

Space weather effects and how they cause geomagnetic storms and substorms

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Goals for this lecture

- Goal 1: Understand differences between substorms and geomagnetic storms.
- Goal 2: Understand how energy circulates in the magnetosphere.
- Goal 3: Learn to compute substorm energy input from solar wind into the magnetosphere.

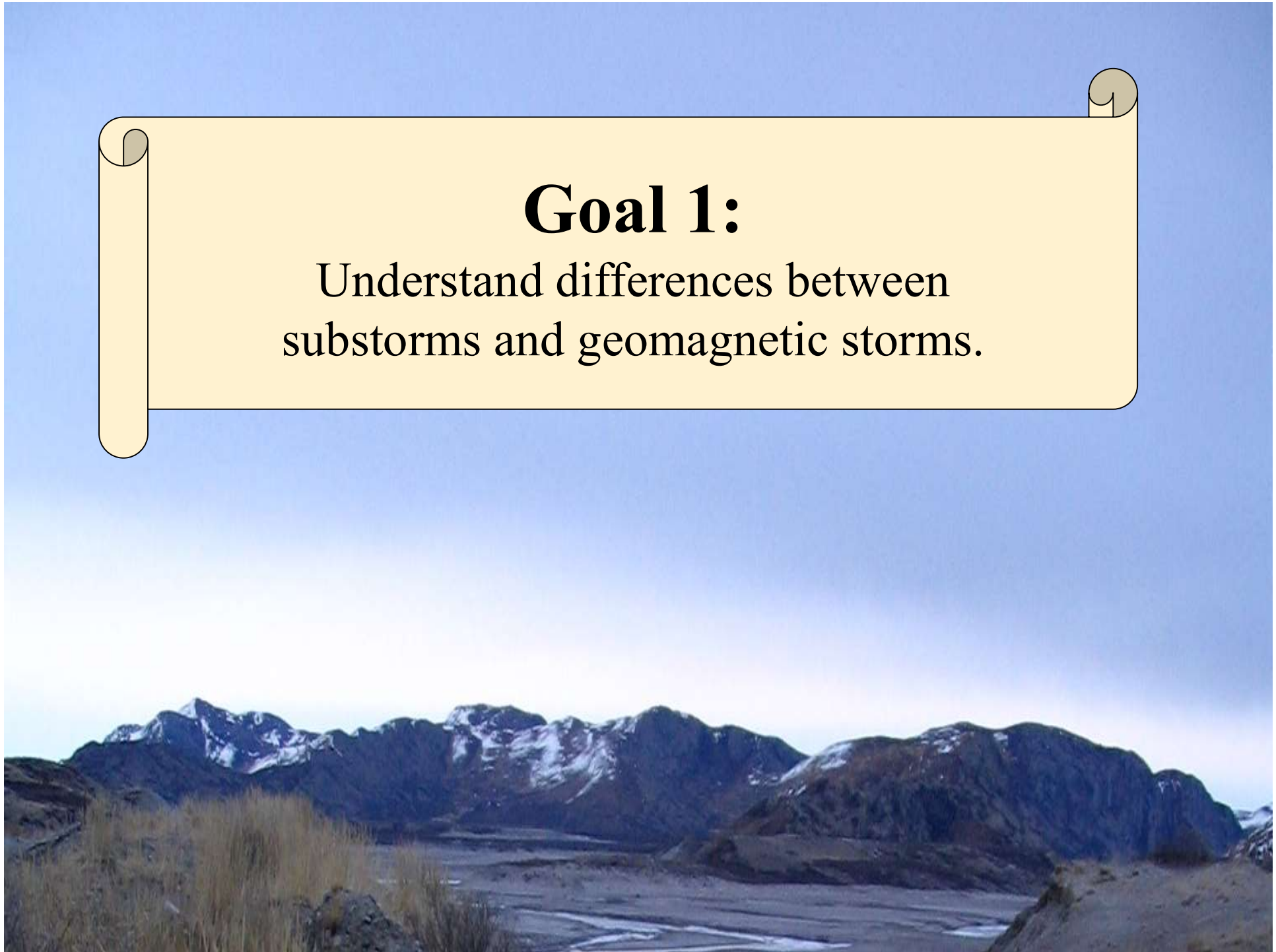
Reference: Weiss et al., Energy dissipation in substorms, 1992.



A yellow scroll graphic with a black outline, featuring a rolled-up edge on the left and a small circular tab on the right. It is positioned in the upper half of the slide.

Goal 1:

Understand differences between substorms and geomagnetic storms.



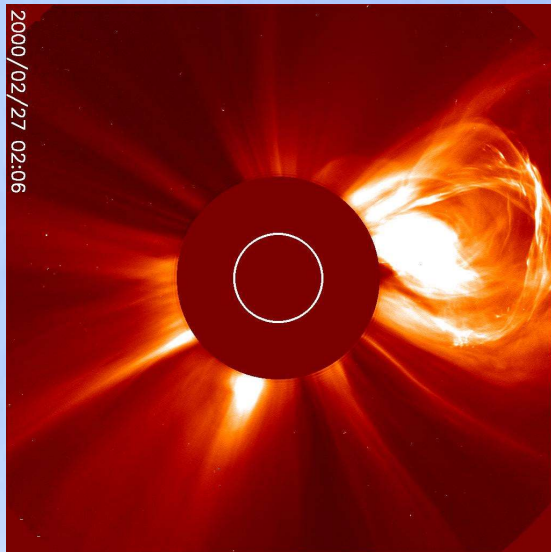


Consider and remember!

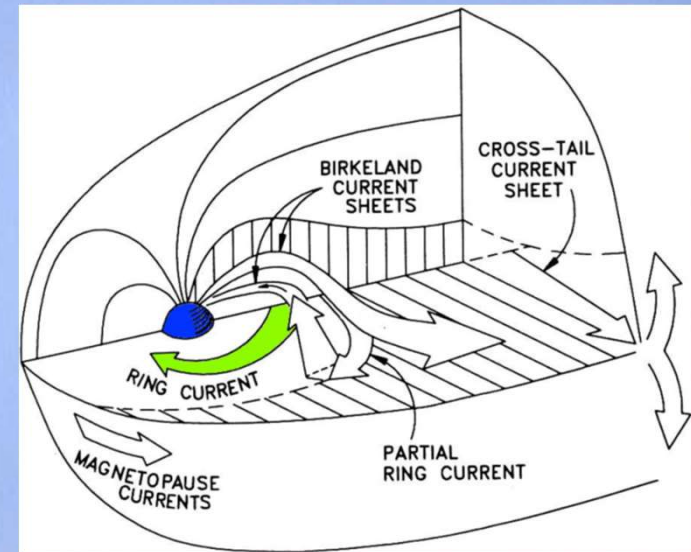
- **Main differences between storms and substorms**

- Locations
- Indices used
- Their sizes
- Lengths in time
- Different storm/substorm phases
- Their energy dissipation channels

Geomagnetic storm



Pressure pulse



- Disturbance of the *ring current*, **global effect**
- Monitored by **Dst index**
- Effect: expansion of auroral oval → auroras at wide latitudinal range

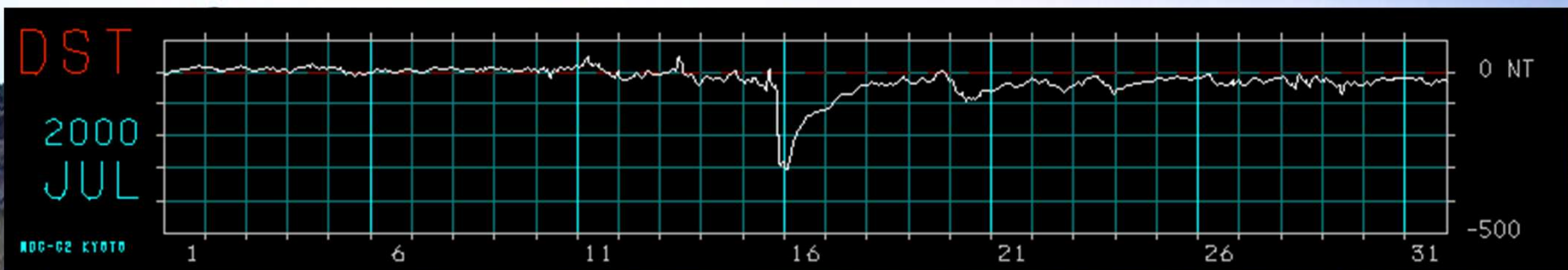


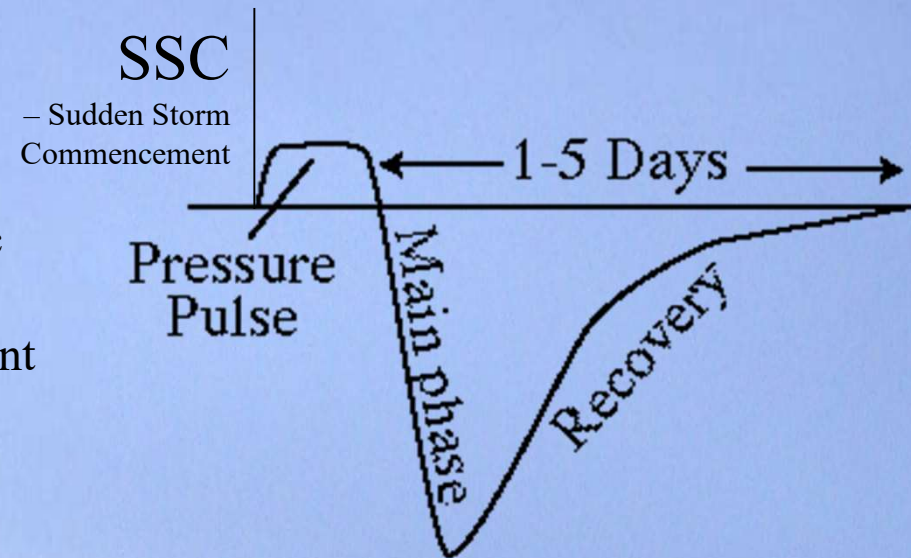
Illustration credit of the magnetosphere figure: David P. Stern

Dst = Disturbance storm time index

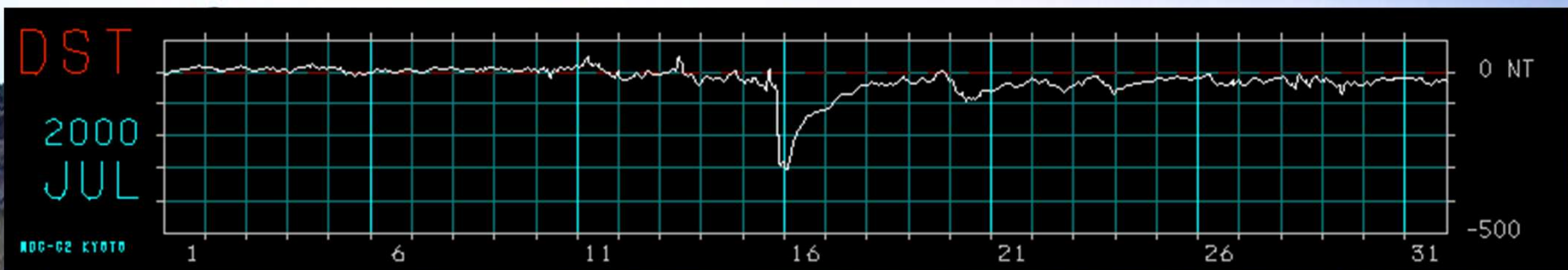
Geomagnetic storm



Magnetic field H-component



- Disturbance of the *ring current*, **global effect**
- Monitored by **Dst index**
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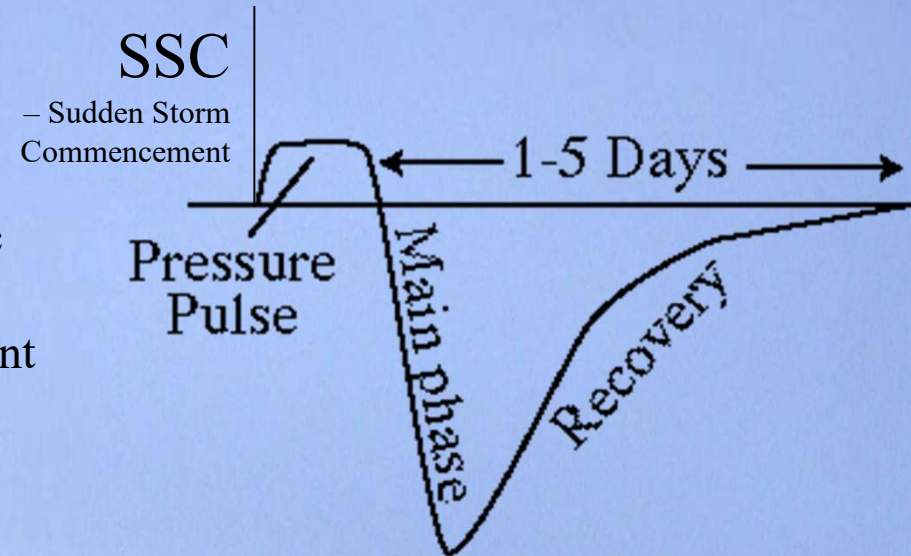


