IMPRS Retreat 2011

Lecture on June 21
by Rainer Schwenn

c) Space weather

- The source of space weather
- Why should we care?
- How does the Sun shape space weather?
- The role of Bz south
- M-regions and high-speed streams
- CMEs: piled-up plasma and ejecta clouds
- Problems in forecasting
- Open issues, future work needed

The term "space weather" refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life or health.

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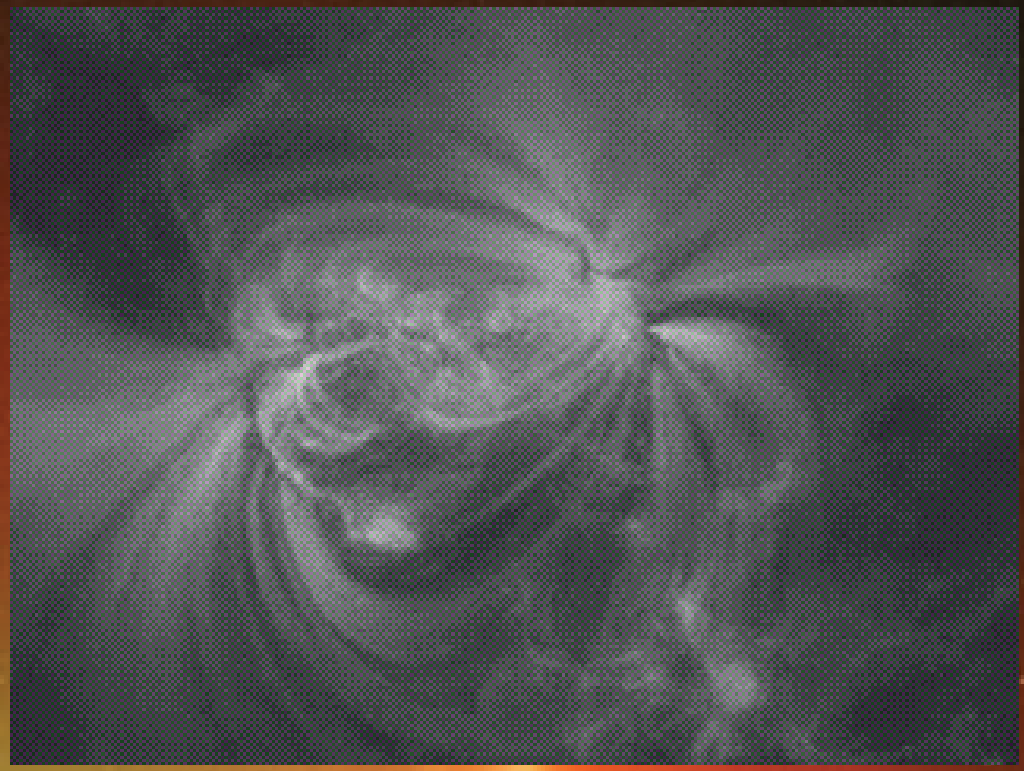
Flares and the begin of space weather research

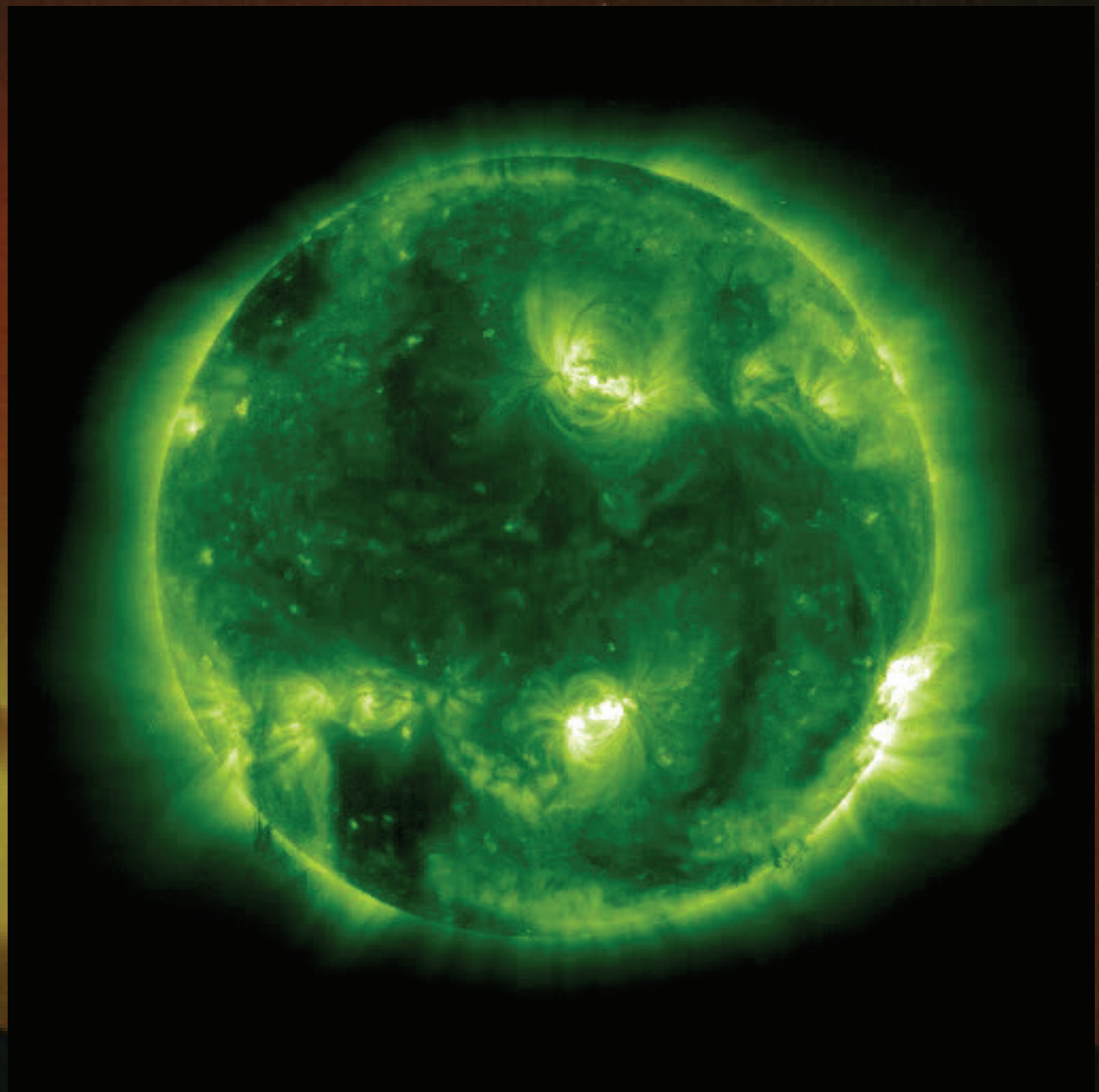


A solar flare, as observed by **TRACE**

Carrington was the first man who happened in 1859 to observe a flare and also to notice the connection with the strong geomagnetic storm 17 hours later. Note what the "father of space weather" noted at the end of his report:

"...one swallow does not make a summer!"

The source of space weather: the dynamic Sun!



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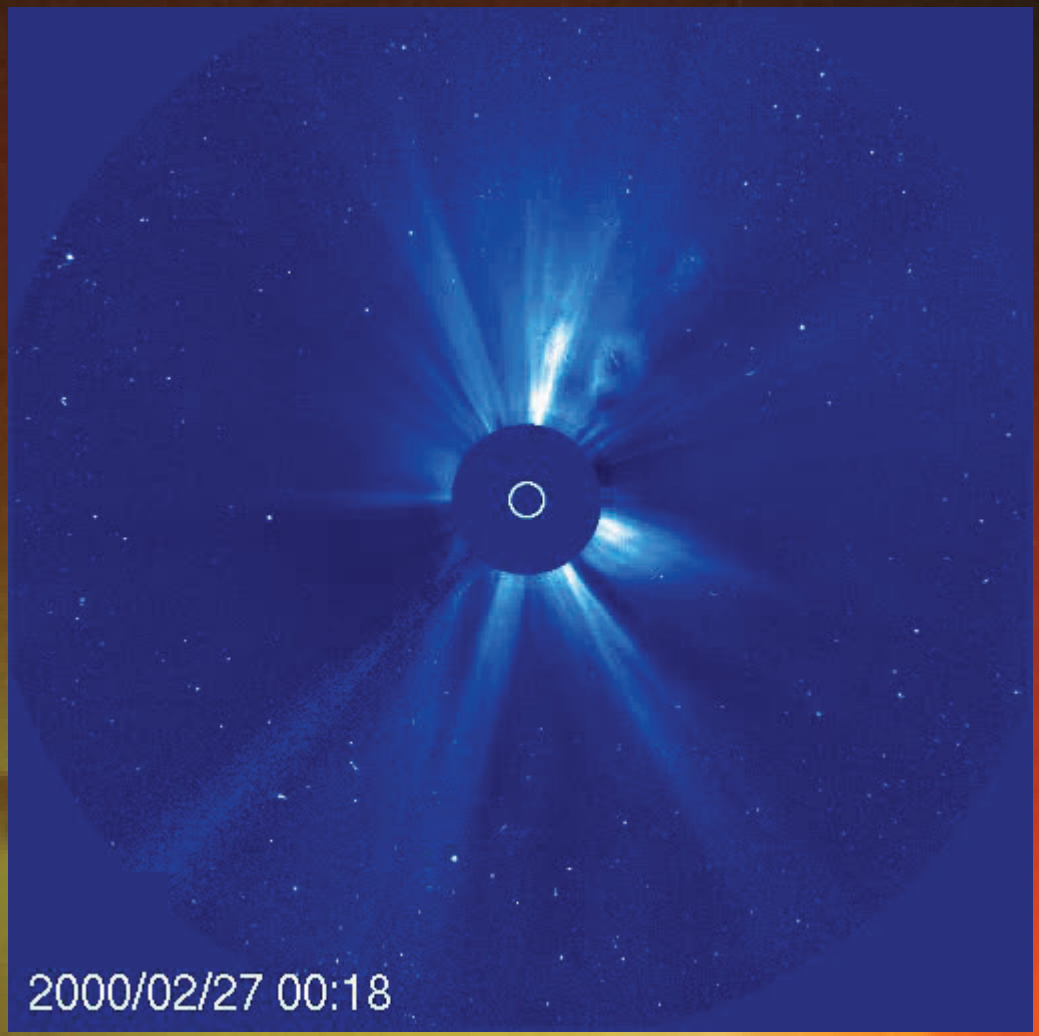
The source of space weather: the dynamic Sun!



A huge „Coronal Mass Ejection" (CME), observed by the LASCO coronagraph on SOHO

At times she releases gigantic explosions!

The „thunder" from such explosions literally shatters the whole solar system!

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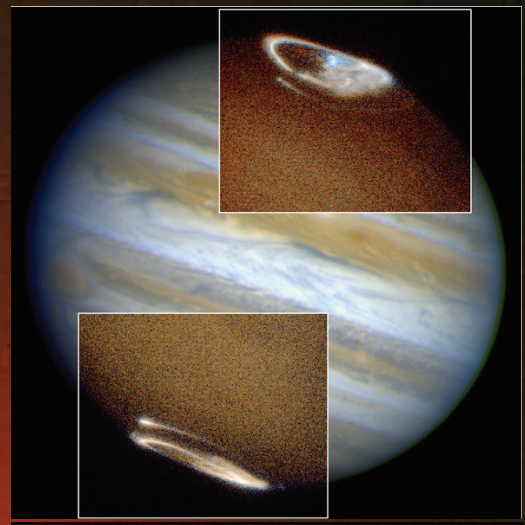
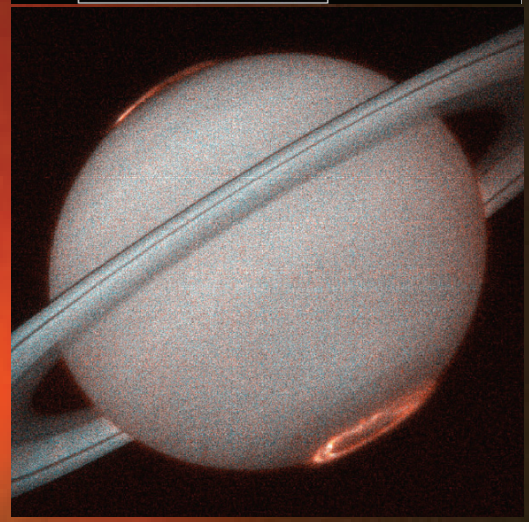
Space storms all over the solar system!

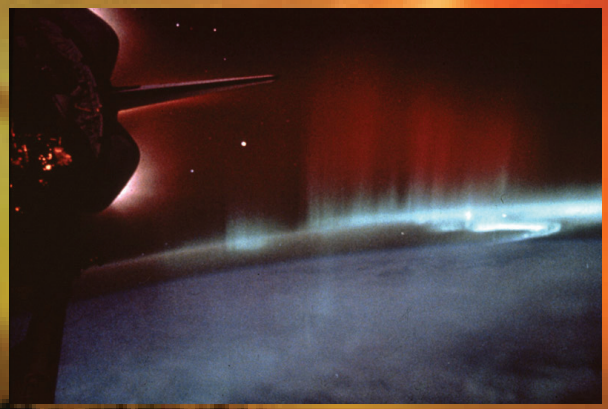
but also on Jupiter





and on Saturn

On Earth,



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Space weather: why should we care?

Our society is much more dependent on technology than ever before.

The most rapidly growing sector of the communication market is satellite based:

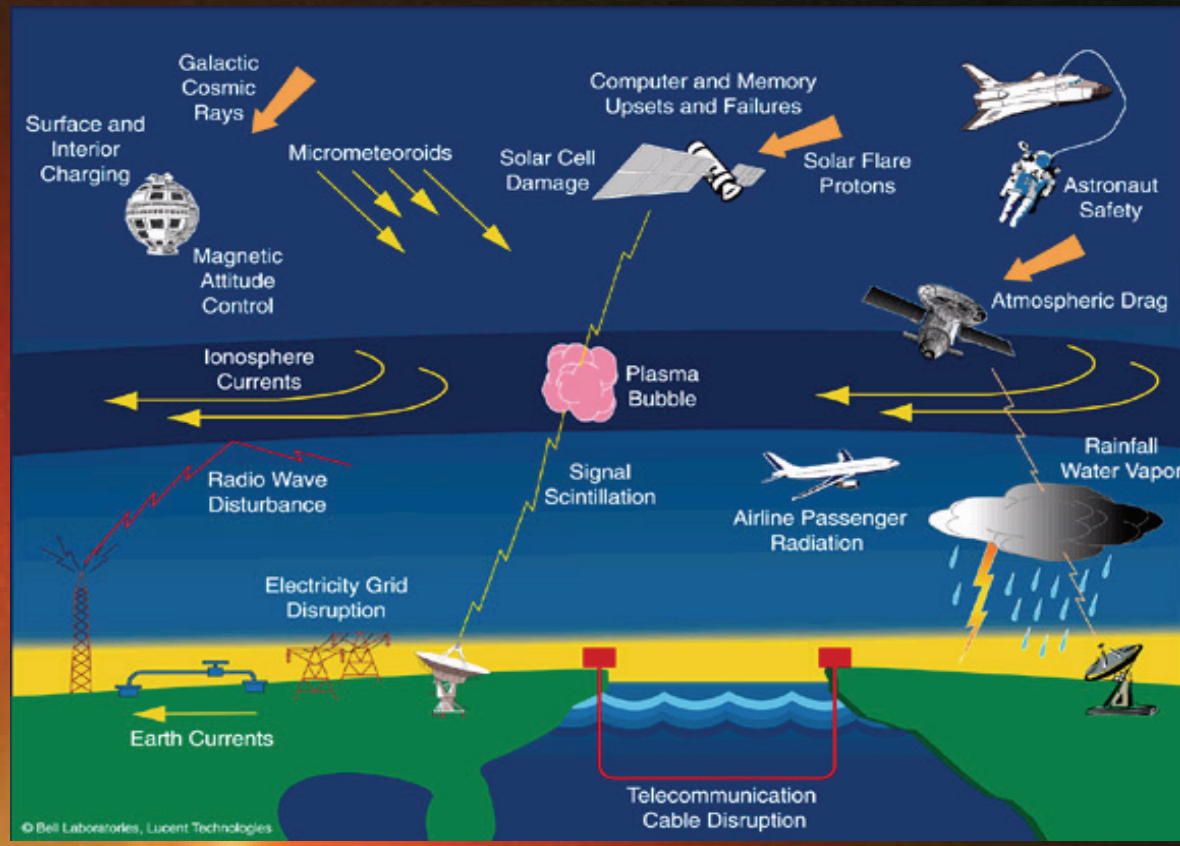
- broadcast TV/Radio
- long-distance telephone service, cell phones, pagers
- internet, finance transactions

Change in technology:

- more sensitive payloads
- high performance components
- lightweight and low cost

Humans in space:

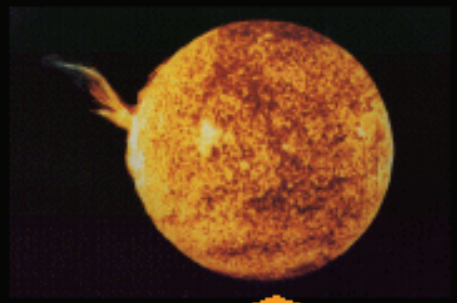
- more and longer manned missions



Consequences:

- Intensify fundamental research,
- Improve prediction capabilities,
- Invent technical measures.

Effects from solar storms



Flares

CMEs/Flares

CMEs/Coronal Holes

ELECTROMAGNETIC RADIATION
ARRIVAL: IMMEDIATELY
DURATION: 1-2 HOURS

HIGH ENERGY PARTICLES
ARRIVAL: 15 MIN TO FEW HOURS
DURATION: DAYS

LOW-MEDIUM ENERGY PARTICLES
ARRIVAL: 2-4 DAYS
DURATION: DAYS

X-RAYS, EUV, RADIO BURSTS

- SATCOM INTERFERENCE
- RADAR INTERFERENCE
- SHORTWAVE RADIO FADES

PROTON EVENTS

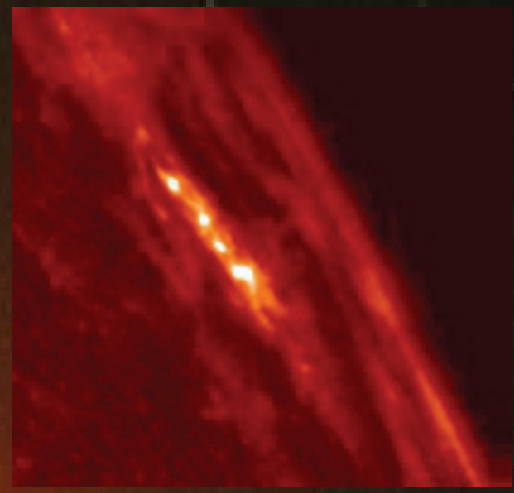
- SATELLITE DISORIENTATION
- FALSE SENSOR READINGS
- SPACECRAFT DAMAGE
- LAUNCH PAYLOAD FAILURE
- HIGH ALTITUDE AIRCRAFT RADIATION
- SHORTWAVE RADIO FADES

GEOMAGNETIC STORMS

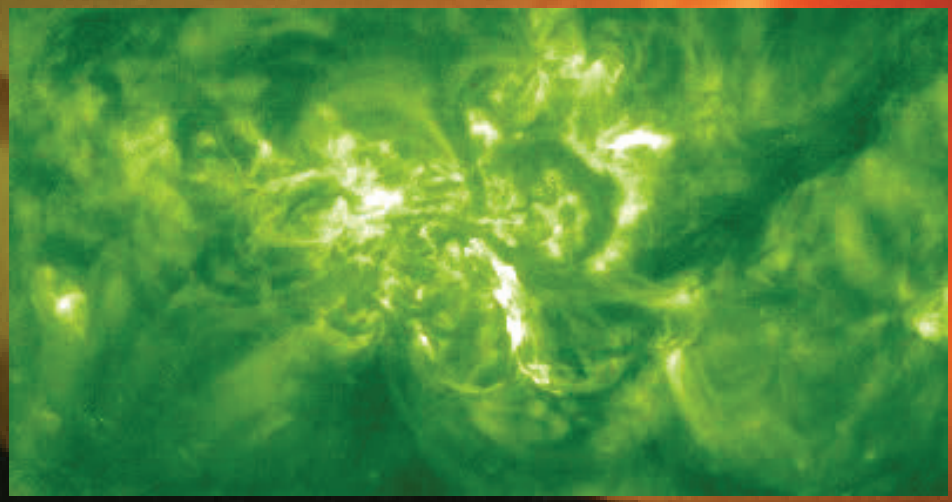
- SPACECRAFT CHARGING & DRAG
- SPACETRACK ERRORS
- LAUNCH TRAJECTORY ERRORS
- RADAR INTERFERENCE
- RADIO PROPAGATION ANOMALIES
- POWER BLACKOUTS

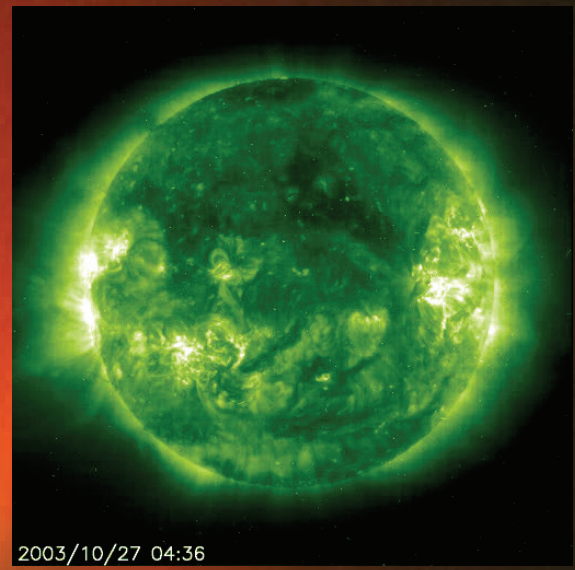
1. Electromagnetic radiation from flares

Radio, visible light, EUV, X-rays, Gamma-rays



Physics:	Unclear, but under intense study...
Arrival:	Simultaneously in all wavelengths
Duration:	Minutes to hours
Predictions:	Still impossible!
Effects:	Sudden heating of the Earth's upper atmosphere
Impacts:	* Radio communications disturbed, * Sudden satellite drag.





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A solar research satellite (SMM) was brought down by the Sun itself!

