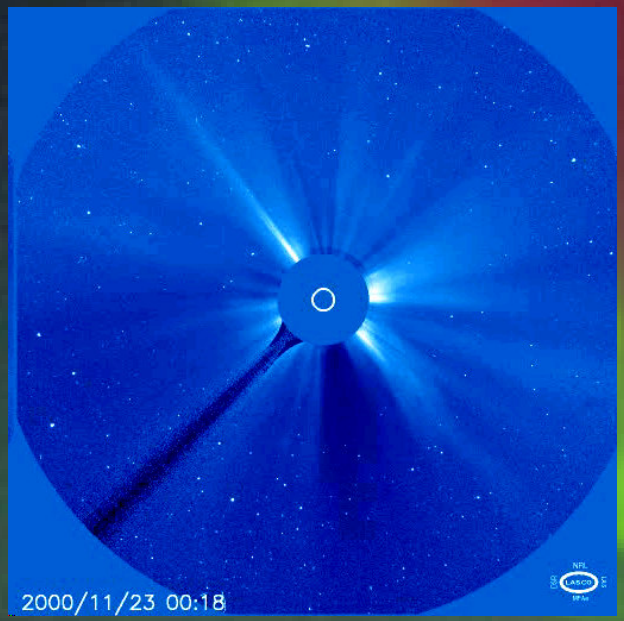
Space Weather –
A New Science Discipline

Presentation at
„Culture and Astronomy"
Bibliotheca Alexandrina
Alexandria, Egypt
March 26, 2006

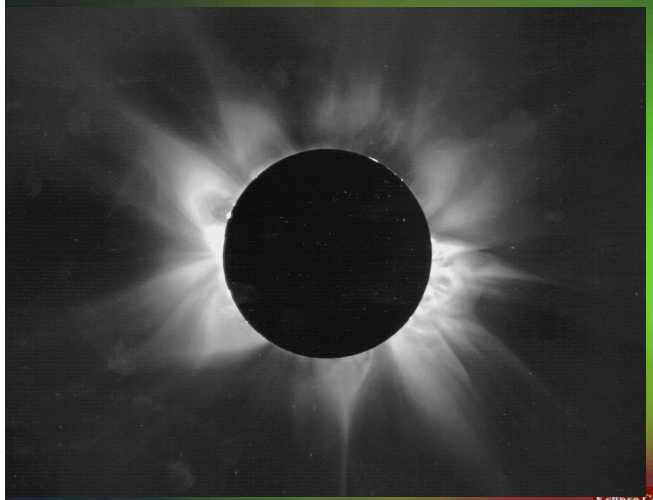


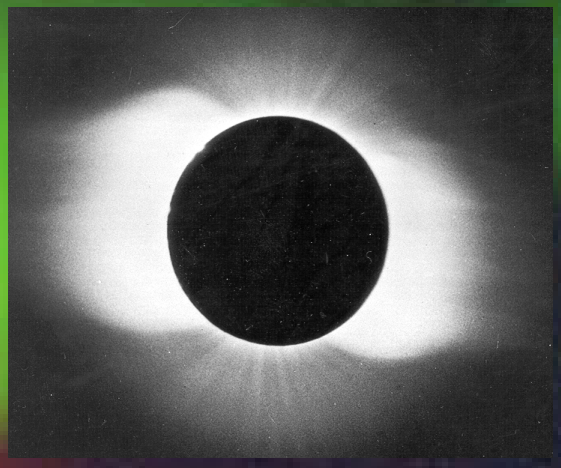
Rainer Schwenn
Max-Planck-Institut für Sonnensystemforschung
Lindau, Germany

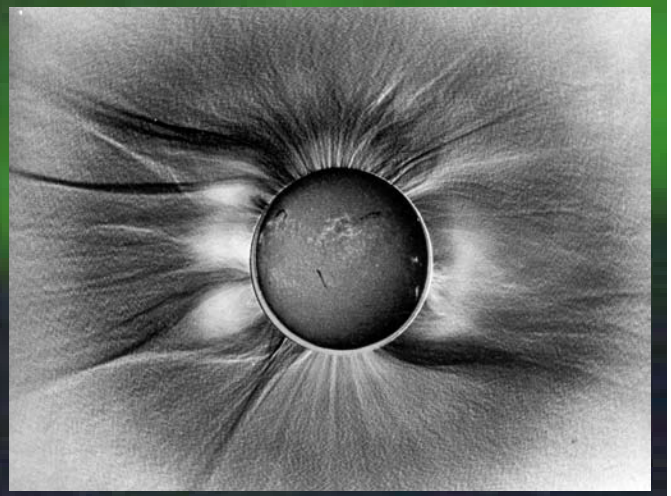
Ägypten2006

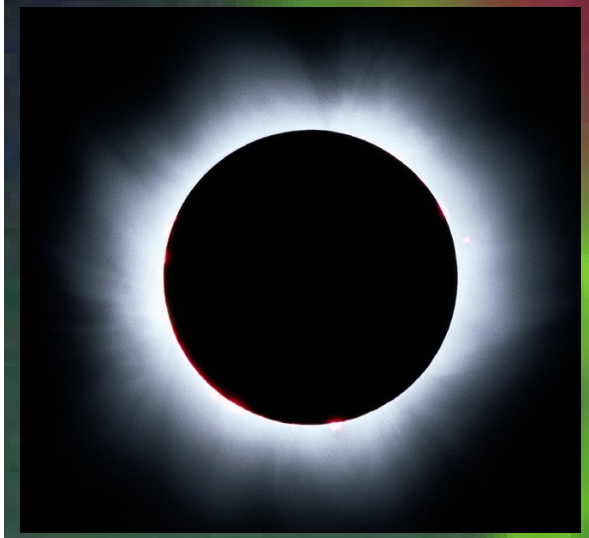
The miracle of eclipses

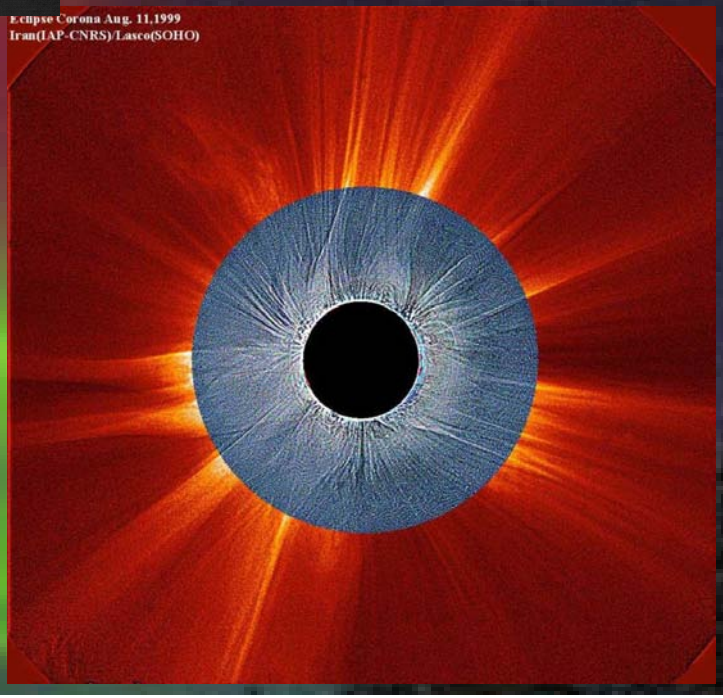
Mankind is stunned at the rare occasions of eclipses

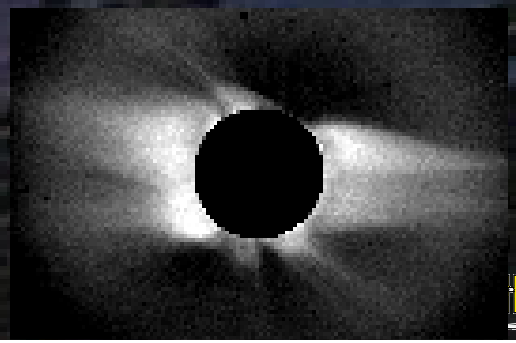












Coronal mass ejections (CMEs)

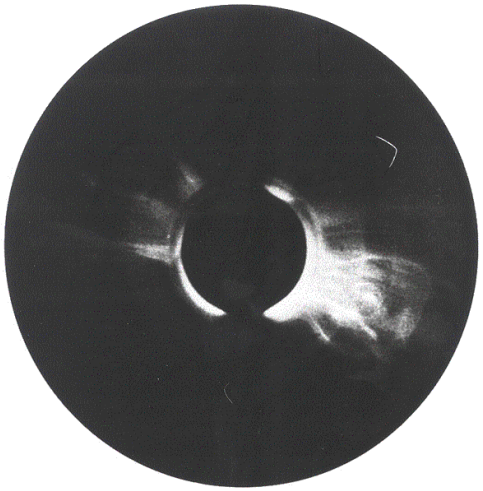


Fig. 1. Coronal photograph taken 0954 UT 10 June 1973 (11 min after Fig. 2 of MacQueen *et al.*, 1974) by HAO White Light Coronagraph Experiment on first NASA Skylab mission. Diameter of occulting disk is about 1.5 $R_\odot$. Transient feature at lower right (in northeast quadrant) was observed for about 30 min and moved outward with an apparent velocity of 450 km/s

The first CME ever seen (?)

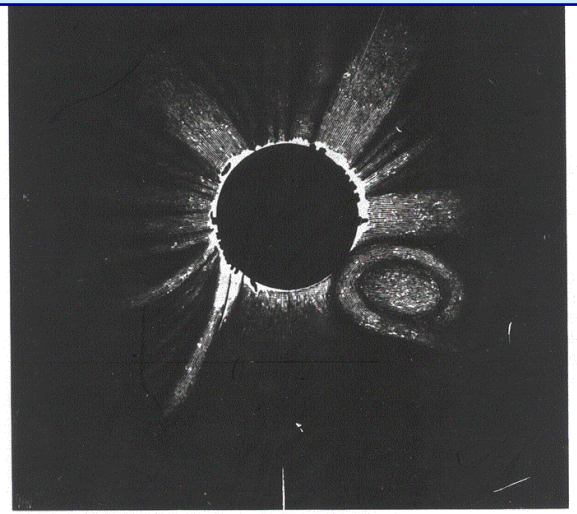


Fig. 2. Drawing of the corona as it appeared to Tempel at Torreblanca, Spain during the total solar eclipse of 18 July 1860 (Ranyard, 1879). South is at bottom, west at right

Eclipses let the Sun appear quiet. Wrong! It is highly dynamic, with huge explosions:

CMEs and flares.

Skylab people claimed to have discovered CMEs. They are not right...

Unfortunately, this observation at the eclipse of 1860 was not taken seriously.

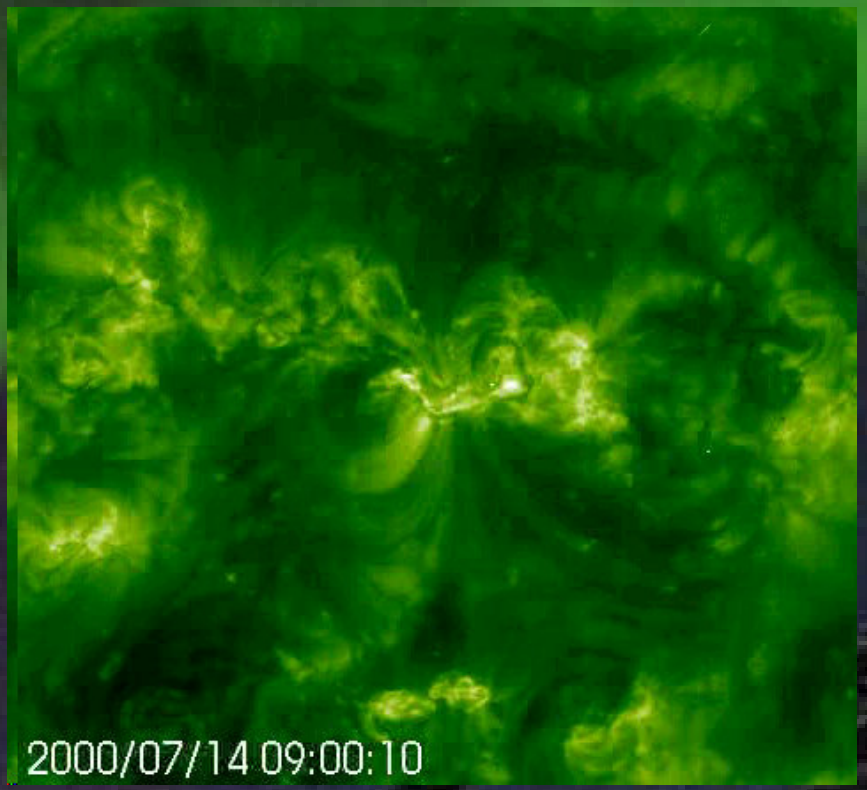
Ägypten2006

MPS

Flares: gigantic explosions in the Sun's atmosphere

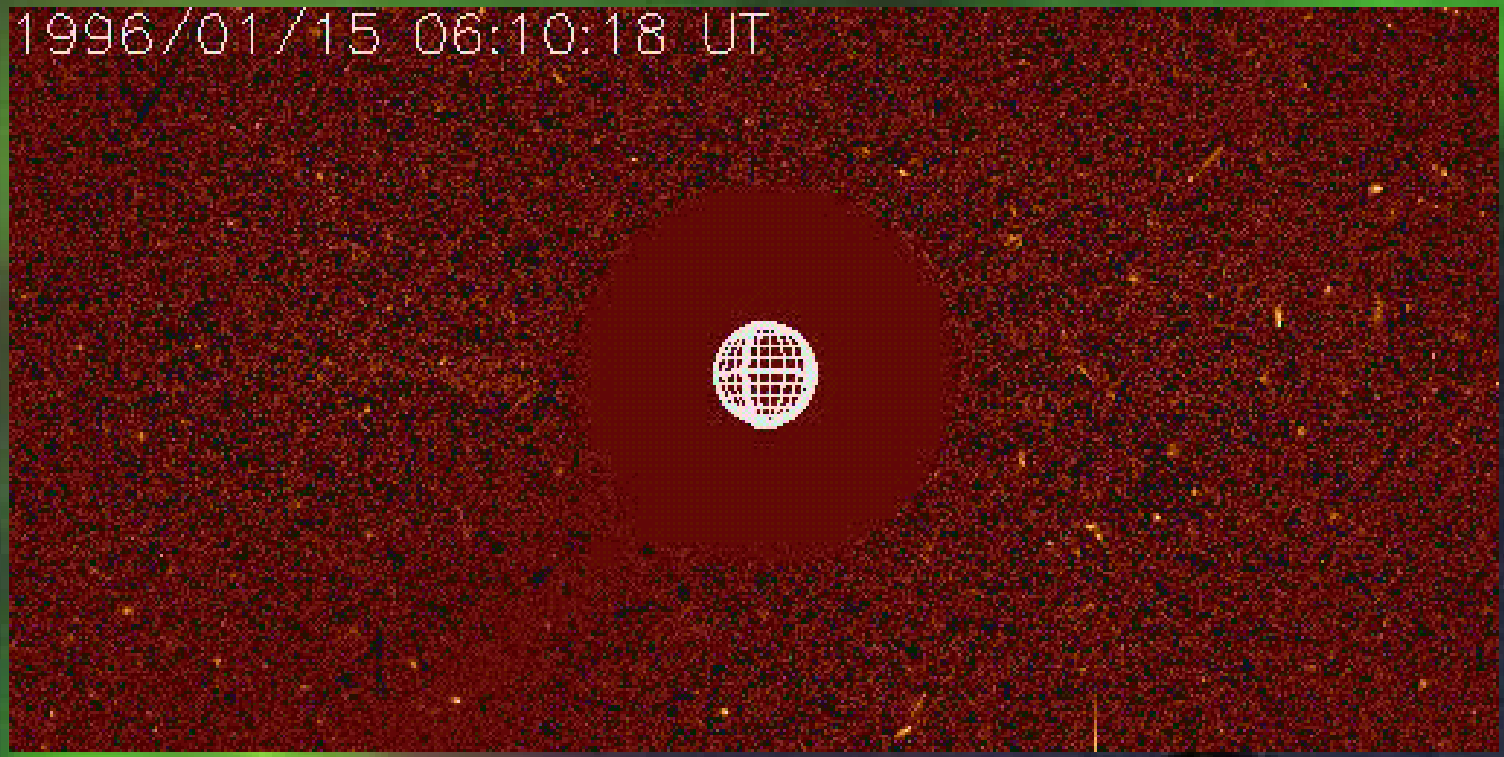
Carrington was the first man who happened in 1859 to observe a flare and also to notice the connection with the strong geomagnetic storm 17 hours later. Note what the "father of space weather" noted at the end of his report:

