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United Nations Educational, Scientific and Cultural Organization

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310/1749-42

ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

The Dynamic Magnetosphere: Reaction to and Consequences of Solar Wind Variations

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The Dynamic
Magnetosphere
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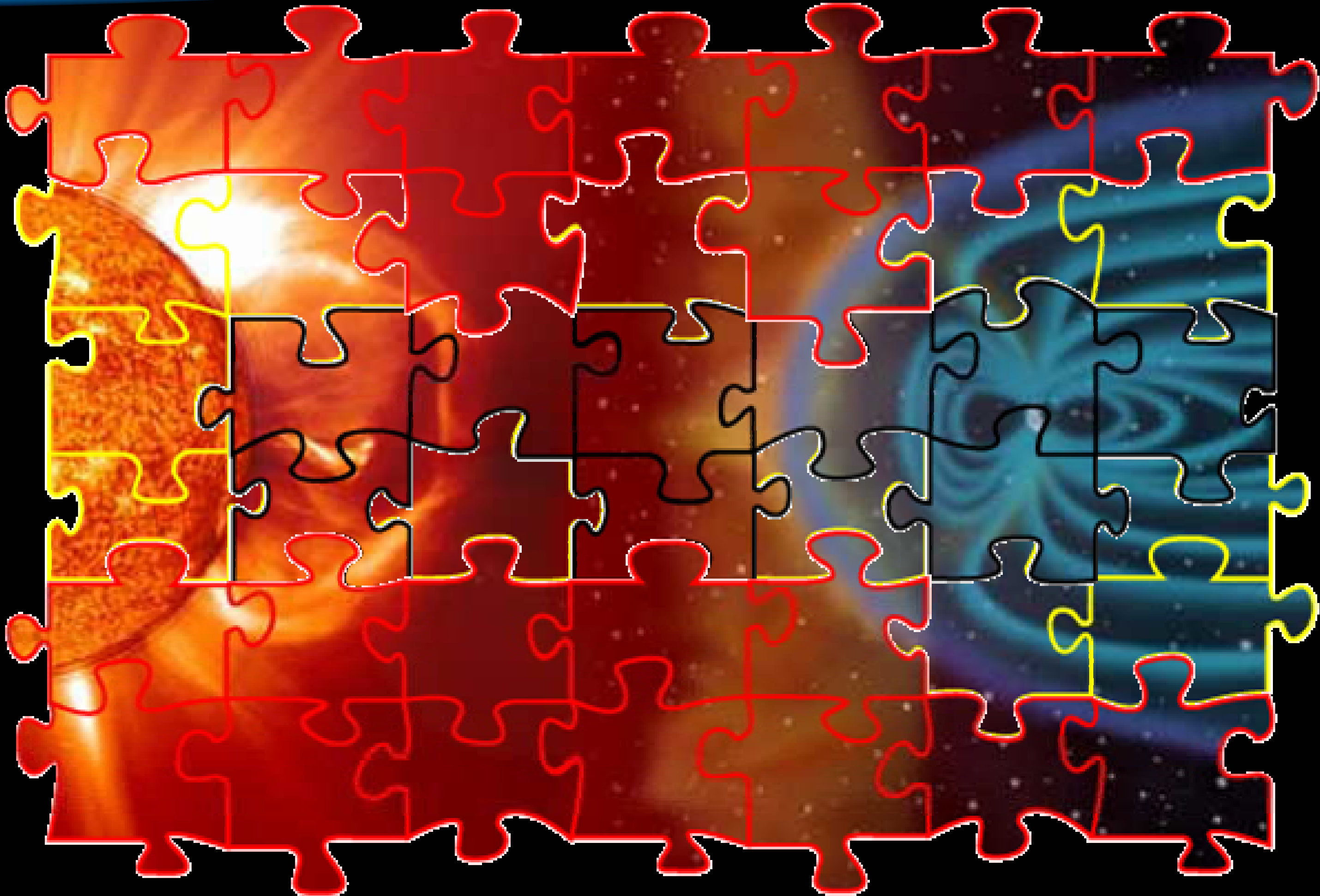
The Dynamic Magnetosphere

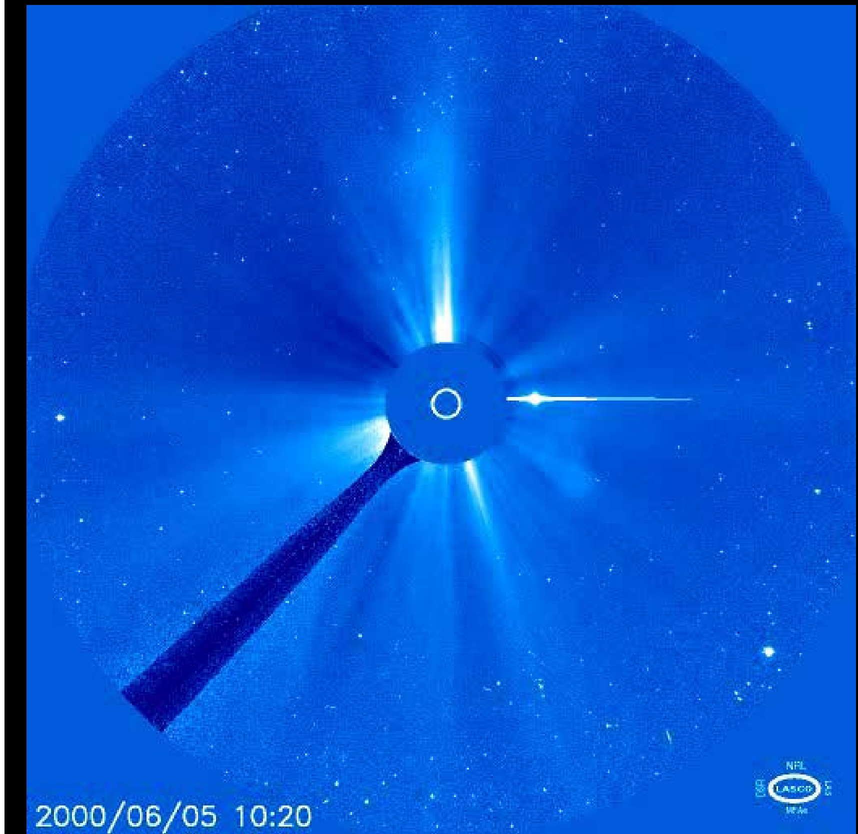
Outline:

- Introduction
- Basic concepts
- IMF and merging / reconnection
- Magnetospheric substorms
- Geospace magnetic storms

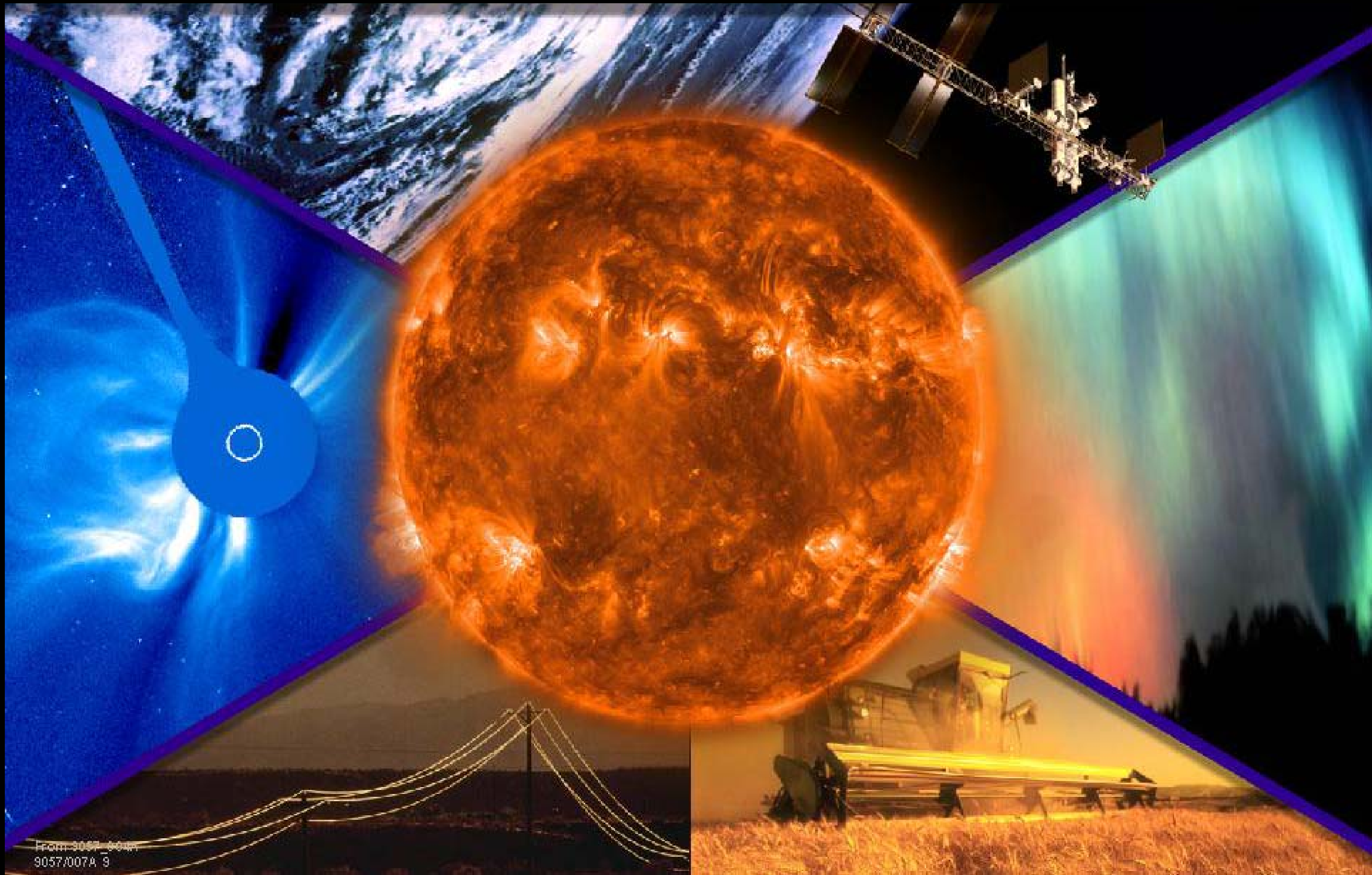
Sun-Earth Connection: still a puzzle!



Sun-Earth Connection: spectacular!



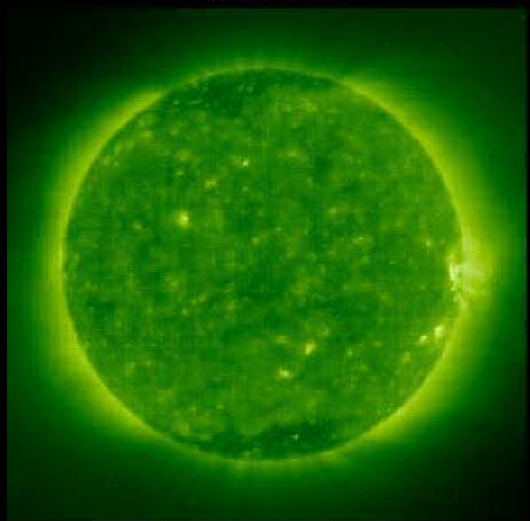
Why worry about Sun-Earth Connection?



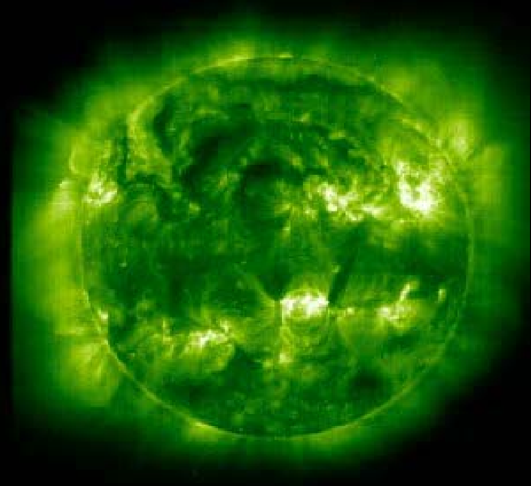
The Sun: driver of magnetospheric dynamics

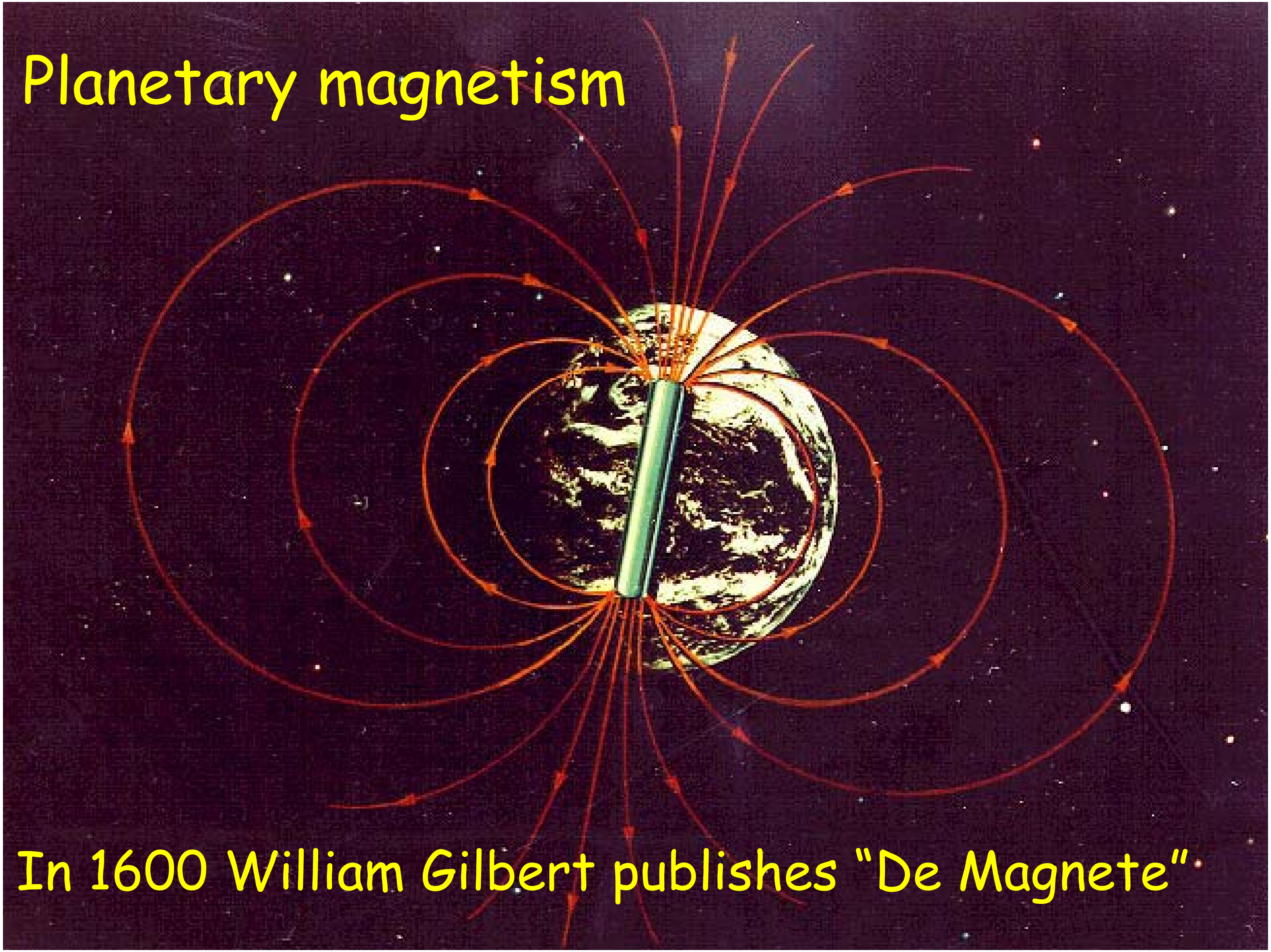
Age:	4.6 x 10^9 yrs		
Mass:	2 x 10^9 kg	or	330 000 M_{Earth}
Diameter:	1.4 M km	or	109 D_{Earth}
Power:	3.86 x 10^{26} W	or	4 Mtons/s matter -> energy
Distance	150 M km	or	390 x distance to Moon

