THE SUN:
Benefits and Damages, Impacts on Human Technology and Well-Being

Lecture at the Summer School Alpbach 2002

Space Weather: Physics, Impacts and Predictions

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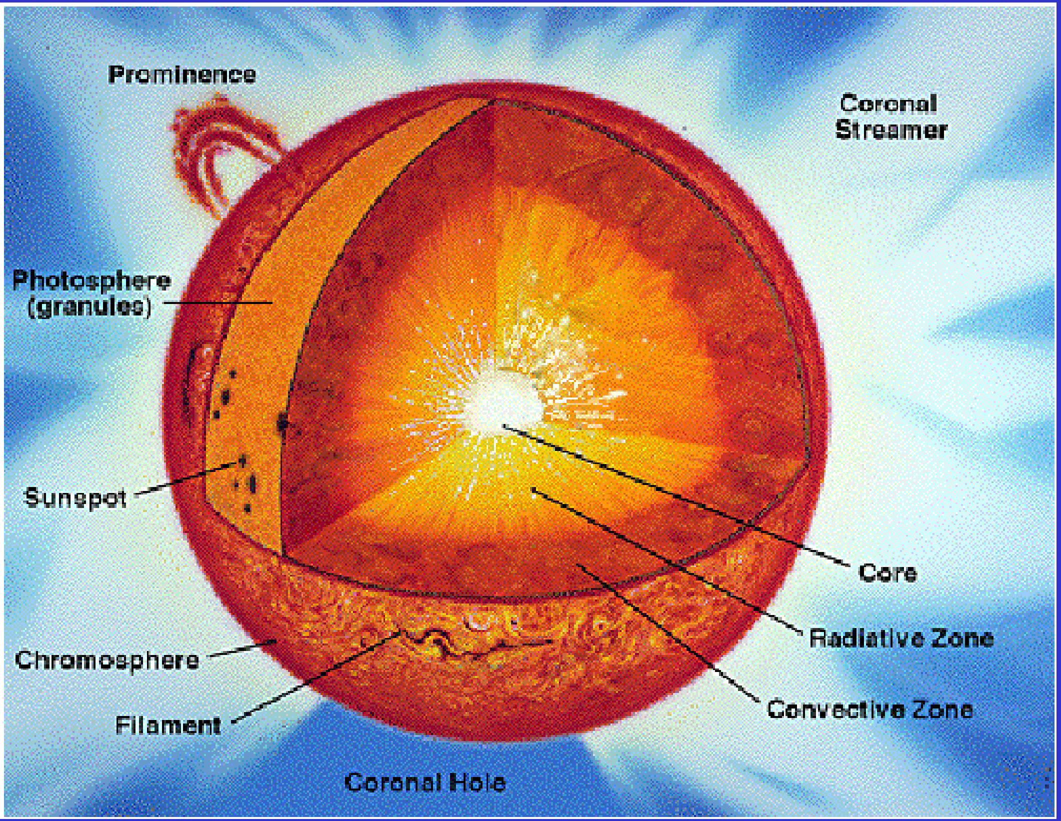
Outline

- Solar impacts and space weather
- Space weather effects
  - in space
  - on ground
- Space weather and atmosphere
- Toward a space weather programme
  - monitoring and services
  - space weather and Europe
- Space weather is not only engineering and applications
  - some big scientific questions

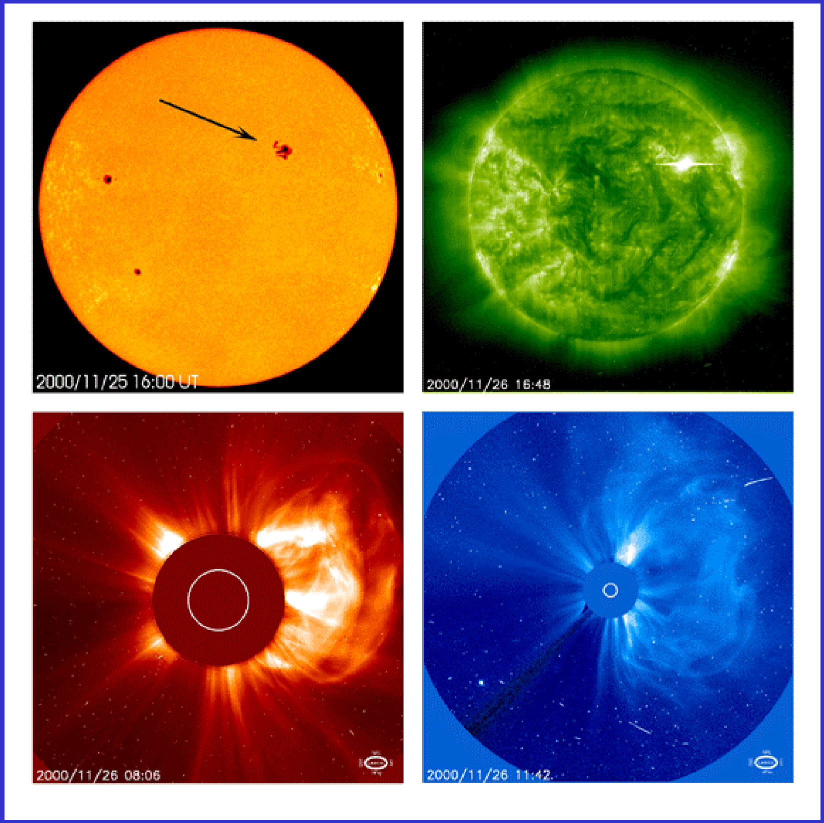
Worshipping the Sun;
Past and present

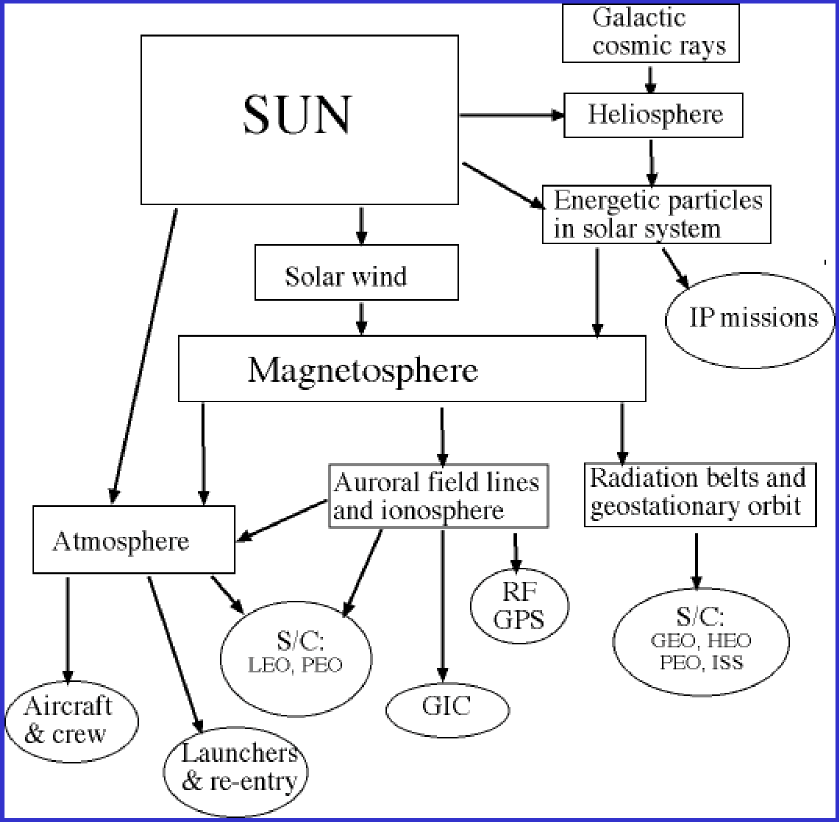
The ultimate energy source



- total solar power: 3.86 x 10^{26} W
  - 60 million 1-GW nuclear power units for every person on Earth

Solar activity controls space weather





All solar impacts are not bad

- average temperature
- photosynthesis
- structure of the atmosphere
  - ozone layer
  - ionosphere
- cosmic rays
  - effects on genetic evolution

There is, however a very delicate balance between various mechanisms

But good news are no news

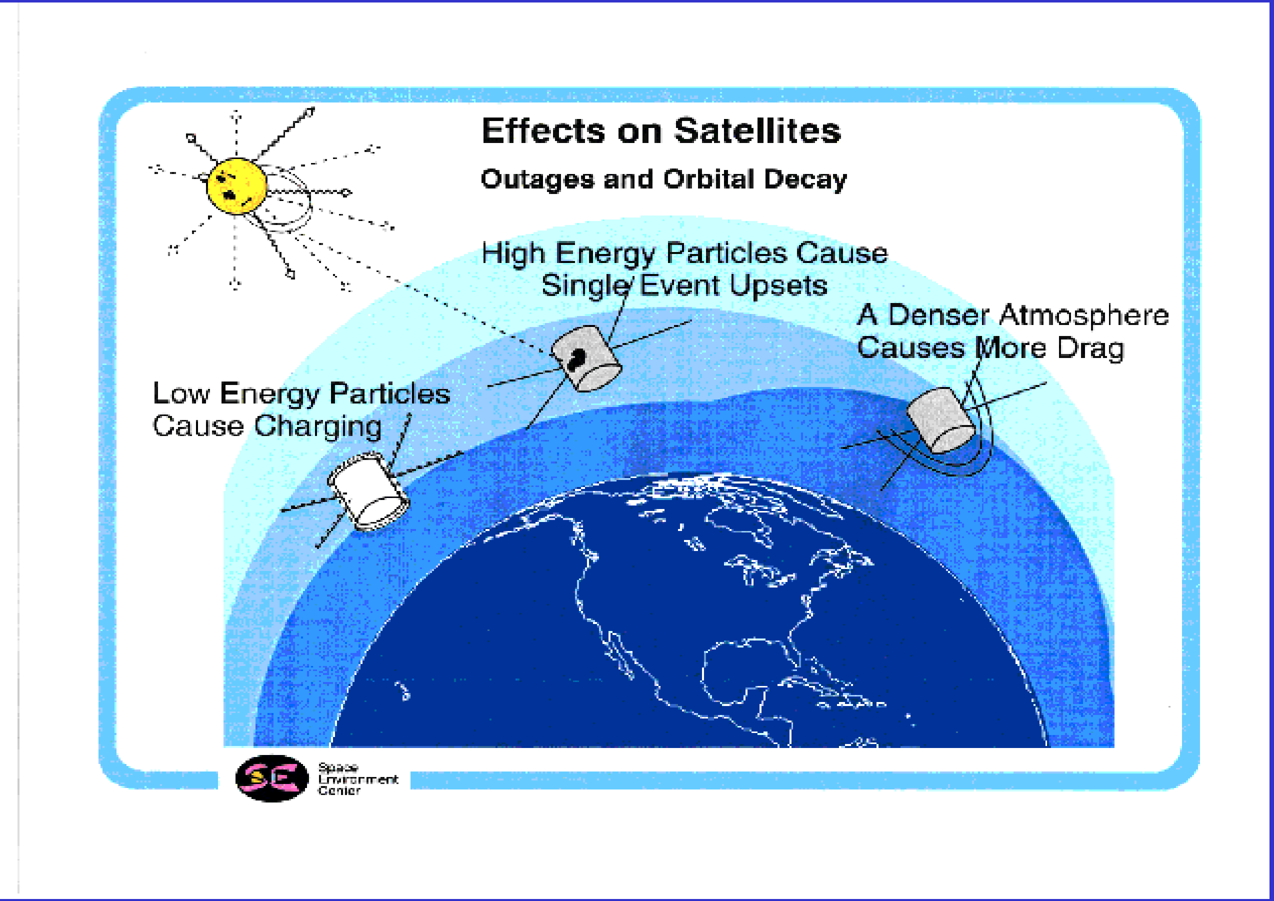
- We define space weather according to its negative impacts:

Space weather refers to temporally variable conditions in the Sun, solar wind, magnetosphere, ionosphere, and atmosphere that can damage space-borne or ground-based technological systems and may threaten human health and life.