Dst = Disturbance storm time index

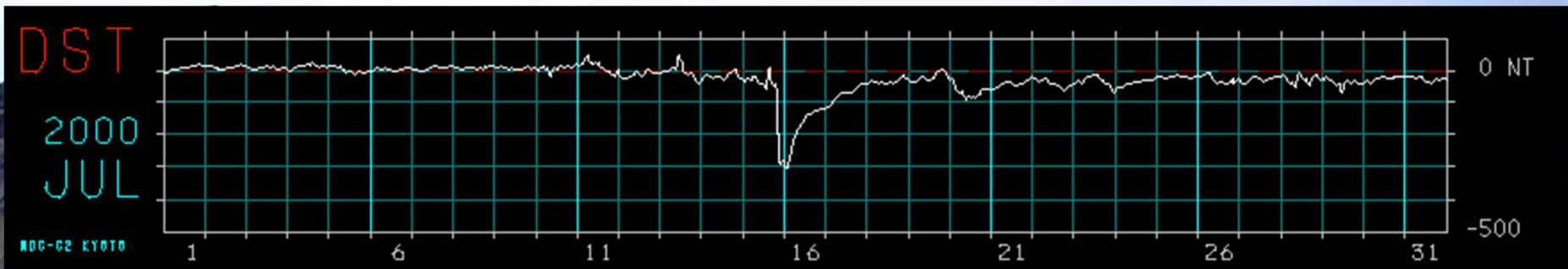
Geomagnetic storm



Magnetic field H-component



- Monitored by **Dst index**
- **-50 nT** or lower for moderate storms
- **-350 nT** or lower for great storms

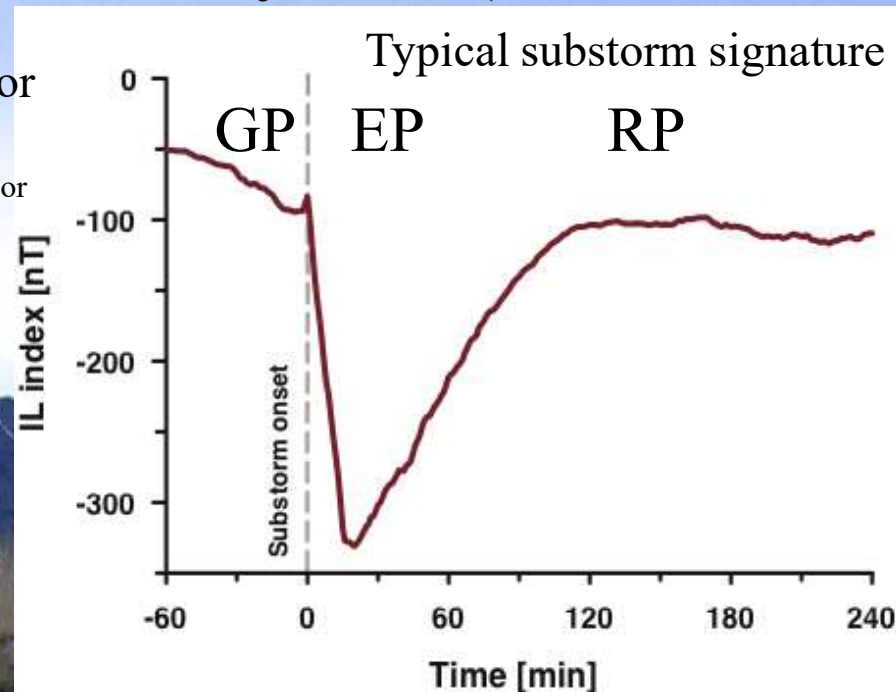


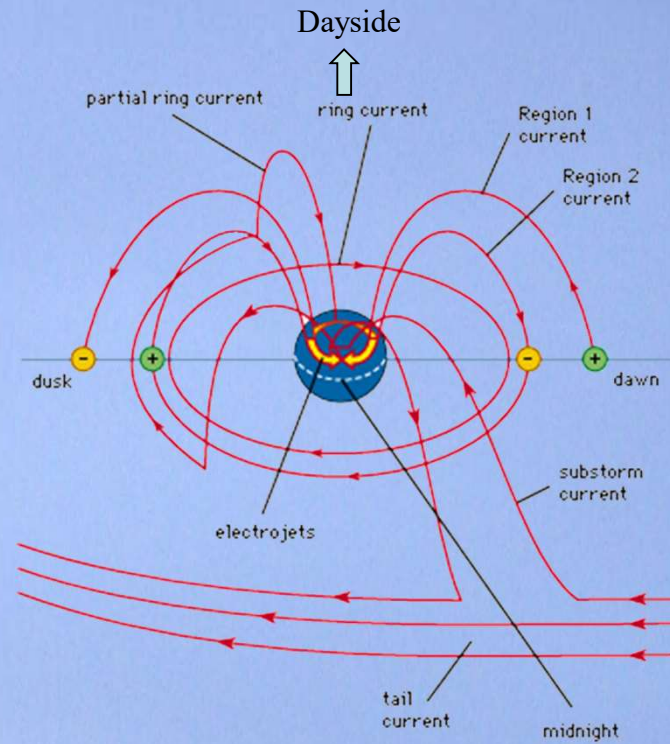
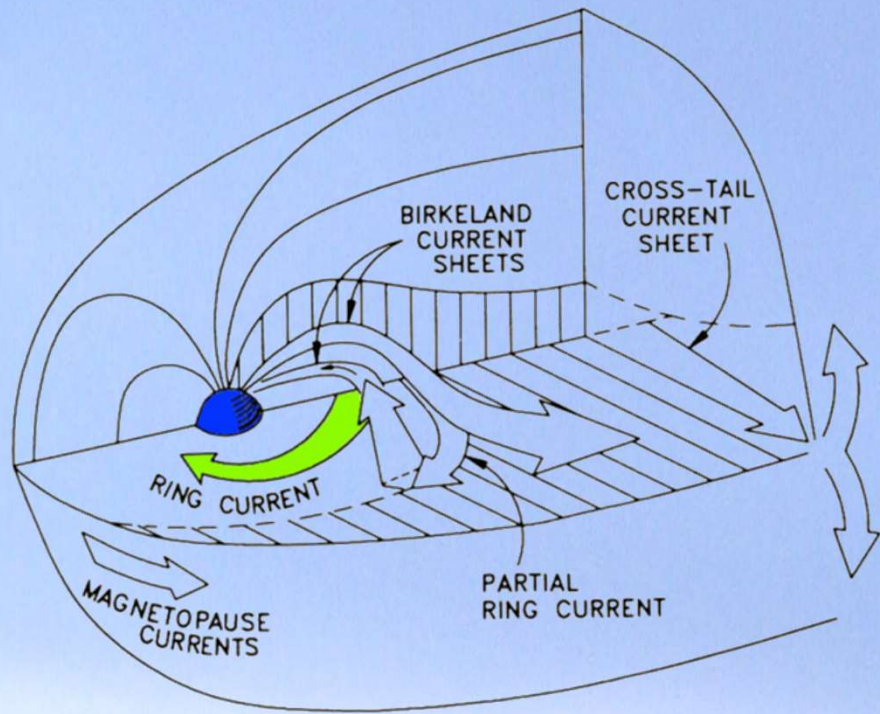
Dst = Disturbance storm time index

Substorm

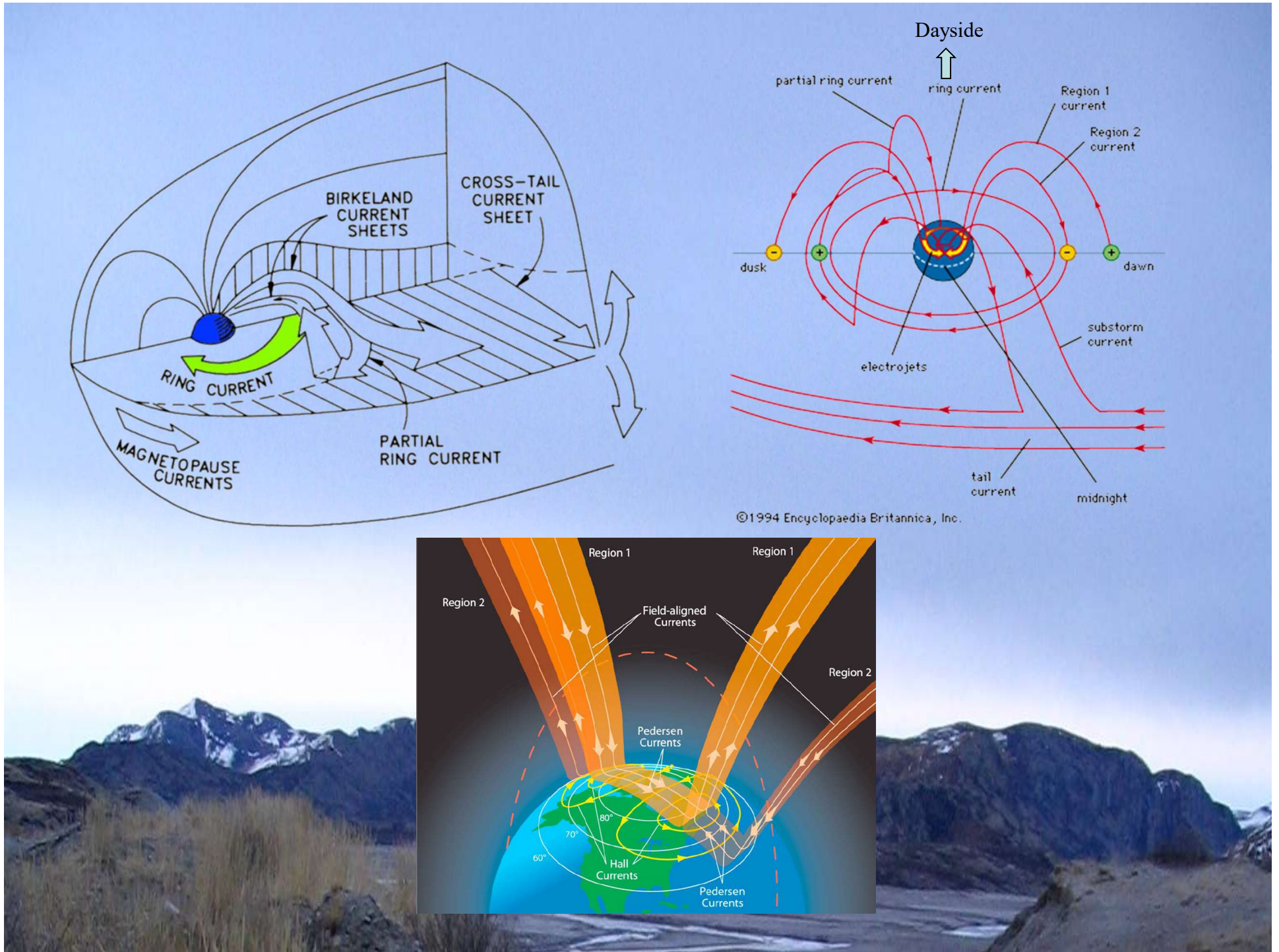
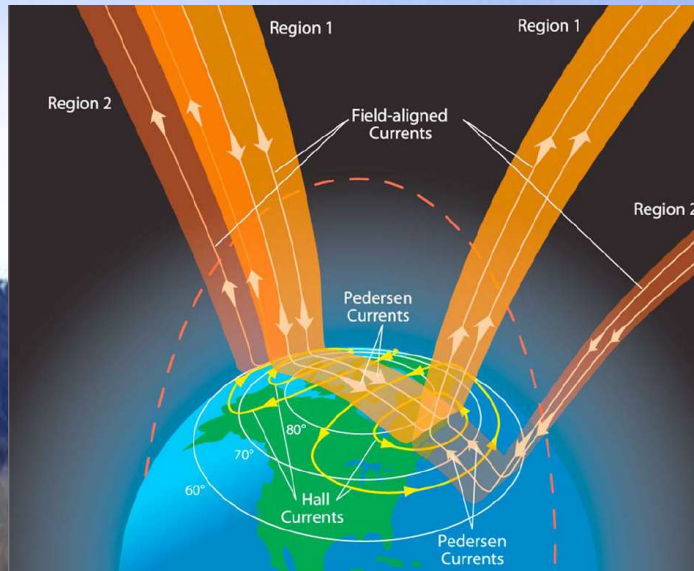
- Disturbance of the auroral electrojet current, **at the auroral oval**.
- **Local phenomenon**: visually detected as aurora, magnetically by the disturbance of the magnetic field.
- **All substorms are different**, there is no “normal” substorm. Statistical properties can be computed, but they need to be understood as **average properties**.
- A typical substorm signature: **a negative bay in north-south (X) component** of the terrestrial magnetic field.
- Monitored by **auroral electrojet indices** (like IL but also AE/AL).