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



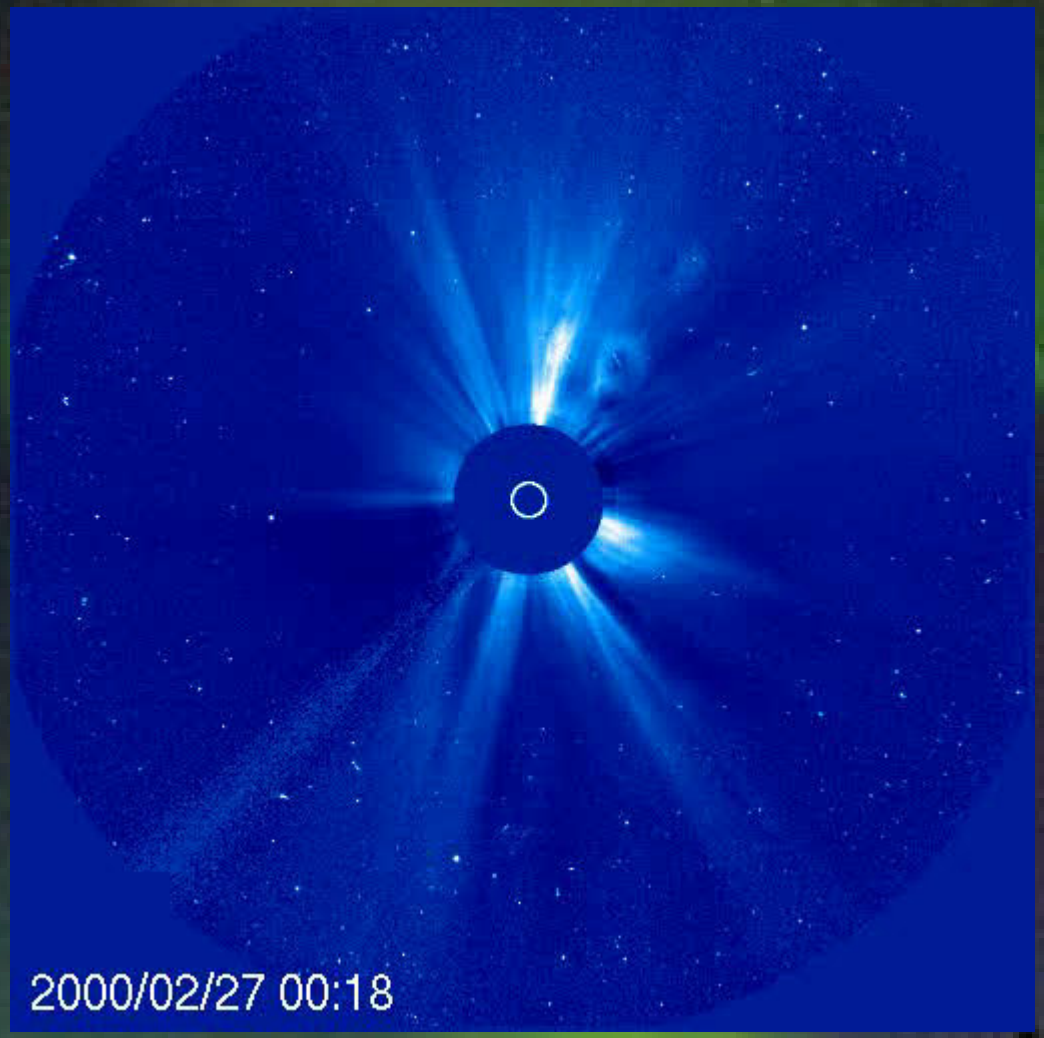
Flares and CMEs are probably symptoms of a more basic "magnetic disease" of the sun.

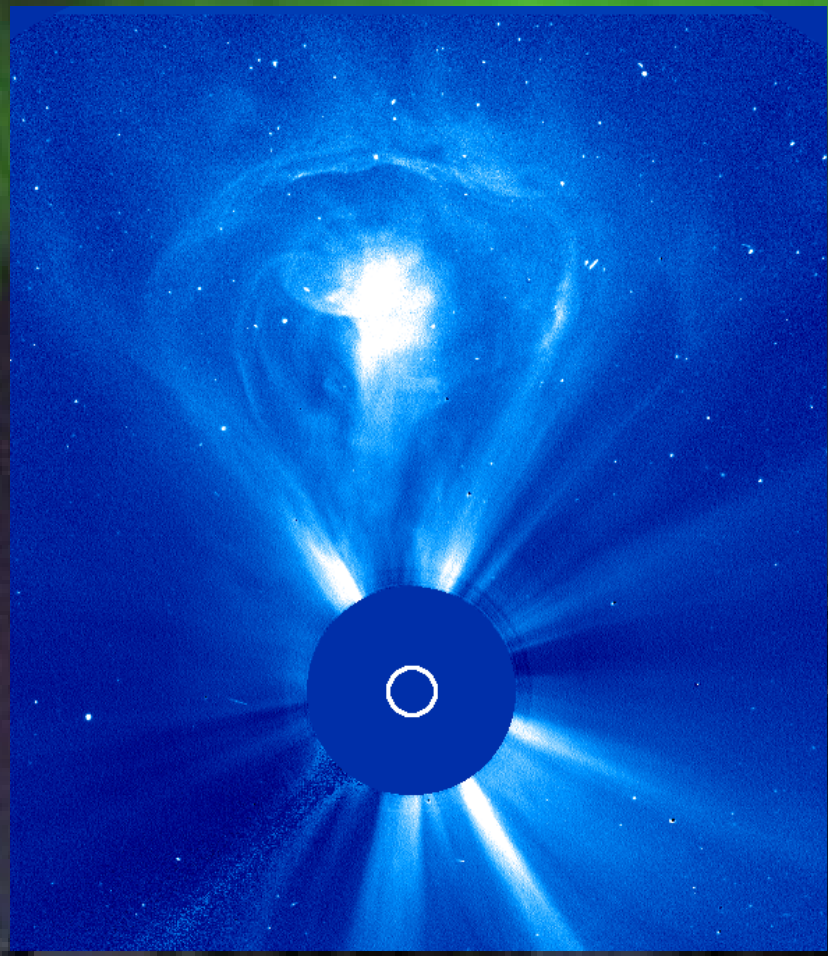
Coronal mass ejections (CMEs)



The CME of Jan 15, 1996, as seen by LASCO-**C3** on **SOHO**

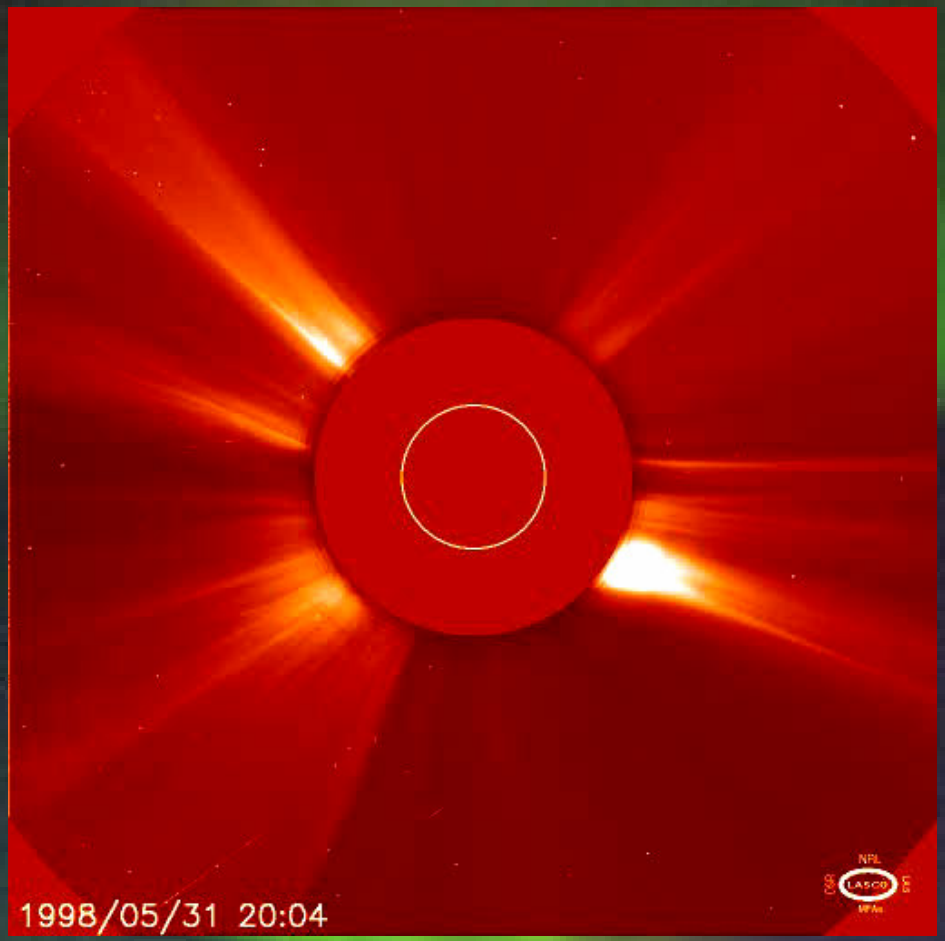
Some CMEs are really spectacular!





The „lightbulb" CME,
observed in February 2000
by LASCO C3 on SOHO

Some CMEs are really spectacular!



Two small comets were evaporating near the Sun.
A few hours later a huge ejection occurred. Coincidence?
A unique observation by **LASCO-C2**.
Note the helical structure of the prominence filaments!

The „thunder" of such explosions may literally shake up the whole heliosphere!

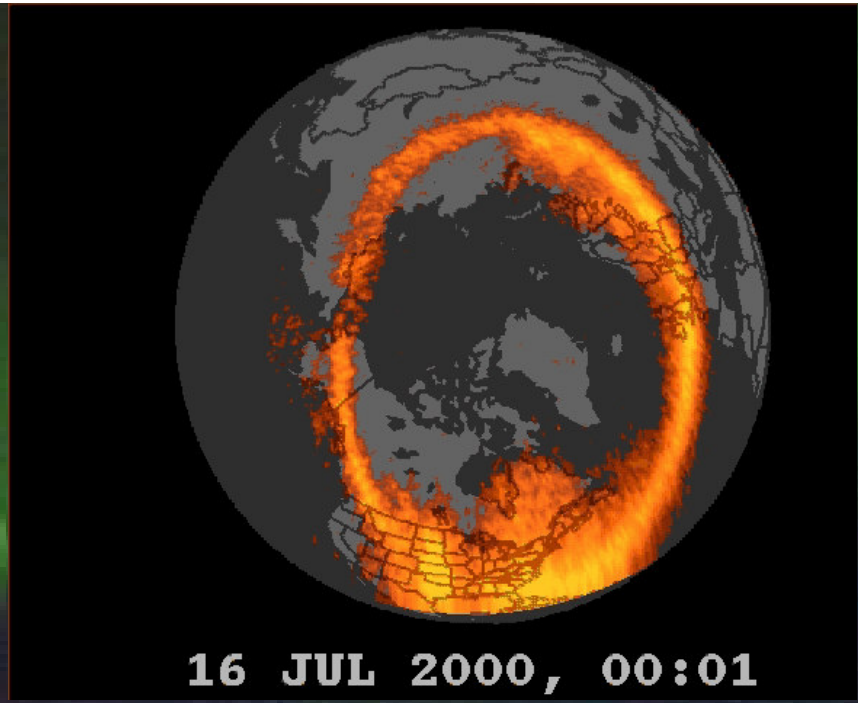
A result: Geomagnetic storms!

Then on Earth the compass needles will tremble and spectacular auroral displays fascinate observers:

Aurora!

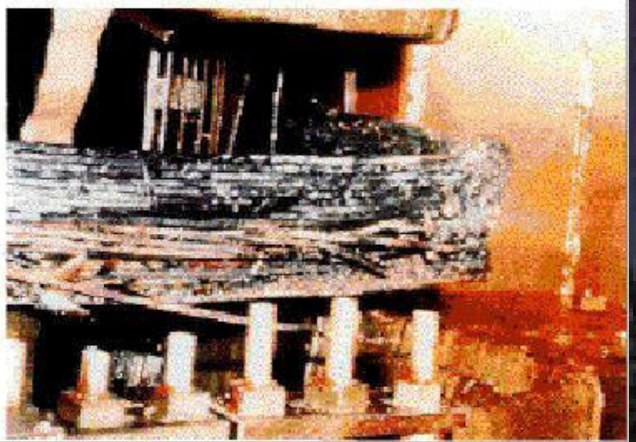
Ägypten2006

MPS



PJM Public Service
Step Up Transformer

Severe internal damage caused by the space storm of 13 March, 1989



Space “storms” may cause not only spectacular aurorae, but severe damage to, e.g., power systems on Earth!

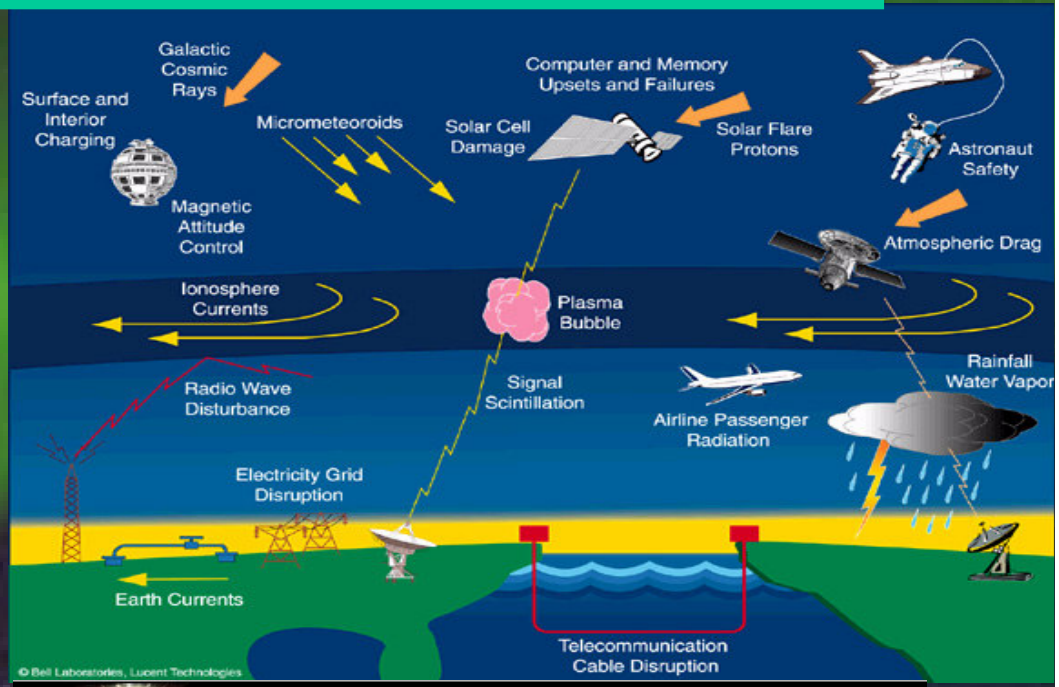
Space Weather!