EIT 195 Å
Dec. 1996



EIT 195 Å
June 1999




Planetary magnetism
In 1600 William Gilbert publishes “De Magnete”

Planetary magnetism

Planet	Radius (km)	Rotation period (days)	Equatorial magnetic field (nT)
Mercury	2439	58.6	340
Venus	6052	243	0.4
Earth	6371	1	31,000
Mars	3397	1	< 0.5
Jupiter	71,398	0.4	424,000
Braille	*0.8*	*3.6*	*92,500*
Saturn	60,000	0.41	21,500
Uranus	26,200	0.72	22,800
Neptune	24,300	0.70	14,400

The result:

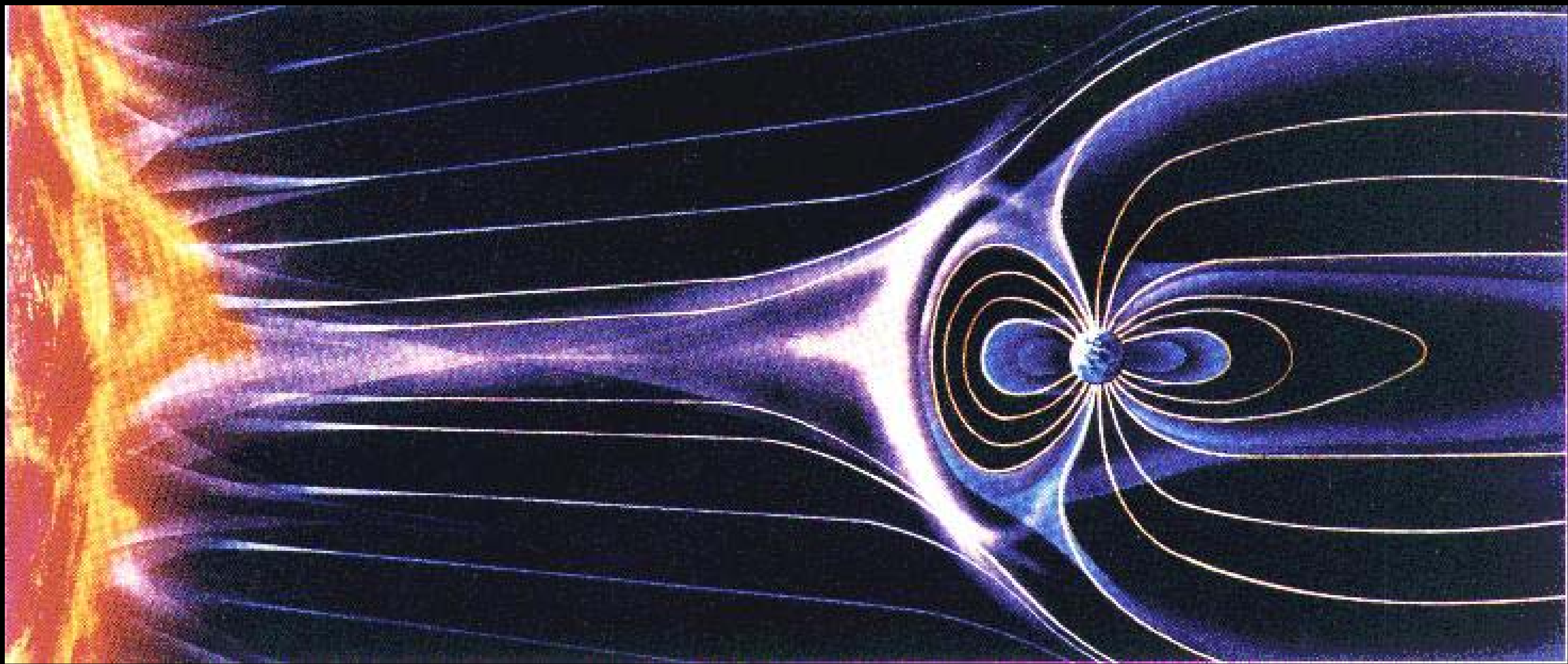


Illustration by K. Endo / Y. Kamide

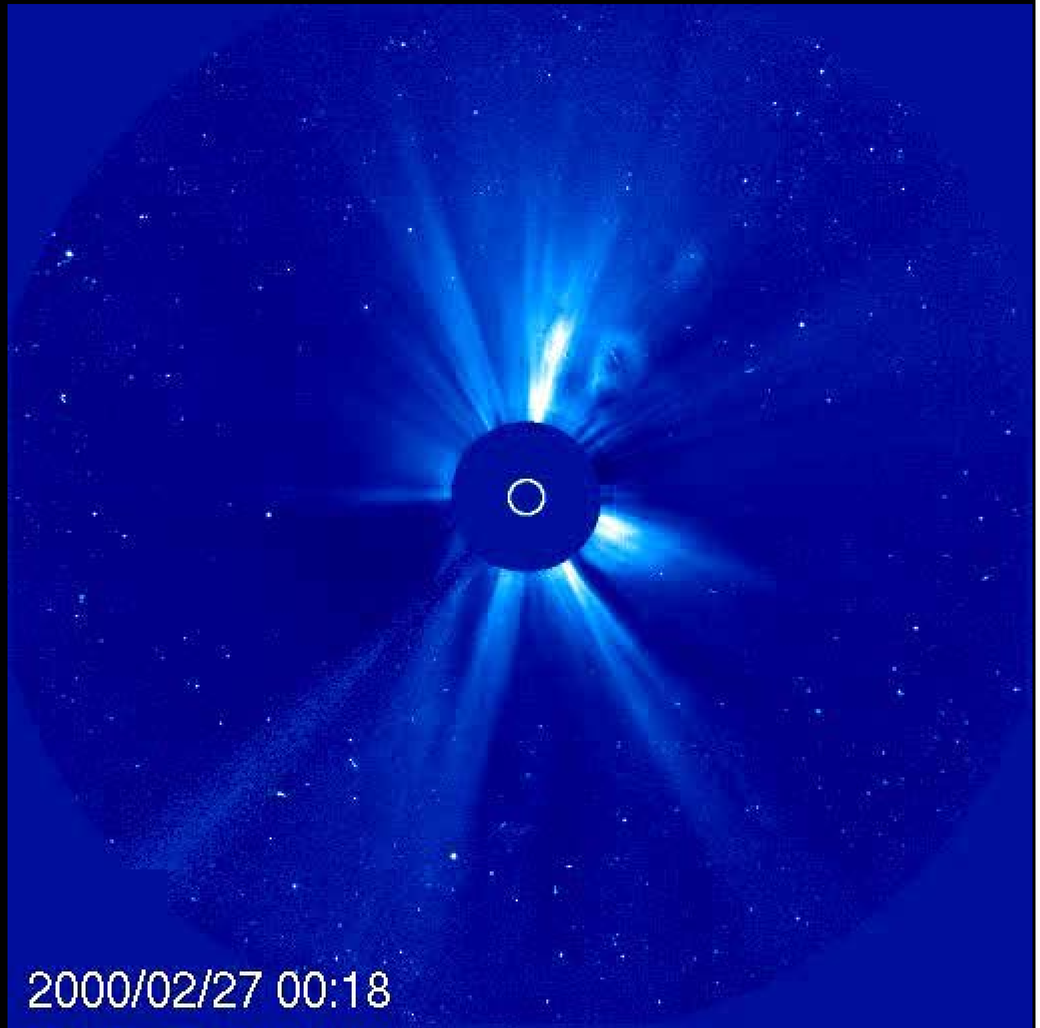
The Sun ejects vast magnetic clouds

Magnetic clouds @ Earth

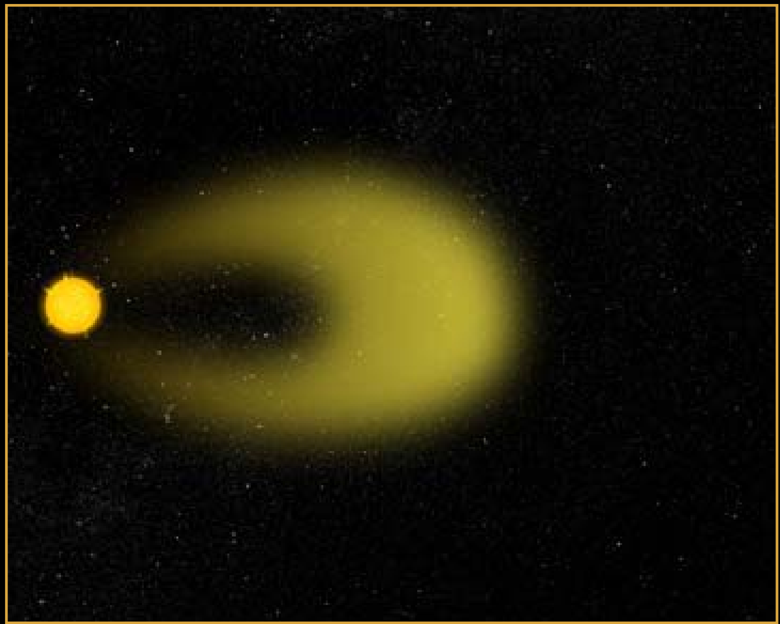
- Size: 50 Mkm
- Mass: 10^{13} kg
- Velocity: 500-1000 km/s

Ejection rate from Sun

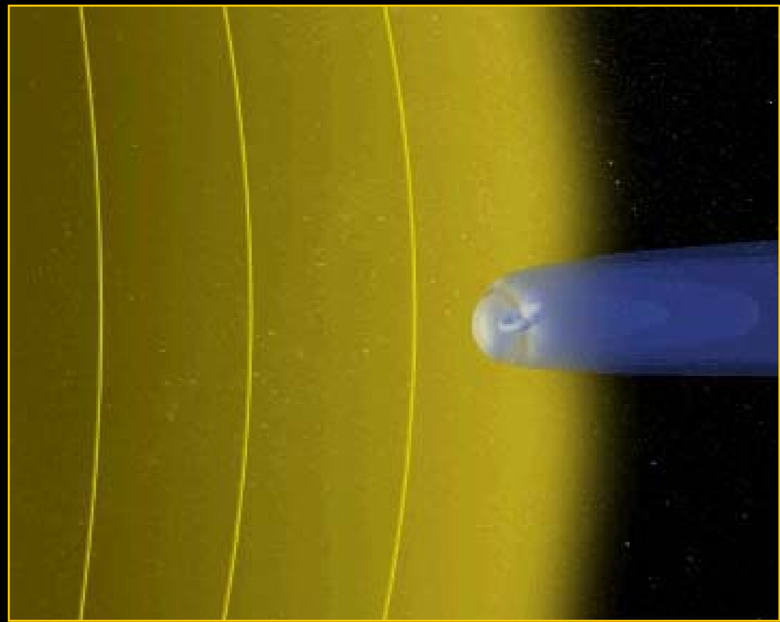
- 1/week (solar min)
- 3/day (solar max)



Clouds need 1-2 days to Earth orbit



Magnetic cloud leaving the Sun



Cloud reaching the Earth

Magnetospheric response

Enhanced upstream pressure
changes the position of the magnetopause
by several R_E resulting in
large-scale magnetosphere
reconfigurations

Magnetospheric response

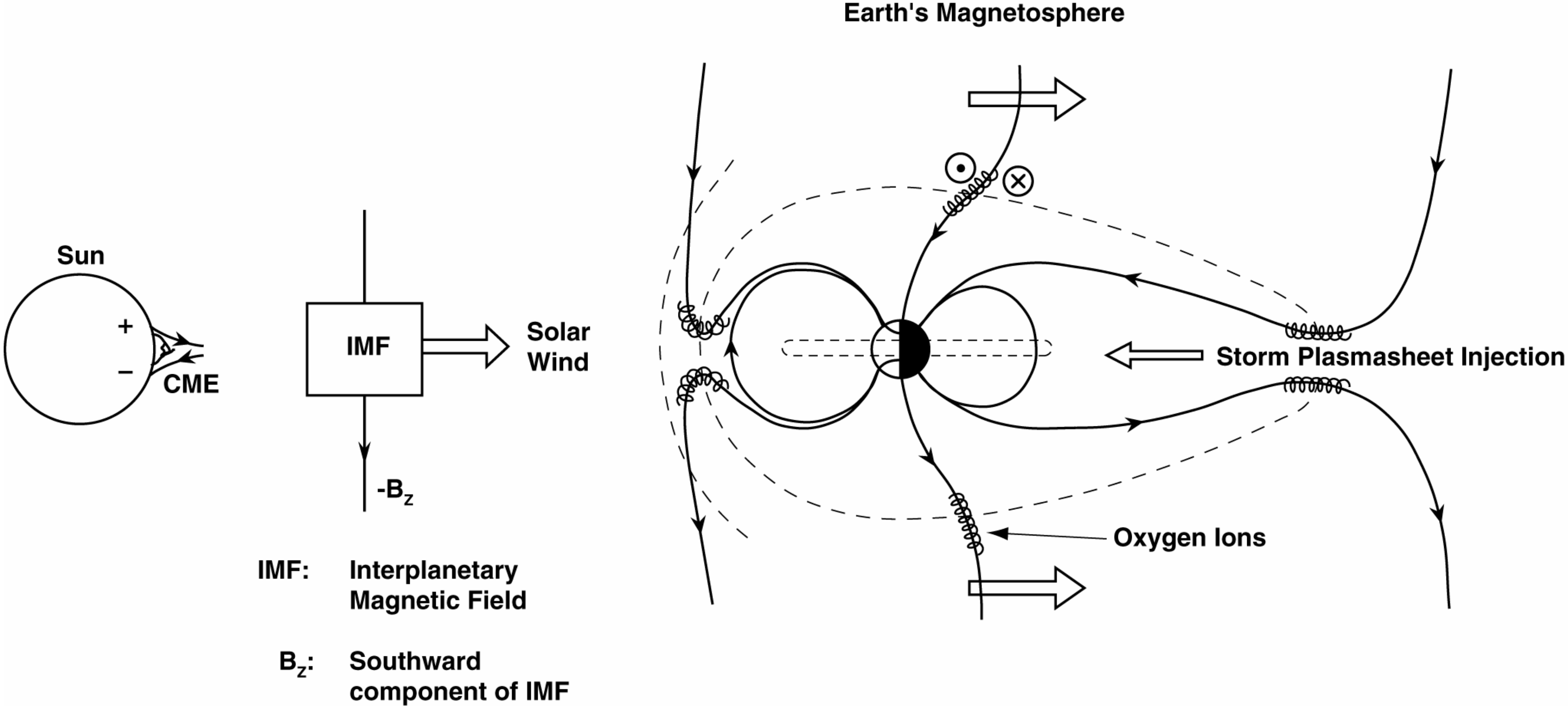
Major critical parameter:

The orientation of IMF (sign of B_z) - if **southward** (i.e. anti-parallel to the direction of geomagnetic field) then **merging** (reconnection) of solar wind and terrestrial magnetic field lines occurs.

