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.

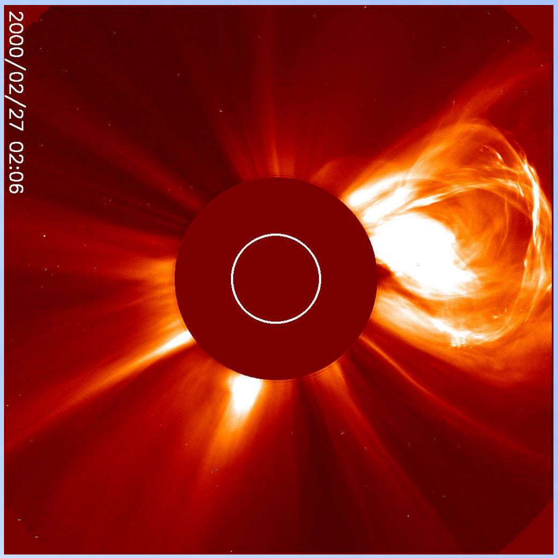
Goal 1:

Understand differences between substorms and geomagnetic storms.

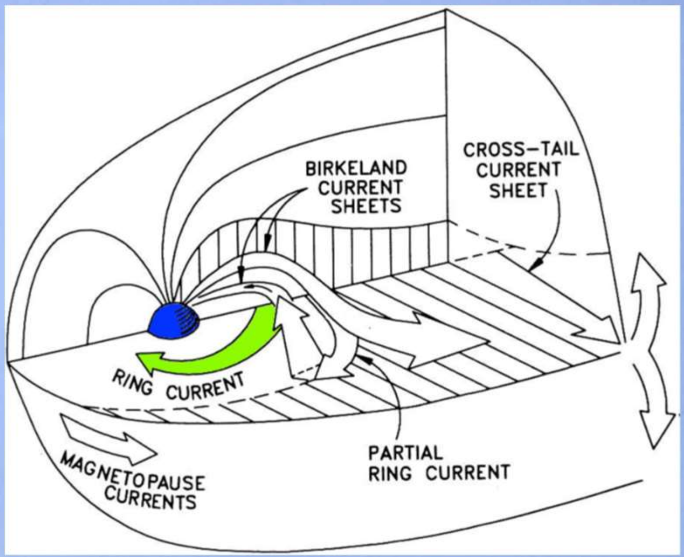
Consider and remember!

- **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

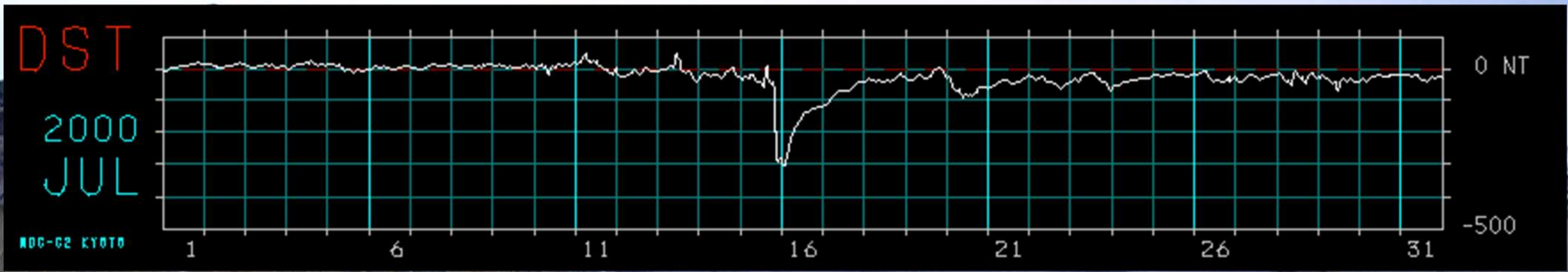
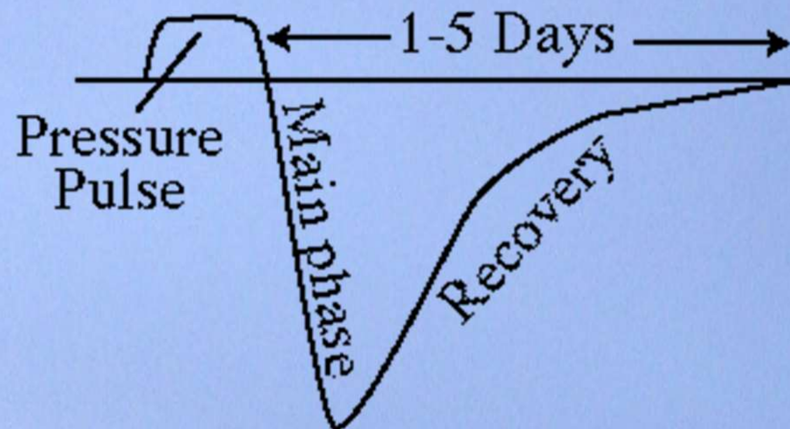


Illustration credit of the magnetosphere figure: David P. Stern

Dst = Disturbance storm time index

Geomagnetic storm

Magnetic field H-component



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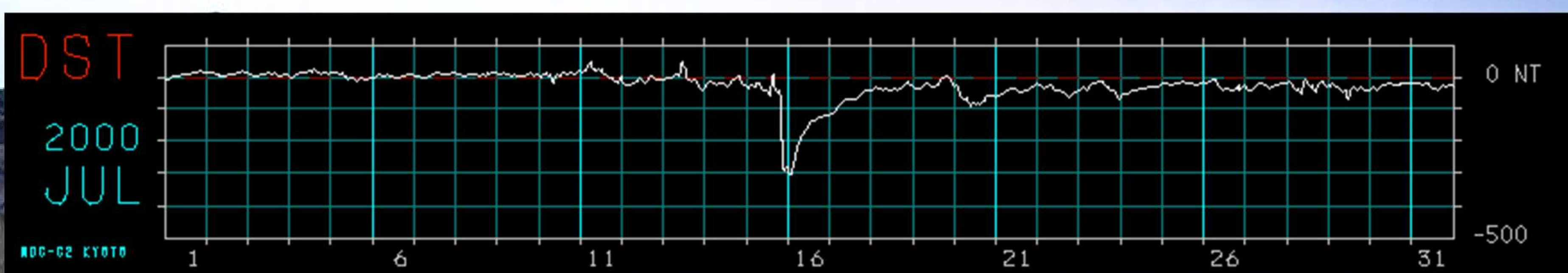
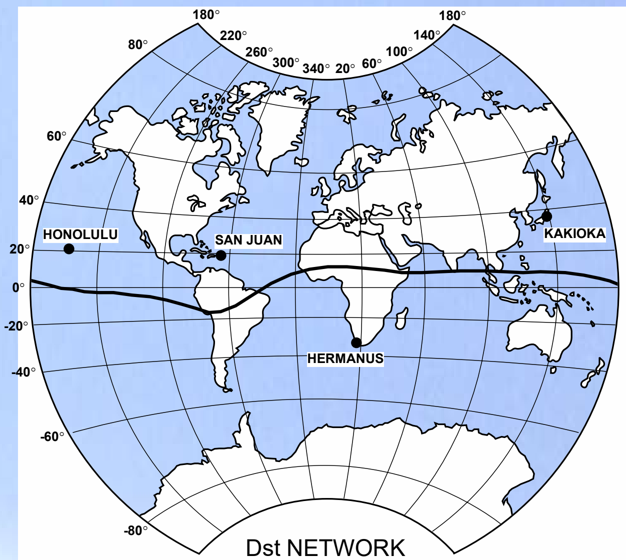
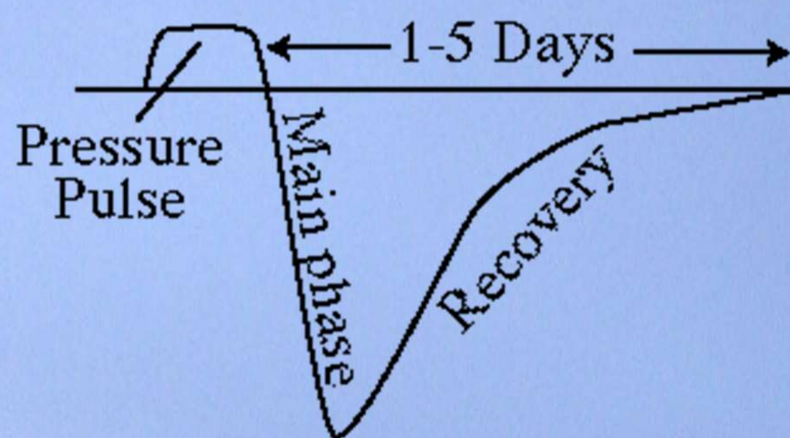


