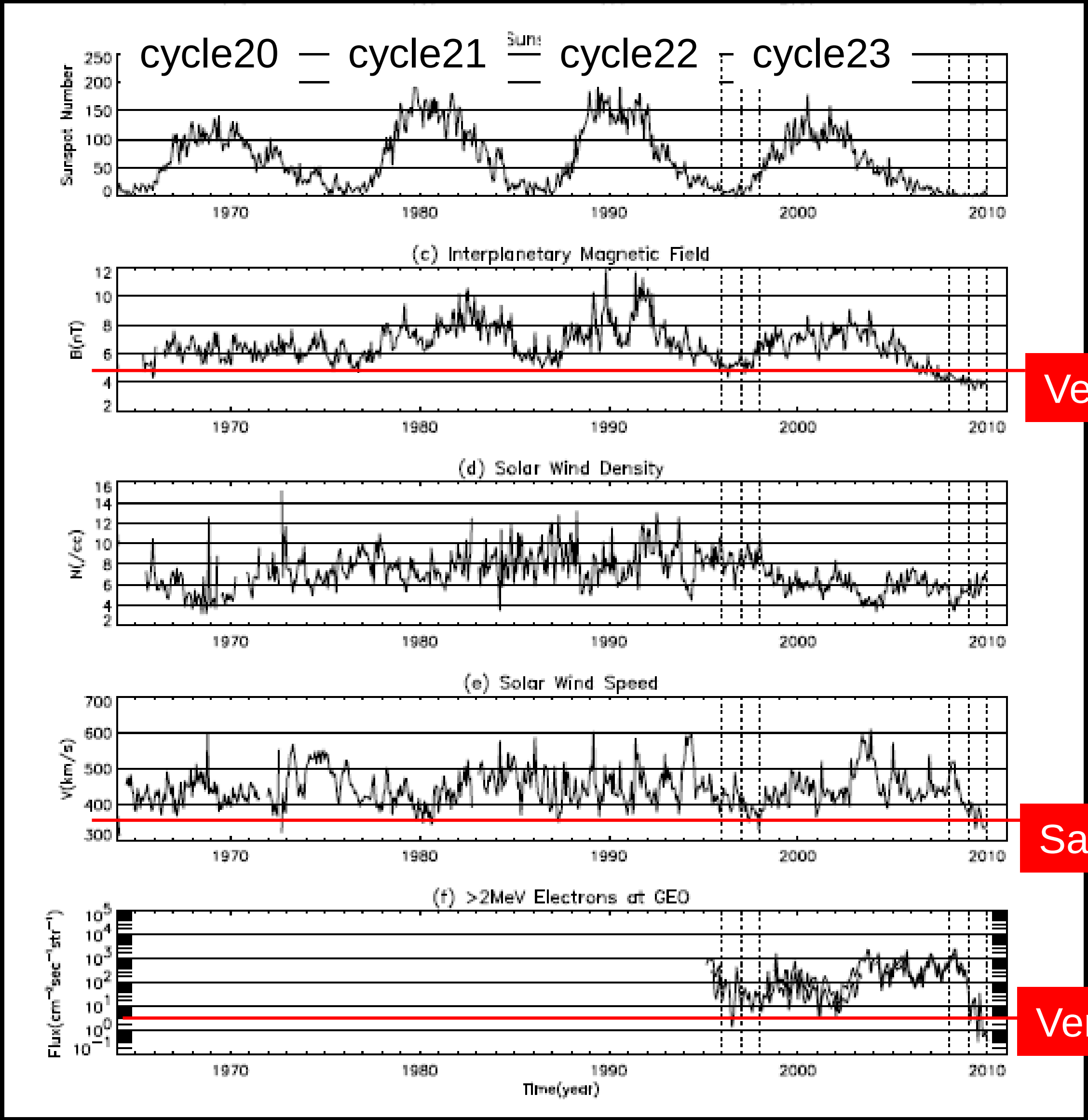
Sunspot number

IMF

Solar wind density

Solar wind speed

MeV electrons



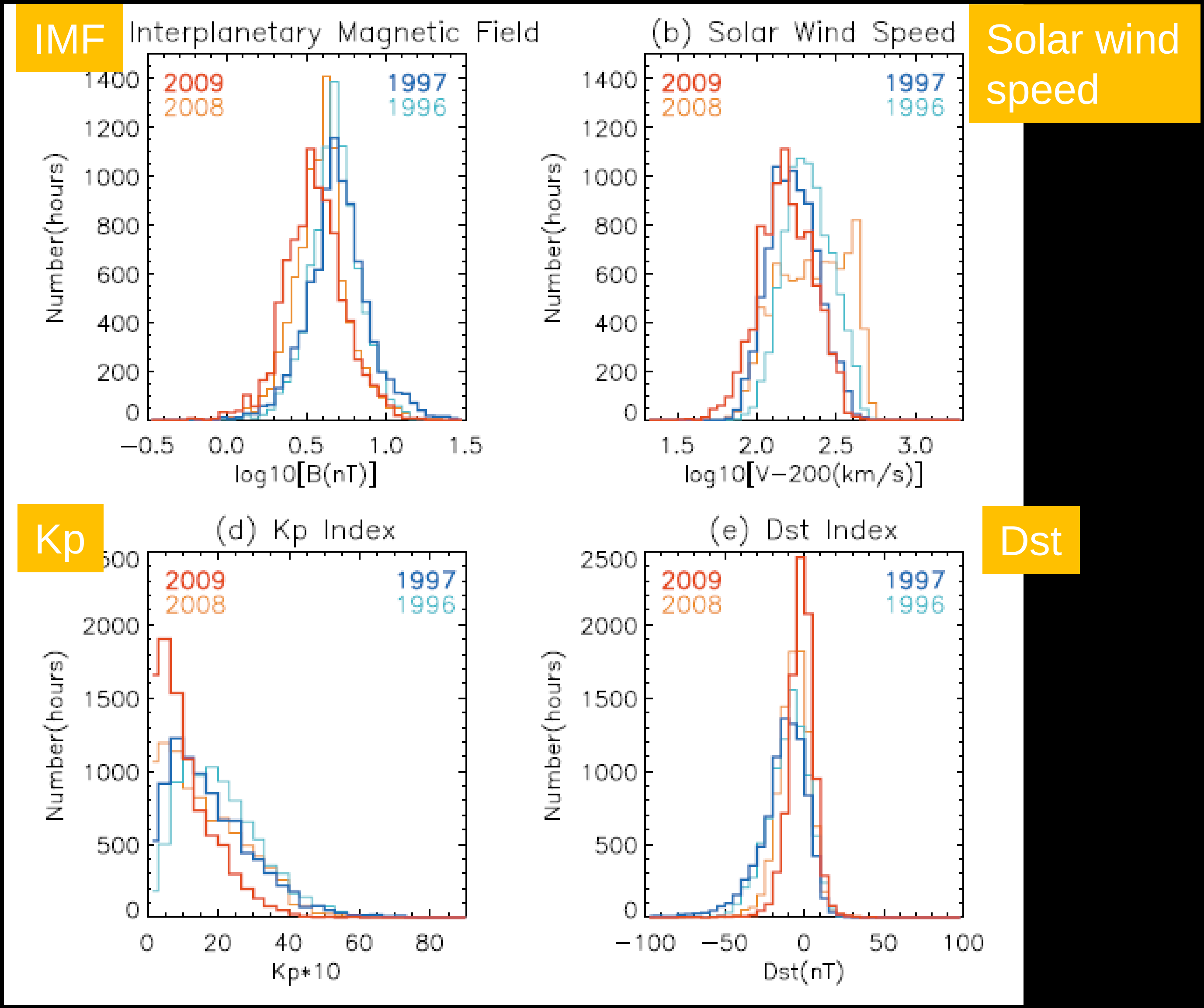
Very small

Same as 1997

Very small

Kataoka and Miyoshi [2010]

Unusual solar wind / radiation belts of cycle 24



Kataoka and Miyoshi [2010]

Summary

Parameter dependences :

- substorms :	southward IMF
- storms (ring current):	intense duskward electric field
- radiation belts :	solar wind speed or southward IMF

Summary

Structure depedence:

- CMEs -- large magnetic storms
- CIRs (high speed streams) -- large flux enhancement in the outer belt.

Alfvenic fluctuations of high speed stream is too weak to drive storms but very important to cause the enhancement of the outer belt.