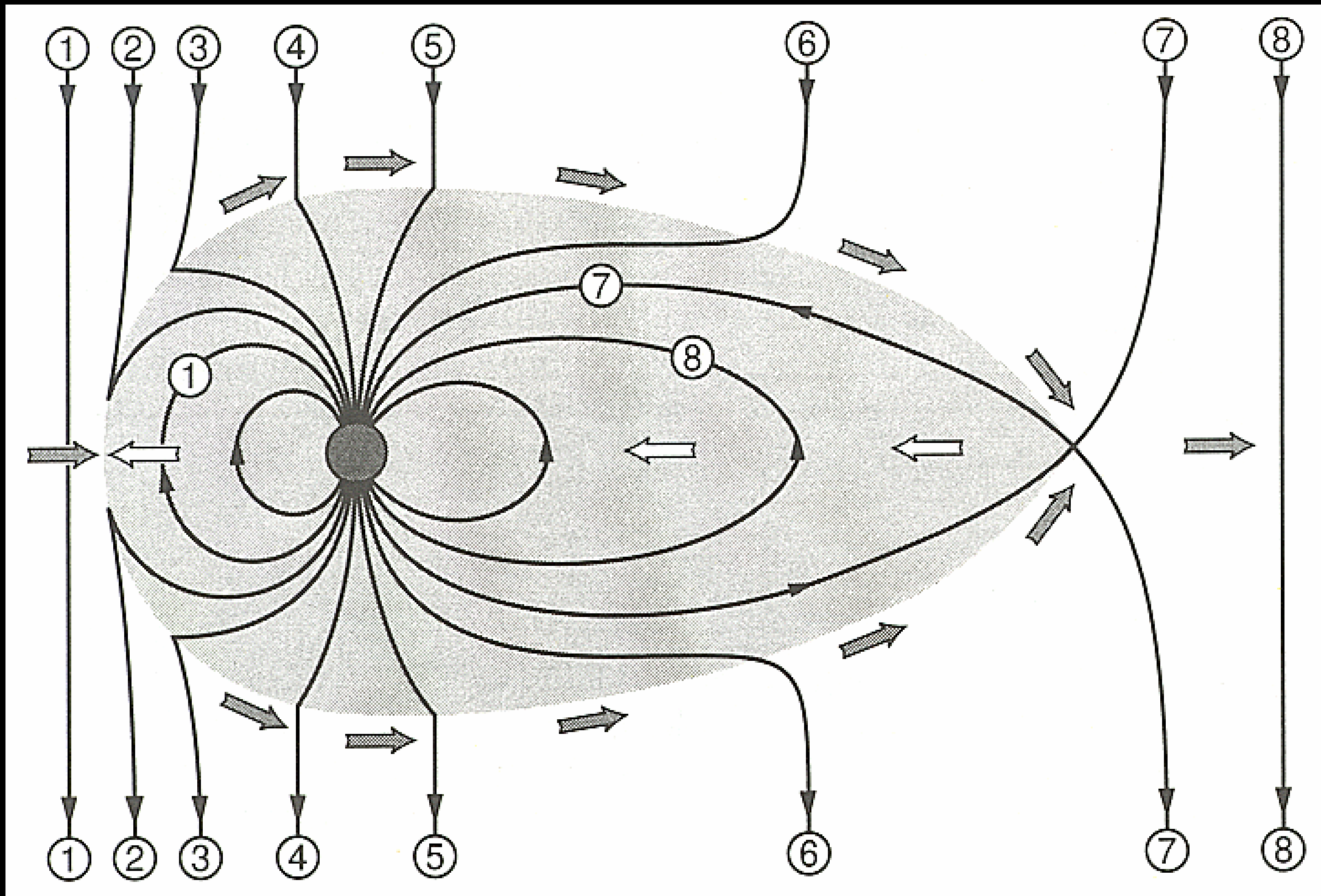
Origin of B_{south}

- Alfvenic fluctuations in SW (quiet Sun)
- Deflections in front of and inside magnetic clouds or ICMEs (active Sun)

Magnetic reconnection in geospace

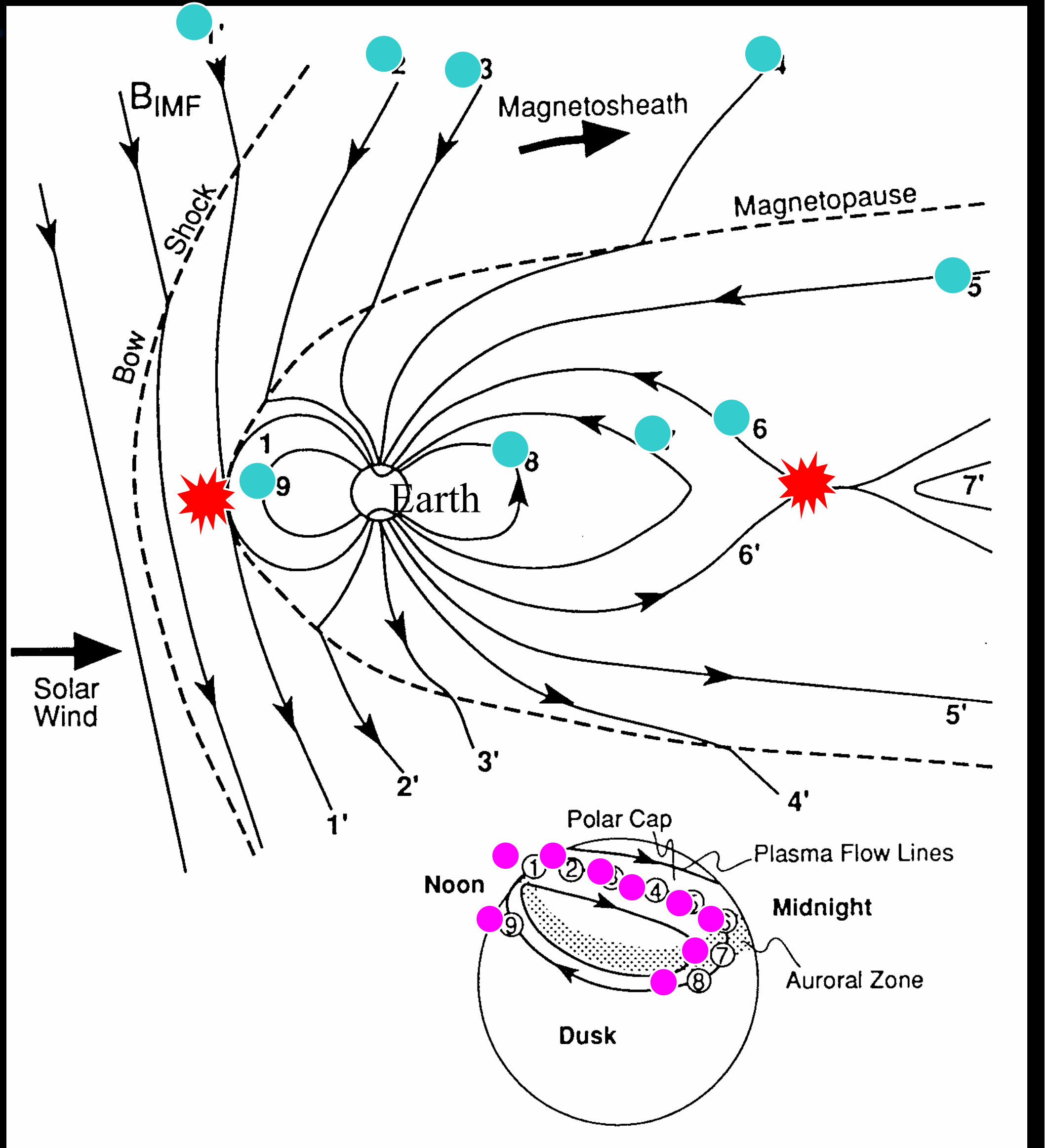


The overall picture



Magnetic reconnection in geospace

Merging of the interplanetary magnetic field and the geomagnetic field at the magnetopause drives **reconnection in the magnetotail** and the **plasma convection cycle.**



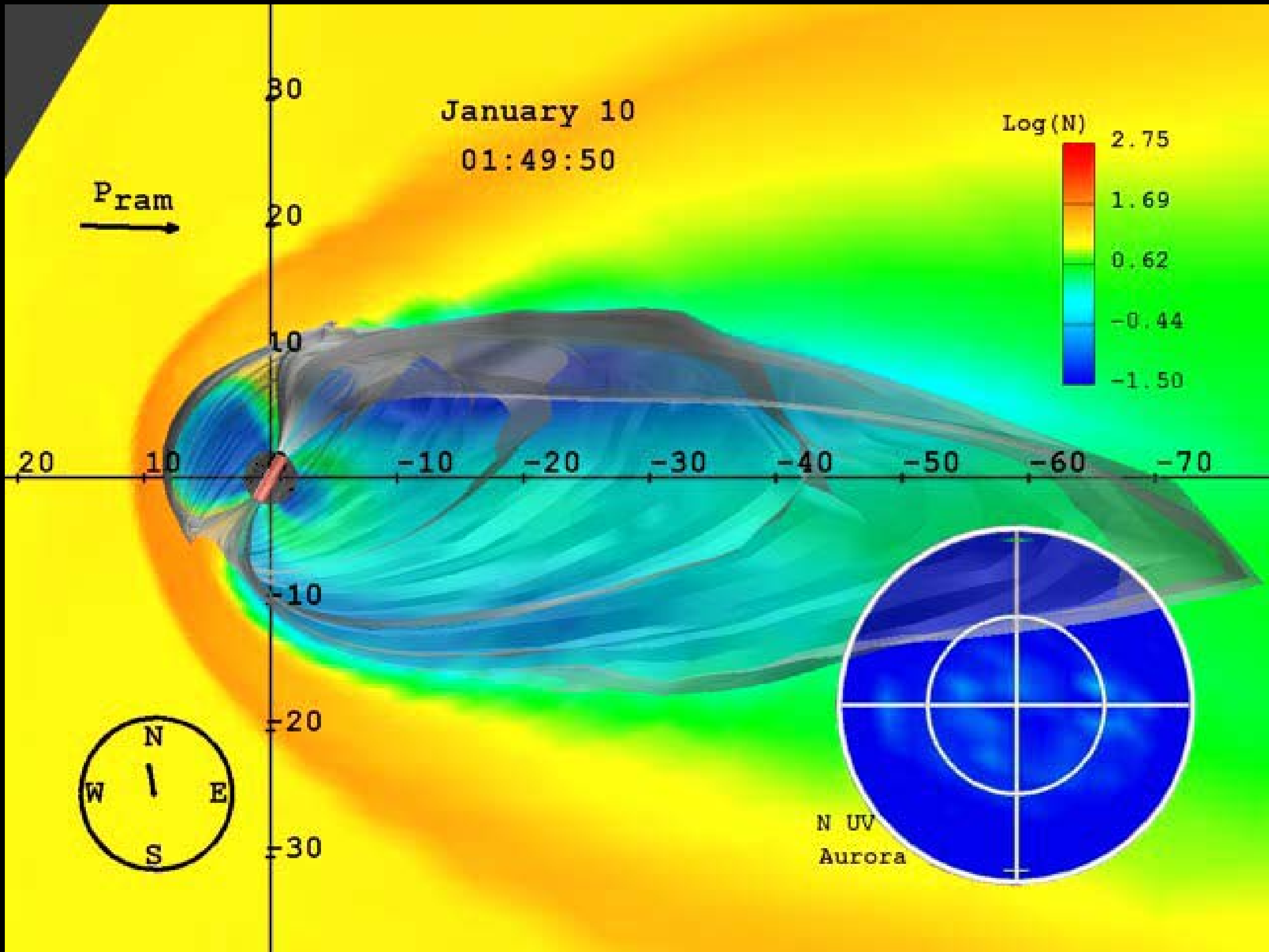
Magnetospheric response to merging

In case of $B_z < 0$, merged magnetic field lines allow **solar wind plasma** to **penetrate** from outer space into the magnetosphere. Magnetic flux is added to and **stored** in the magnetotail.