Ägypten2006

MPS

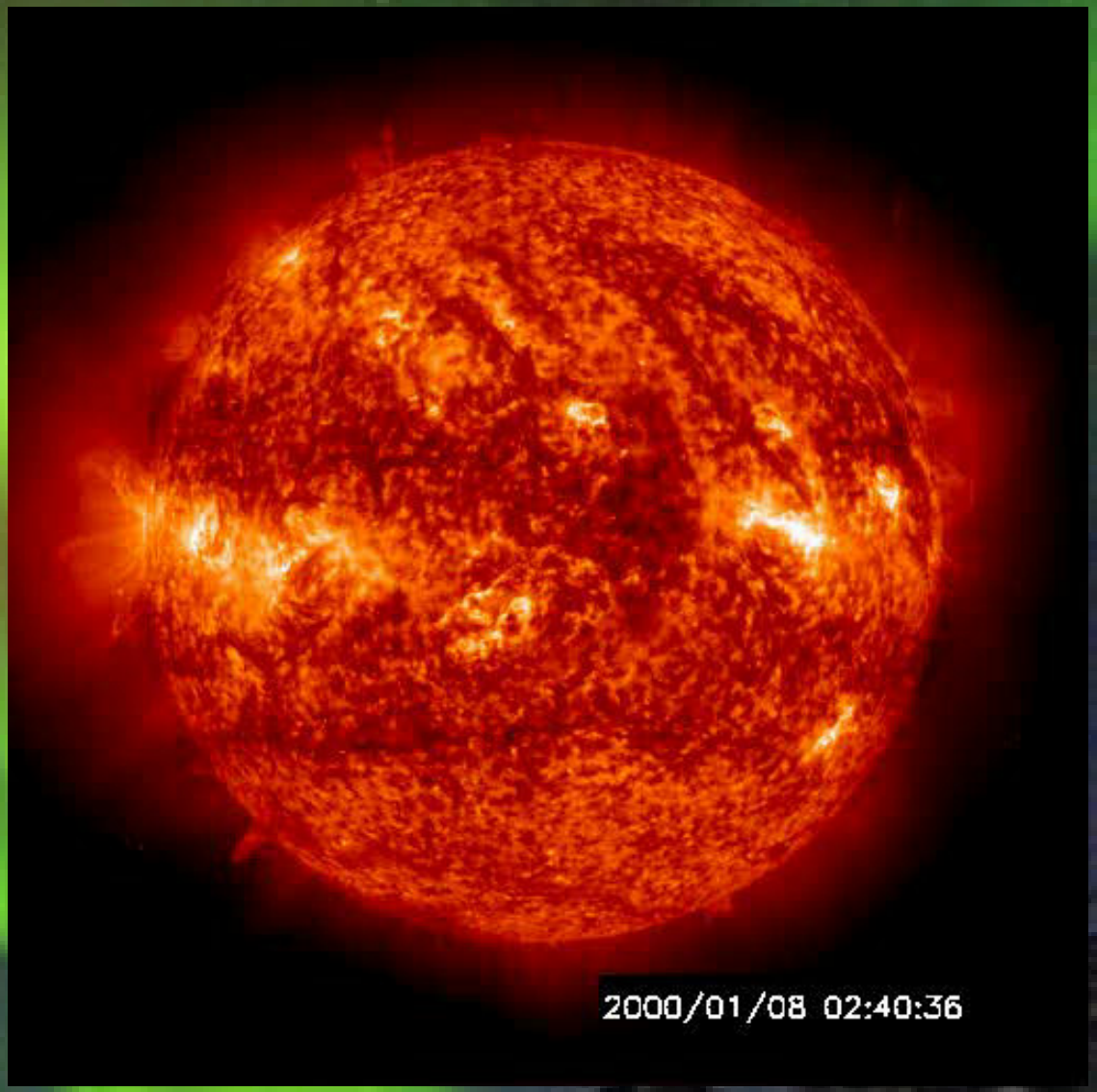
Space weather: why should we care?

- 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 satellite technology
  - more sensitive payloads
  - high performance components
  - lightweight and low cost
- Humans in Space
  - More and longer manned missions



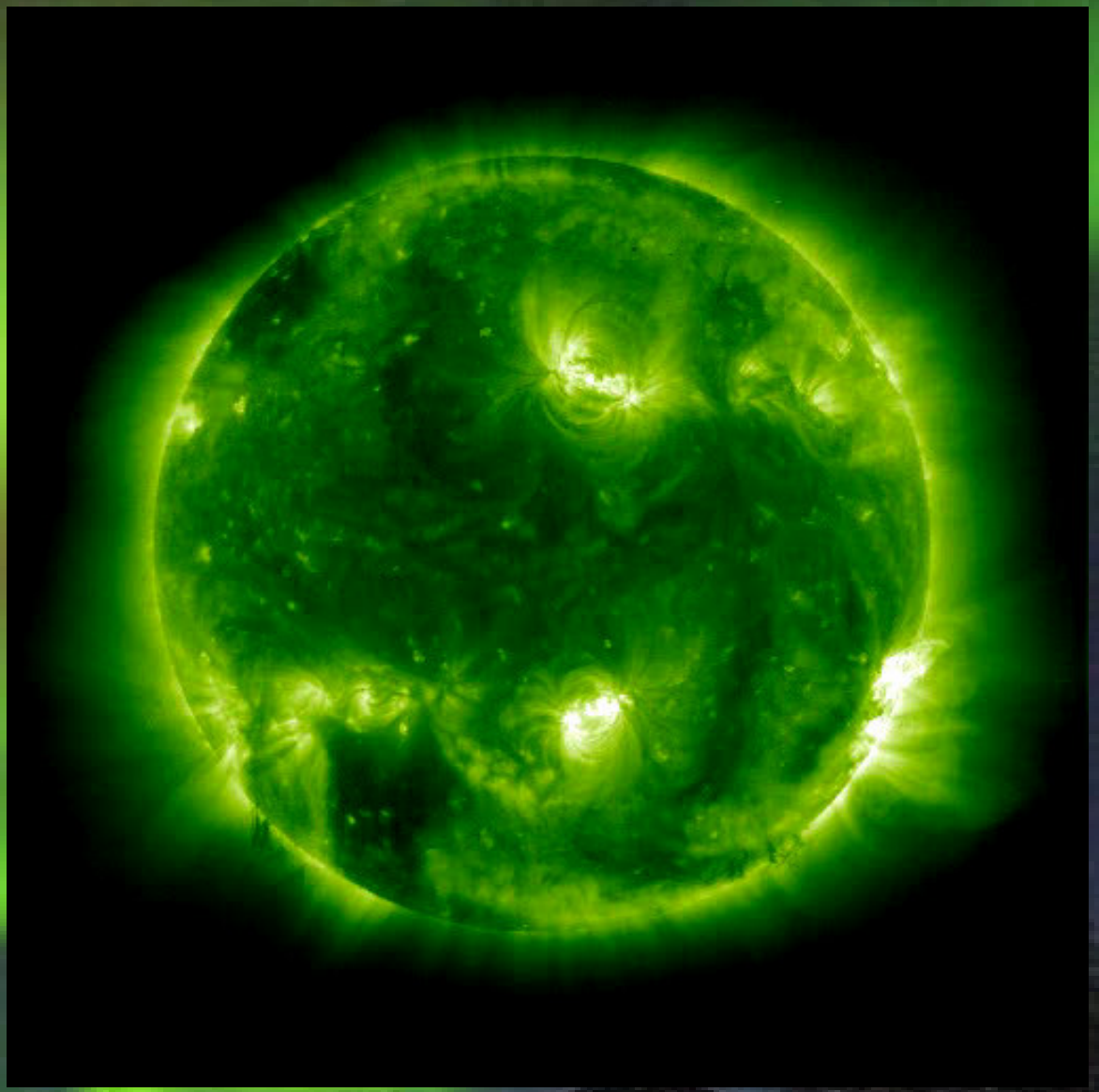
Space Weather warning will be very important for our society in the future.

The source of space weather: the active Sun!



The „active" sun, seen in EUV by EIT on SOHO

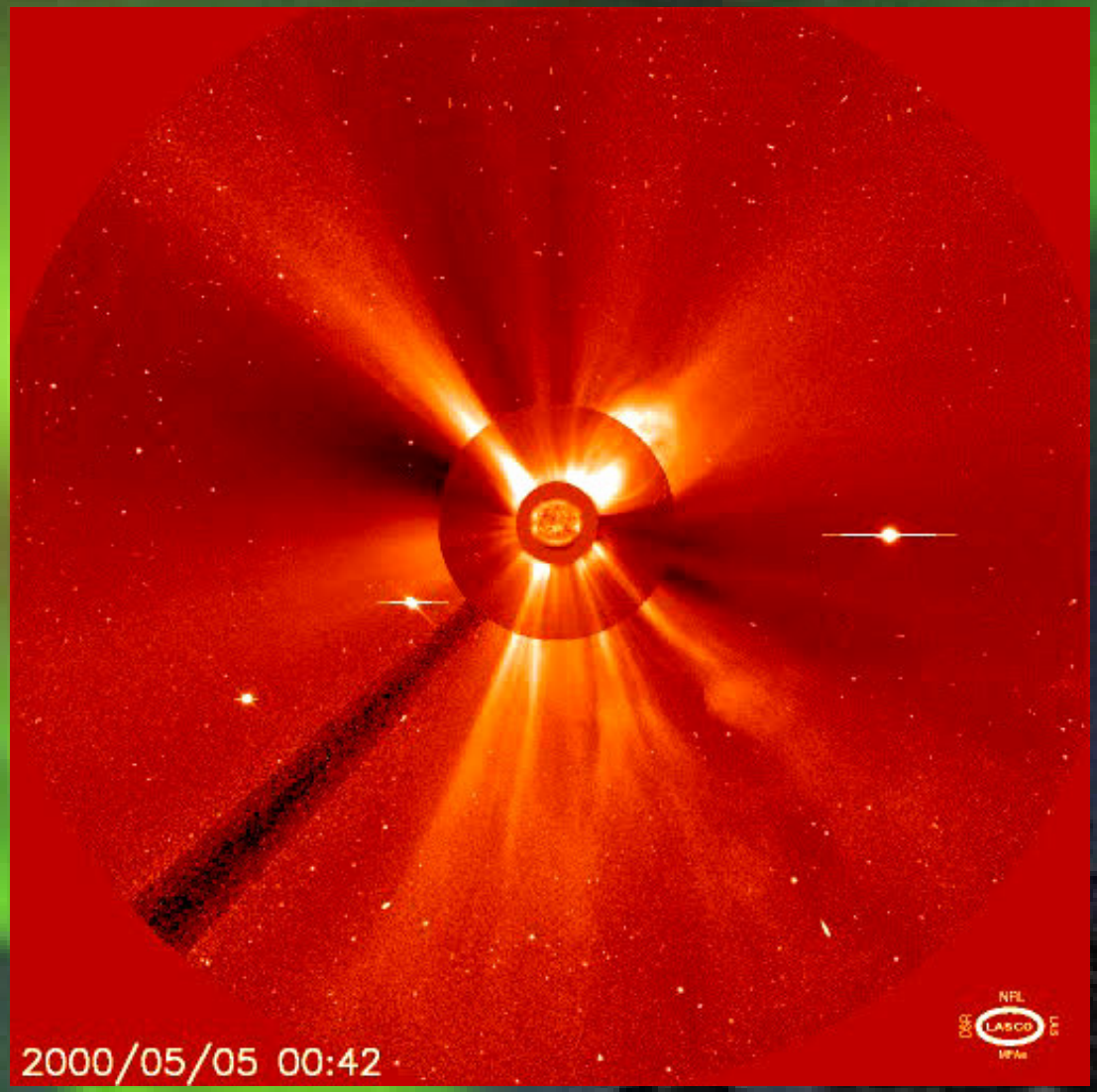
The source of space weather: the active Sun!



The „active" sun, seen in EUV by EIT on SOHO

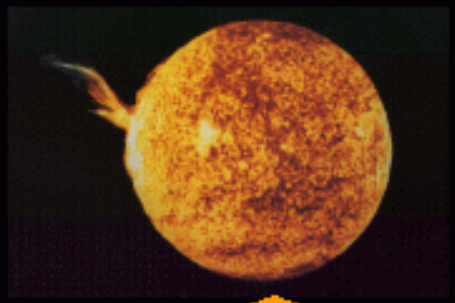
MPS

The source of space weather: the active Sun!



The „active" sun, seen by LASCO-C3 on SOHO

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	**PROTON EVENTS**	**GEOMAGNETIC STORMS**
SATCOM INTERFERENCE RADAR INTERFERENCE SHORTWAVE RADIO FADES	SATELLITE DISORIENTATION FALSE SENSOR READINGS SPACECRAFT DAMAGE LAUNCH PAYLOAD FAILURE HIGH ALTITUDE AIRCRAFT RADIATION SHORTWAVE RADIO FADES	SPACECRAFT CHARGING & DRAG SPACETRACK ERRORS LAUNCH TRAJECTORY ERRORS RADAR INTERFERENCE RADIO PROPAGATION ANOMALIES POWER BLACKOUTS

Let us inspect the three branches w.r.t.
basic understanding, prediction reliability, needs for the future.

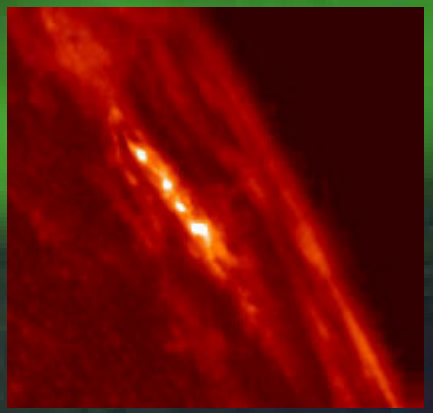
1. Electromagnetic radiation from flares

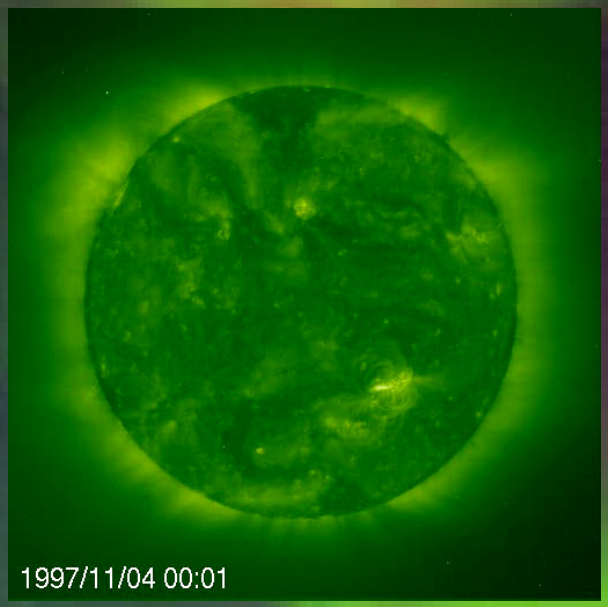
Visible light, EUV, X-rays, Gamma-rays

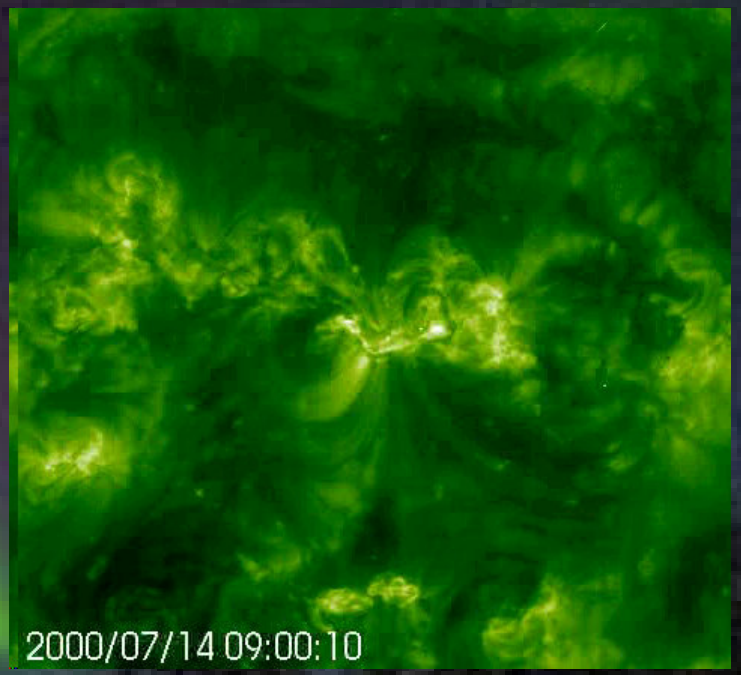
Physics: Unclear, but under intense study...

