Space Weather

Joachim Raeder

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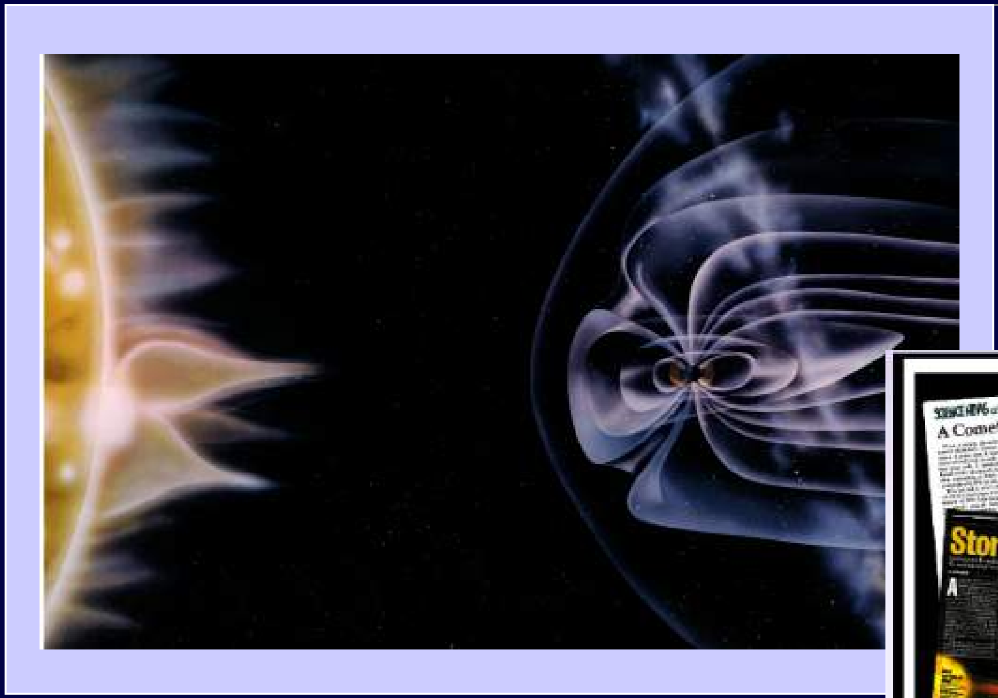
Physics Department