- Drop of -80 nT or more in 15 min
(can go down *hundreds* or *thousands* of nT)



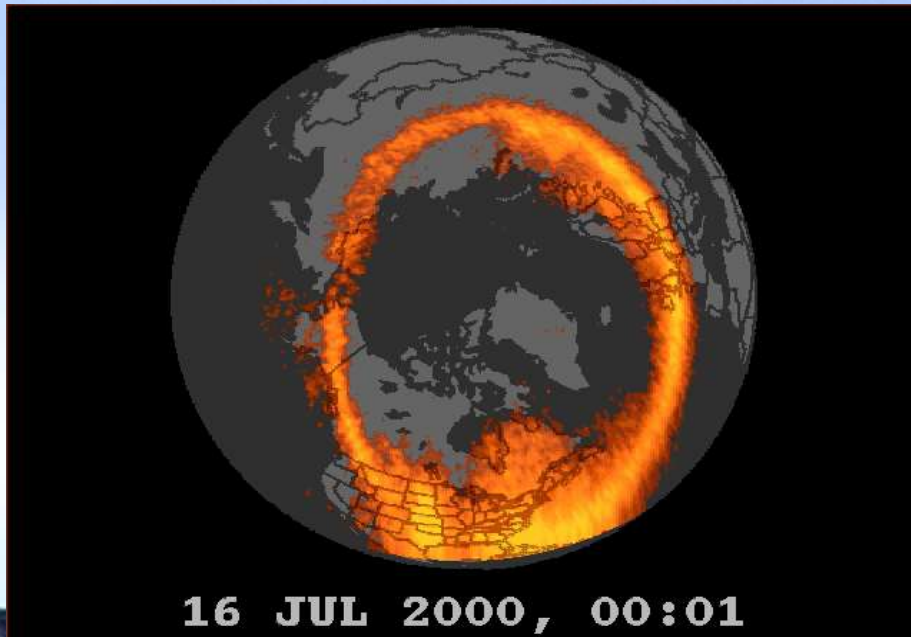


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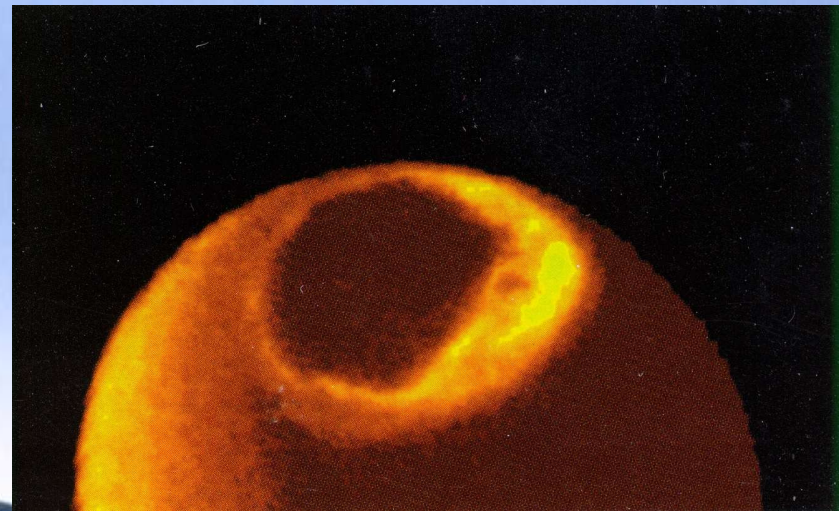


Auroral oval during storms & substorms

Storms

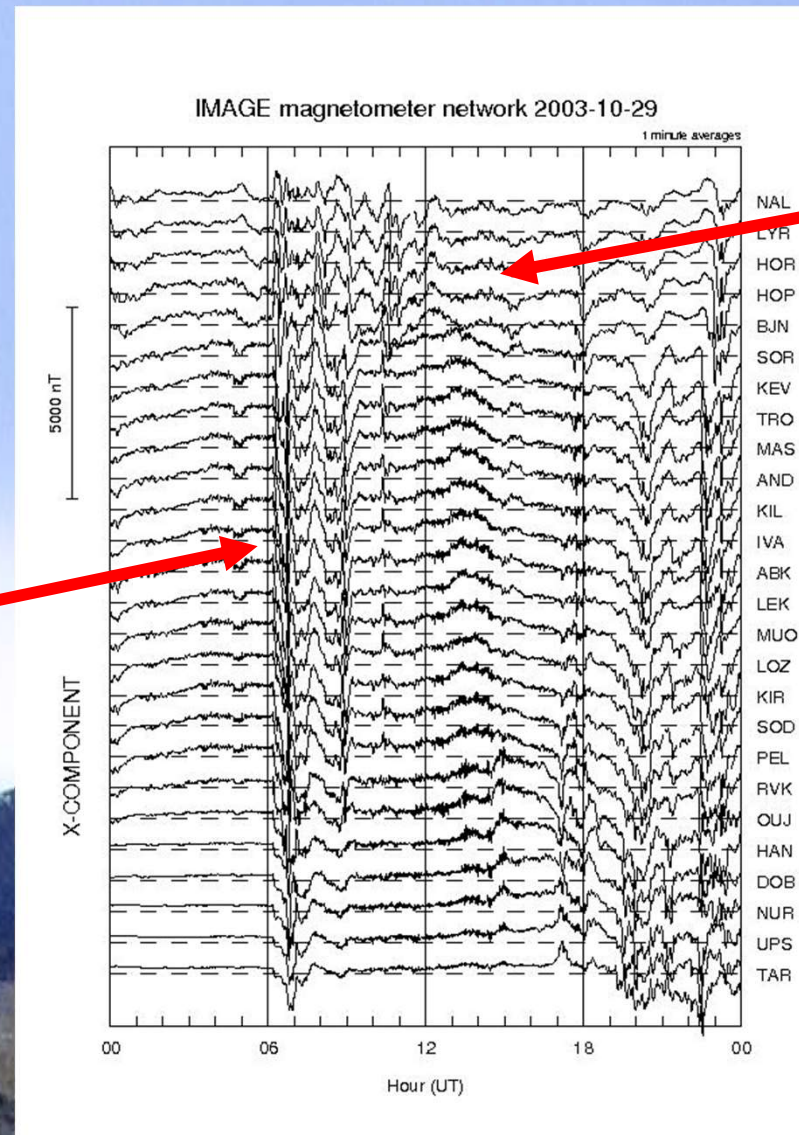


Substorms

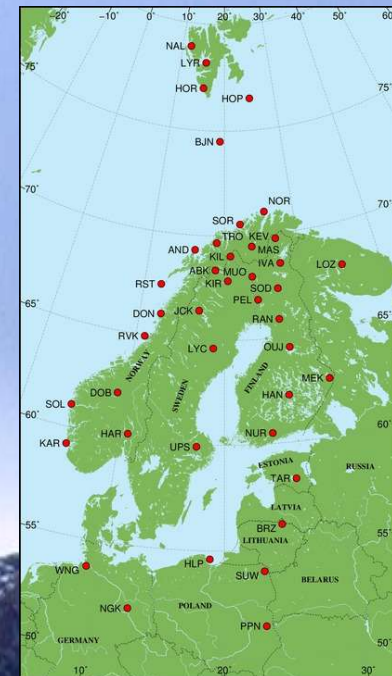


Storm-time activity at high latitudes

Storm-time
substorms

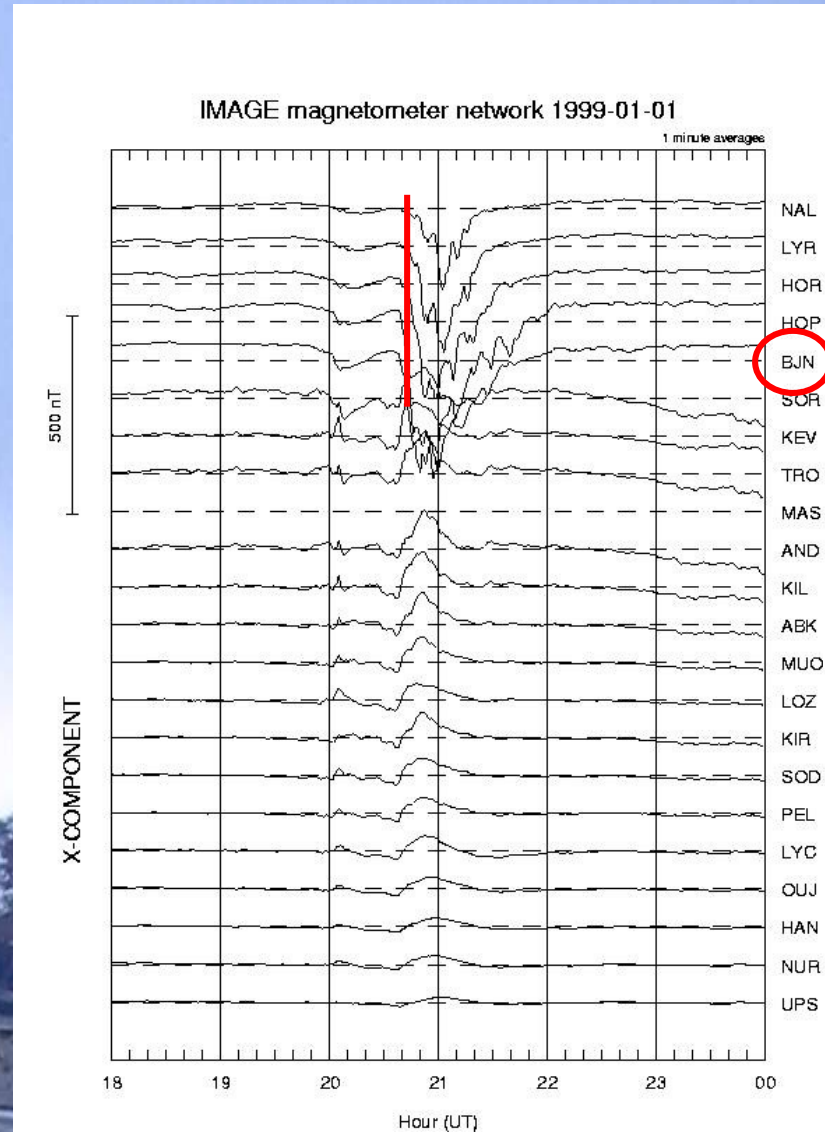


Pulsations



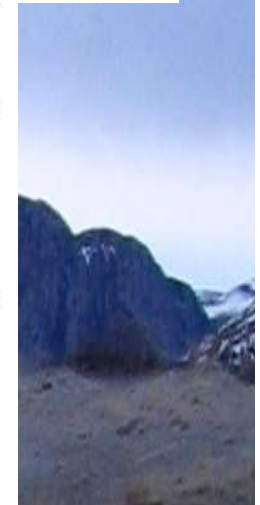
Substorm at poleward oval edge

- Main substorm activity in Svalbard and Bear Island observatories
- Weak or no activity south from Abisko
- Intensity $|\min(IL)| = 439 \text{ nT}$
- Duration $\sim 2 \text{ hours } 30 \text{ min}$