Arrival: Simultaneously

Duration: Minutes to hours







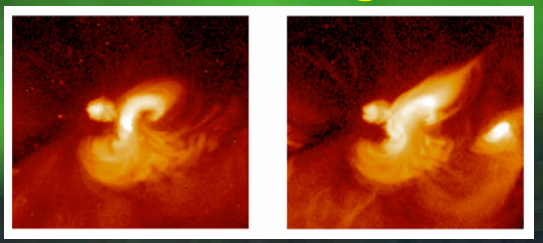
1. Electromagnetic radiation from flares

Effects: Sudden heating of the Earth's upper atmosphere

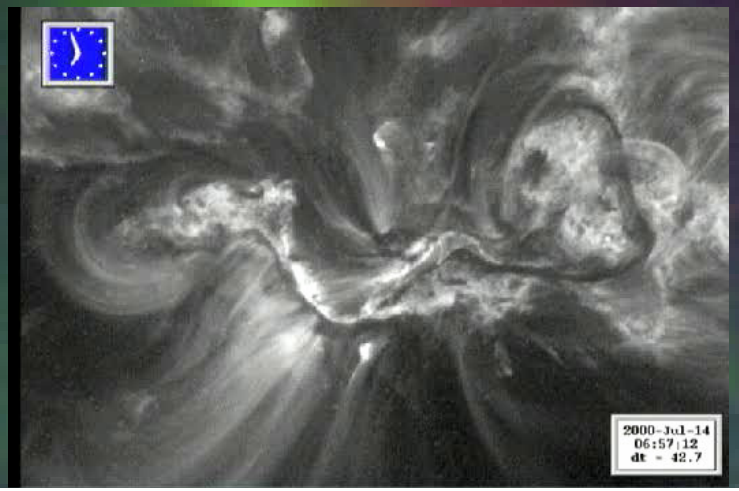
Impacts: * Radio communications disturbed,
* Sudden satellite drag

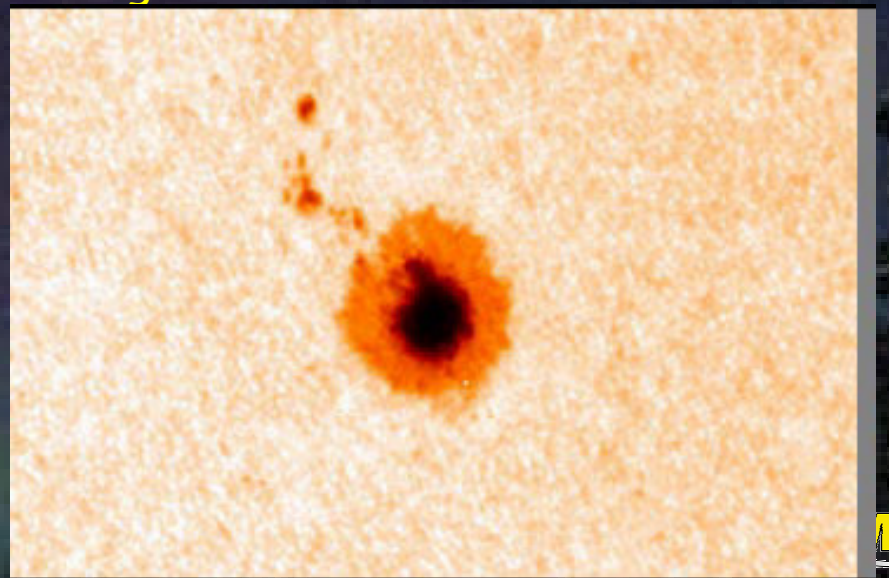
Predictions: very uncertain

„Sigmoids"



Needed: * Fundamental research for understanding basic mechanism, source and amount of energy to be released,
* High time resolution optical observations of flare onset,
* Search for „dormant volcanos" by MDI type measurements and modelling.



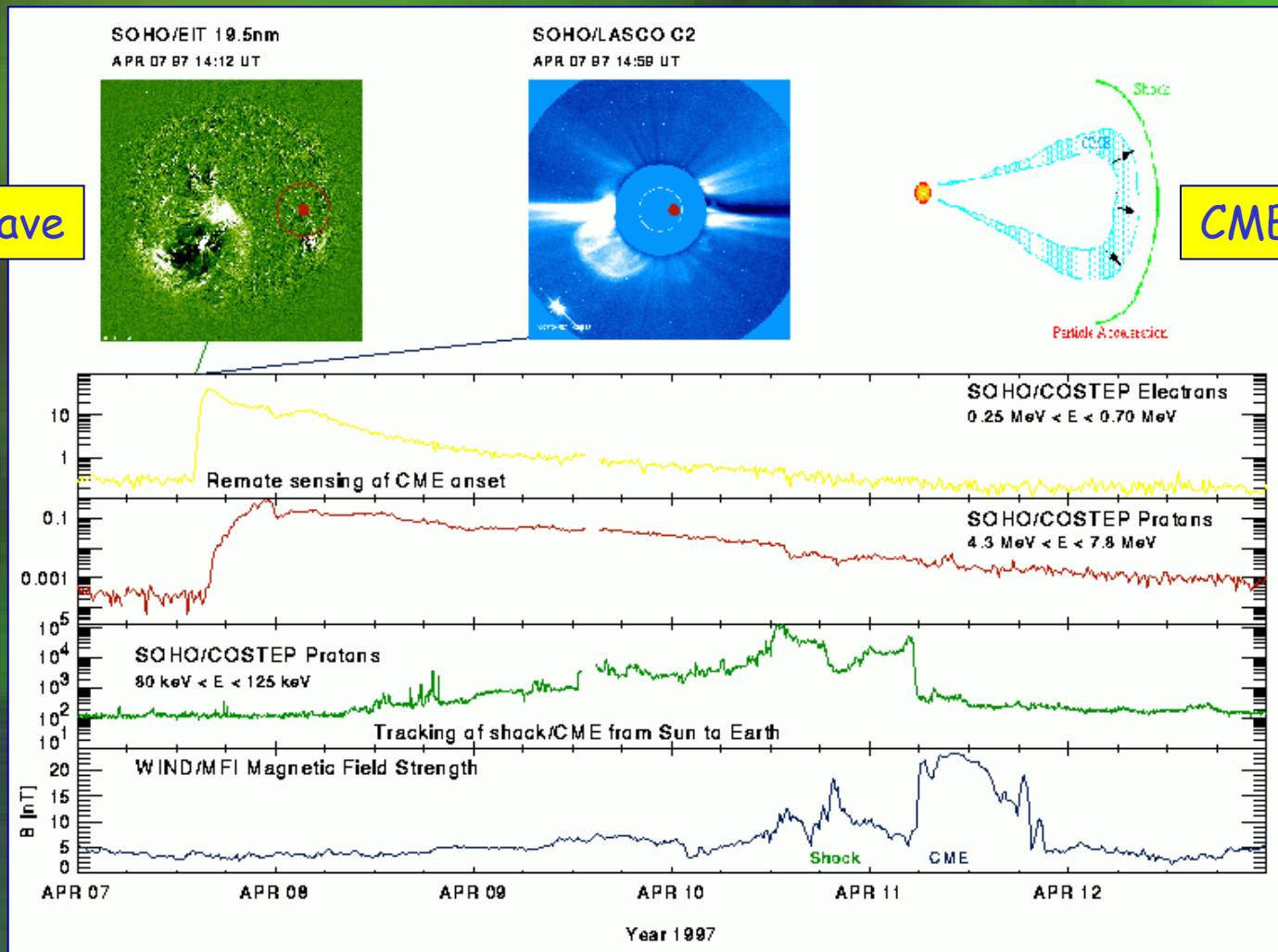


2. High energy particles from flares and CME shocks

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

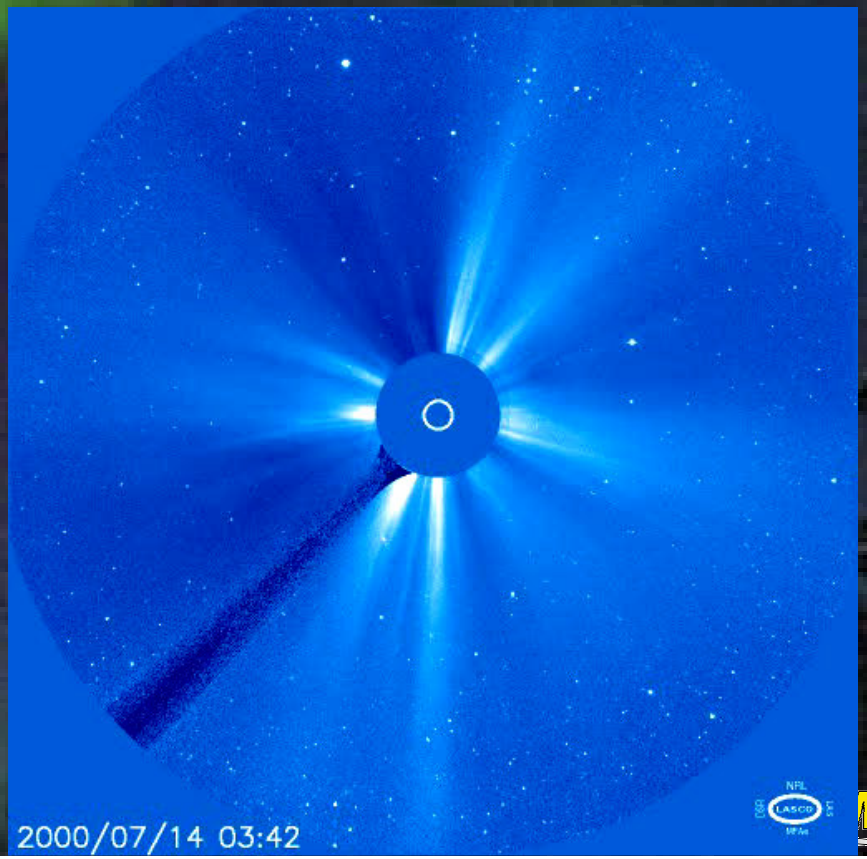
2. High energy particles from flares and CME shocks

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

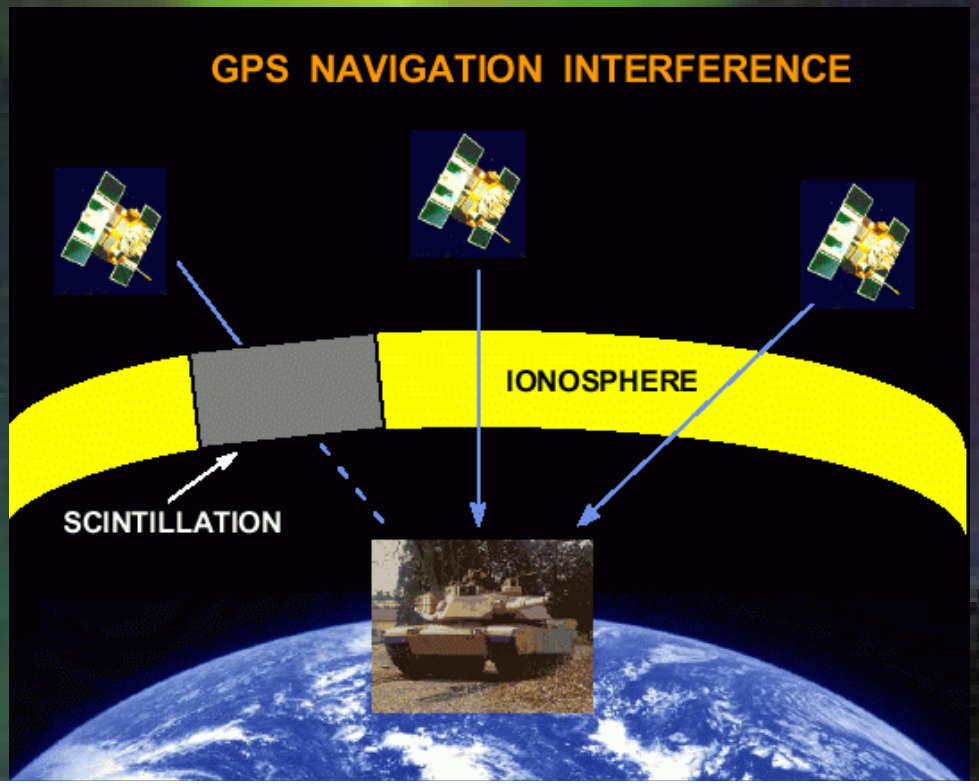
Duration: Hours to days



2. High energy particles from flares and CME shocks

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

Impacts:
* Radio communications disturbed,
* Damage to satellite surfaces, causing degradations,
* Damage to satellite electronics,
* Blinding of CCD cameras in Earth orbit,



2. High energy particles from flares and CME shocks

Enhanced radiation doses are a substantial risk for astronauts on EVAs at the space station or on their way to the moon or to Mars.

Predictions: Very uncertain

Needed:
* Fundamental research for understanding basic mechanism,
* High time-resolution optical observations of flare onset,
* Radio observations, in continuous frequency ranges.

3. Low to medium-energy particles, plasma clouds

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

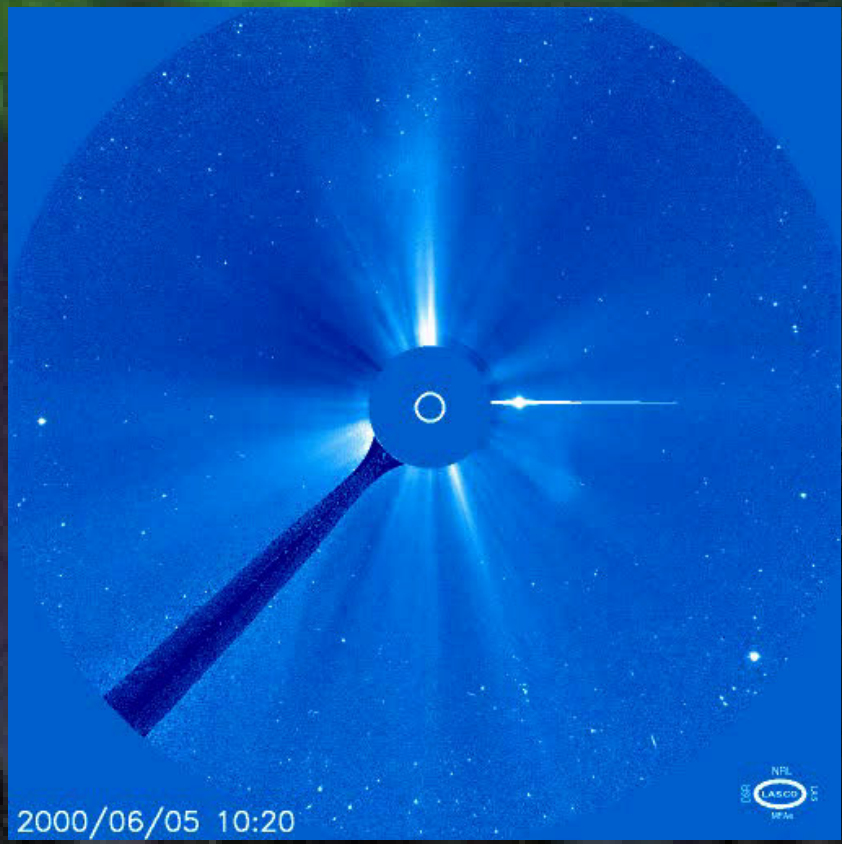
Geomagnetic storms.