Dst = Disturbance storm time index

Geomagnetic storm



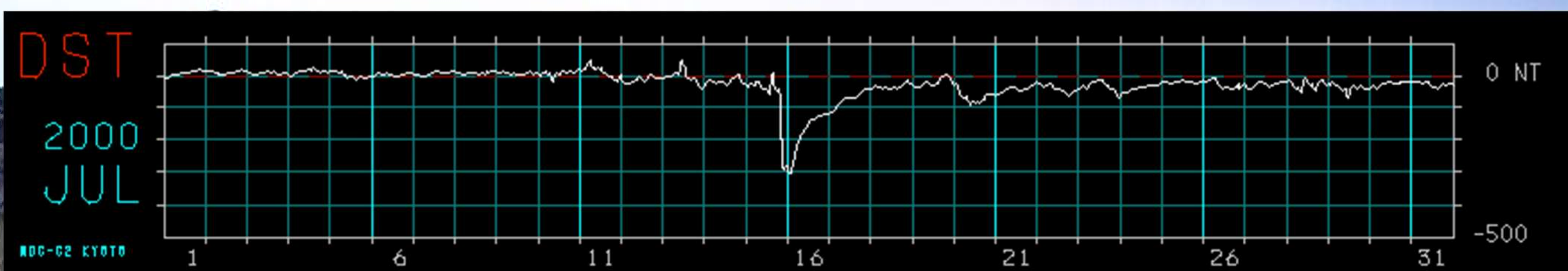
Magnetic field H-component



- Monitored by **Dst index**

→ **-50 nT** or lower for moderate storms

→ **-350 nT** or lower for great storms

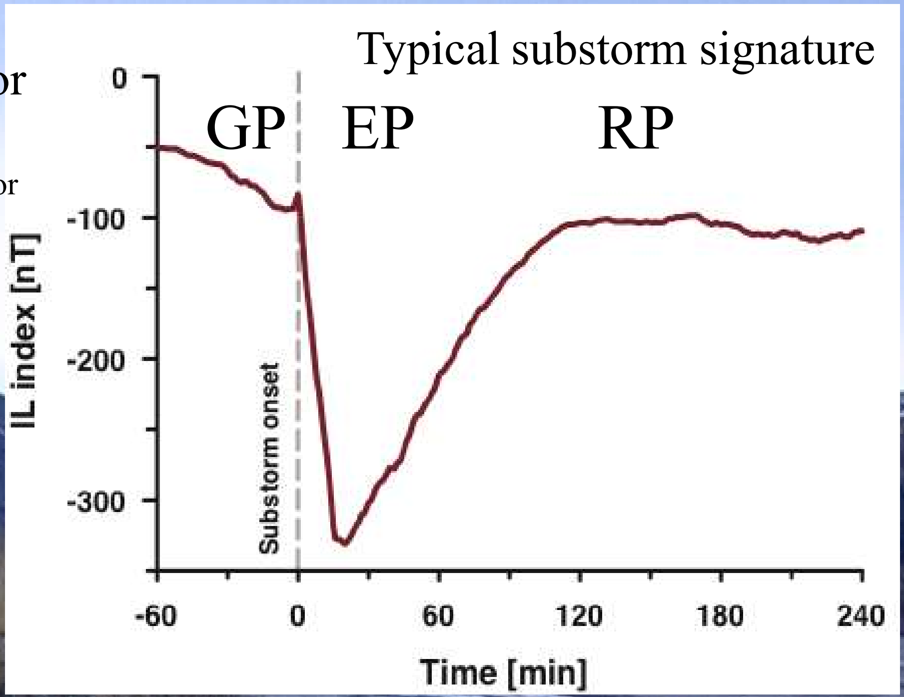


Dst = Disturbance storm time index

Substorm

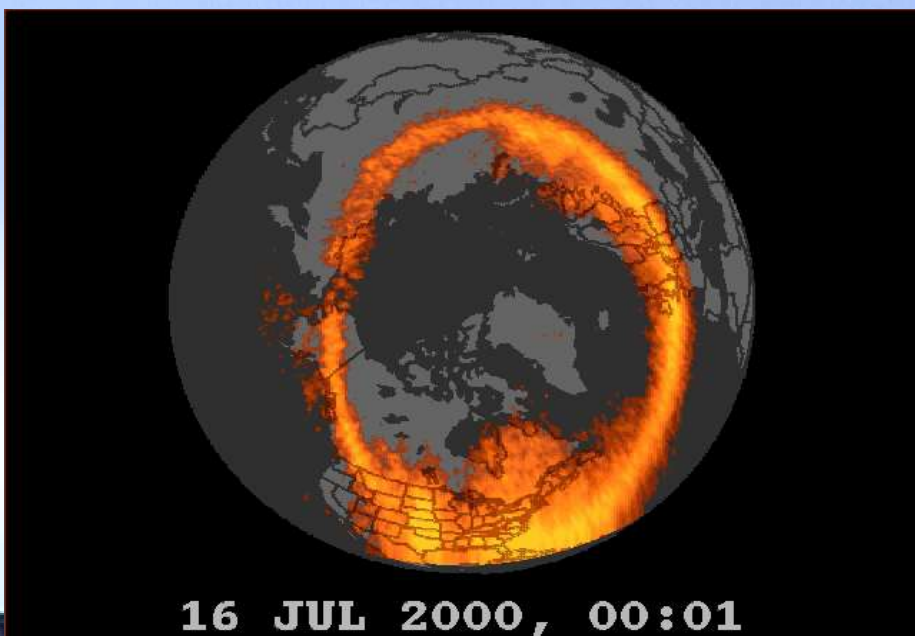
- Disturbance of the auroral electrojet current, **at the auroral oval**.
- **Local phenomenon**: visually detected as aurora, magnetically by the disturbance of the magnetic field.
- **All substorms are different**, there is no “normal” substorm. Statistical properties can be computed, but they need 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)

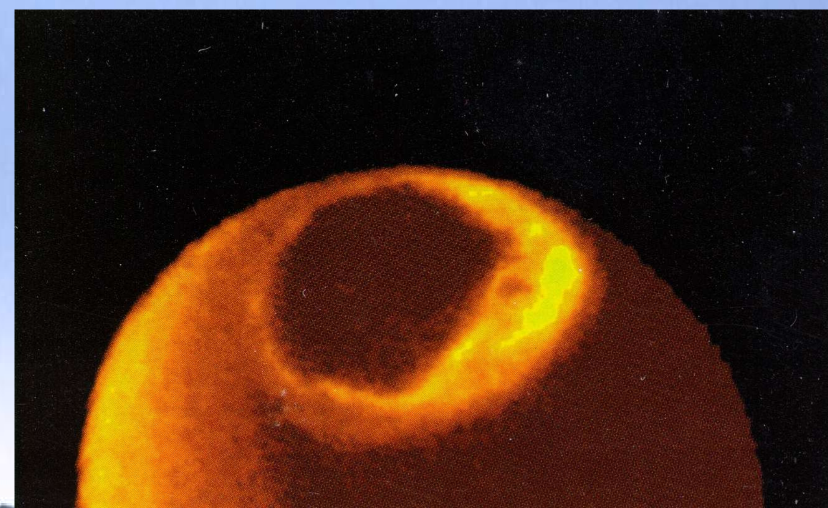


Auroral oval during storms & substorms

Storms

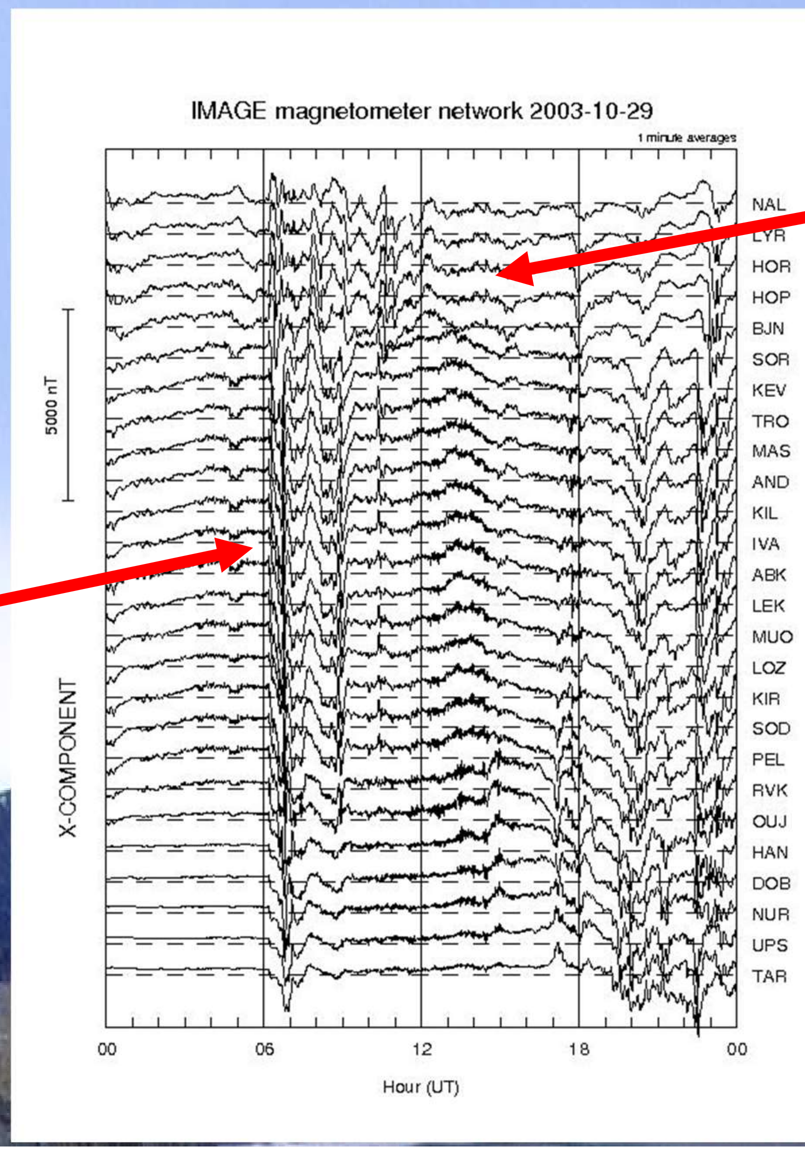


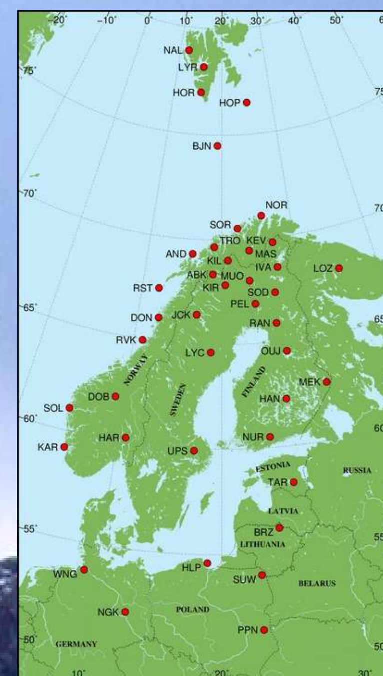
Substorms



Storm-time activity at high latitudes

Pulsations

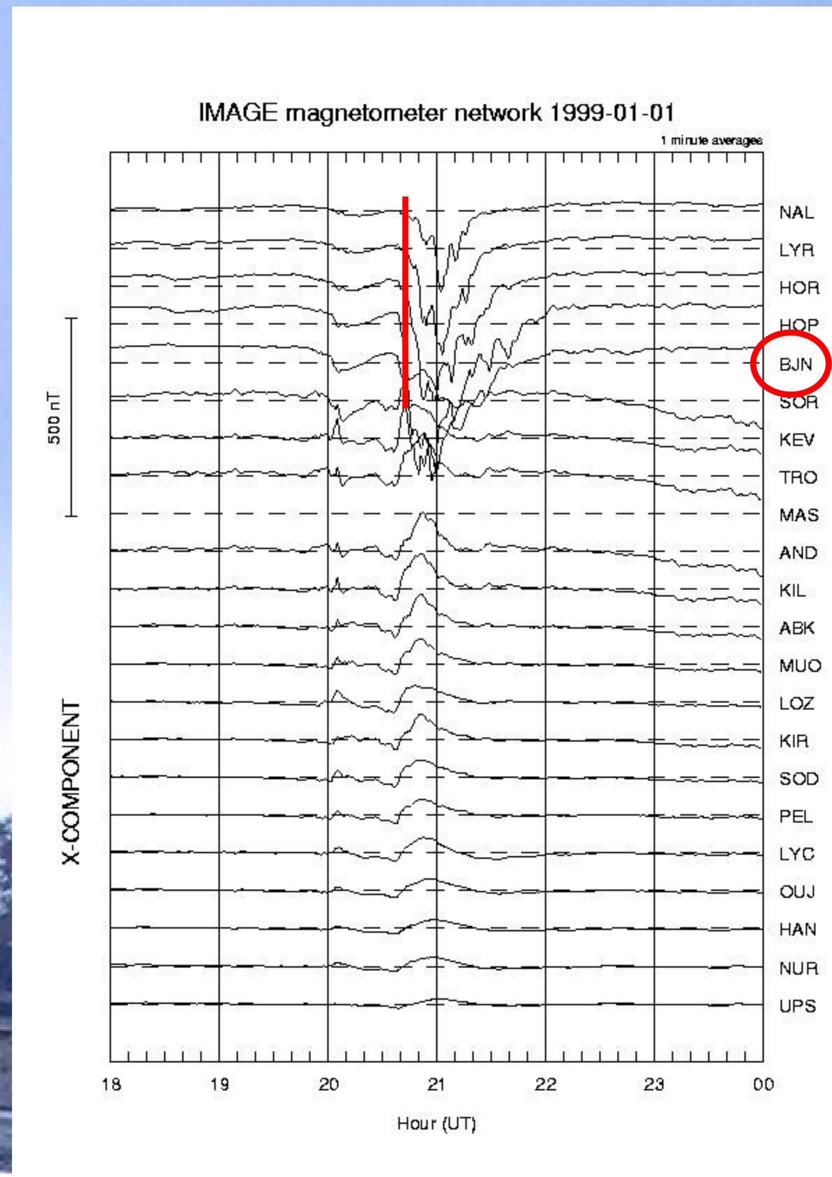




Storm-time substorms

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 nT
- Duration ~ 2 hours 30 min