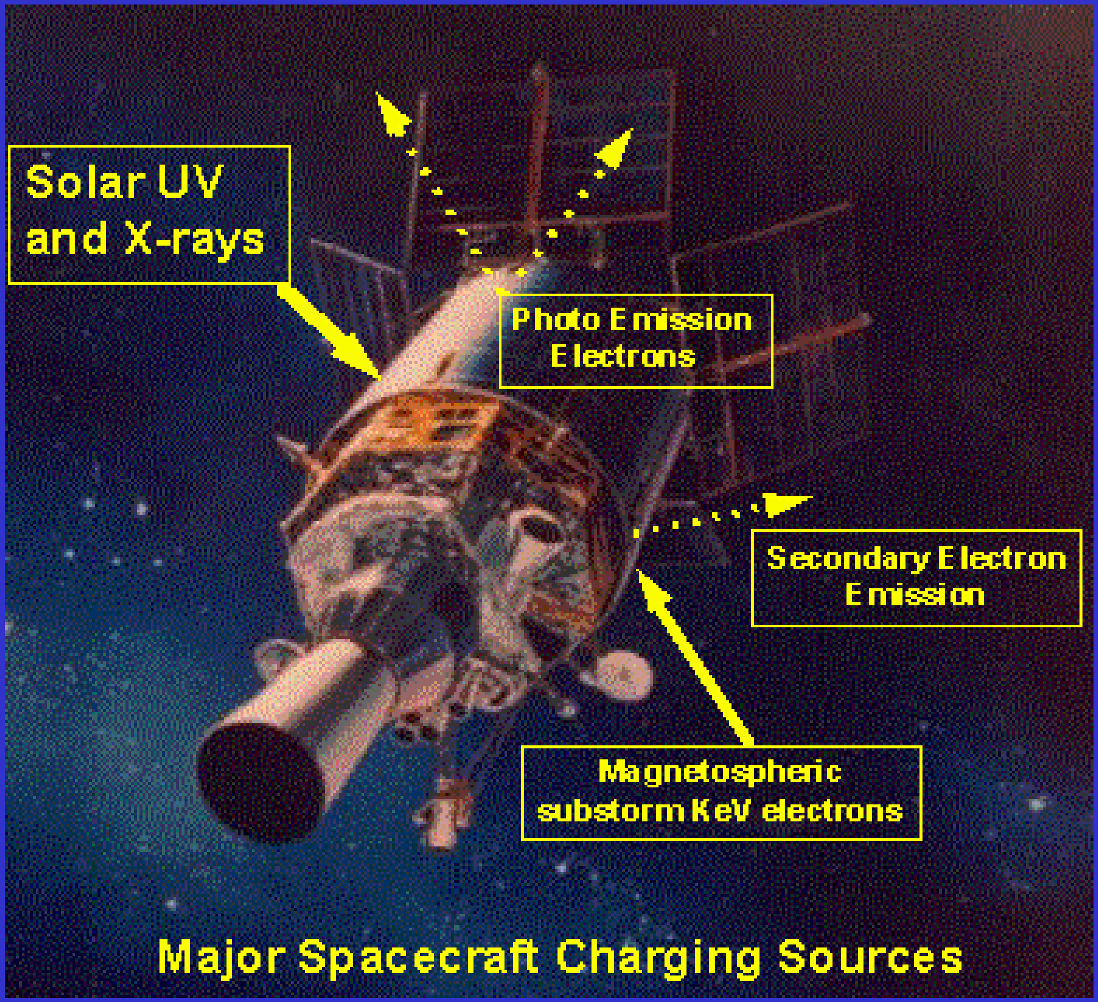
Relative importance of space weather hazards

- March 13, 1989
  - so far the worst space weather event
  - most of Quebec without power for a half-day
- Many other natural phenomena are much more serious
  - earthquakes
  - volcanic eruptions
  - hurricanes (and also smaller atmospheric storms)
  - greenhouse effect
  - ozone depletion
- Space weather is important but it may not be wise to over dramatize its effects

Space weather effects in space



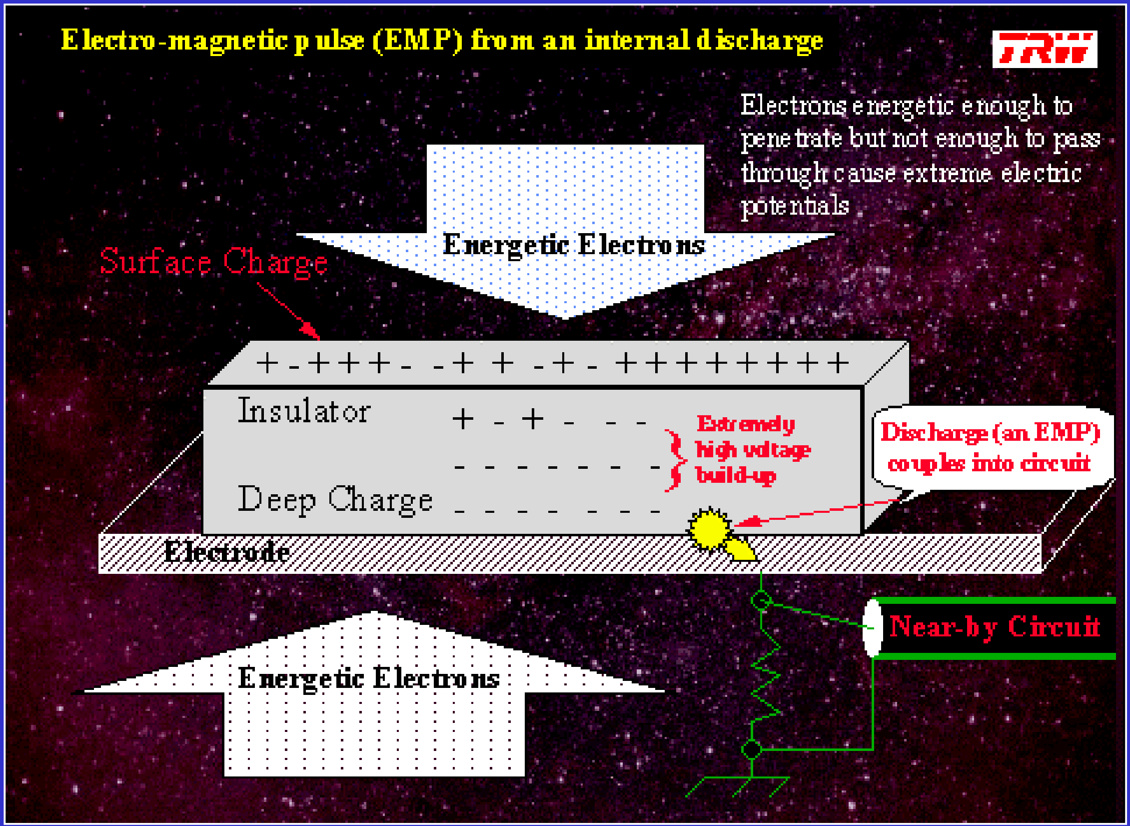
Spacecraft charging



Deep dielectric charging

- Assume 0.5 mm Al:
  - electrons > 300 keV
  - protons > 8 MeV

  penetrate through the shielding
- This is about the same shielding as provided by the space suit plus the human skin

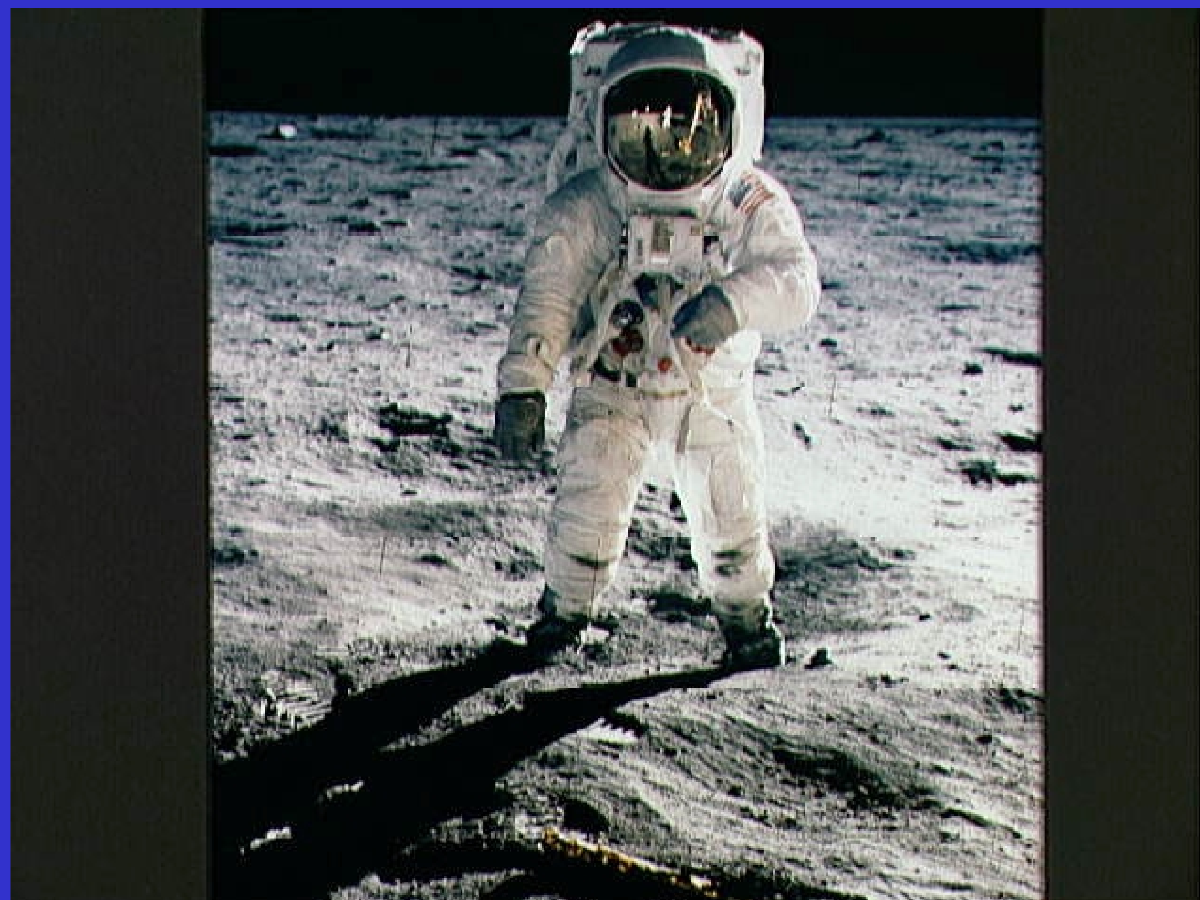


Effects on manned space-flight

n astronaut has only a
ew tens of minutes to
eek cover after a
article event on the Sun

