The Solar wind - magnetosphere - ionosphere interaction

Research seminar on Sun-Earth connections

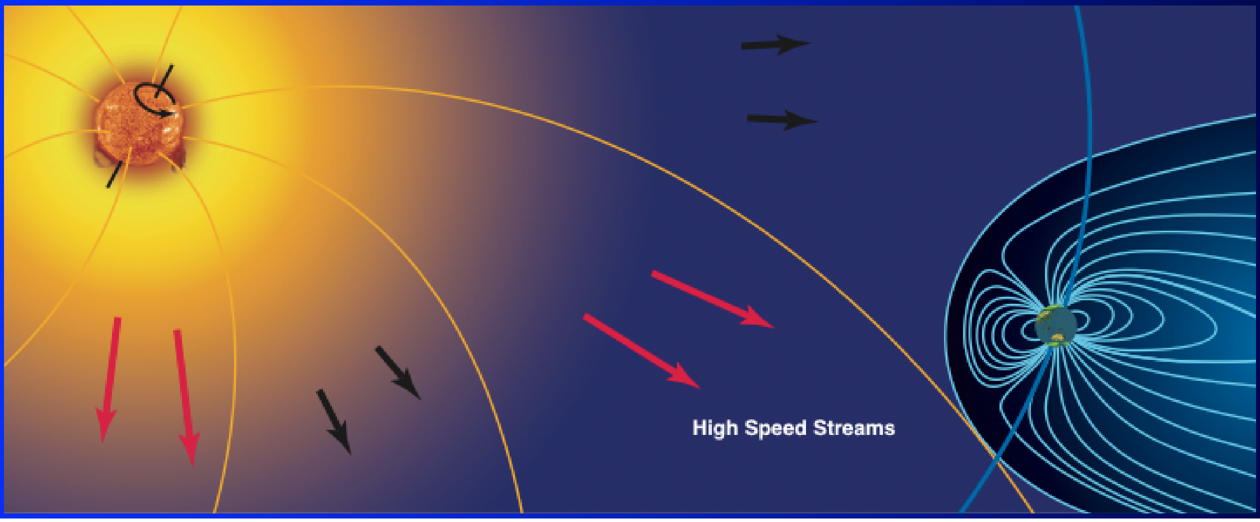
Eija Tanskanen

Friday January 27, 2006

12-14 a.m., D115

Outline

1. Basics of the Earth's magnetosphere and ionosphere
2. Magnetospheric dynamics
    - storms,
    - substorms and
    - continuous magnetospheric dissipation
3. Geoeffective solar wind parameters
4. Global energy flow
5. What causes variations in the Earth's dynamics?
    - Geoeffective solar wind structures
    - State of the Sun
    - Earth's position in the heliosphere: location and orientation
    - Heliosphere's position in the interstellar media



Terminology

- Solar wind-magnetosphere interaction

  Interaction between magnetosphere and solar wind (including materia originating beyond the heliosphere).

- Solar wind -magnetosphere - ionosphere interaction

  Interaction between solar wind and magnetosphere including phenomena in the lower part of magnetosphere (called ionosphere).

- Sun-Earth's magnetosphere interaction

  Relationship between phenomena originating at the Sun and phenomena existing at the Earth's magnetosphere and ionosphere.

- Geoeffective solar wind structures

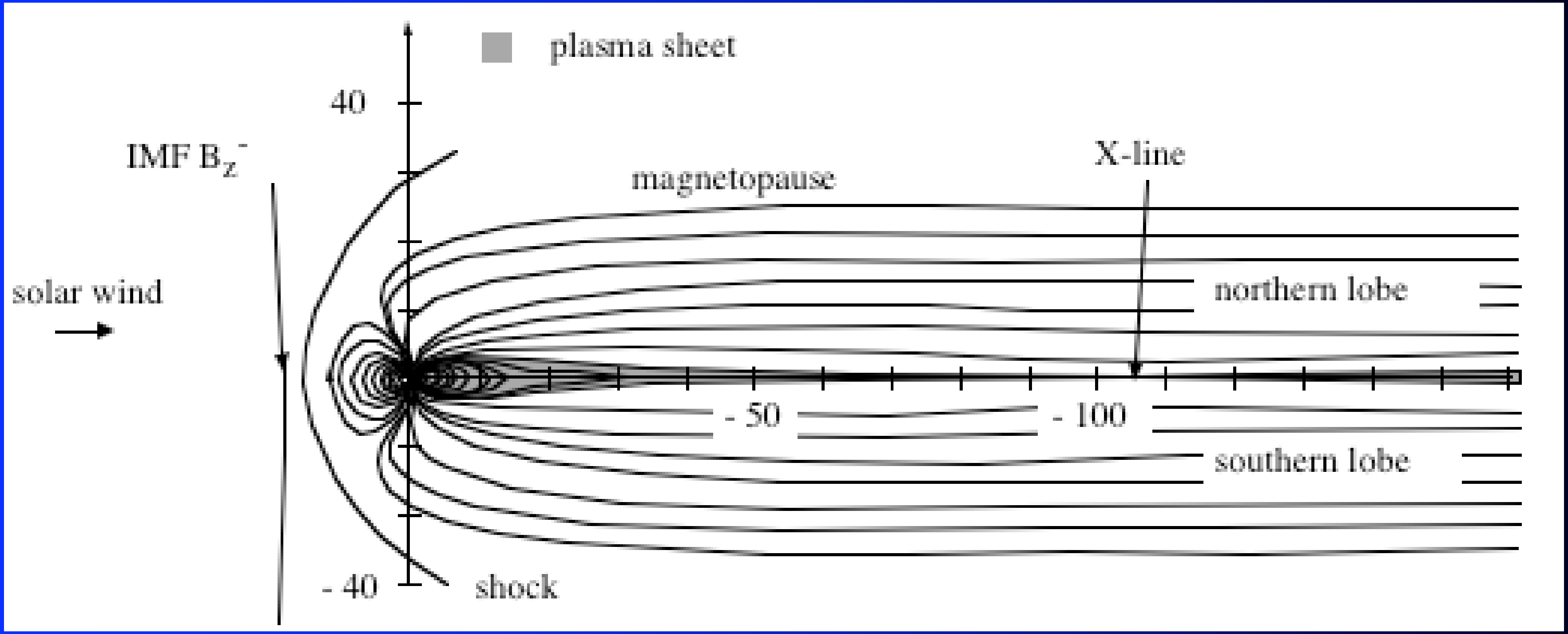
  Physical structures in the solar wind, which have strong effects to the Earth's dynamics.

- Magnetospheric dynamics

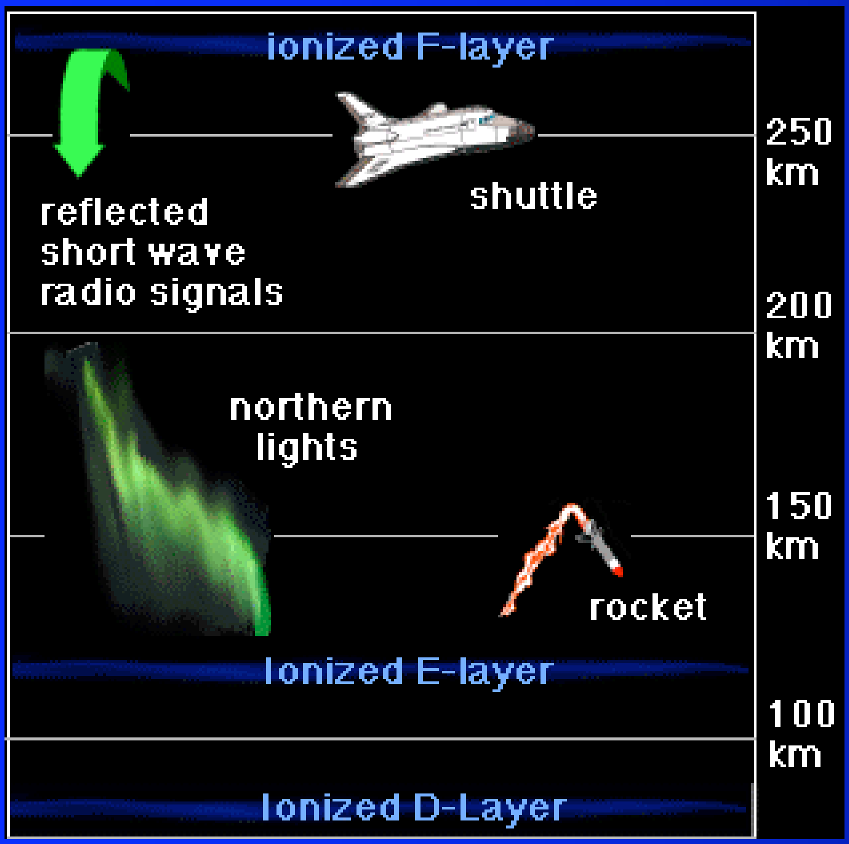
  Most powerful phenomena in magnetosphere over time scales of days are storms while substorms carry most of the power over time scales of years.

1. Basics of the Earth's magnetosphere and ionosphere

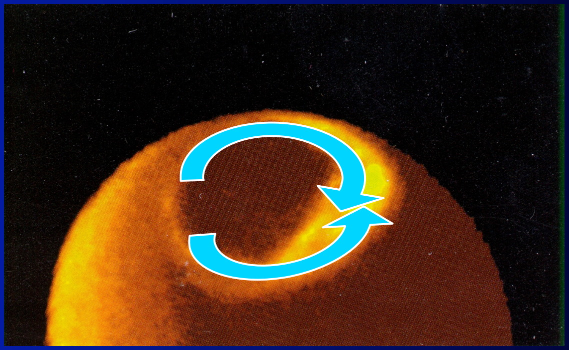
Structure of the Earth's magnetosphere



Structure of the Earth's ionosphere



Ionosphere is the location of the strong westward and eastward currents.



What causes dynamic variations in the magnetosphere?

- I. State of the Sun

  - Dynamic structures in the Sun

  - Location and occurrence rate of sunspots and coronal holes, etc.

- II.Geoeffective structures in the solar wind

  - Interplanetary coronal mass ejections

  - Shocks

  - High speed streams etc.

- III. Earth's location in the heliosphere

  Heliographic latitude (large heliospheric structures and local inhomogenities).

- IV. Orientation of the Earth's magnetosphere related to the Sun

  - Earth's dipole tilt angle (season)

  - Magnetotail tilt angle

  - Flaring angle etc.

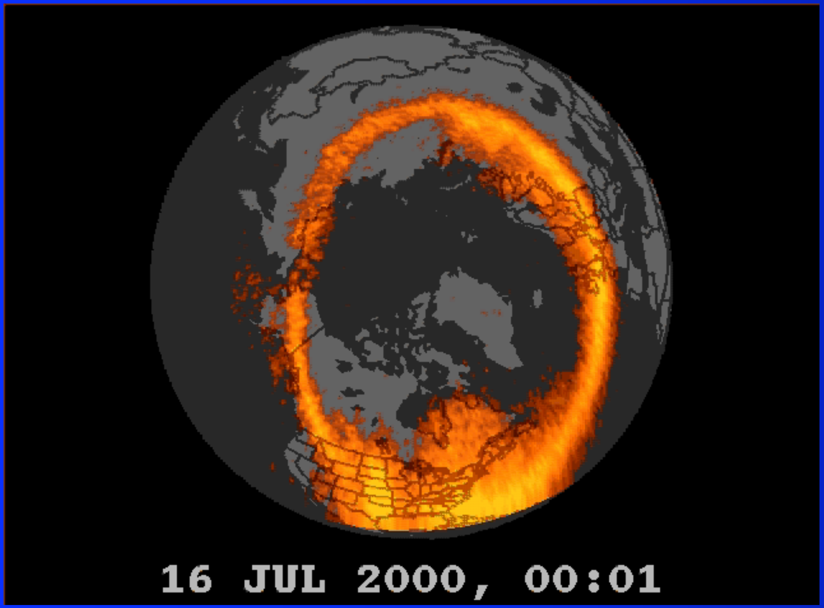
- V. Heliosphere's location in the interstellar media

  Cosmic rays etc.

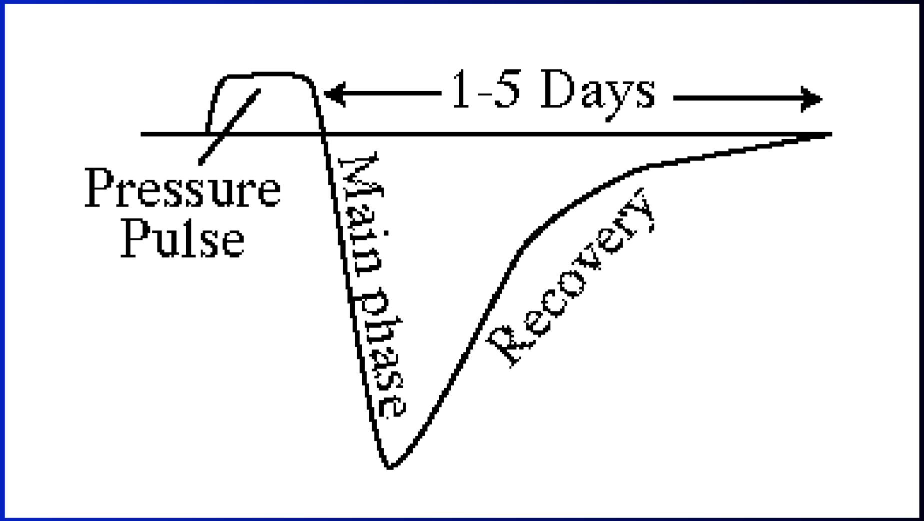
2. Magnetospheric dynamics

Magnetospheric storms

i.e. space storms, equatorial storms etc.



Auroral oval expands as far as to the Southern Europe.



Typical storm signature in Dst index.