In March 1989 SMM ran into a „brick wall", built by UV flux from a major solar flare

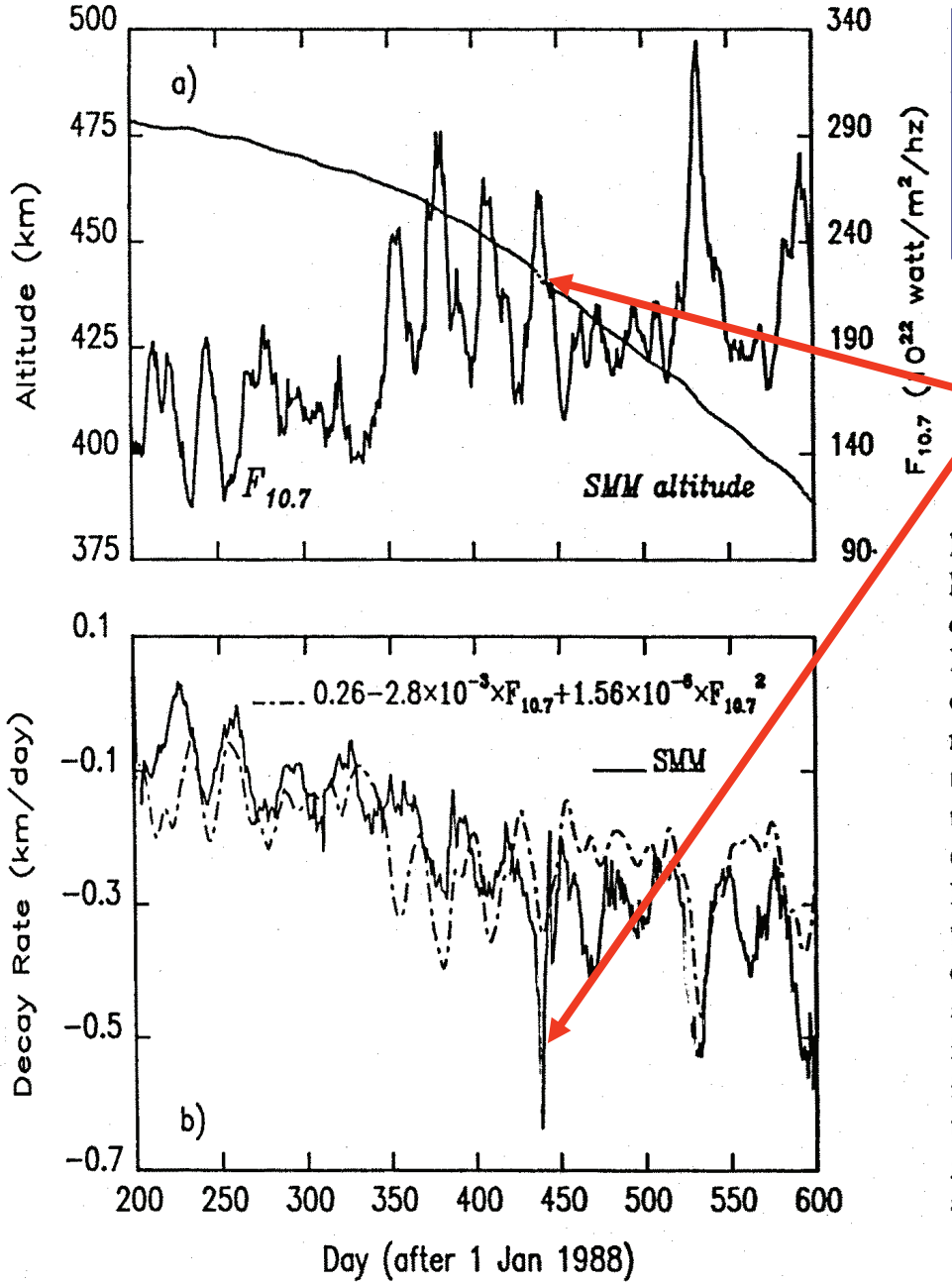
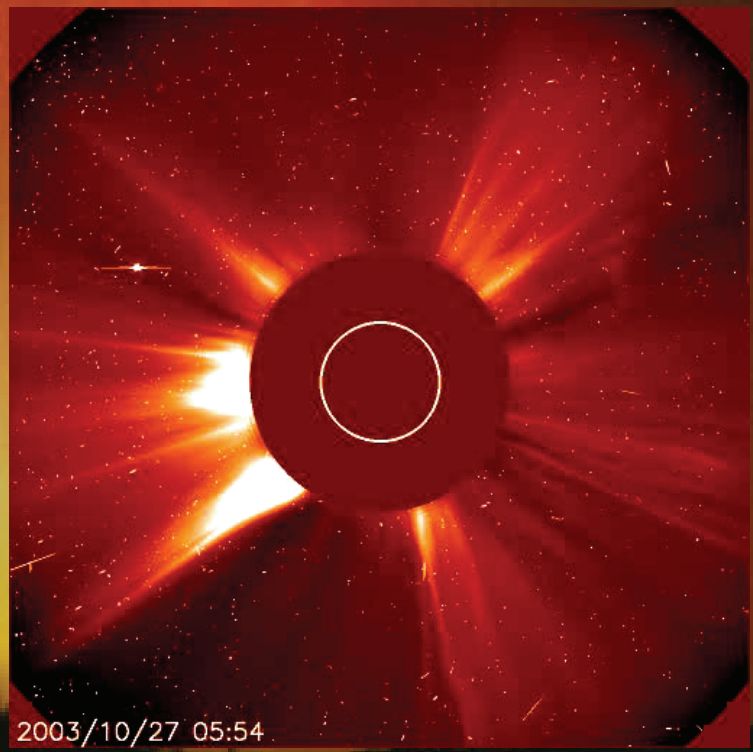


Figure 5. (*a*) The decreasing altitude of the Solar Maximum Mission (SMM) satellite (D. Messina and G. Share, private communication, 1990), just prior to its reentry into the Earth's atmosphere in December 1989, coincident with increasing solar activity as encapsulated in the Sun's 10.7-cm radio flux, $F_{10.7}$. (*b*) The orbital decay rate (solid line), determined as the change per day in the altitude shown in Figure 5*a*, is compared with variations in the daily $F_{10.7}$ flux (linearly transformed to an equivalent decay rate (dashed line)). A definite but imperfect correlation is apparent between the two. The dominant cycle of ~27 days occurs because the Sun's rotation causes active regions to move across the face of the solar disc seen at the Earth, modulating its output of UV radiation. When the Sun's UV radiation is brightest, the Earth's atmosphere expands outward, and the rate of decay of the satellite orbit increases. Active regions that cause enhancements of the UV radiative output also modify the 10.7-cm radio flux.

2. High energy particles from flares and CME shocks

Electrons, protons and other ions with energies
of few 100 MeV, at times several GeV

Physics:	Onset still unclear, particle acceleration under intense study...
Arrival:	Some 10 minutes to 1 hour after the flare
Duration:	Hours to days
Predictions:	Very uncertain, in all aspects!



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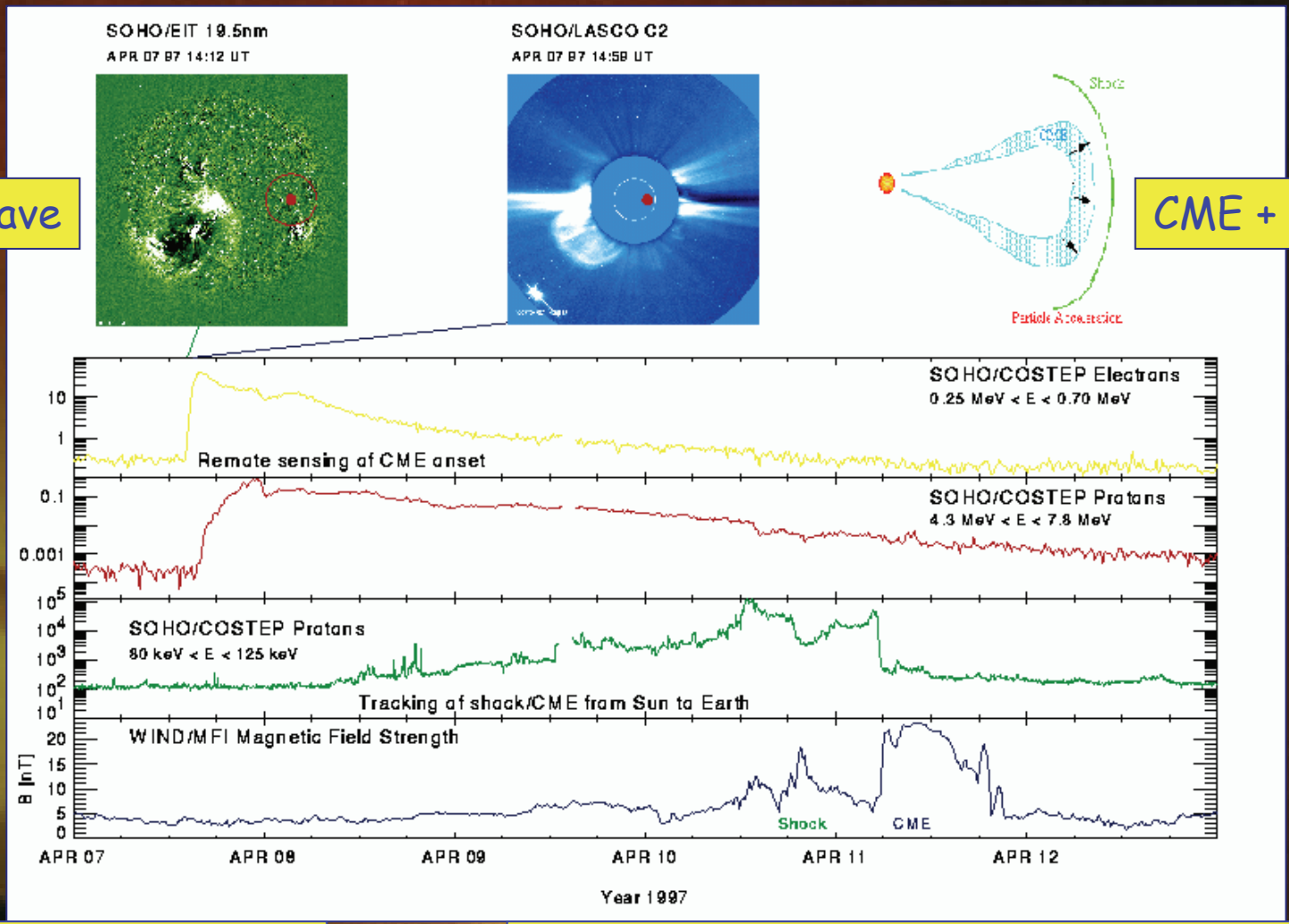
2. High energy particles from flares and CME shocks

Electrons, protons and other ions with energies
of few 100 MeV, at times several GeV



EIT-wave

CME + shock

Flare-accelerated

Shock-accelerated energetic particles

2. High energy particles from flares and CME shocks

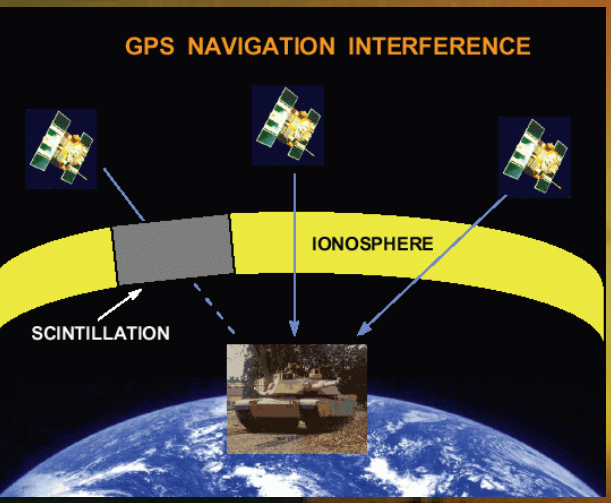
Effects: * Heating and ionization of the Earth's upper atmosphere,

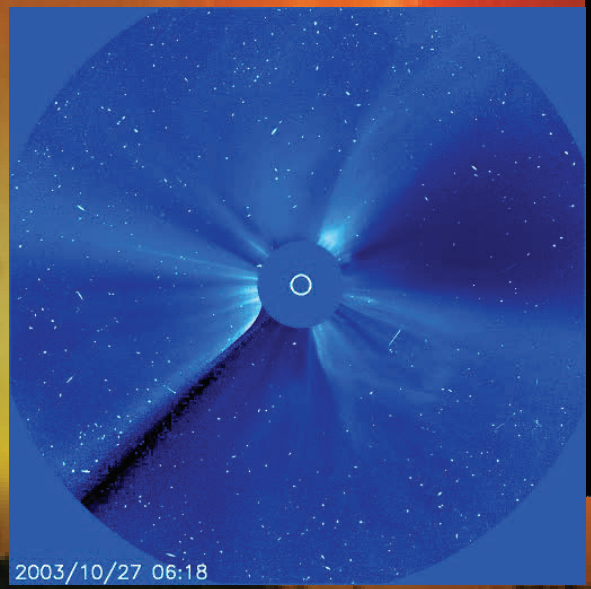
Impacts: * Radio communications disturbed, damage to exterior satellite surfaces,

* Damage to solid state devices, leading to malfunctions, single event upsets, latch-ups etc. in satellite electronics,

* Blinding of CCD cameras in Earth orbit,

* Enhanced radiation doses for astronauts, particularly dangerous during EVAs.





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3. Low to medium-energy particles, plasma clouds

CMEs, interplanetary shocks, magnetic clouds, plasma turbulence as products of coronal mass ejections, all contributing to generate

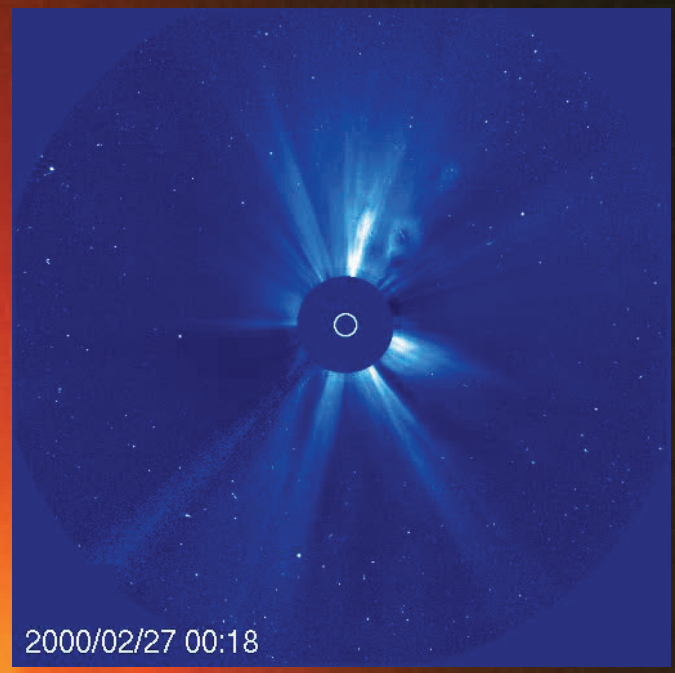
Geomagnetic storms.

Physics: * Origin of CMEs unclear, but under intense study.
* Propagation is being modelled, empirical approaches under development.

Arrival: 1 to 5 days after CME launch

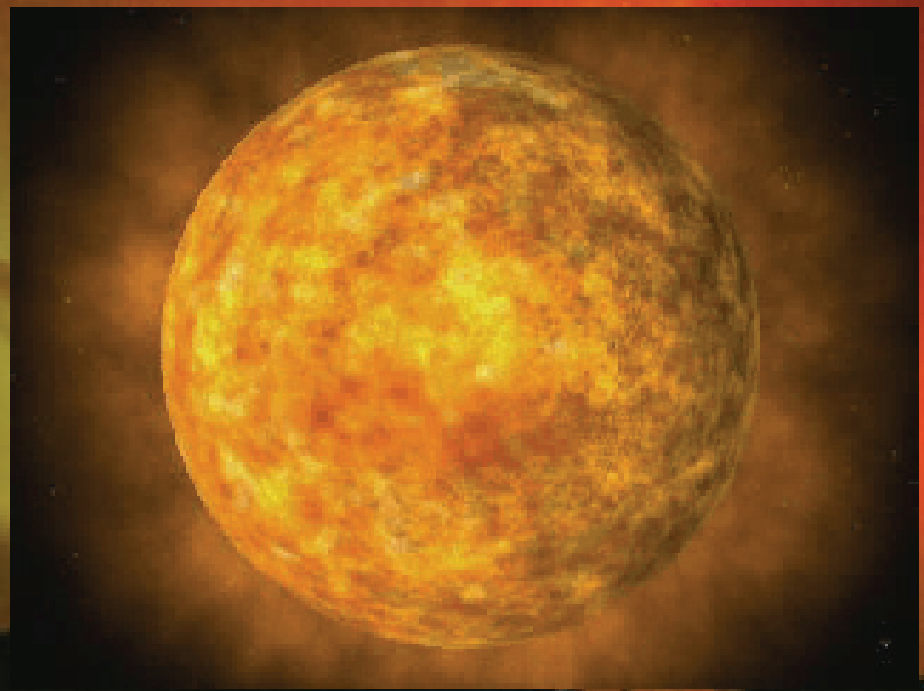
Duration: hours to days

Prediction: +/- 24 hrs after halo CME



3. Low to medium-energy particles, plasma clouds

Effects:
* Sudden compression of the Earth's magnetosphere,
* Distortion and depletion of the radiation belts, leading to release of large fluxes of energetic particles,
* Injection of plasma from magnetotail into polar magnetosphere/ionosphere, thus causing aurorae,
* Severe disturbances of ring currents, i.e. geomagnetic storms,
* Heating of ionosphere and upper atmosphere,



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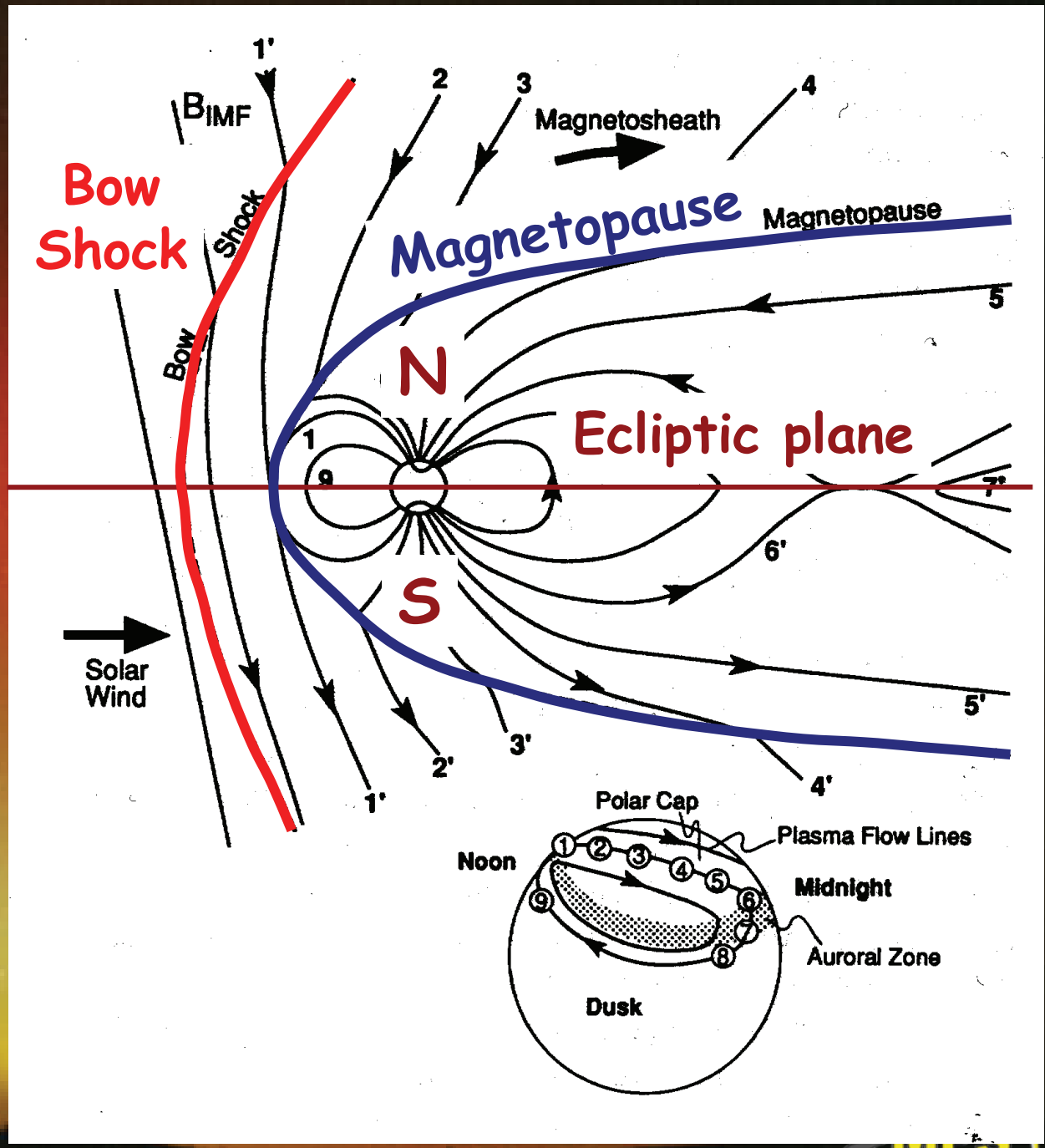
A magnetosphere at work

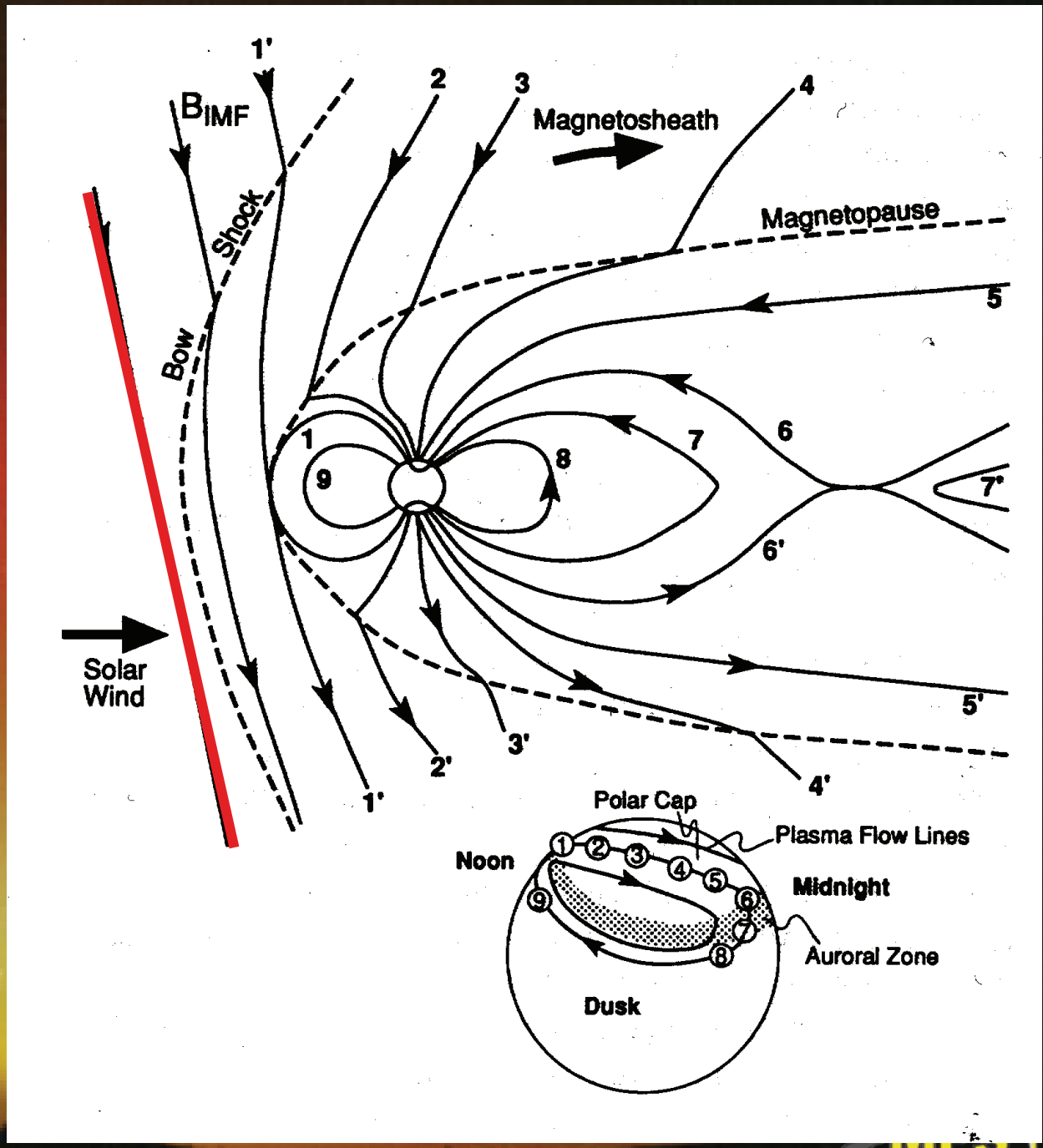
What makes geospace vulnerable?

B_z south!

Magnetic reconnection at the front side of the magnetosphere occurs, when the interplanetary Bz turns south, i.e. anti-parallel to the Earth's intrinsic field.