pollo astronauts were
xtremely lucky on the
loon

his will certainly be an
sue with the manned
ghts to Mars



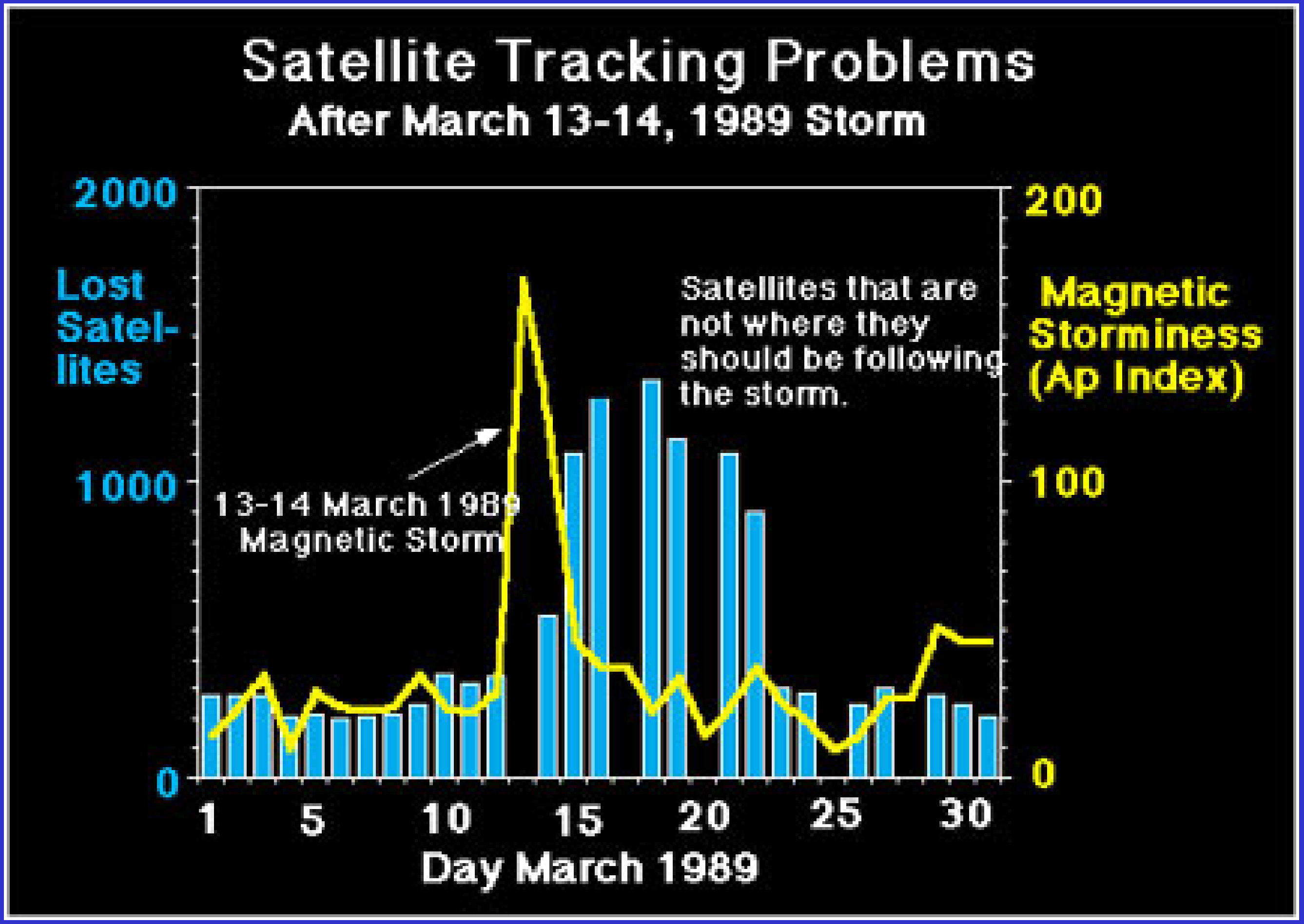
Effects on ISS

International Space Station has increased interest in the radiation effects at low Earth orbit

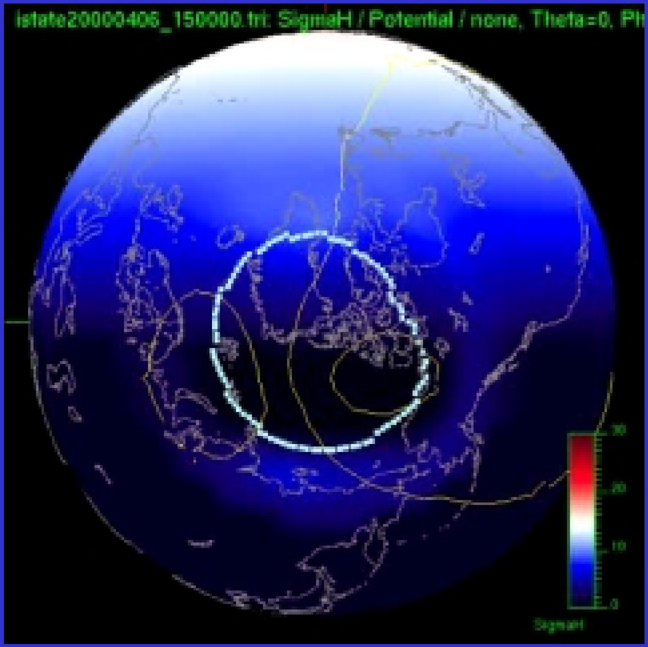
Example of drag effects: Deorbiting of MIR in 2001

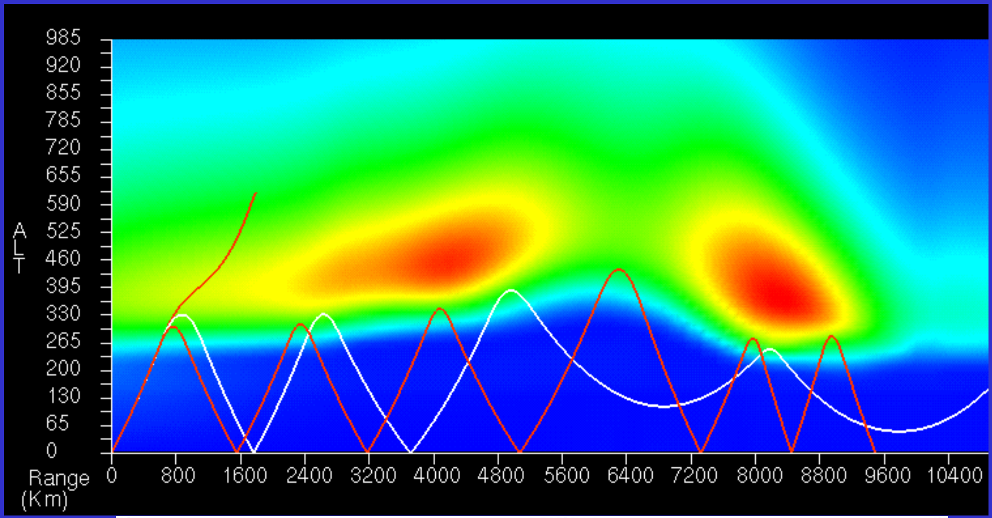
- all low altitude spacecraft experience orbital decay due to drag
- the drag varies strongly following the solar activity
  - UV heating of the upper atmosphere
- ”good” space weather slowed down the early descent of MIR for about one week