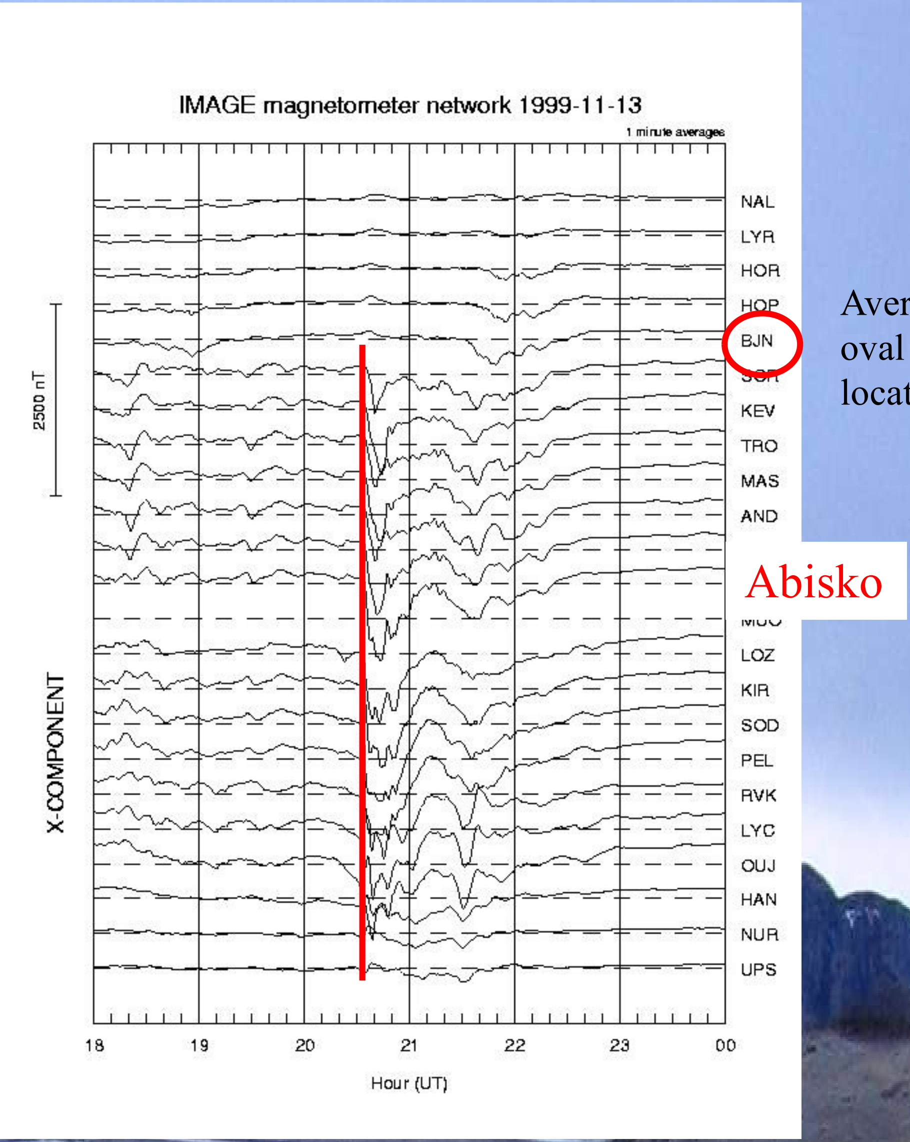


Average oval location

Abisko

Substorm at equatorward oval edge

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

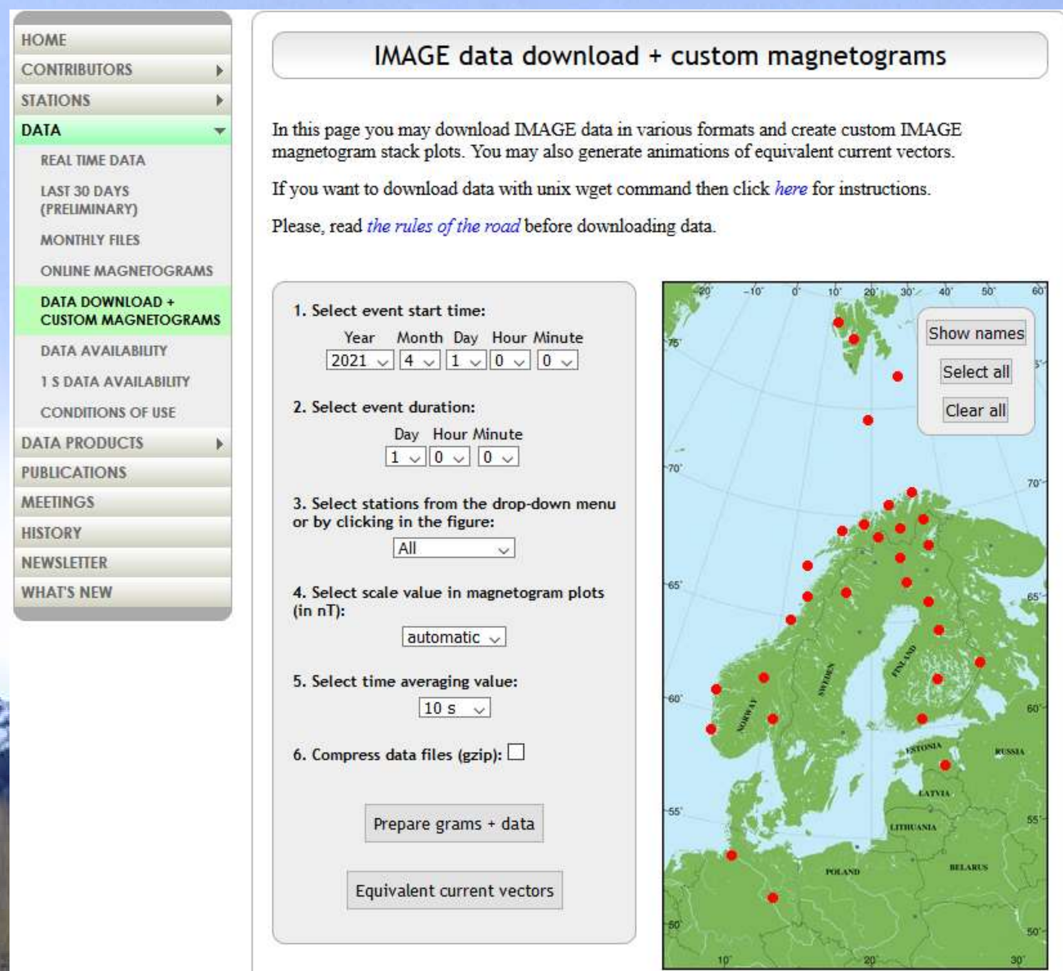


Average oval location

Where to find magnetograms?

https://space.fmi.fi/image

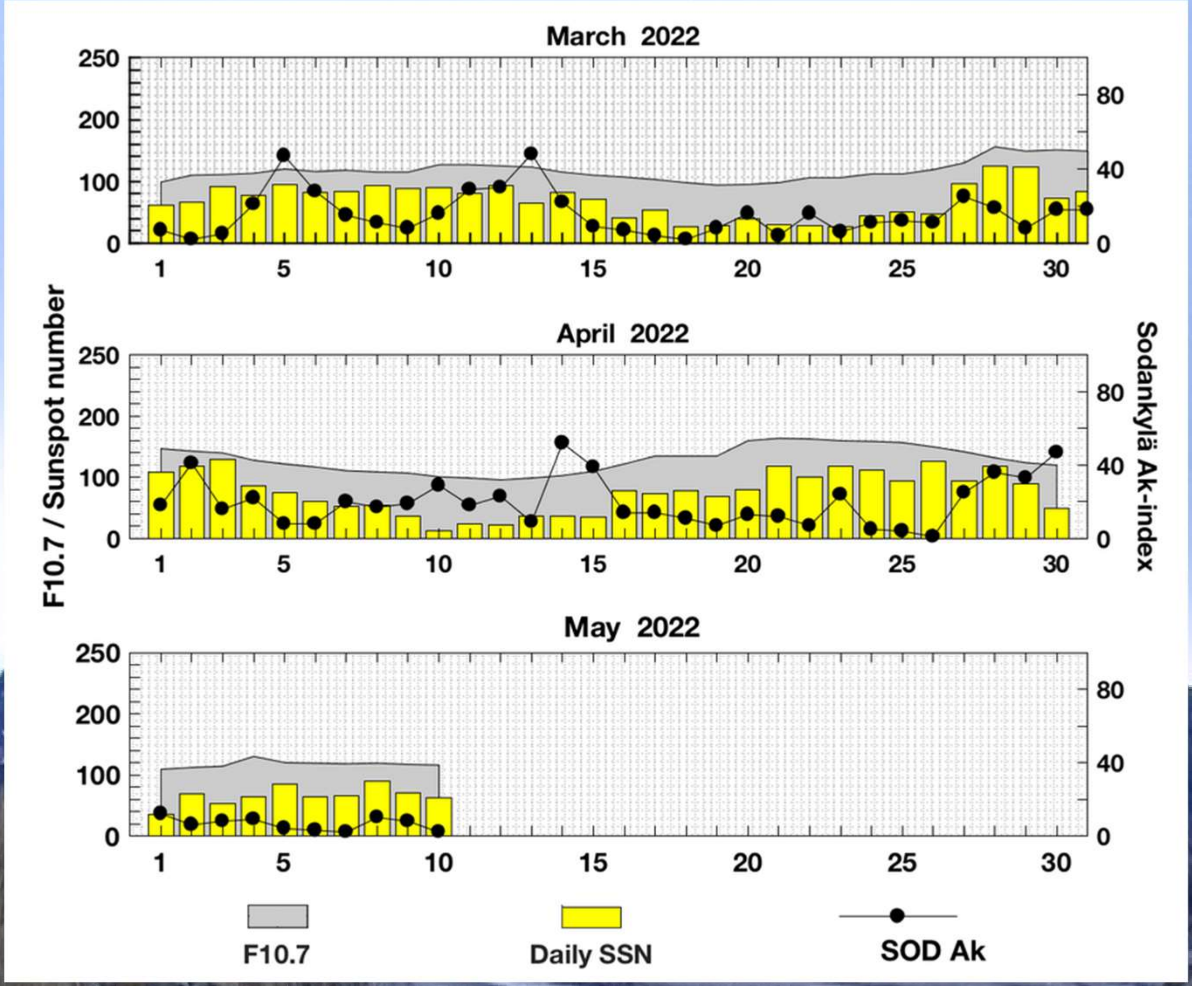
→ Data



Where to find magnetograms?