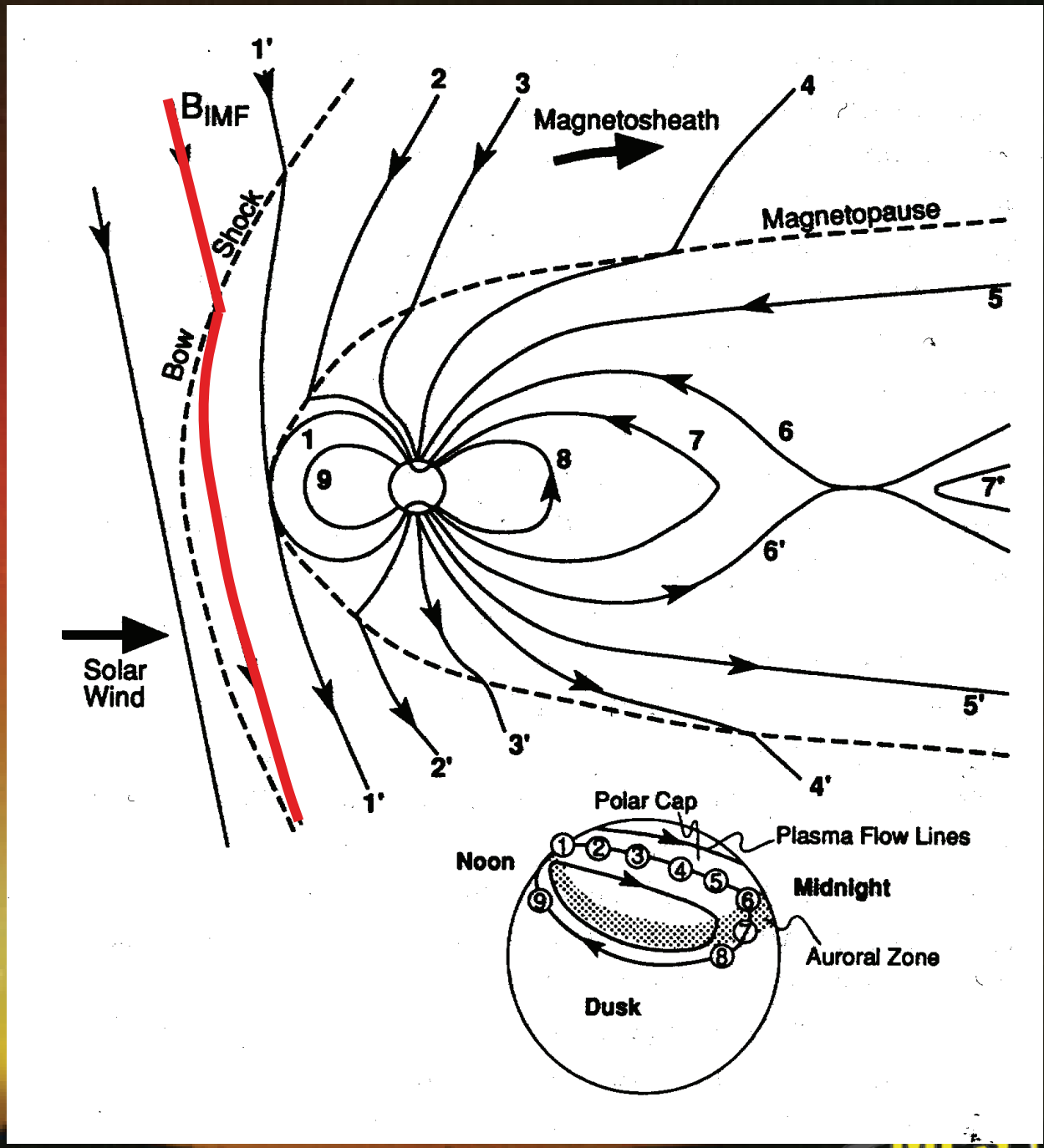


A magnetosphere at work



In case of B_z south:

A magnetosphere at work



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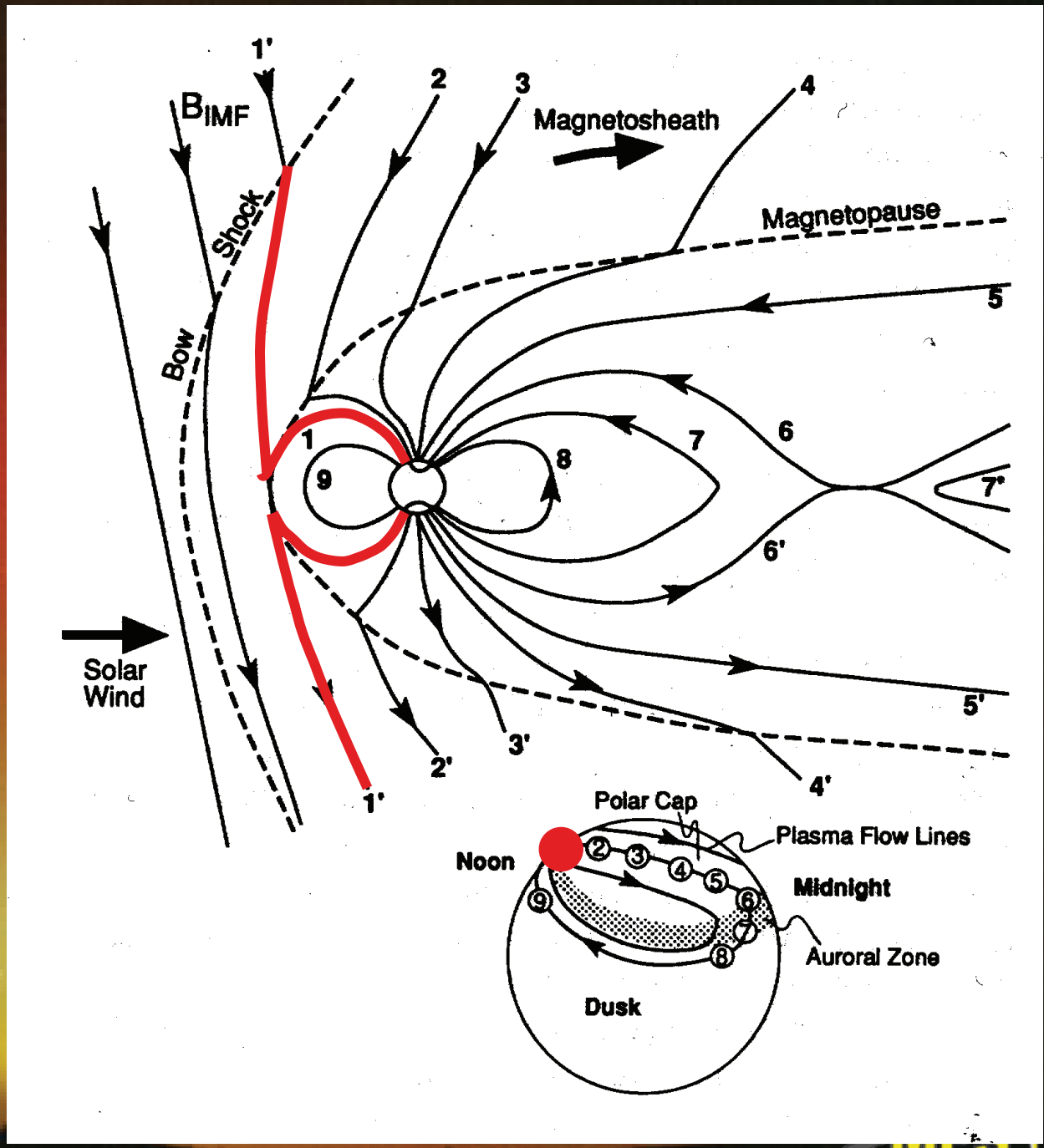
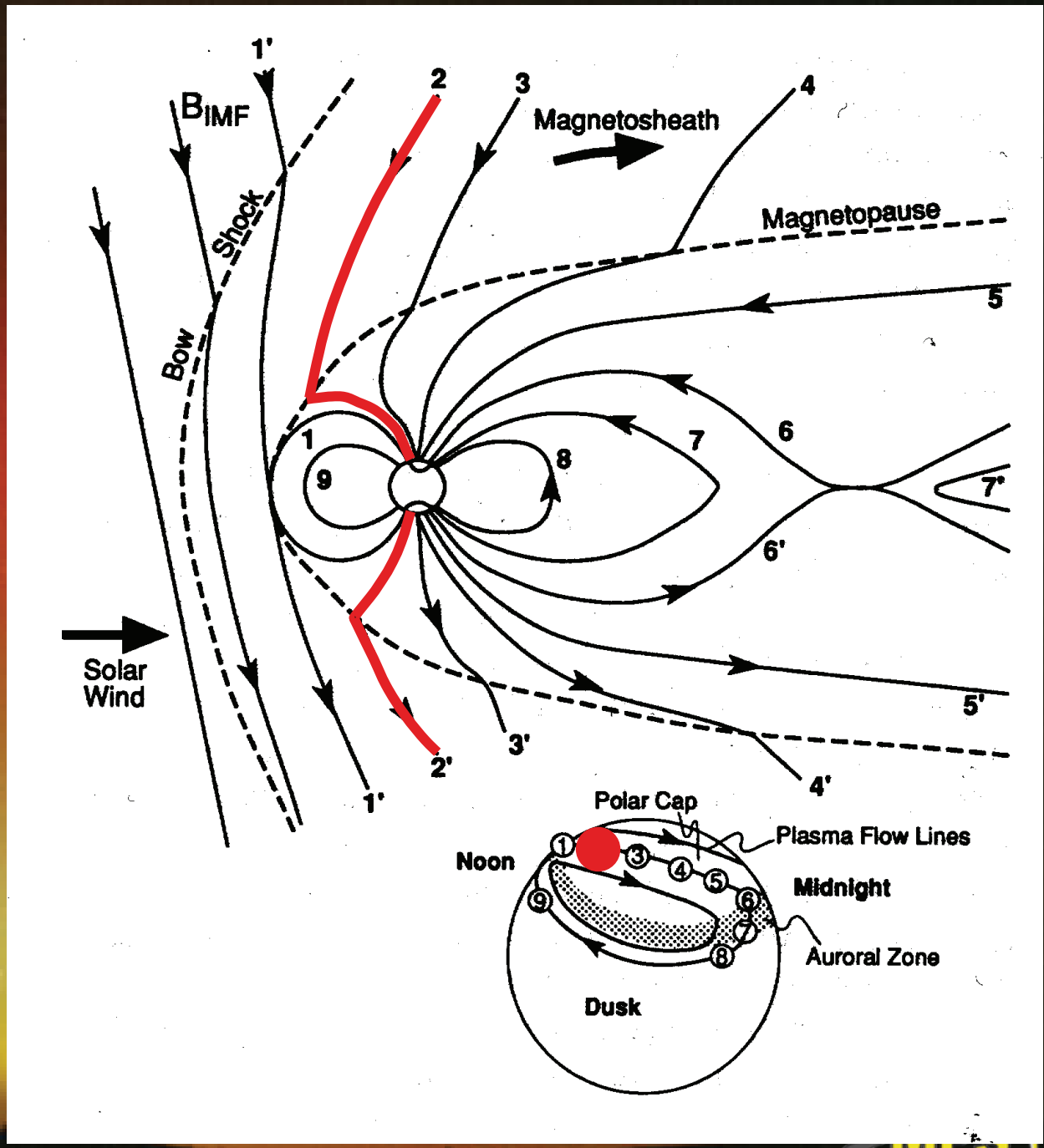


In case of B_z south: reconnection at the magnetopause!

A magnetosphere at work



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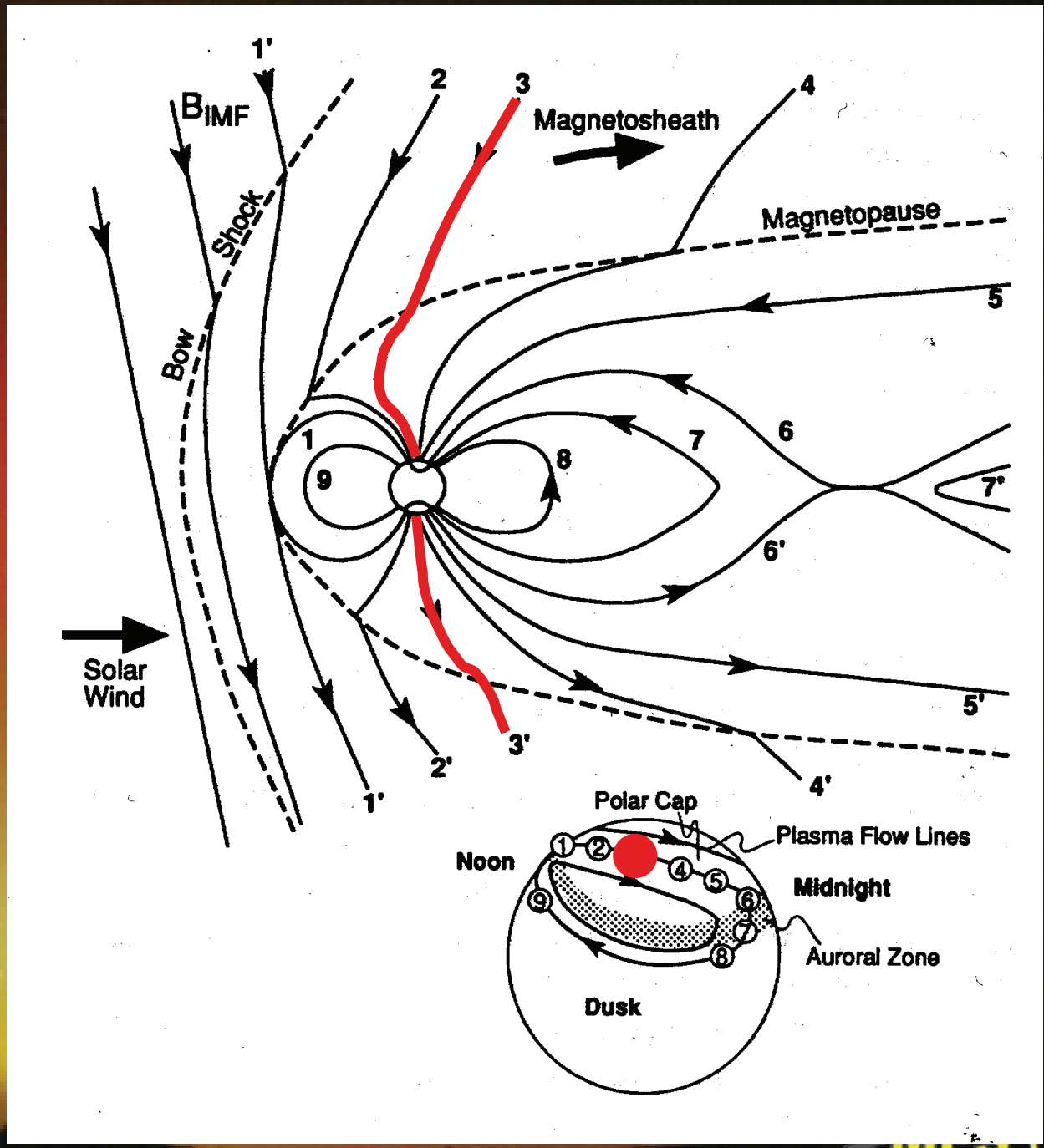

In case of B_z south: reconnection at the magnetopause!

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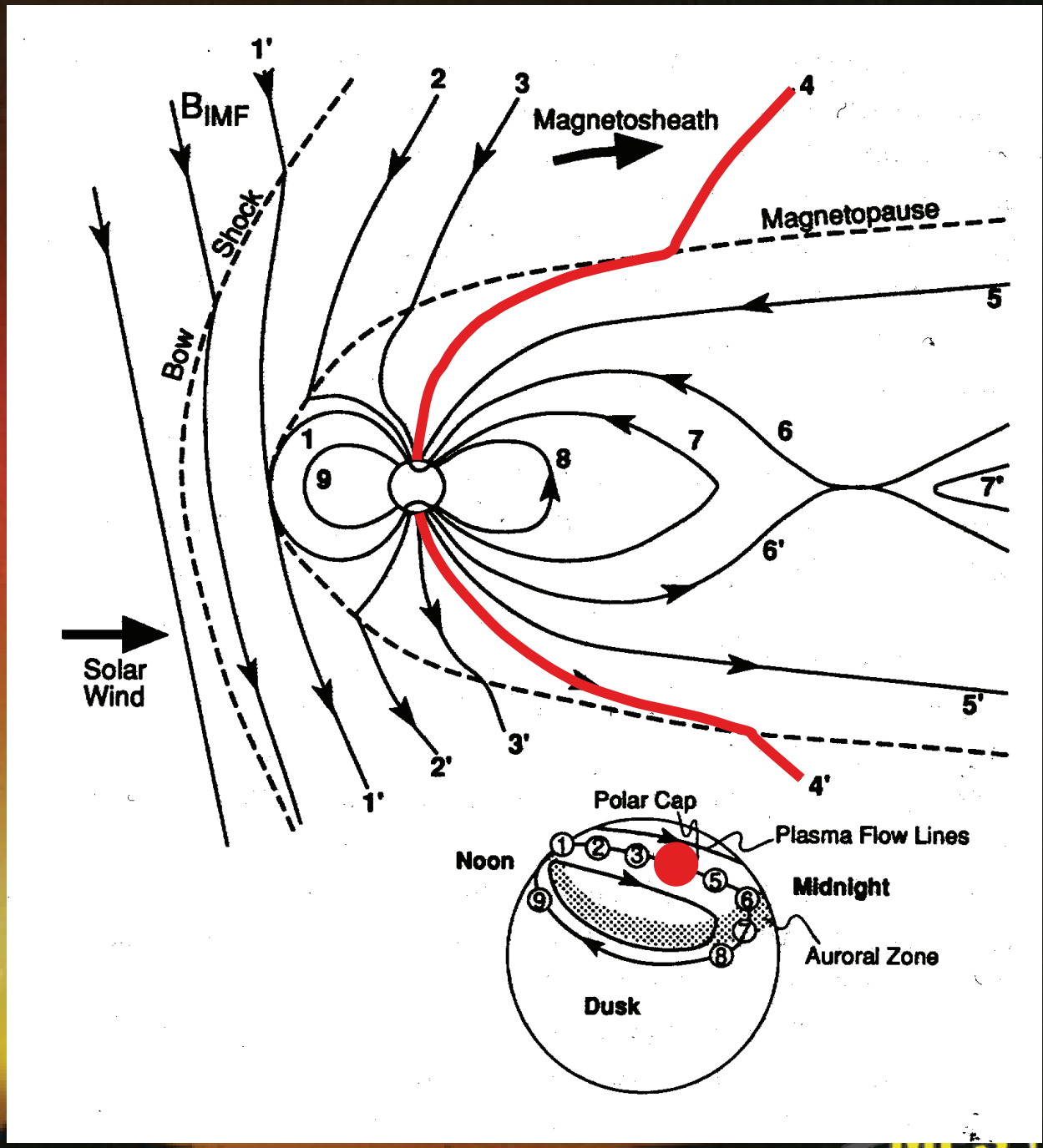
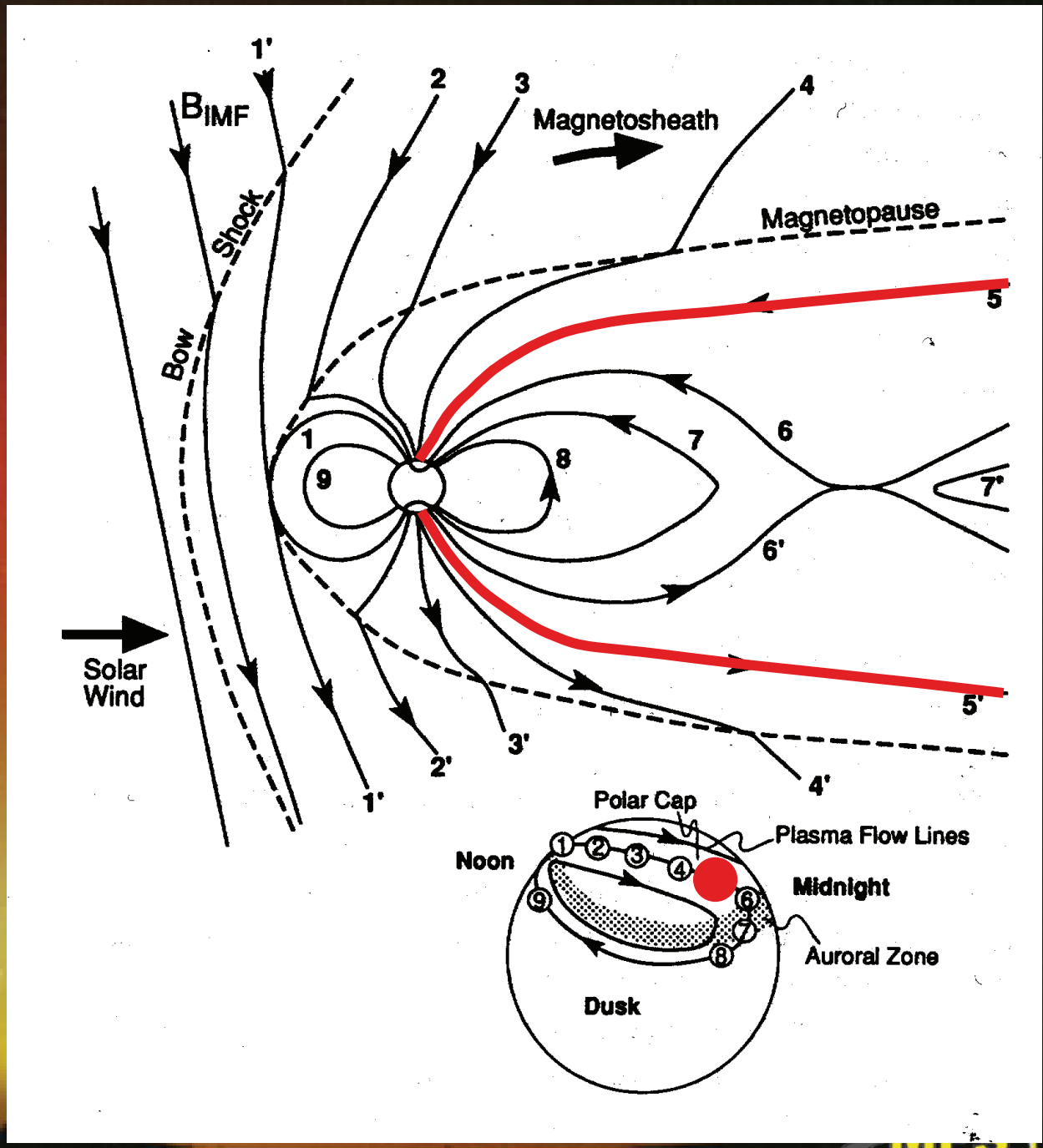


In case of B_z south: reconnection at the magnetopause!