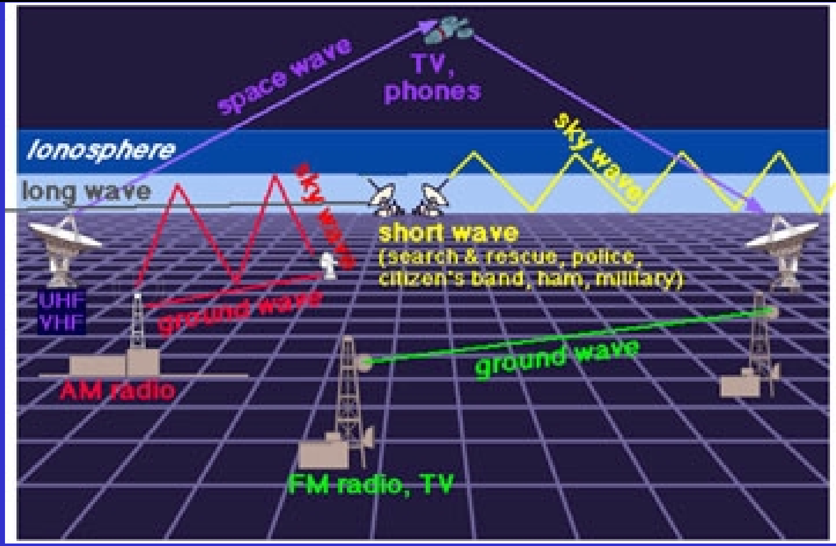
Drag effects after a great storm



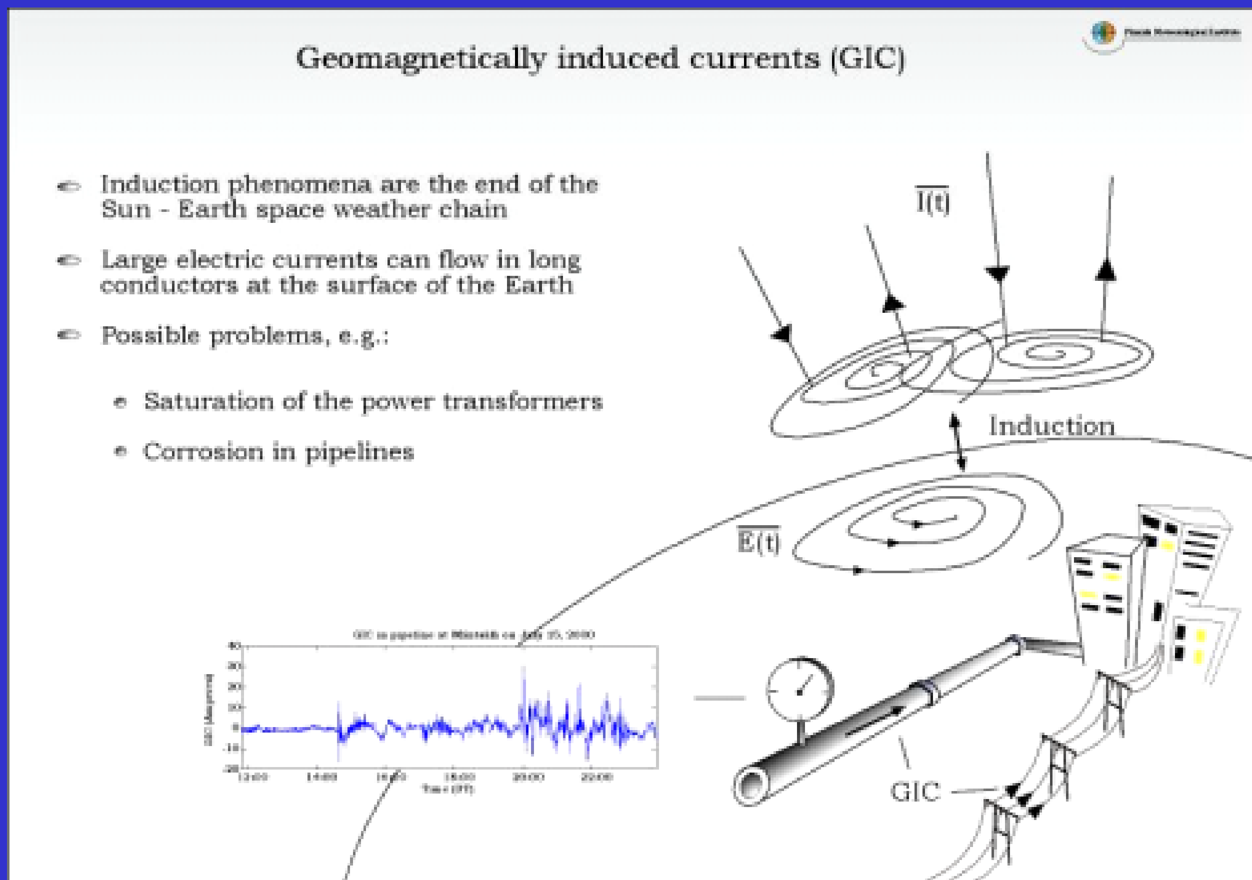
Space weather in the ionosphere



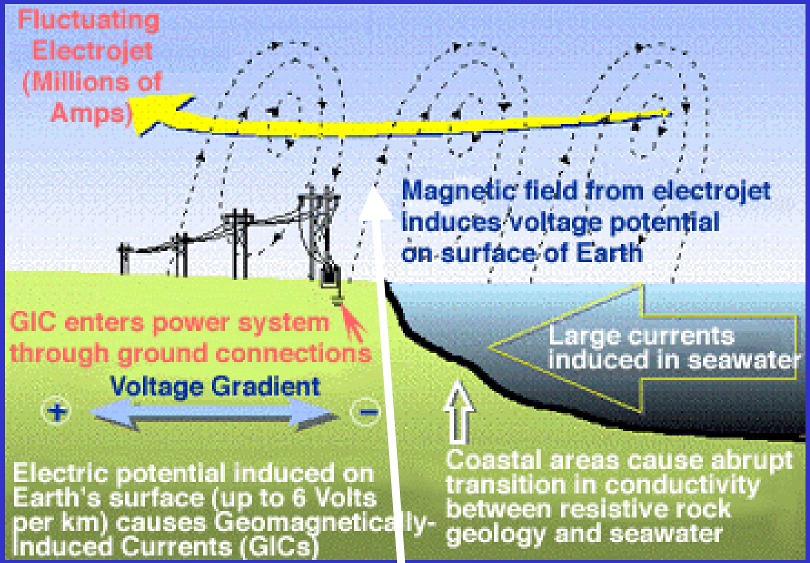




Effects on ground



Extreme induction effects

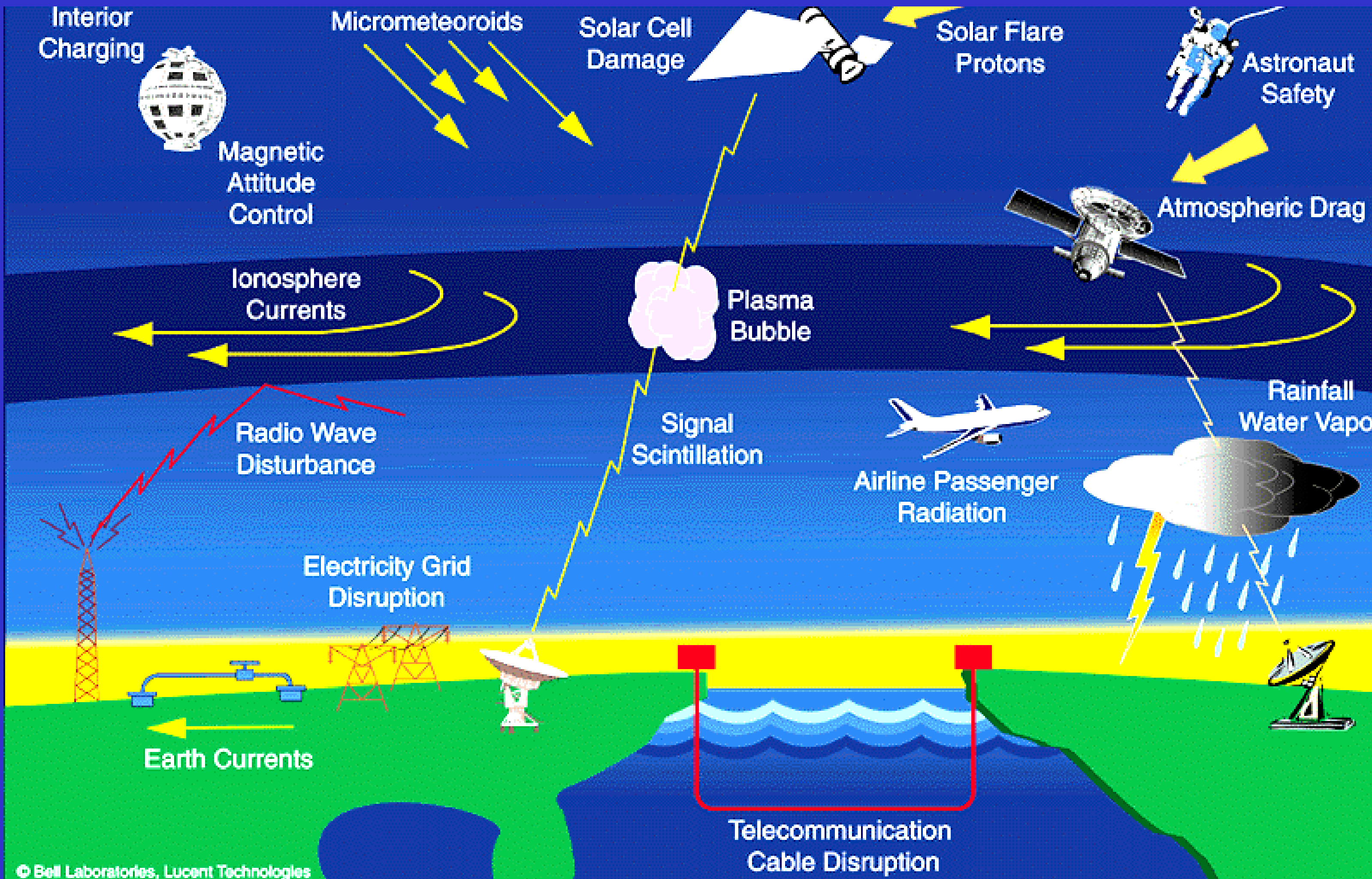


The time derivative of **B** is most essential!

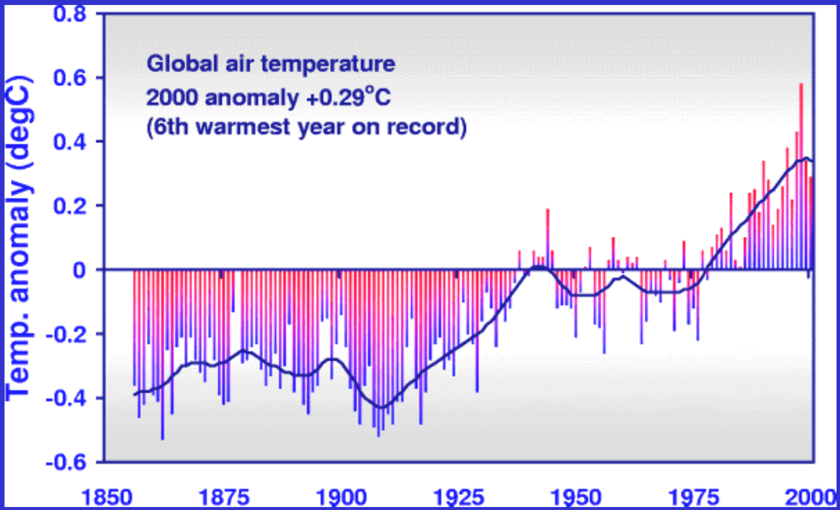
$$\partial \mathbf{B} / \partial t = -\nabla \times \mathbf{E}$$

$$\rightarrow \quad \mathbf{J} = \sigma \mathbf{E}$$

Summary of space weather effects



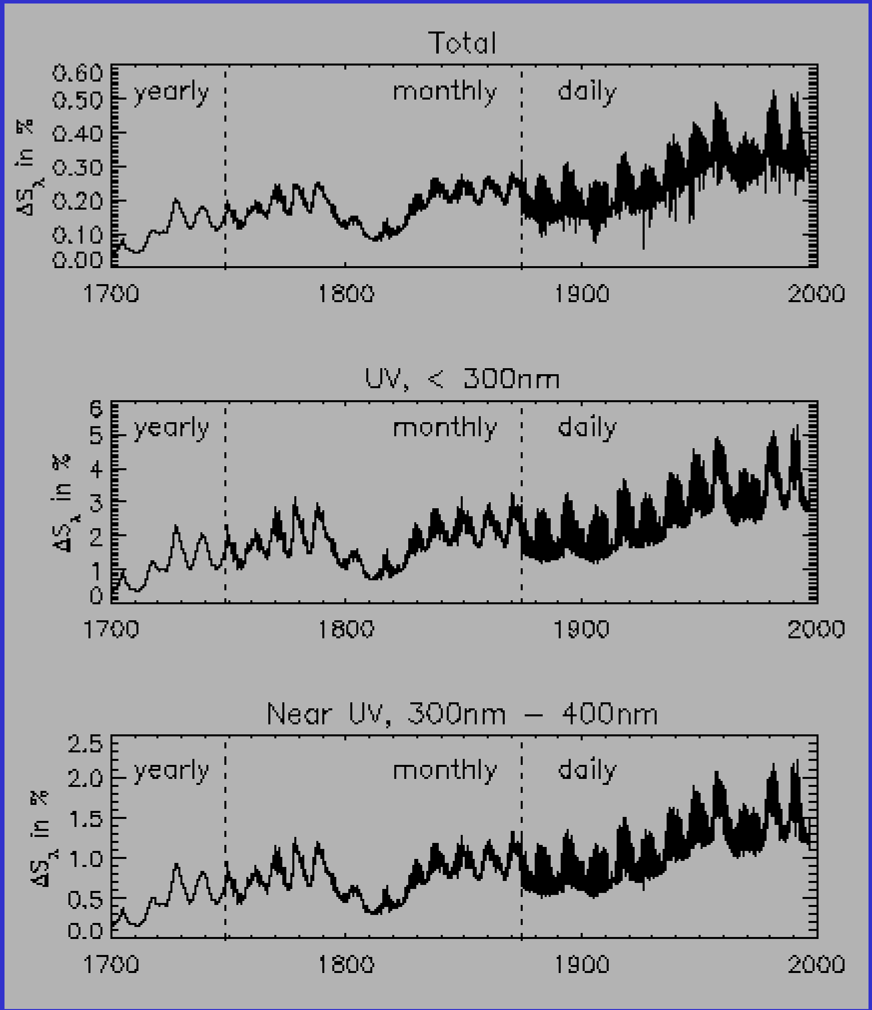
Coupling atmospheric weather and climate ?



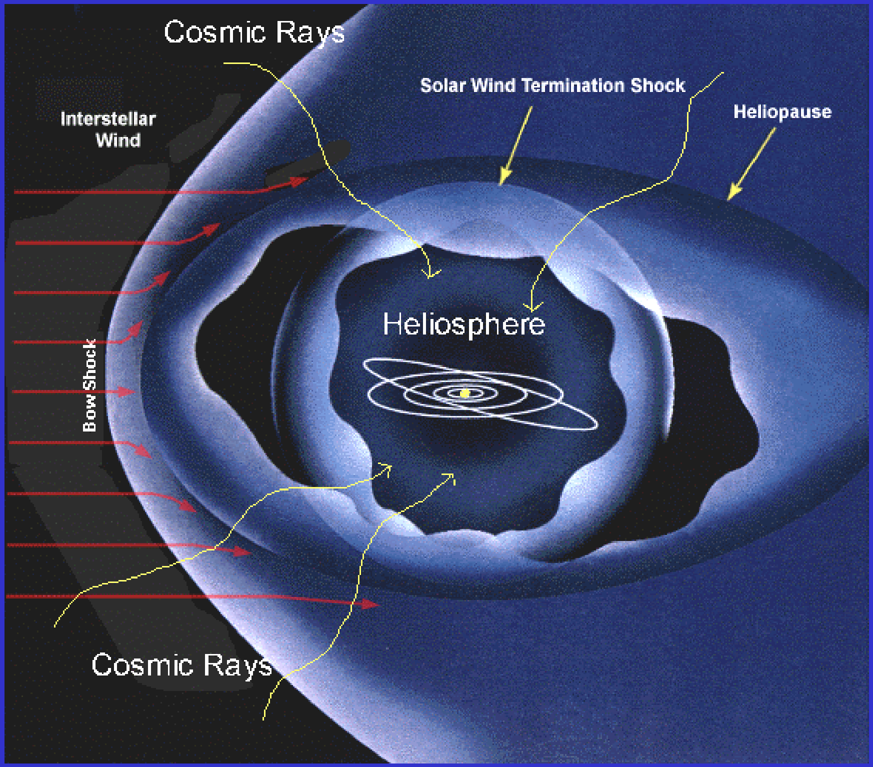
The atmosphere is warming up.