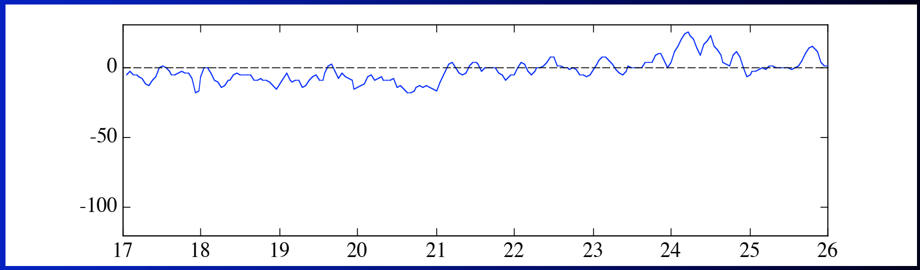
Storm process

Storm process:

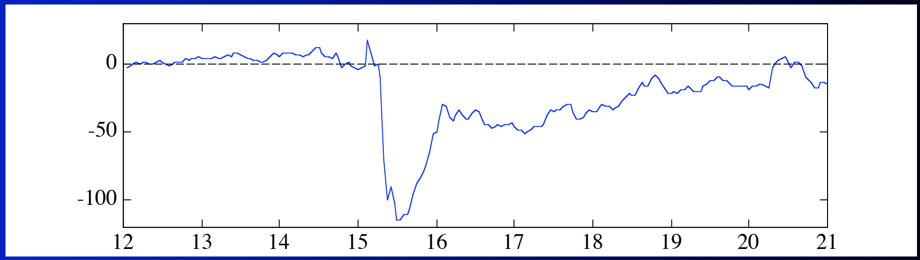
(1) Pressure pulse in solar wind

(2) Magnetosphere reforms such that magnepause moves Earthward

(3) Symmetric and/or asymmetric equatorial currents form



Quiet time

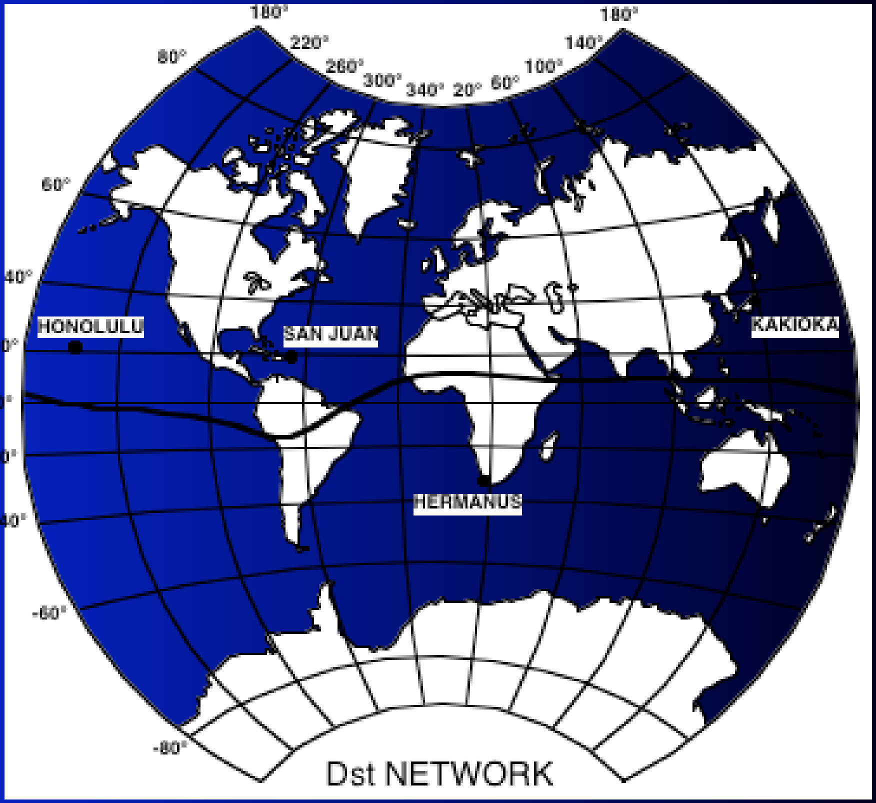


Storm time

Standard storm observatories

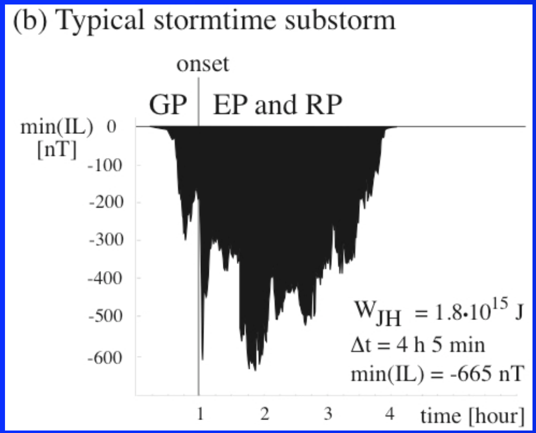
- Four storm observatories located around the Earth's magnetic equator:

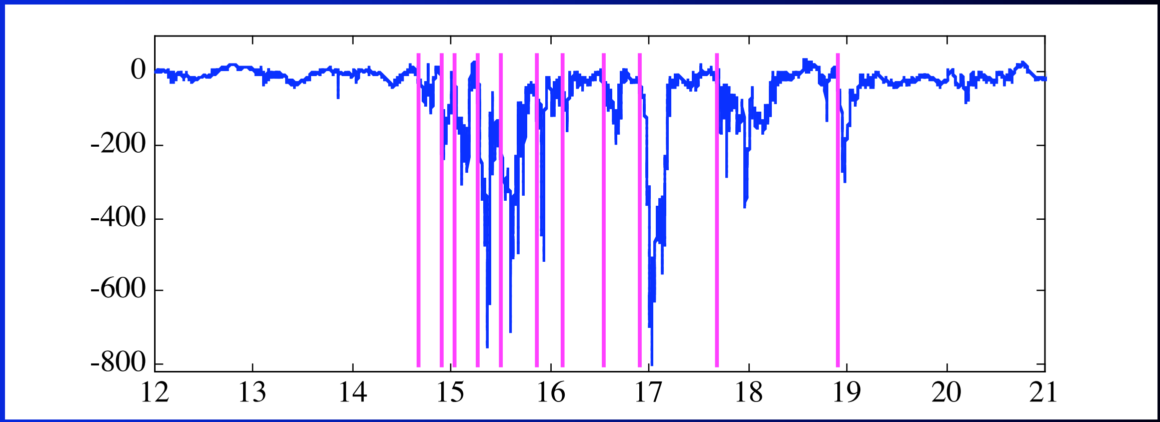
  Kakioka, San Juan, Hermanus and Honolulu.

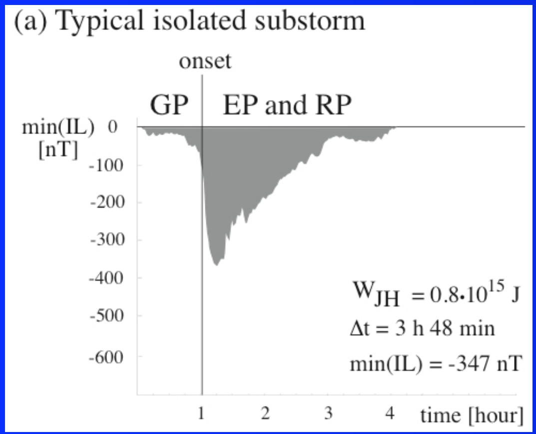


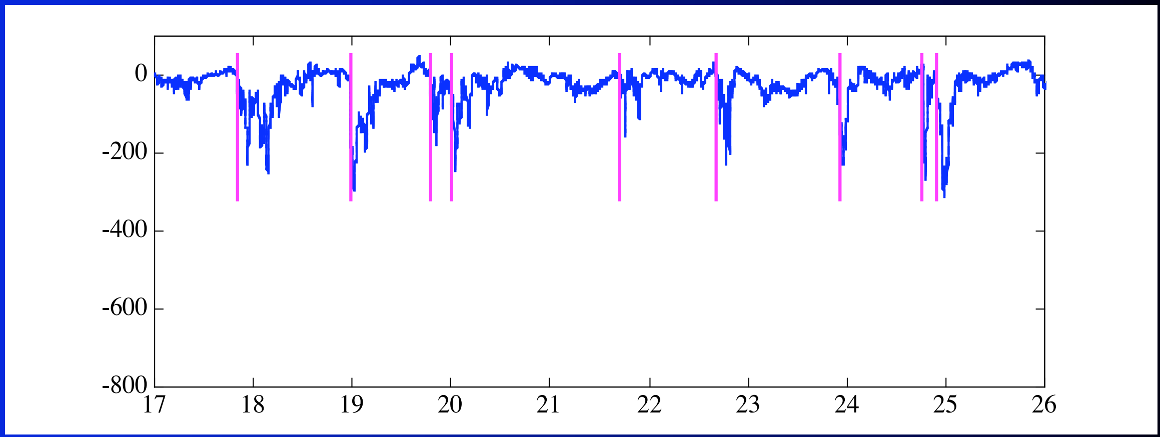
Substorms

Magnetospheric substorms i.e. Birkeland's polar elementary storms, auroral substorms, etc.









Aurora

Aurora borealis and australis - only visual signature of substorms.

Ari's lecture contains more information about the space weather.

Substorm process

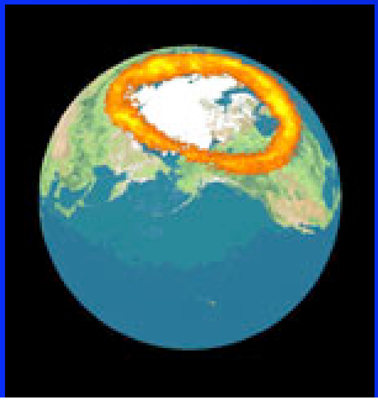
Substorm process:

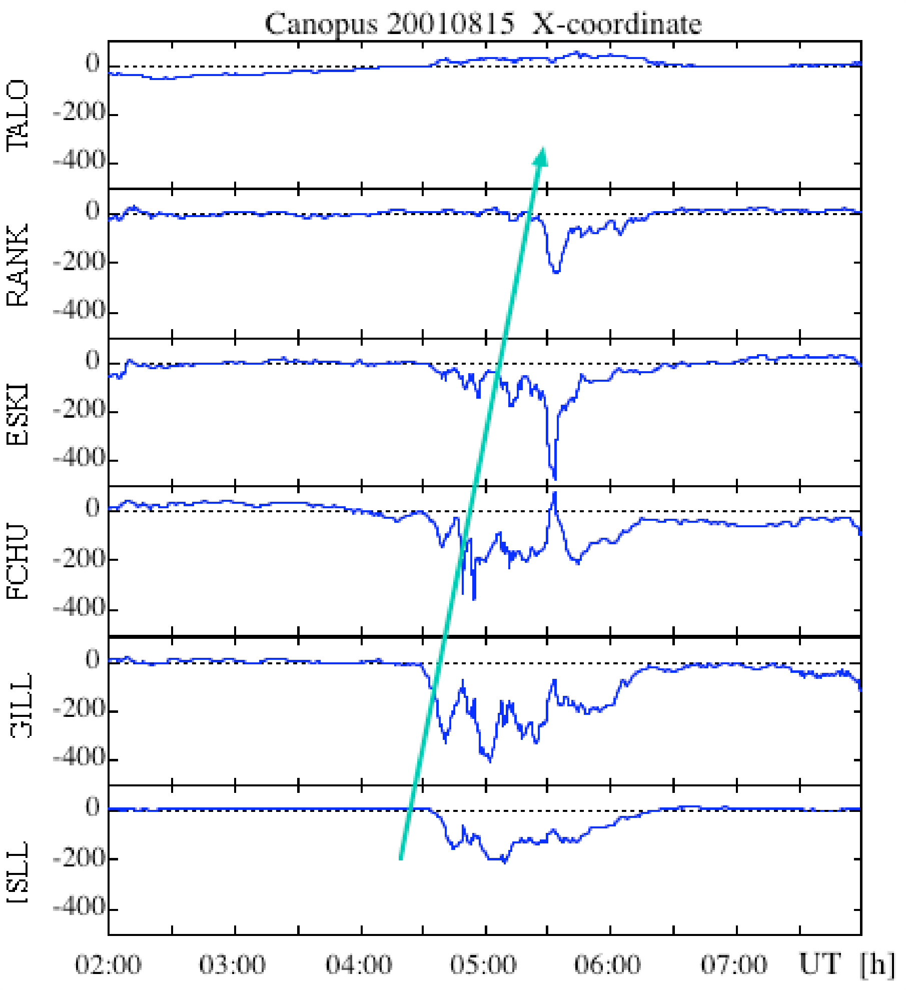
(1) Energy input from solar wind,

(2) Magnetosphere and particularly magnetotail preconditioned,

(3) Plasma sheet and auroral oval activates,

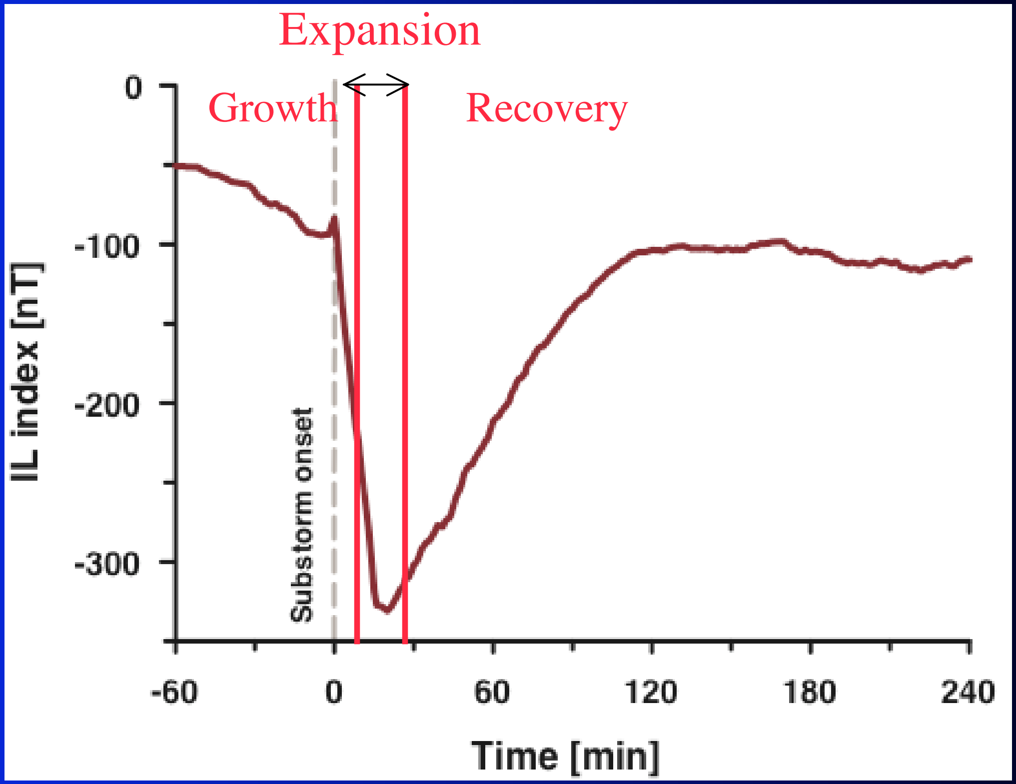
(4) Substorm expansion onset i.e. auroral oval rapidly expands poleward and ionospheric currets (eastward and westward) intensifies.