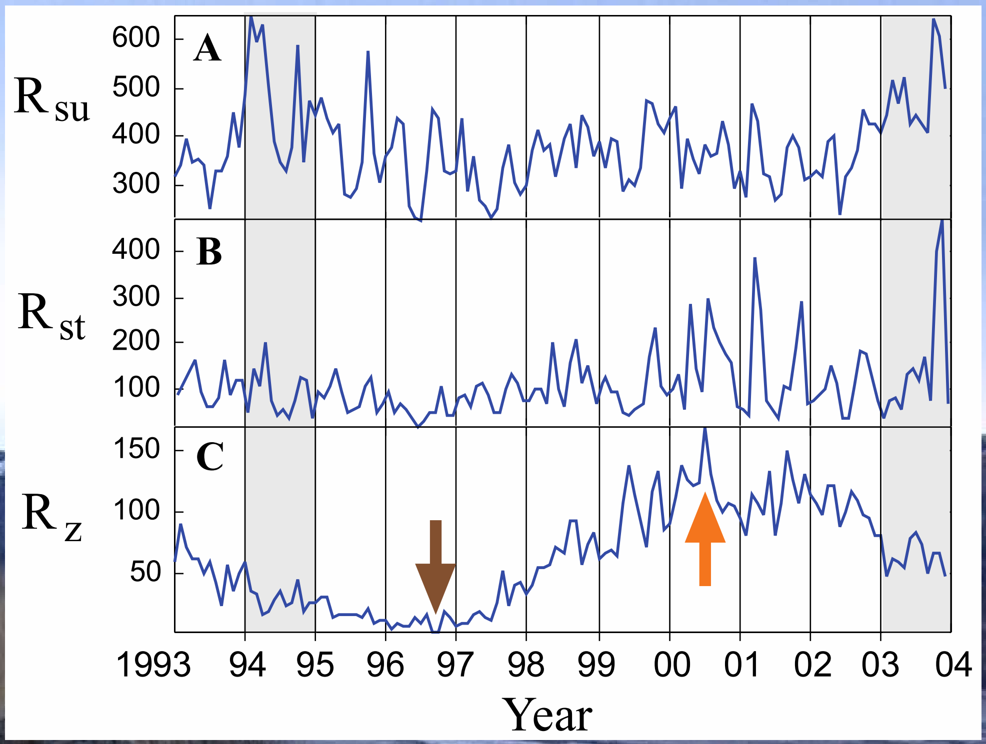
https://www.sgo.fi/Data/

→ Latest data → Magnetometer



Year-to-year comparison: storms and substorms

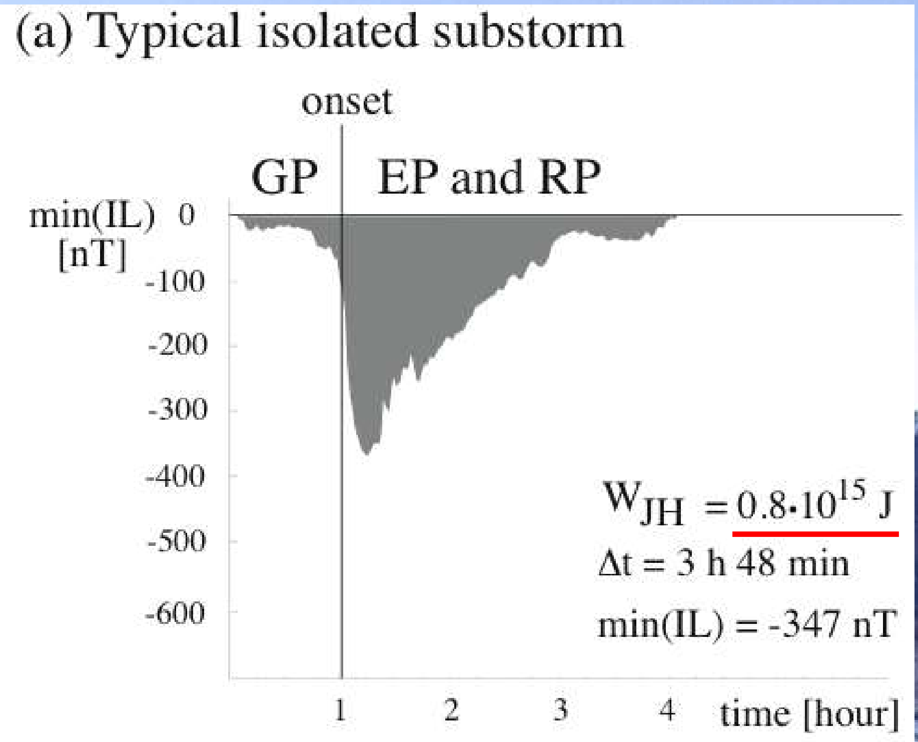
- Substorm activity peaks at declining solar cycle phase
  - …but it's always there.
- Storm activity typically maximizes around solar maximum.
  - Almost ceases during solar minimum.

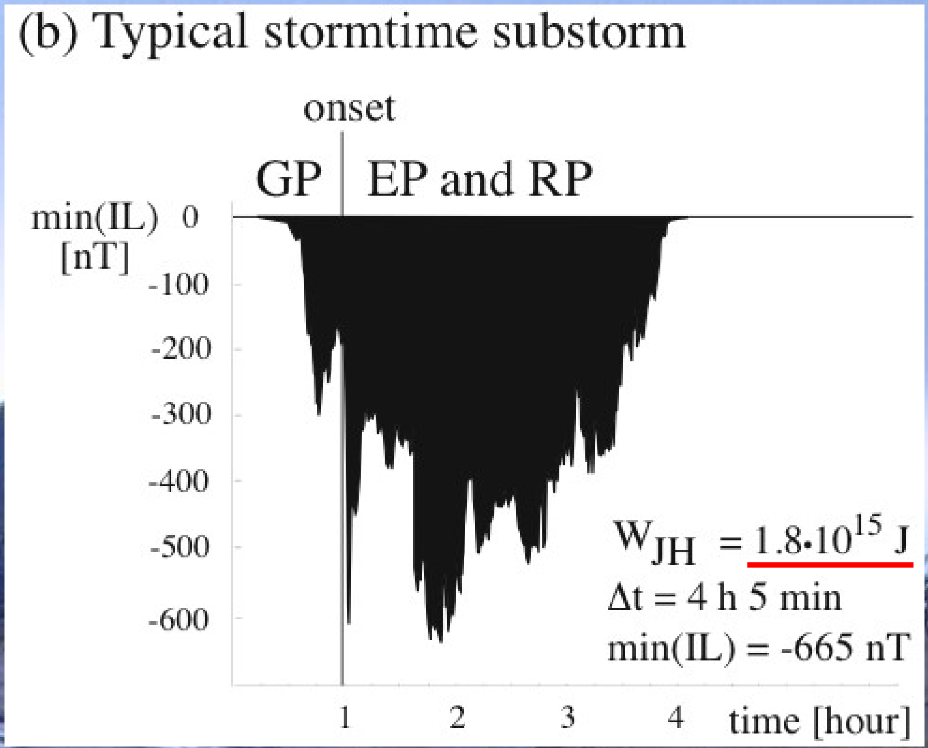


Storm-time and non-storm substorms

- 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.





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)

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.

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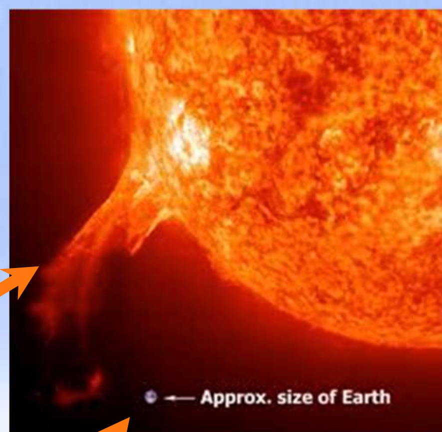
Understand where substorm energy originates from and how does it circulate in the magnetosphere.

Consider during this part of the lecture!

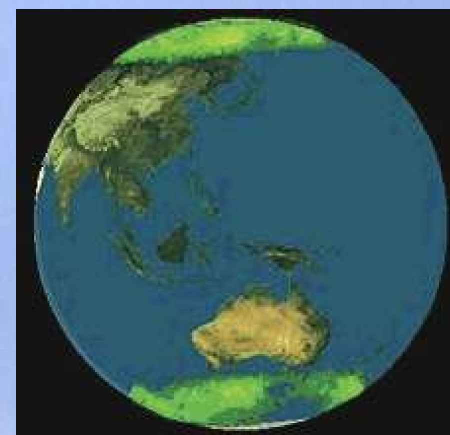
1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)