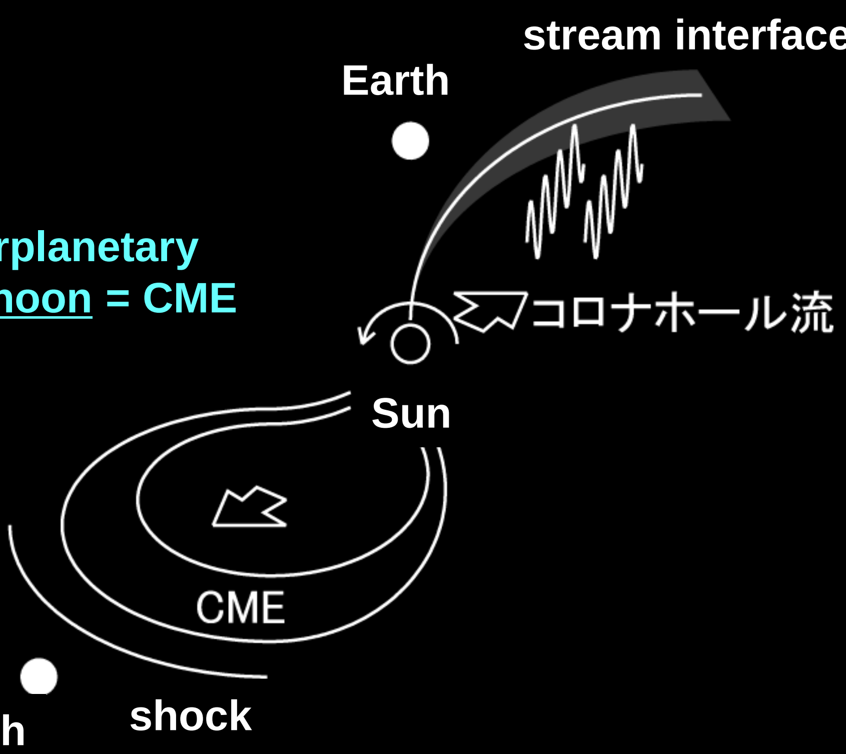
Summary

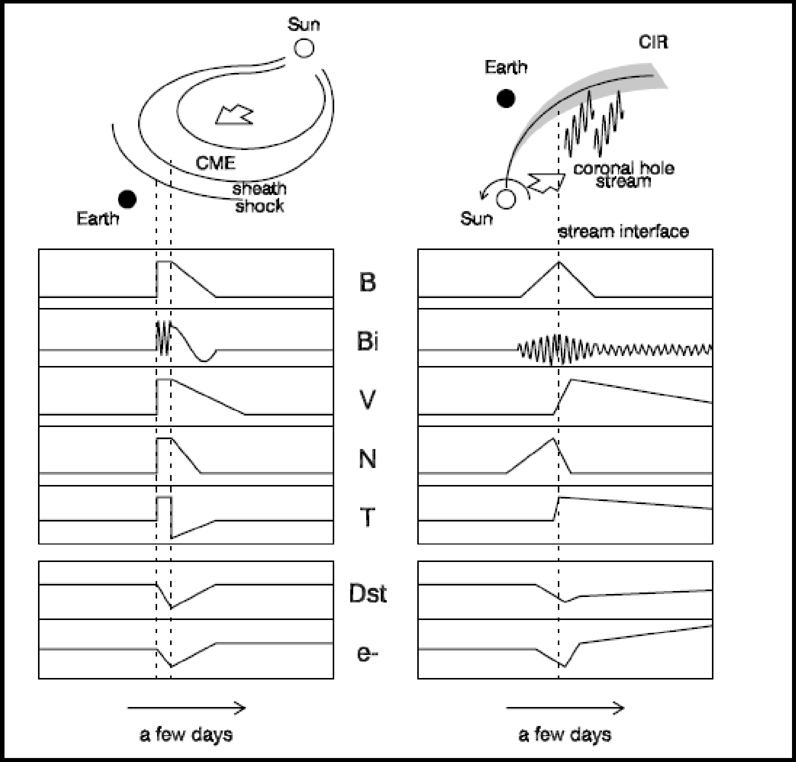
Importance of interplanetary air mass concept:

It is very difficult to predict IMF Bz, solar wind speed accuracy.
However, the prediction on the large scale structure CIR, CMEs are possible.
Understanding the average responses of ring current/radiation belts on large scale structures are essential for the space weather forecast.

Interplanetary <u>Cold Front</u> = CIR

Interplanetary <u>Typhoon</u> = CME





Summary

Unusual solar wind during solar cycle 24

Our knowledge on the solar wind –magnetosphere coupling depends on past data since 1960. If unexpected solar wind comes to the Earth, something will happen that we have never expected.

We have to watch the solar wind – magnetosphere coupling process in this solar cycle.

Thank you very much for your attention.