Magnetospheric response to merging

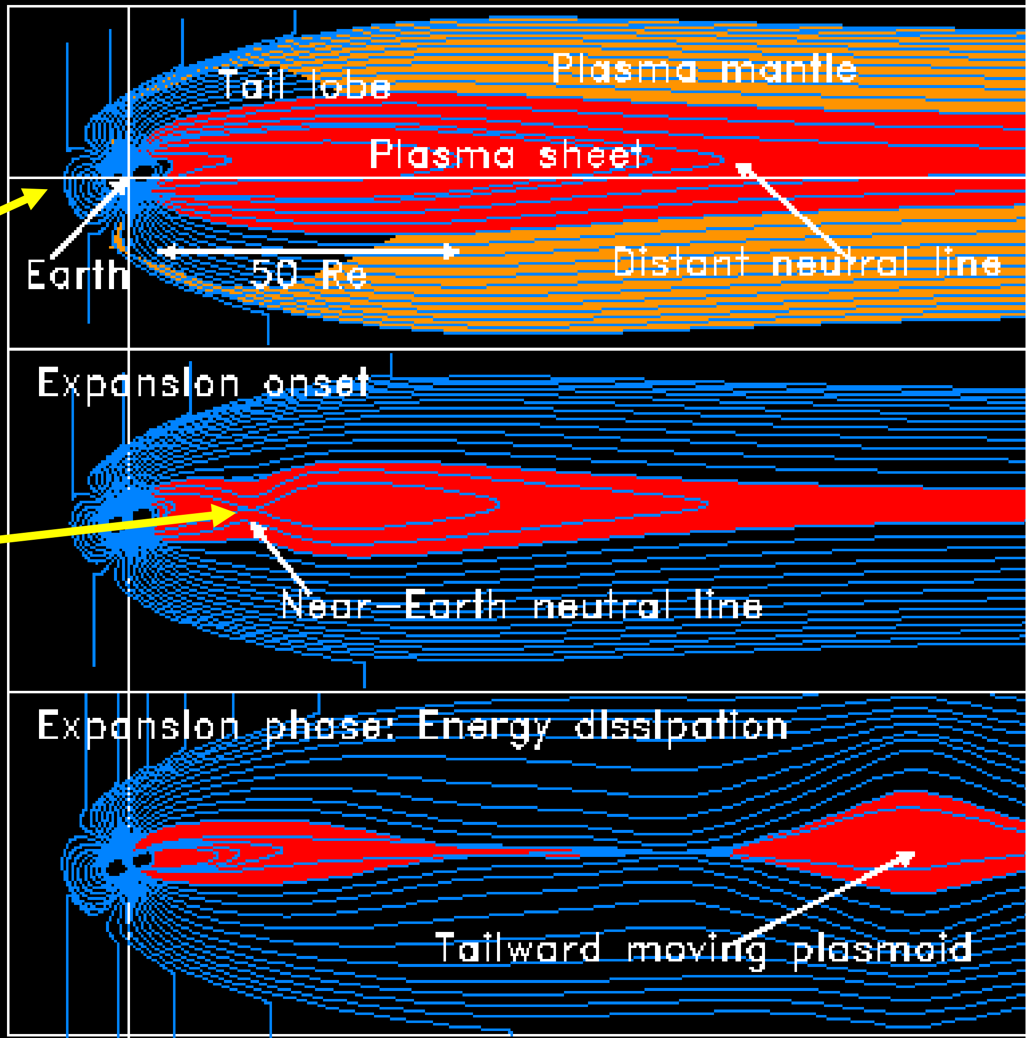
This excess of stored magnetic energy eventually leads to the occurrence of magnetospheric **substorms** and geospace magnetic **storms**, as a means of **energy dissipation**.

Simulated magnetospheric reaction



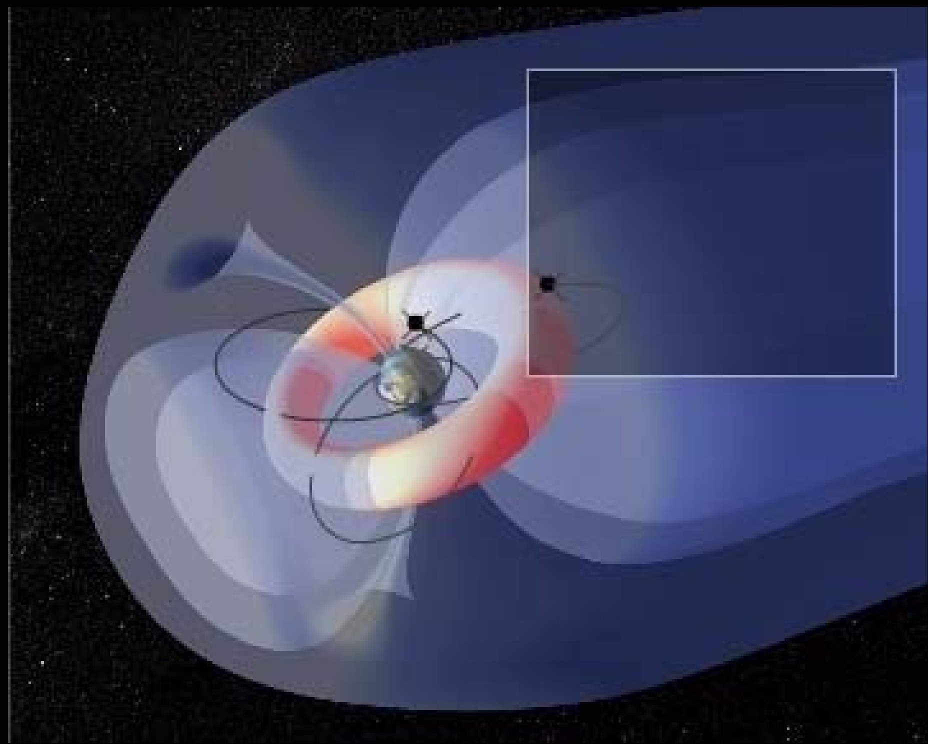
Magnetospheric substorms

- Duration: 1-3 hours
- Energy: 10^{15}-10^{16} J
- dayside reconnection = energy loading
- nightside reconnection = msph. reconfigurations, energy dissipation, particle acceleration, plasmoid ejection
- auroral brightening, field-aligned currents, Joule heating
- Rate: several / day



Geospace magnetic storms

- Duration: 1-3 days
- Energy: 10^{16} - 10^{17} J
- Magnetosphere:
  - global B disturbances
  - intense currents (RC)
  - particle acceleration
- Auroral regions
  - bright auroral displays
  - intense ionospheric currents (electrojets)
  - rapid surface B variations
- Rate: 1/month

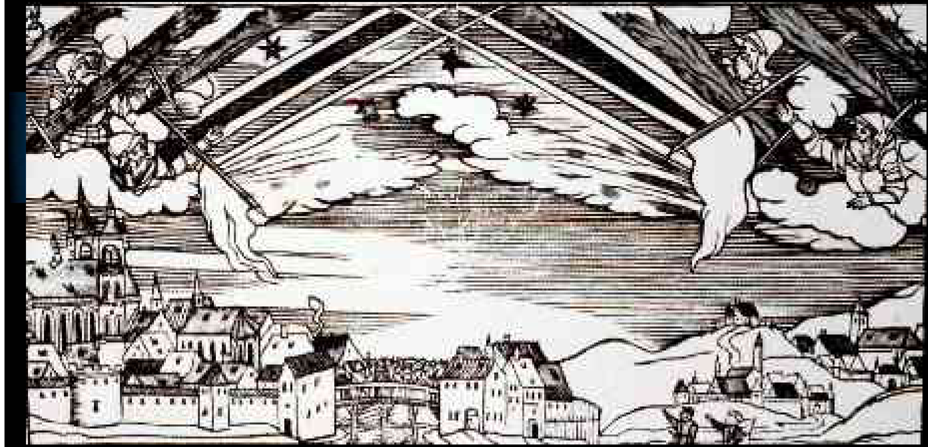


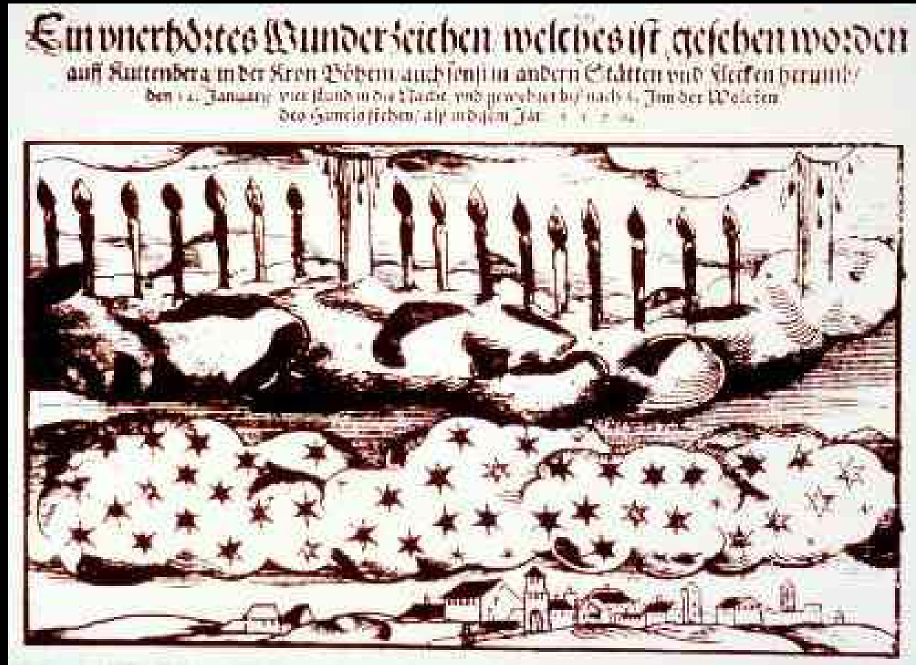
Storms and substorms

Similiraties:

- Collective phenomena
- Merging / reconnection
- Particle acceleration
- Intensification of currents
- Auroral displays

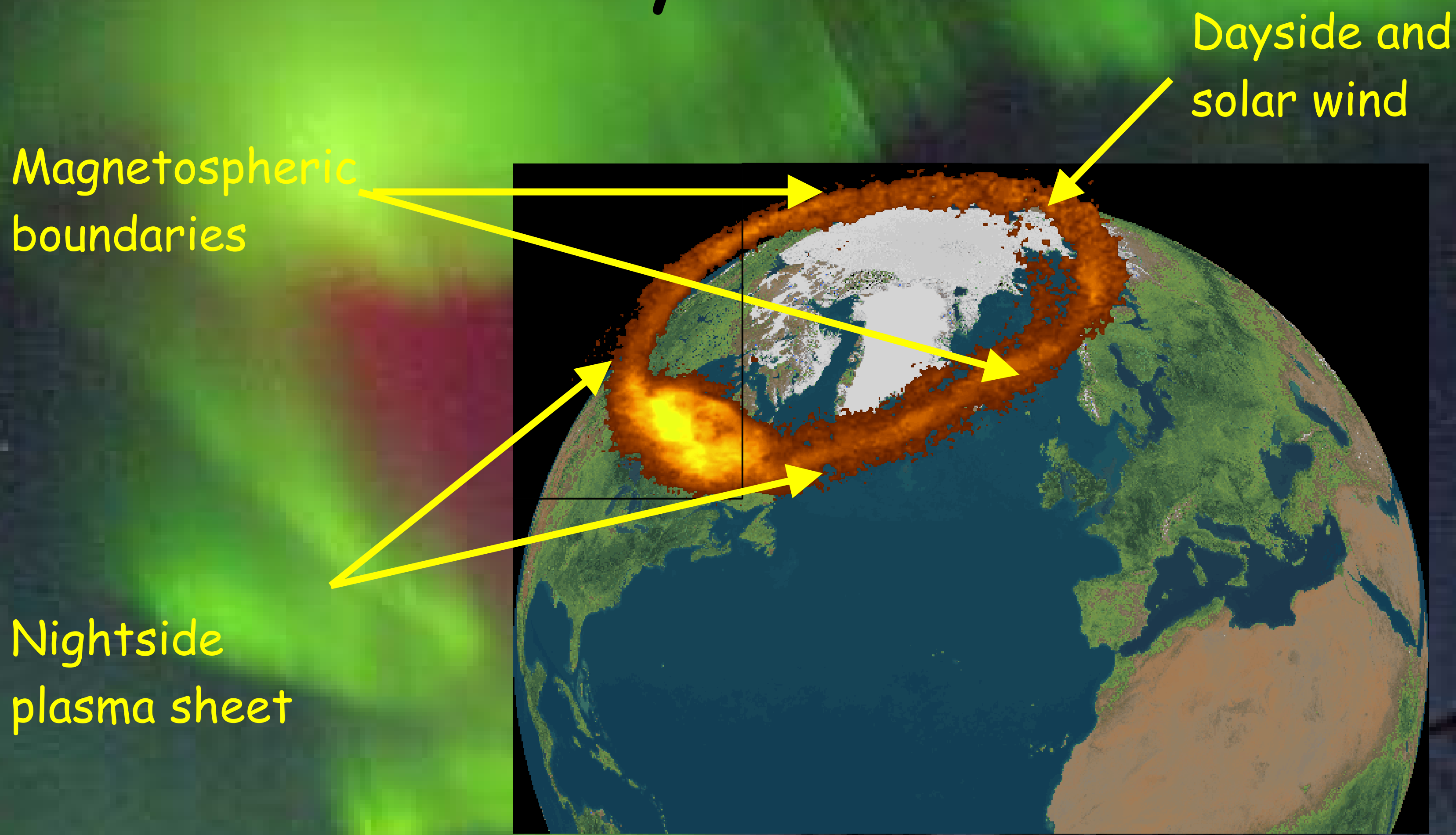



Ein vnerhörtes Wunderzeichen welches ist gesehen worden
auff Kuttenberg in der Kron Böhem auch sonst in andern Stätten vnd Flecken herumb/

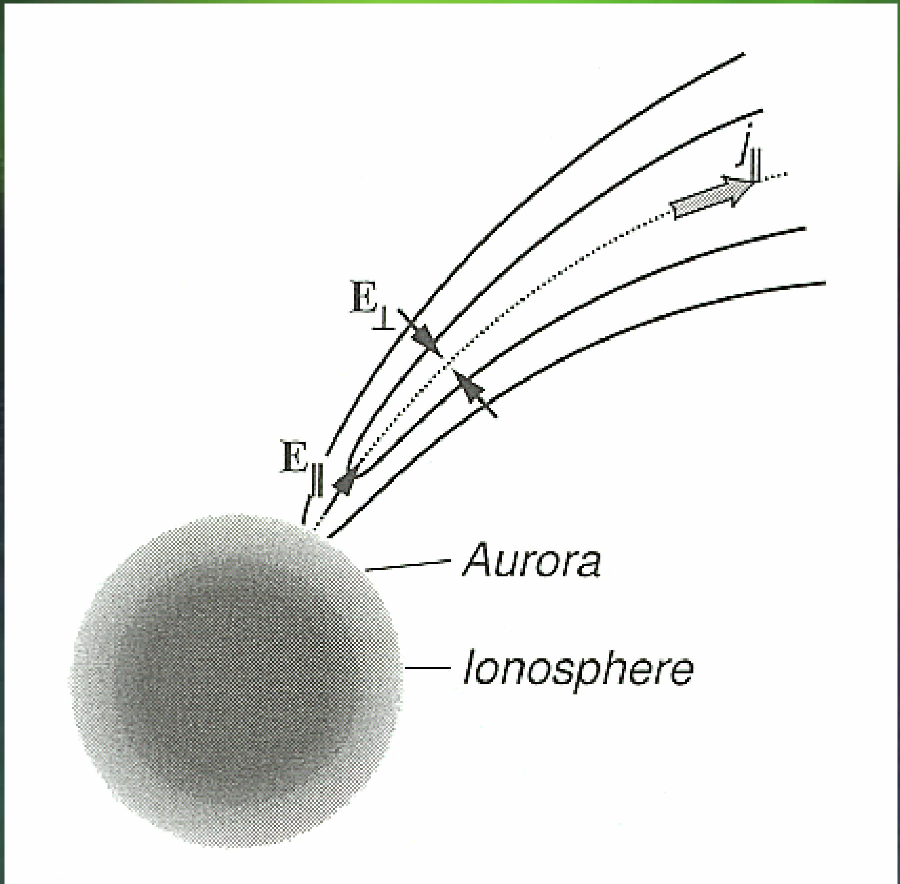

Wunderwerck/ so abermal den 5. October/im 1591. Jar/in der Nacht zu Nürnberg ist gesehen worden.