Solar sources of substorm energy

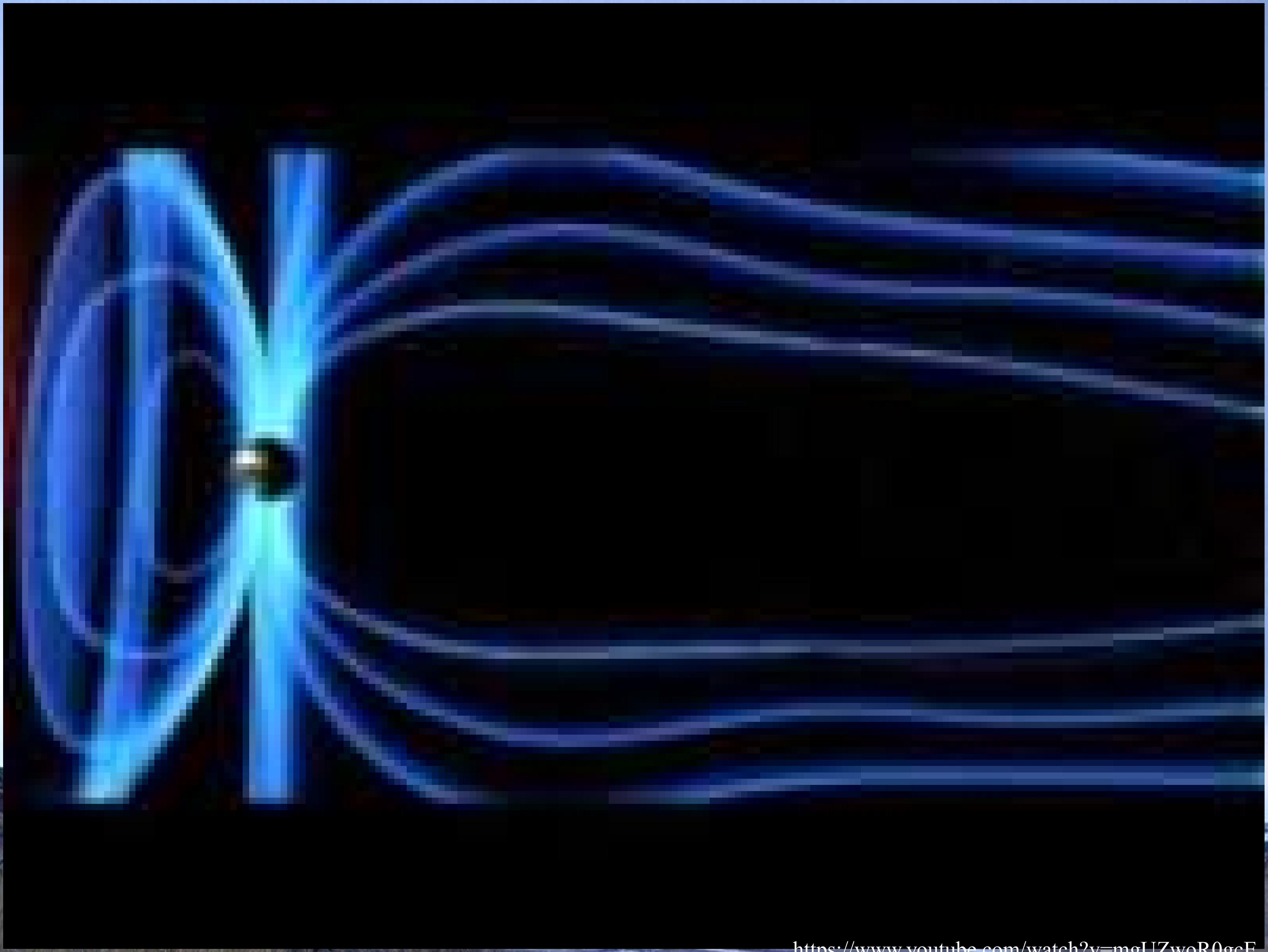


Solar disturbance

The Earth

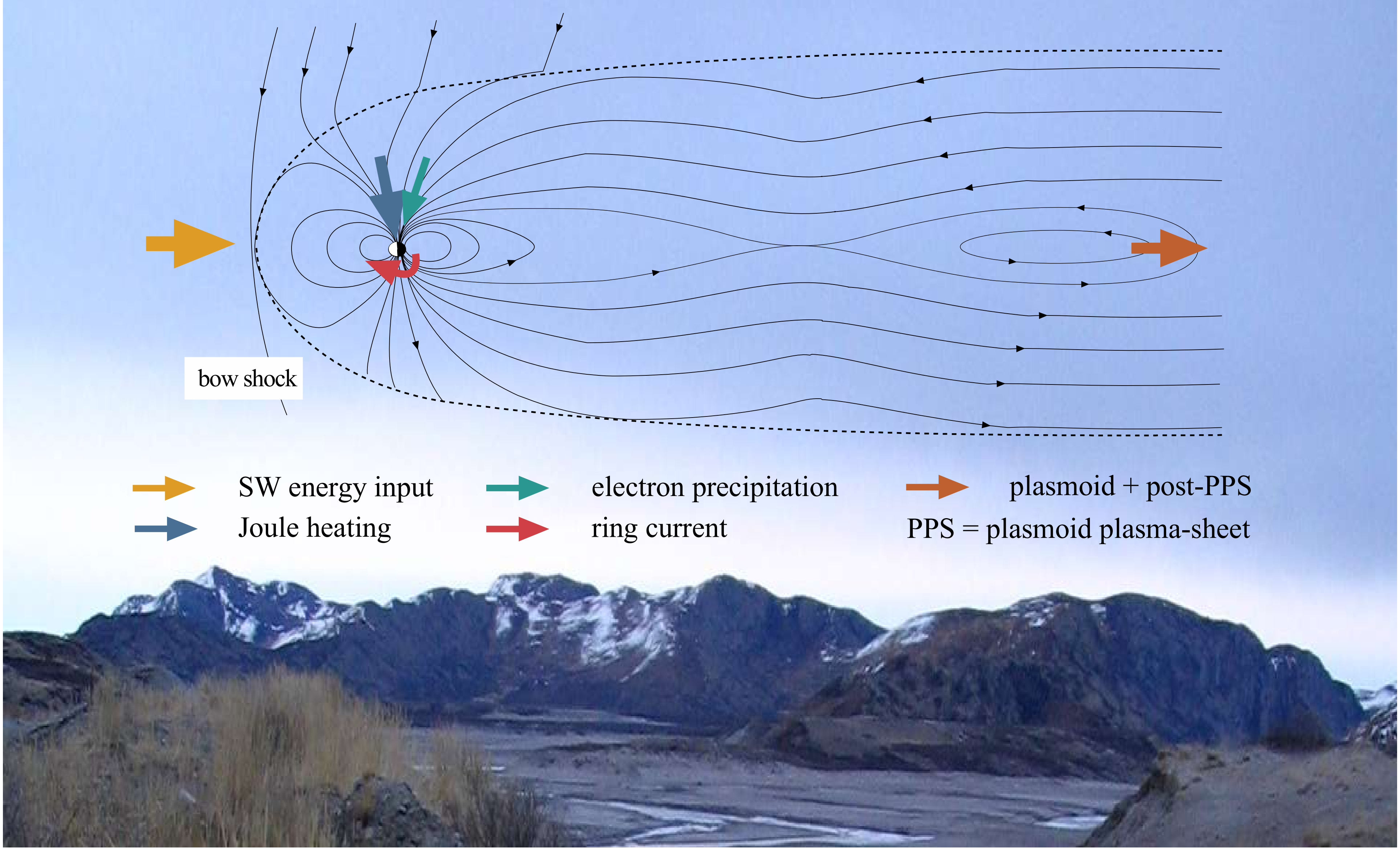


Auroral ovals

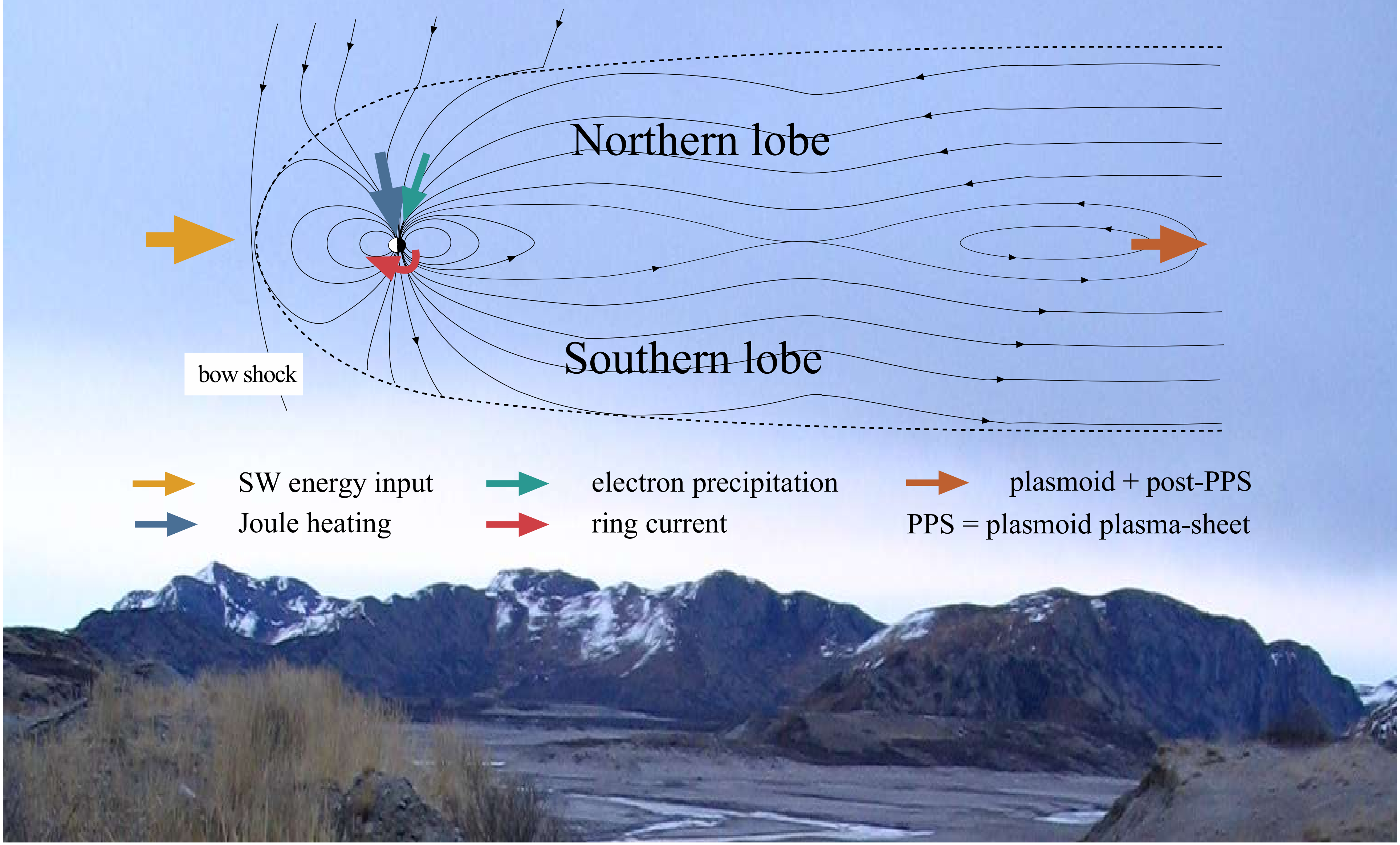


https://www.youtube.com/watch?v=mgUZwoR0gcE

Substorm energetics: input and sinks



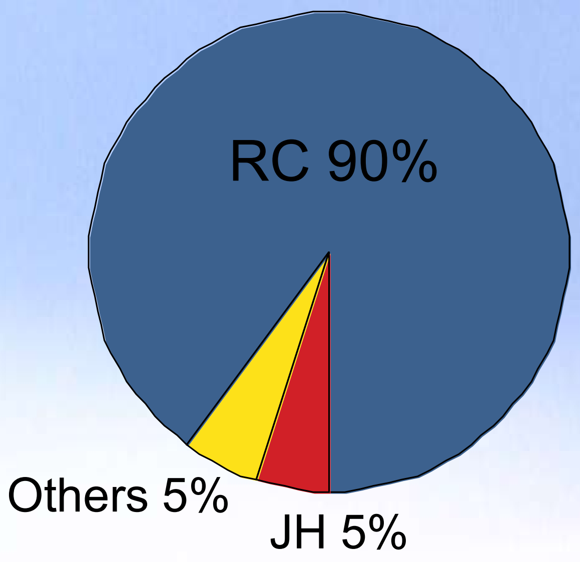
Magnetotail lobes store magnetic energy



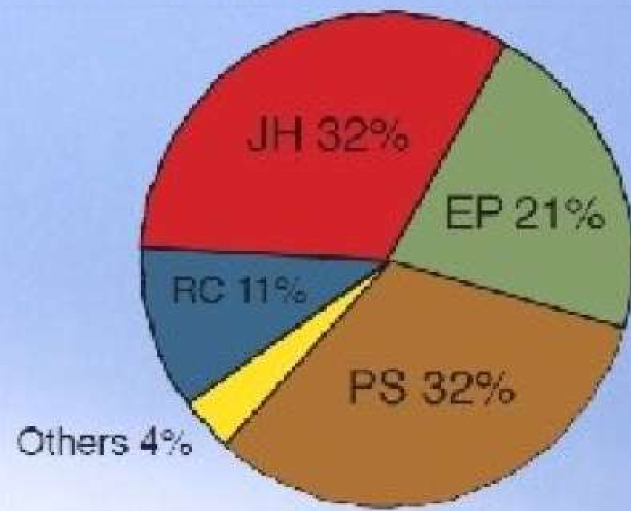
super-important!