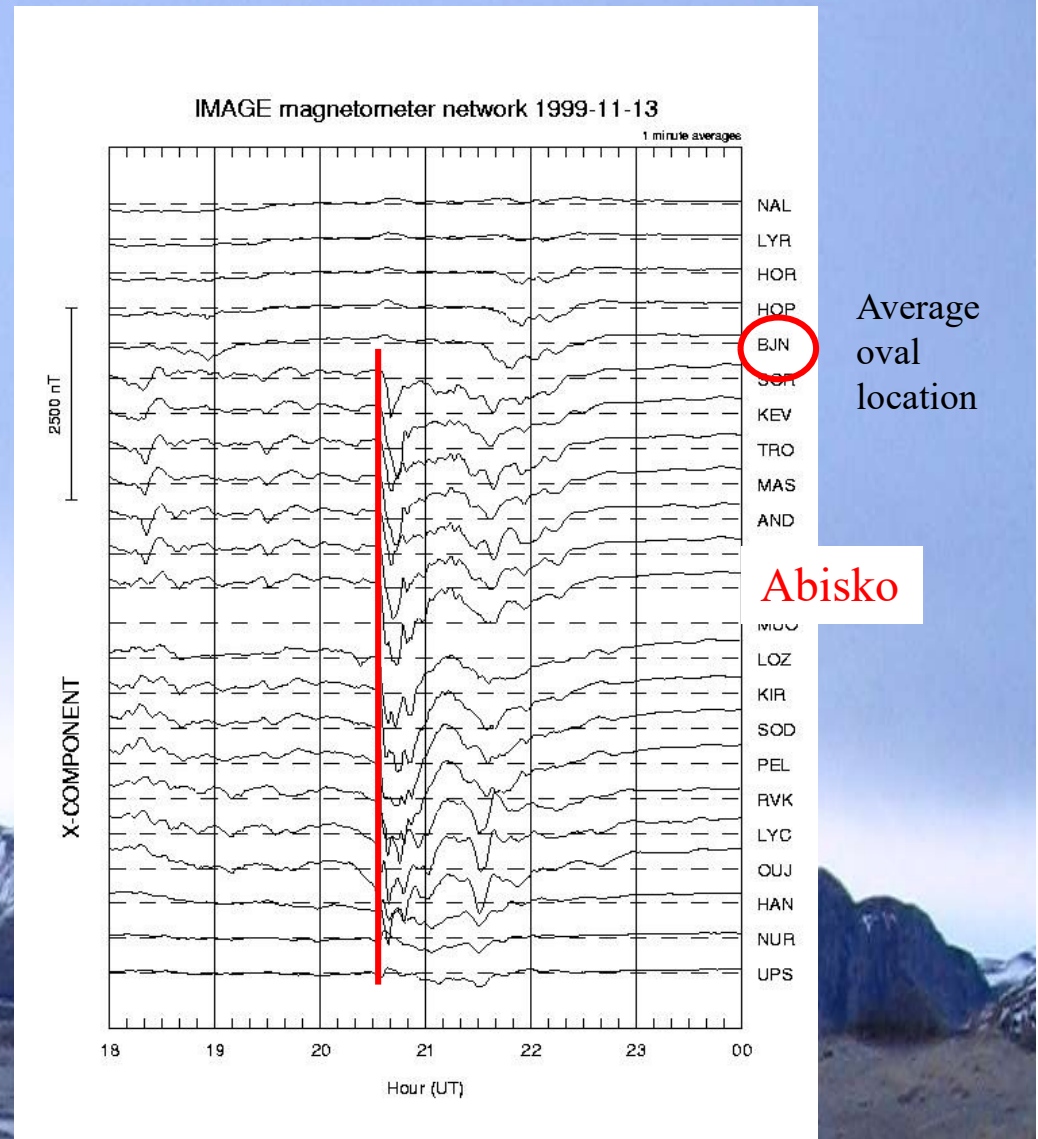
Average
oval
location

Abisko



Substorm at equatorward oval edge

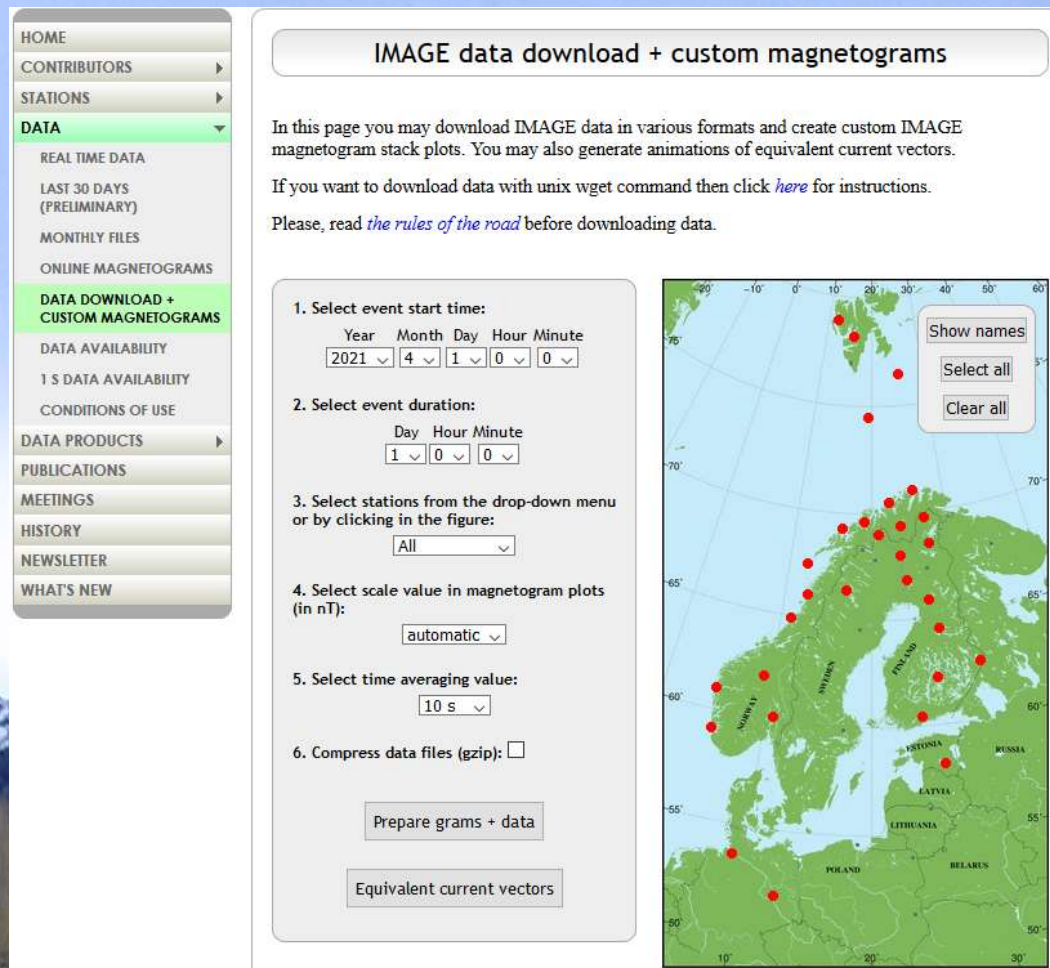
- A substorm detected from Sørøya to Hankasalmi.
- Simultaneous onset (sharp drop) in all latitudes around 20:30 UT.



Where to find magnetograms?

<https://space.fmi.fi/image>

→ Data



The screenshot shows the 'IMAGE data download + custom magnetograms' page. On the left is a navigation menu with 'DATA' highlighted. The main content area contains instructions and a form with six steps for selecting data parameters. A map of Europe on the right shows station locations marked with red dots.

HOME
CONTRIBUTORS
STATIONS
DATA
REAL TIME DATA
LAST 30 DAYS (PRELIMINARY)
MONTHLY FILES
ONLINE MAGNETOGRAMS
DATA DOWNLOAD + CUSTOM MAGNETOGRAMS
DATA AVAILABILITY
1 S DATA AVAILABILITY
CONDITIONS OF USE
DATA PRODUCTS
PUBLICATIONS
MEETINGS
HISTORY
NEWSLETTER
WHAT'S NEW

IMAGE data download + custom magnetograms


In this page you may download IMAGE data in various formats and create custom IMAGE magnetogram stack plots. You may also generate animations of equivalent current vectors.

If you want to download data with unix wget command then click [here](#) for instructions.

Please, read [the rules of the road](#) before downloading data.

1. Select event start time:
Year: 2021, Month: 4, Day: 1, Hour: 0, Minute: 0
2. Select event duration:
Day: 1, Hour: 0, Minute: 0
3. Select stations from the drop-down menu or by clicking in the figure:
All
4. Select scale value in magnetogram plots (in nT):
automatic
5. Select time averaging value:
10 s
6. Compress data files (gzip):

Prepare grams + data
Equivalent current vectors

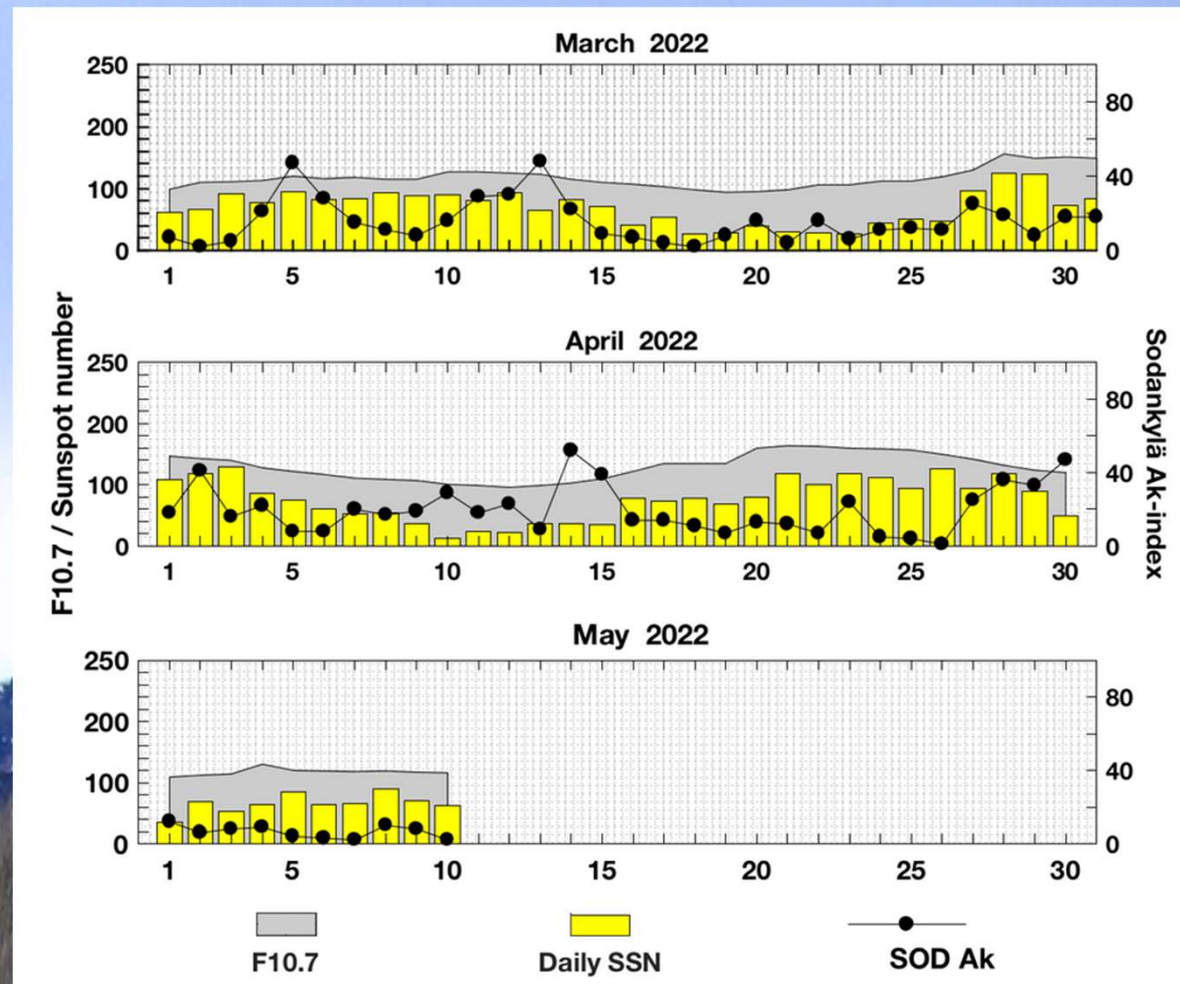


Map showing station locations (red dots) across Europe. The map includes labels for countries: NORWAY, SWEDEN, FINLAND, ESTONIA, RUSSIA, LITHUANIA, POLAND, and BELARUS. A legend box contains: Show names, Select all, Clear all.

Where to find magnetograms?