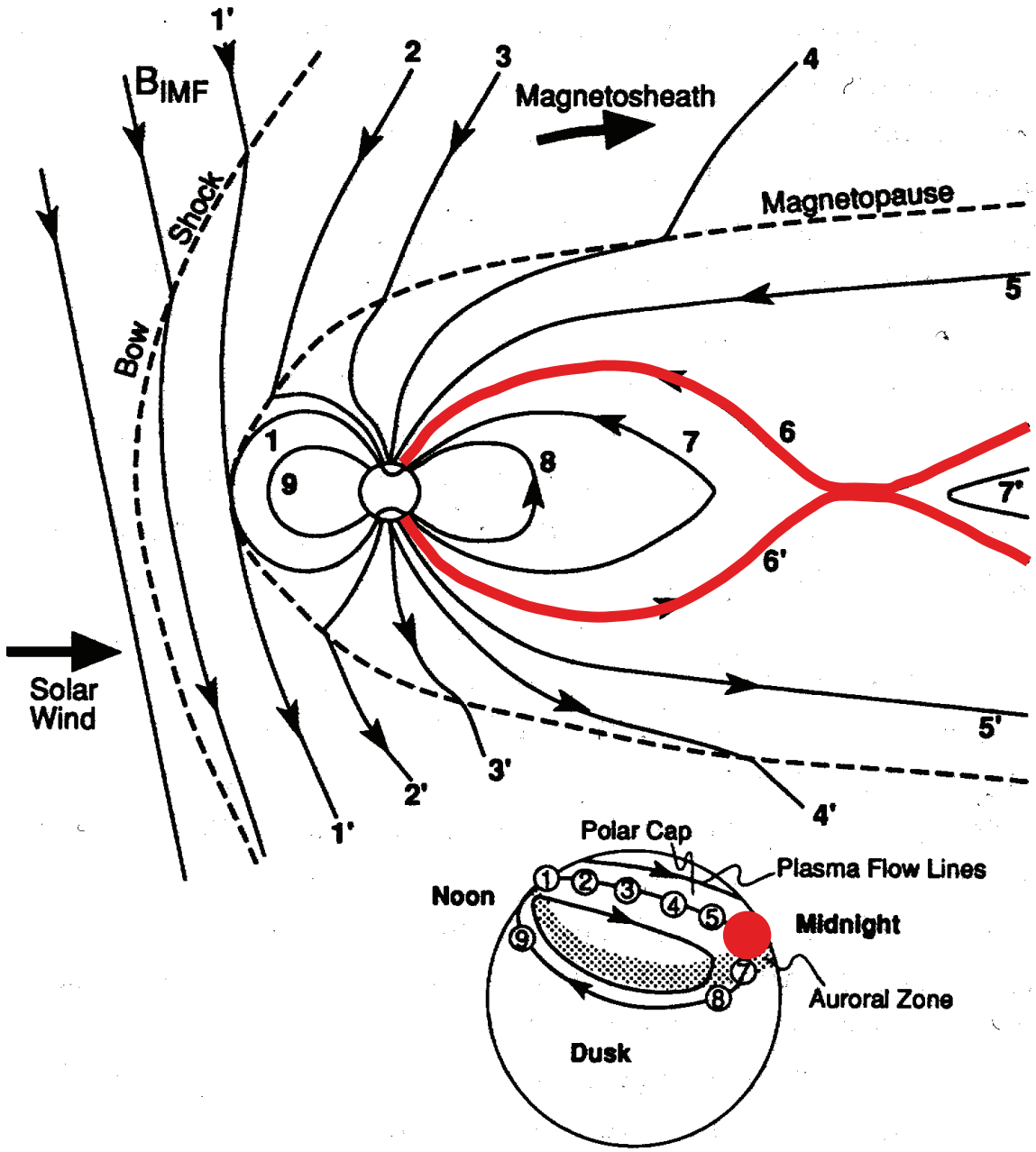
A magnetosphere at work



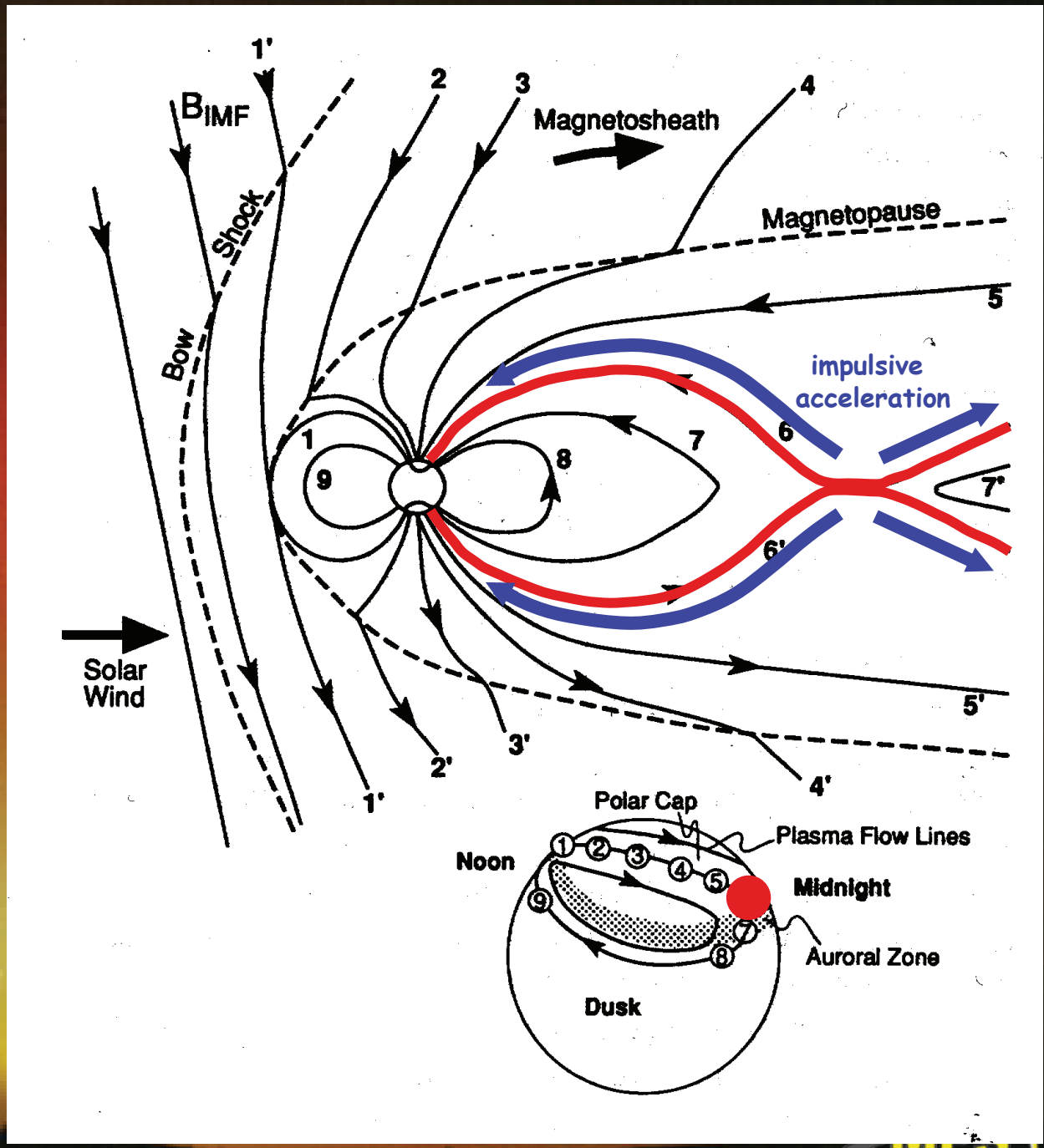
In case of B_z south: reconnection at the magnetopause!

A magnetosphere at work

In case of B_z south: reconnection at the magnetopause, and reconnection in the magnetotail!

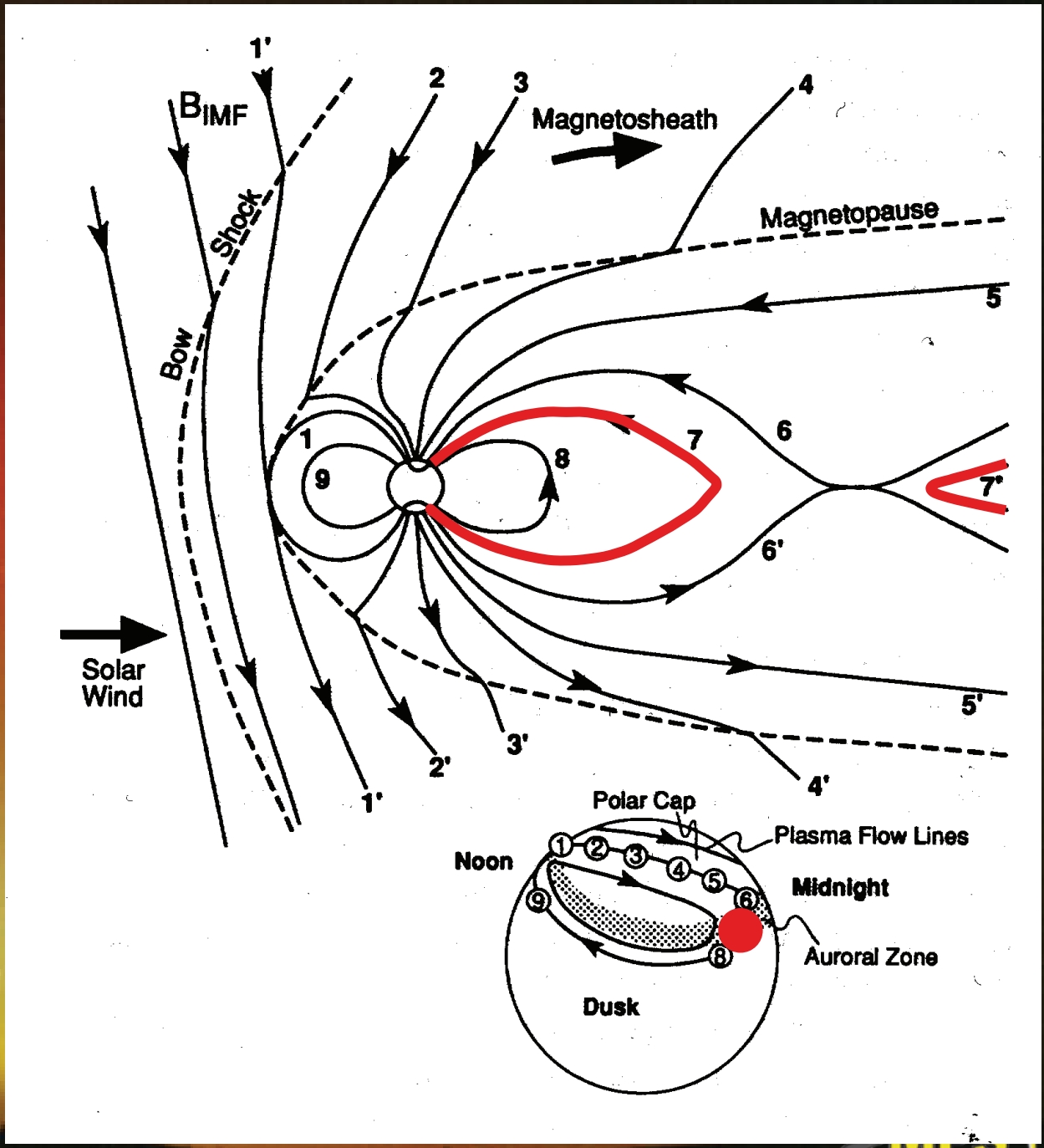


A magnetosphere at work



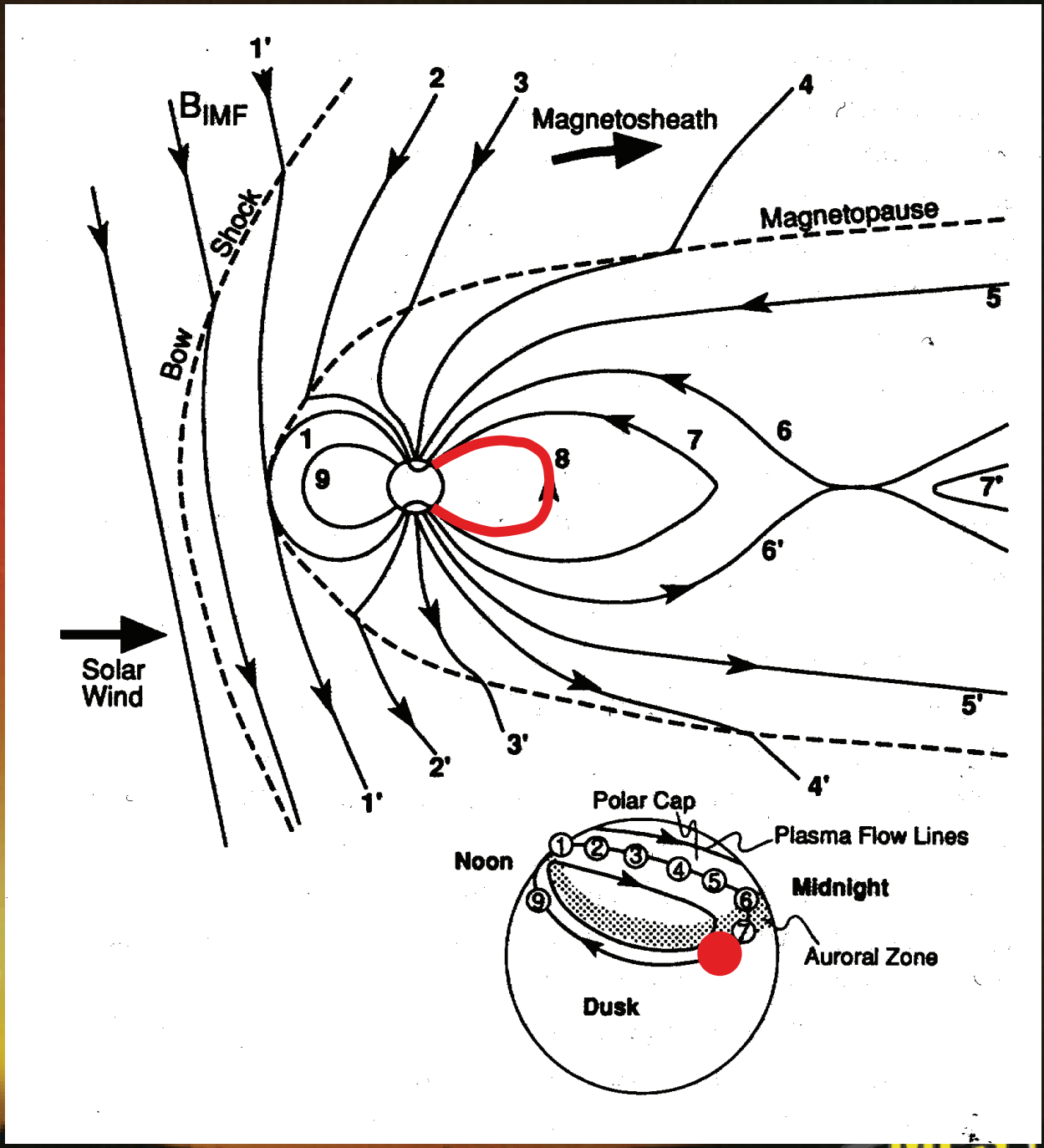
In case of B_z south: reconnection at the magnetopause, and reconnection in the magnetotail!

A magnetosphere at work



In case of B_z south: reconnection in the magnetotail and plasma injection into the high latitude ionosphere!

A magnetosphere at work

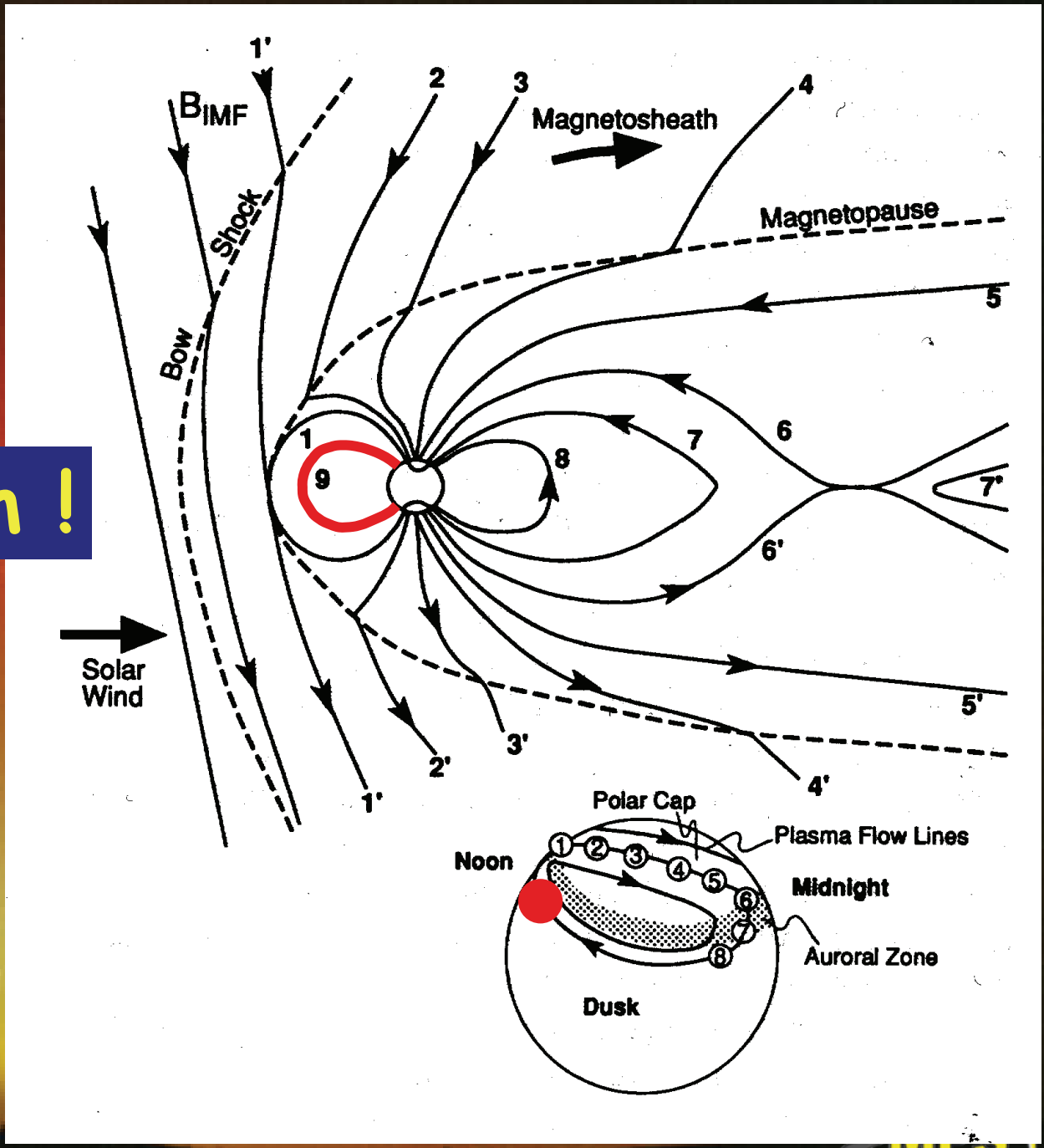


In case of B_z south: reconnection in the magnetotail and plasma injection into the high latitude ionosphere!

A magnetosphere at work

A substorm !

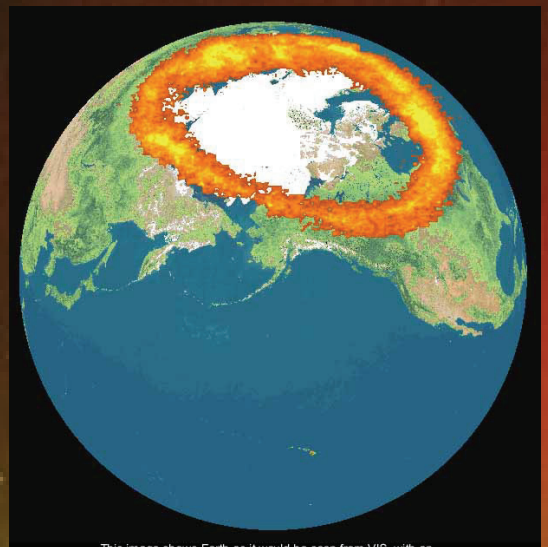
In case of B_z south: Finally, the stored radiation belt particles are released and may cause damage!



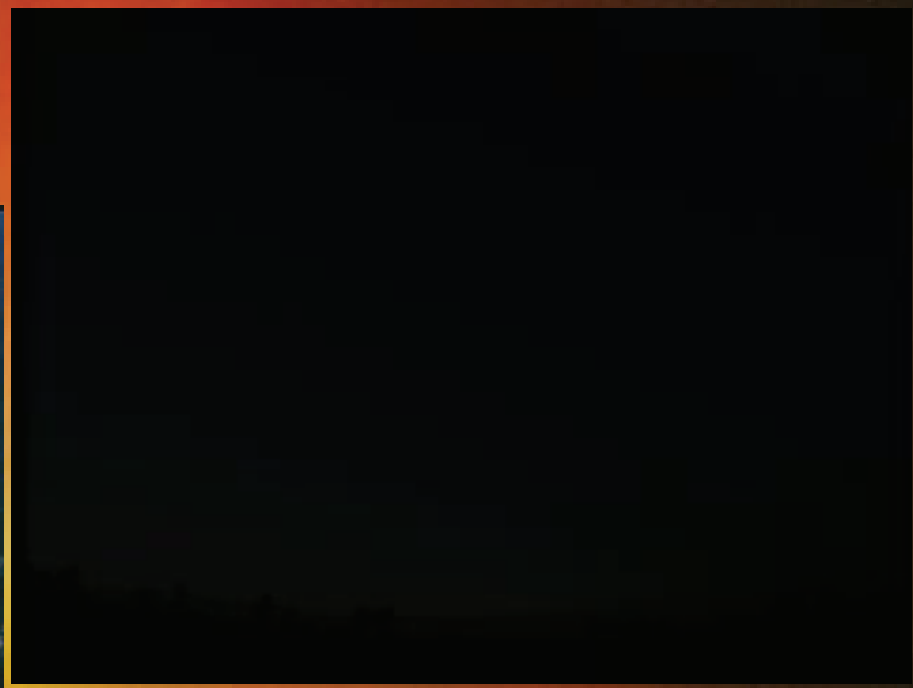
3. Low to medium-energy particles, plasma clouds

Impacts:

* Bright aurorae, even at low latitudes,
* Strong fluctuations of geomagnetic field,
* Radio communications disturbed,
* Sudden satellite drag due to heating of the upper atmosphere,
* Charge-up of satellite surfaces due to high fluxes of energetic electrons.



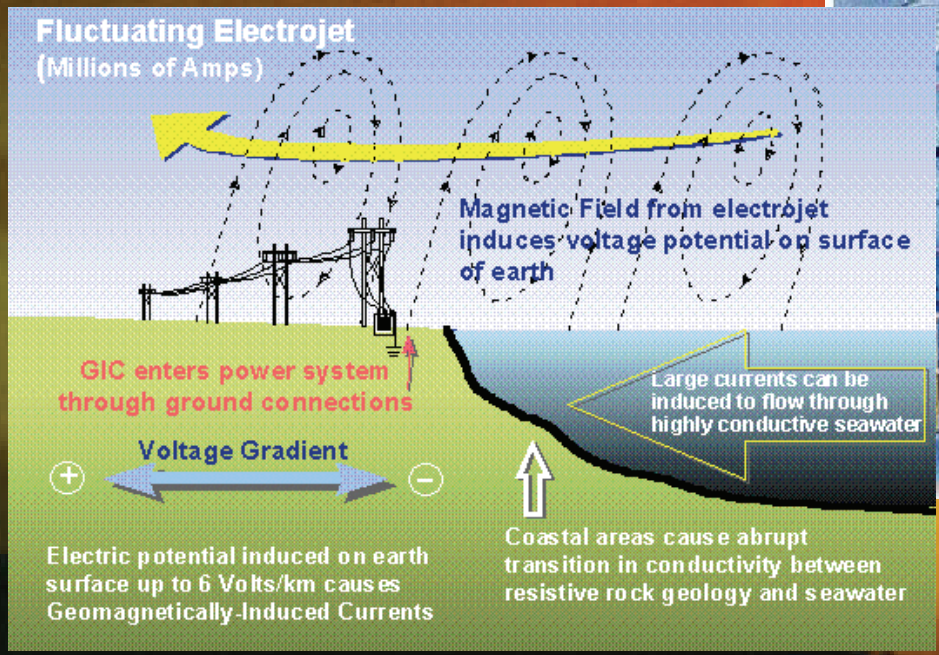
This image shows Earth as it would be seen from VIS, with an image of the northern aurora superimposed on an image of the Earth from March 25, 1996.