Energy pie for storms and substorms

Typical storm energy pie:

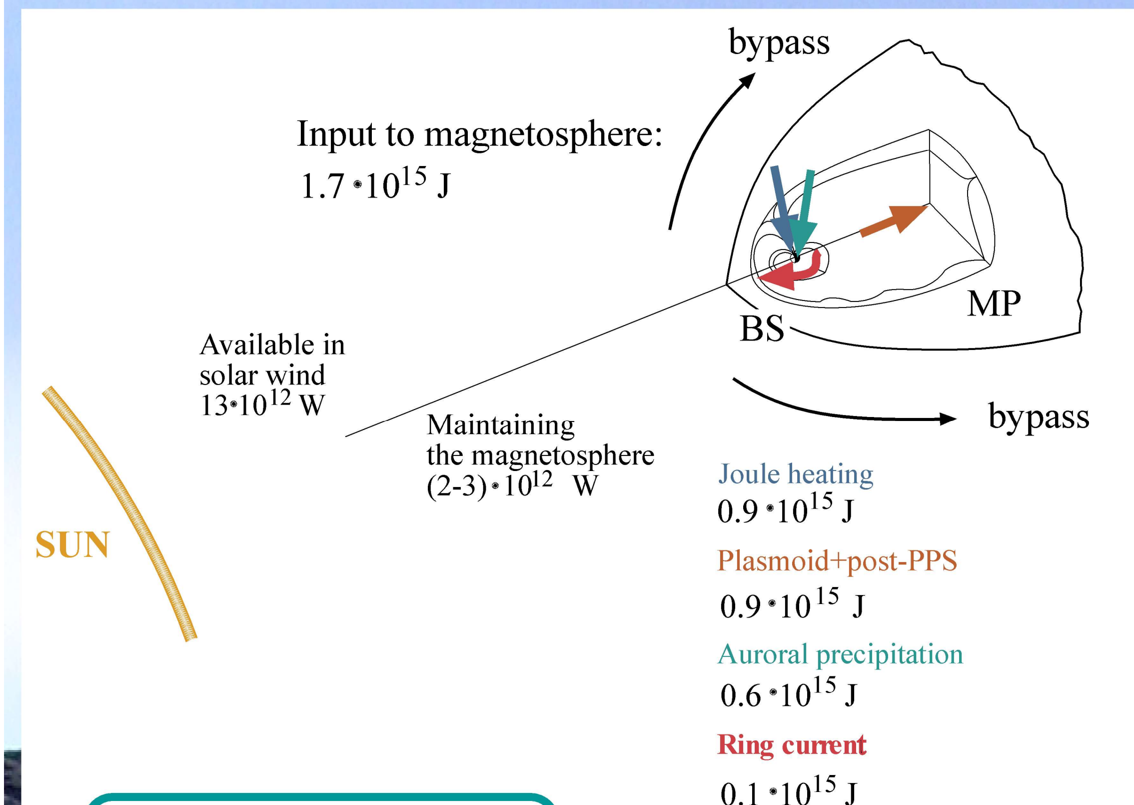


Typical substorm energy pie:



RC = Ring current
JH = Joule heating (electric currents through atmosphere)
EP = Electron precipitation
PS = (Magnetospheric) Plasma sheet heating

Storm-substorm energy budget



Compare to storms:

Input (4-25)$\bullet 10^{16}$ J

Total dissipation (10-21)$\bullet 10^{16}$ J

Total dissipation $2.5 \bullet 10^{15}$ J

$\approx 1.7 \cdot 10^{11}\ W$

- Joule heating estimate

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

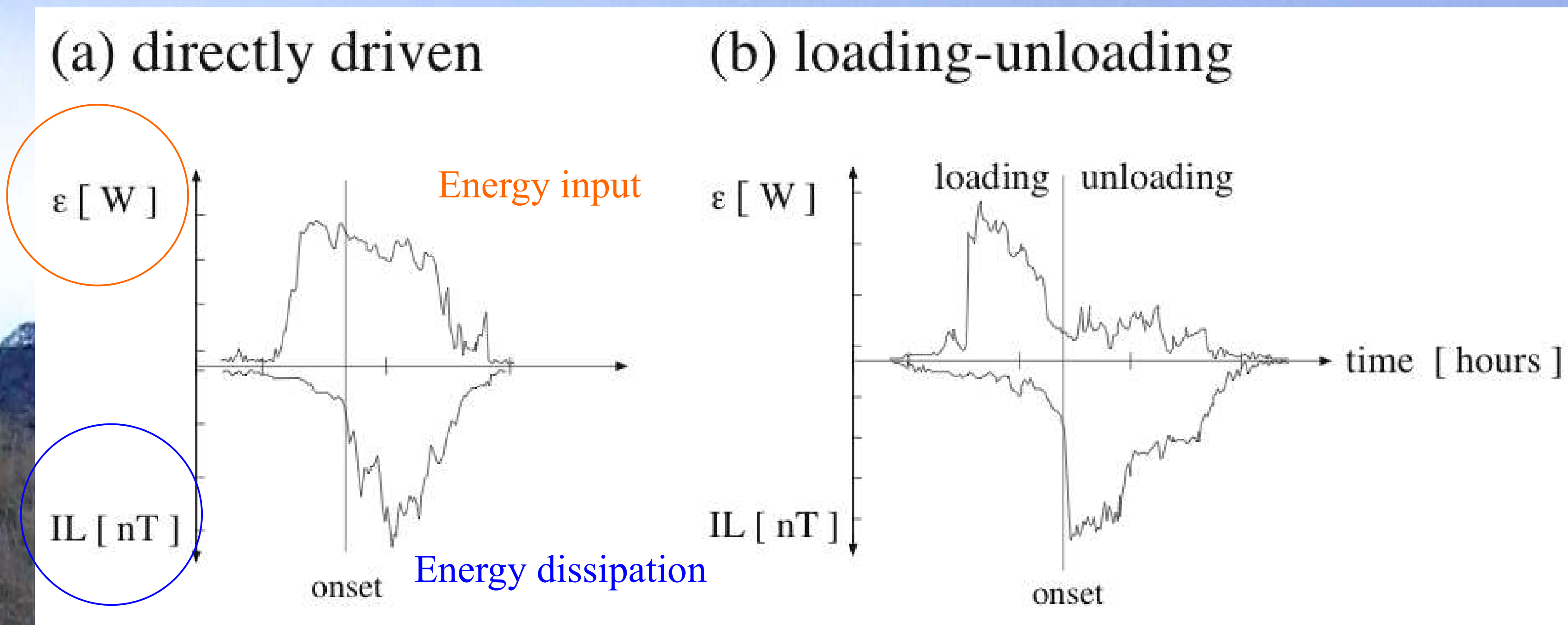
- Electron precipitation estimate

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

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

Loading-unloading processes

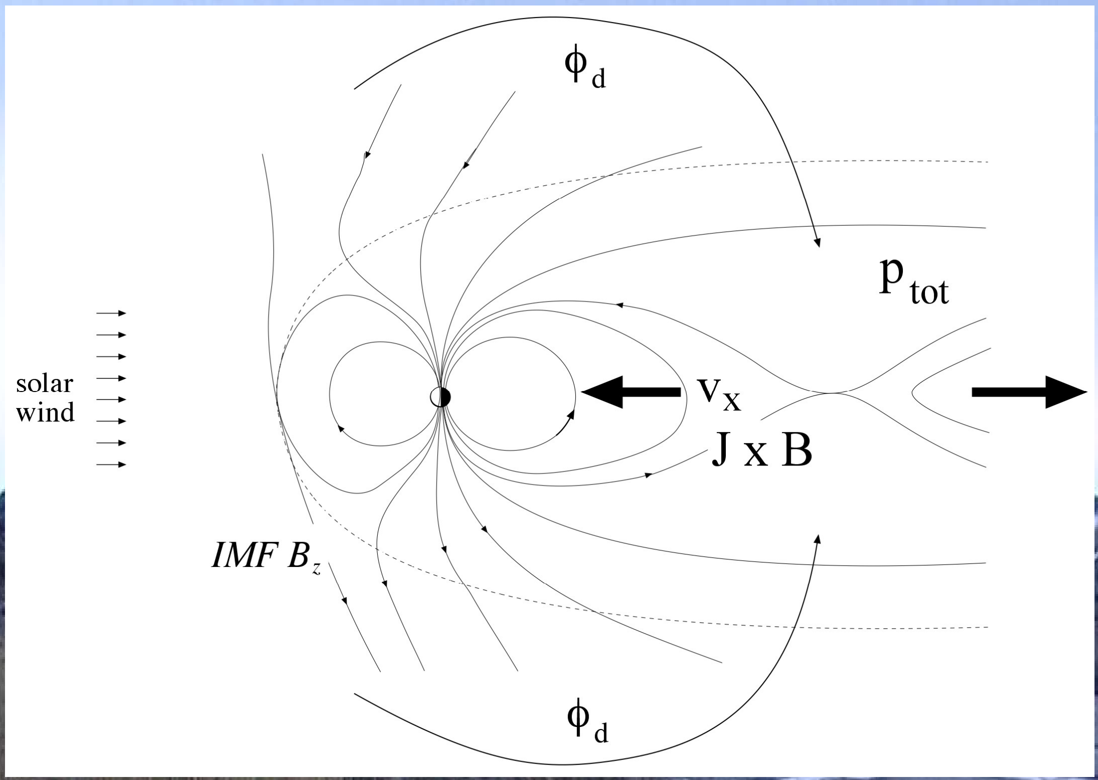
- Over 80% of substorms are directly powered by solar wind (i.e. type a).
- Substorm growth phase is necessary for preconditioning the magnetotail to allow a global instability to grow.
- Size of substorm depends on mostly of the energy dissipated in substorm expansion phase.



Magnetotail convection modes

Four magnetospheric convection modes:

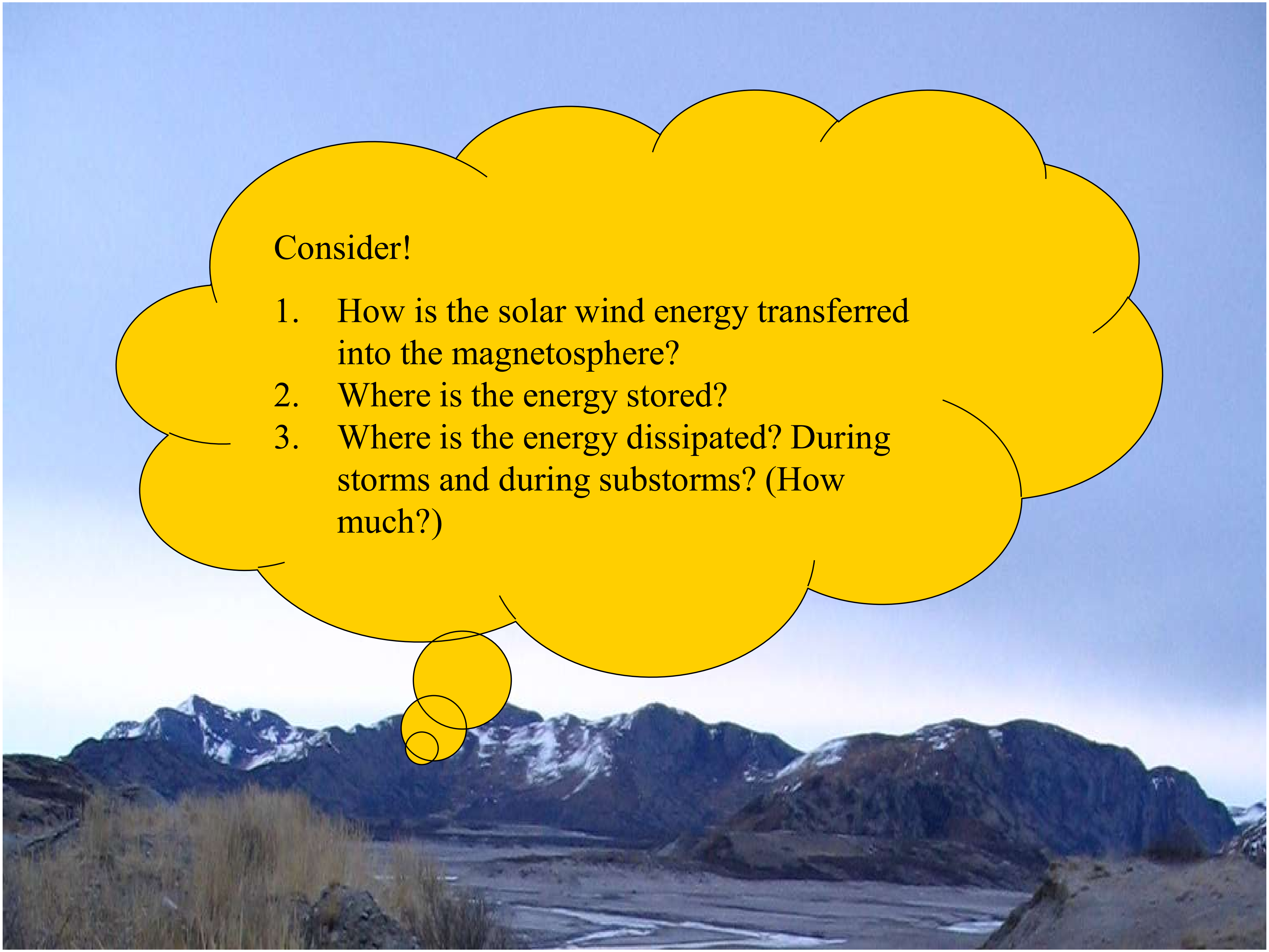
(1) Loading: magnetic flux ϕ_d into magnetosphere
(2) Unloading: magnetic flux and particle flows towards the Earth
(3) Continuous magnetospheric dissipation, CMD: continuous flux flow from SW to Earth
(4) Steady magnetospheric convection, SMC: continuous and steady flux flow



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

Consider!

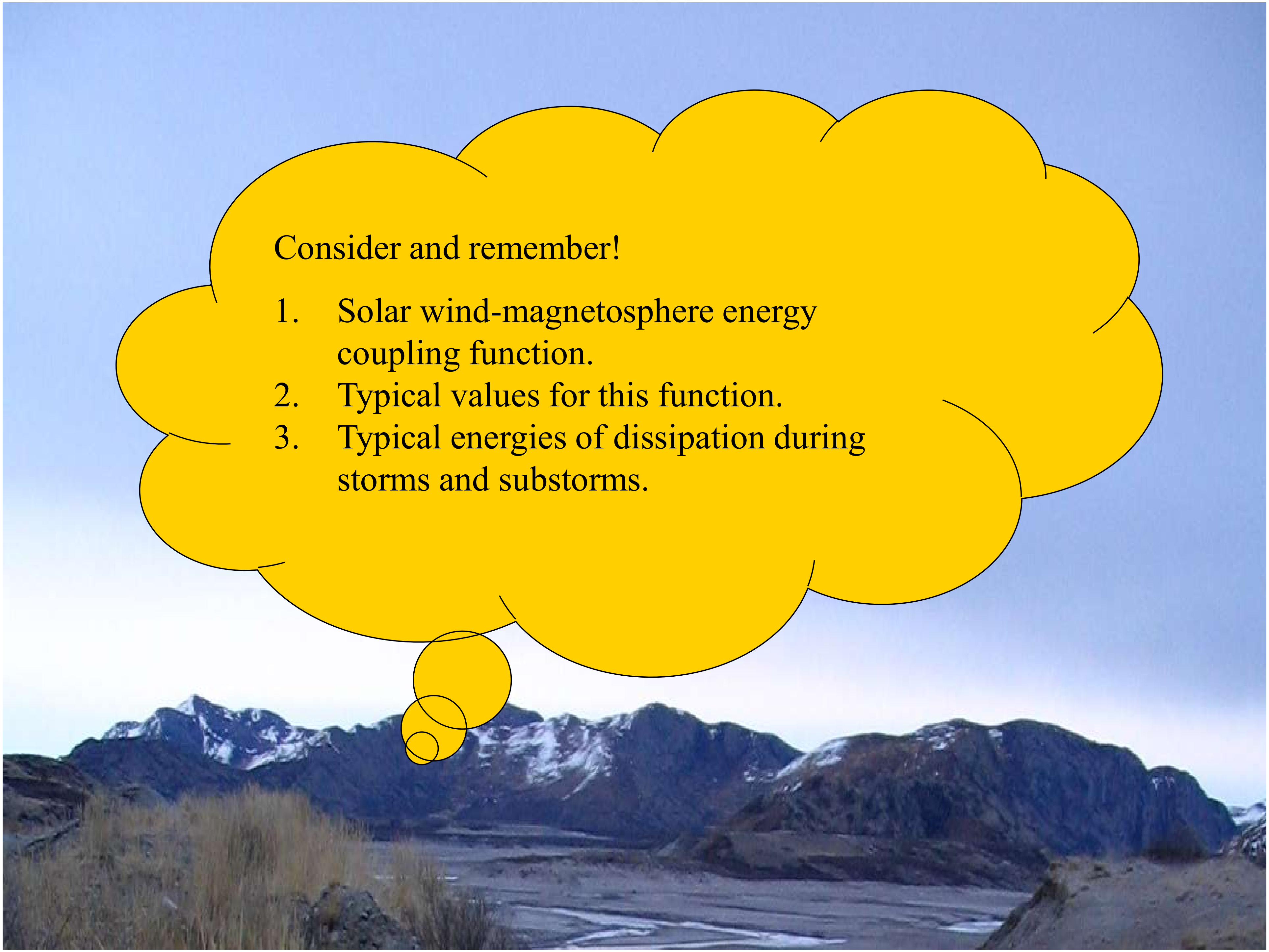
1. How is the solar wind energy transferred into the magnetosphere?
2. Where is the energy stored?
3. Where is the energy dissipated? During storms and during substorms? (How much?)



Goal 3:

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

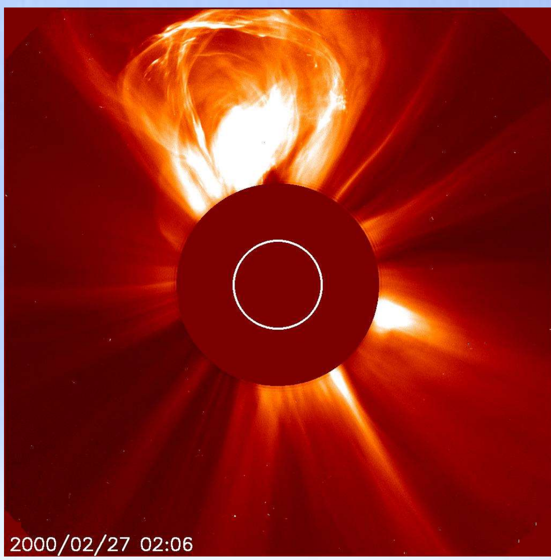
Reference: Weiss, L.A, P.H. Reiff, J.J. Moses et al., Energy dissipation in substorms, Proceedings of the International Conference on Substorms (ICS-1), Kiruna, May 1992.



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 → Kinetic energy
  - Magnetic field: B → Magnetic energy
  - Size of the magnetosphere l_0 → Cross-section for energy channels
  - Magnetic field clock angle $\theta = \tan^{-1}(B_y/B_z)$ → 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.

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

- 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 x $\mathbf{10^{15}\ J}$.

Energy input , W_ε

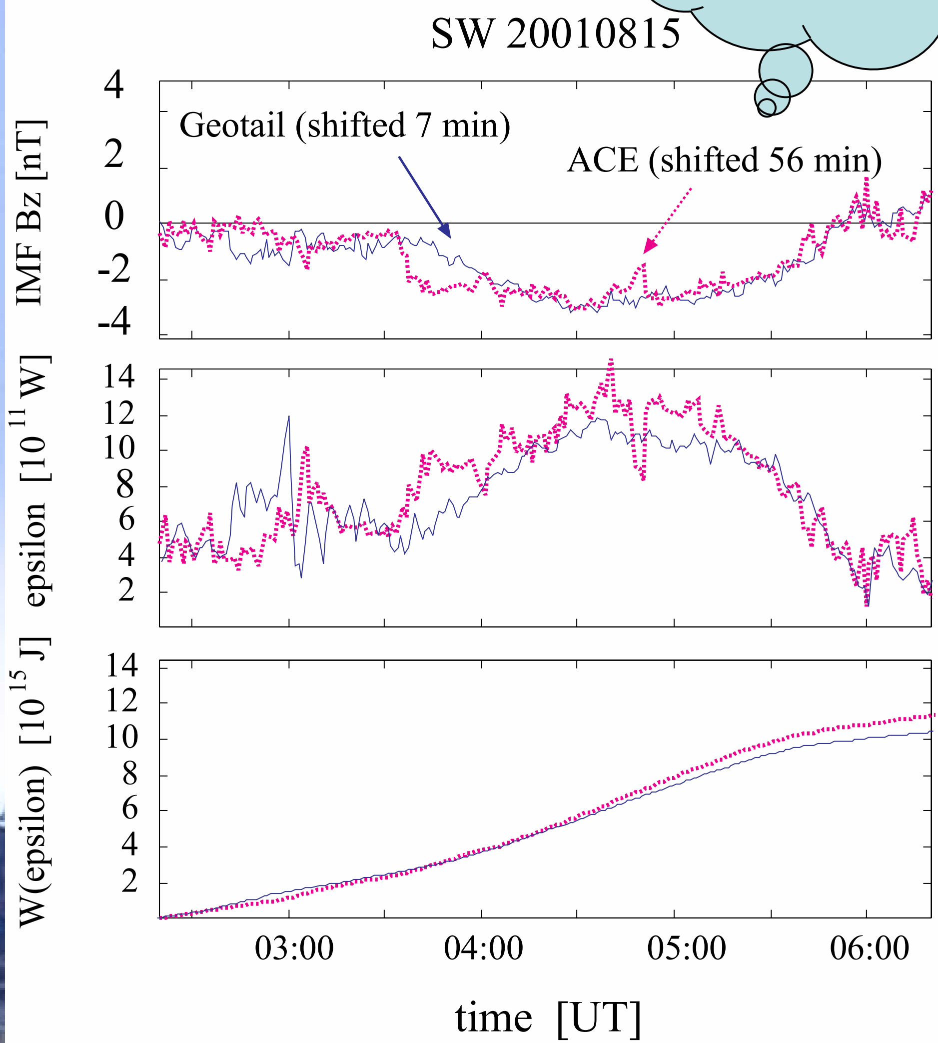
Shifting data will be studied few slides later.