The Sun is brightening, but only very little.

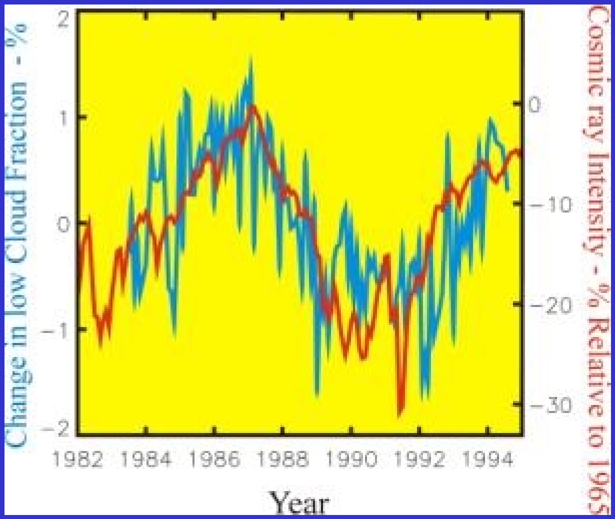
Can there be a link?



Controversy:
Cosmic rays and the climate



The changing Sun modulates the cosmic ray intensity



Correlation between CR intensities and low clouds.

Is this one way how the Sun drives the climate?

Instead of emotional arguments, we should study the physics.

Svensmark and Friis-Christensen, 1997

Toward a space weather programme

- a full-fledged space weather programme requires
  - thorough monitoring of several critical parameters
  - efficient data acquisition and processing
  - use of sophisticated models for specification and forecasting
  - fast dissemination of service products
- this requires significant resources, thus we need to
  - understand benefits of space weather services
  - find a solid customer basis
- but this cannot be done without strong emphasis in the underlying science

Space weather programmes can have different levels of ambition

- full-scale system with reliable forecasting capacity
  - based on comprehensive and continuous monitoring
  - requires a variety of predictive models
  - level of reliability depends on user’s needs
- limited warning system (e.g. traffic lights)
  - based on selected observations
  - tailored to the customer’s needs
- engineering approach
  - statistical predictions for mission design
  - specification of the environment after an event

July 15, 2002 1604 UT, SOLAR ALERT

HELIOSYNOPTICS, BOULDER, COLORADO.

SERIES OF EXCEPTIONAL FLARES EXPECTEDFROM SUPER-REGION NOAA 10,030.

REGION 10030 HAS GROWN 40% SINCE YESTERDAY. IT IS SHOWING RAPID SHEARING MOTIONS INVOLVING THE STRONG CENTRAL SUNSPOT. MULTIPLE DELTA CONFIGURATIONS ARE EVIDENT. SPOT GROWTH IS CONTINUING, INCLUDING COALESCENCE OF UMBRAE EAST OF THE CENTRAL SPOT THAT WILL MAKE THE GROUP AREA INCREASE ANOTHER 40% IN THE NEXT 24 HOURS. THESE DYNAMICS ARE COMPARABLE TO THOSE PRECEDING THE BASTILLE-DAY FLARE OF JULY 14, 2000.

THE LOCATION AT N19 AND CENTRAL MERIDIAN FAVORS A DIRECT HIT ON EARTH WITH CORONAL MASS EJECTA. THE COMPLEX MAGNETIC TOPOLOGY OF THIS REGION PROMISESHIGHLY COMPLEX INTERPLANETARY STRUCTURE THAT MAY GENERATE A TRULY MAJOR GEOMAGNETIC STORM TWO DAYS (OR LESS) AFTER THE NEXT GREAT EVENT. THE MAGNITUDE OF THE SUNSPOT GROUP PROMISES AN EXCEPTIONALLY FAST CME WITH THE EXPECTED GREAT XRAY FLARE.

THIS MAY BECOME ONE OF THE SUPER-REGIONS OF THIS SOLAR CYCLE. THE REGION IS SURROUNDED BY A CLUSTER OF GROWING CORONAL HOLES RESEMBLING THE SITUATION WITH THE GREAT FLARING REGION OF JUNE-JULY 1982. THAT REGION WAS THE STRONGEST IN THE NORTHERN SOLAR HEMISPHERE FOR SOLAR CYCLE 21. LIKE THE PRESENT REGION, IT ALSO LAY ADJACENT TO THE LONG POLARITY BOUNDARY THAT LIES UNDER THE HELIOSPHERIC CURRENT SHEET. TODAY'S REGION IS POSITIONED NEAR THE LONGEST FILAMENT OF THE CYCLE, EXTENDING DIAGONALLY ACROSS THE SOLAR DISK FROM THE POLAR CROWN LATITUDE TO THE EQUATOR.

What needs to be mon

- the Sun (today by SOHO)
  - CMEs, flares, active reg
    particles
- upstream sola
  - magnet
- inn the GOES series S/C
  O)
  - particles, maybe ENA
- g termination of
  -
  - io pheric currents and dynamics
  - various storm indices (AE, Dst, Kp, Ap, etc.)

Note, however, that scientific instruments or spacecraft are not always the best for routine monitoring

- no long-term commitments
- sometimes unnecessarily sophisticated
- limited coverage
- no operative-type of data streams

Where do European space weather efforts stand today?

- Good but thin (politically weak?) STP community
  - in 1984 the STP community was in the lead of defining the Horizon 2000 Cornerstone programme of ESA
  - today we have only Solar Orbiter on the (troubled) ESA science program agenda and no single mission to the magnetosphere
- Europe has one real flag-ship: SOHO
- But the future space weather is uncertain
  - ESA SCI is passive concerning space weather
  - ESA TOS is trying to get something running
    - but they must do it from technology and application viewpoint
    - and the resources are very limited

Recent ESA activities

- Two competing consortia (led by RAL and Alcatel) were funded to investigate requirements for European space weather system 2000 – 2001
  - a full-scale space segment would cost about 1000 M€
    - solar, solar wind, and inner magnetosphere monitors
  - benefits were estimated to that same level in 5 – 10 years
    - but how to measure immaterial benefits?
  - difficult to find paying customers in Europe
- A pilot project is planned to start this year

But please keep in mind that 1000 M€
is only about 3 € per ESA member state citizen

This is Europe

I have a magnetometer

I have two!

Space debris is part of space weather

No, it's not!

Hα … ed with better time resolution

I can predi… the Dst …

… ar-side of the Sun

You did not mention …

Fascinating,
but do we want to
continue this way??

… companies are very interested!

Do not forget the riom…ters

But they won't pay

We can make radio maps of the Sun

What should WE do?

- Space weather activities in Europe need
  - a leadership
    - can ESA take this?
    - should it be handled to EU?
    - or what?
  - continued strong emphasis on solar-terrestrial physics
- Solar-terrestrial physics in Europe needs
  - a major vision for the future
    - it must be big and scientifically challenging
  - space weather can provide one

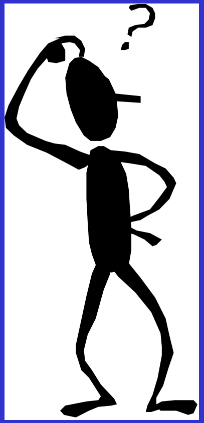
THINK BIG!

Space weather is not only engineering and applications

- Three major physical themes
  - What happens in the Sun?
  - What determines geoefficiency?
  - How does the magnetosphere process space weather?
- All this means that we have to look for understanding of solar-terrestrial connections in
  - all time-scales
  - all spatial scales
  - quantitative details

In STP we have moved from exploration to physics, now we need to move from cartoons to quantitative science

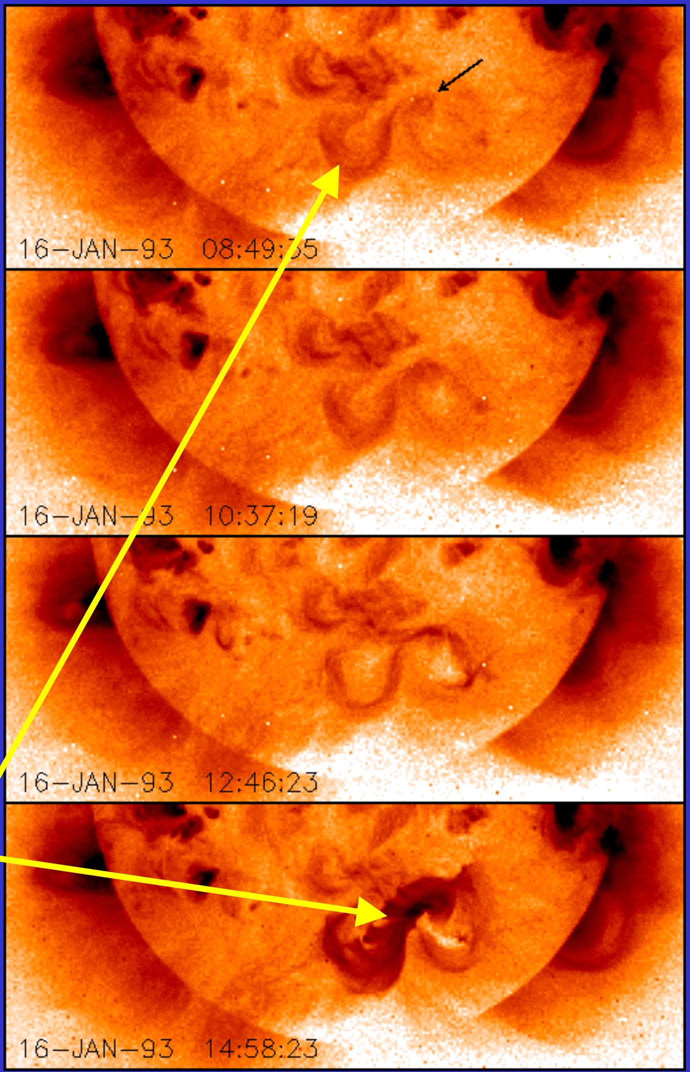
Big questions



- when and where on the Sun
- what happens on the way
- what determines the geoeffectivity
- energy and plasma transfer through the magnetopause
- rapid particle acceleration
- coupling to the ionosphere
- coupling to atmospheric weather and climate
- extreme induction effects

When and where on the Sun ?

- We cannot reliably forecast
  - CME release
  - whether or not it is associated with a flare
  - whether or not it is associated with a SPE

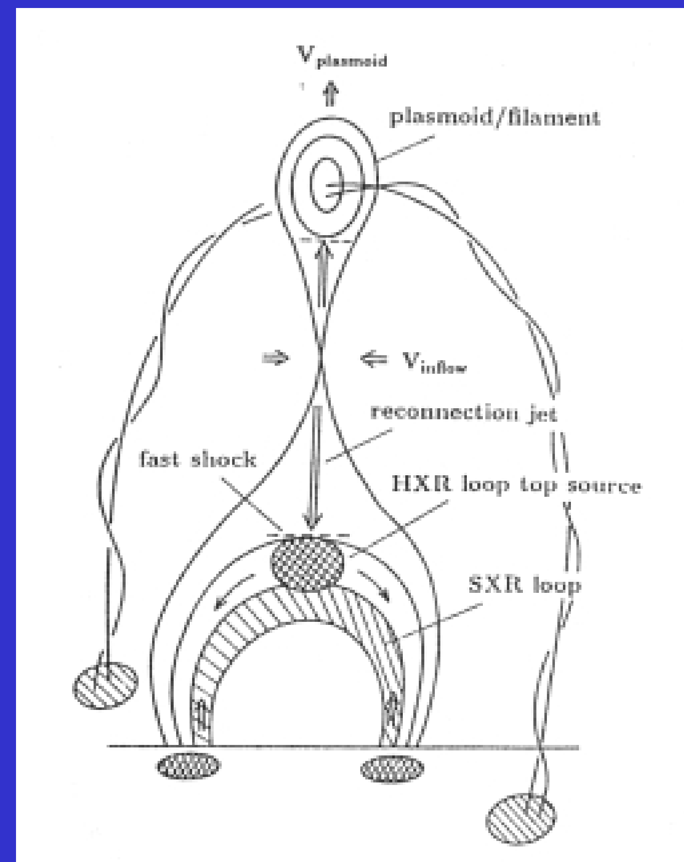


A sigmoid often precedes a CME but it is neither a sufficient nor a necessary condition for CME!