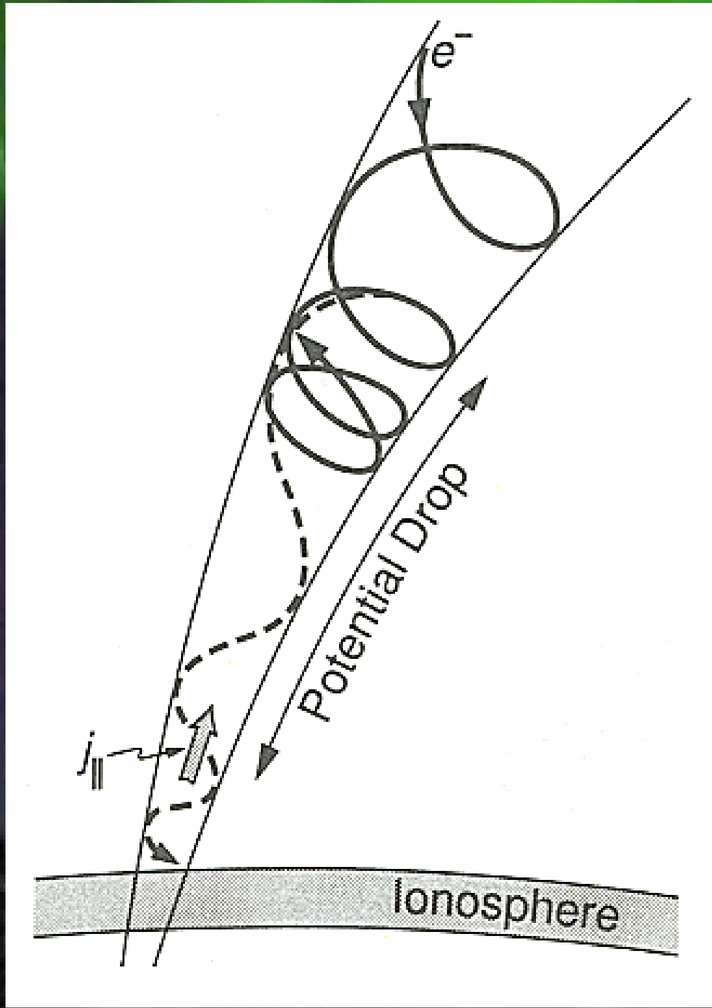
Auroral oval: A projection of magnetospheric particle dynamics