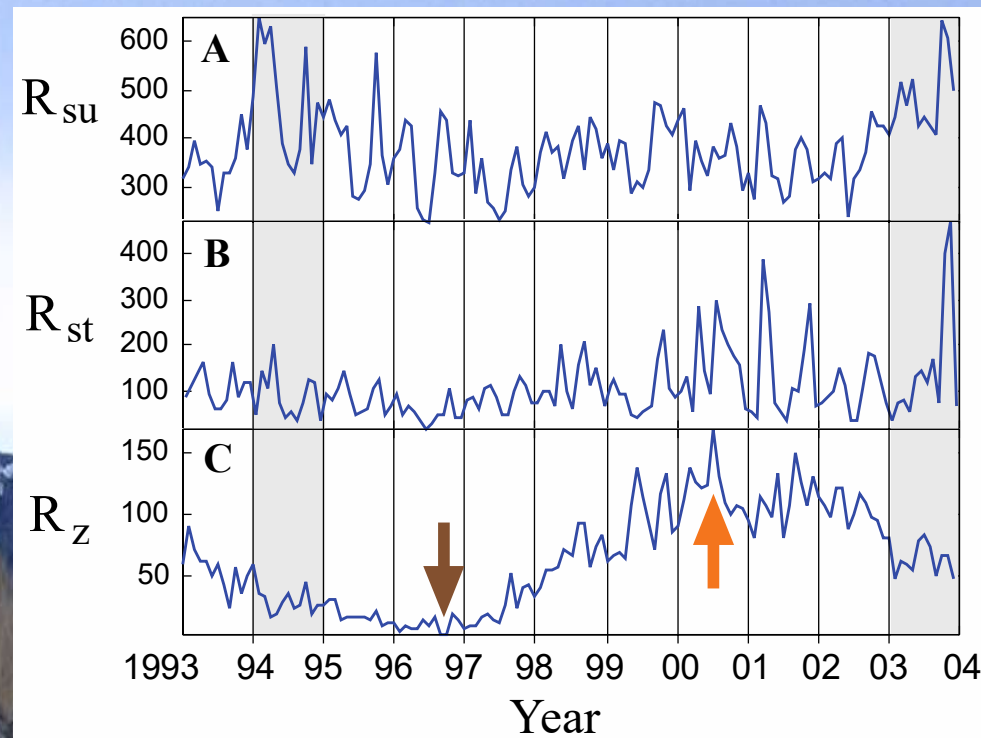
<https://www.sgo.fi/Data/>

→ Latest data → Magnetometer



Year-to-year comparison: storms and substorms

- Substorm activity peaks at declining solar cycle phase
 - ...but it's always there.
- Storm activity typically maximizes around solar maximum.
 - Almost ceases during solar minimum.

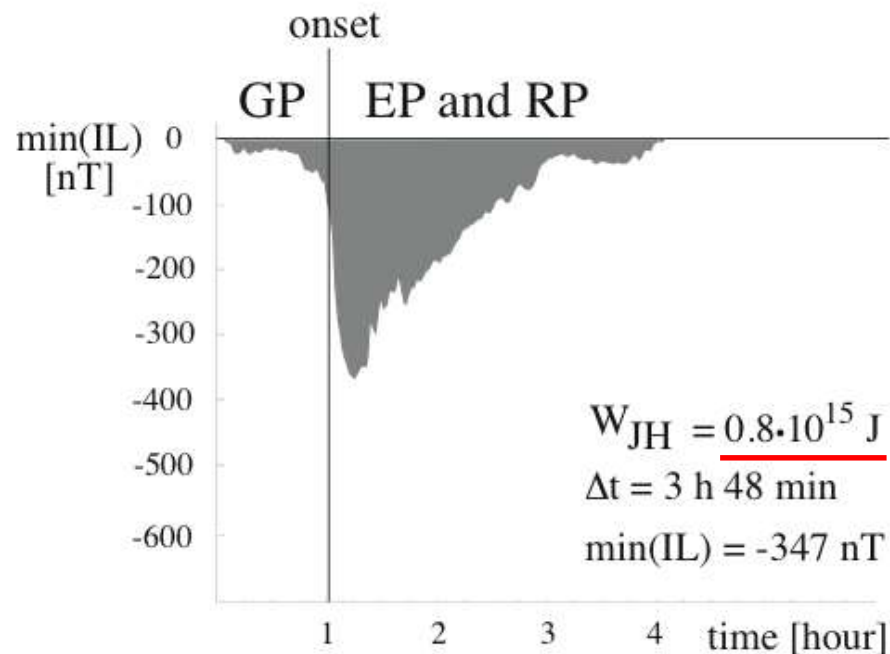


Storm-time and non-storm substorms

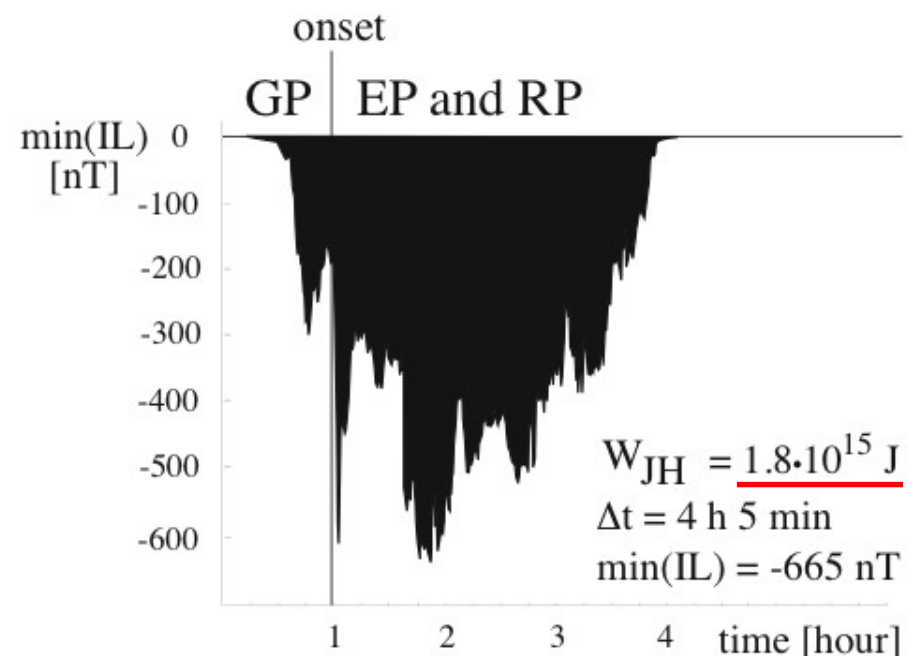
- Substorms occur both as isolated and during geomagnetic storms.

Typical storm-time substorm is about twice as intense and carries about 2.5 times more energy into the ionosphere than a typical non-storm substorm.

(a) Typical isolated substorm



(b) Typical stormtime substorm



Remember!

- Main differences between storms and substorms:
 - **Locations:** equator or auroral region
 - **Indices:** Dst or AE/AL/IL
 - **Size:** 10s of nT or 100s of nT
 - **Length:** days or hours
 - They have different **phases**
 - Different **dissipation channels** (further slides)

A landscape photograph of a mountain range with snow-capped peaks and a dry riverbed in the foreground. A large, light blue thought bubble with a black outline is superimposed over the sky and mountains. Inside the bubble, the text 'Consider!' is followed by a bulleted list. The list includes 'Substorms act differently while:' with sub-bullets 'isolated' and 'during storm-time', and 'Sunspots matter!' with a sub-bullet 'Both storms and substorms have dependency on solar cycle phase'.

Consider!

- **Substorms act *differently* while:**
 - isolated
 - during storm-time
- **Sunspots matter!**
 - Both storms and substorms have dependency on solar cycle phase

Goal 2:

Understand where substorm energy originates from
and how does it circulate in the magnetosphere.



Goal 2:

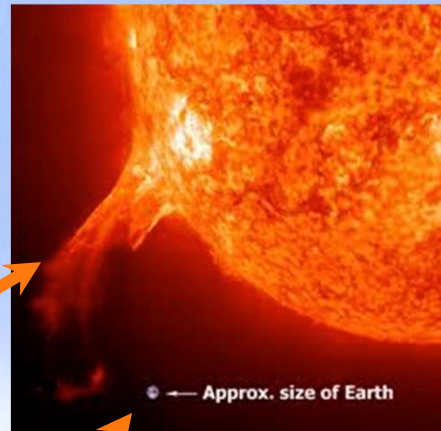
Understand where substorm energy originates from and how does it circulate in the magnetosphere.

Consider during this part of the lecture!

1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)