Flare – CME relationship ?

Eruptive prominence → CME

Flare in UV   Flare X-ray sites



But only some 40% of CMEs have a clear flare-association

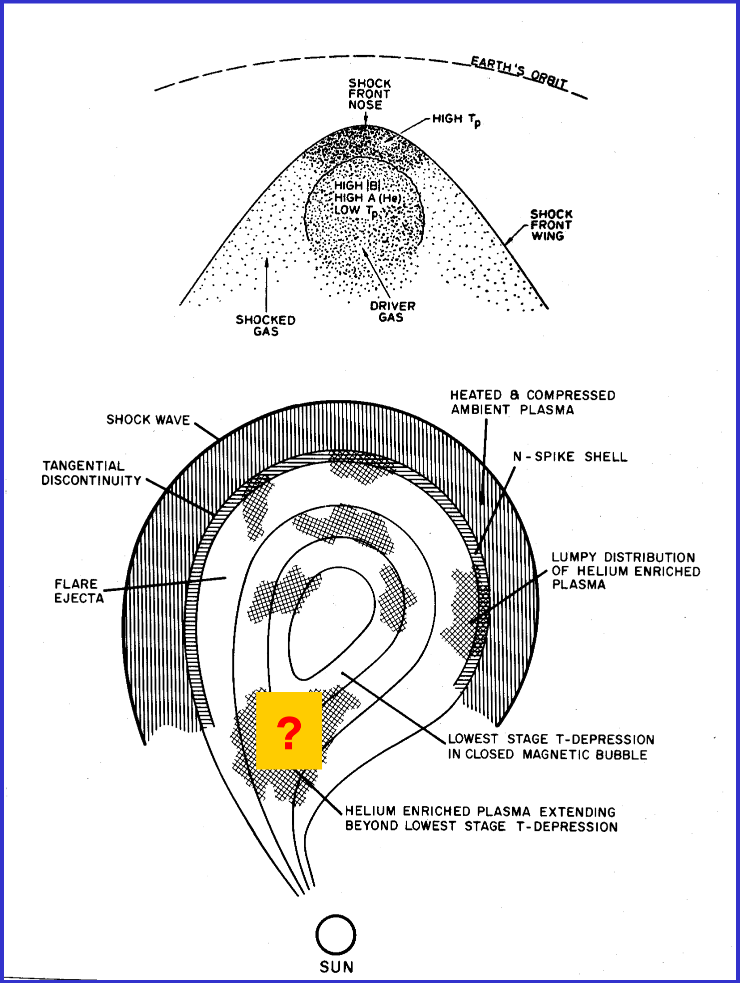
Shibata's plasmoid-driven flare model

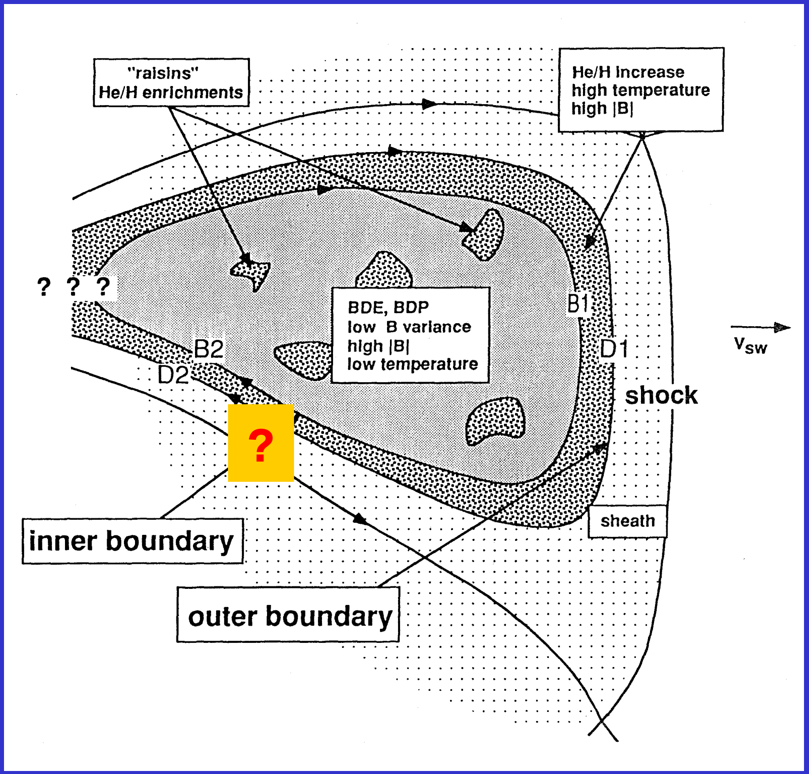
What happens between the Sun and the Earth?

- We know that
  - solar energetic particles are accelerated both
    - close to the Sun (flares)
    - at shocks associated with CMEs
  - slow CMEs are accelerated and fast CMEs decelerated close to the ambient solar wind flow
  - structure of ICMEs change before the Earth

    (ICME = interplanetary manifestation of a CME)
  - a faster CME can catch a preceding one (cannibalism)
- but this is all still very qualitative and a rich playground for space cartoonists

We cannot follow the evolution of the ICME until near the Earth (today at L1)