POLAR VIS imager, courtesy of Lou Frank, U. Iowa

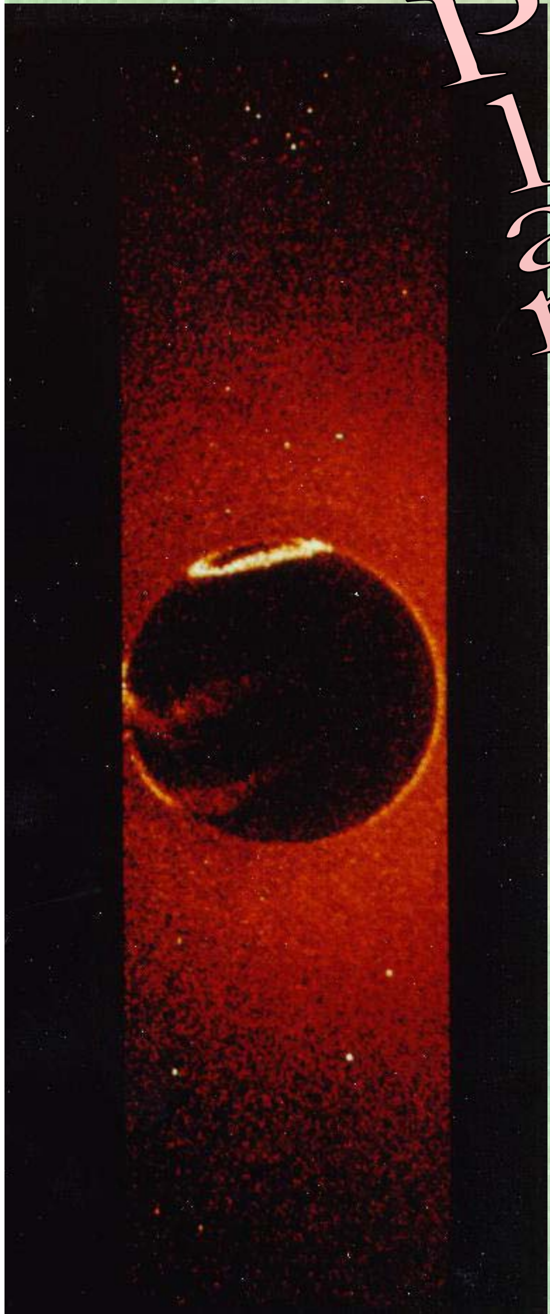
Mechanism of aurora

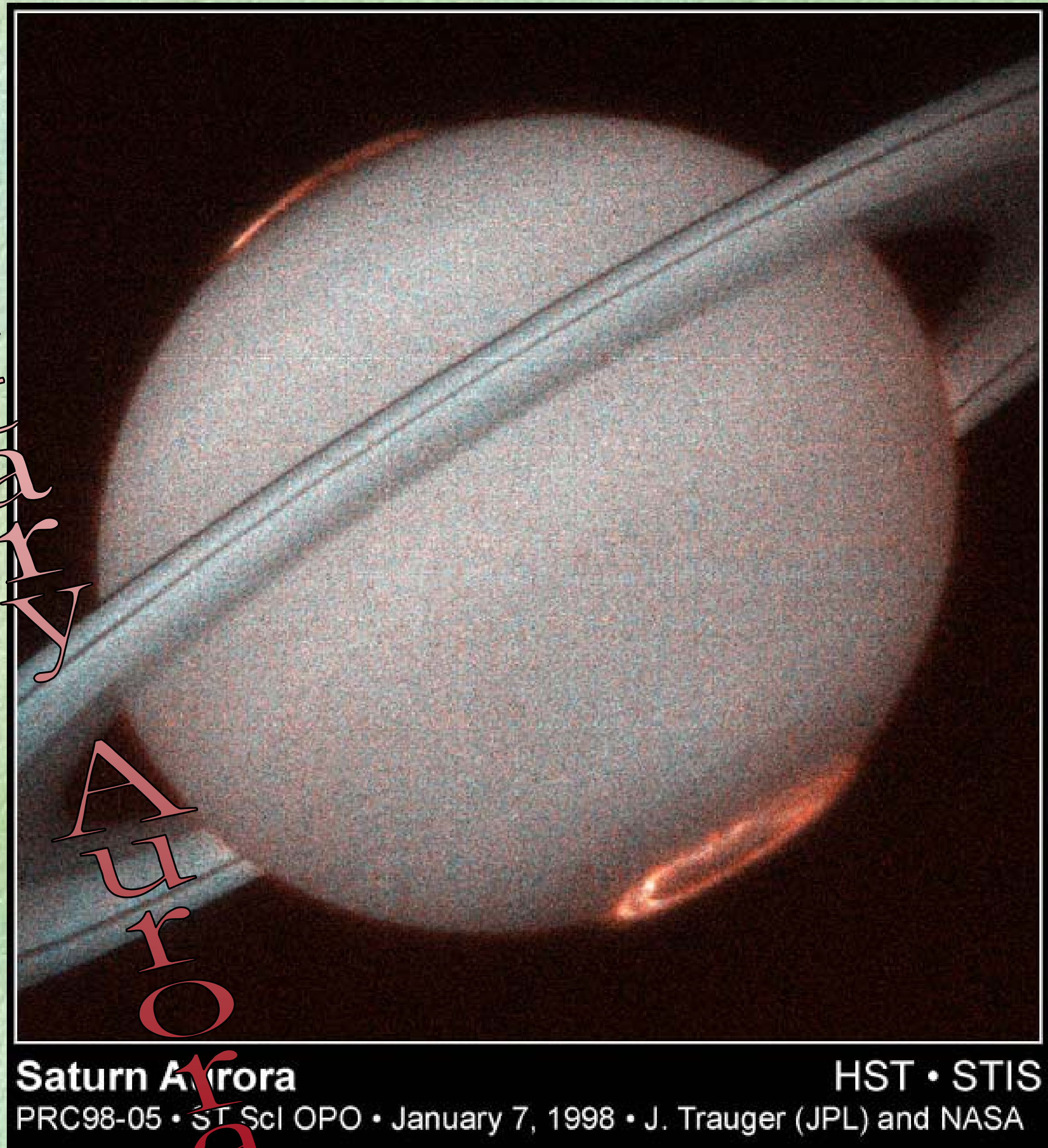




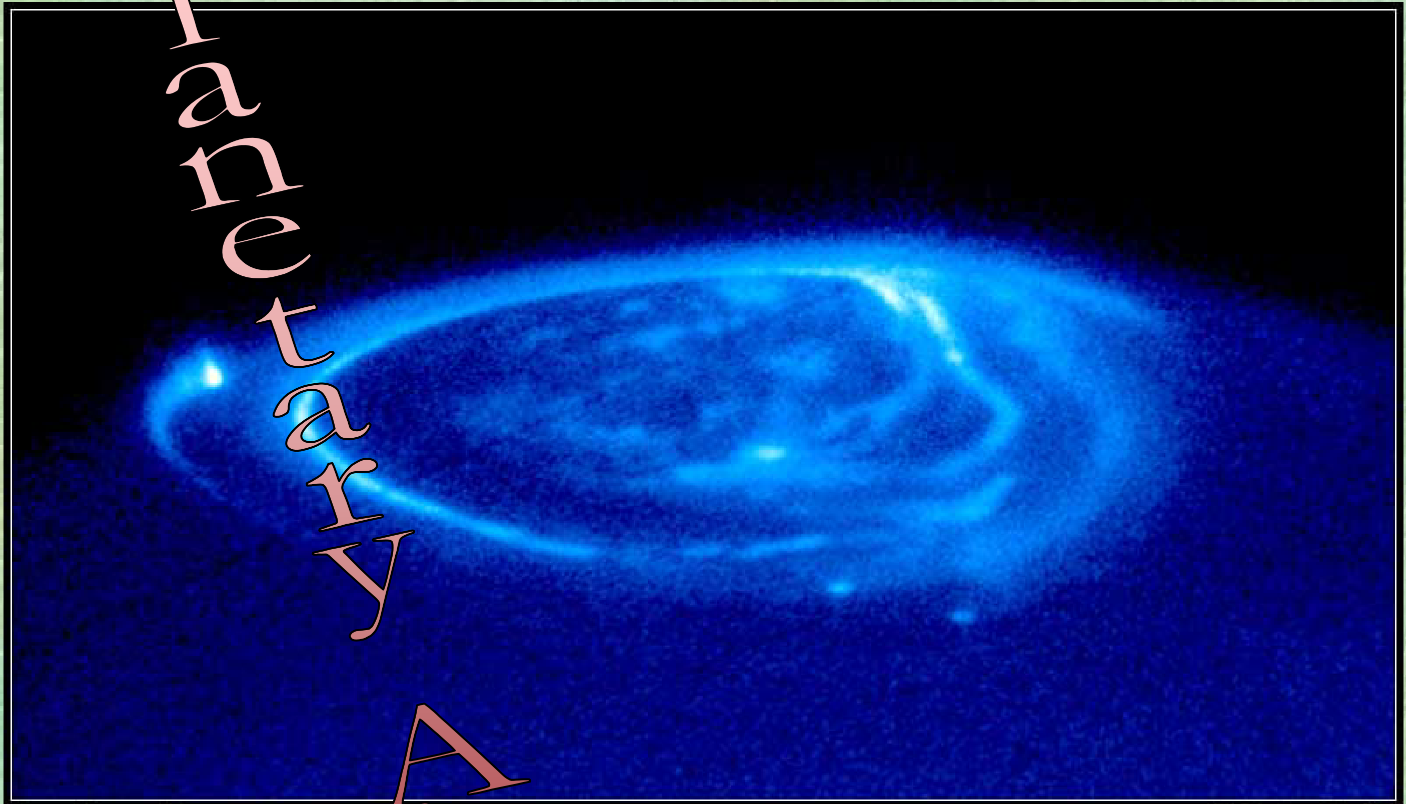
Birkelan
terrel

Planetary Aurora



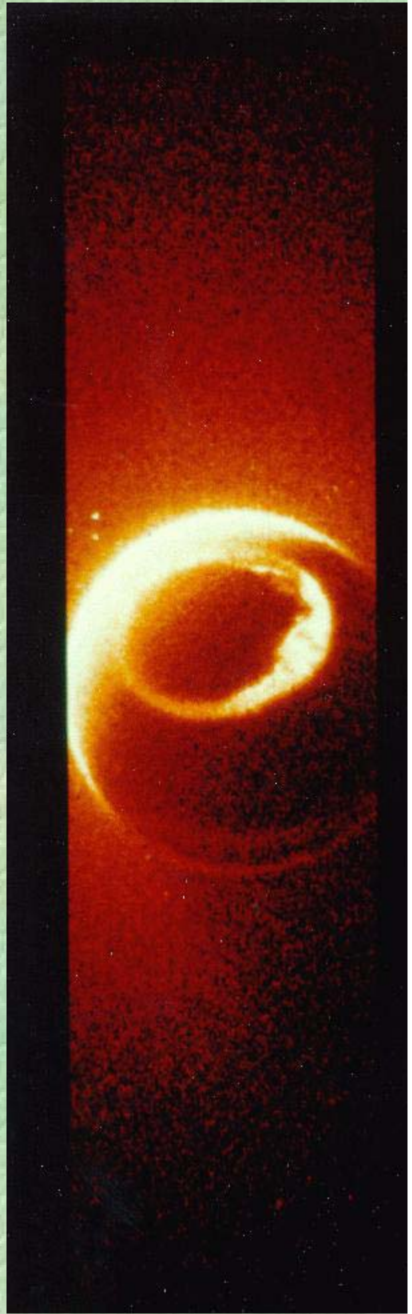


Planetary Aurora



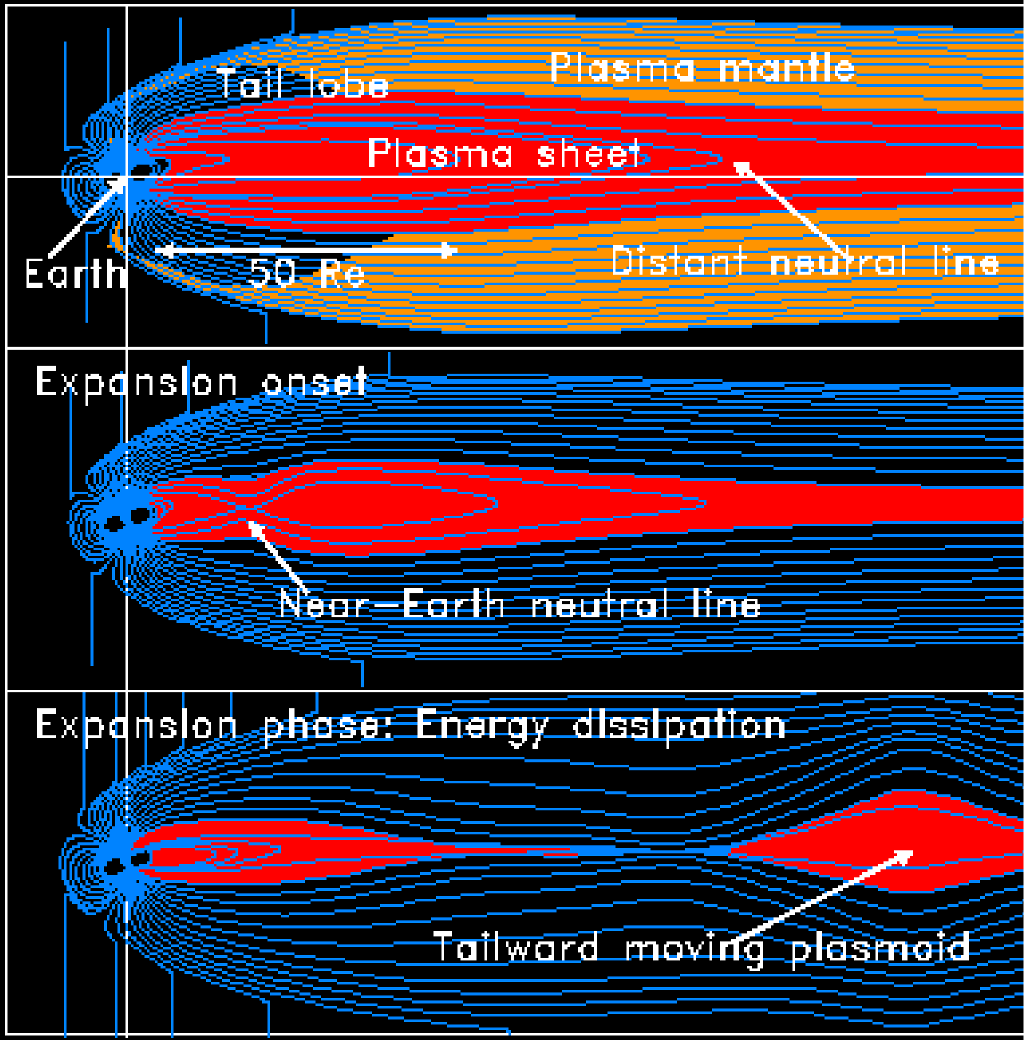
Jupiter Aurora

NASA and J. Clarke (University of Michigan) • STScI-PRC00-38



Magnetospheric substorms

- Duration: 1-3 hours
- Energy: 10^{15}-10^{16} J
- Rate: several / day



Magnetospheric substorms

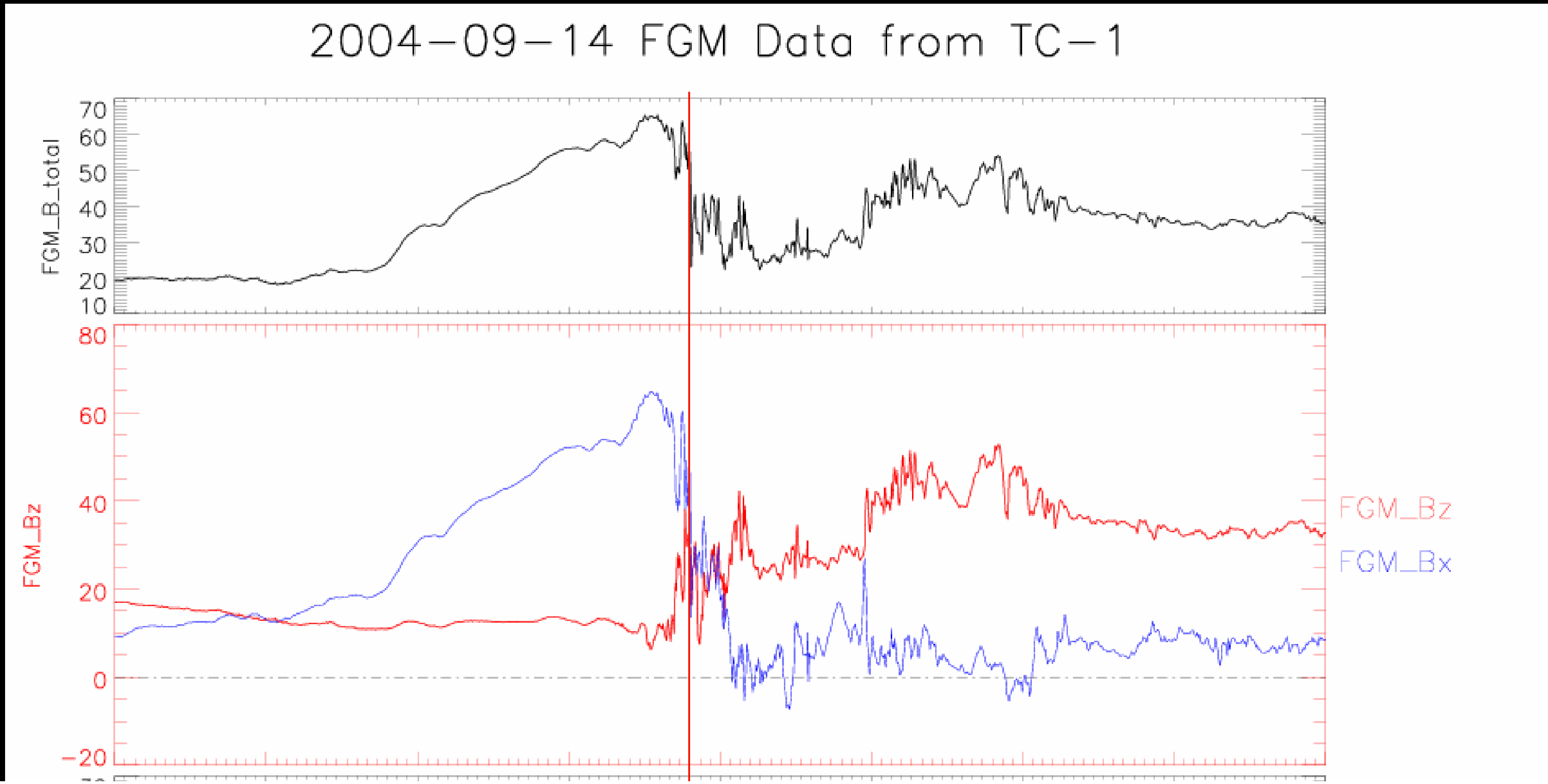
Fundamental mode of magnetospheric disturbance. Response to specific IMF variation resulting in increased energy transfer from SW to magnetosphere.

Main features:

- reconfigurations
- particle acceleration
- plasmoid ejection
- auroral brightening
- electrojets and field-aligned currents
- Joule heating

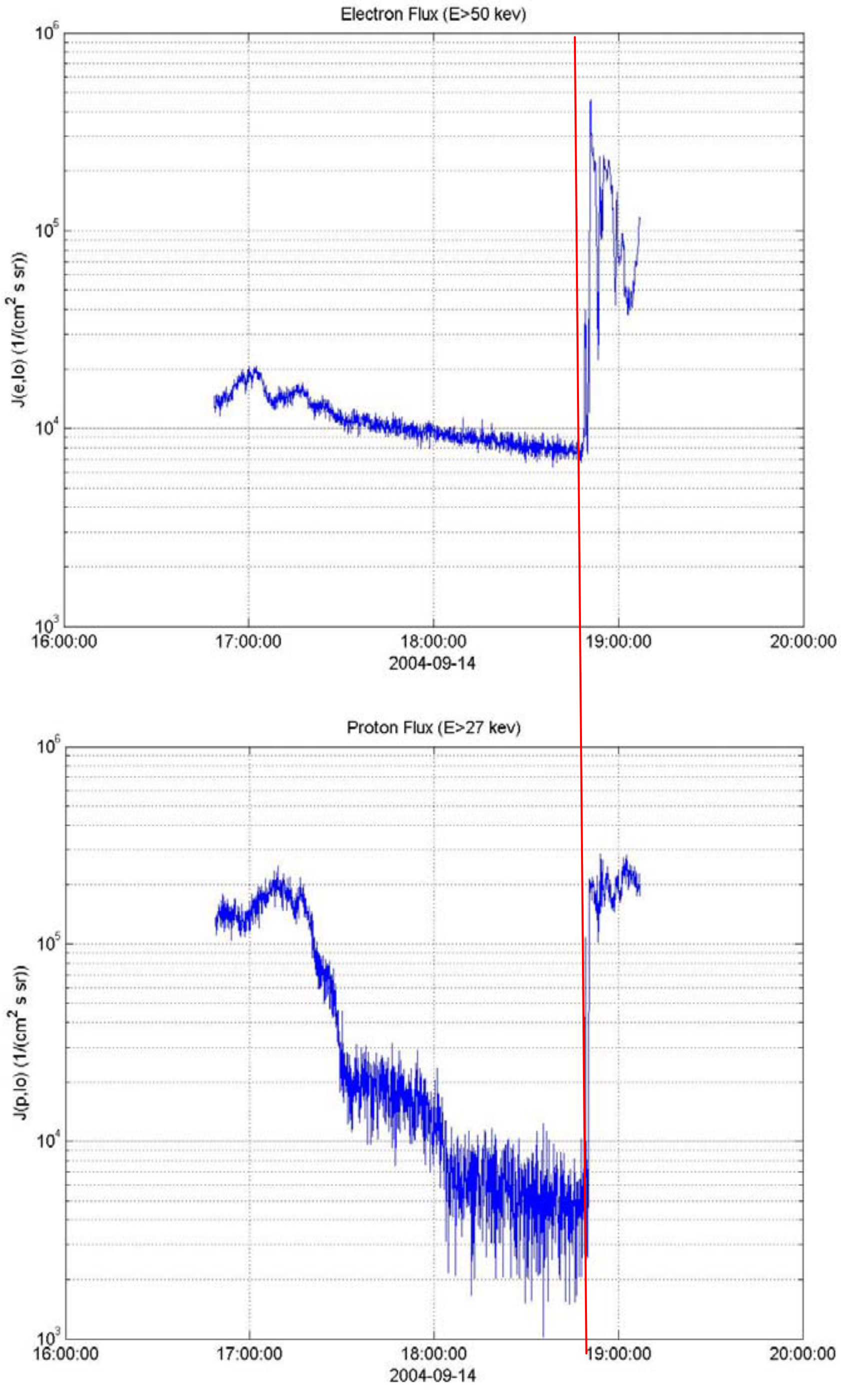
Typical substorm features

Magnetic field reconfigurations (stretching followed by dipolarization)