Physics: * Origin of CMEs unclear, but under intense study.

* Propagation is being modelled, empirical approaches under development.

Arrival: after 1 to 5 days

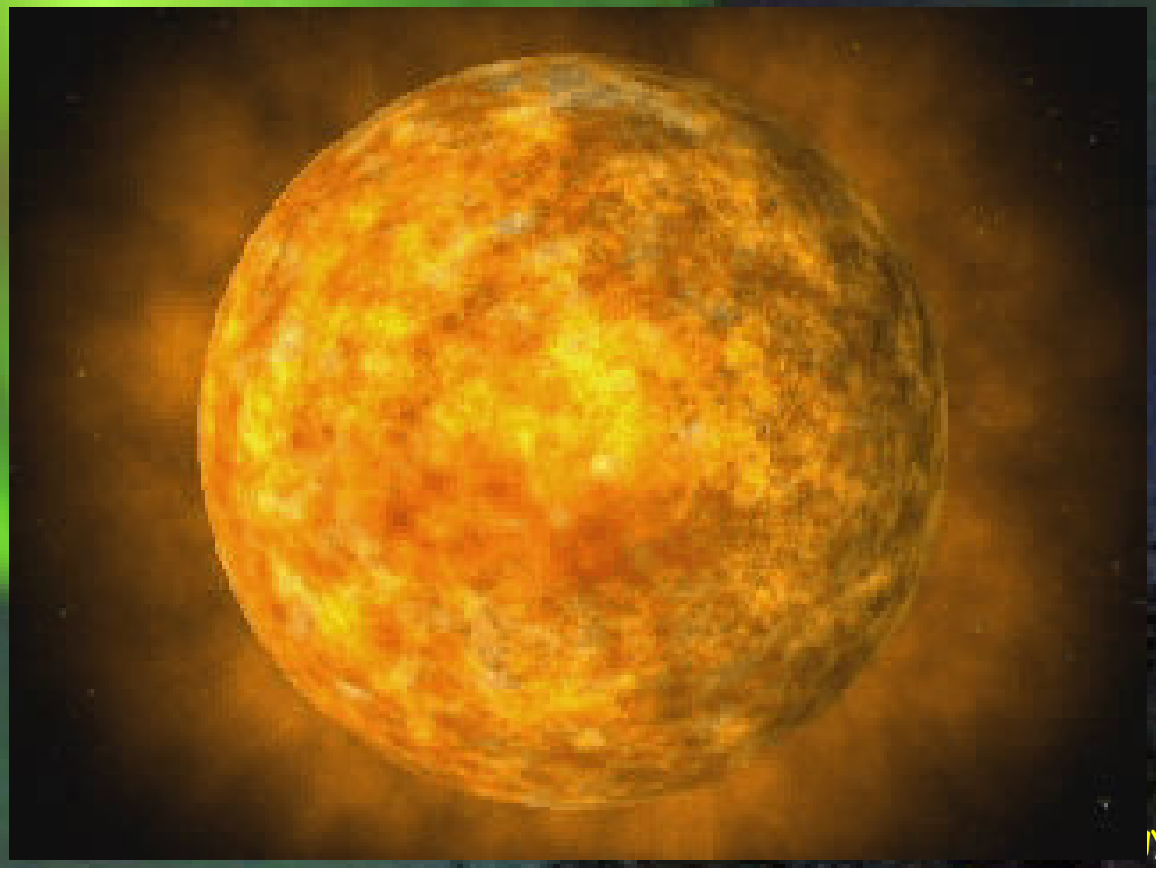
Duration: hours to days



3. Low to medium-energy particles, plasma clouds

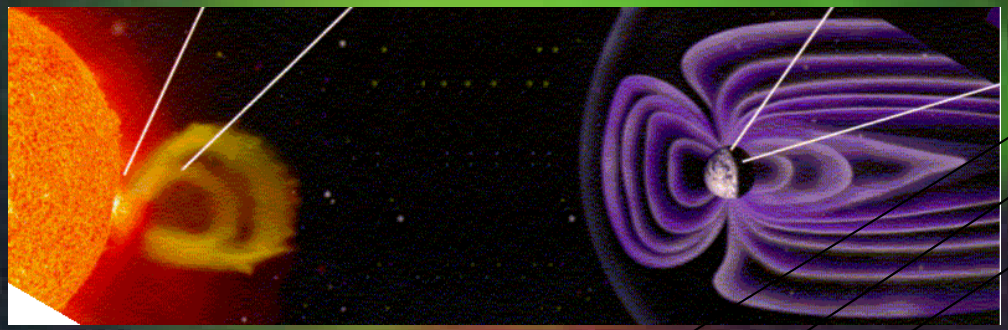
Effects:

* Sudden compression of the Earth's magnetosphere,
* Distortion and depletion of the radiation belts,
* Injection of plasma from magnetotail into polar magnetosphere, thus causing aurorae,
* Geomagnetic storms,
* Heating of ionosphere and upper atmosphere.



3. Low to medium-energy particles, plasma clouds

What happens at Earth when ejecta arrive?

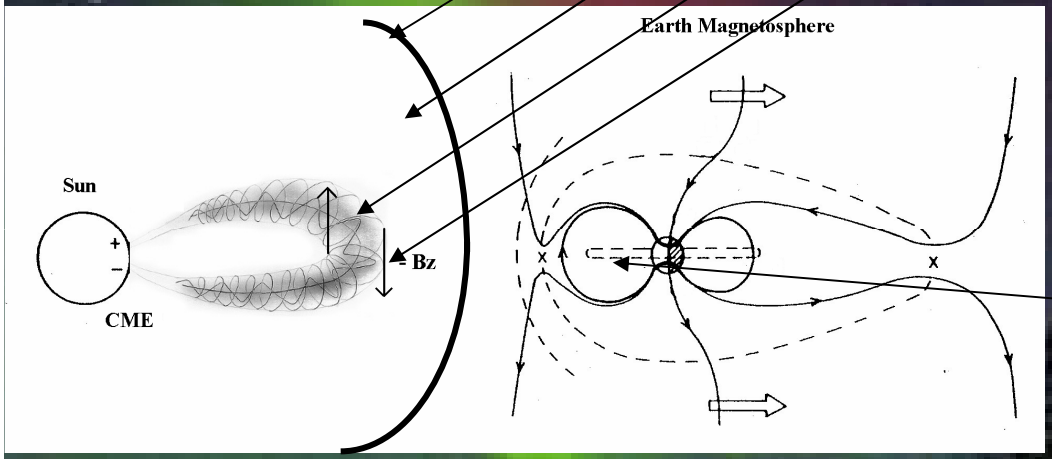


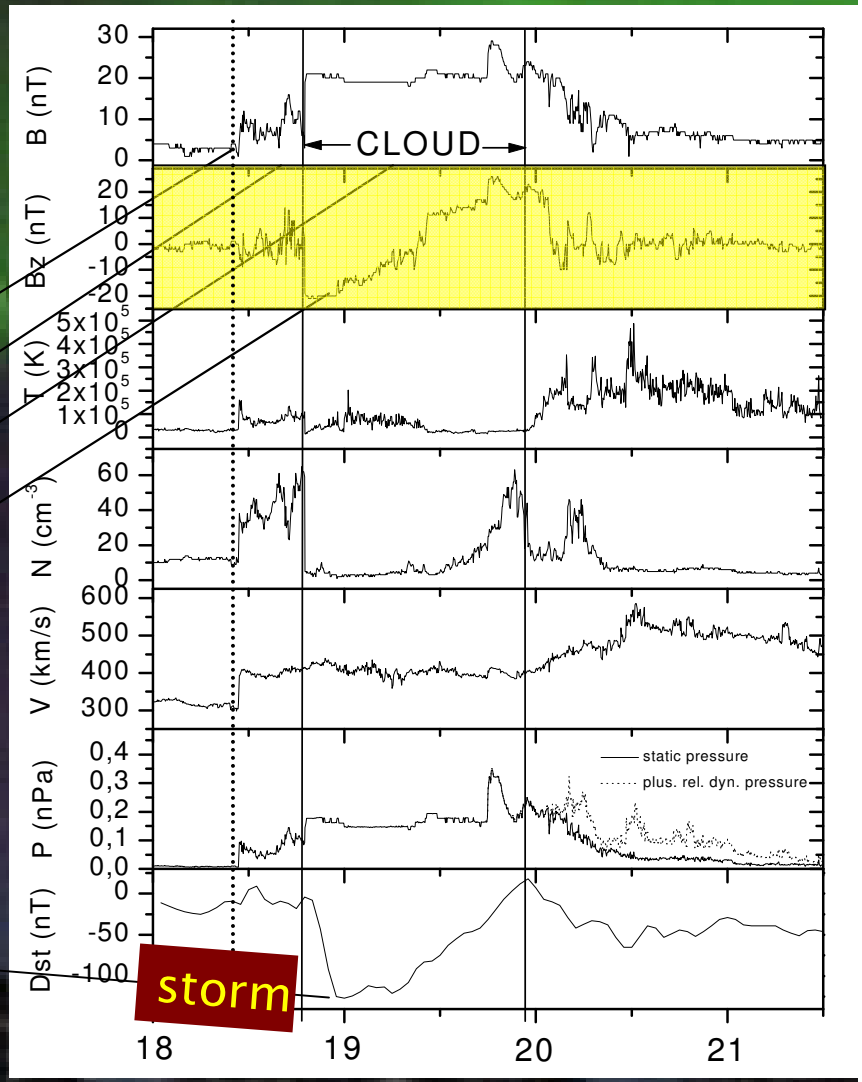
shock

sheath

cloud

Bz south

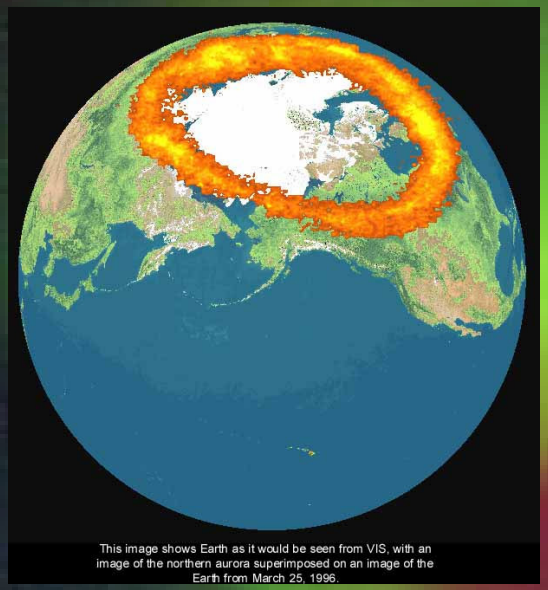




MPS

3. Low to medium-energy particles, plasma clouds

Impacts:



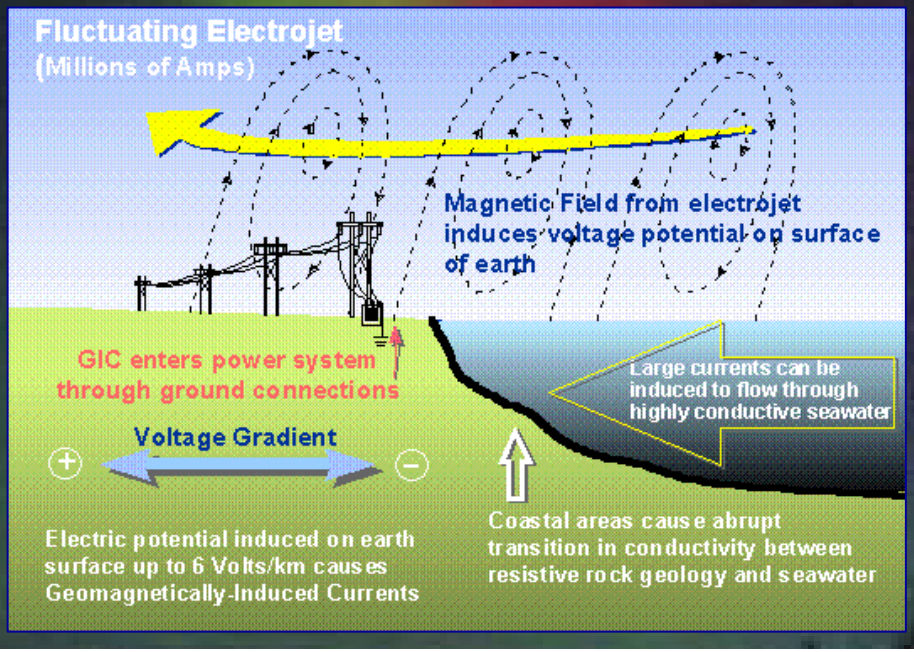
This image shows Earth as it would be seen from VIS, with an image of the northern aurora superimposed on an image of the Earth from March 25, 1996.

* 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.

3. Low to medium-energy particles, plasma clouds

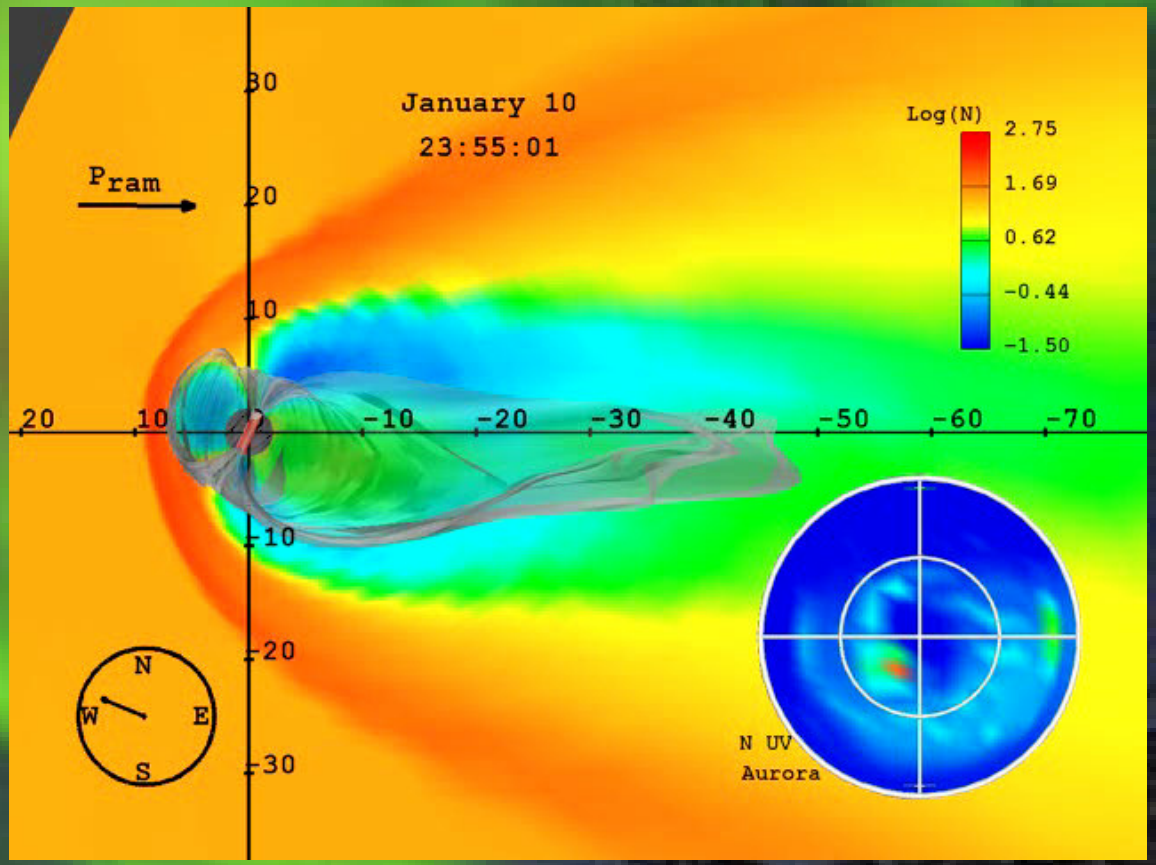
Impacts:

* 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.