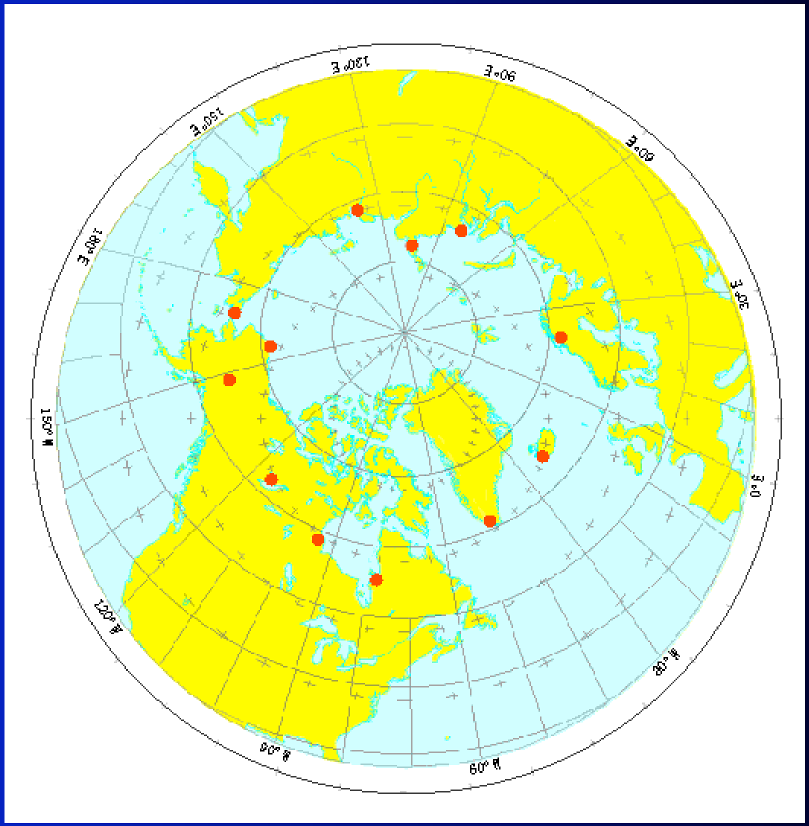
Substorm phases

- Growth phase
- Expansion phase
- Recovery phase



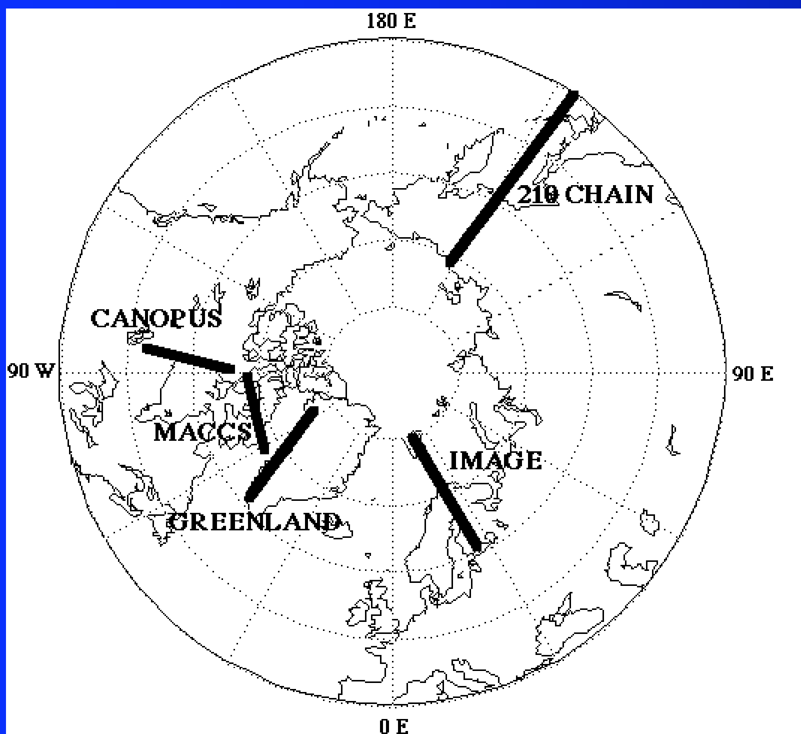
Substorm observatories

- 12 standard observatories
- Substorms identified from AL/AE index, which is an envelope curve of measured north-south components (X_{GSM}).

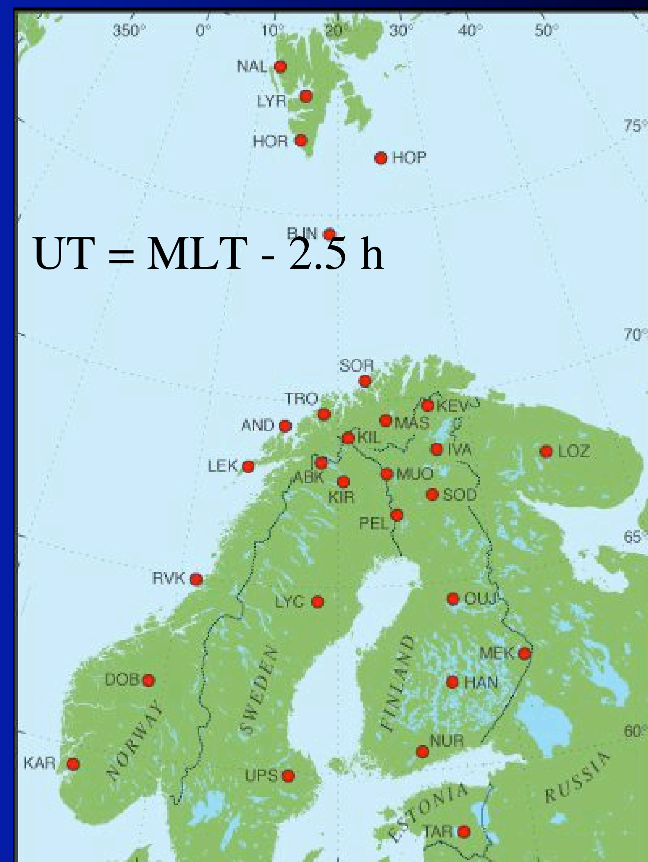


Magnetometer chains

CARISMA



29 IMAGE observatories

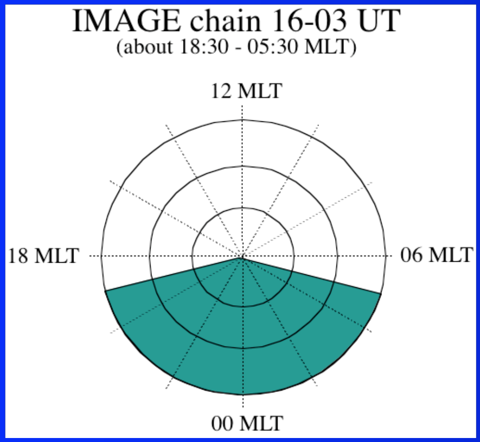


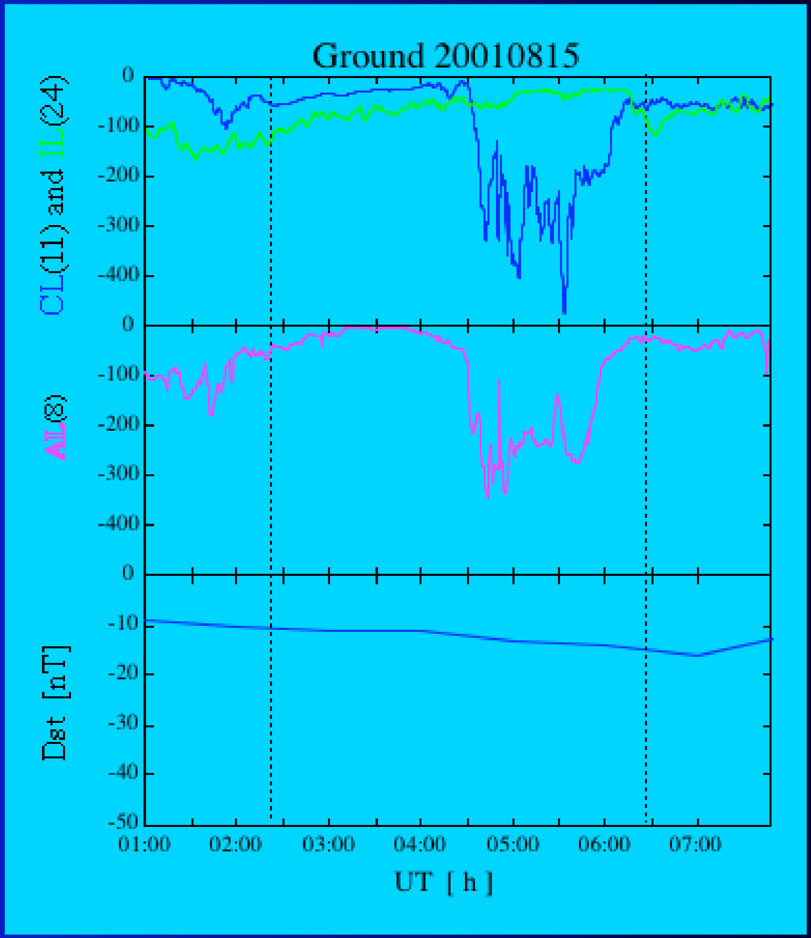
UT = MLT - 2.5 h

Courtesy of Häkkinen

Limited UT-sector substorm activity indices

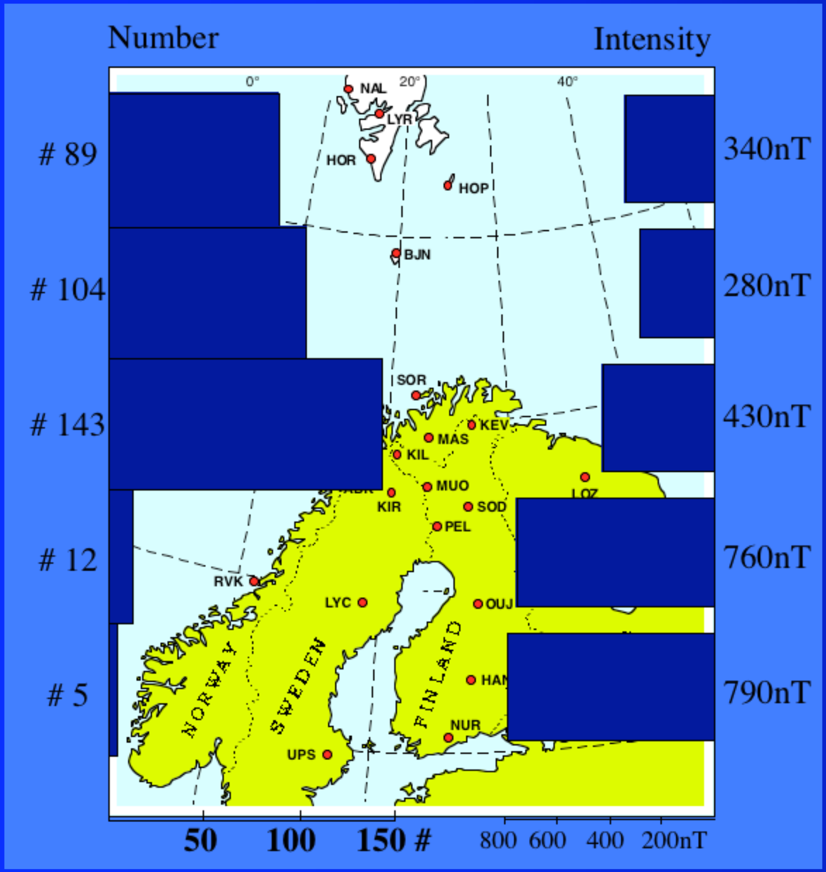
Following AL description IL and CL indices are formed based on IMAGE and CARISMA ground-based magnetic measurements.