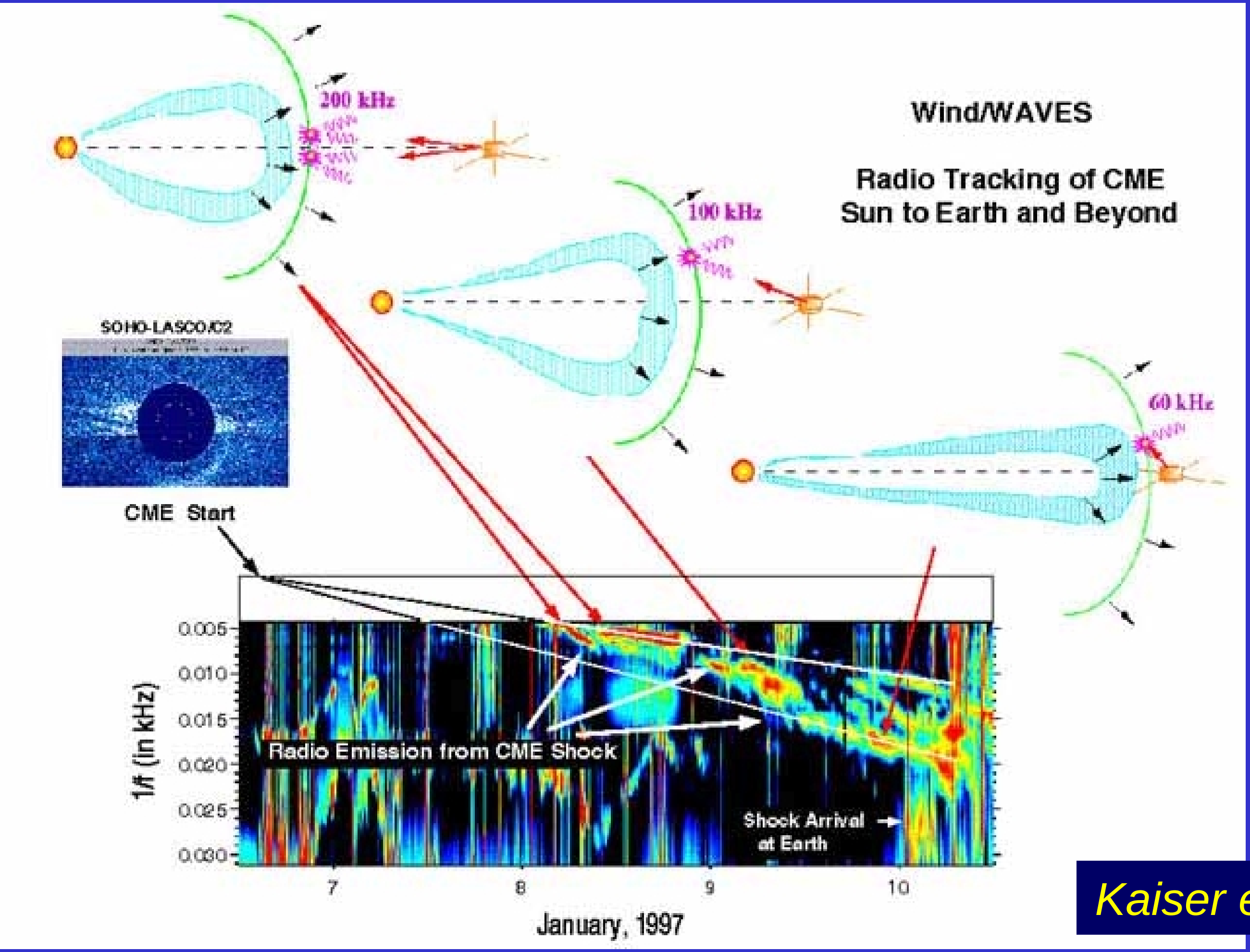




Borrini et al., 1982

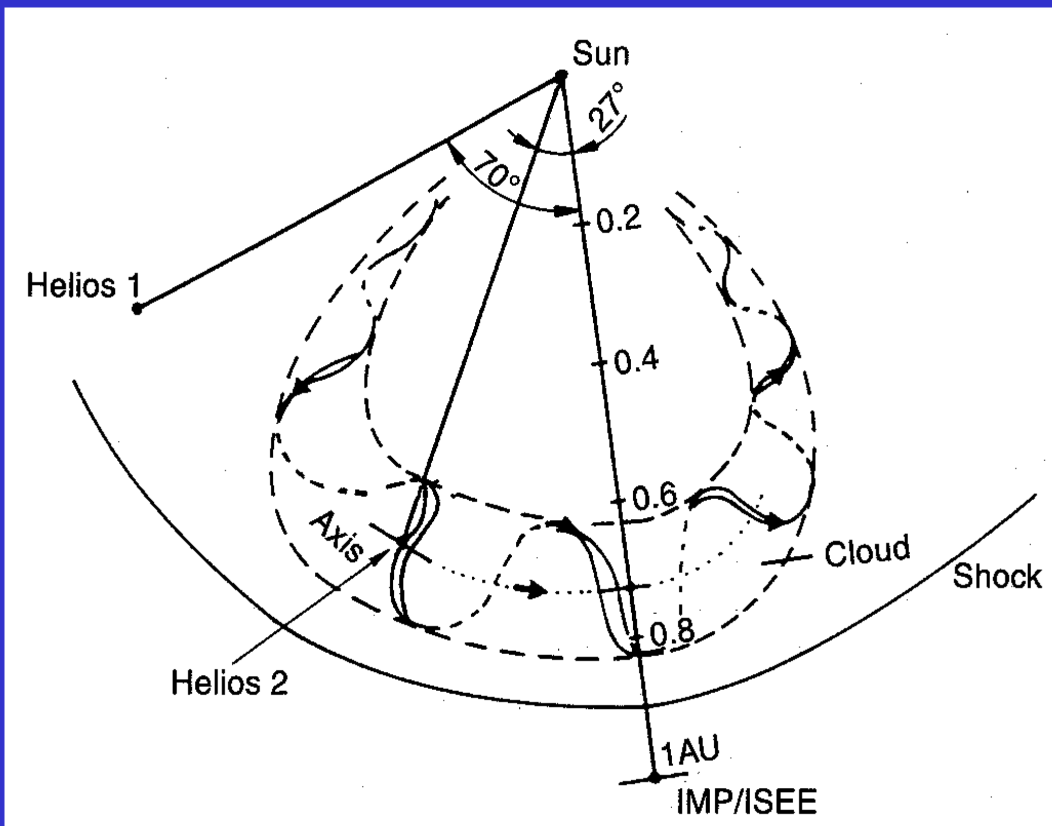
Bame et al., 1979

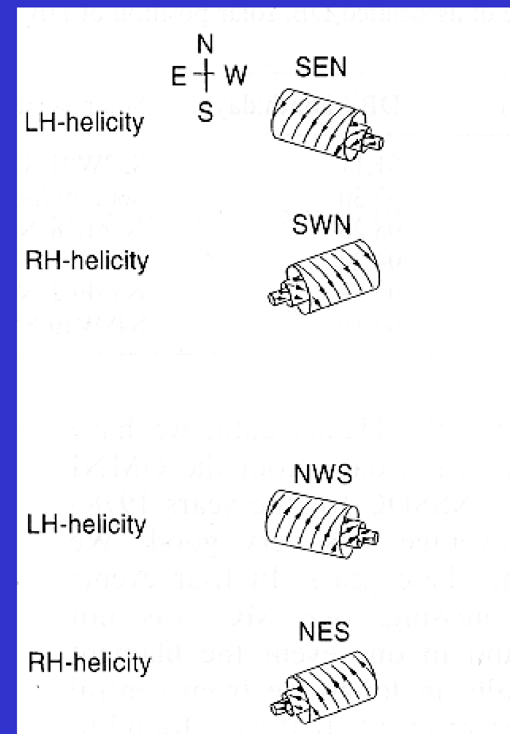
Radio emissions may tell us more than we know



Kaiser et al., 1998

The magnetic field structure of the magnetic cloud is critical





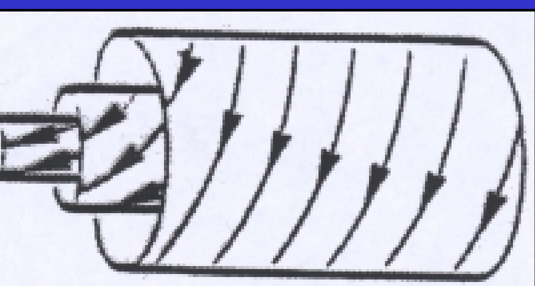
Bothmer & Schwenn, 1998

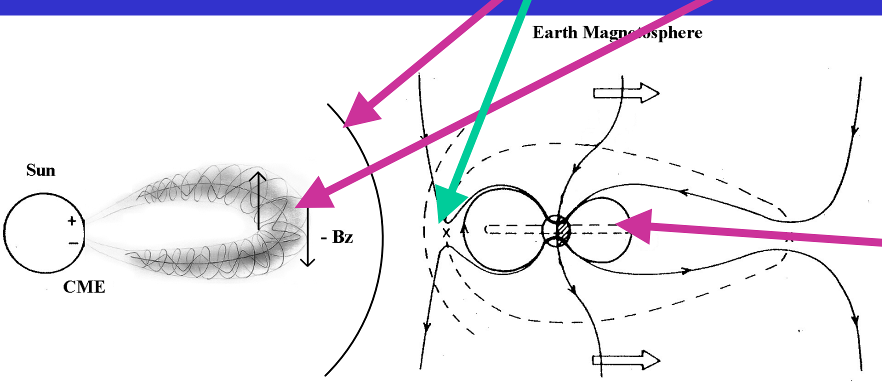
All 4 types are observed and correspond well to their filament sources but their geoefficiencies are dramatically different

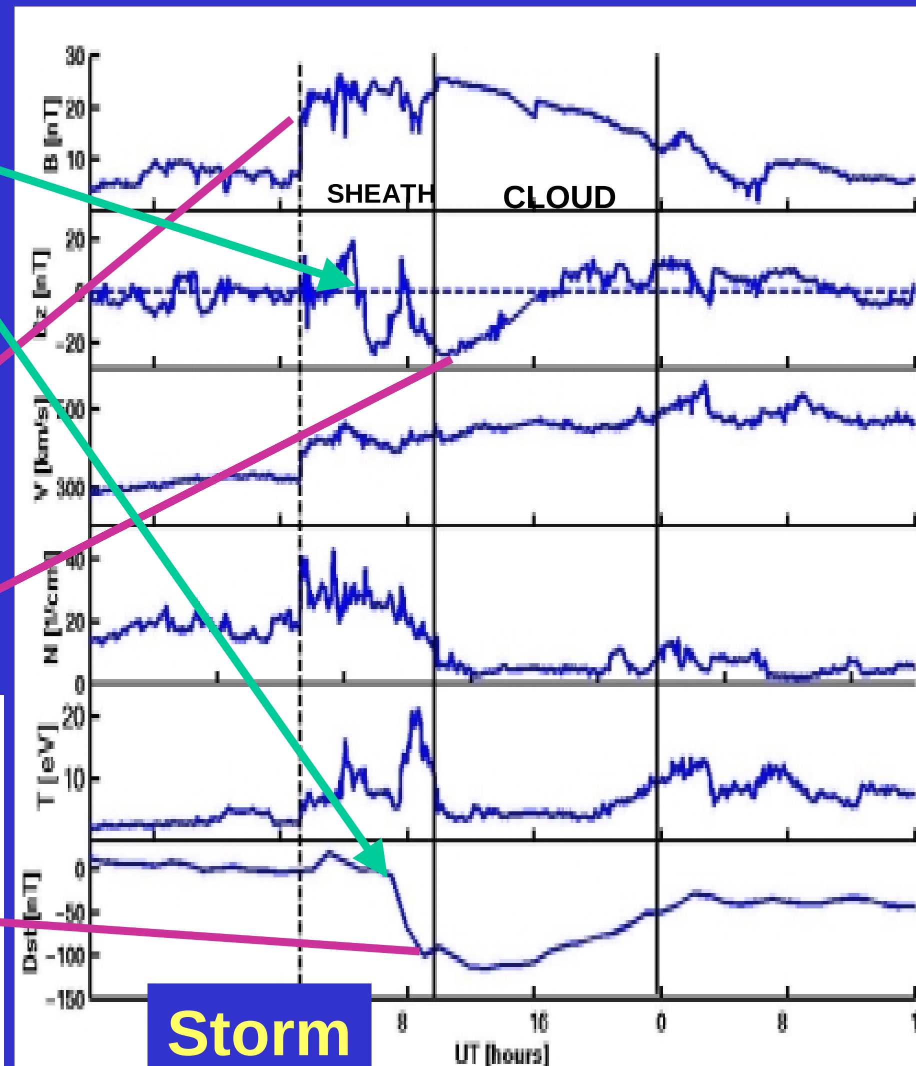
Geoefficiency of magnetic clouds

$B_Z < 0$ is essential **!**

flux rope structure







Shock

Cloud

Storm

Forecasting is difficult

Essen, Germany, April 7, 2000 at 01:00 UT

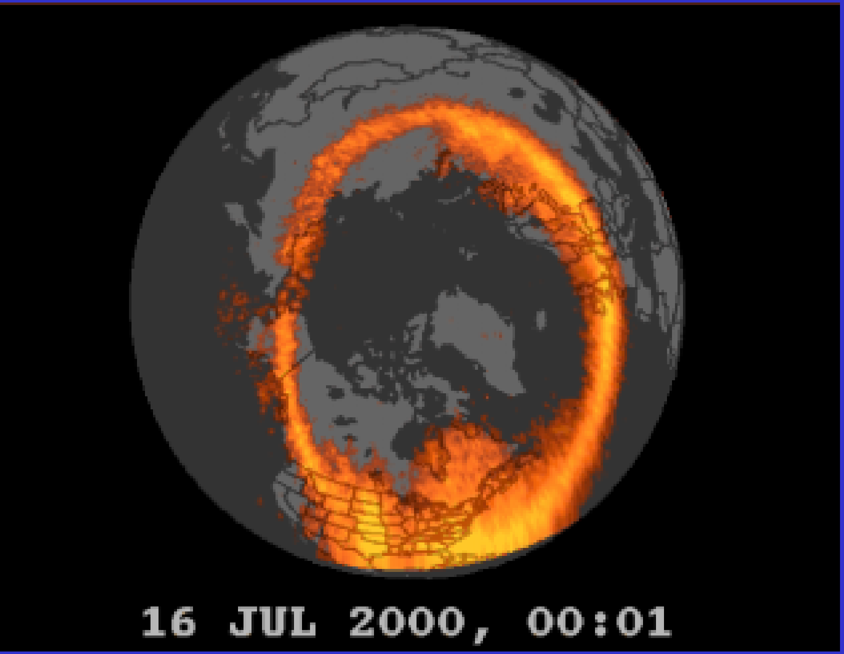
The April 4 – 7, 2000 events

C 9.8 flare (near western limb):	April 4, 16:37
Arrival of energetic particles at 1 AU:	none
Shock at 1 AU:	April 6, 16:02
Travel time:	47.5 hours
Initial CME speed:	980 km/s
Average travel speed:	880 km/s
Shock speed at 1 AU:	810 km/s
Kp max:	8
Dst min:	– 310 nT

USAF/NOAA forecast at 22 UT on April 5 for April 6:
Active: 30 – 35 %; Minor storm: 35 – 40 %; Major-severe storm: 6 – 11 %

The second-biggest storm of the present solar cycle!

Forecasting is difficult



The "Bastille-day 2000" events

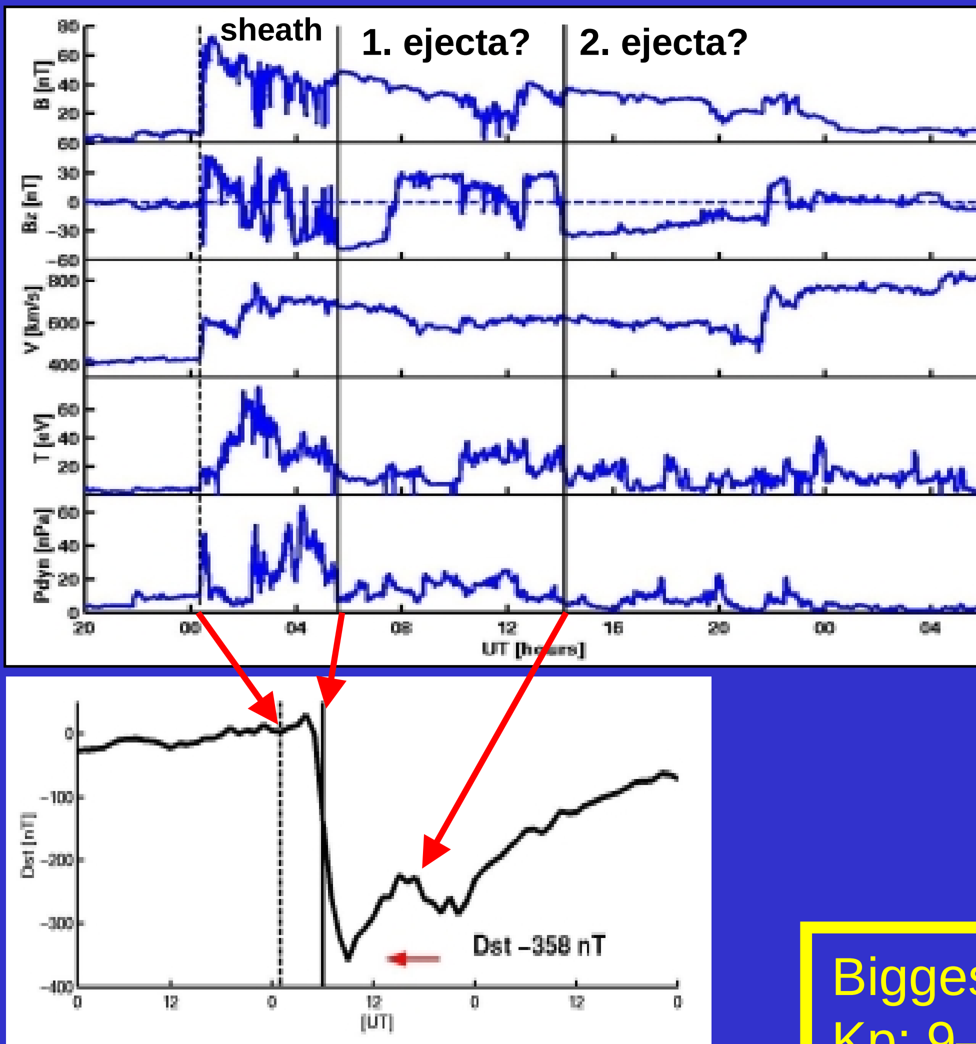
X 5.7 flare:	July 14, 10:24
Arrival of energetic particles at 1 AU:	10:38
Shock at 1 AU:	July 15, 14:29
Travel time:	28 hours
Initial CME speed:	>1775 km/s
Average travel speed:	1520 km/s
Shock speed at 1 AU:	900 km/s
Kp max:	9
Dst min:	– 300 nT