Solar sources of substorm energy

Solar disturbance

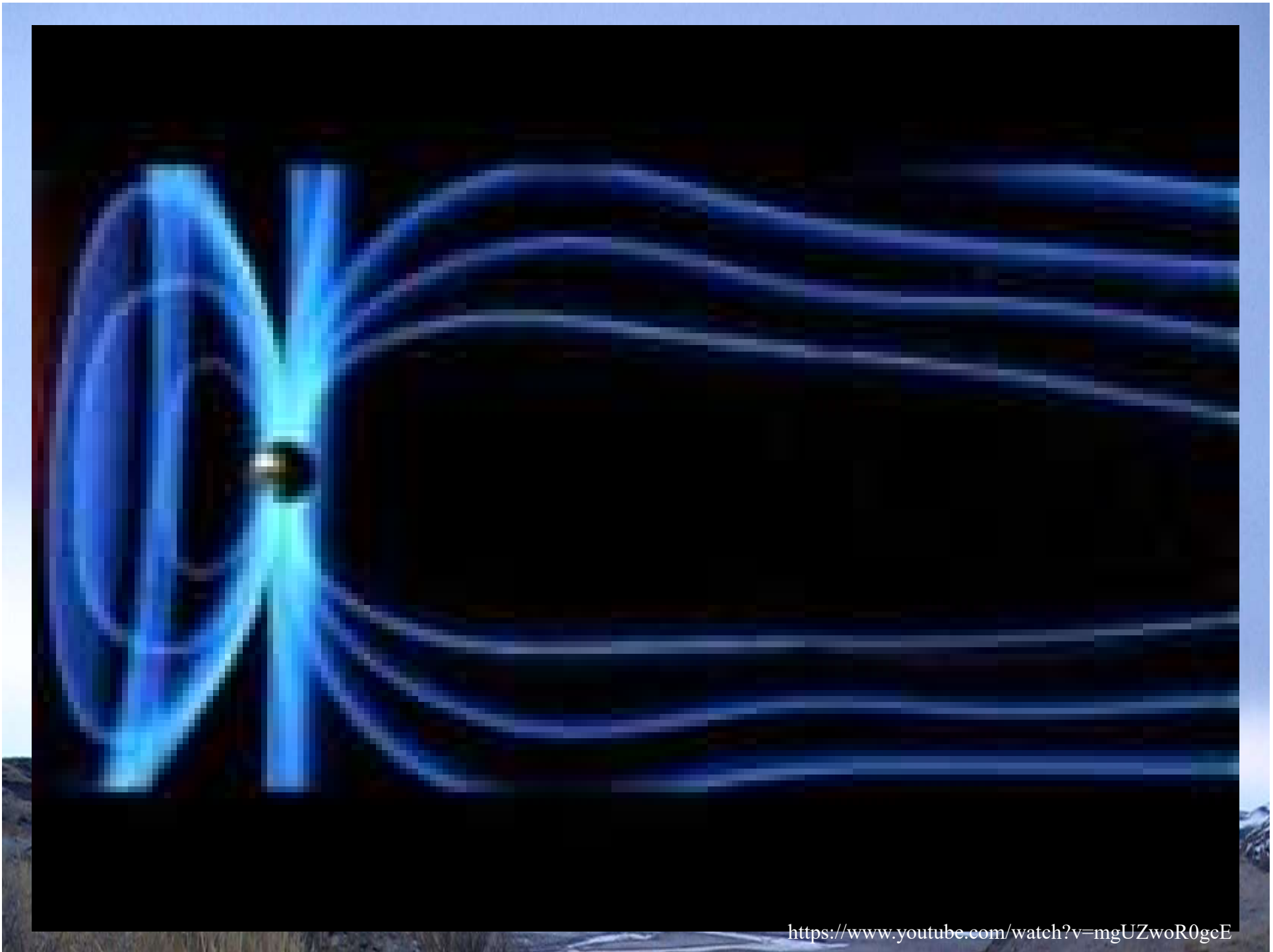


The Earth



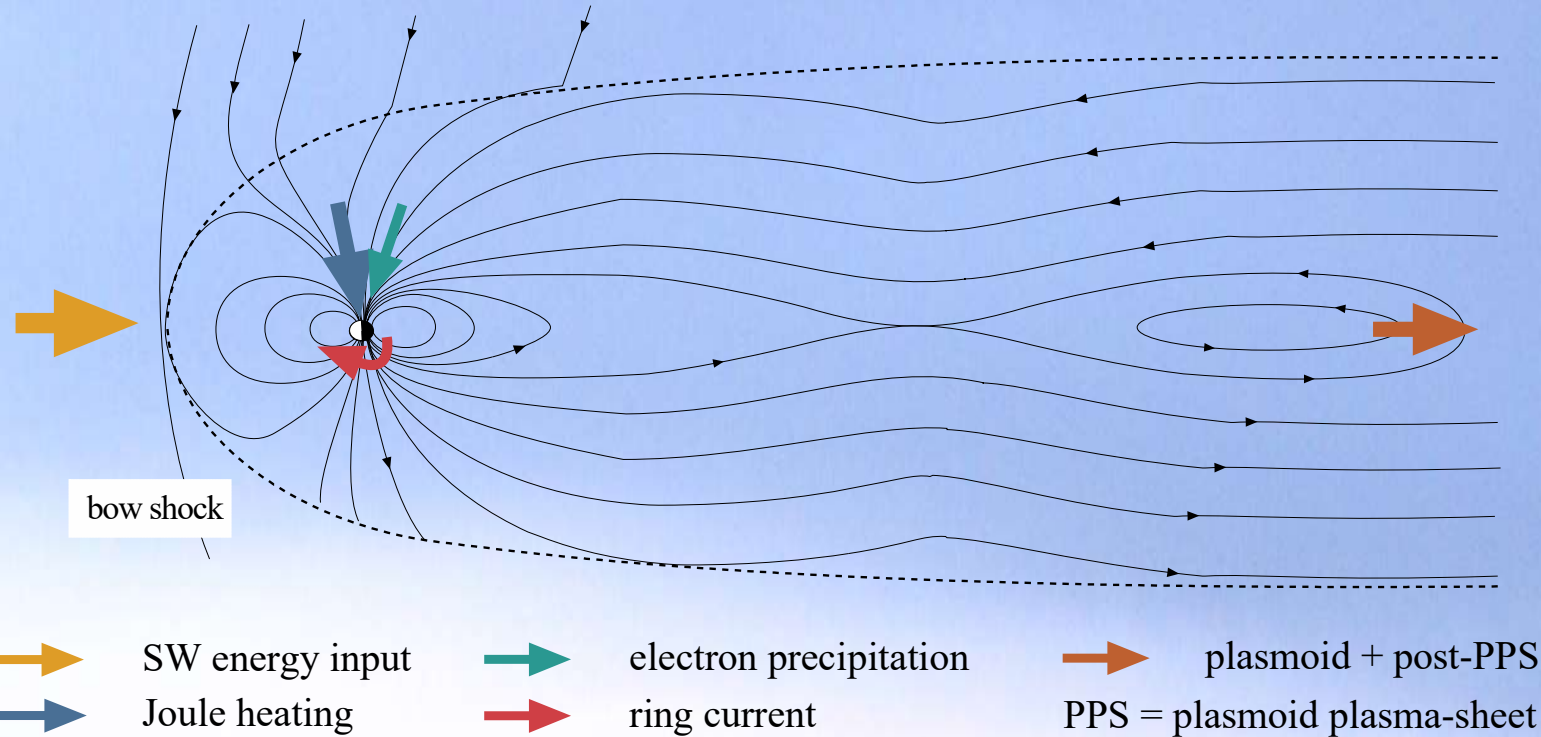
Auroral ovals



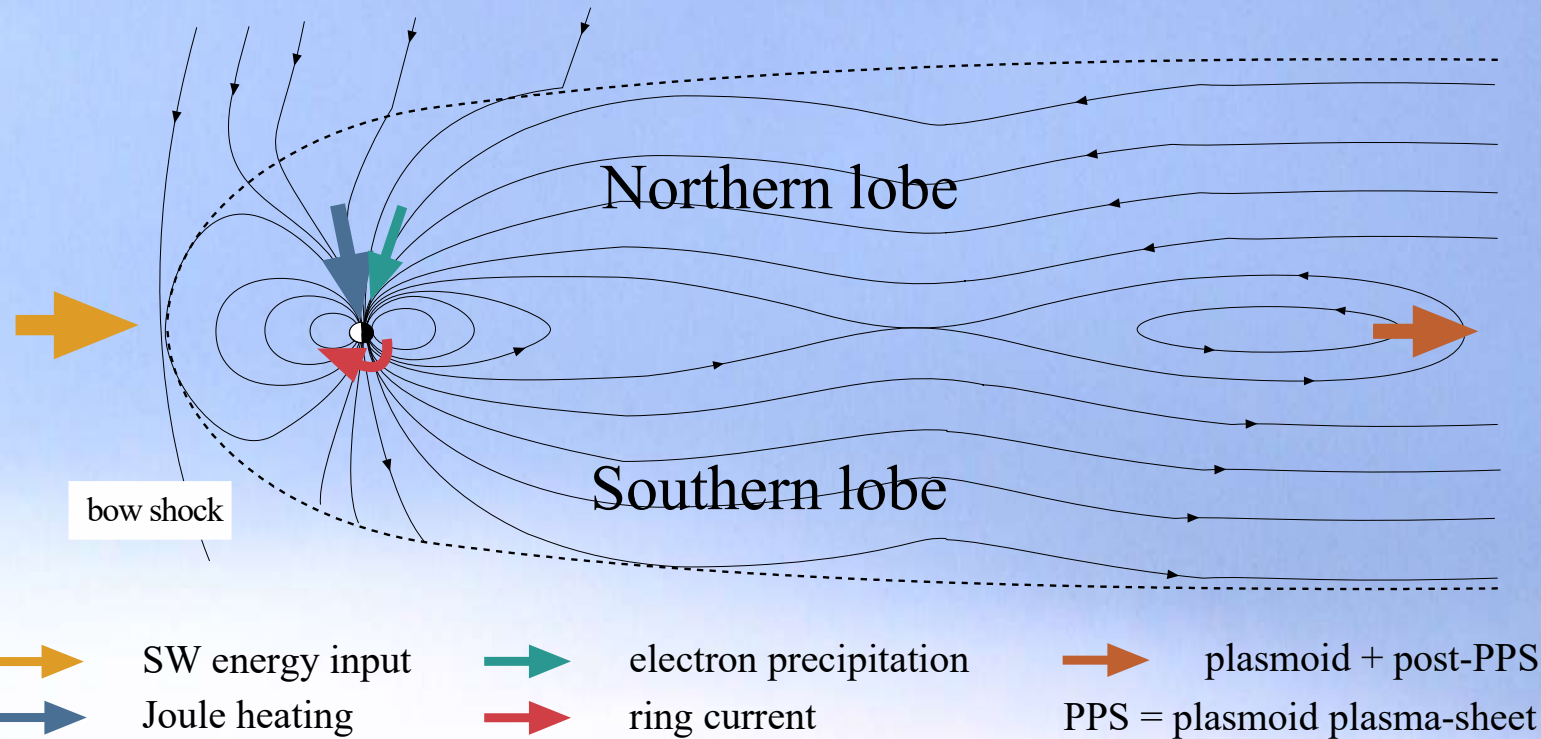


<https://www.youtube.com/watch?v=mgUZwoR0gcE>

Substorm energetics: **input** and **sinks**



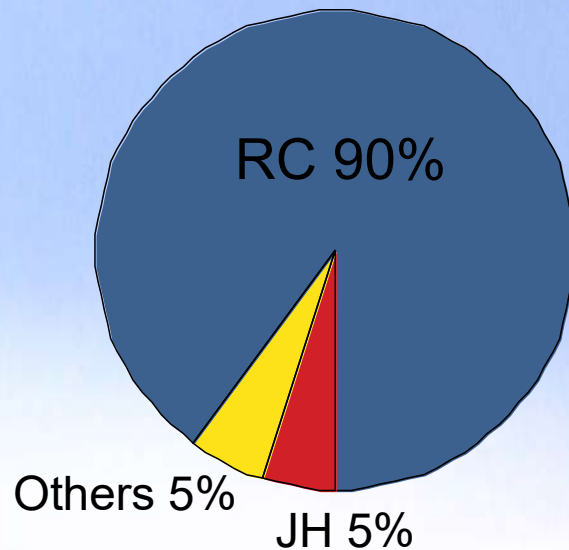
Magnetotail lobes store magnetic energy



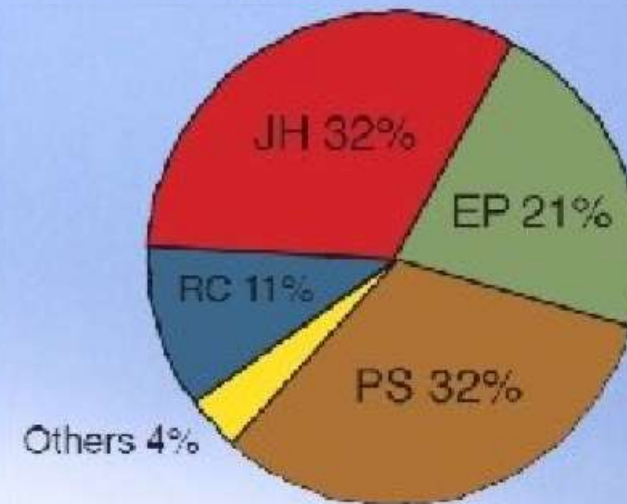
super-important!

Energy pie for storms and substorms

Typical storm energy pie:



Typical substorm energy pie:



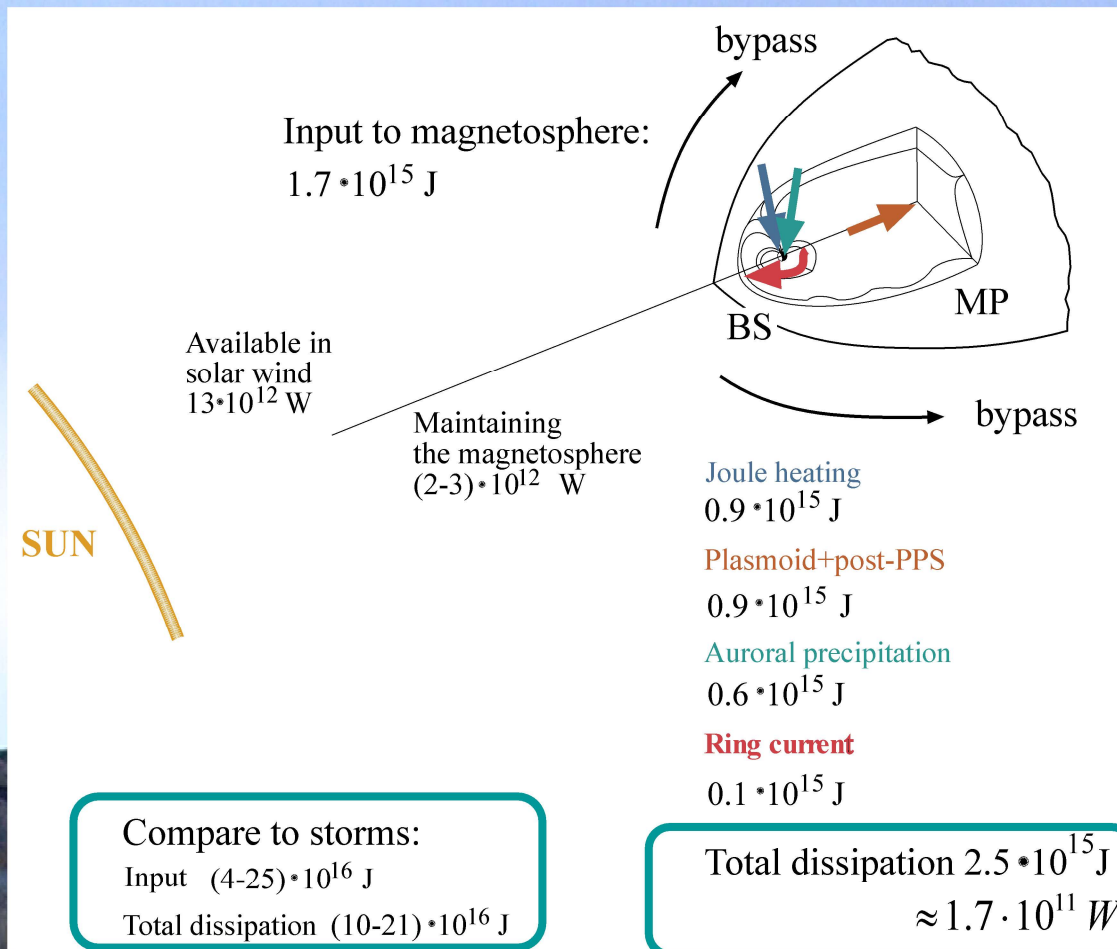
RC = Ring current

JH = Joule heating (electric currents through atmosphere)

EP = Electron precipitation

PS = (Magnetospheric) Plasma sheet heating

Storm-substorm energy budget



- Joule heating estimate

$$W_{JH} = 3 \cdot 10^8 \cdot IL$$

- Electron precipitation estimate

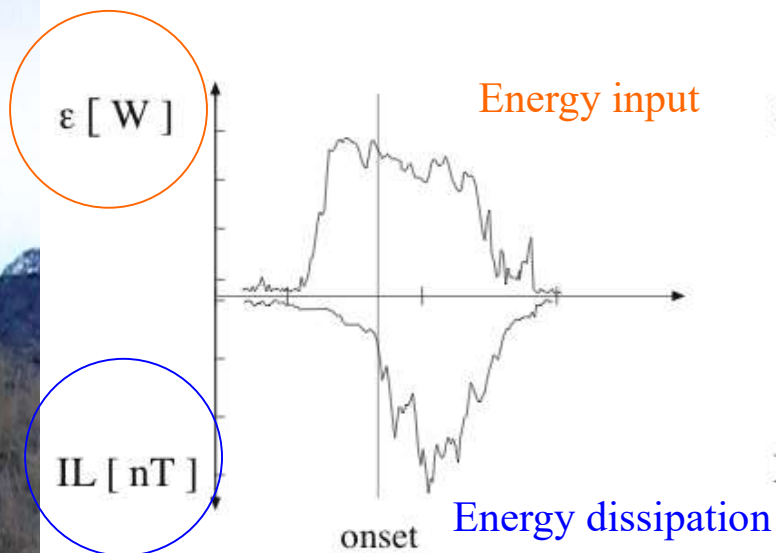
$$W_{ep} = 0.8 \cdot 10^8 \cdot IL$$

- The energy coupling efficiency is about 1% for substorms.