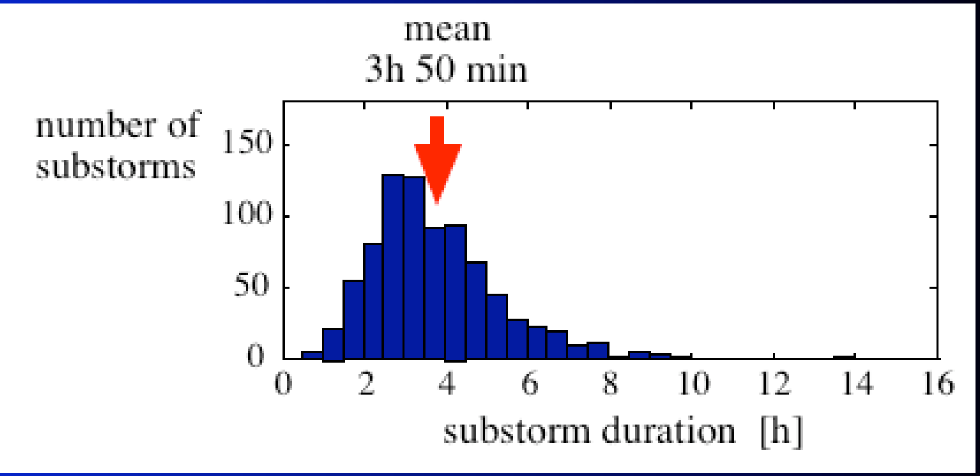


Substorm occurrence rate, peak amplitude and duration

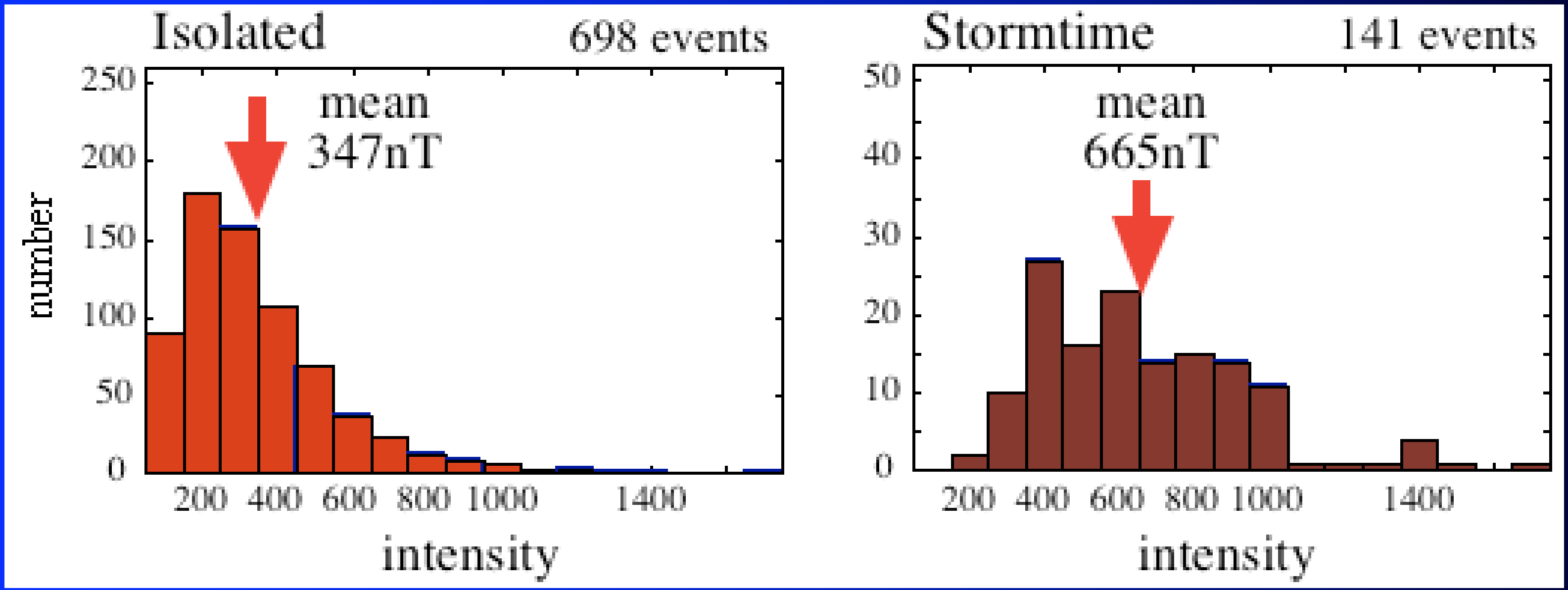
1997 & 1999



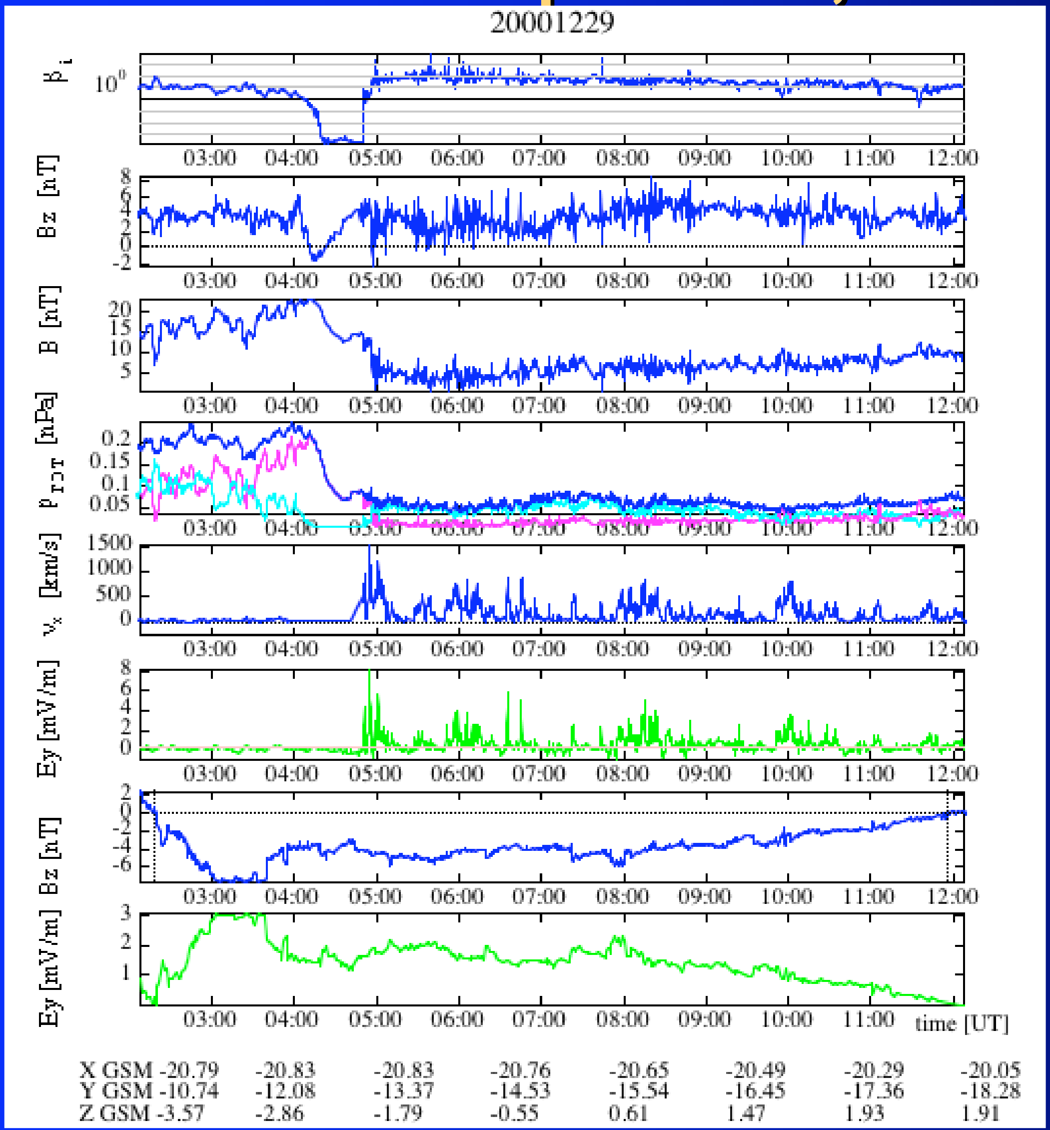
1997 & 1999



Storm-time and non-storm substorms



Continuous magnetospheric dissipation, CMD



Pressures:
- Total
- Thermal
- Magnetic

μ(IMF Bz) ≈ -4 nT

min(IMF Bz) ≈ -7 nT

3. Geoeffective solar wind parameters

Most geoeffective parameters in the solar wind:

- Solar wind bulk speed, V_x
- Interplanetary magnetic field (IMF):
  - strength
  - orientation
- Solar wind pressures
  dynamic

  $$P_{dyn} = N m_p v^2$$

  magnetic

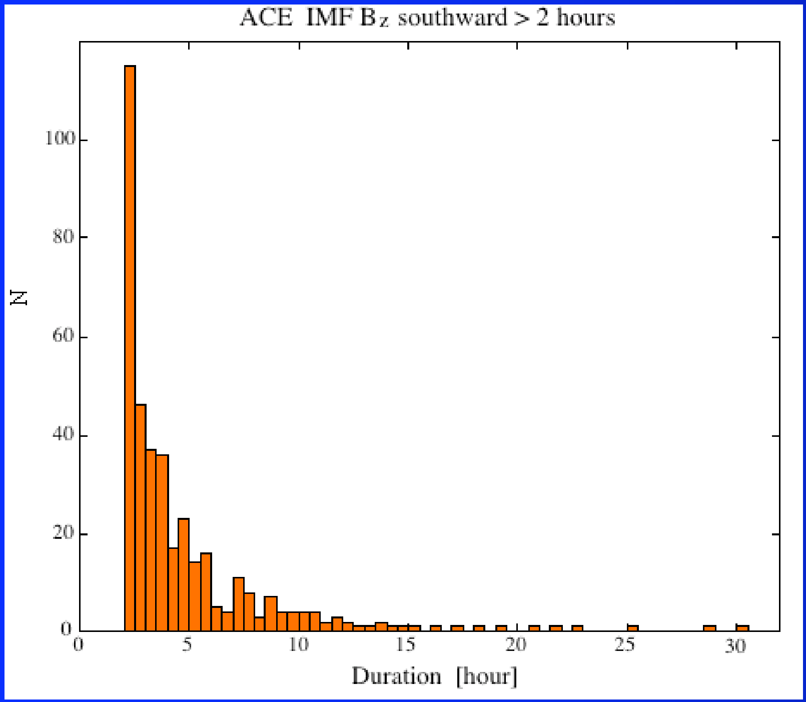
  $$P_{magn} = \frac{B^2}{2\mu_0}$$

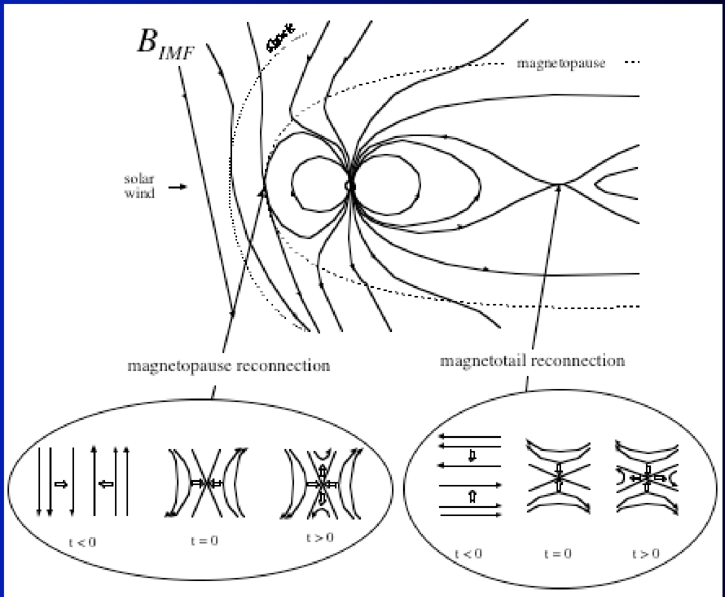
  thermal

  $$P_{th} = NkT$$

Interplanetary magnetic field, IMF

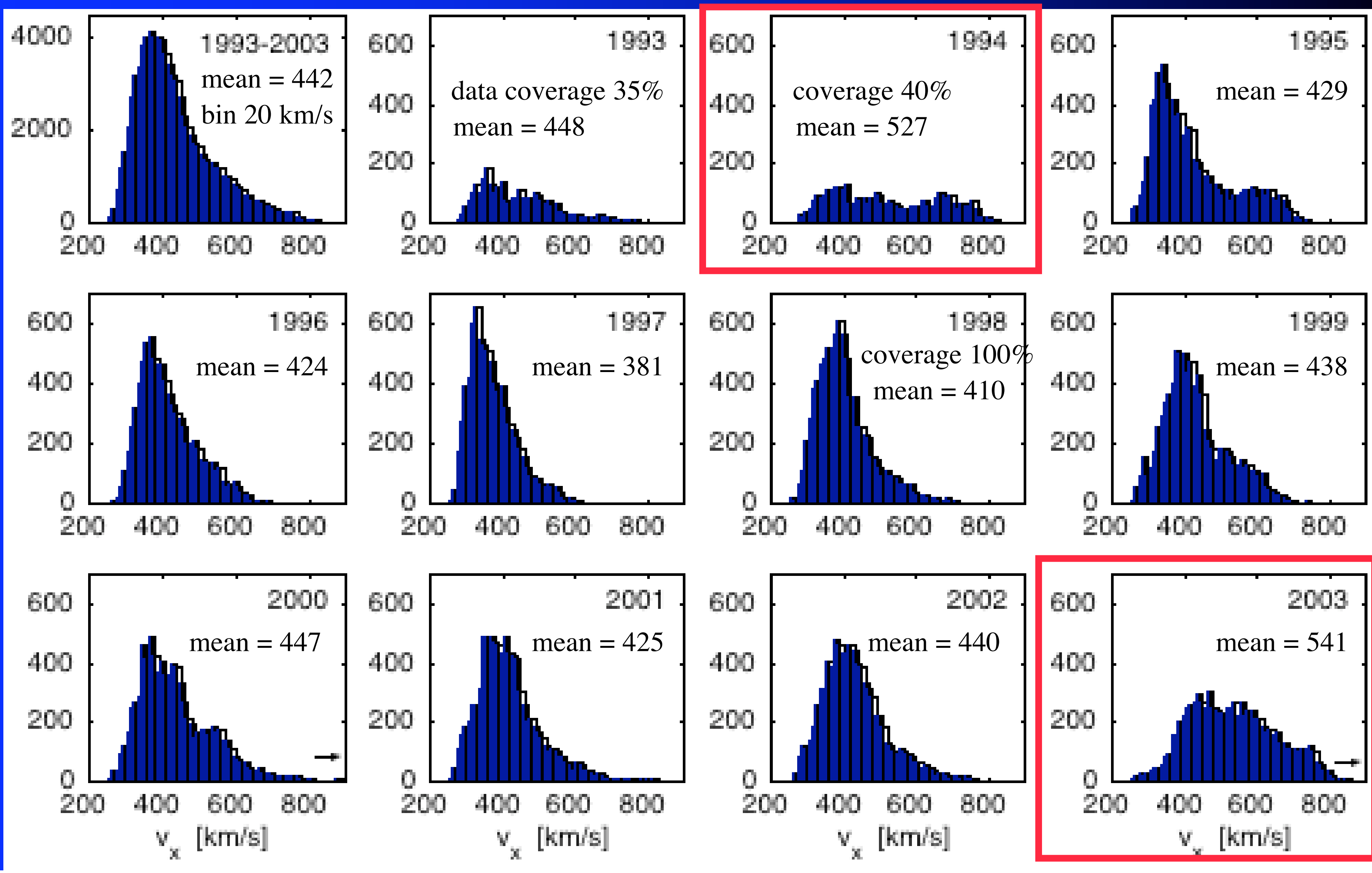
Solar wind - magnetophere coupling strongest during southward IMF B_z intervals.





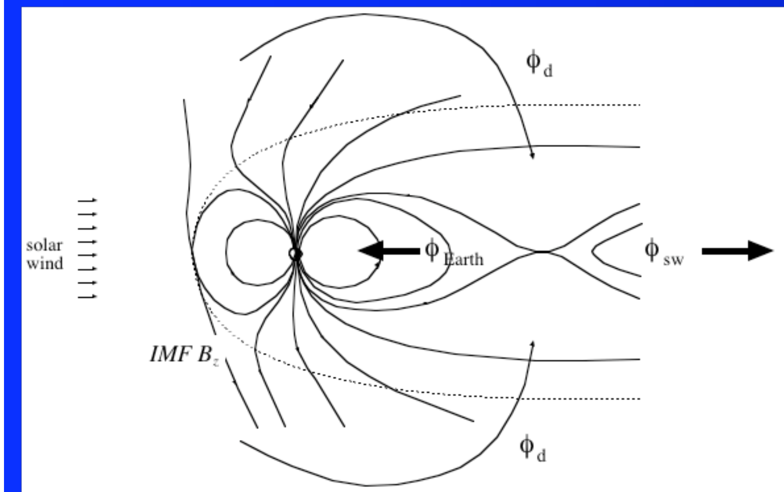
Increased reconnection rate during IMF B_z^-.