Many thanks to Howard Singer (NOAA/SEC) for much of the material

SPACE WEATHER, STORMS IN SPACE, AND THE AURORA

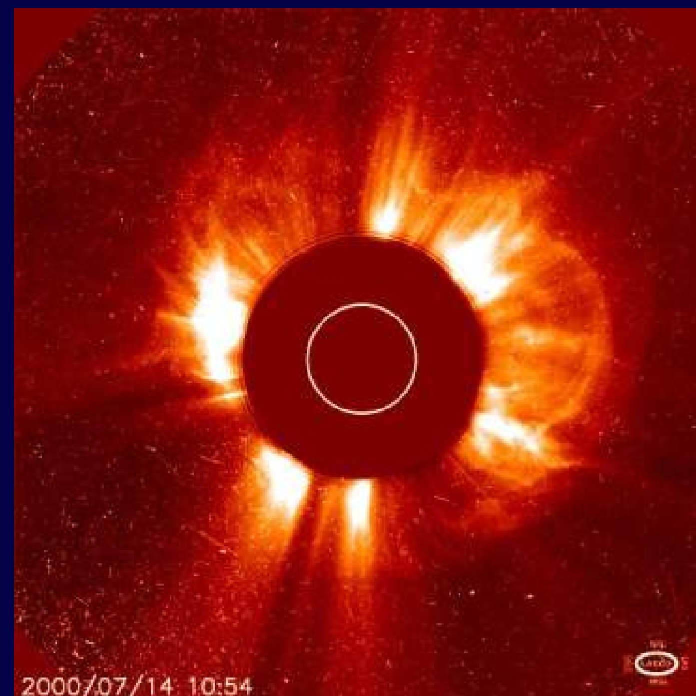


SPD Summer School, UNH, June 2006

SPACE WEATHER, STORMS IN SPACE, AND THE AURORA

Weather

Space Weather



Hurricanes and Tornados

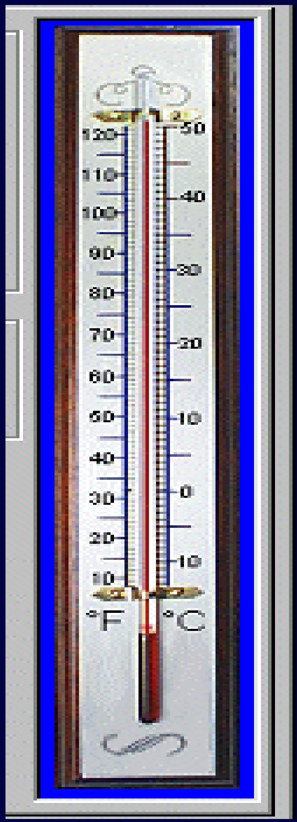
Solar Corornal Mass Ejection

SPACE WEATHER, STORMS IN SPACE, AND THE AURORA

Monitor and Measure

Weather

Space Weather



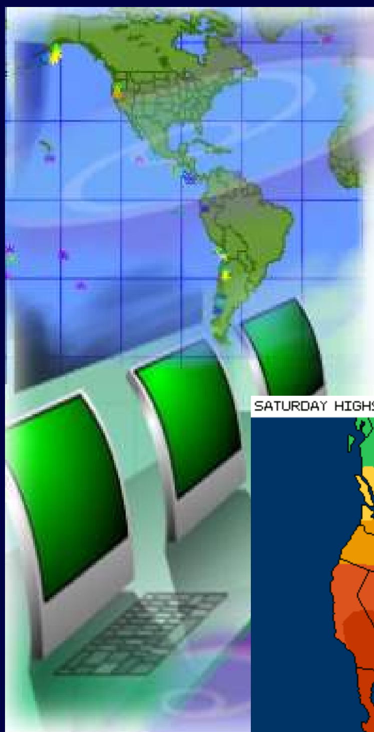
Thermometer

Energetic Particle Sensor

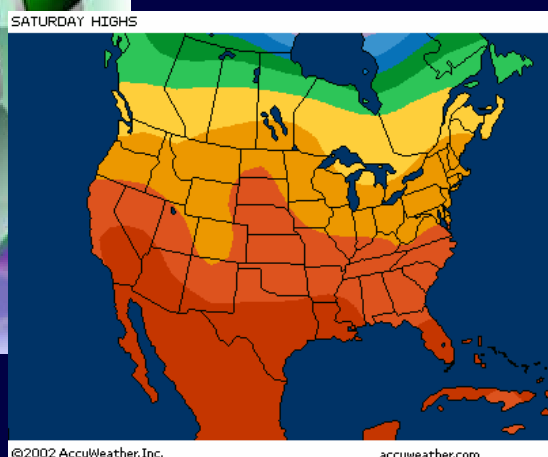
SPACE WEATHER, STORMS IN SPACE, AND THE AURORA

Services

Weather



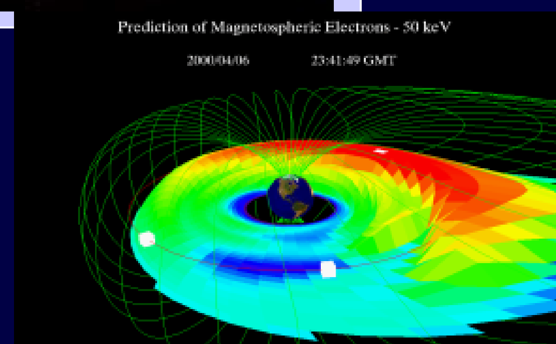
NOAA National Weather Service



Accuweather

Space Weather

NOAA Space Environment Center



Vendors with enhanced Products

SPACE WEATHER, STORMS IN SPACE, AND THE AURORA

Electric Power Transformer

Auroral Research in Kiruna Sweden

International Space Station

Geomagnetic Storm Effects on Telegraph Operations - September 3, 1859

***Boston (to Portland operator*).--"Please cut off your battery entirely from the line for fifteen minutes."**

***Portland*.--"Will do so. It is now disconnected."**

***Boston.*--"Mine is also disconnected and we are working with the auroral current. How do you receive my writing?"**

***Portland*.--"Better than with our batteries on. Current comes and goes gradually."**

***Boston.*--"My current is very strong at times, and we can work better without batteries, as the aurora seems to neutralize and augment our batteries alternately, making the current too strong at times for our relay magnets. Suppose we work without batteries while we are affected by this trouble?"**

***Portland*.--"Very well. Shall I go ahead with business?"**

Boston.--"Yes. Go ahead."

(Annual of Scientific Discovery, ed. by D.A. Wells, Boston, Gould and Lincoln, p414, 1860; Singer, H.J., Magnetospheric Pulsations, Model and Observations of Standing Alfven Wave Resonances, Thesis, UCLA, 1980.)

1958 Geomagnetic Storm

- On February 9, 1958 an explosive brightening was observed on the solar disk at the Sacramento Peak Observatory
- A notice was radioed to the IGY Data Center on Solar Activity at the Univ. Colorado's High Altitude Observatory in Boulder
- 28 hours later one of the greatest magnetic storms on record began
- It was the 13th most disturbed day from 1932 to the present
- Effects:
  - Toronto area plunged into temporary darkness
  - Western Union experienced serious interruptions on its nine North Atlantic telegraph cables
  - Overseas airlines communications problems

Brooks, J., The Subtle Storm, *New Yorker Magazine*, 39-77, Feb. 7, 1959.

1958 Geomagnetic Storm and Prophecy

- **"The forecasters at the Central Radio Propagation Laboratory are among the most valorous of prophets, since they are called upon to make their predictions with very little in the way of scientific knowledge to guide them."**
- **"In future years, it may be that the Weather Bureau or some Space Age equivalent will warn us of approaching magnetic storms, just as we are now warned of approaching hurricanes,…"**
- **"…nobody knows what kinds of apparatus still undreamed of may come along to be thrown out of whack by their [storms] caprices."**

Brooks: The Subtle Storm, *New Yorker Magazine*, 1959.