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

$$\varepsilon = 10^7 vB^2 \sin^4(\theta/2) \cdot l_0^2$$
$$where \quad l_0 = 7R_E$$

Total energy input:

$$W_\varepsilon = \int \varepsilon\, dt$$



$1.1*10^{15}$ J

$1.0*10^{15}$ J

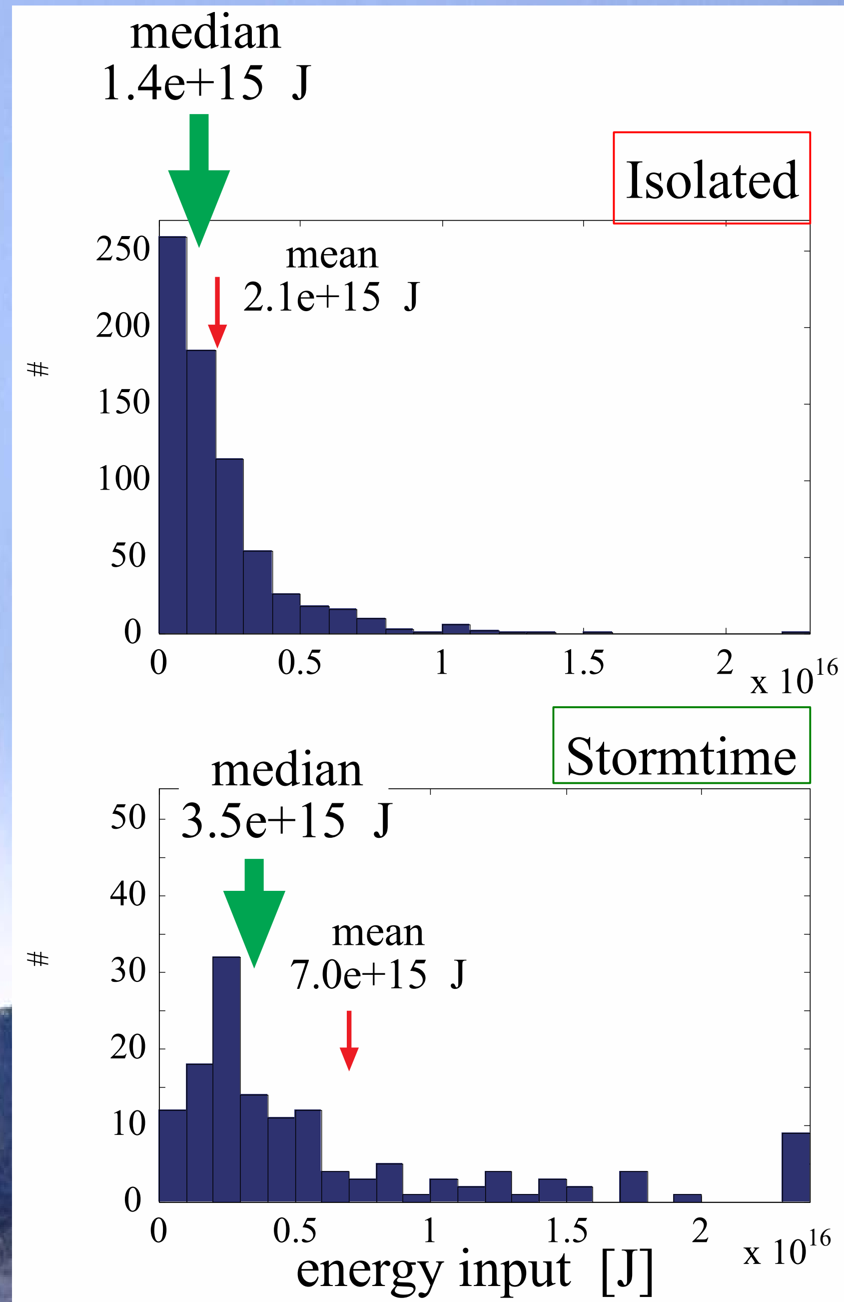
Typical energy input

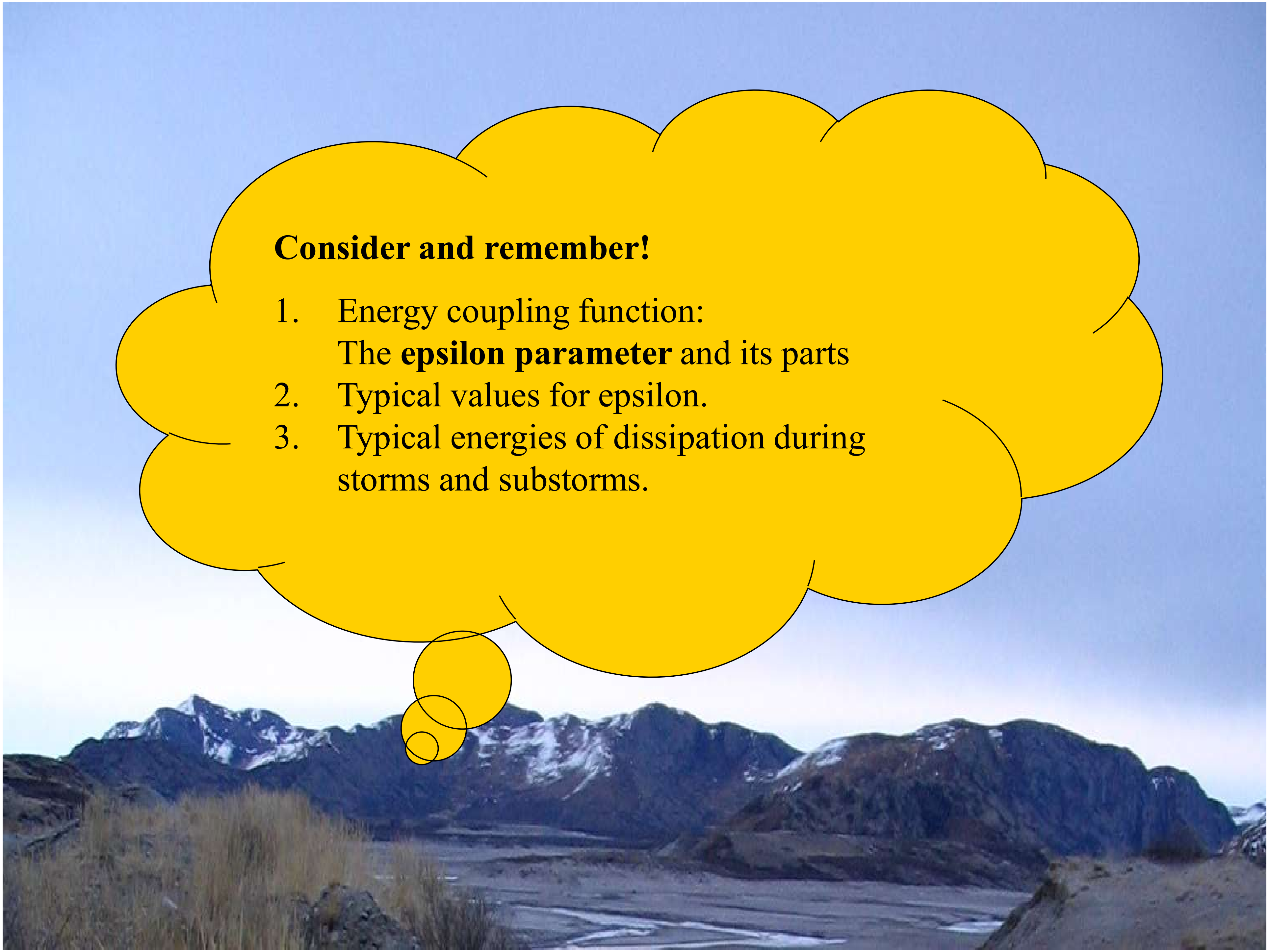
Isolated substorm =
Substorm that occur when
storm-index Dst > -50 nT
i.e. no simultaneous storms.

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.

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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:

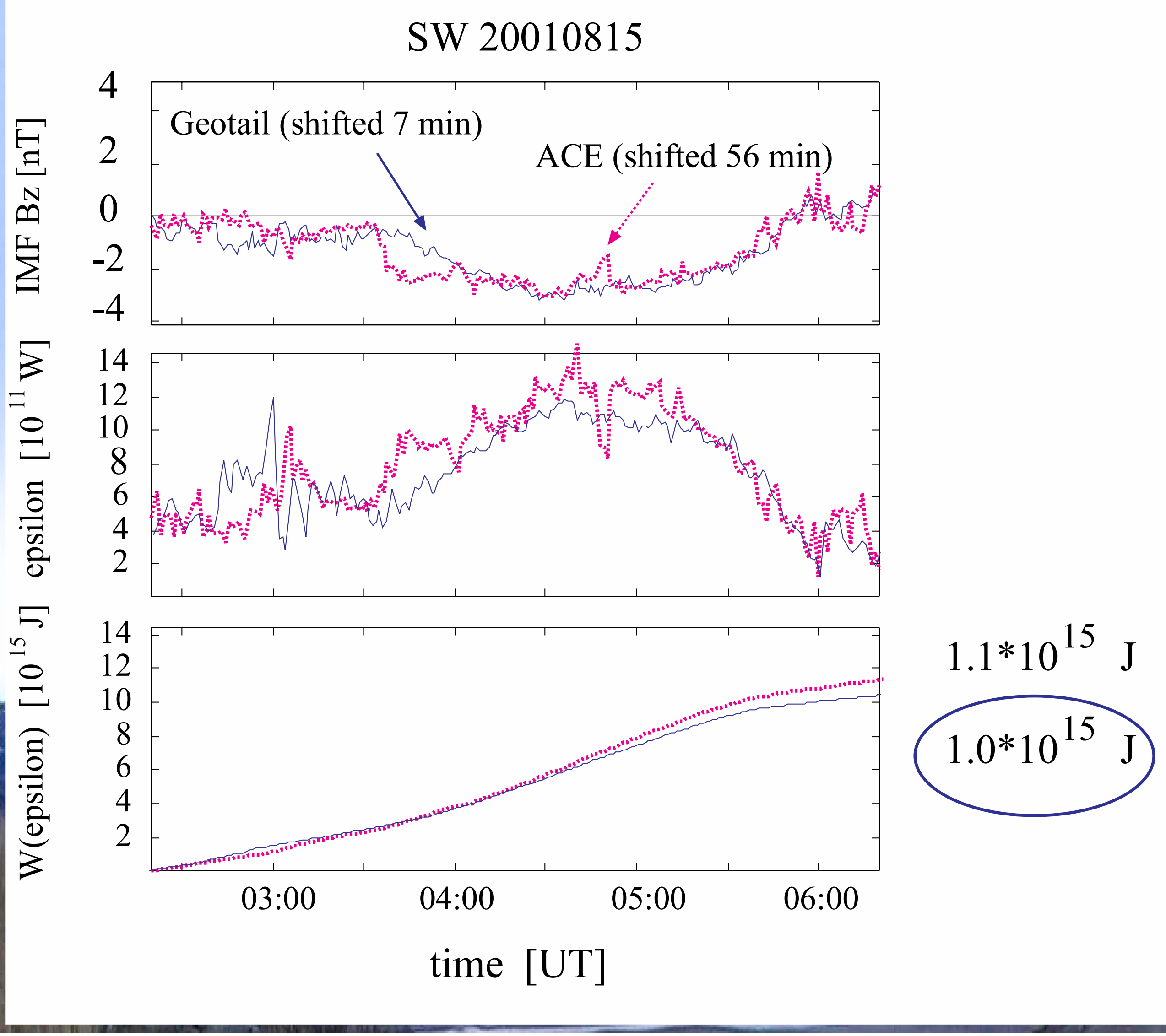
(1) Convection shift by an **average velocity** during the event of interest. MOSTLY USED

(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