Solar wind bulk speed, v_x



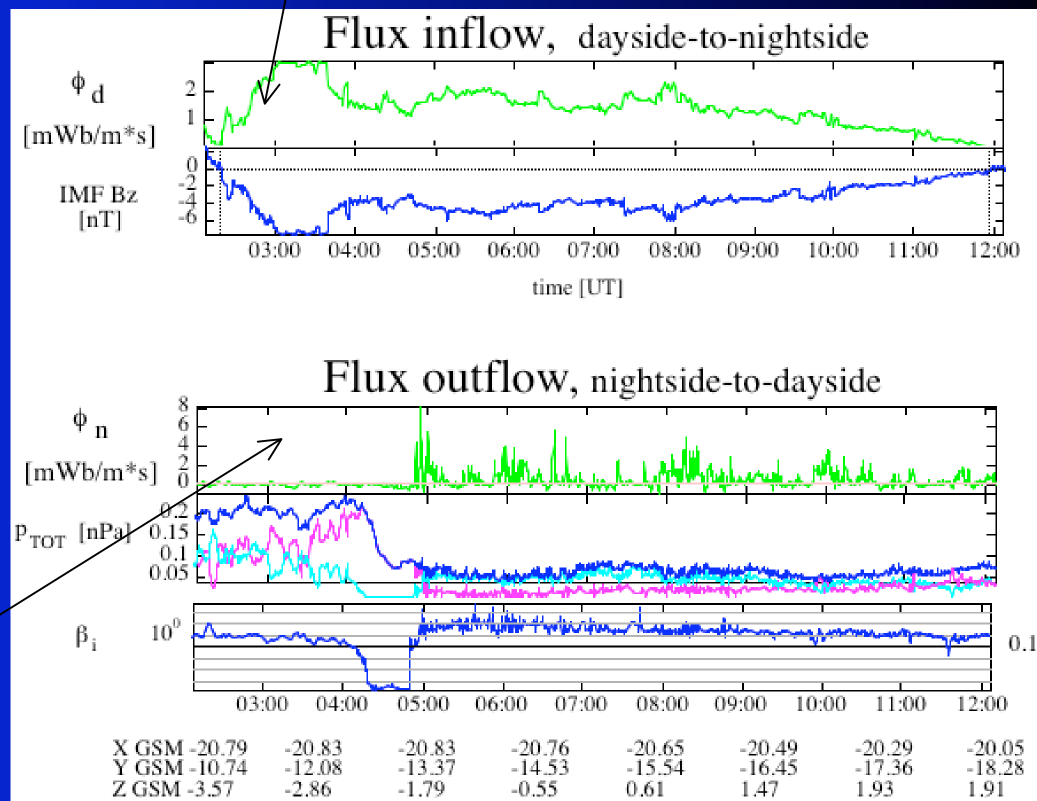
Magnetic flux

Cartoon of the Earth's convection



$\phi_d = v_x * B_y * L$
dayside-to-nightside flux transfer rate,
where L = length of the x-line
ϕ_{Earth} = nightside-to-dayside flux transfer rate
ϕ_{sw} = nightside-to-solar wind flux transfer rate

Steadily decreasing flux inflow

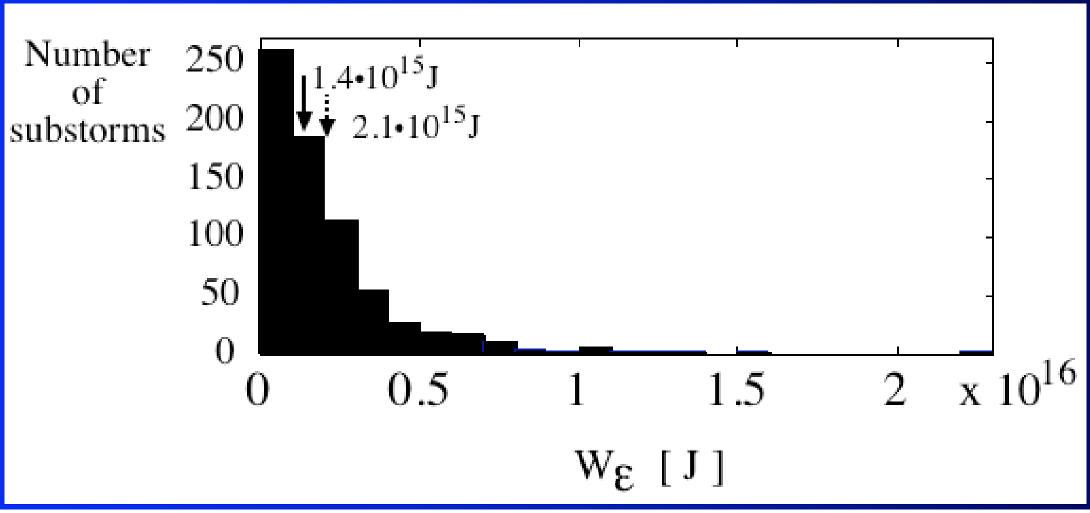


Bursty outflow

Solar wind-magnetosphere coupling functions

- vB, v^2B, vB^2, ε, etc.
- Akasofu's epsilon parameter:

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

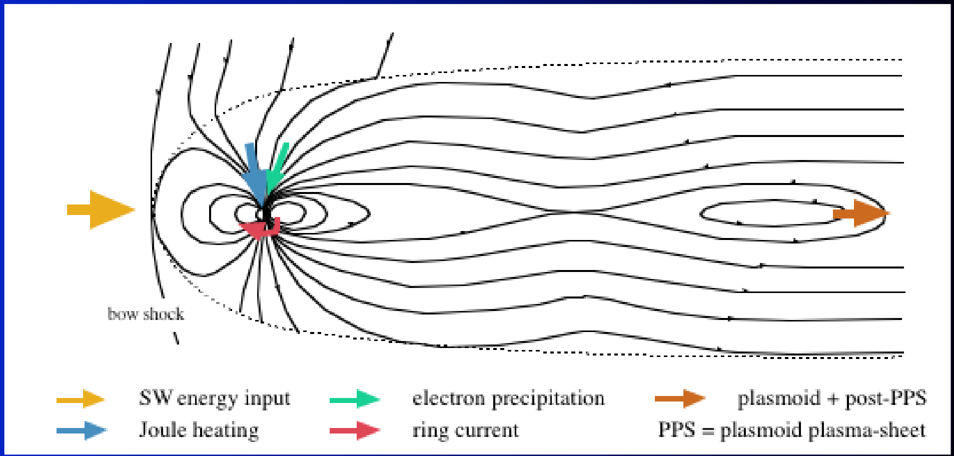


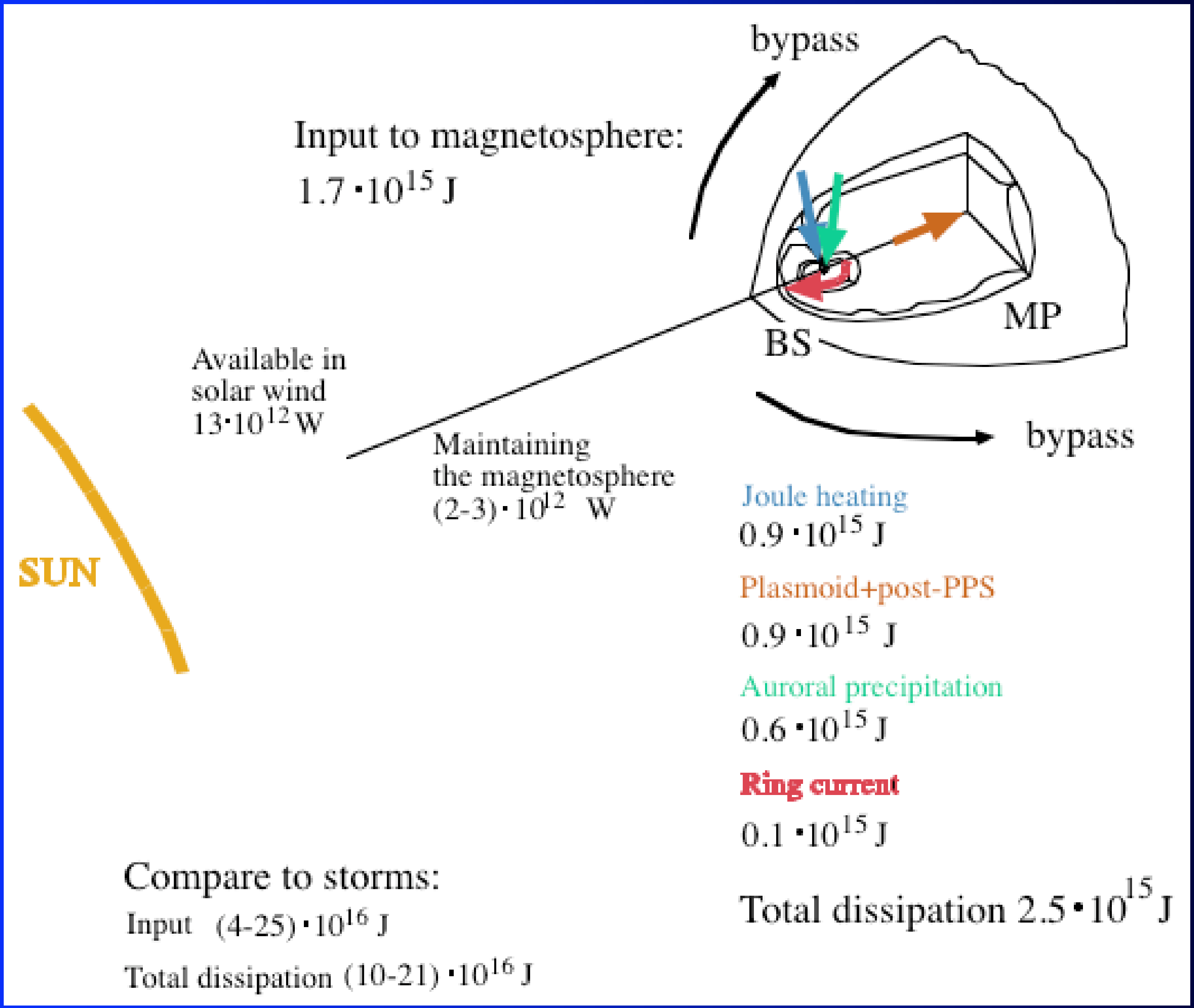
4. Global energy flow

Energy budget

- Only less than 1% of the available solar wind energy flows into the magnetosphere. Solar wind- magnetosphere coupling efficiency about 1% (e.g. Ostgaard and Tanskanen, 2004).

- Largest energy sinks:
  - joule heating
  - electron precipitation
  - ring current
  - plasma sheet heating and
  - plasmoid ejection





Minna's lecture contains more information about the energy flow through the magnetopause.

Ionospheric dissipation estimates: Joule heating

- Joule heating

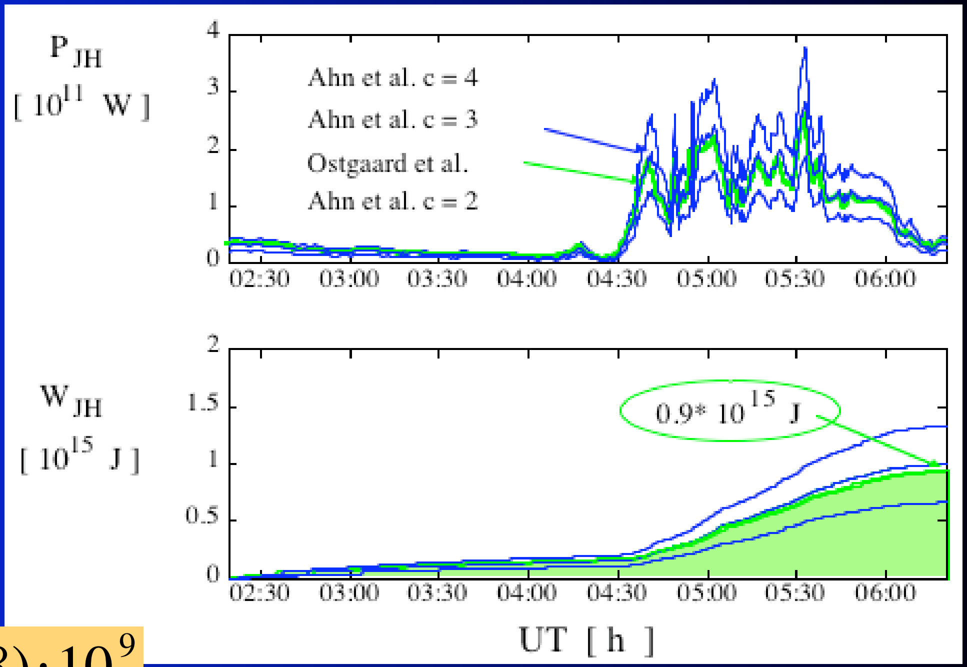
Ahn et al., 1983 , Richmond et al., 1990