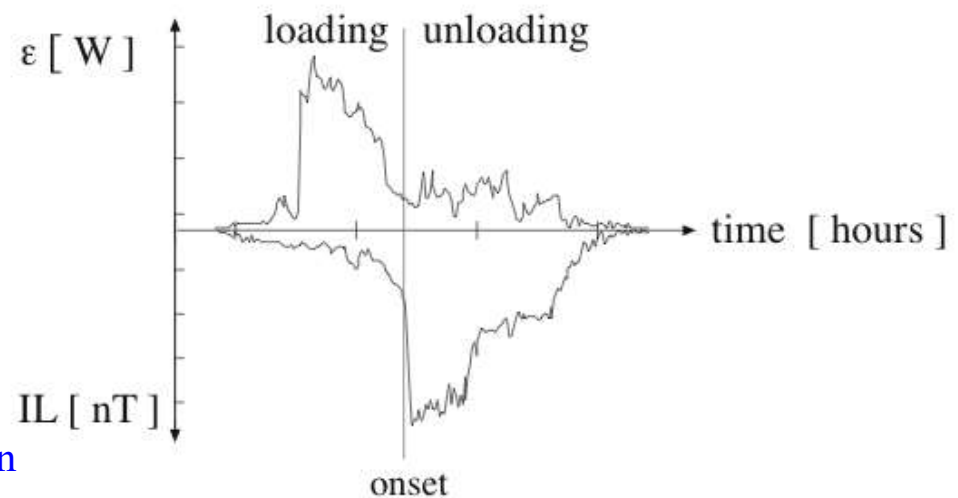
Loading-unloading processes

- Over 80% of substorms are directly powered by solar wind (i.e. type a).
- Substorm growth phase is necessary for preconditioning the magnetotail to allow a global instability to grow.
- Size of substorm depends on mostly of the energy dissipated in substorm expansion phase.

(a) directly driven



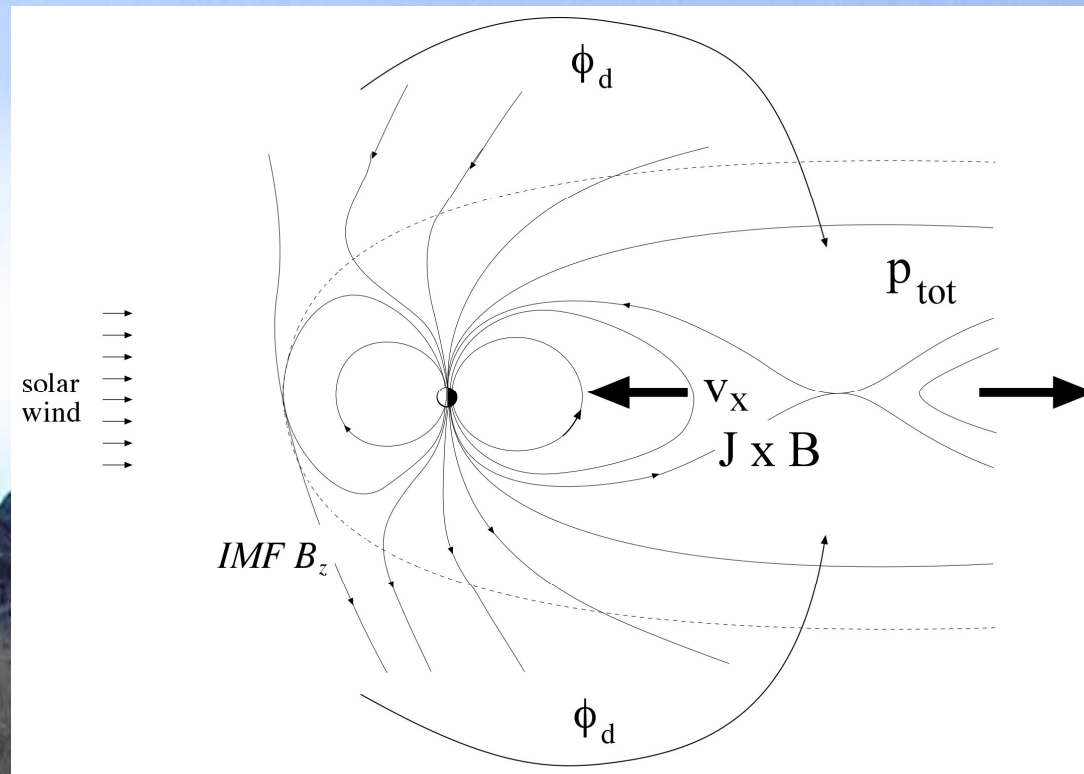
(b) loading-unloading



Magnetotail convection modes

Four magnetospheric convection modes:

- (1) Loading: magnetic flux ϕ_d into magnetosphere
- (2) Unloading: magnetic flux and particle flows towards the Earth
- (3) Continuous magnetospheric dissipation, CMD: continuous flux flow from SW to Earth
- (4) Steady magnetospheric convection, SMC: continuous and steady flux flow



CMDs are as common as substorms (loading-unloading cycles).



Consider!

1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)

Goal 3:

Learn to estimate energy input
from the solar wind during substorms.

Reference: Weiss, L.A, P.H. Reiff, J.J. Moses et al., Energy dissipation in substorms, Proceedings of the International Conference on Substorms (ICS-1), Kiruna, May 1992.

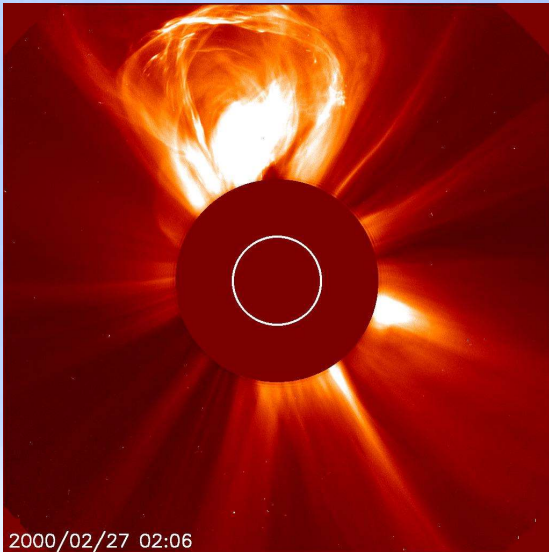




Consider and remember!

1. Solar wind-magnetosphere energy coupling function.
2. Typical values for this function.
3. Typical energies of dissipation during storms and substorms.

Energy coupling function



- How much energy is in the solar wind?
How much is bestowed upon magnetosphere?
- Interesting parameters:
 - Solar wind speed: $v \rightarrow$ Kinetic energy
 - Magnetic field: $B \rightarrow$ Magnetic energy
 - Size of the magnetosphere l_0
 \rightarrow Cross-section for energy channels
 - Magnetic field clock angle $\theta = \tan^{-1}(B_y/B_z)$
 \rightarrow Effect of the magnetic field southward component



→ Epsilon parameter

- Akasofu's epsilon parameter is the most commonly used parameter to estimate the energy input from the solar wind into the magnetosphere.

$$\varepsilon = \left(\frac{4\pi}{\mu_0} \right) v B^2 l_0^2 \sin^4 \left(\frac{\theta}{2} \right), \quad l_0 = 7R_E$$

- Parameters:
 - Solar wind speed: v
 - Magnetic field: B
 - Size of the magnetosphere l_0
 - Magnetic field clock angle $\theta = \tan^{-1}(B_y/B_z)$
- Average solar wind energy input during a single substorm is $1.7 \times 10^{15} \text{ J}$.



Energy input , W_ϵ

Shifting data will be studied few slides later.

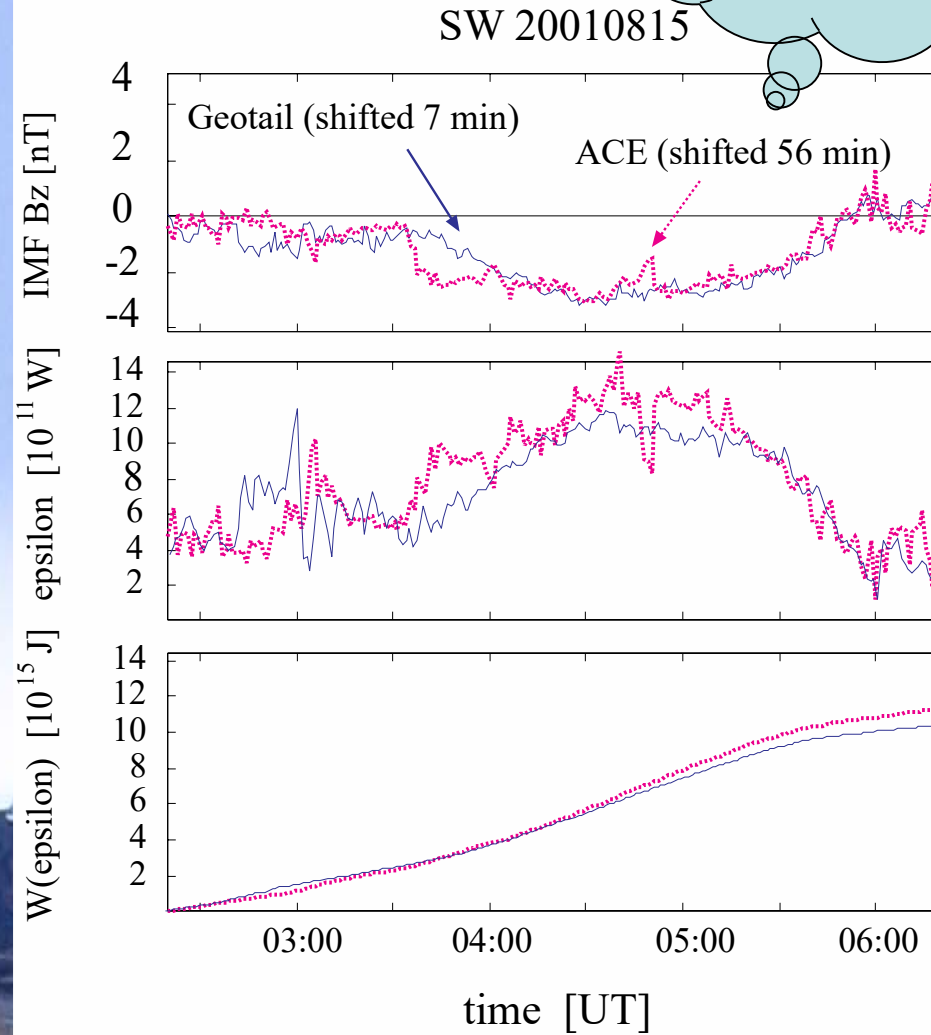
Interplanetary magnetic field north-south component from ACE and Geotail spacecraft.