3. Low to medium-energy particles, plasma clouds

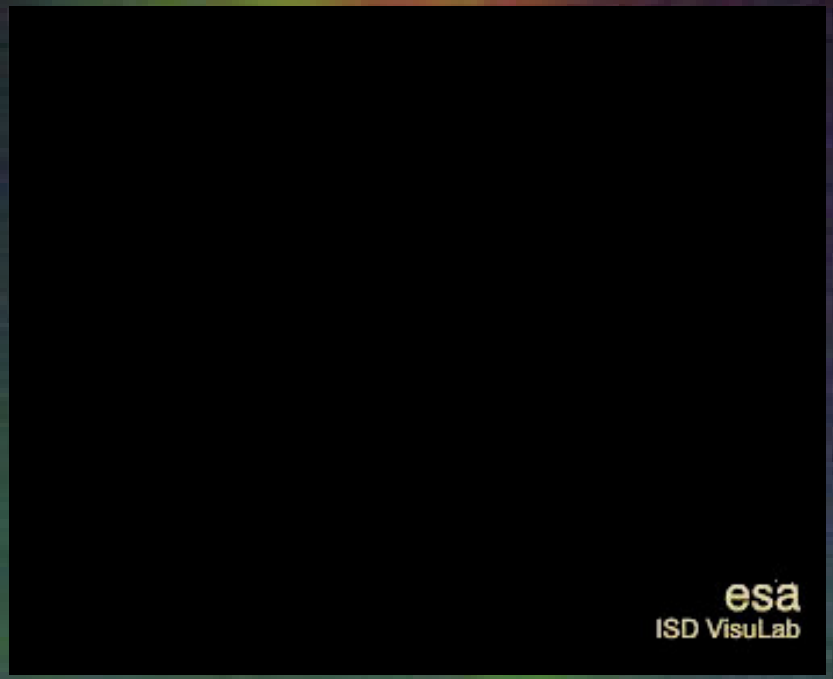
Needed: * On-line computer model of the heliosphere, continously updated, that allows to simulate CME ejections and propagation in realistic and near-real-time way.



3. Low to medium-energy particles, plasma clouds

Needed:

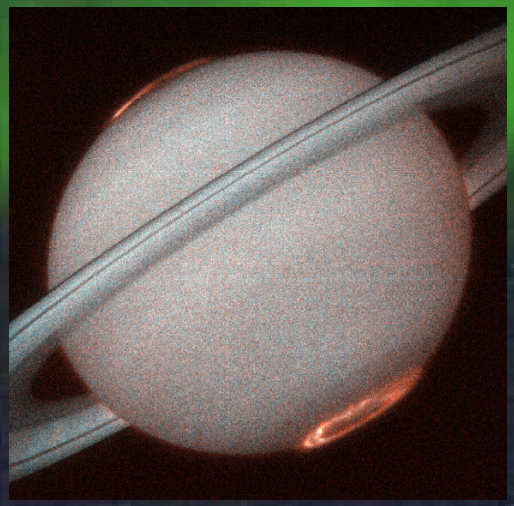
* A dedicated spacecraft in front of Earth, carrying:
  an EUV/X-ray imager of the Sun,
  a sensitive coronagraph, for quantifying halo CMEs,
  a complete set of standard particle and field instruments,
  a MDI type instrument to monitor the Sun' s interior.
* A space weather warning center on the ground, 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

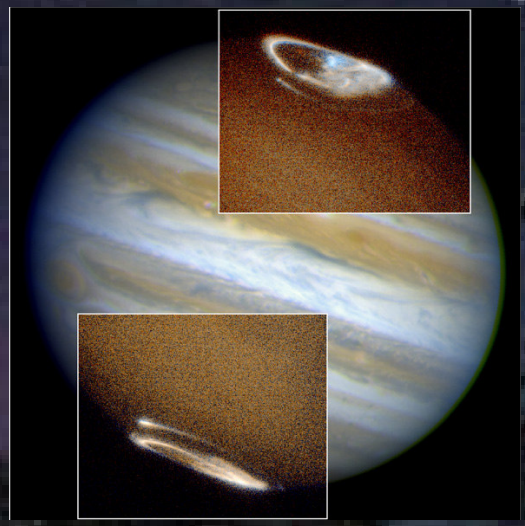


SOHO !

Space storms all through the solar system!

but also on Saturn





and on Jupiter

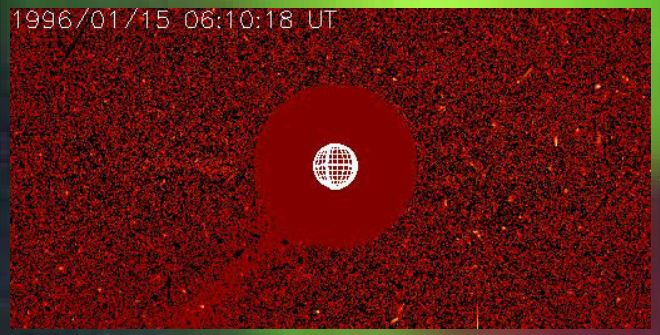
On Earth,

Ägypten2006

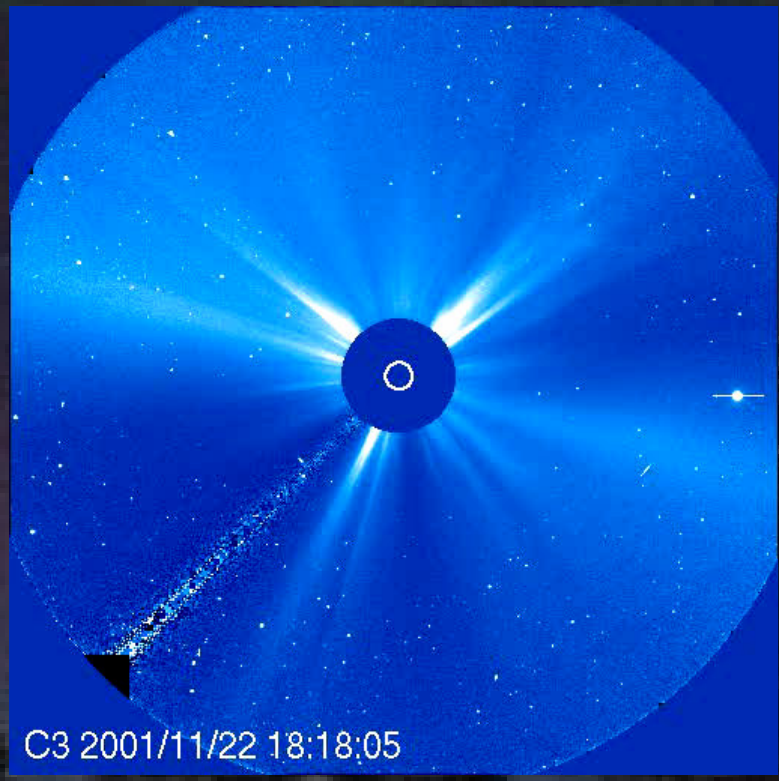
MPS

Why are space weather predictions still that uncertain?

1. We cannot predict eruptions before they occur,
2. We cannot predict the topology of the ejecta and their geoeffectiveness.
3. We cannot measure the propagation speed of halo CMEs towards Earth!



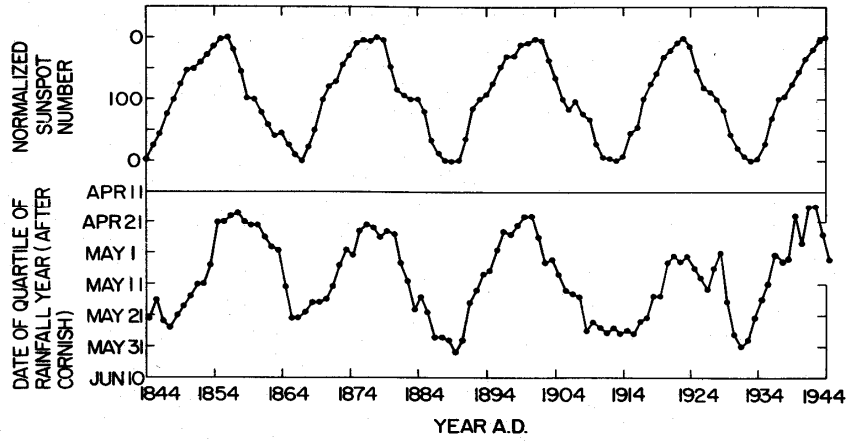
?



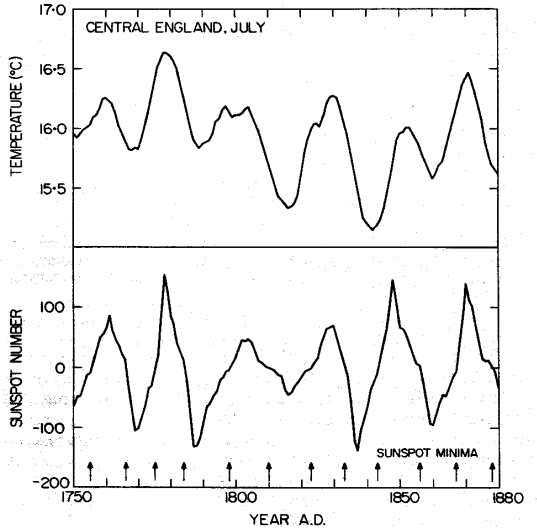
Ägypten2006

MPS

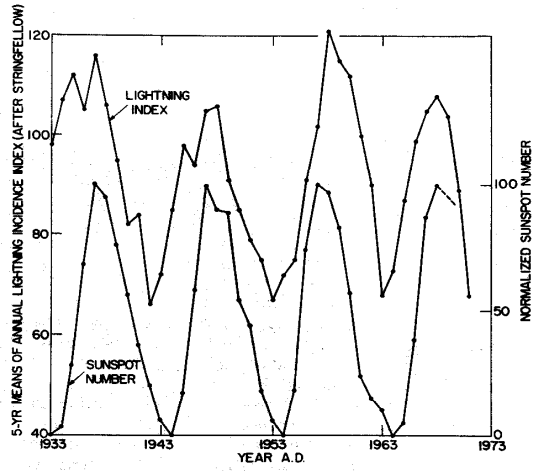
Impact of space weather on Earth's weather and climate?



F-5 Ten-year smoothed means (lower curve) of the annual rainfall "quartile" (the date by which one quarter of the annual rainfall had occurred) for Adelaide, Australia. After Cornish (1954). The date fluctuates by about six weeks in phase with the double sunspot cycle plotted in the form shown in the upper curve. The Cornish data points are slightly displaced because he used smoothed means for an even number of years.



F-6 Smoothed means of the July central-England temperatures (upper curve) published by Manley (1974) compared with the conventional double sunspot cycle (lower curve). The period includes 12 sunspot minima. Since 1880 the influence of the double sunspot cycle on the temperature in Britain has been less apparent than the influence of the 11-year cycle.



F-7 LIGHTNING AND SUNSPOT CYCLE
Upper Curve: Five-year means of the annual "lightning incidence index", that is, the number of thunderstorms plotted on a scale designed to indicate variations in the frequency of lightning strikes on the electrical-power distribution system in Britain. After Stringfellow (1974).
Lower curve: Normalized sunspot numbers (not available after 1968).

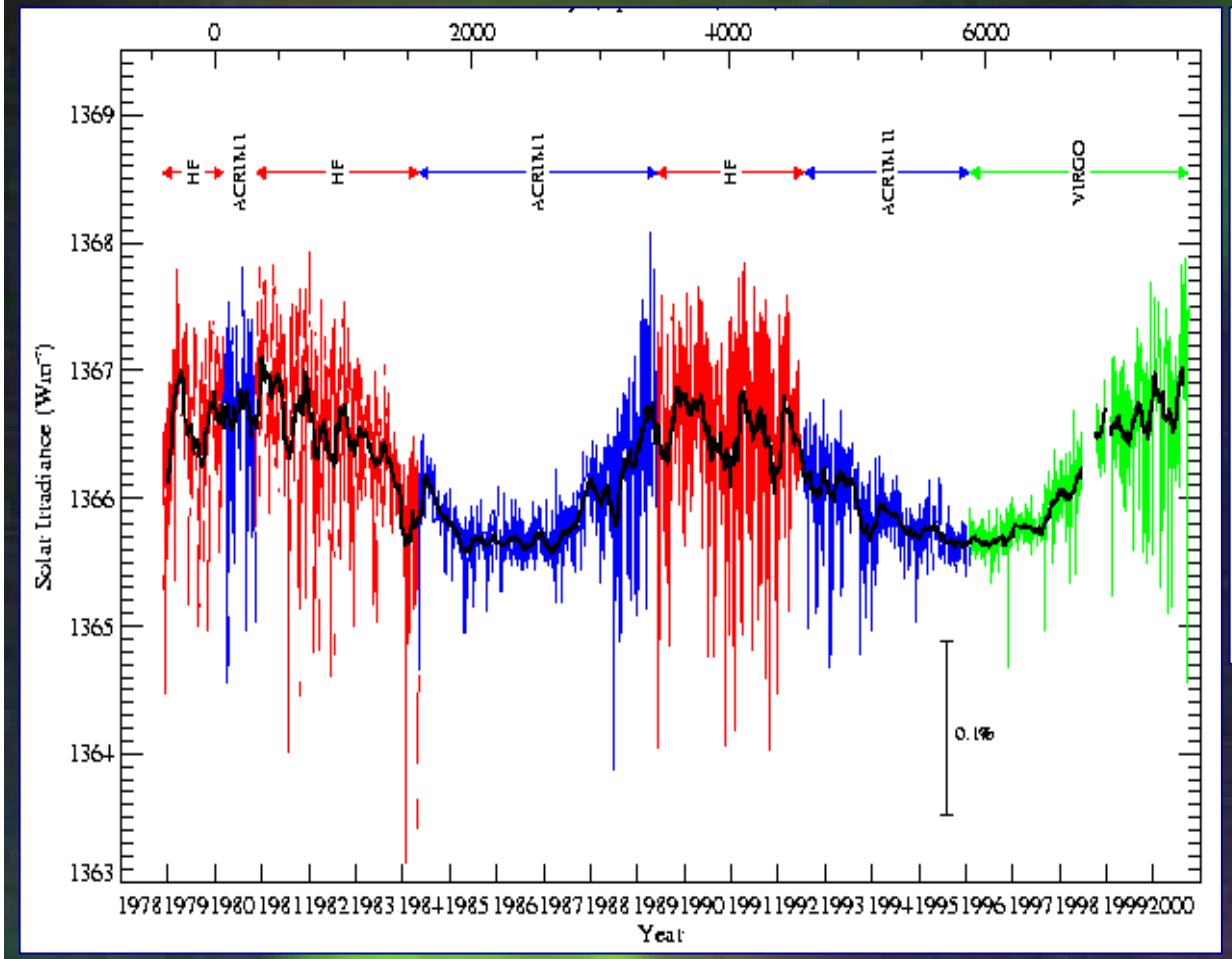
Solar cycle effects in various weather records

Still under heavy debate...