The Sun

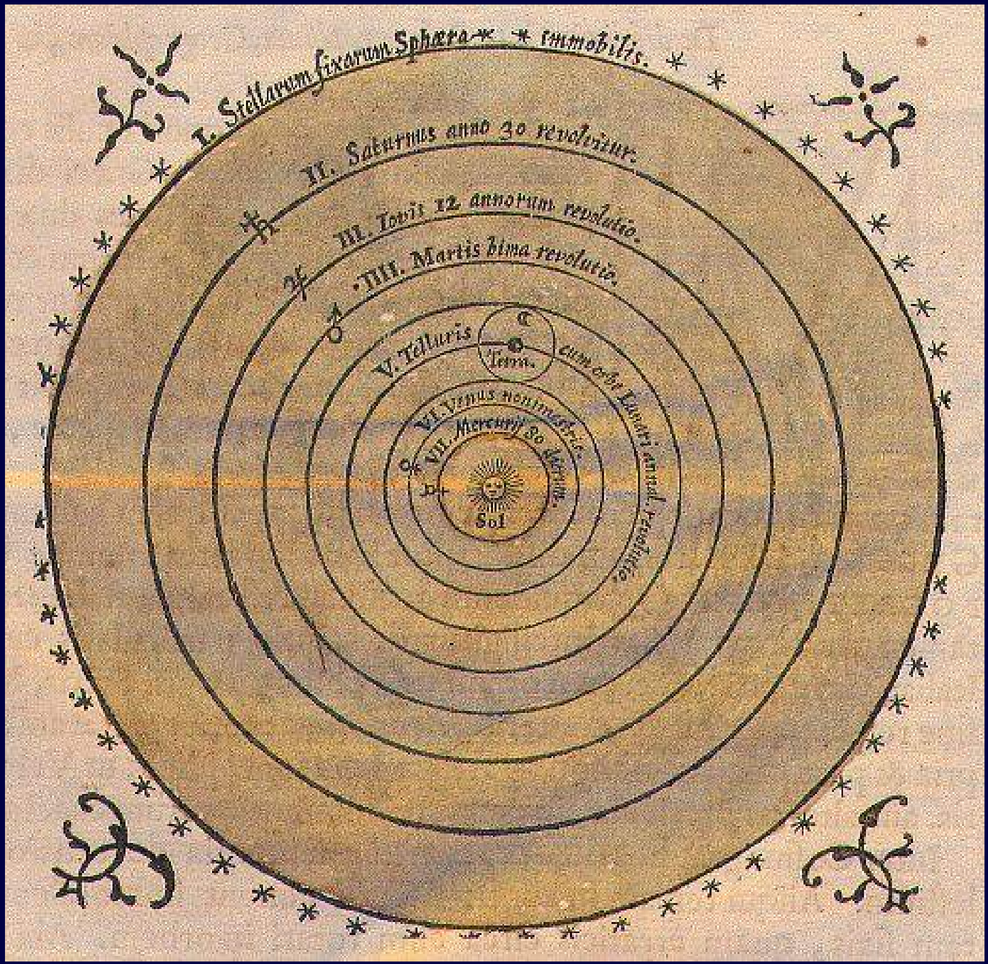
Nicholas Copernicus, Polish Astronomer (1473 -1543)

"In the middle of everything is the sun... For, the sun is not inappropriately called by some the lantern of the universe, by others, its mind, and, its ruler by others still….Thus indeed, as though seated on a royal throne, the sun rules the family of planets revolving around it."

-- And is the birthplace of Earth's Space Weather.