$$P_{JH} = 2 \cdot c \cdot 10^{8} AL(nT), \quad c = 2,3,4$$

Øtgaard et al., 2002

$$P_{JH} = 0.33 \cdot AE \cdot 10^{9} + (0.21 \cdot AE + 1.8) \cdot 10^{9}$$

$$W_{JH} = \int P_{JH} dt$$



Ionospheric dissipation estimates: Electron precipitation

- Electron precipitation

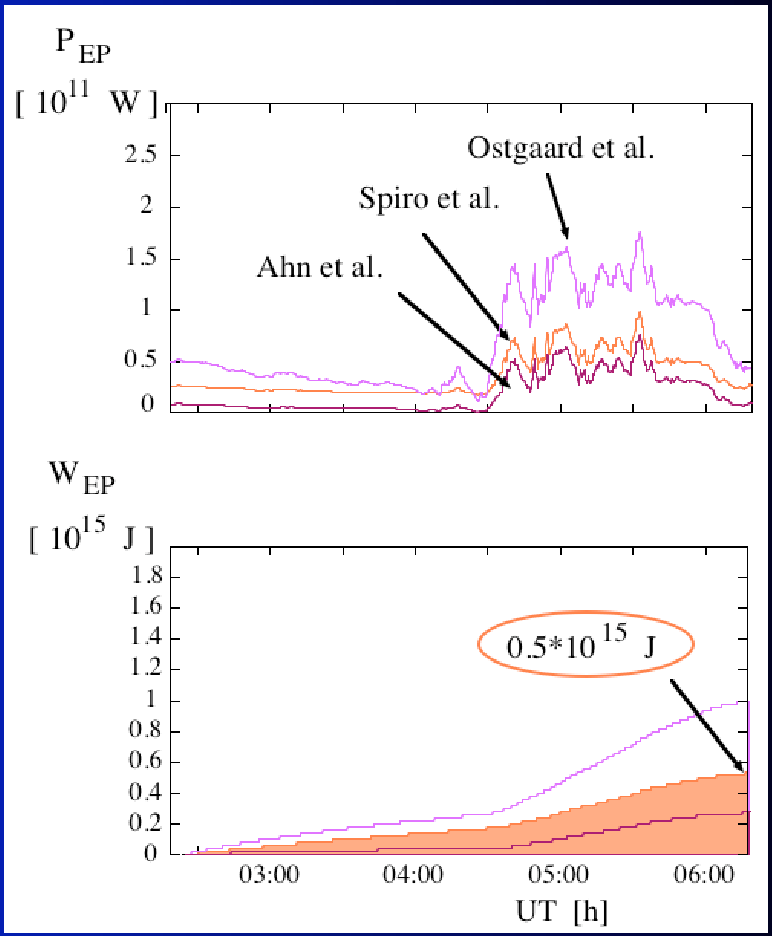
Ahn et al., 1983

$$P_{EP}(W) = 2 \cdot 0.8 \cdot 10^{8} \cdot AL(nT)$$

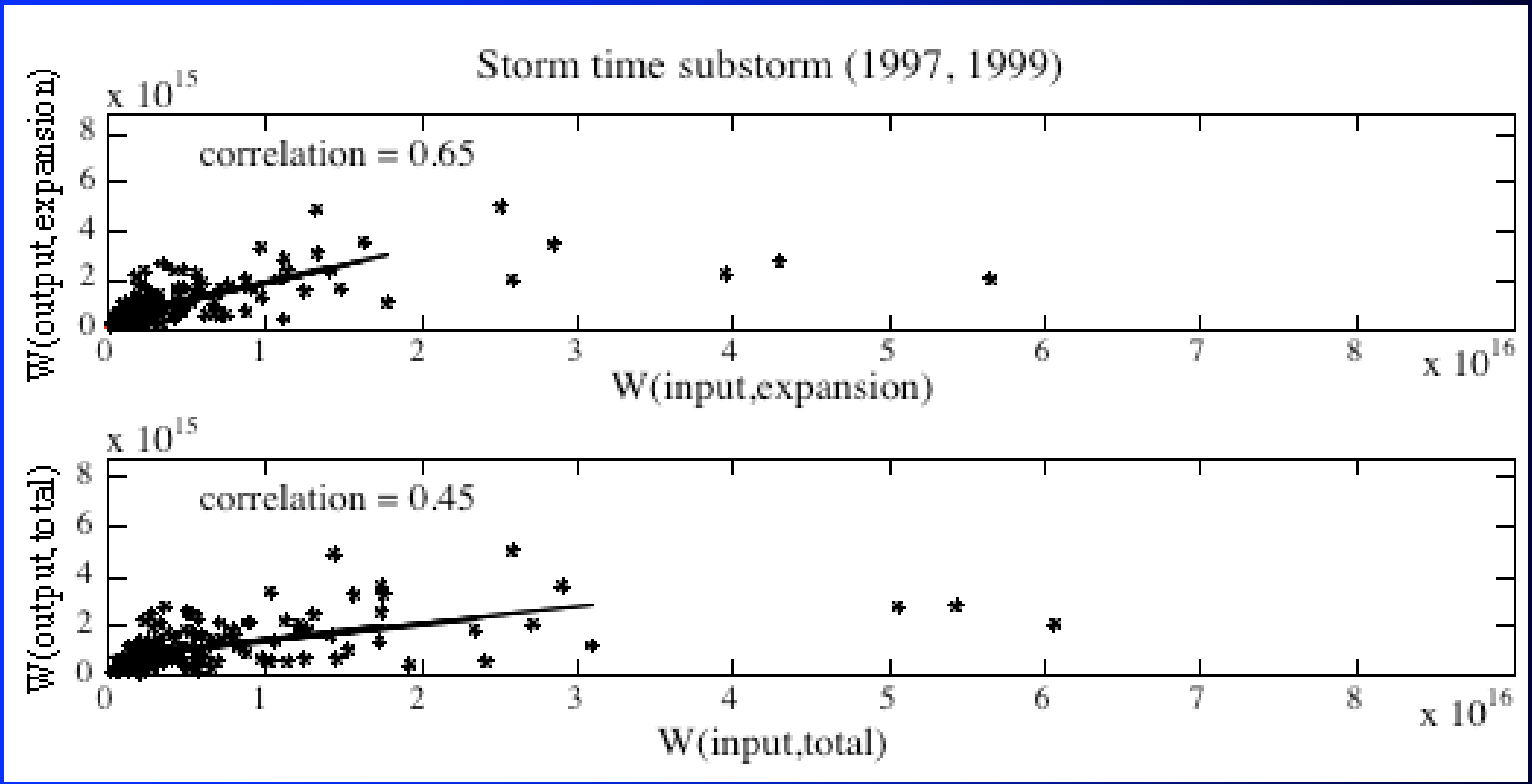
Øtgaard et al., 2002

$$P_{EP}(W) = 2 \cdot \left(4.4 \cdot AL^{1/2} - 7.6\right) \cdot 10^{9}$$

$$W_{EP} = \int P_{EP}\,dt$$

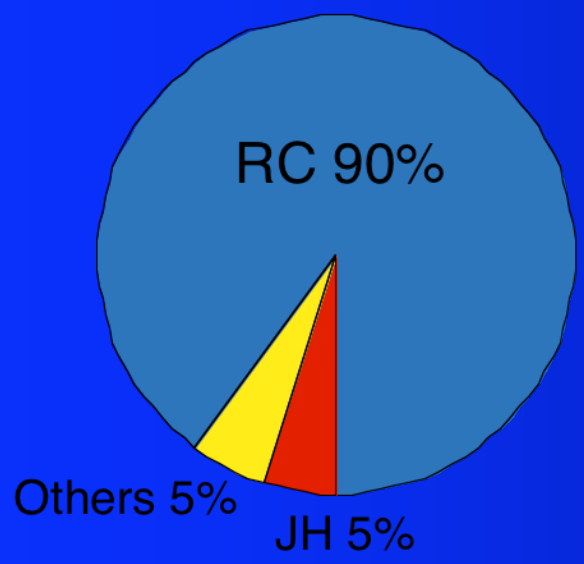


Input-output analysis

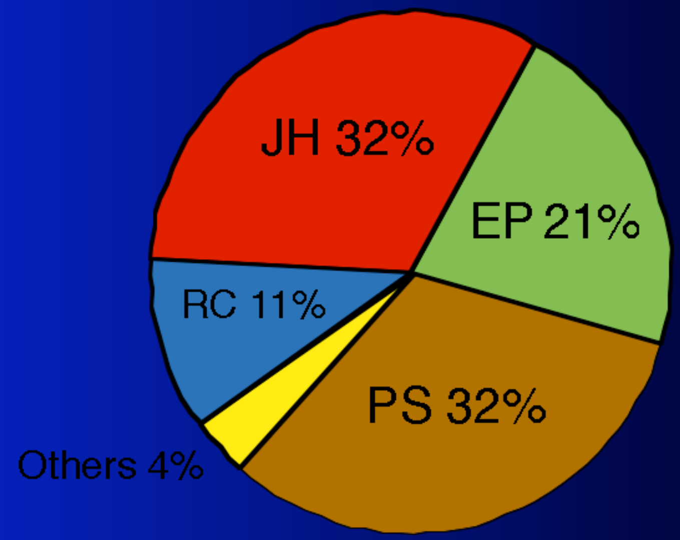


Empirical energy sink estimates

OLD view:



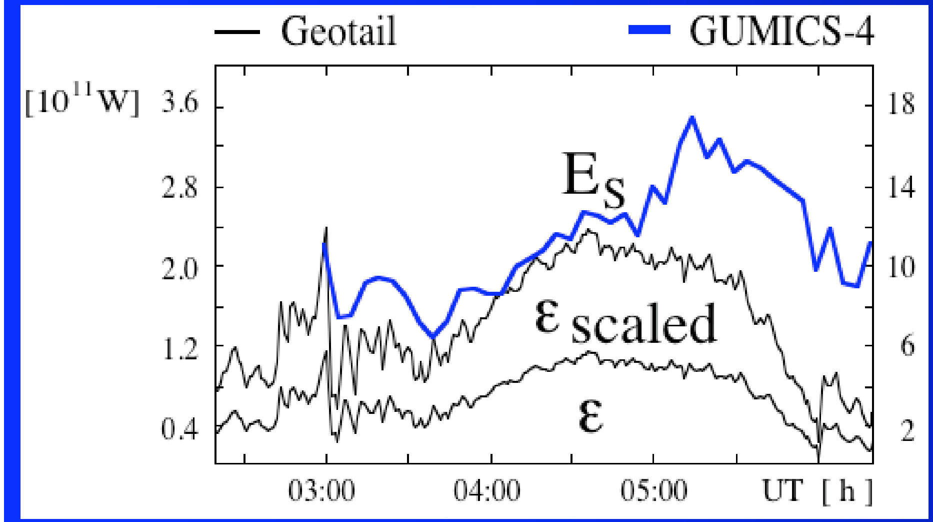
NEW view:

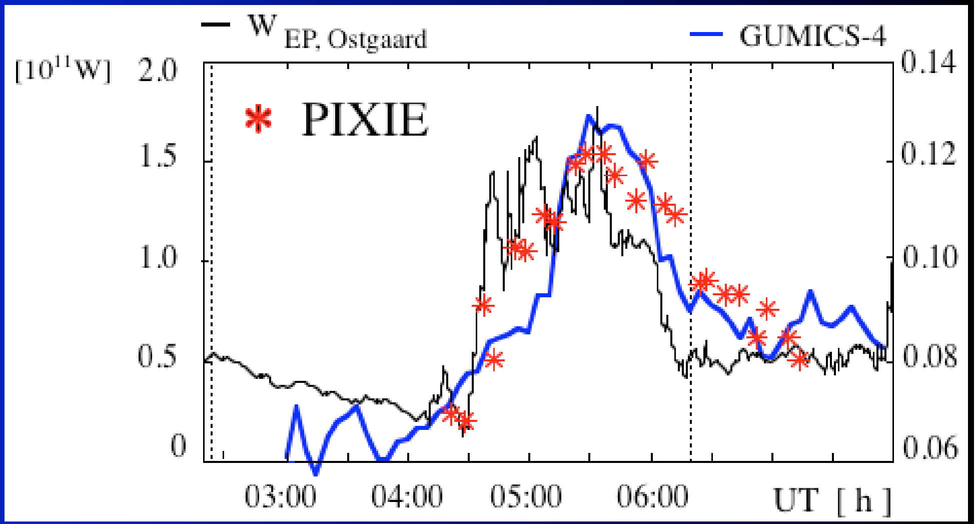


- The ionosphere (joule heating and electron precipitation) receives the major part of the energy during storms and substorms, dissipating at least 50% during storms and even over 70 % during substorms.
- Joule heating, JH; Electron precipitation, EP; Ring current, RC; Plasmoid and plasma sheet heating, PS

Comparing energy budget observations and MHD simulation results

- Simulation and empirical input proxy gives similar temporal variations during growth and expansion phases, but show differences during recovery phase.
- Simulation and empirical dissipation proxy for electron precipitation gives similar temporal variations, but the simulation gives almost ten times smaller values.





Pekka's (Janhunen) lecture contains more information about simulations.

5. What causes variations in the Earth's dynamics?

Causes for dynamic variations in the magnetosphere

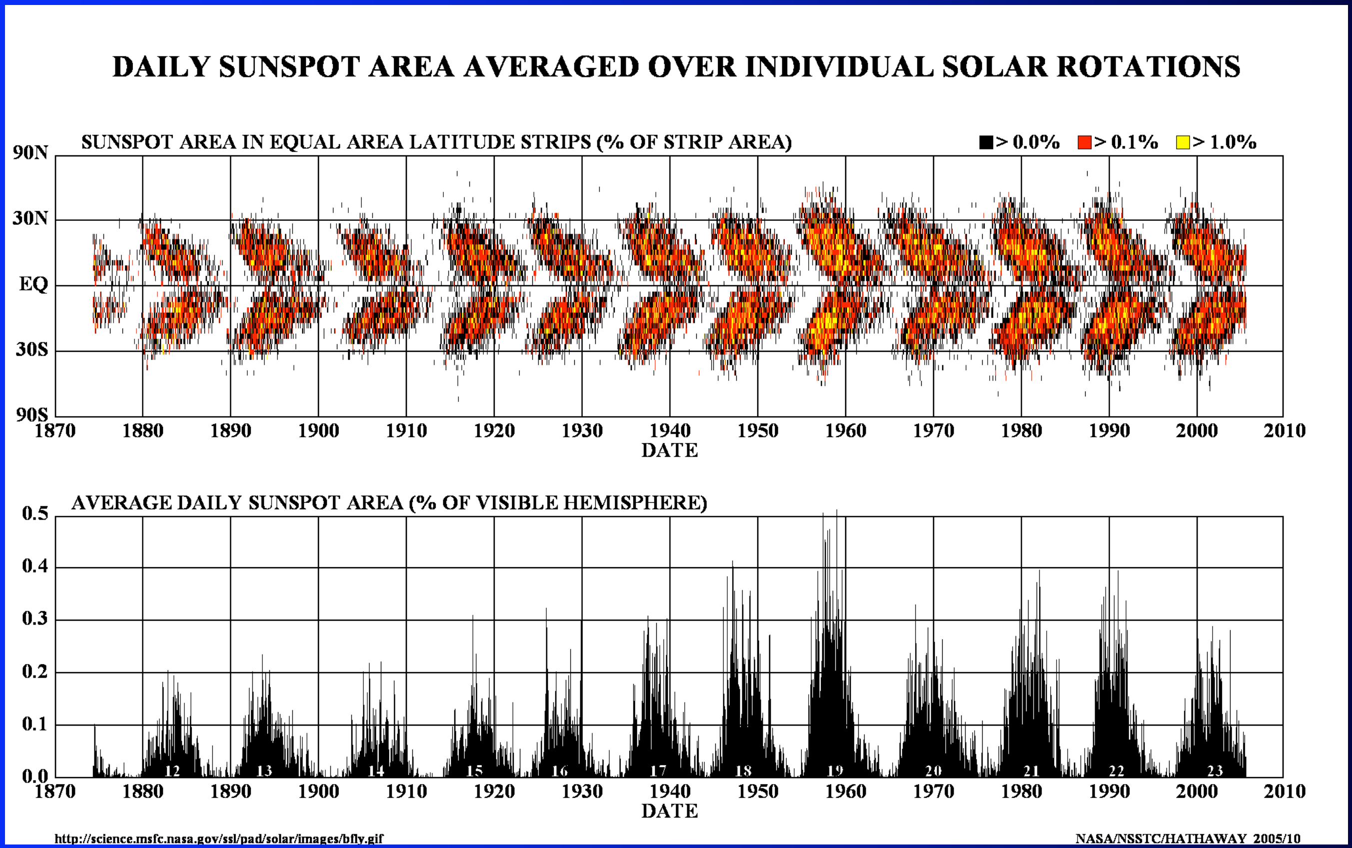
- I. State of the Sun
  - Dynamic structures in the Sun
  - Location and occurrence rate of sunspots and coronal holes, etc.
- II. Geoeffective structures in the solar wind
  - Interplanetary coronal mass ejections
  - Shocks
  - High speed streams etc.
- III. Earth's location in the heliosphere

  Heliographic latitude (large heliospheric structures and local inhomogenities).
- IV. Orientation of the Earth's magnetosphere related to the Sun
  - Earth's dipole tilt angle (season)
  - Magnetotail tilt angle
  - Flaring angle etc.
- V. Heliosphere's location in the interstellar media

  Cosmic rays etc.