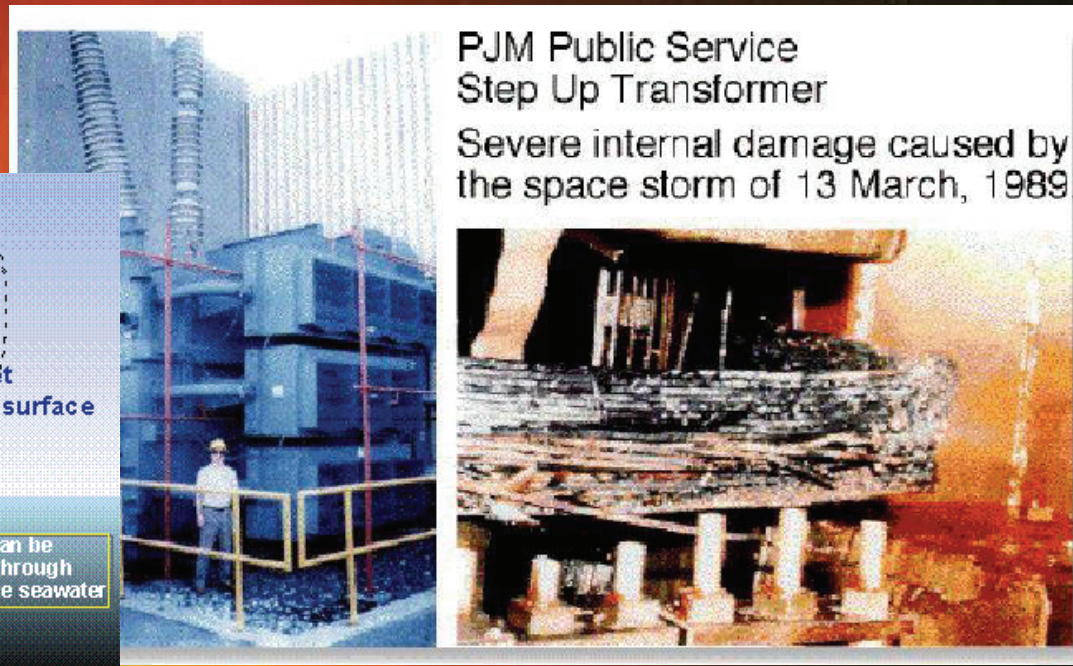


3. Low to medium-energy particles, plasma clouds

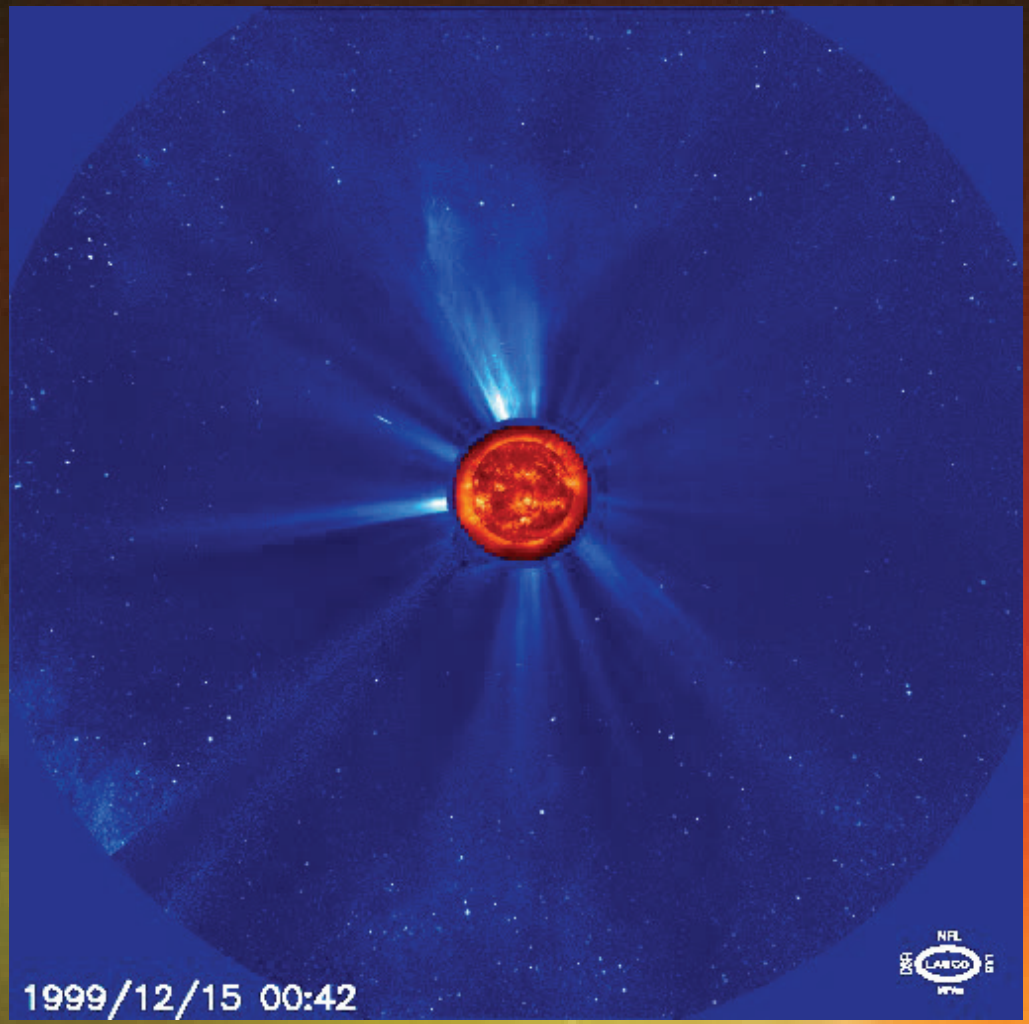
Impacts:

* Satellite damages from penetrating energetic particles,
* Satellite disorientation due to magnetic field distortion,
* GICs endangering power distribution nets, pipelines, telecommunication lines etc,
* Effects on biological systems.





What makes the interplanetary B_z turn southward?



1) Fluctuations (Alfvénic) in high speed streams from the quiet Sun

2) Deflections in front of and inside ejecta from transient events on the active Sun

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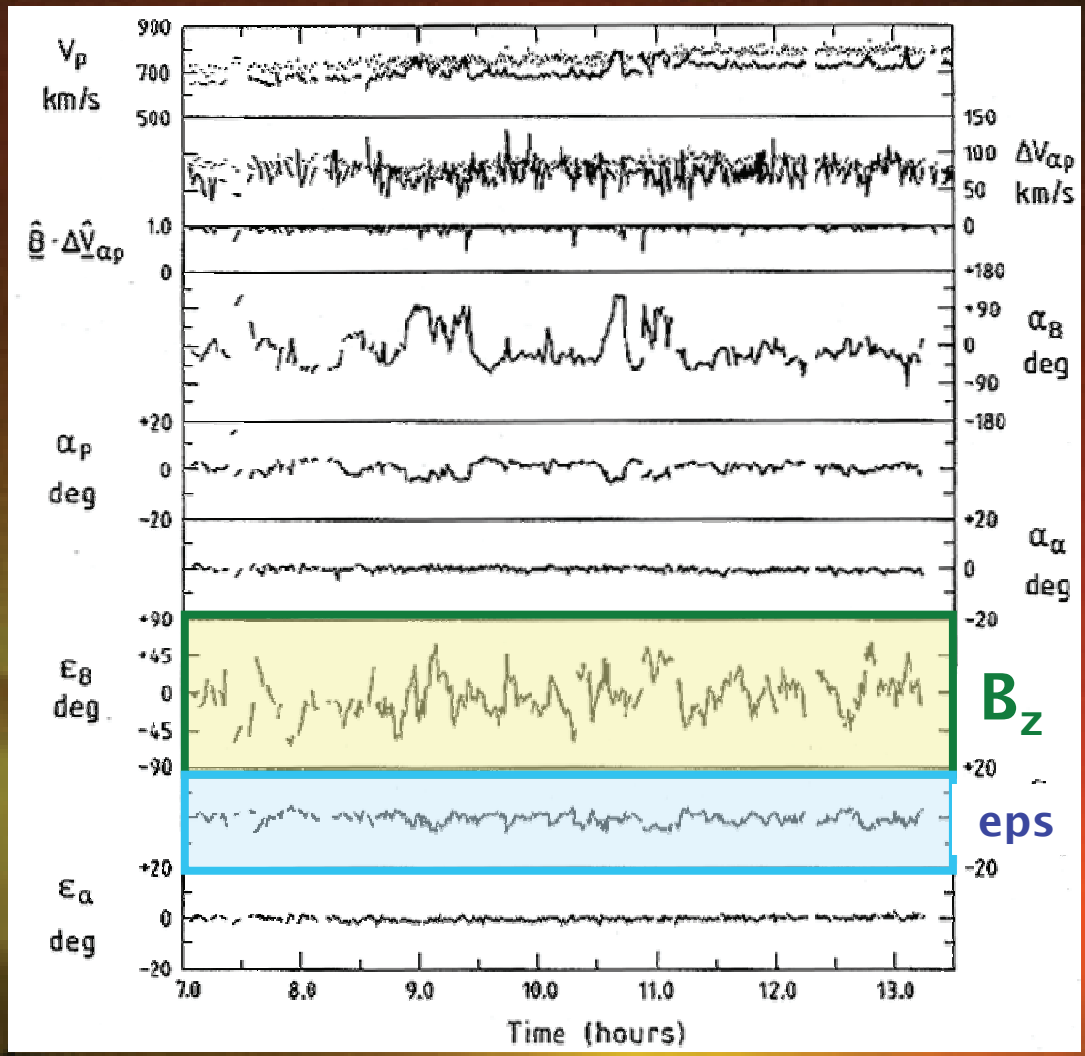
What makes the interplanetary B_z turn southward?

1. Alfvén waves in high speed streams



Alfvén waves occur only in high speed streams from coronal holes, i.e., the quiet Sun.

Alfvén waves cause substantial deflections in both: flow direction and magnetic field.

That is the origin of north-south field excursions in high speed wind streams that cause moderate geomagnetic effects:

"M-regions"

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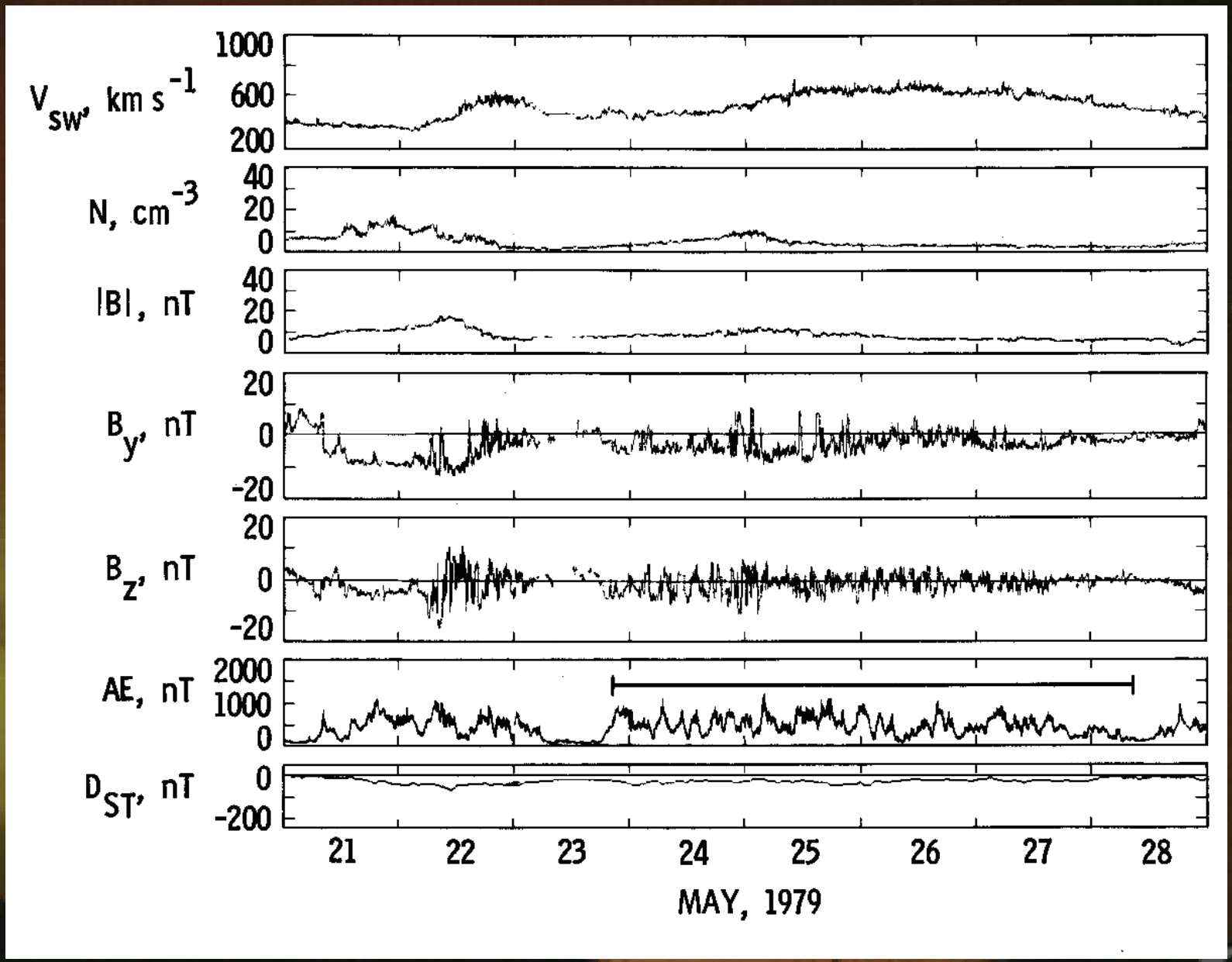
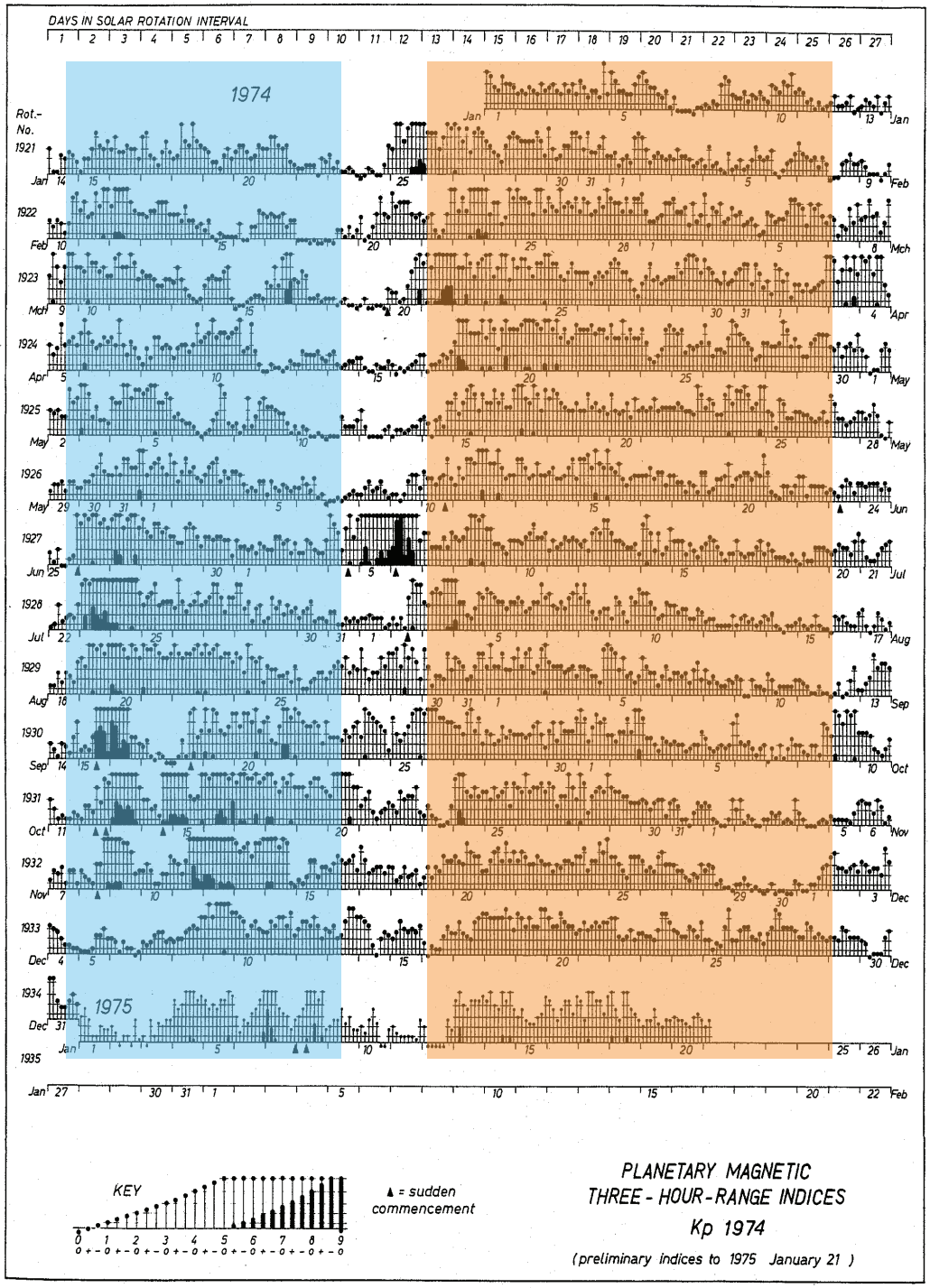
High speed streams: M-regions!





High speed streams: M-regions!

M-regions often persist for many solar rotations, in particular at low solar activity. So do high speed streams from coronal holes (i.e. the „inactive" Sun).

These effects on space weather are fairly well predictable, using particle&field observations at L1

The "musical diagram" of geomagnetic activity, according to the scheme introduced by Bartels (1930)

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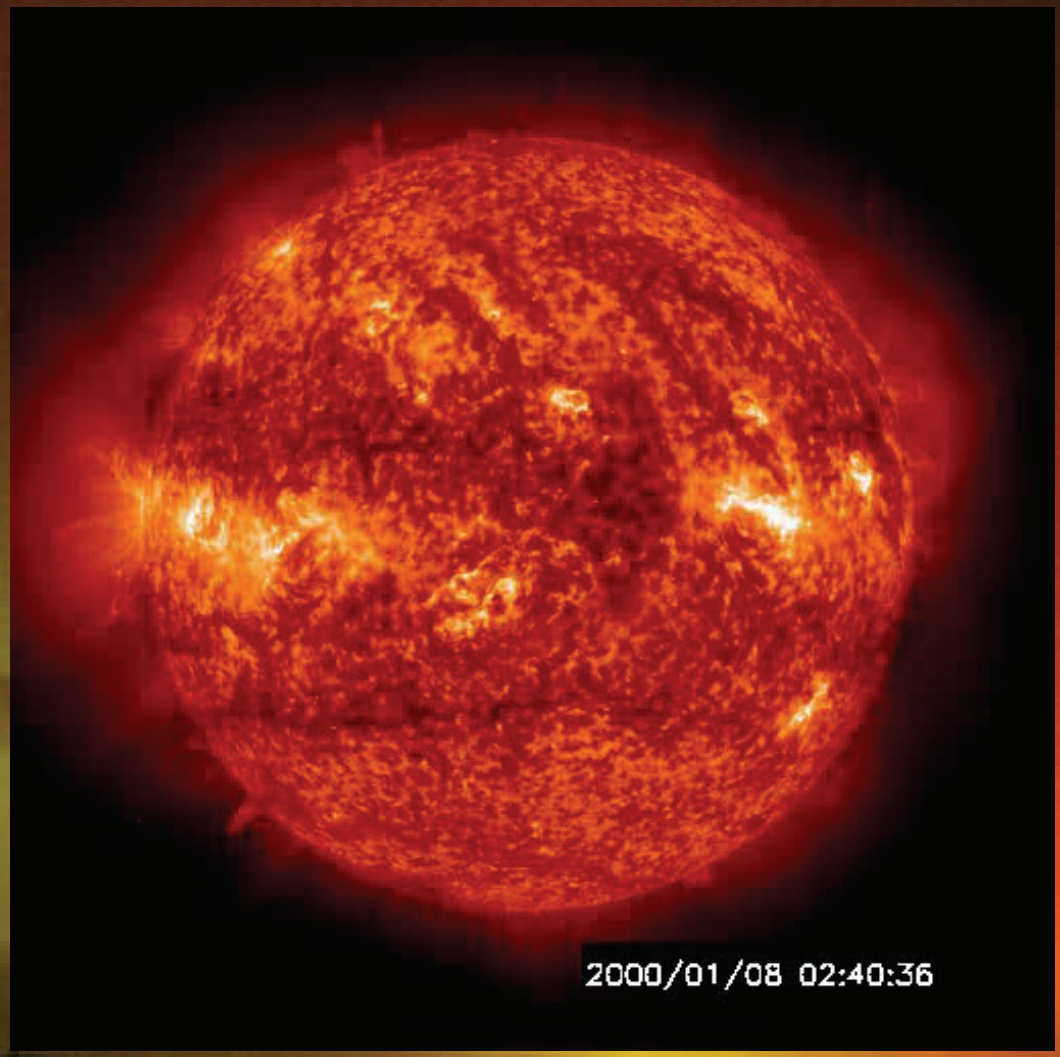
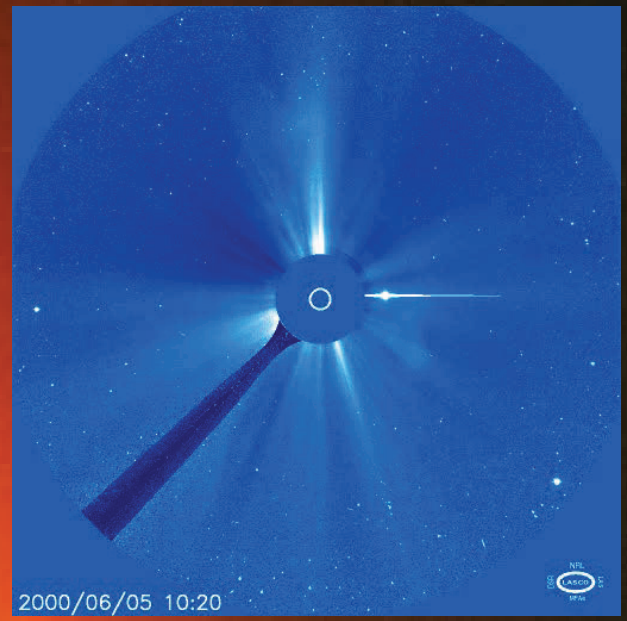
How to obtain B_z south?
2. Here comes the **active Sun**!



Flares/CMEs,
interplanetary shocks,
turbulence, SEPs…



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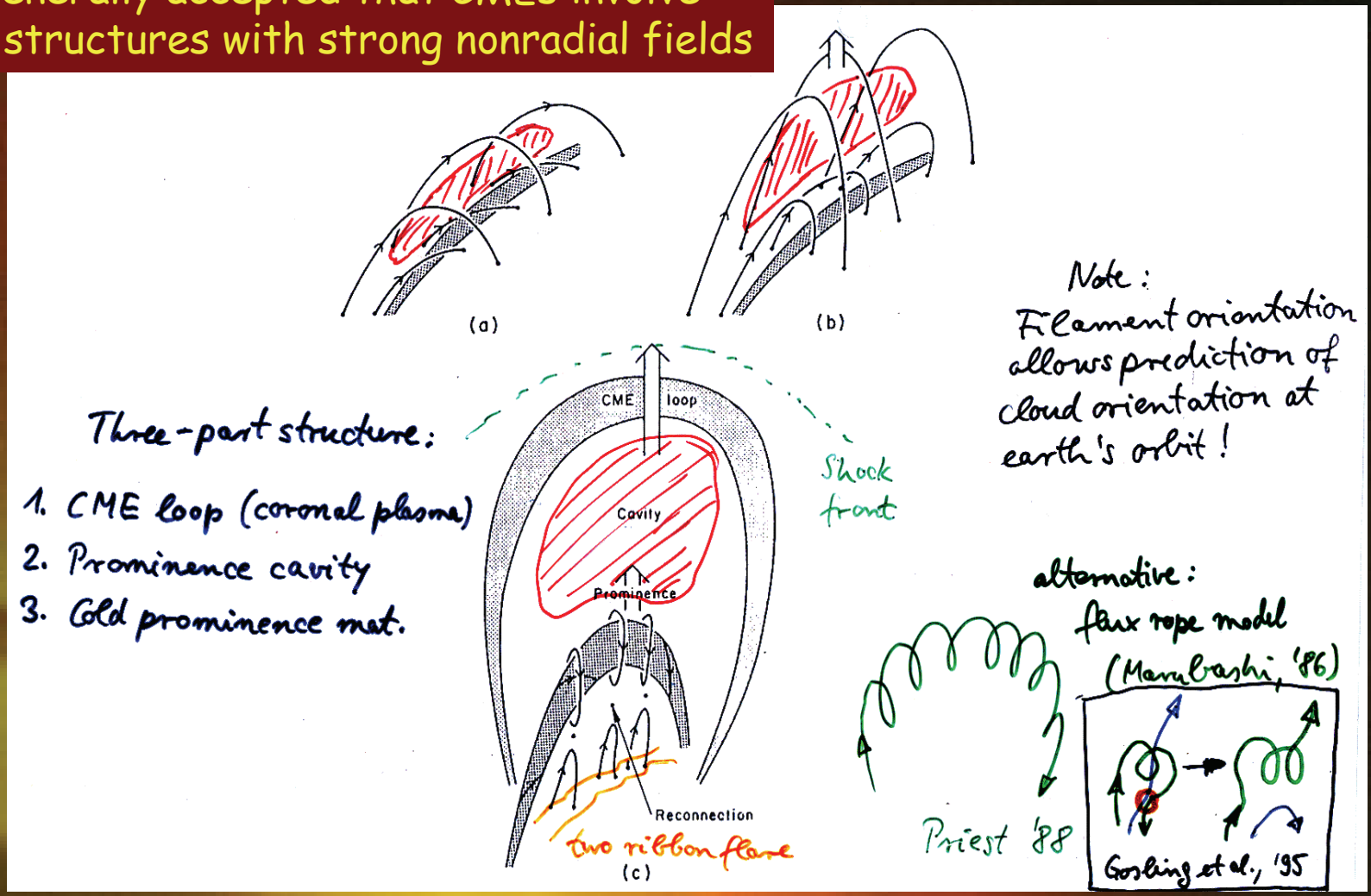
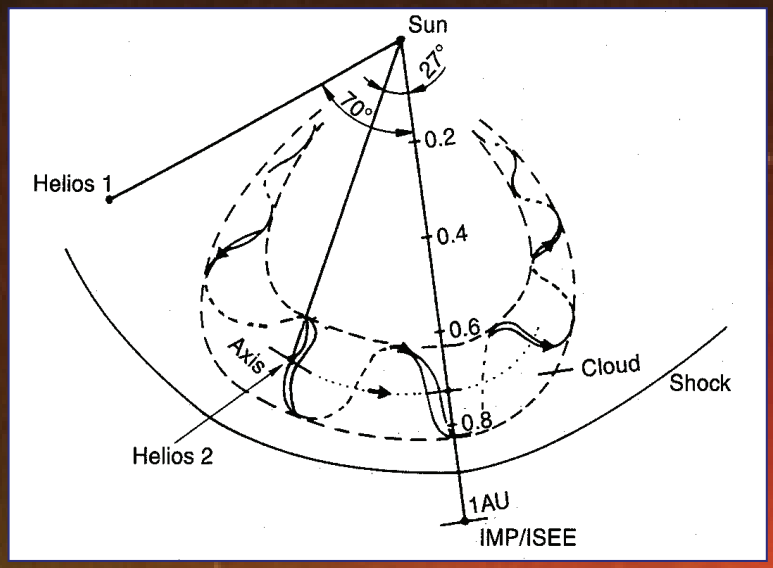
Why does B_z turn south following CMEs?