$$\epsilon = 10^7 v B^2 \sin^4(\theta/2) \cdot l_0^2$$

where $l_0 = 7 R_E$

Total energy input:

$$W_\epsilon = \int \epsilon dt$$



$1.1 \cdot 10^{15} \text{ J}$

$1.0 \cdot 10^{15} \text{ J}$

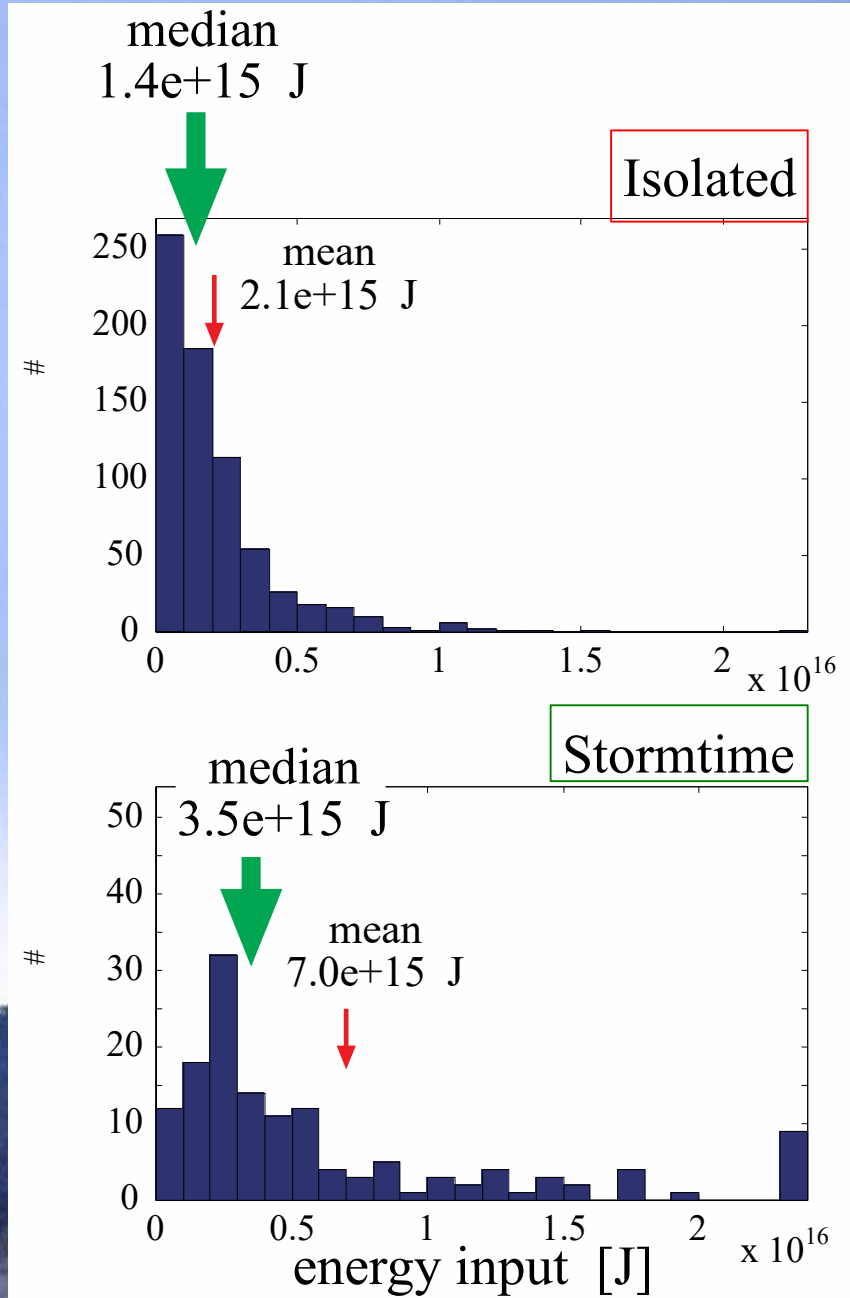
Typical energy input

Isolated substorm =
Substorm that occur when
storm-index Dst > -50 nT
i.e. no simultaneous storms.

Typical: 1.4×10^{15} J

Storm-time substorm =
Substorm that occur when
storm-index Dst < -50 nT

Typical: 3.5×10^{15} J





Consider and remember!

1. Energy coupling function:
The **epsilon parameter** and its parts
2. Typical values for epsilon.
3. Typical energies of dissipation during storms and substorms.



Goal 3.2:

Shift the solar wind data at L1 to magnetopause.





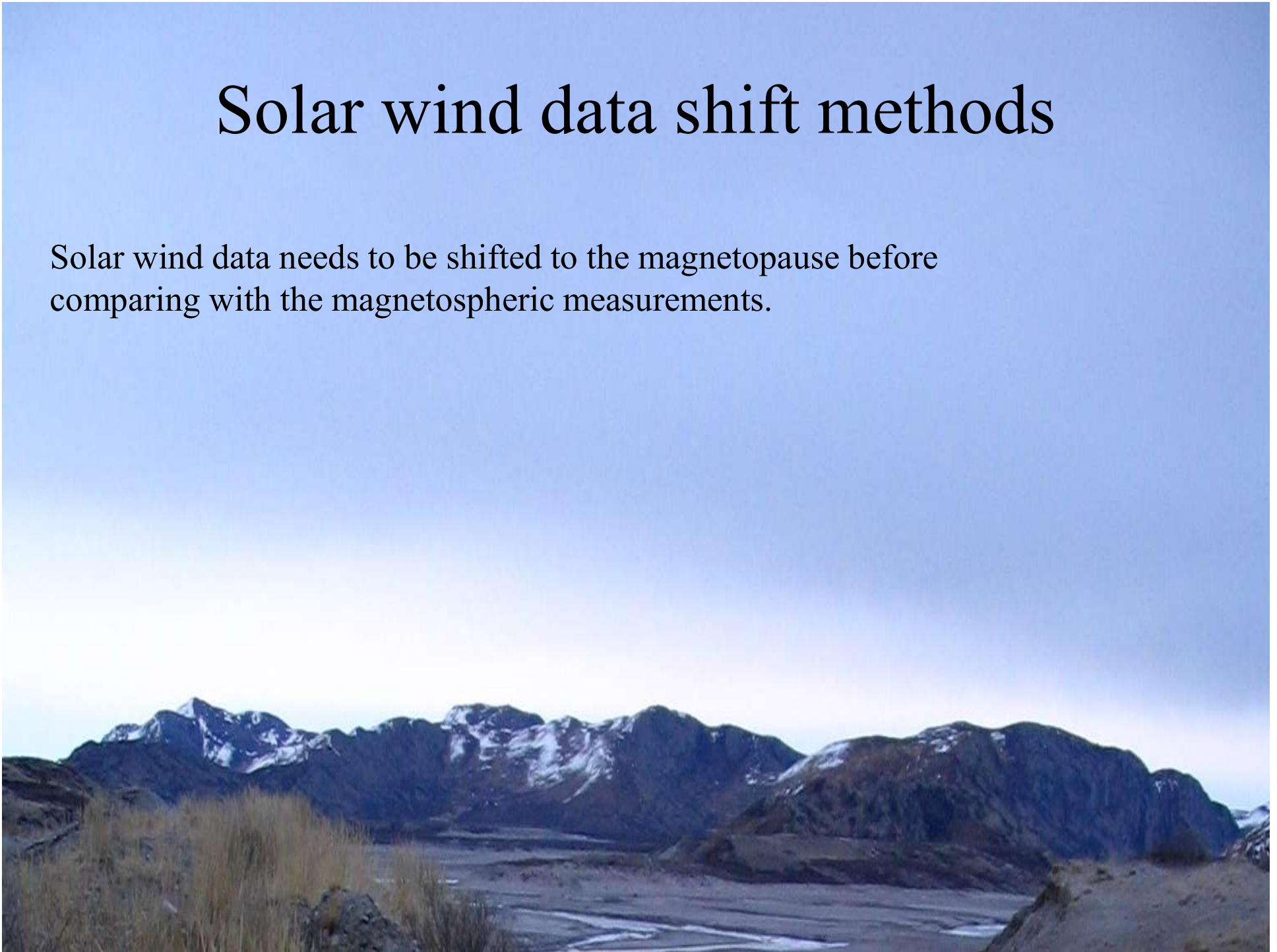
Goal 3.2:

Shift the solar wind data at L1 to magnetopause.

But why?

Solar wind data shift methods

Solar wind data needs to be shifted to the magnetopause before comparing with the magnetospheric measurements.



Solar wind data shift methods

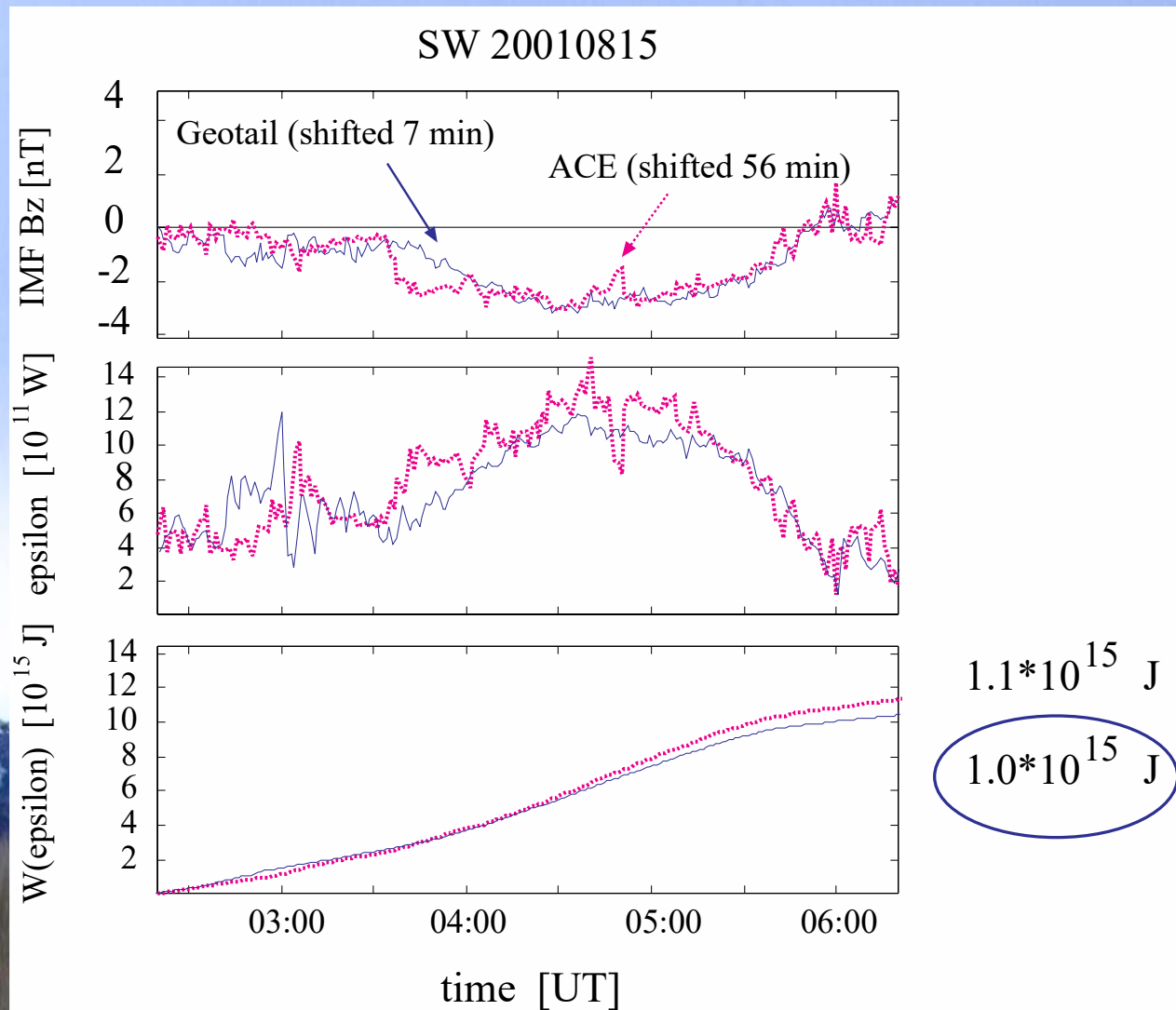
Solar wind data needs to be shifted to the magnetopause before comparing with the magnetospheric measurements.

Most typical methods are:

- (1) Convection shift by an **average velocity** during the event of interest. MOSTLY USED
- (2) Convection shift + **disturbance orientation correction**. Needs data from multiple spacecraft or modeling efforts. NEEDS MULTIPLE SPACECRAFT
- (3) Shifting each data point **separately** → causes non-continuous data. NOT GOOD.
- (4) **Finding signatures** on same structures in other measurements and **estimating the time shift** based on the structures seen. WORKS FOR SINGULAR EVENTS



Convection shifted data



Most asked stuff!
(but all slides are in the oral exam)

Consider and remember!

- **Main differences between storms and substorms**
- **Their energy dissipation channels**
+ avg. and rel. energy in each
- **SW-MS energy coupling function,**
the epsilon parameter
+ avg. magnitude