I. State of the Sun

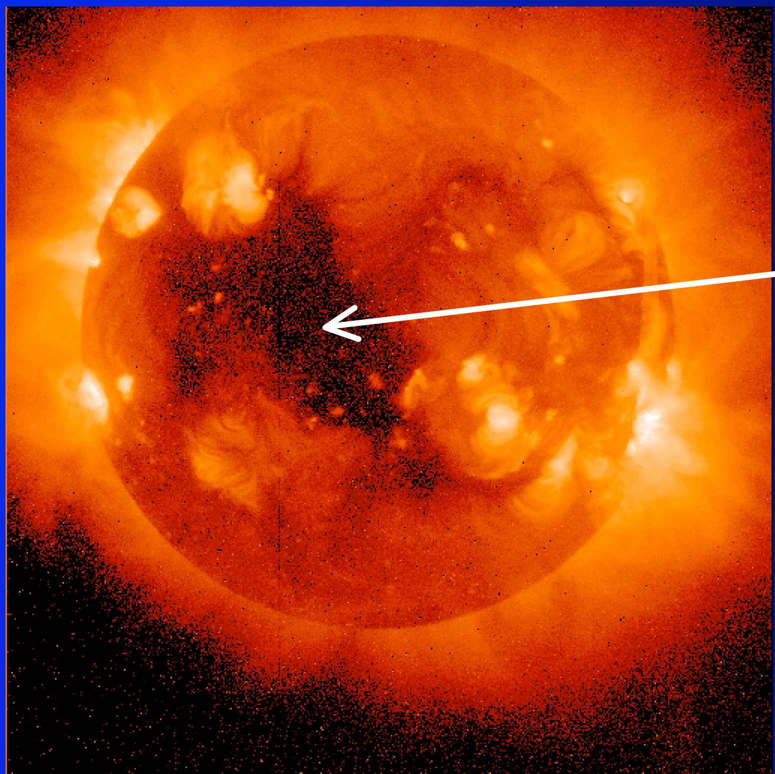
- Location and occurrence rate of sunspots and coronal holes, etc.



Coronal holes locating near the Sun’s equator produce stronger geomagnetic activity (magnetic storms) than coronal holes locating near the poles (Nolte et al., 1976).

Coronal holes vs.solar wind bulk speed

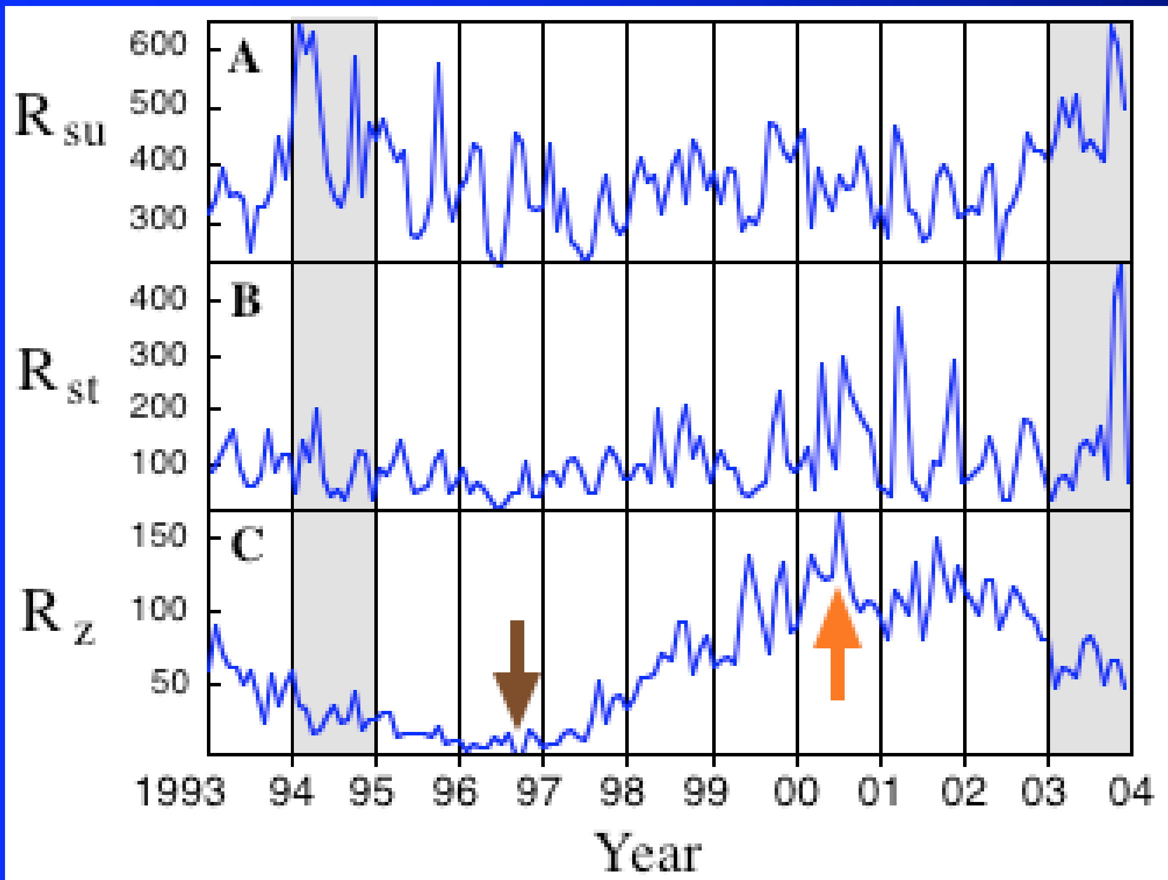
- Velocity of the solar wind is roughly proportional to the area of coronal holes (Watari, 1997).



A coronal hole lasting longer than 7 months.

Sunspots vs. storms

- 11 and 22-year periodicity

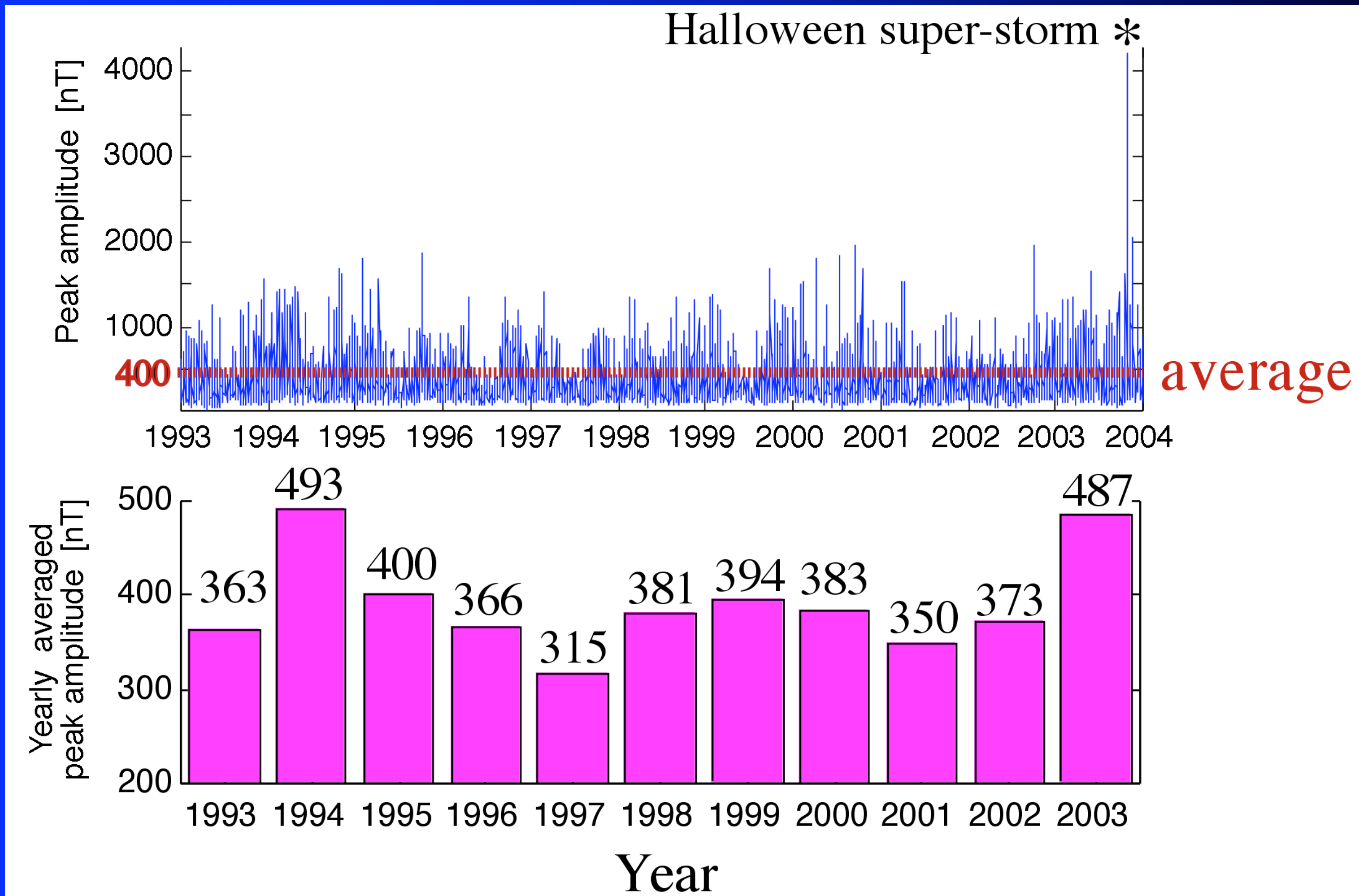


substorms

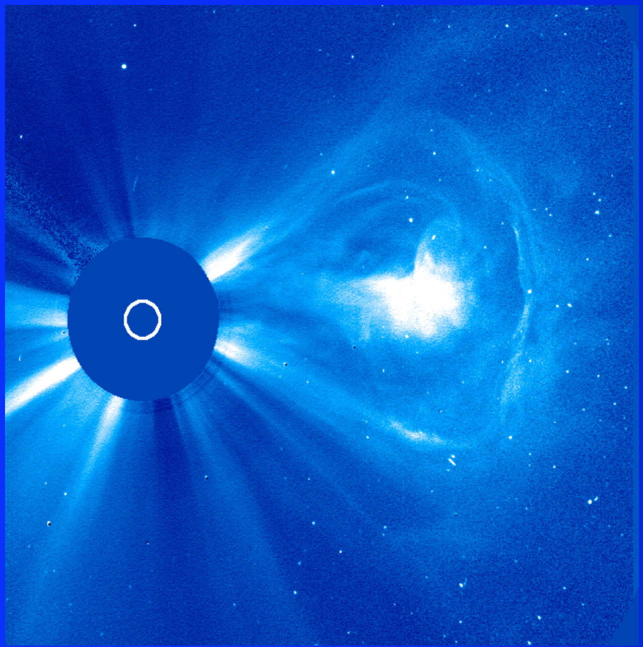
storms

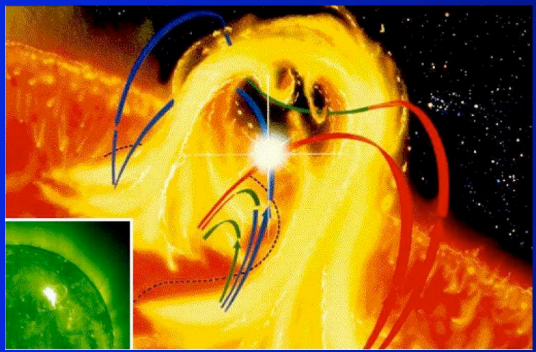
sunspots

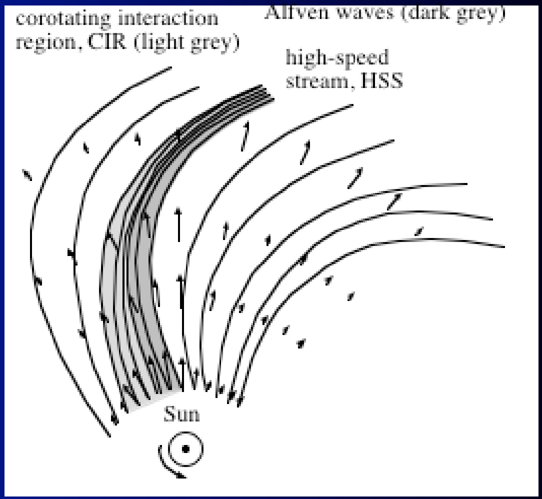
Sunspots vs. substorms



Dynamic structures in the Sun







Coronal mass ejections   flares   high speed streams

See previous lectures of Hannu, Rami and Arto

II. Geoeffective solar wind structures

- Interplanetary CMEs, ICMEs

  CMEs observed in the interplanetary space.

- Interplanetary magnetic cloud, IMC

  ICMEs with a well-defined flux rope structure.

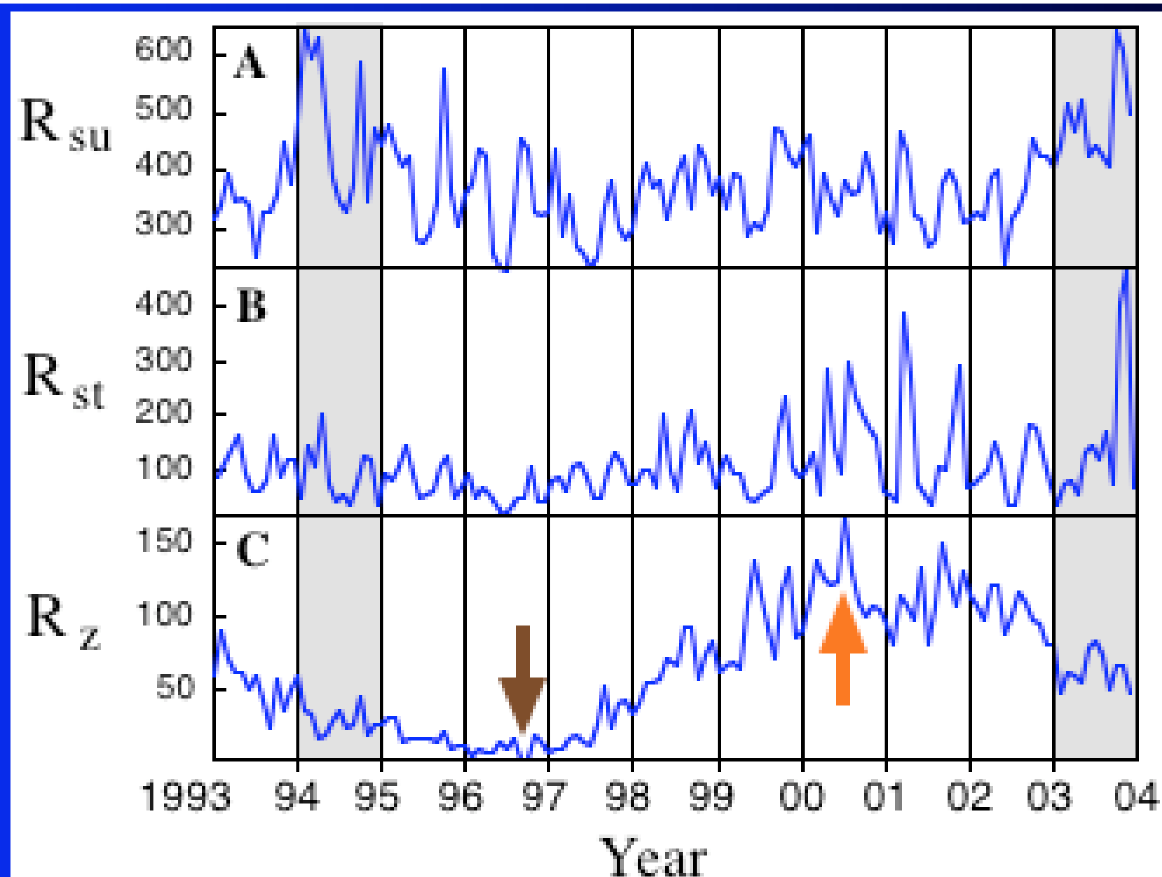
- Interplanetary shocks, IS

- High speed streams, HSS

  Bulk speeds over 700km/s lasting longer than 24 hours.