It is generally accepted that CMEs involve fluxrope structures with strong nonradial fields

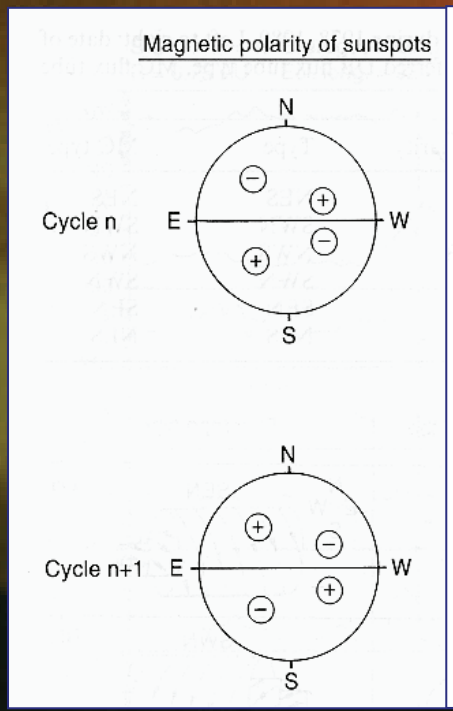


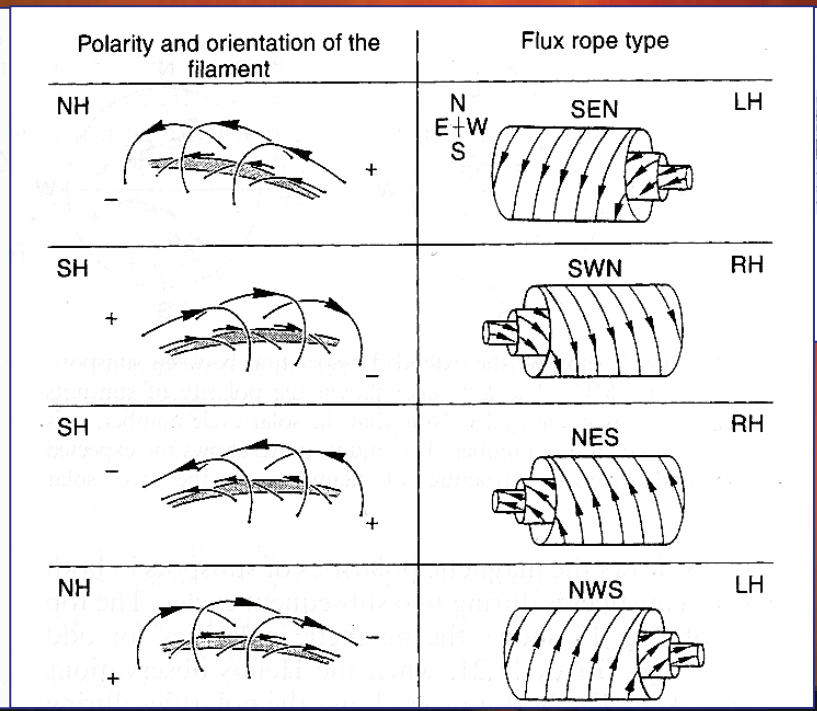
Ejected plasma clouds in space

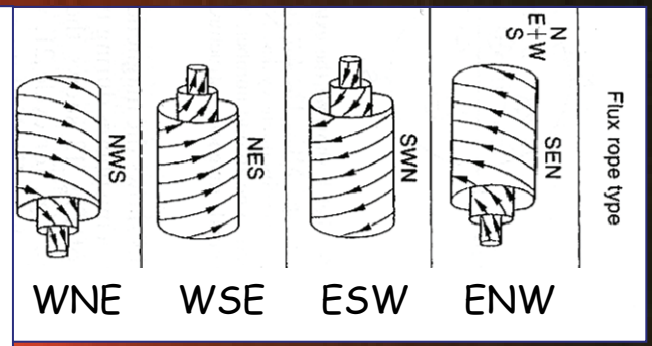


When a flux rope passes an observer, he may encounter B_z south fields at times!

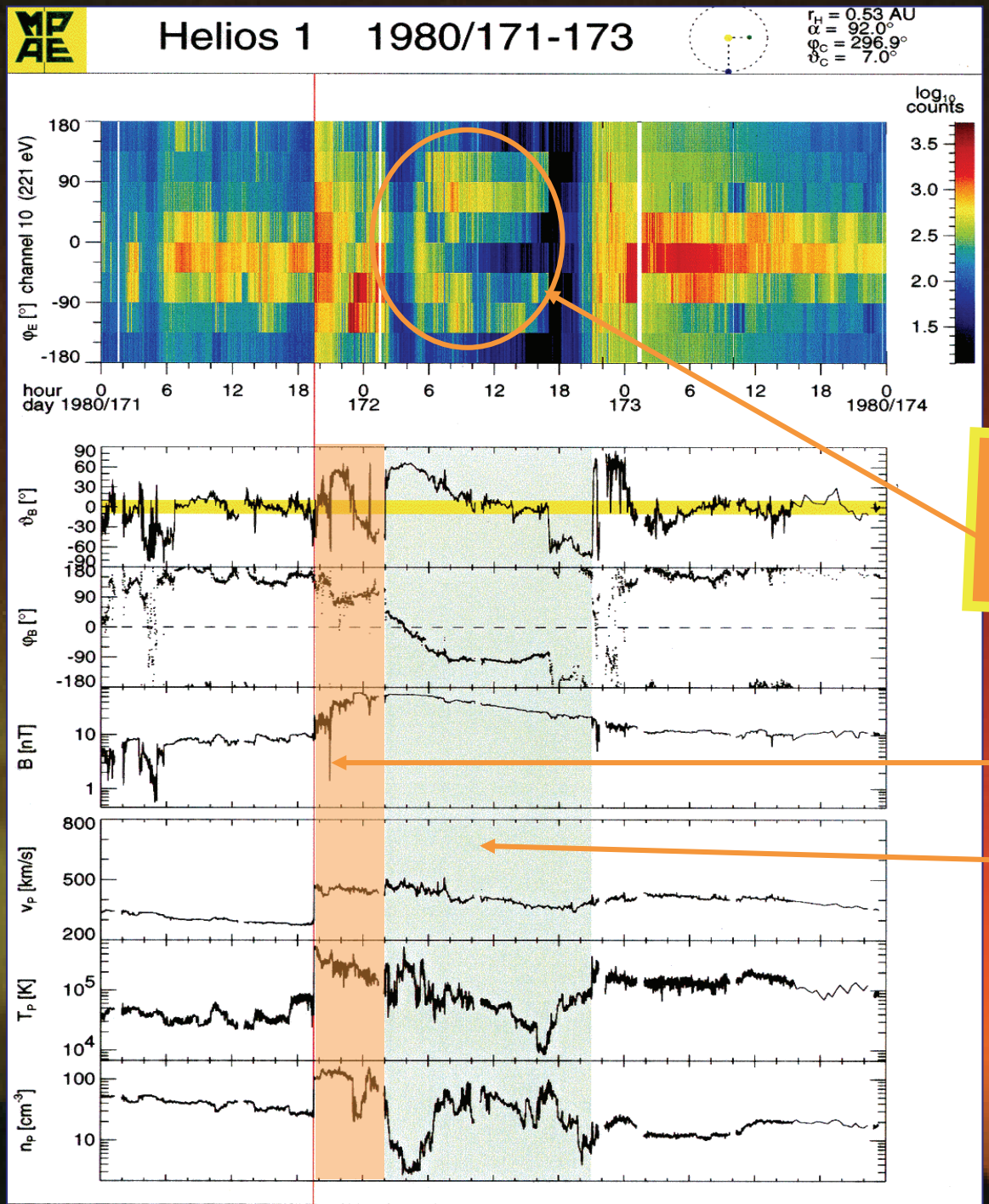
Also possible at times







Note: No S in WNE and ENW clouds!



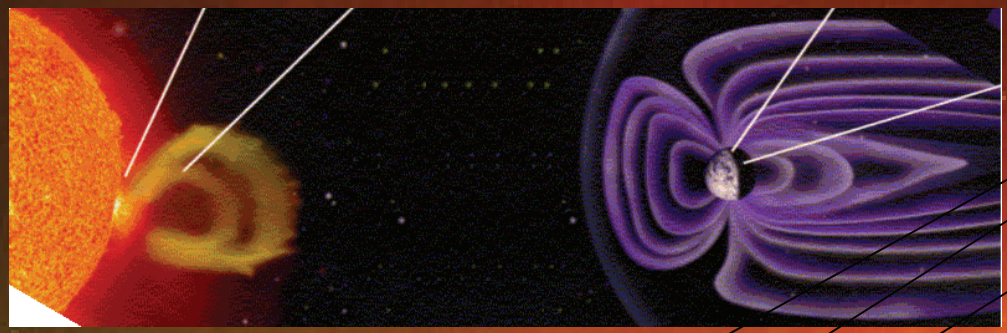
Fast ICMEs may involve magnetic clouds with major B_z south components.

This cloud contains "bidirectional electrons", evidence for magnetic cut-off

Typical CME products in the interplanetary medium:

- shocked "sheath" plasma (compressed and heated),
- and sometimes "driver gas", including magnetic clouds,

What happens at Earth when ICMEs arrive?

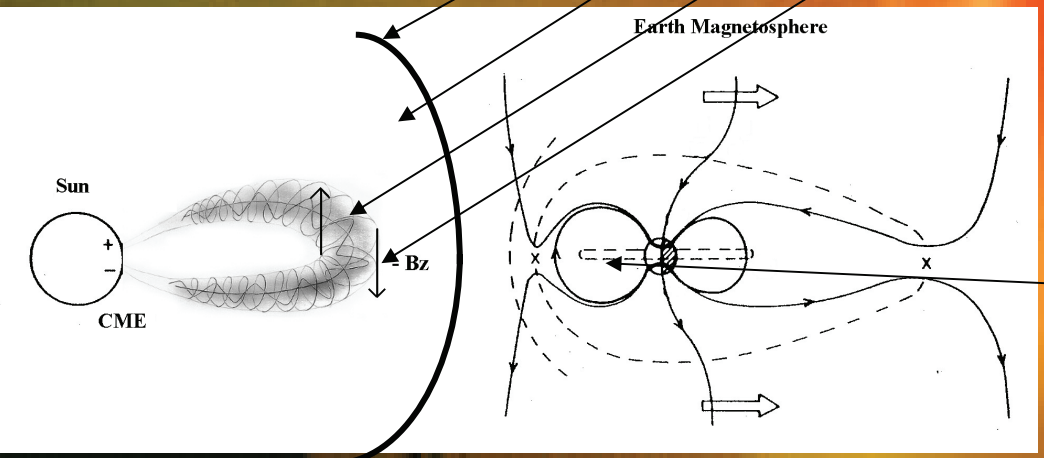


shock

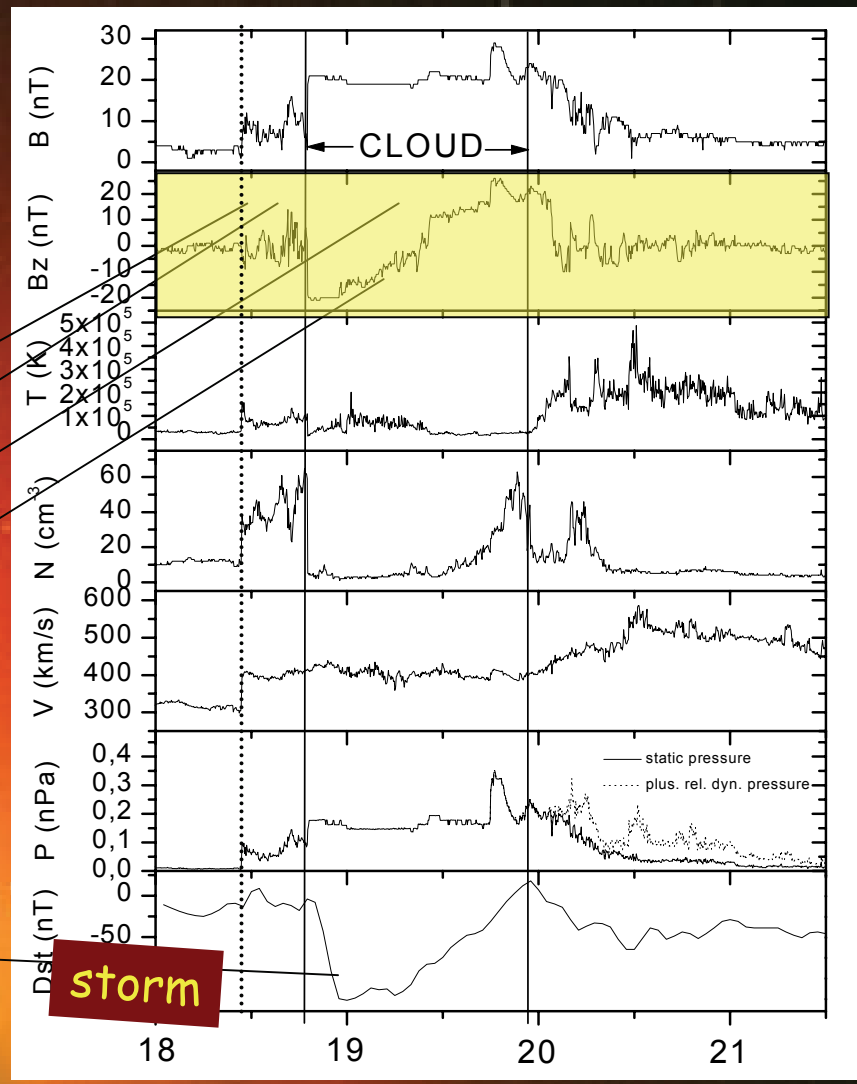
sheath

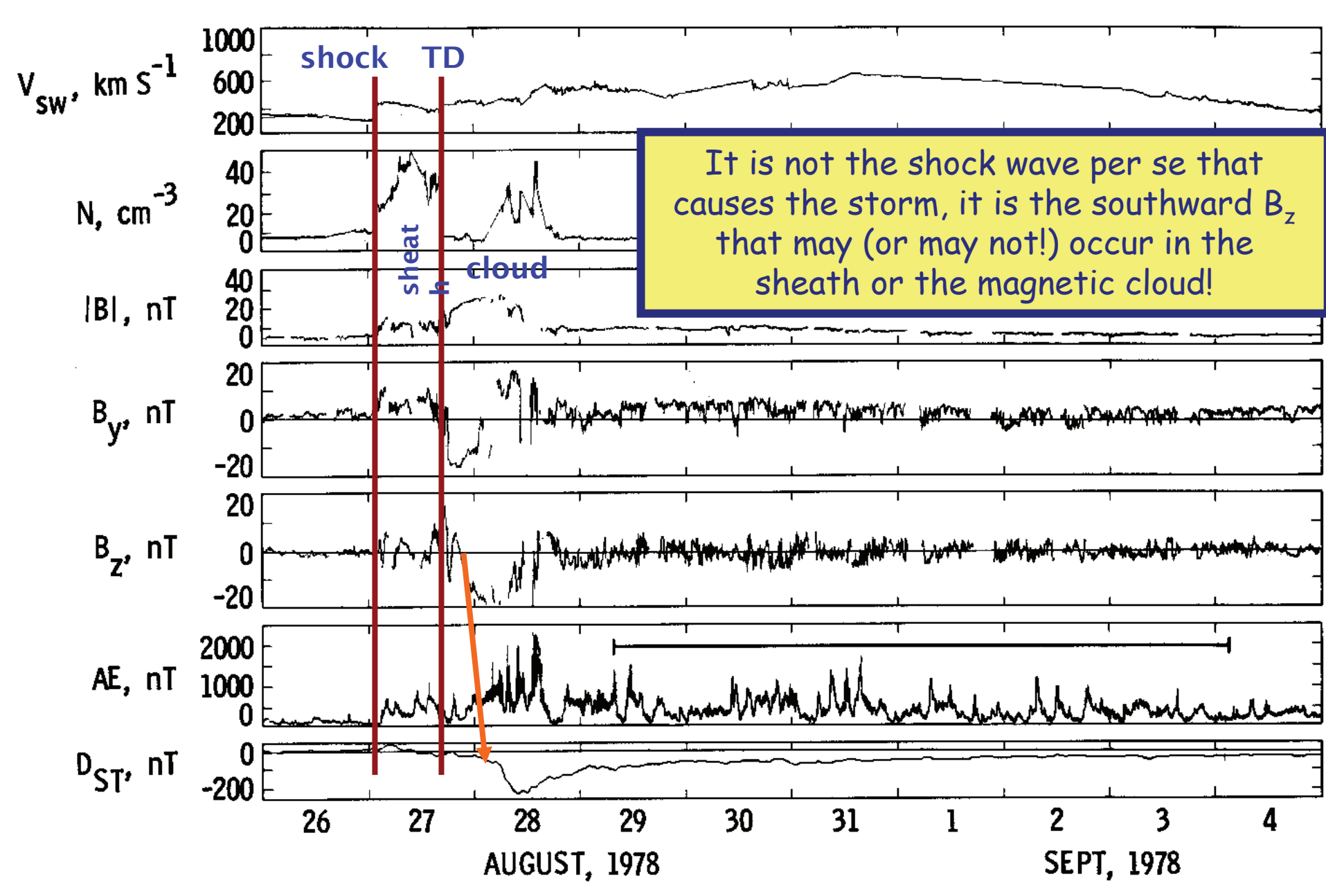
cloud

B_z south



Shock





It is not the shock wave per se that causes the storm, it is the southward B_z that may (or may not!) occur in the sheath or the magnetic cloud!

Relation of a strong geomagnetic storm with the arrival of a magnetic cloud

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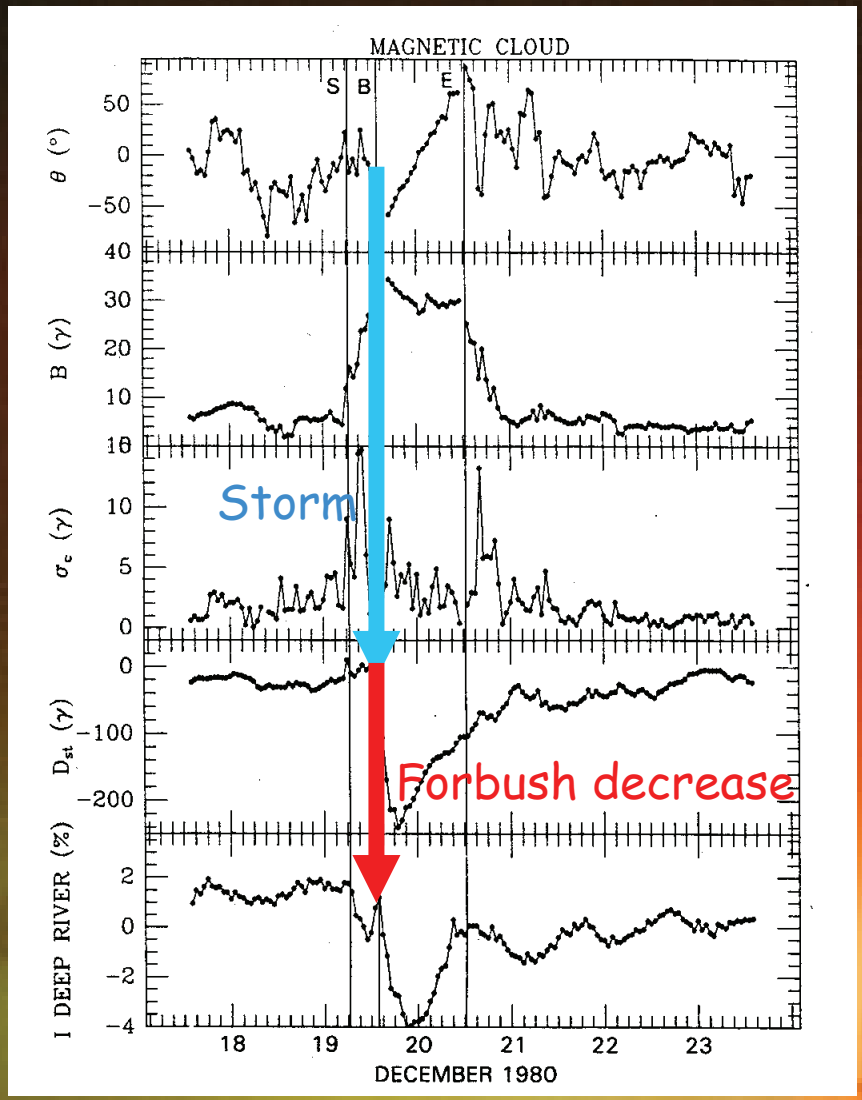
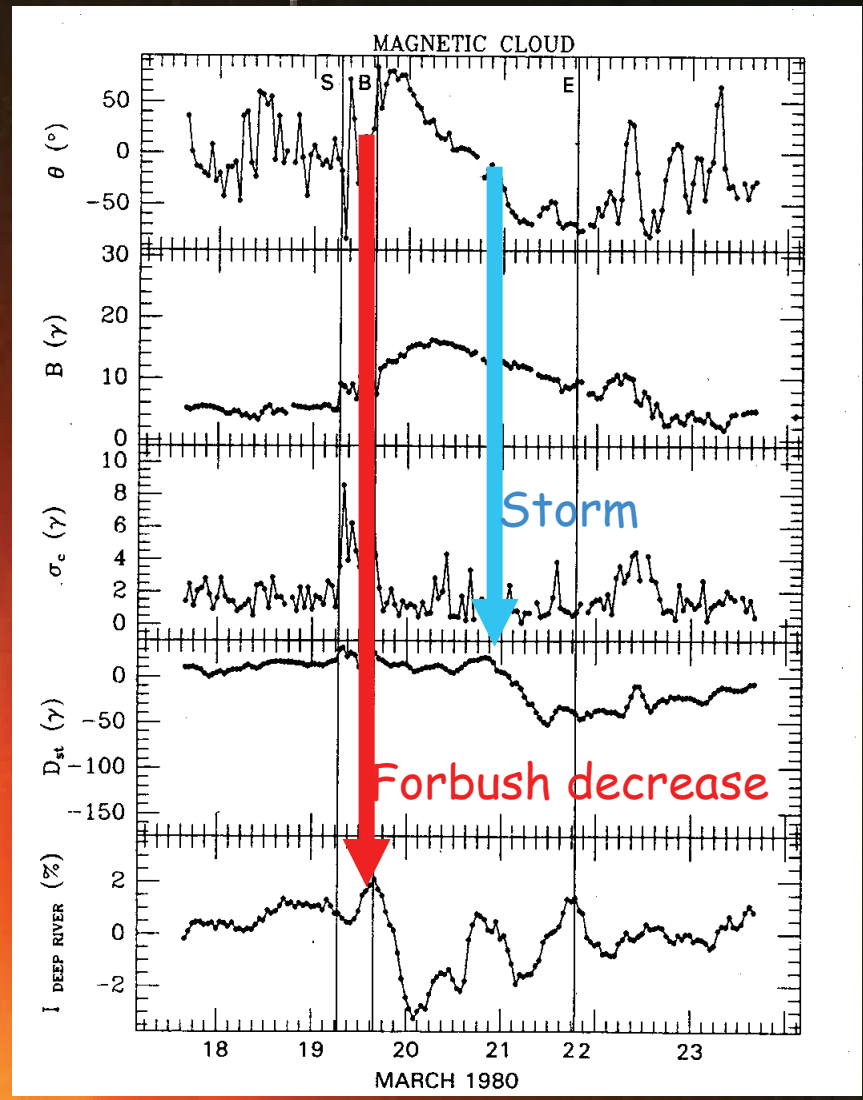


A SEN cloud at 1 AU



A NES cloud at 1 AU

Note how different the geomagnetic response is, despite the similarity of both: the cloud pattern and the Forbush decrease!