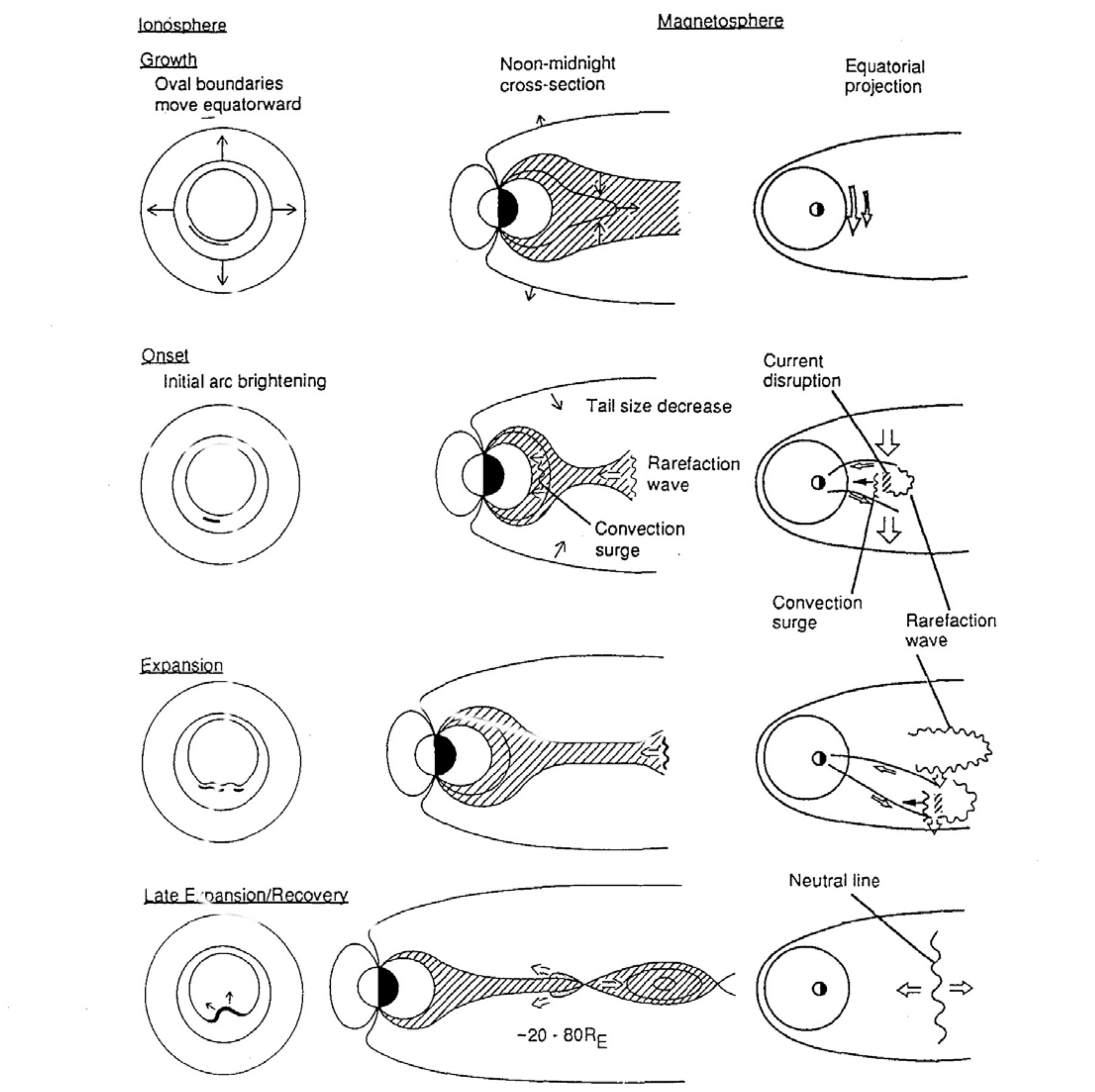


Typical substorm

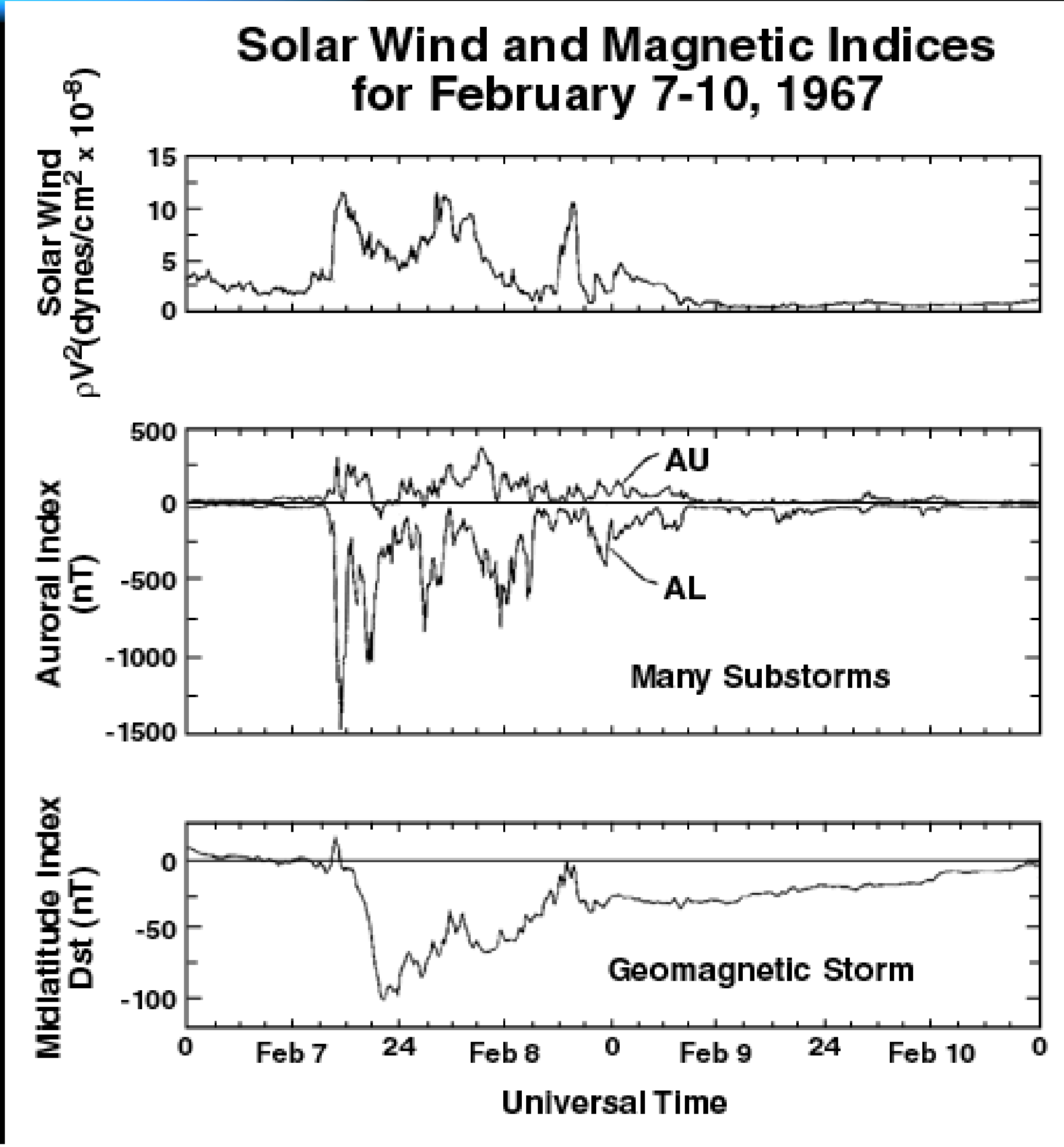
Particle acceleration and injection into inner magnetosphere



Subst


Ionosphere
Magnetosphere
Growth
Oval boundaries move equatorward
Noon-midnight cross-section
Equatorial projection
Onset
Initial arc brightening
Tail size decrease
Rarefaction wave
Convection surge
Current disruption
Convection surge
Rarefaction wave
Expansion
Late Expansion/Recovery
Neutral line
-20 - 80R_E

Monitoring of substorms



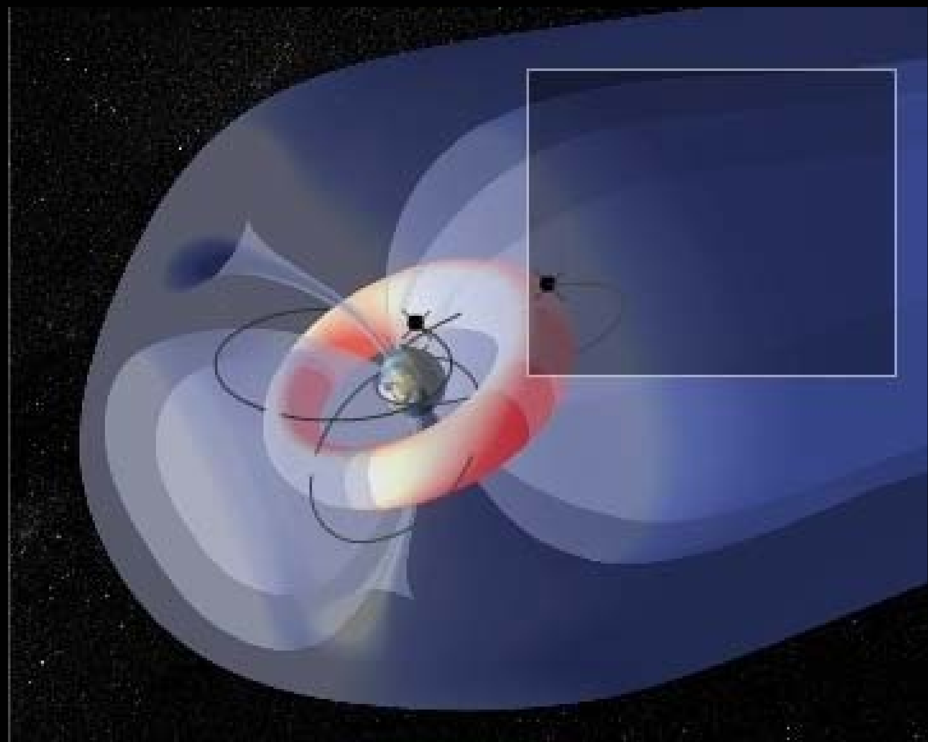
Storms and substorms

Main differences:

- Duration
- Occurrence frequency
- Energy content
- Spatial extent

Geospace magnetic storms

- Duration: 1-3 days
- Energy: 10^{16} - 10^{17} J
- Rate: 1/month



Magnetic storms

Most complex mode of magnetospheric disturbance. Response to long-duration energy input from SW.

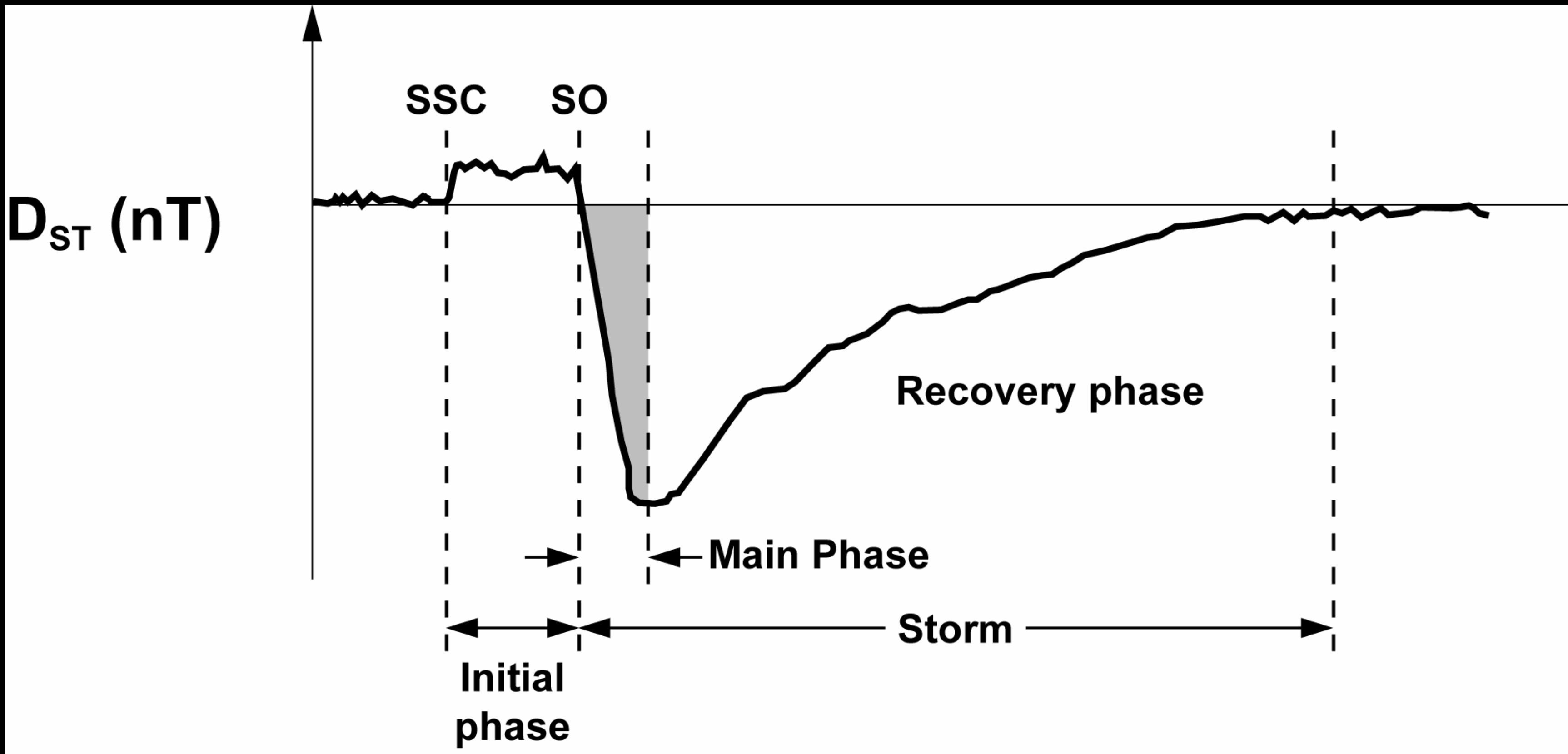
Main features:

- global magnetospheric B disturbances
- intense currents – Ring Current
- particle acceleration
- bright auroral displays
- intense ionospheric currents (electrojets)
- rapid ground B variations

Intense magnetic storms can cause:

- bright aurorae, down to low latitudes,
- damage to high voltage lines in arctic regions,
- anomalous corrosion of oil pipelines,
- damage to long-distance communication cables,
- malfunction of magnetic compasses,
- damage to satellites and satellite systems,
- effects on biological systems.