Yearly variation of magnetic clouds

				1996		1998		2000		2002	
Occurrence rate			8	4	**17**	**11**	4	**14**	**10**	7	4
Average velocity			372	356	419	425	430	**531**	**511**	468	497



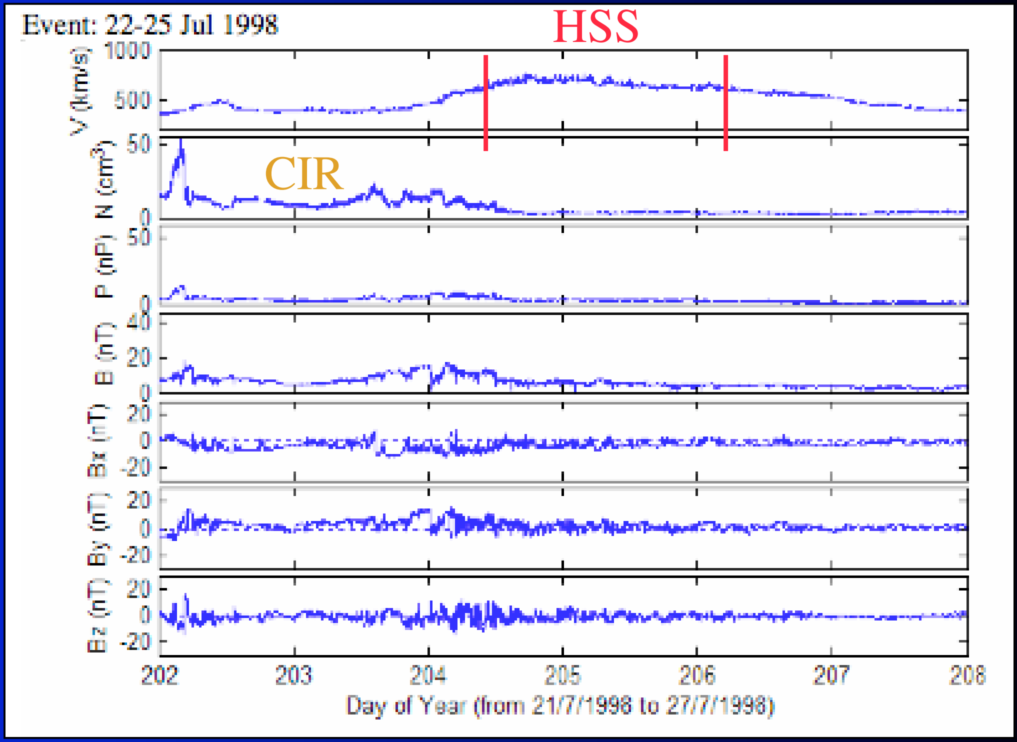
High speed streams, HSS

- Identification from bulk speed, v_x
- Definition:

  $v_x > 700$ km/s lasting > 6 h.
- Duration:

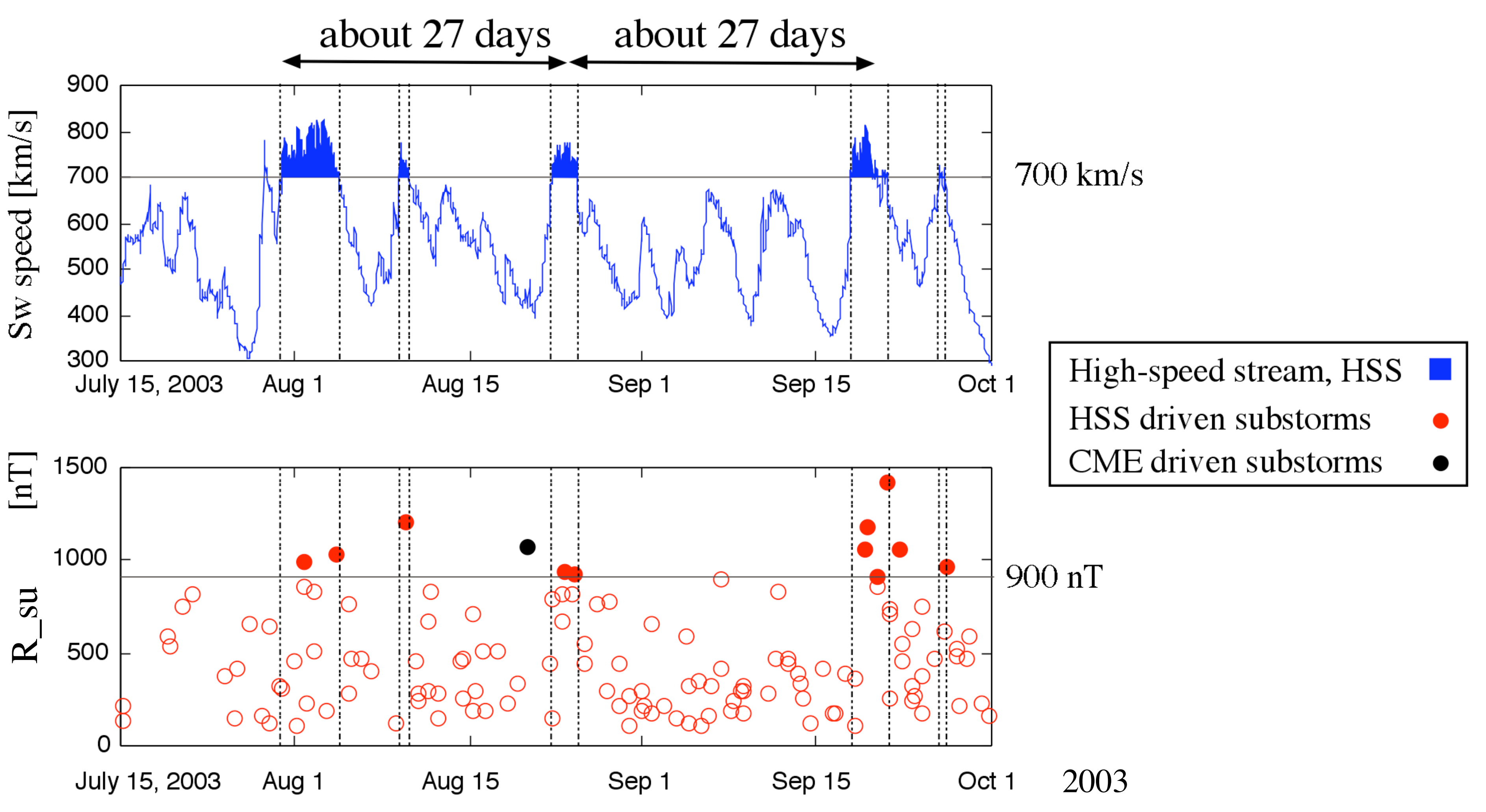
  From several hours to several days
- Occurrence rate:

  About every 27 days during active years and less often during other times.



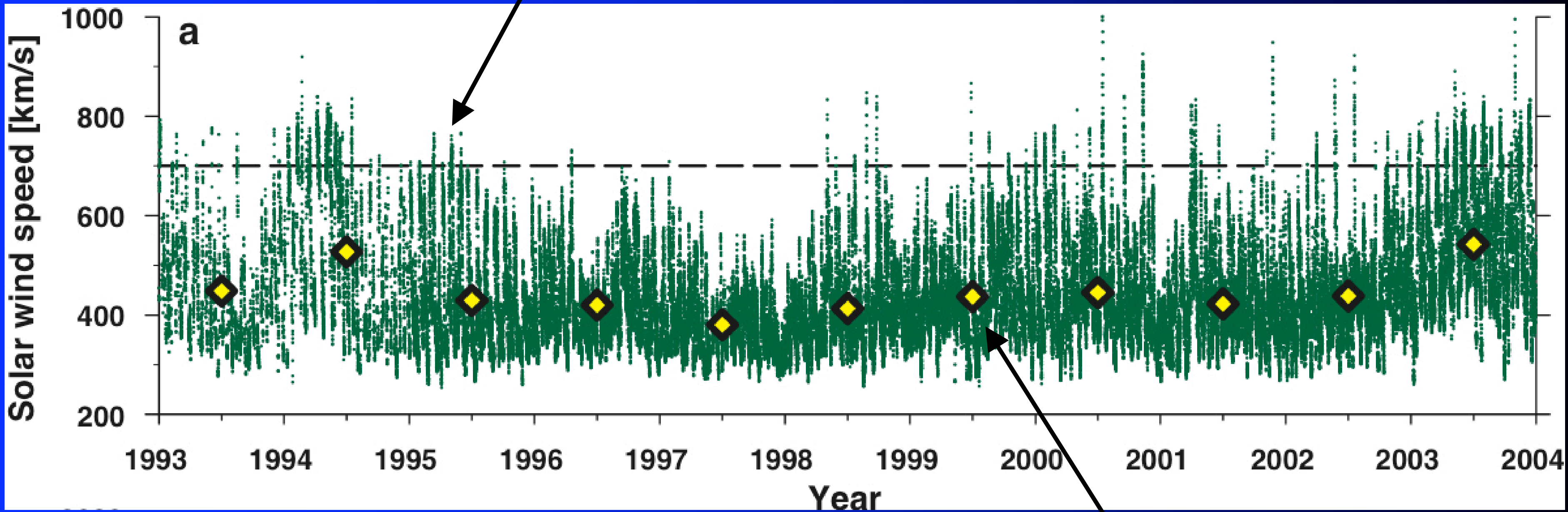
Corotating interaction region, CIR

HSS vs. substorms



Solar wind bulk speed vs. substorms

Daily averaged solar wind speed marked by green.



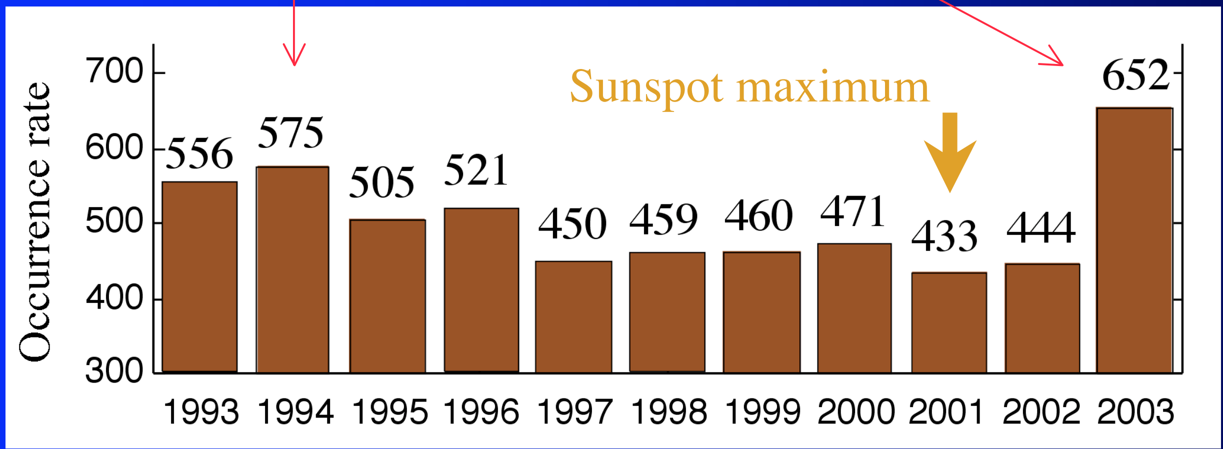
Yearly averages marked by yellow diamonds.

III. Earth's location in the heliosphere

* Terrestrial magnetic storms and substorms are most remarkable during the declining phase of solar cycles (Sheley and Harvey, 1981)

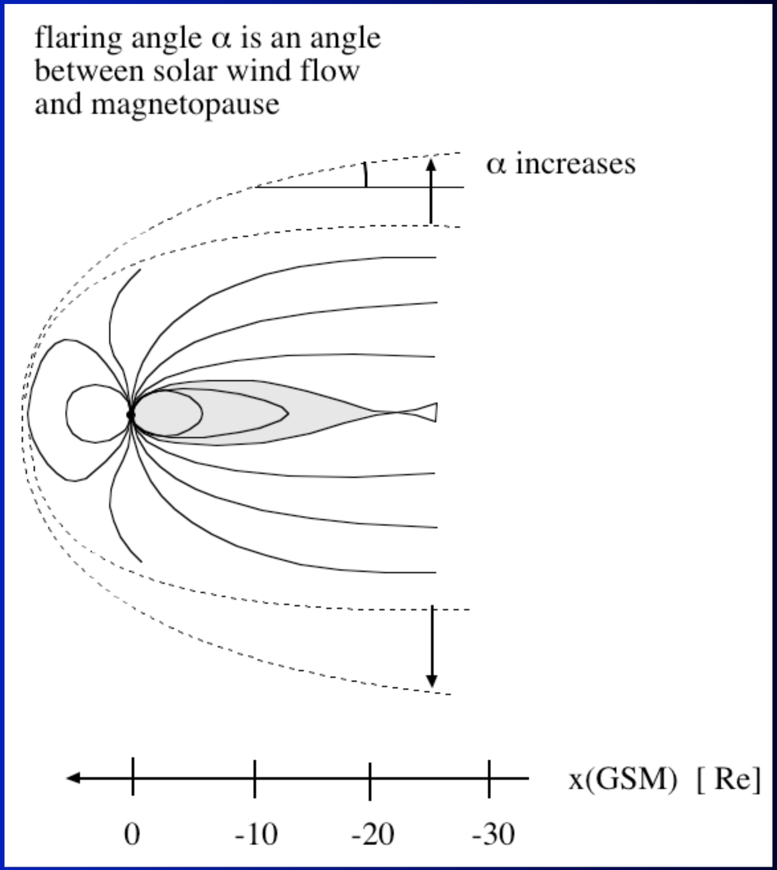
* Storms and substorms follow the 27-day periodicity (Bartels, 1934, Tanskanen et al. 2005).

High speed streams periodically hit the Earth.



IV. Orientation of the Earth's magnetosphere related to the Sun

- Earth's dipole tilt angle (season)
- Magnetotail tilt angle
- Flaring angle etc.



Tail flaring angle can grow up to 45 degrees

V. Heliosphere's location in the interstellar media

Cosmic rays