A classical case for the **Big Flare Syndrome:**

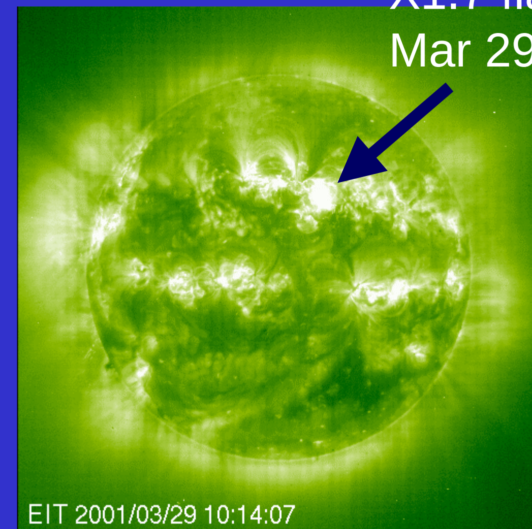
- a really big flare, right in the middle of the solar disk,
- a very fast halo CME,
- a fast shock, right in time, well-developed magnetic cloud

$\rightarrow$ a very strong geomagnetic storm.

Complex event Mar 28 – Apr 1, 2001



X1.7 flare
Mar 29, 10:15



two halo CMEs from the Sun

- Mar 28 13:00 UT
- Mar 29 10:30 UT
- 21.5 hours interval,
- speed difference 350 km/s

travel time 2.5 days

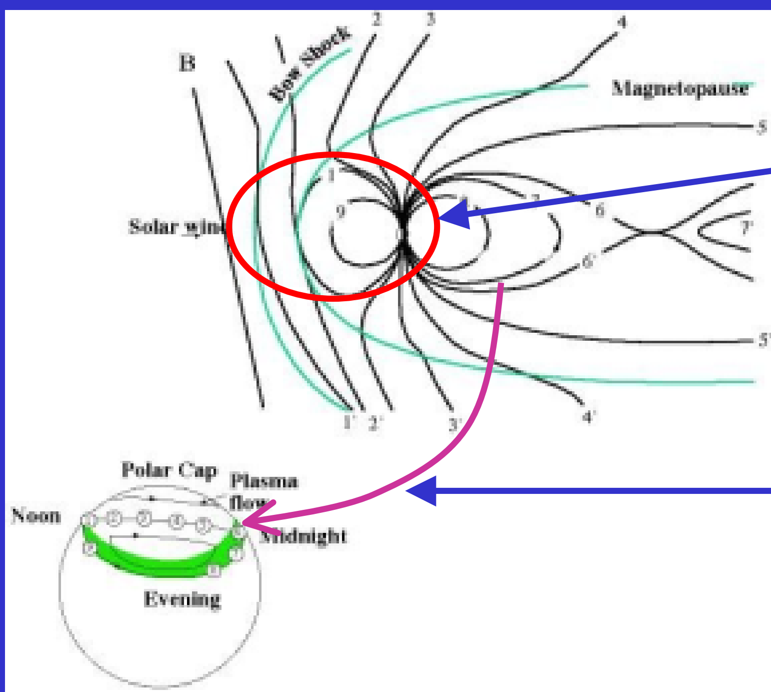
Biggest storm of the present cycle
Kp: 9– Dst: –358 nT

Forecasting geoefficiency is difficult, even after CME detection, because

1. we cannot reliably predict the transfer time
2. we cannot forecast the flux rope structure
    - if there is any
        - only one third of CMEs develop to flux ropes
3. using in situ observations at 1 AU (L1) we have less than one hour before the storm
    - but even then we cannot be sure how the magnetosphere will react!

Energy and plasma transfer through the magnetopause

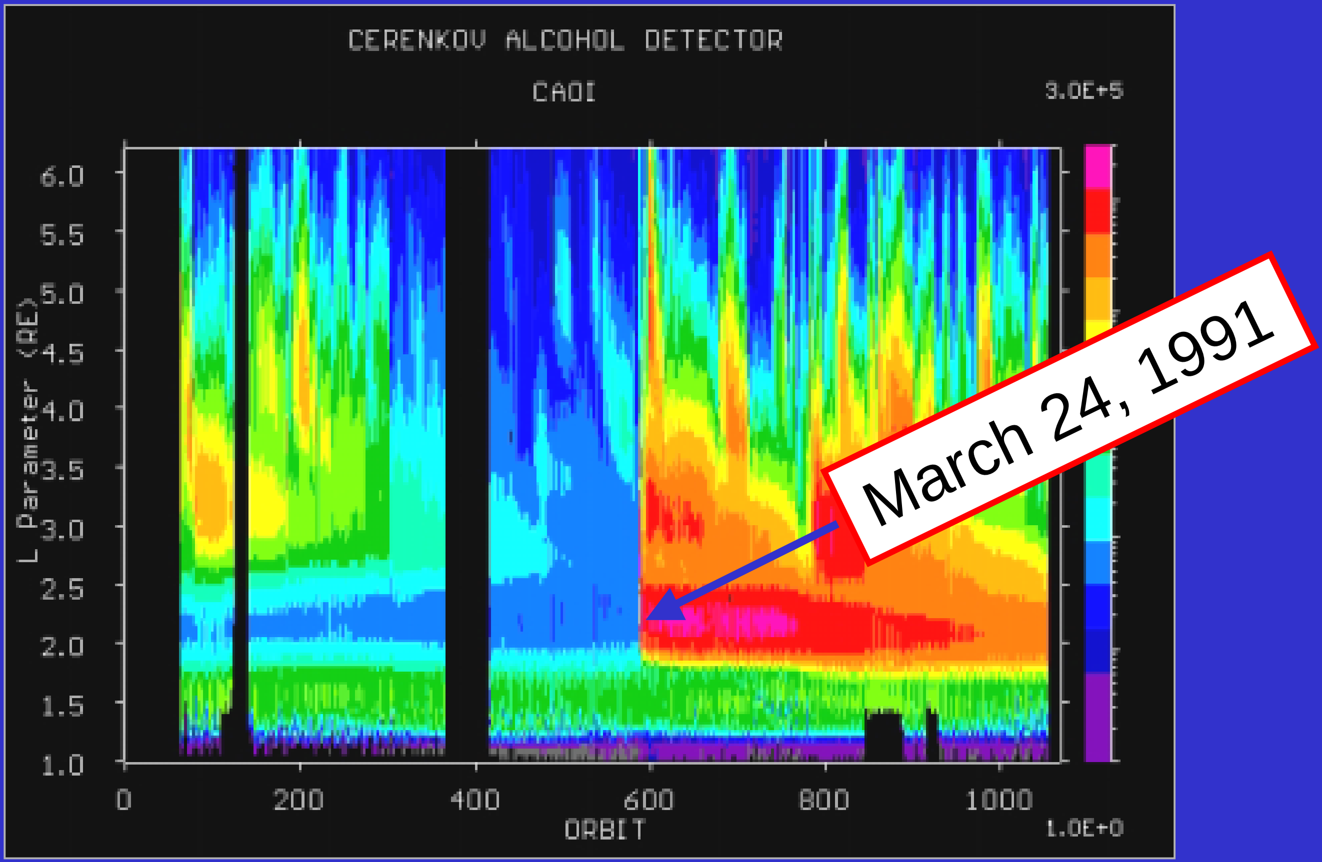
- We know the basics but not the details (much cartooning, less detailed physics)



This is where Cluster fits into the space weather scene, but it is not a space weather satellite

Also coupling to the ionosphere is important

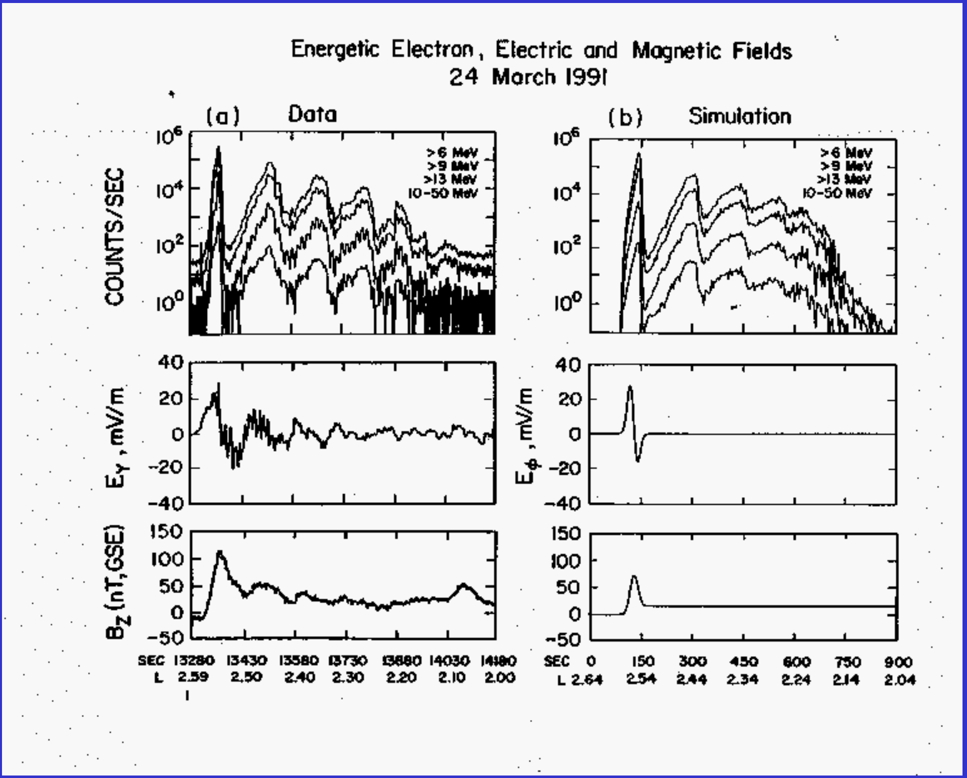
Work of the magnetosphere: Appearance of killer electrons



CRRES observations of electrons > 5 MeV;
August 1990 – October 1991.

Storm-time acceleration

- modelling of the March 1991 storm (Li et al., 1993)
- rapid compression of the magnetosphere
  - $\partial \mathbf{B}/\partial t = -\nabla \times \mathbf{E}$
  - acceleration in MeV–range
  - rapid (~1 min)
  - needs an energetic seed population



In fact, Solar-Terrestrial Physics

couples the grand physics

to everyday life of the 21st century !

THROUGH THE SCIENCE OF SPACE WEATHER