Monitoring of storms



Ring current - the classical picture

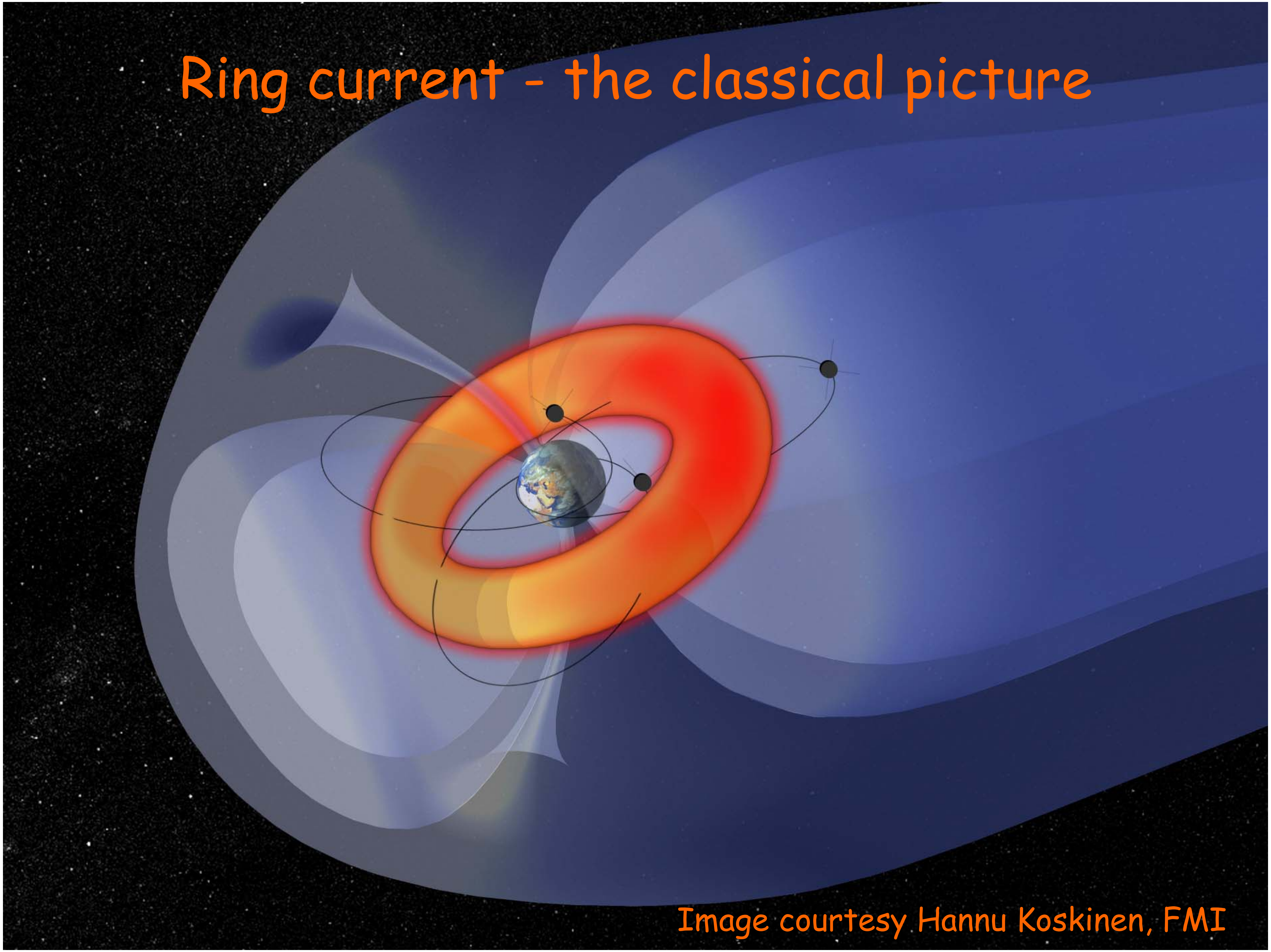


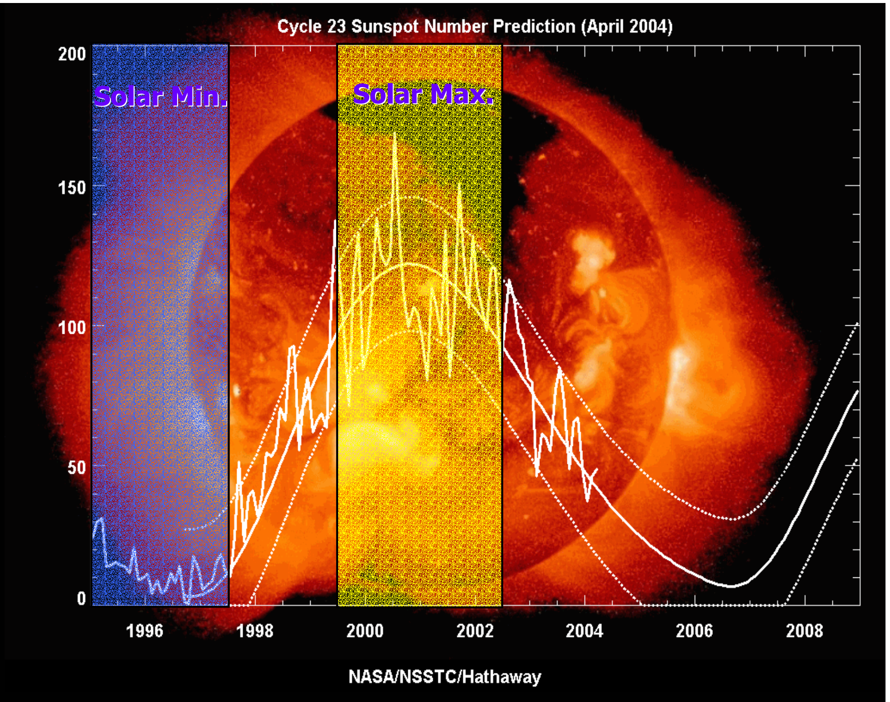
Image courtesy Hannu Koskinen, FMI

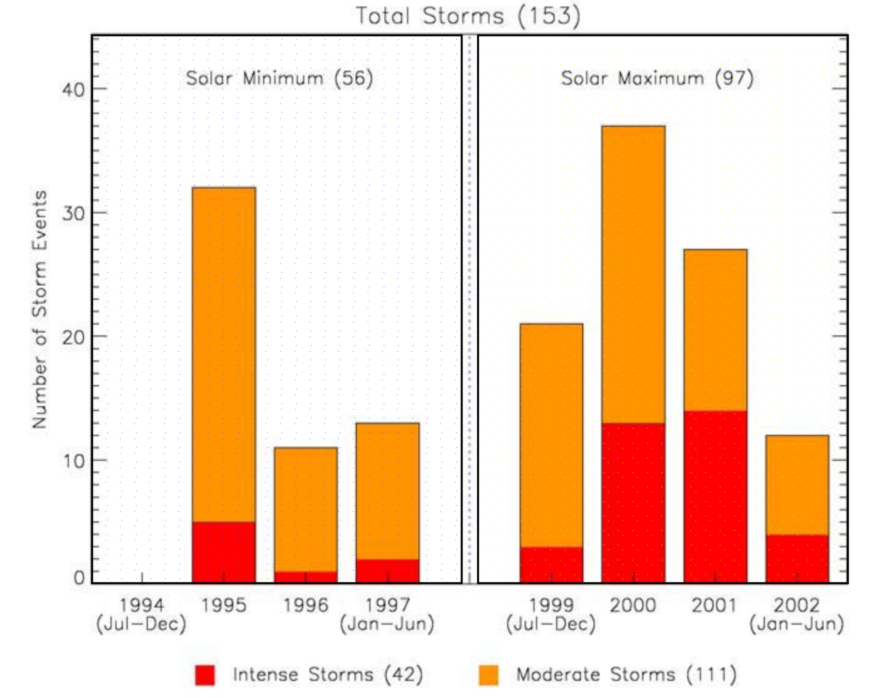
Storm size and solar cycle

- Solar Minimum:
  - Jan., 1995-Jun., 1997
  - 56 Storms (8 Intense + 48 Moderate)

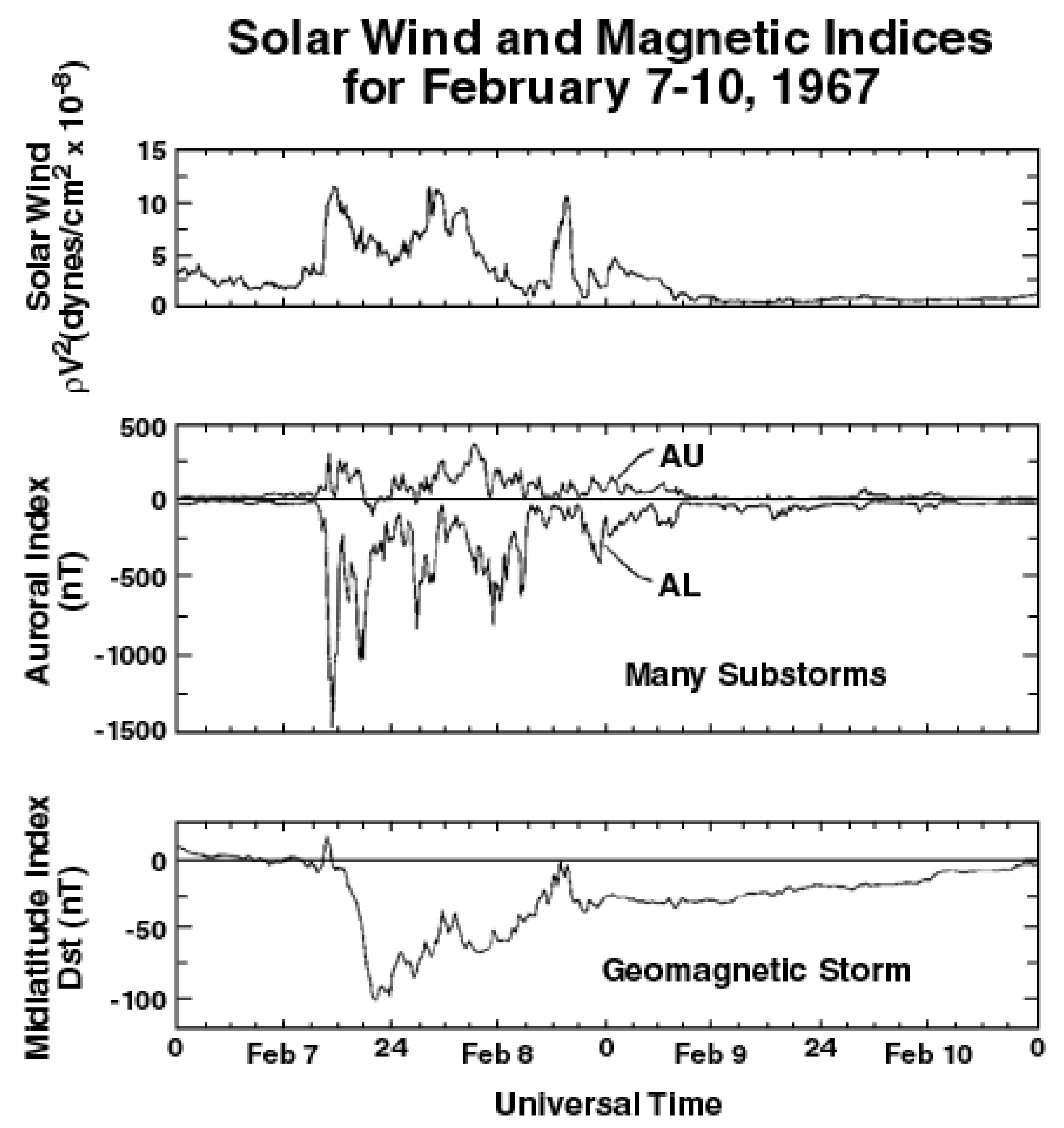
  [Intense Storms: Dst* ≤-100nT
  Moderate Storms: -100nT<Dst* ≤-50nT]

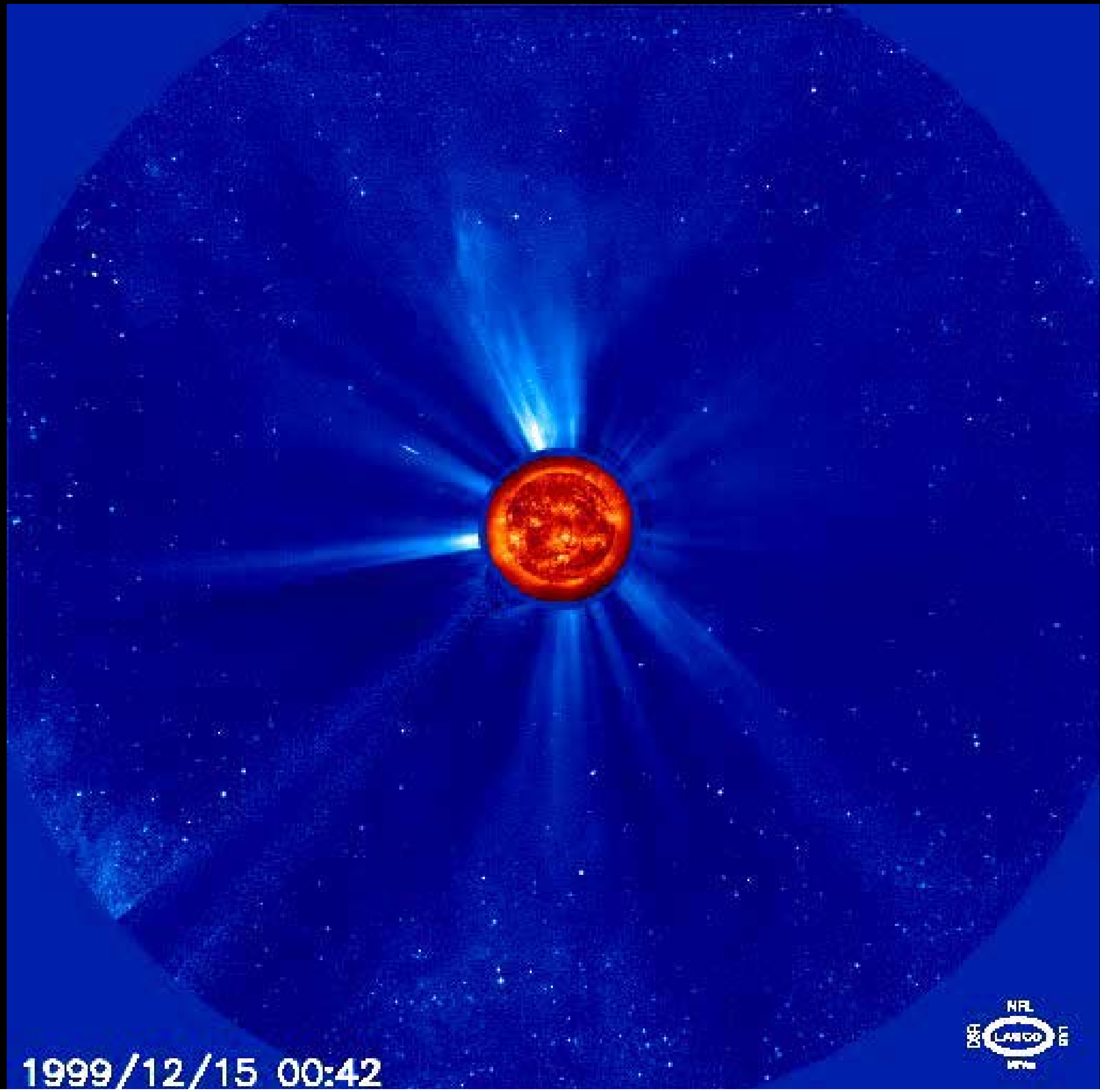
- Solar Maximum:
  - Jul., 1999-Jun., 2002
  - 97 Storms (34 Intense + 63 Moderate)





The storm-substorm controversy

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