The Sun

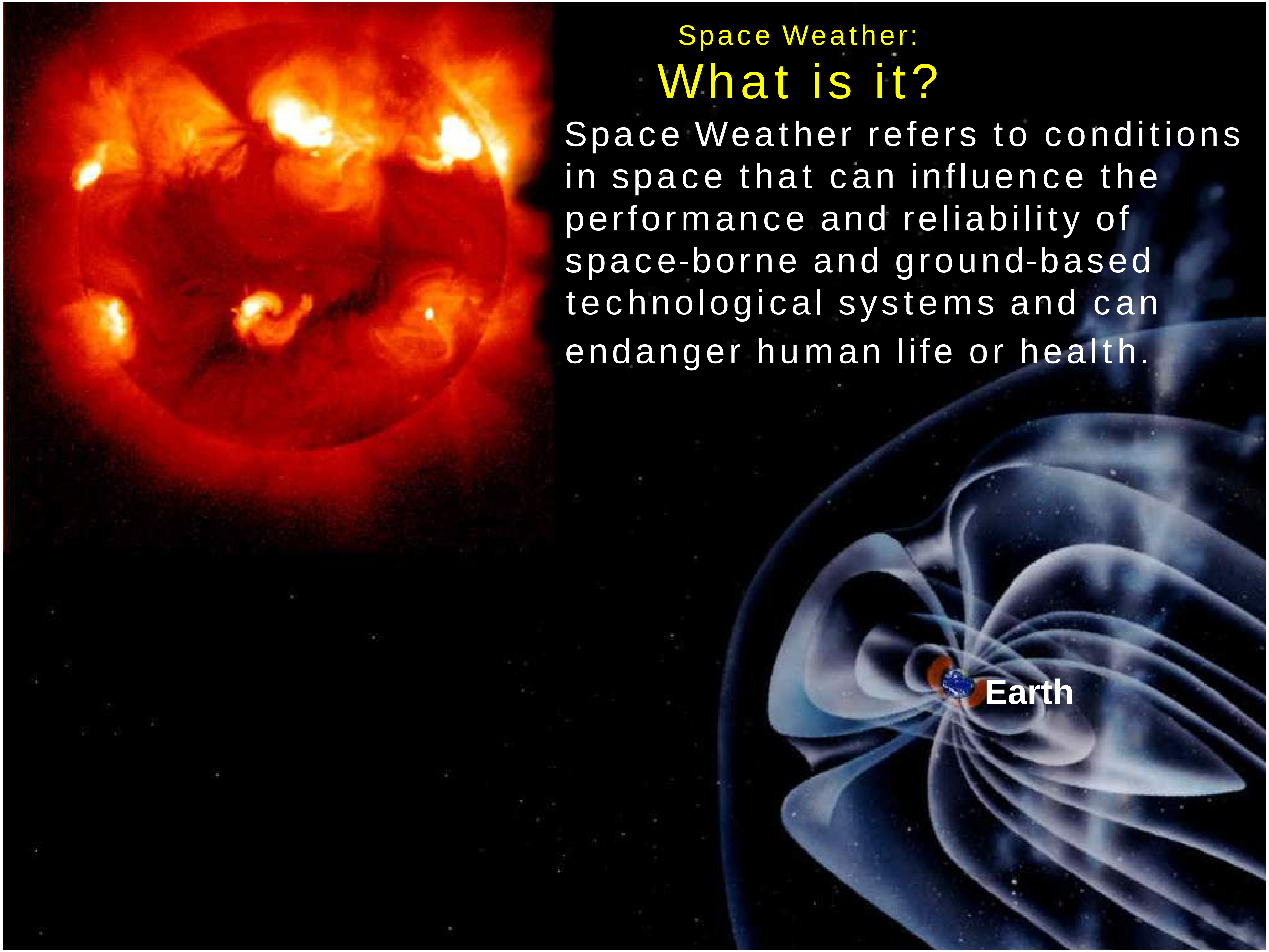
Nicholas Copernicus puts it in the center



Space Weather:

What is it?

Space Weather refers to conditions in space that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.



Space Weather:

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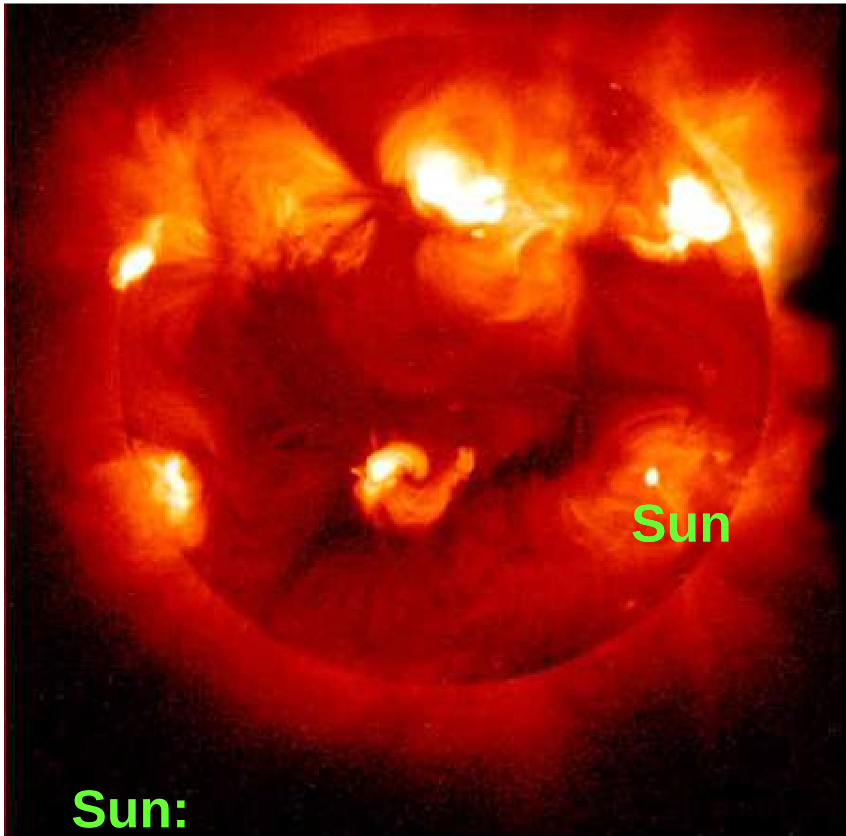
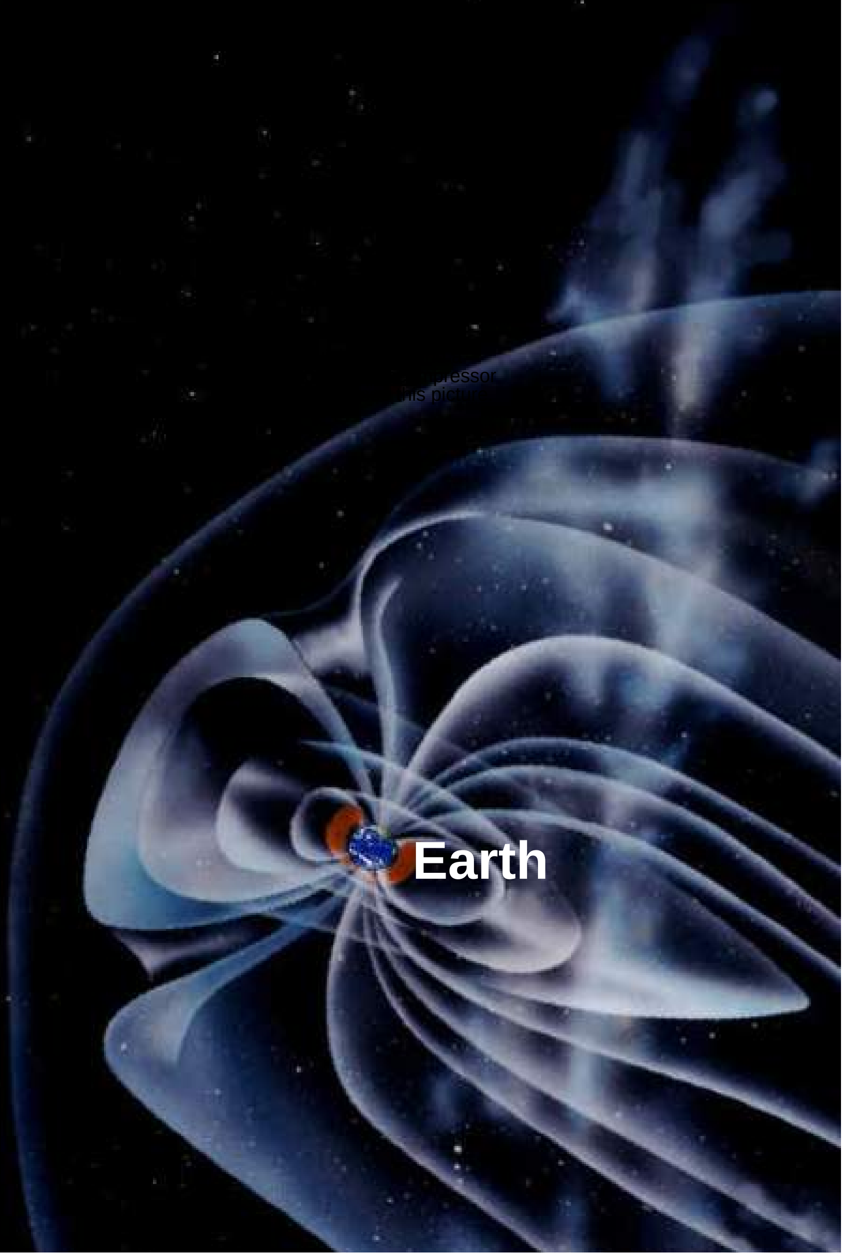
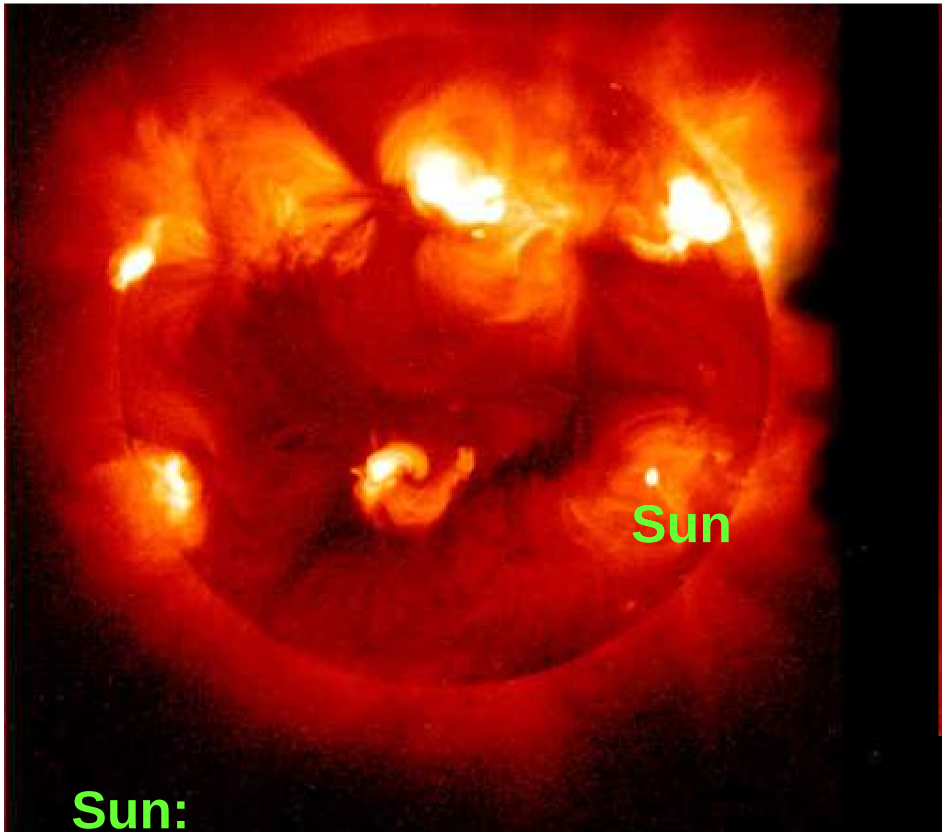