Ägypten2006

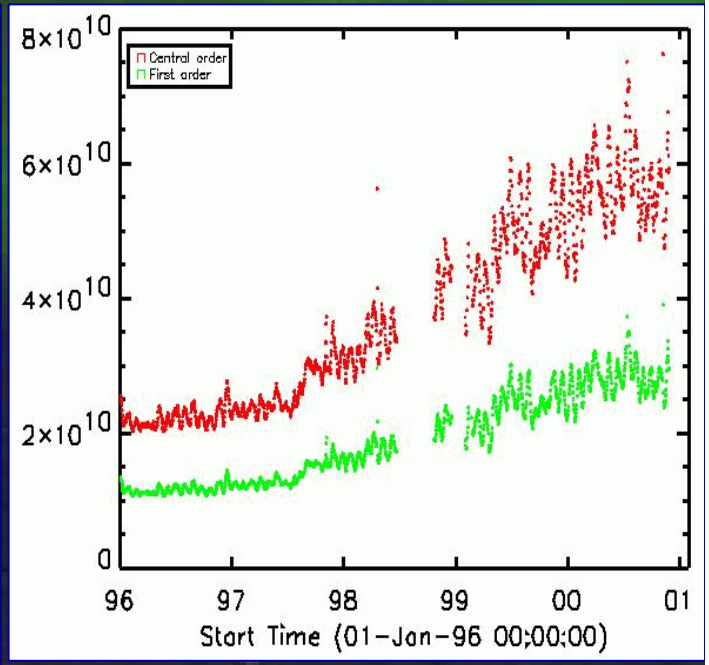
MPS

Solar irradiance variations- the Sun as a star



VIRGO on SOHO: Total solar irradiance

The total irradiance on the Earth does not vary by more than 0.1 %!



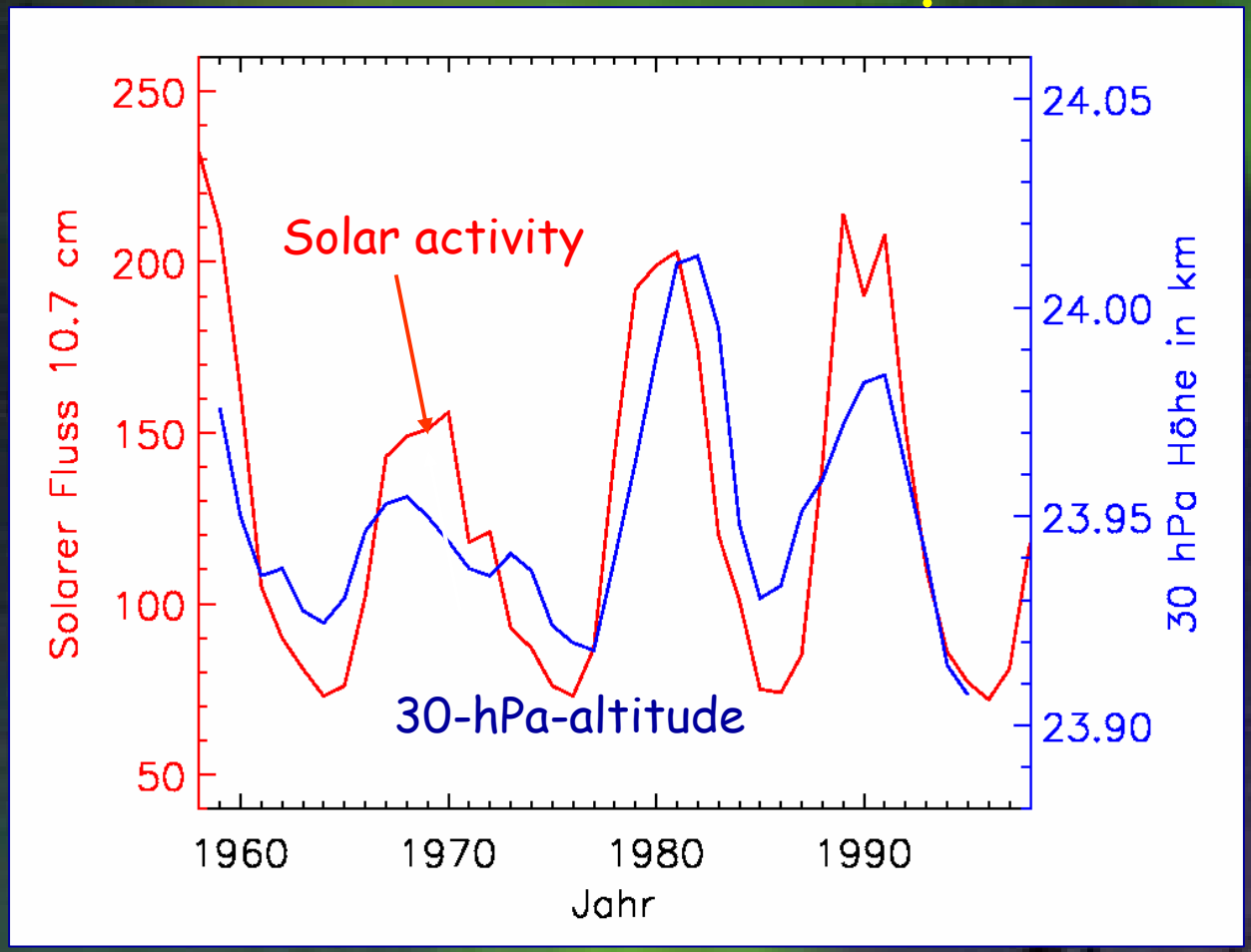
EUV disk integrated flux from SEM (CELIAS) on SOHO:

The UV flux varies by factors, rather than by per mille! It heats the Earth's outer atmosphere and lets it „breath"!

Ägypten2006

MPS

The Earth's atmosphere „breathes" with solar activity!



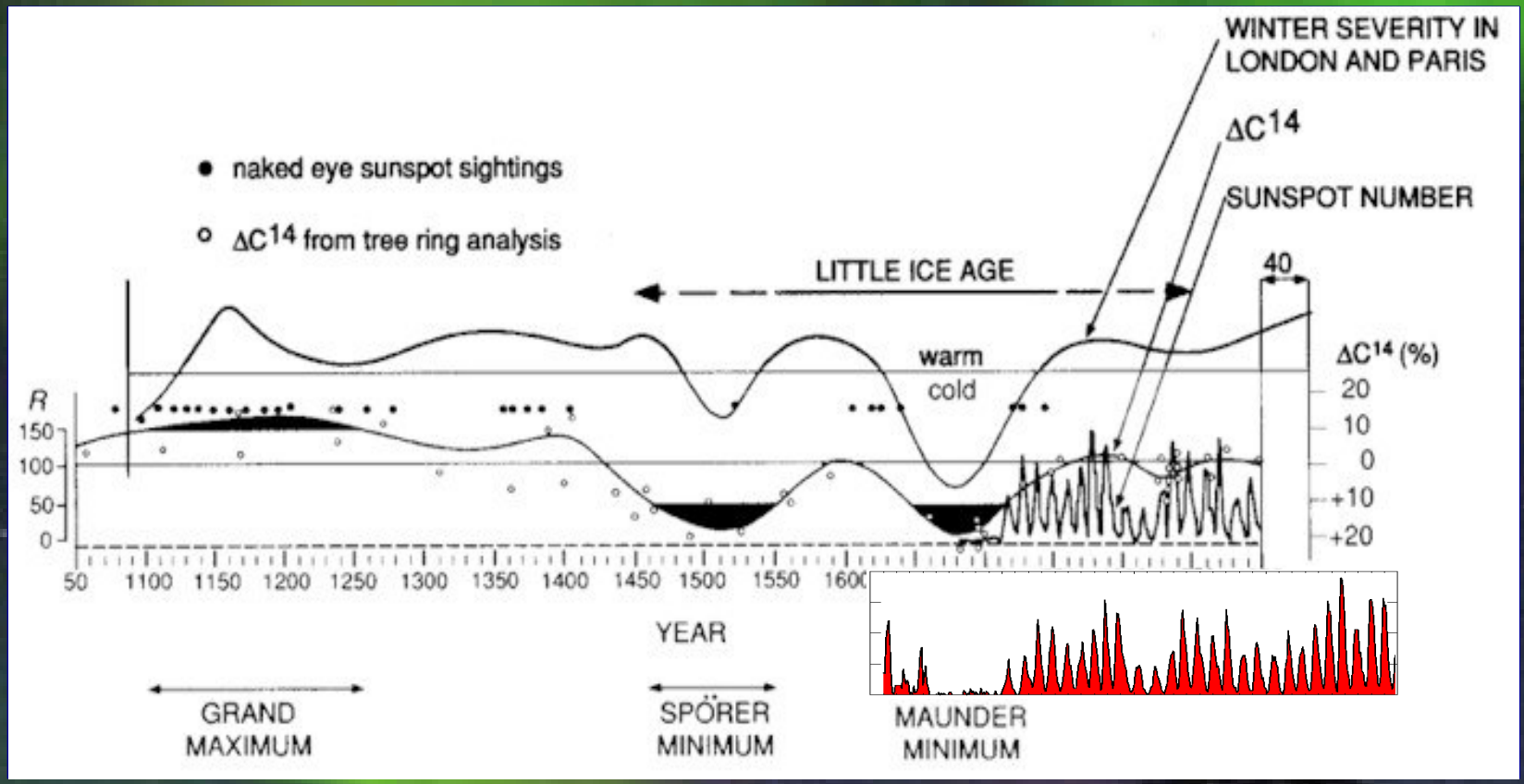
The altitude of the stratosphere varies with solar activity.

With increased activity:

- more UV radiation,
- more Ozone production,
- heating of the stratosphere,
- changes of air motions.

Effects on climate !?!

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

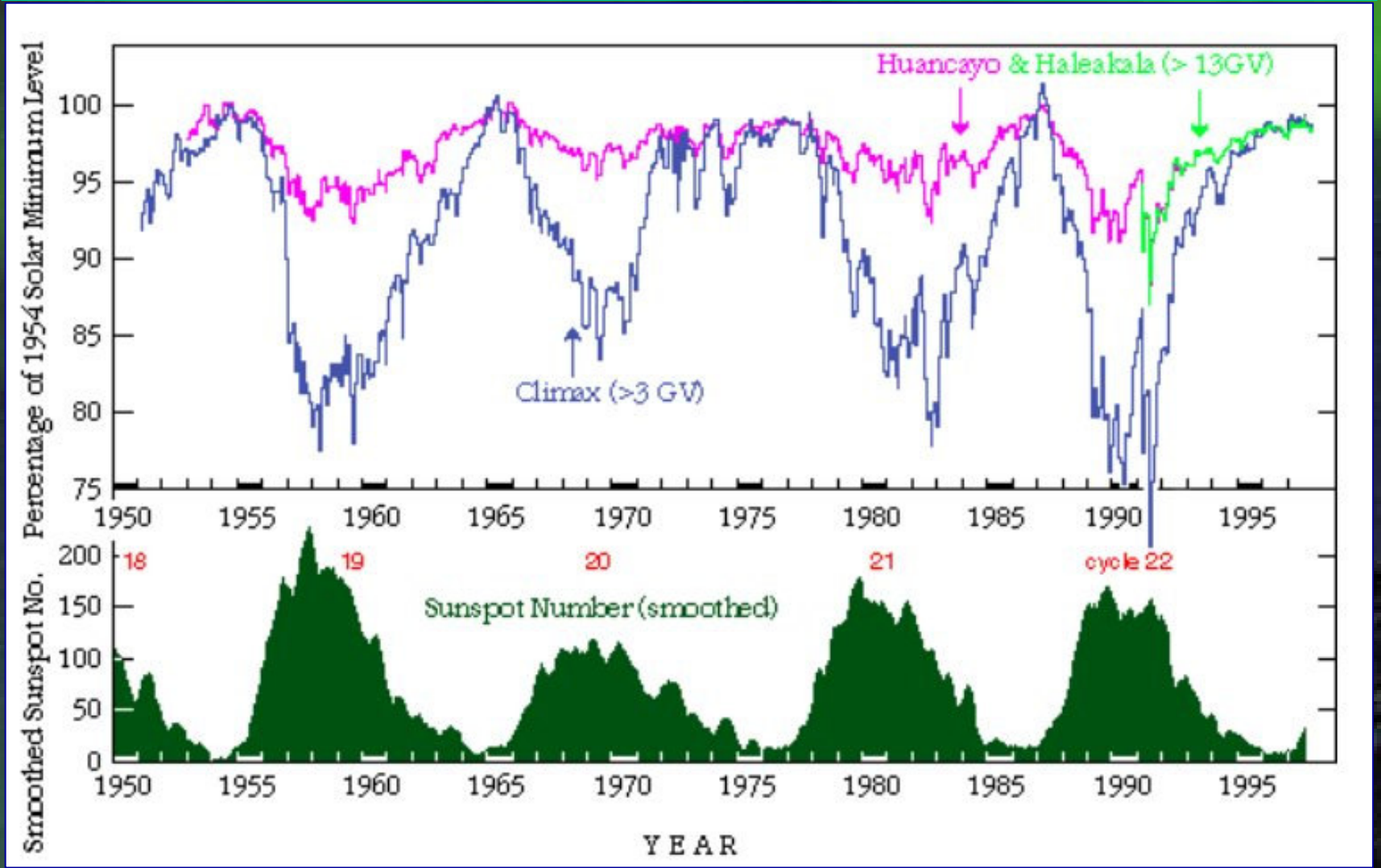


Major climatic fluctuations occurred long before the man-made greenhouse effect became significant!

The „little ice age“ in the late 17th century

Every year: regular markets on the deeply frozen river Thames

The Galactic Cosmic Radiation (GCR) during the solar cycle

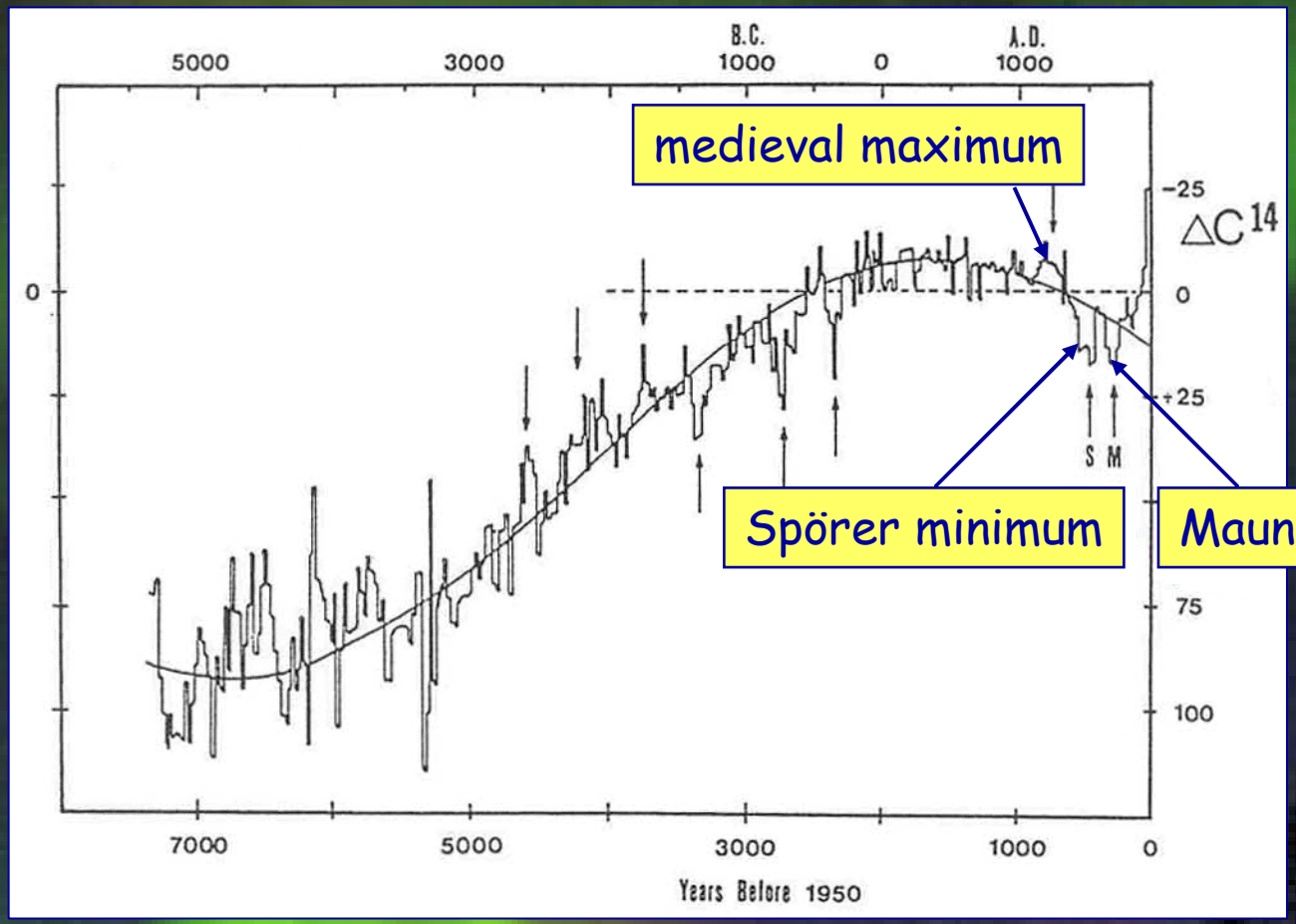


The GCR intensity is anticorrelated to solar activity!