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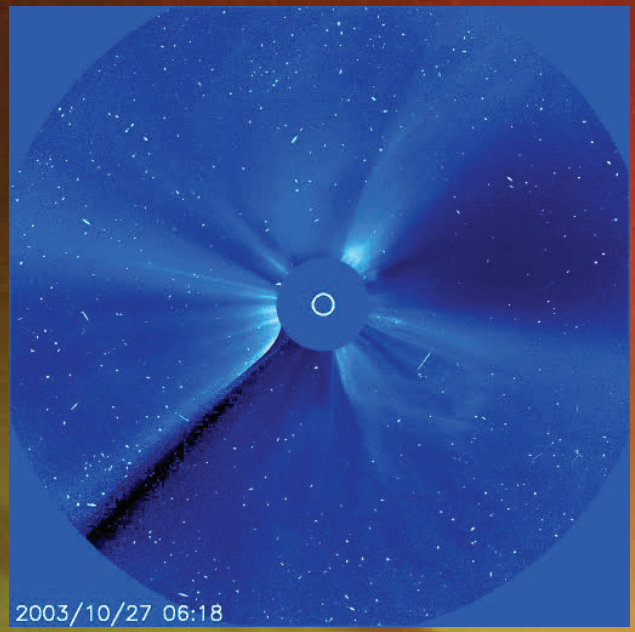
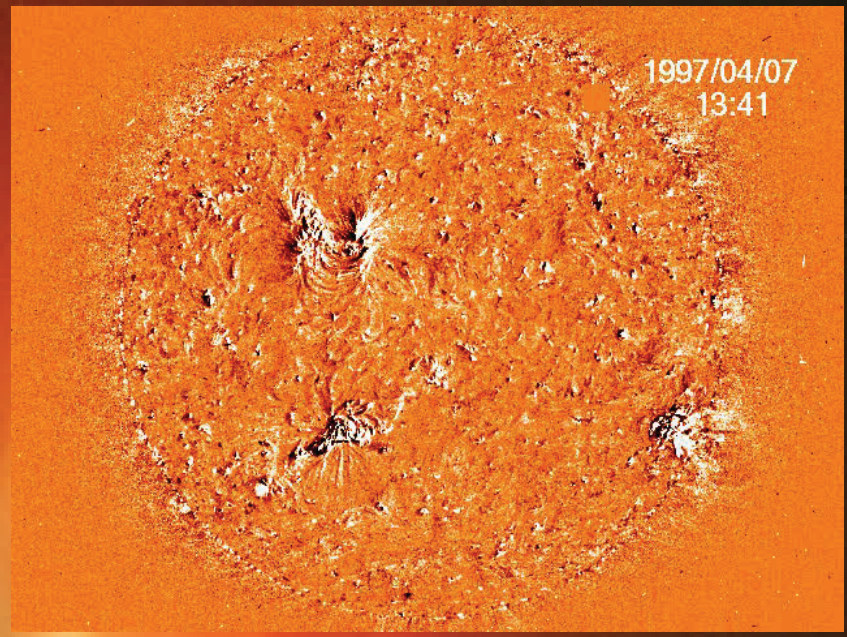
What progress have we made in understanding space weather and predicting it?

Halo CMEs: a new quality from SOHO
We can now watch earthward pointed CMEs early on!



A classical "halo" CME, observed by LASCO-C3 on 29.10.2003



A pressure wave (EIT wave) in the solar atmosphere, pushed by a flare on 7.4.1997,
Evidence for front side CME!

Towards or away from Earth? That knowledge alone grants space weather predictions a new quality!

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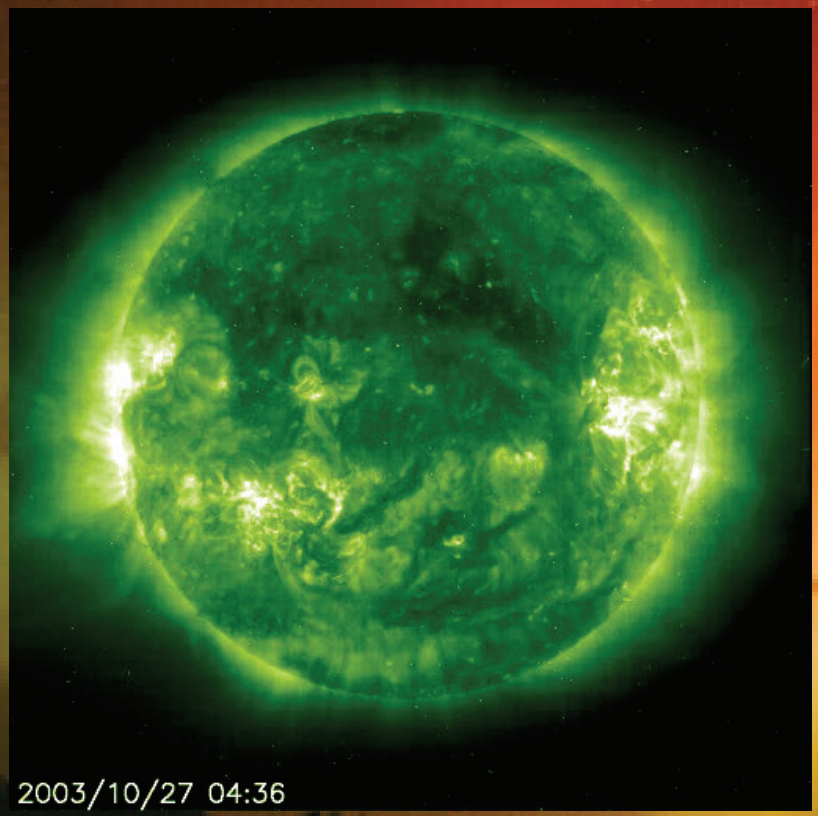
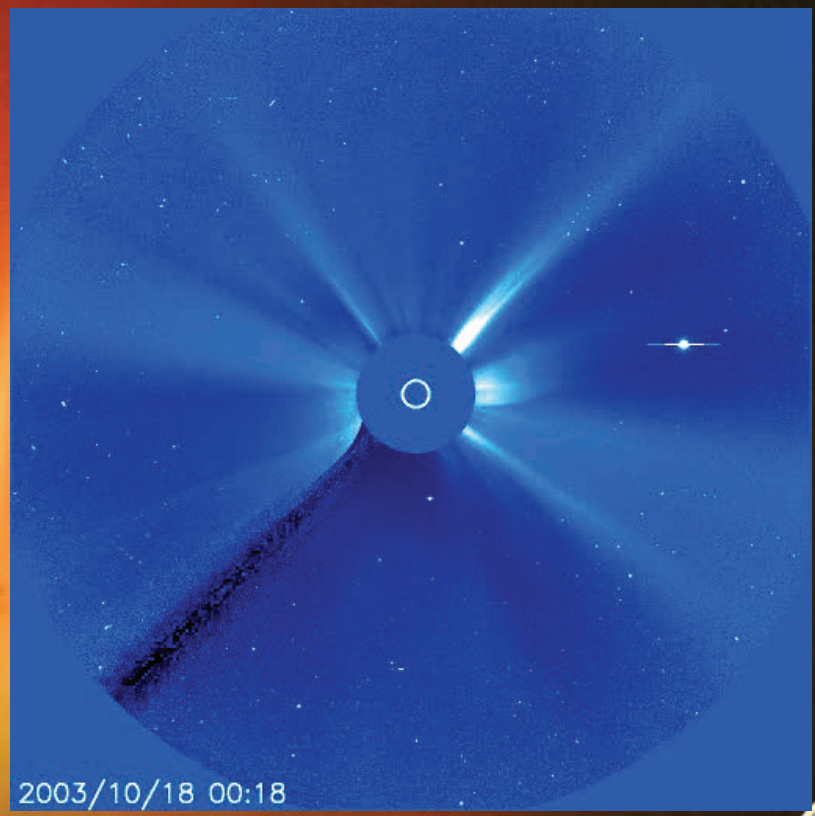
Why are space weather predictions still that uncertain?

1. **We cannot predict eruptions before they occur!!!**
2. We cannot measure the propagation speed of halo CMEs towards Earth!
3. We do not yet have a unique handle on what determines geo-efficiency.





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Why are space weather predictions still that uncertain?

1. We cannot predict eruptions before they occur!!!
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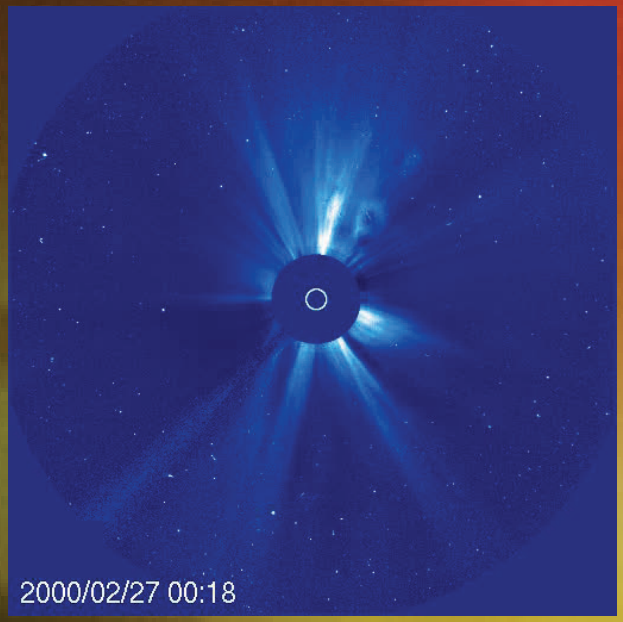
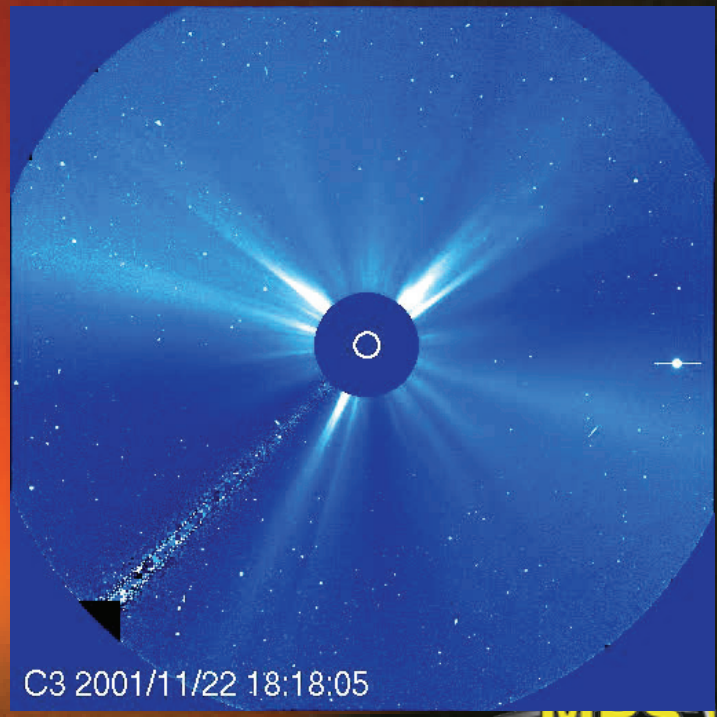


A limb CME: front speed and expansion speed can both be measured

?

A halo CME: only the expansion speed can be measured



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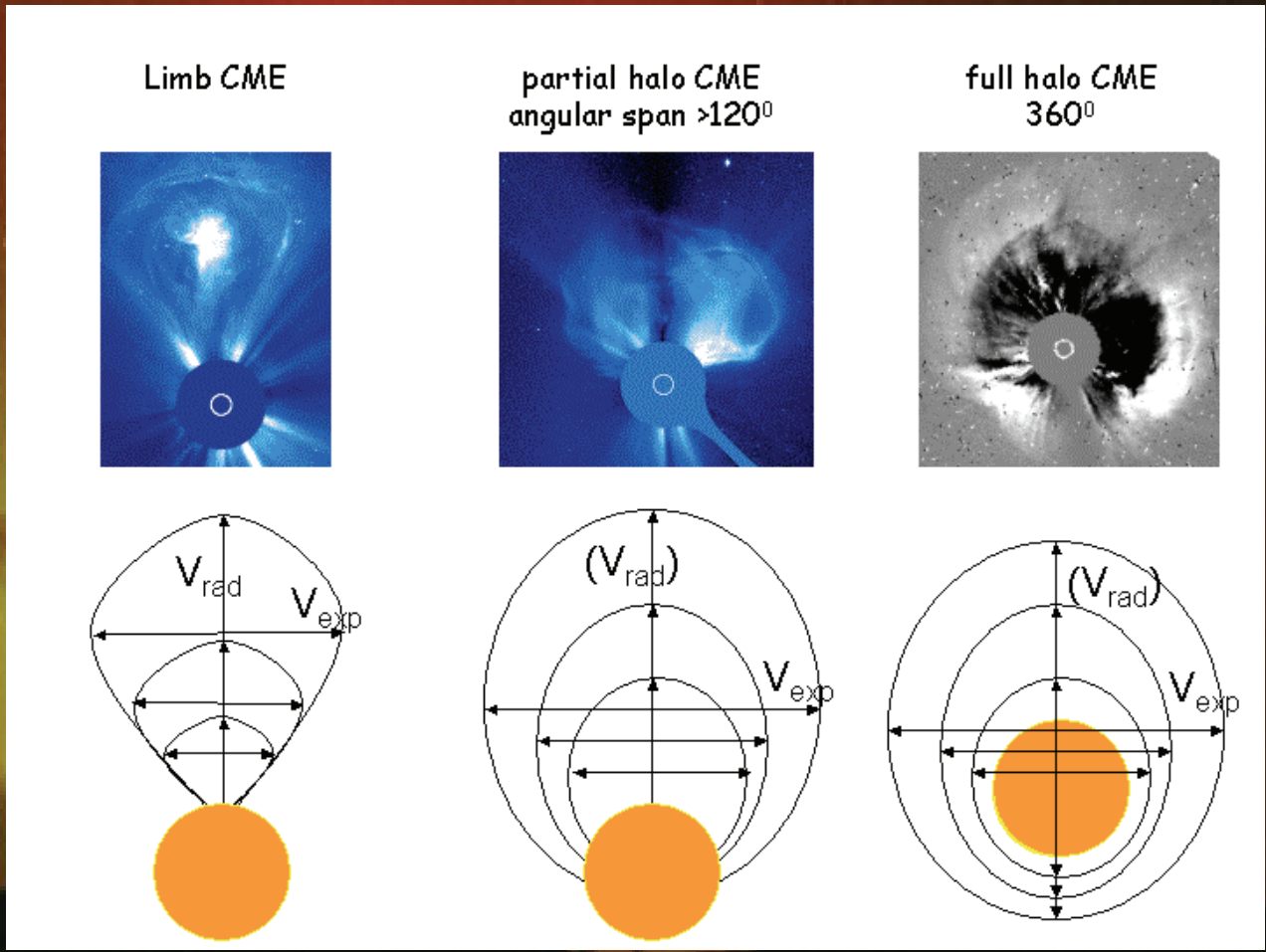
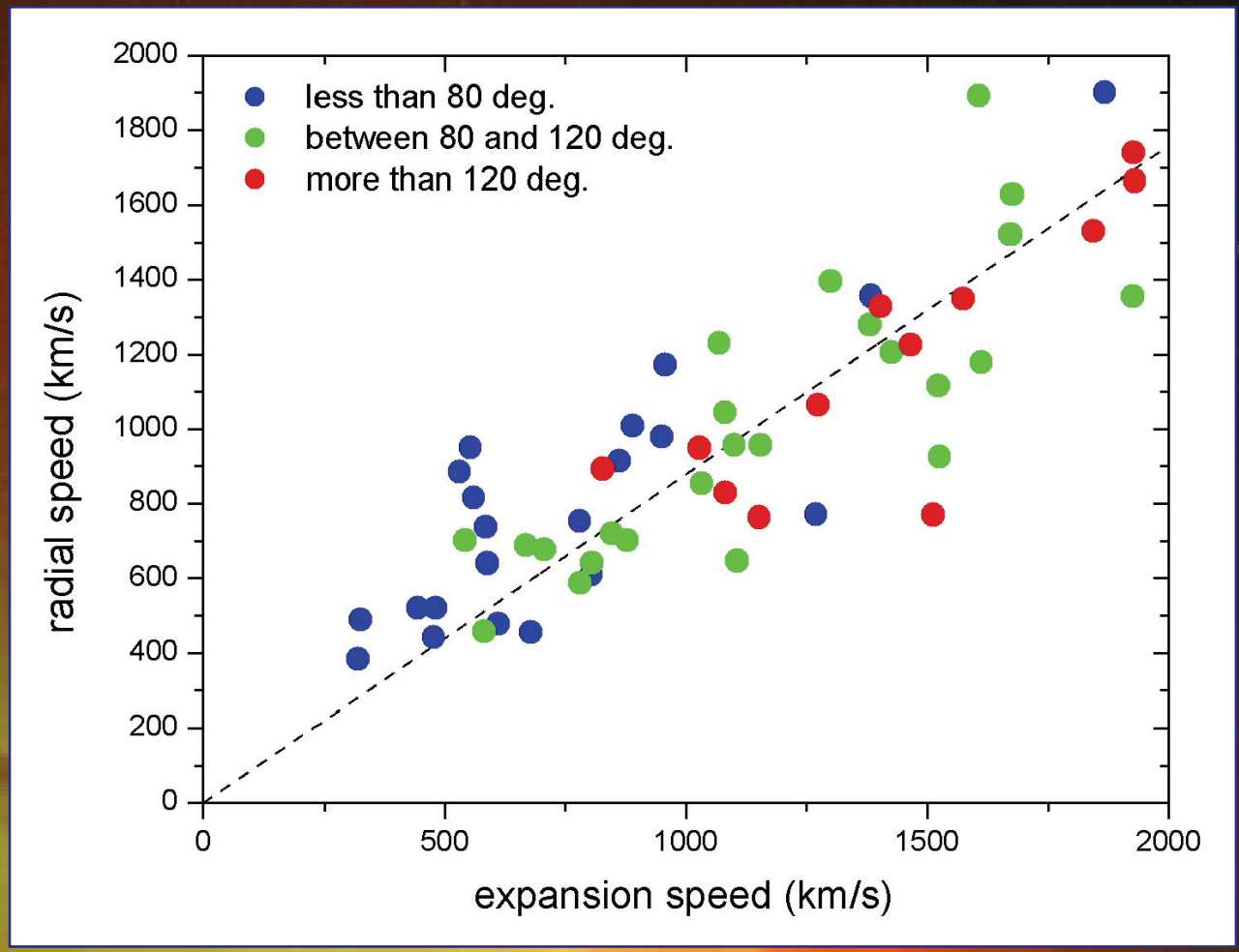


The apparent „plane of the sky speed" V_{rad} depends on the ejection direction.

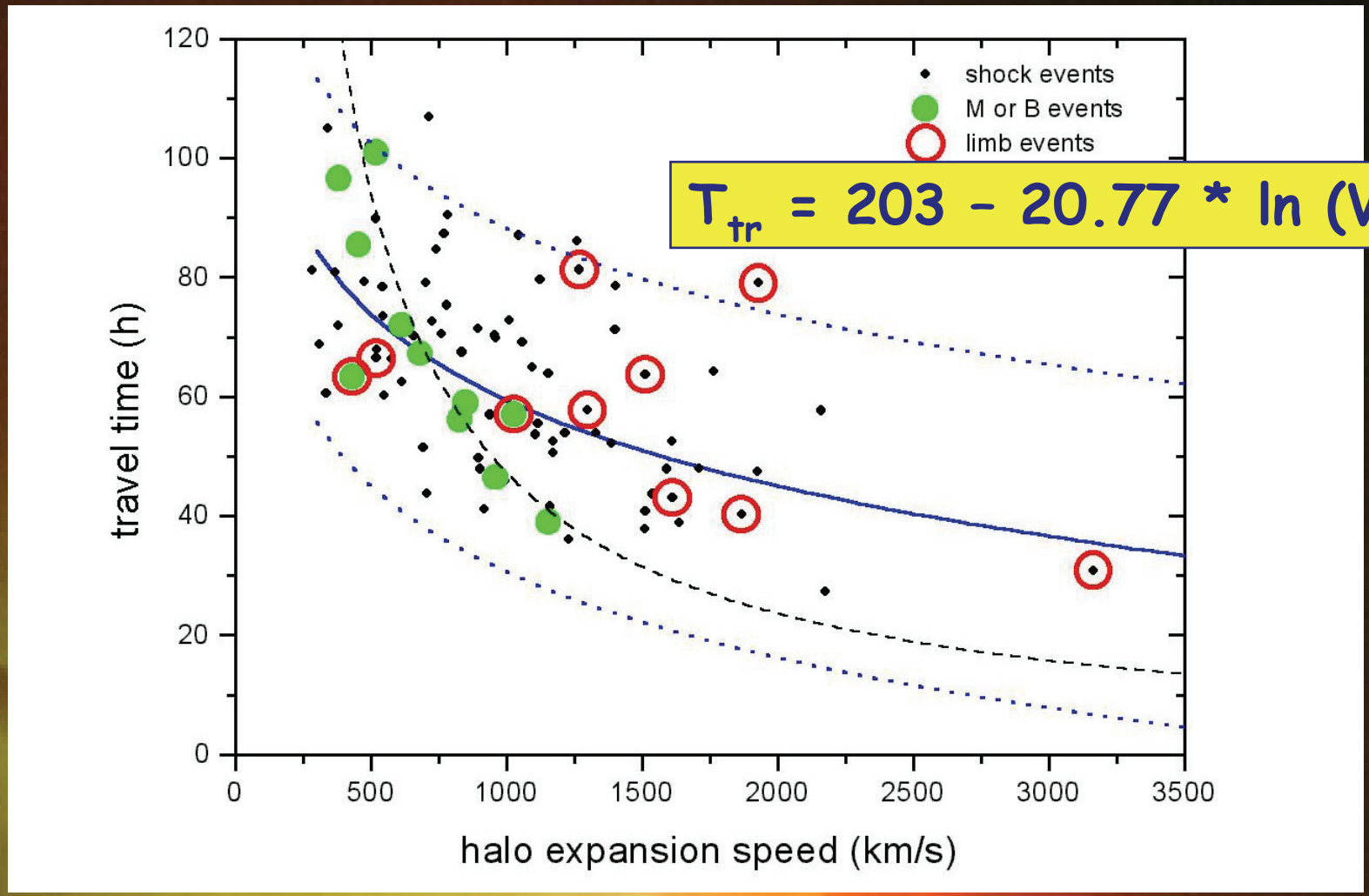
As a unique proxy, we take the „expansion speed" V_{exp} and derive an empirical relation.

Radial and expansion speeds for limb CMEs



The correlation between radial CME speed V_{rad} and the expansion speed V_{exp} for limb CMEs observed by LASCO between 1996 and 2001.

Correlation of CME expansion speed with travel time



For 75 halo CMEs, the expansion speed and the travel times to 1 AU were determined.

An empirical function was derived: **an improved prediction tool!**

Recent studies of CME/ICME correlations show:

- In 85% of all full or partial front side halo CMEs an ICME effect at the Earth can be expected (based on 163 cases).
- The remaining 15 % missed the Earth: potential **false alarms!** That applies also to 7.7 % of the most relevant front side full halo CMEs!
- Among the safely associated CME/ICME cases, 8.6 % are due to NON-halos. Predictors focused on halos would have ignored them: **Missing alarms!** In total, the number of unpredicted shock/storm events amounts to 25 %!
- All very intense storms (D_{st} < -200 nT) were related to halo CMEs.