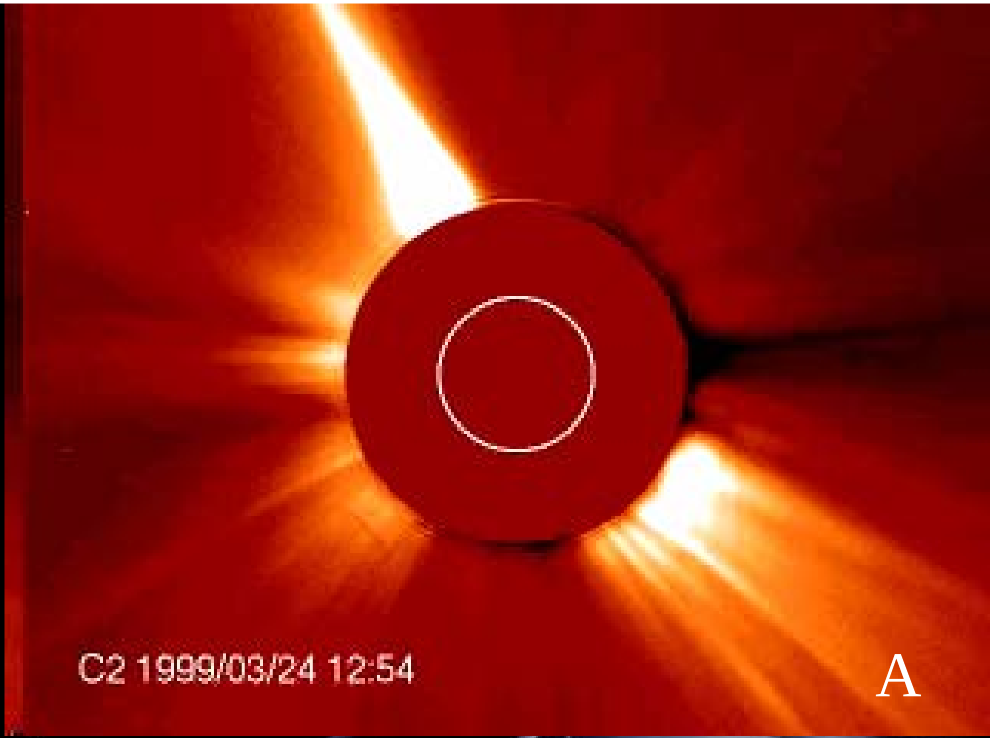
Sun:

- **Energy released in the form of photons, particles, and magnetic fields**

- **Sources of major disturbances:**
  - **Coronal Holes**
  - **Solar Flares**
  - **Coronal Mass Ejections**
  - **Solar Particle Events**