Agypten2006

MPS

Solar activity, cosmic rays, and tree rings



High solar activity causes:

- better shielding of heliosphere against GCRs,
- lower fluxes of GCRs on Earth's atmosphere,
- less production of ^{14}C isotopes in atmosphere,
- less ^{14}C inclusion in tree rings.

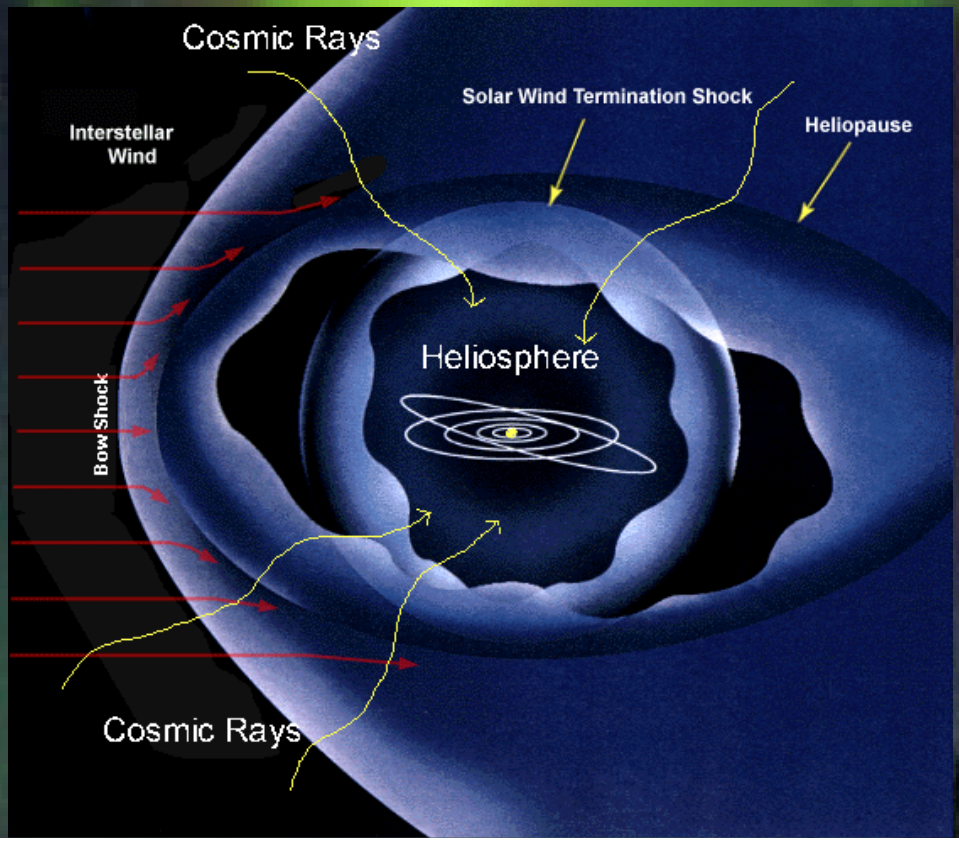
Ägypten2006

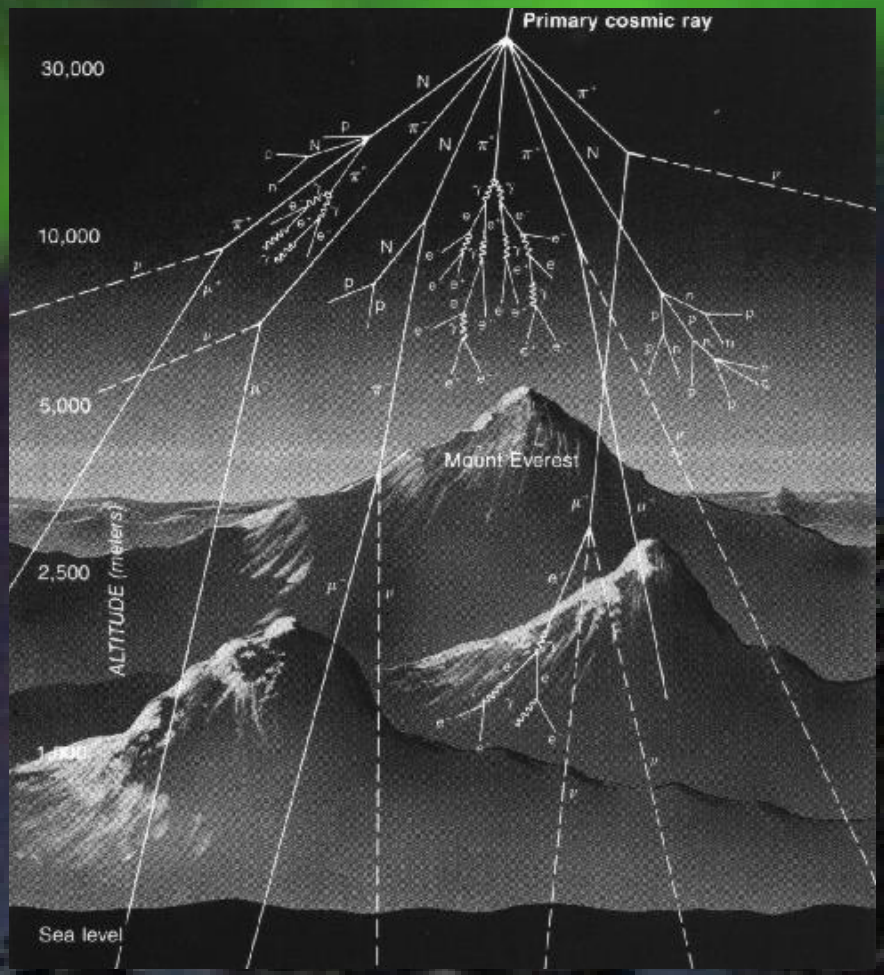
MPS

Solar activity, cosmic rays, and cloud cover on Earth

Variations in the solar activity/magnetic field changes the amount of cosmic particles penetrating into the solar system (and the Earth's atmosphere):

- Strong correlation with cosmic ray flux and low clouds has been found.
- The global cloud cover is an important factor in climate forcing.

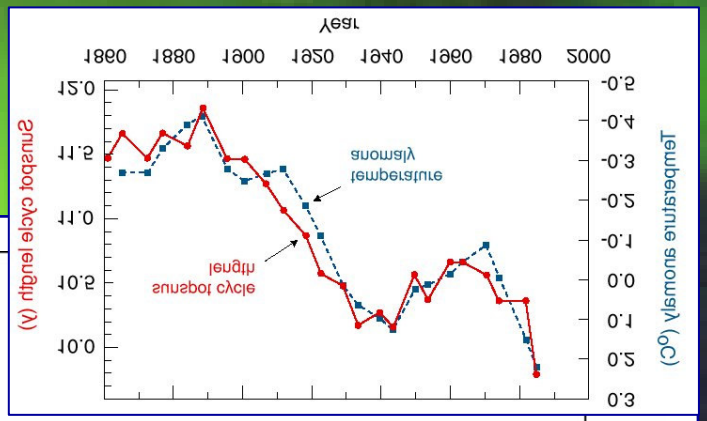




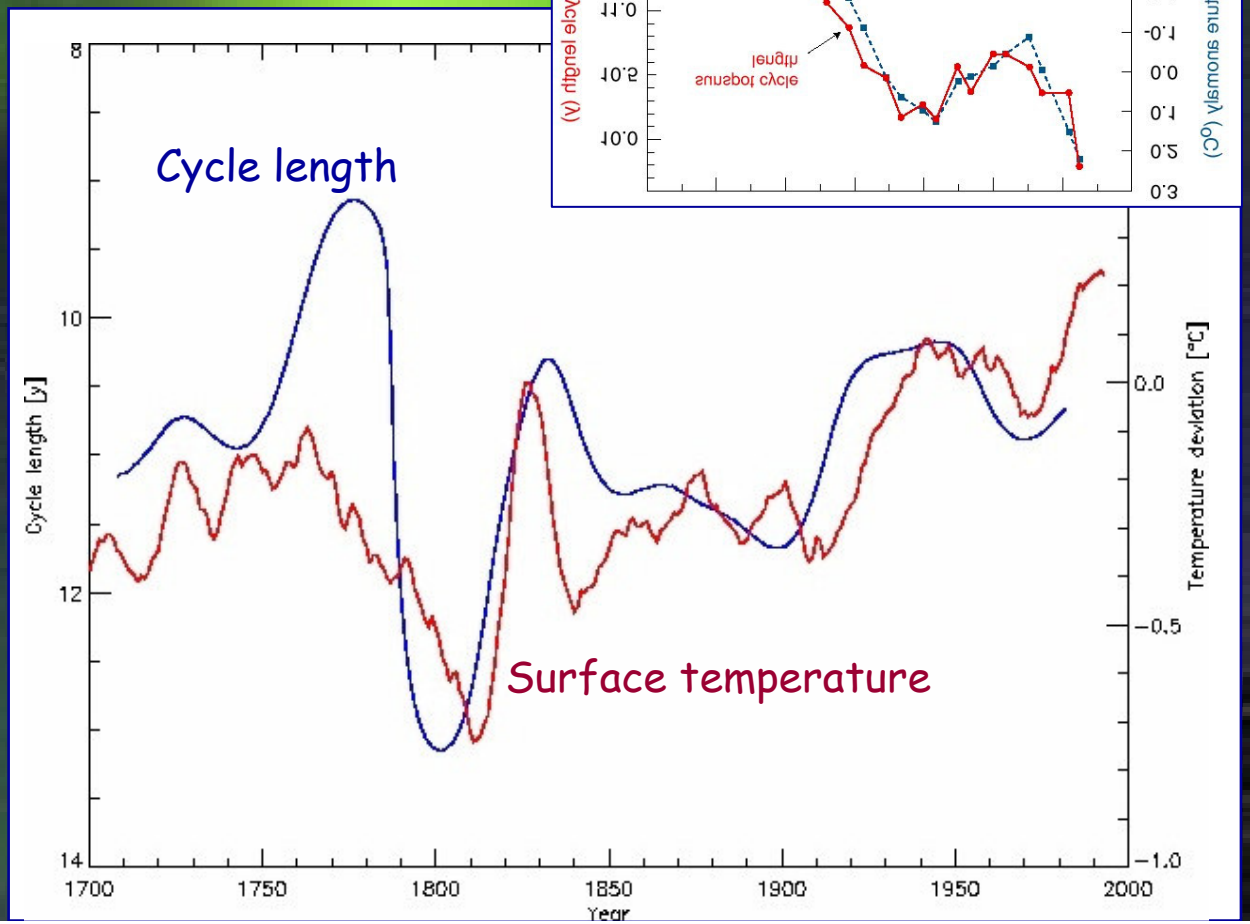
Ägypten2006

Solar cycle length and Earth's surface temperature

A remarkable though strange association!



Friis-Christensen & Lassen (1991)

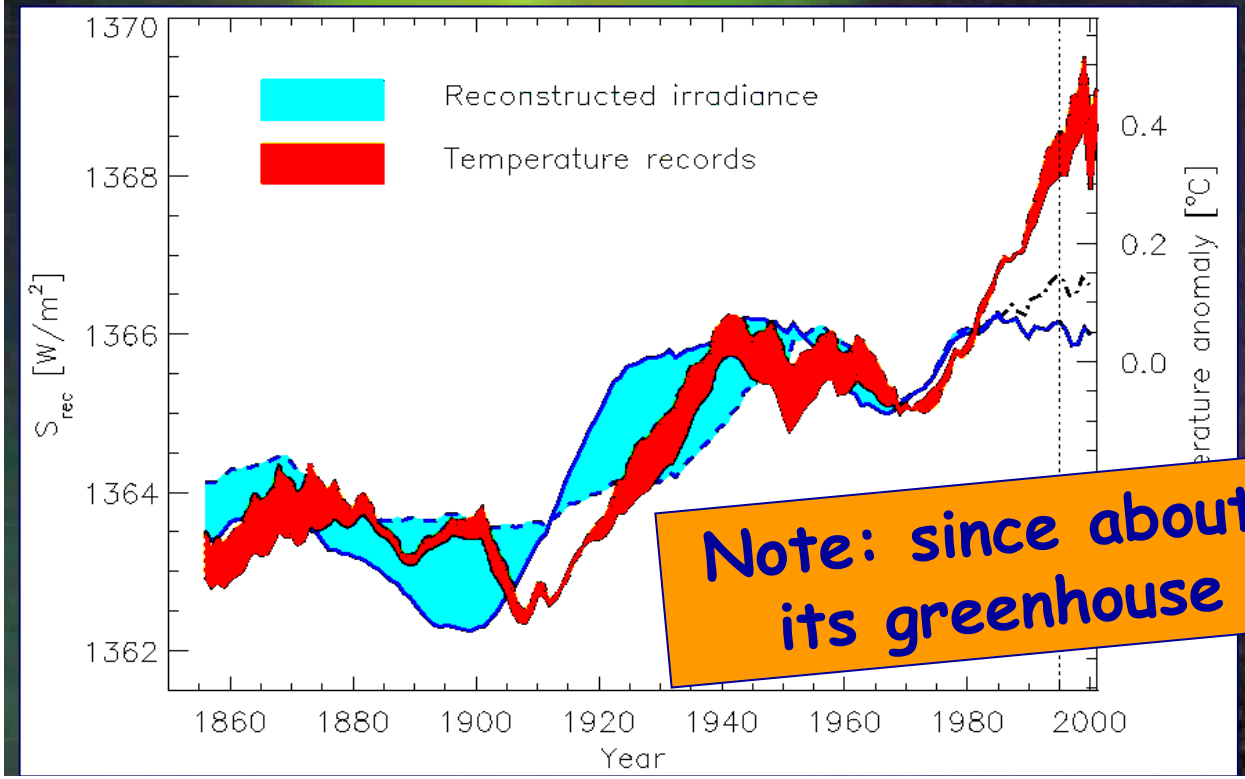


Fligge & Solanki (2001)

The Sun and global warming of the Earth?

Potential causes:

1. Long term variations in total irradiance ("total energy") is assumed to only explain part of the global warming.
2. Long term variation in UV/EUV radiation changes chemistry (ozone!), temperature etc. in the Earth's atmosphere.
3. Long term variation in the Sun's magnetic field modulates galactic cosmic rays and the solar wind.



Note: since about 1980 mankind and its greenhouse effect took over!

Let us take care of our precious blue planet!

Join international research efforts!
All data are public through the Internet.

Try, e.g., http://star.mpae.gwdg.de