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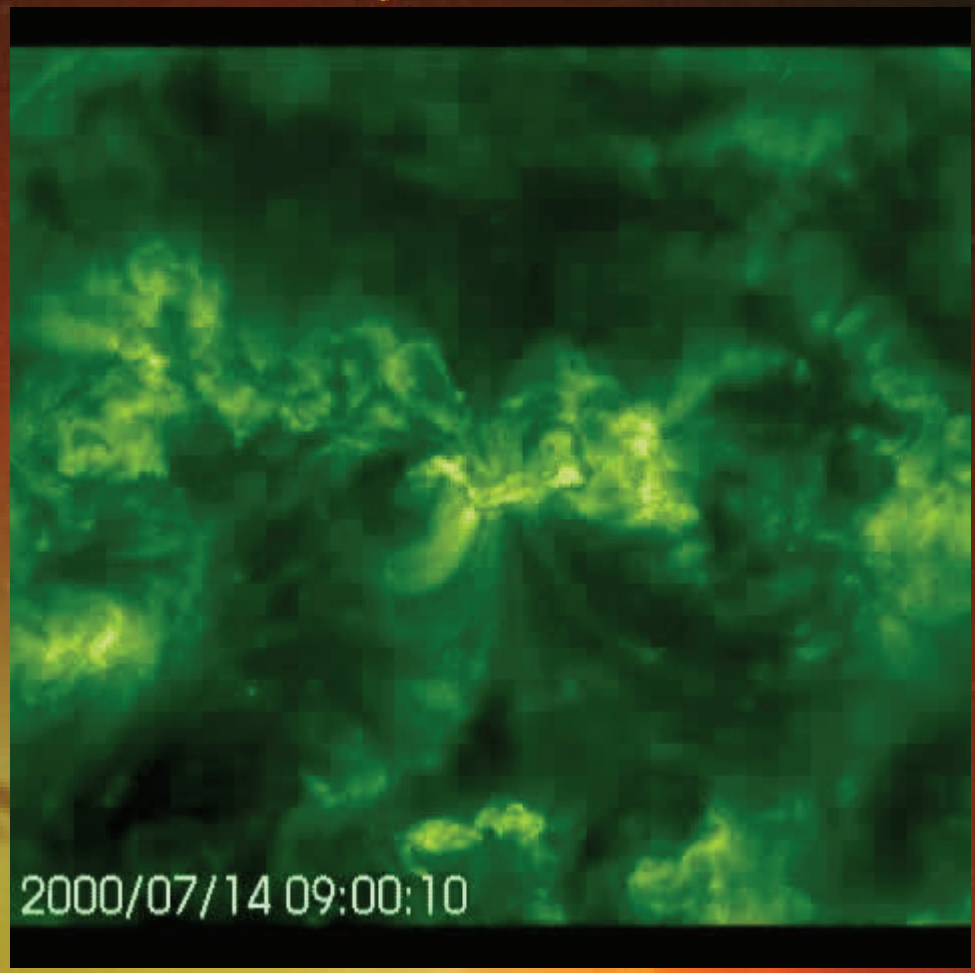
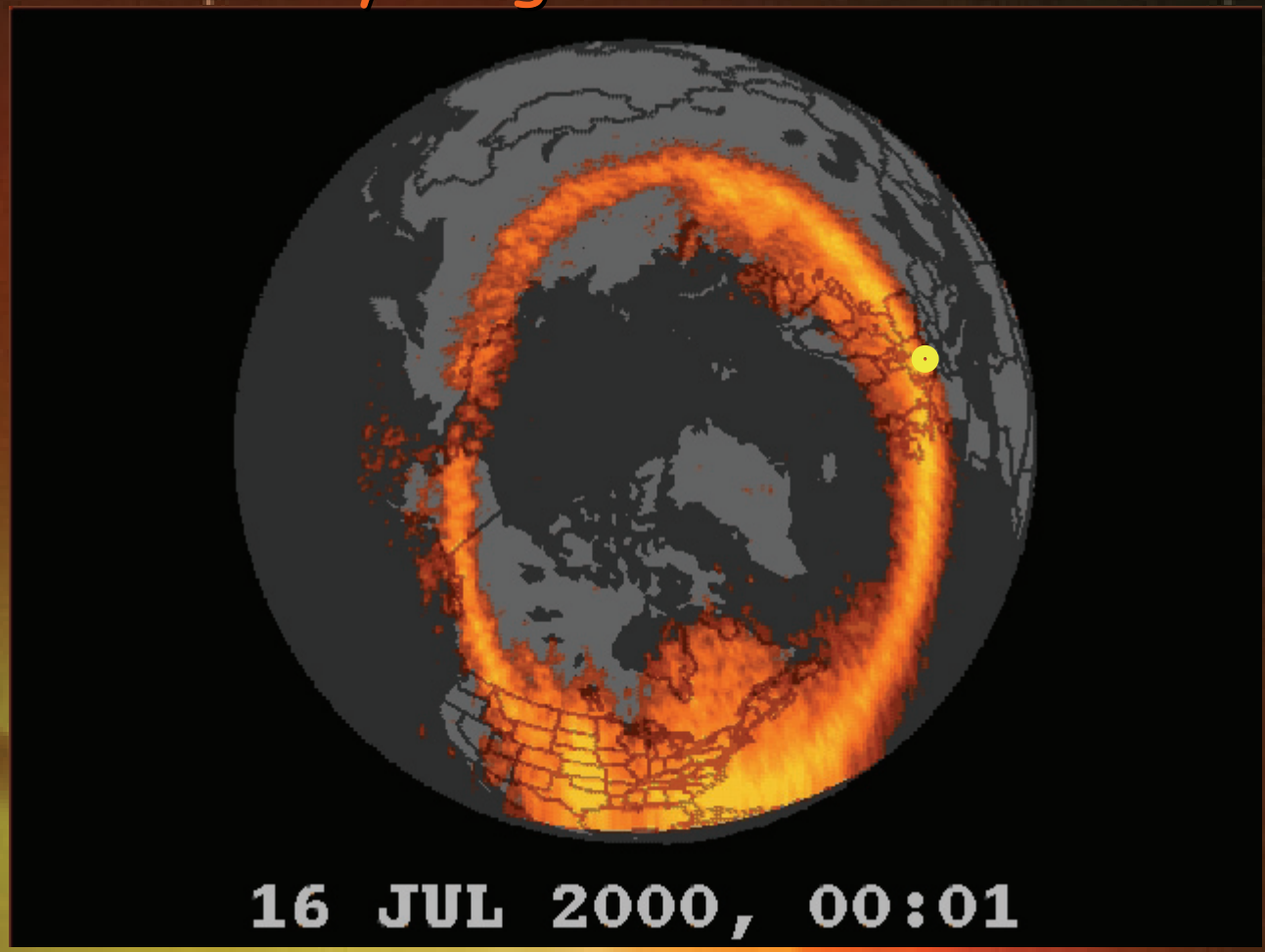
The famous „Bastille-Day"-event on July 14, 2000



The famous „Bastille-Day"-event on July 14, 2000
Extremely bright extended Aurora



That was the auroral oval on July 16, 2000:
aurorae all over the USA and even middle Europe!

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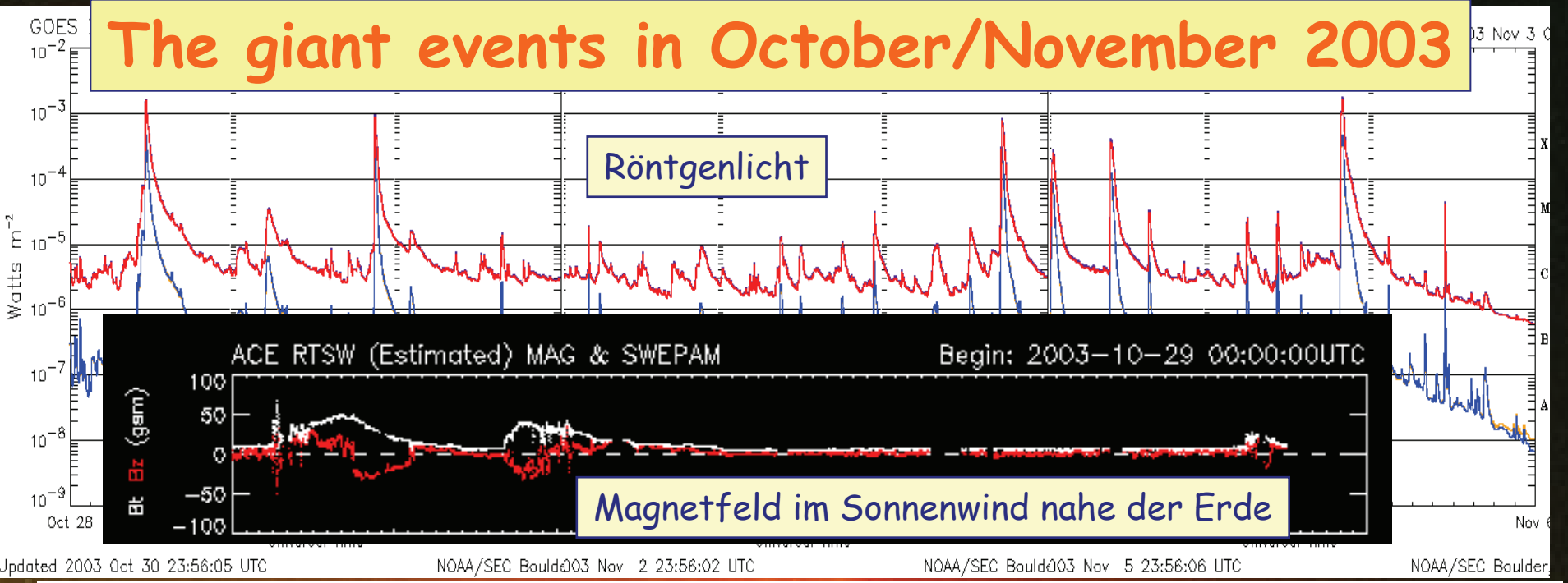
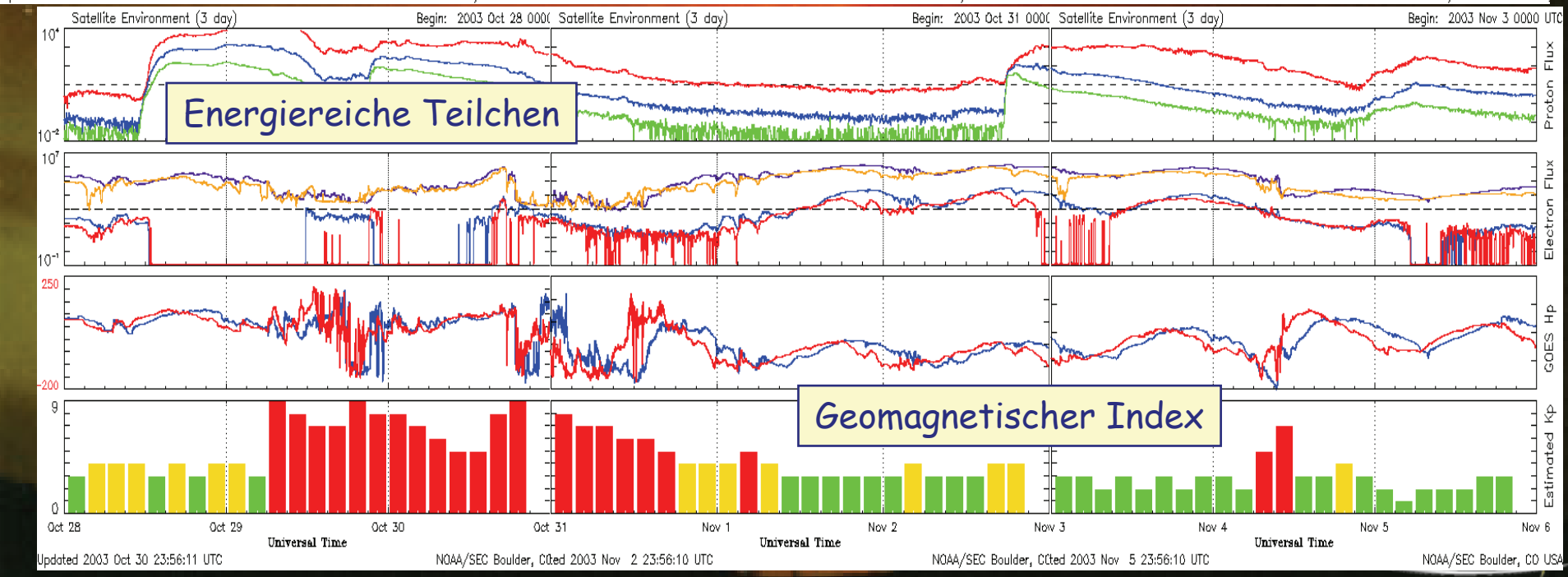
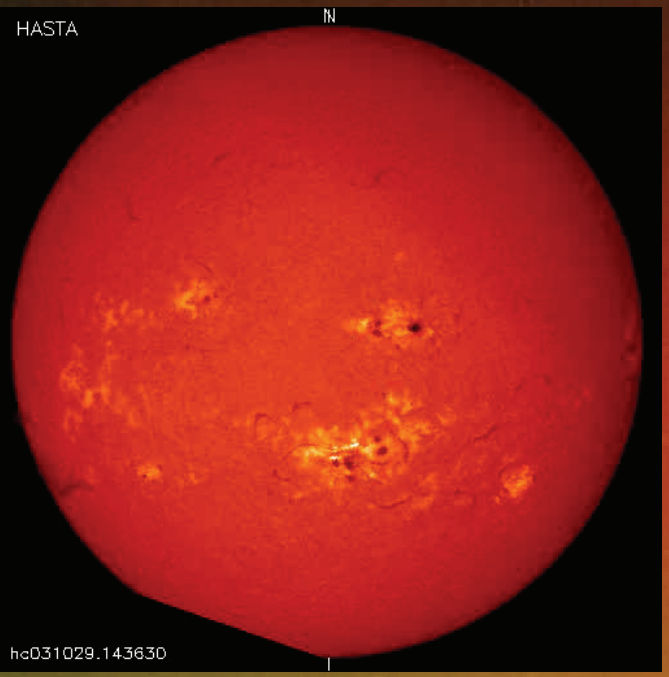
The giant events in October/November 2003



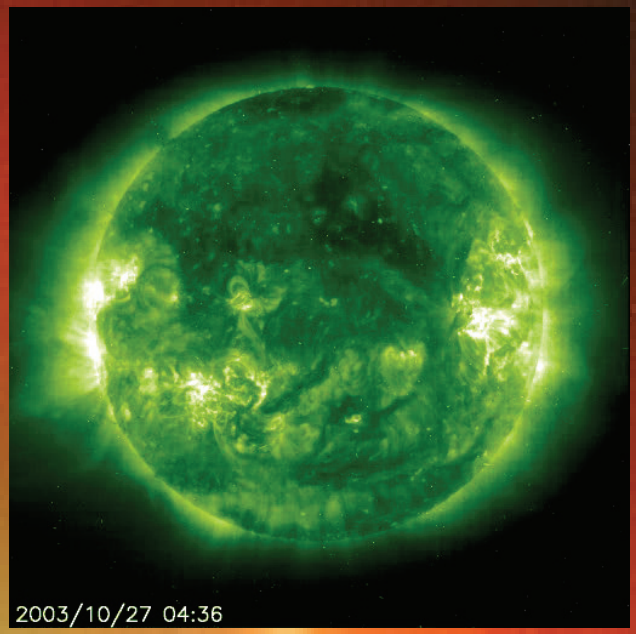


The super events on October 28/29, 2003

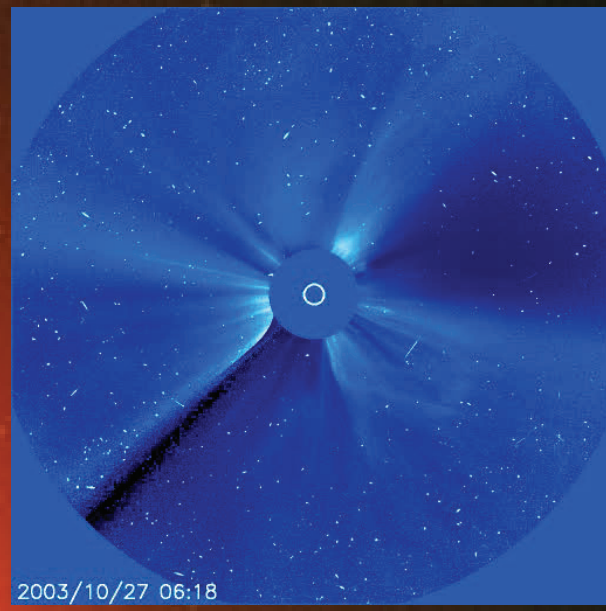


HASTA in El Leoncito

A X 17,2 flare on 28.10.2003,
A X 10,0 flare on 29.10.2003



EIT on SOHO



LASCO-C3 on SOHO

The „snowstorm" is due to high-energy particles accelerated during the flare process. They can penetrate spacecraft and instrument skins!

The super events on October 28/29, 2003

- We watched them in detail and made predictions.
- They were absorbed and announced by the media (e.g. TV news)
- They were pretty correct!
- But weather in most parts of Europe was too bad for aurora sighting.

The super events on October 28/29, 2003

Aurorae all over Europe!

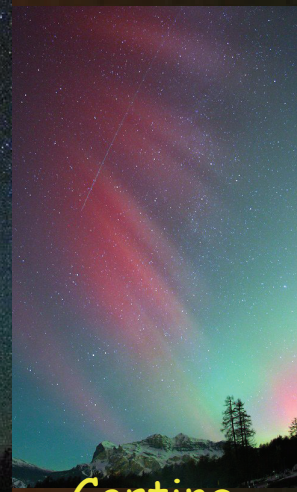

Kroschenbroich


Dortmund


Linz


Bopfingen


Dolomiten


Cortina

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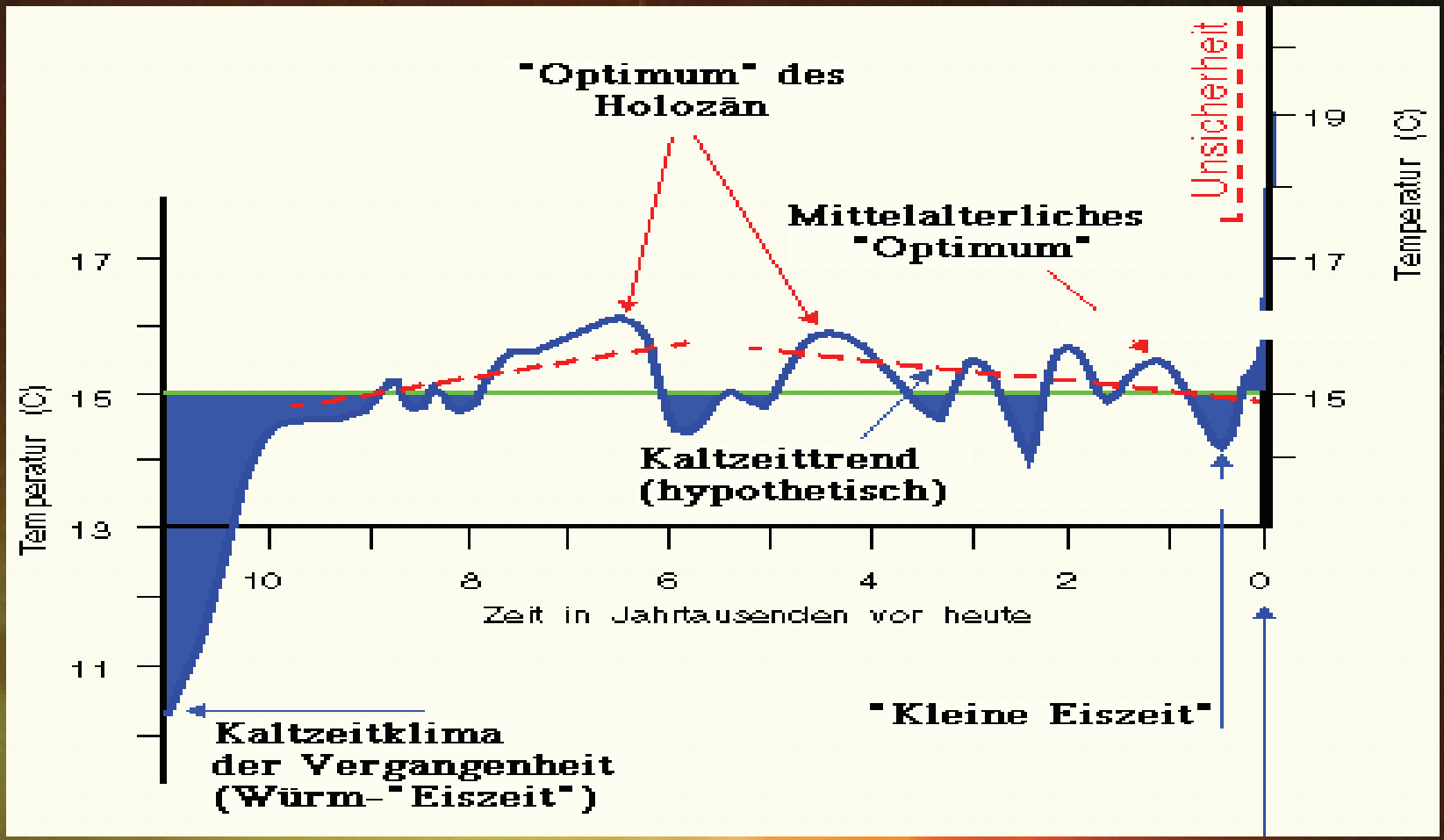
Impact of space weather on Earth's weather and climate?



Major climatic fluctuations occurred long before the man-made greenhouse effect became significant

Future actvities for unserstanding space weather

* Fundamental research for understanding basic mechanism of CME release,
* High time resolution optical observations of CME onset and propagation, simultaneously from different view points (stereo view),
* On-line computer model of the heliosphere, continously updated, that allows to simulate CME ejections and propagation in realistic and near-real-time way.

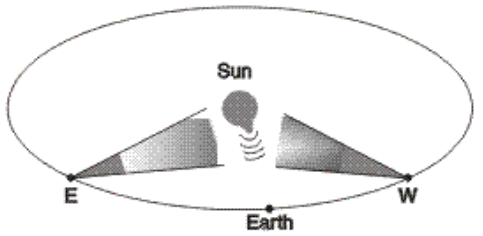
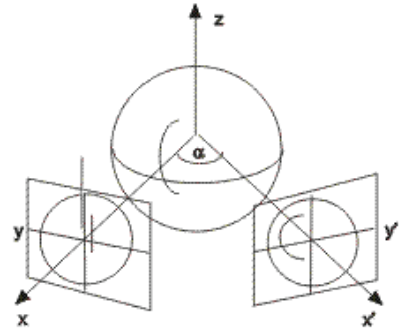


Figure 20. Position of the STEREO spacecraft after about 1 year. STEREO #1, leading Earth, can see around the west limb; STEREO #2, lagging Earth, can see around the east limb.



Coronal loop viewed from two angles separated by α

Coordinates of two views related by simple rotational transform

$x = x'\cos\alpha + y'\sin\alpha$

$y = y'\cos\alpha - x'\sin\alpha$

$z = z'$

Given y,y' , Solve for x,x'

$x = \frac{y' - y\cos\alpha}{\sin\alpha}$

Just launched, October 25, 2006

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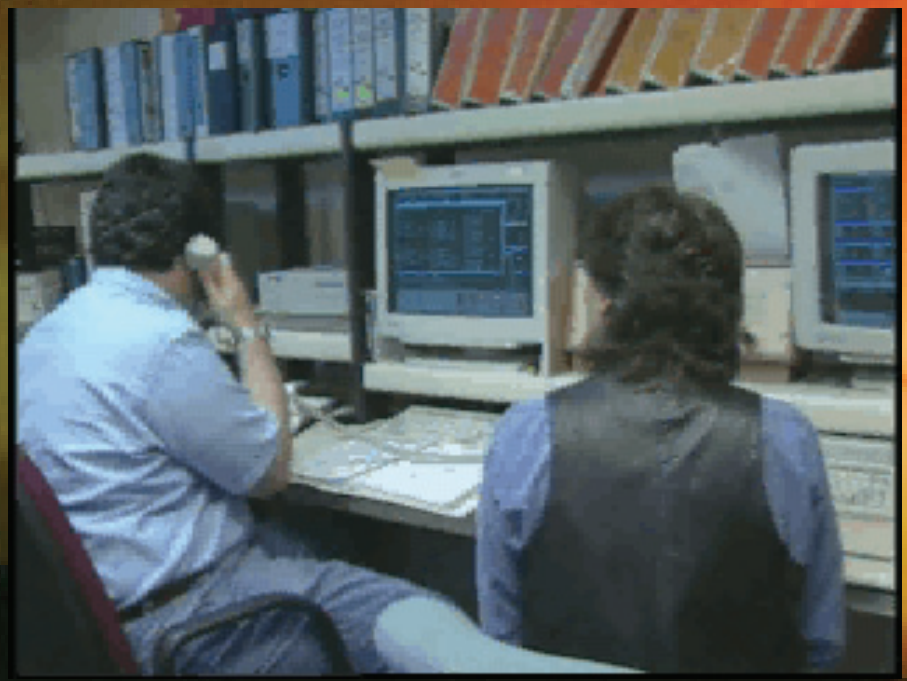
Future actvities for unserstanding space weather

* A dedicated spacecraft at L1 (or closer to the Sun!), carrying:
  an EUV/X-ray imager of the Sun,
  a sensitive coronagraph, for quantifying halo CMEs,
  a complete set of standard particle and field instruments,

* A space weather warning center on the ground, equipped with real-time data links both to the spacecraft in orbit and to the modelling computers, to produce near-real-time reports through the Web

in order to avoid this:



IMPRS Retreat 2011

Lecture on June 21
by Rainer Schwenn

c) Space weather

- The source of space weather
- Why should we care?
- How does the Sun shape space weather?
- The role of Bz south
- M-regions and high-speed streams
- CMEs: piled-up plasma and ejecta clouds
- Problems in forecasting
- Open issues, future work needed

The term "space weather" refers to conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life or health.

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