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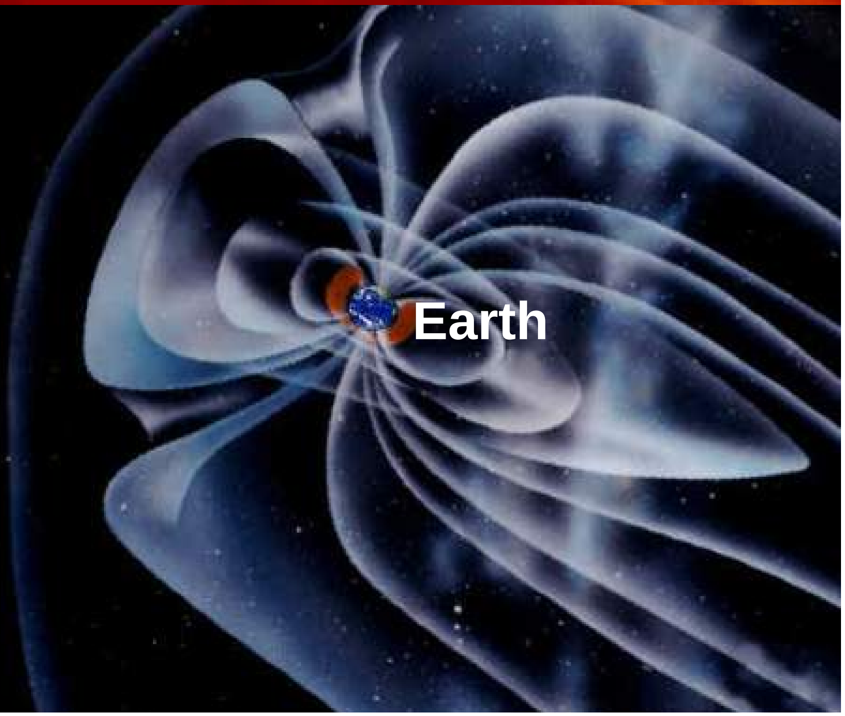
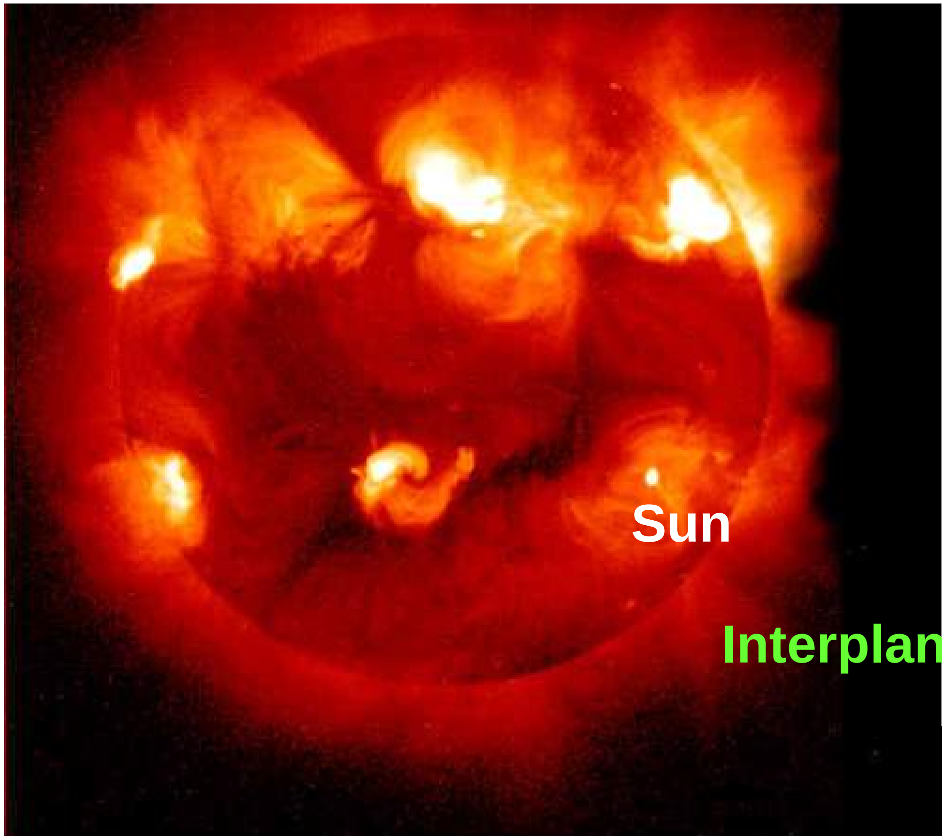
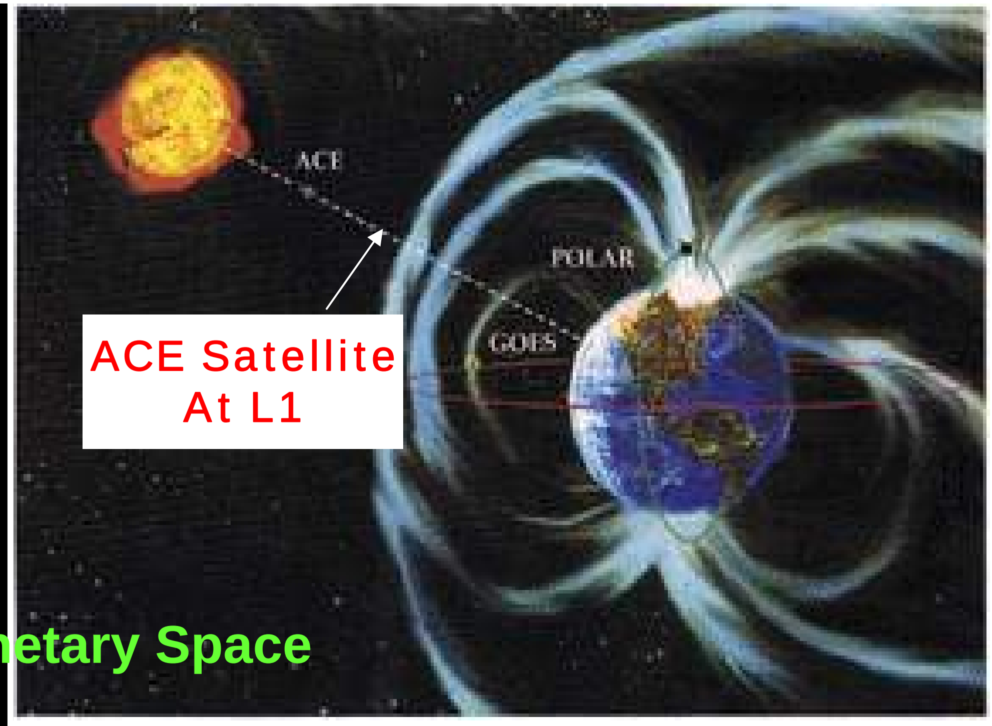
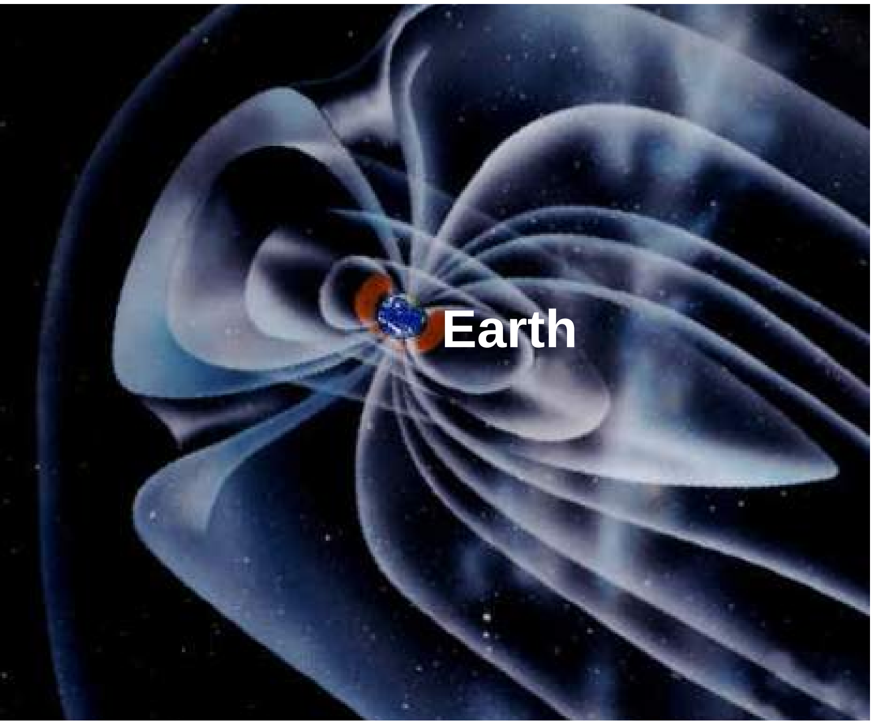




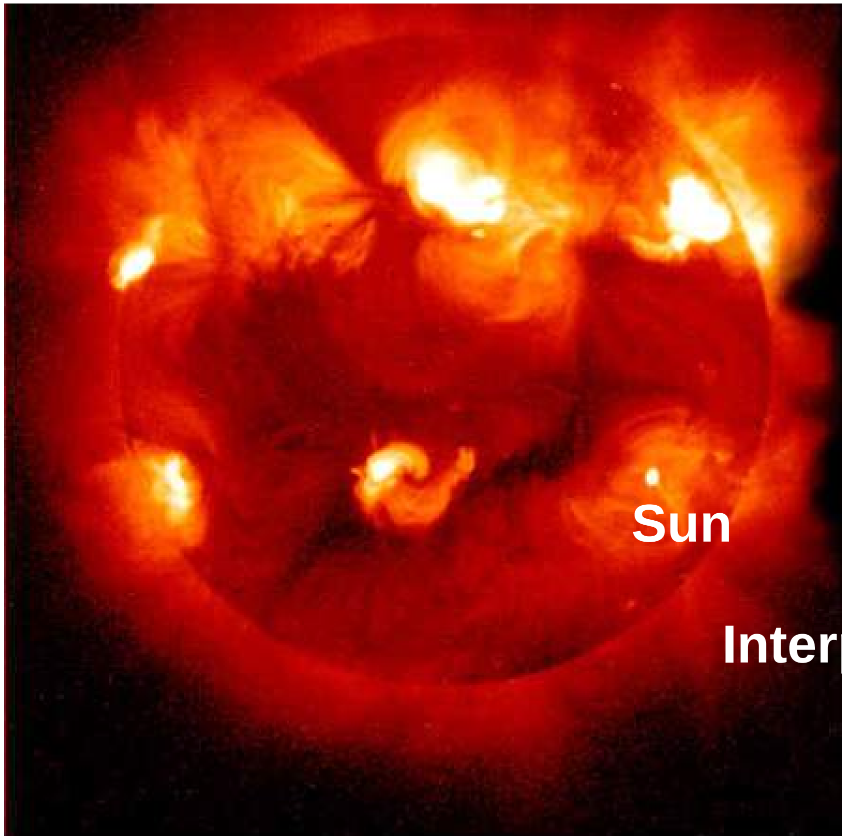


Interplanetary Space

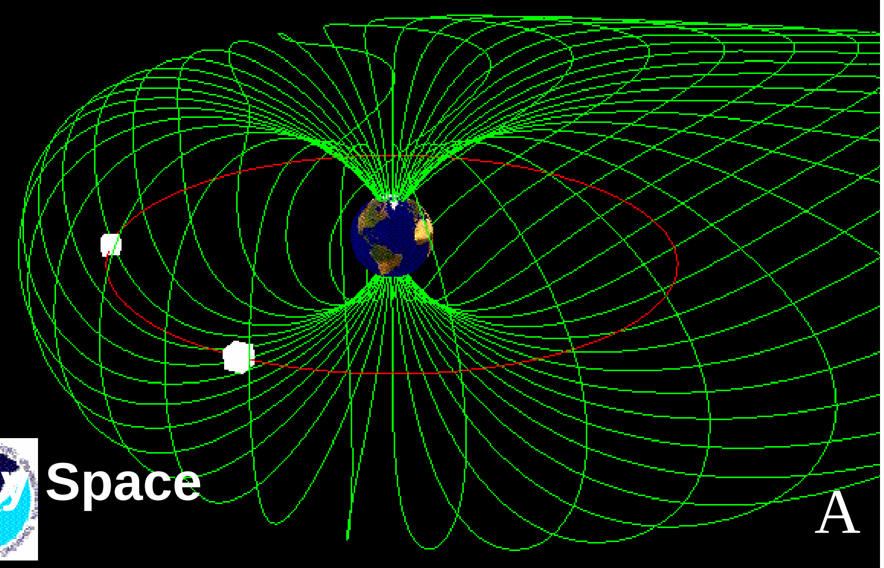


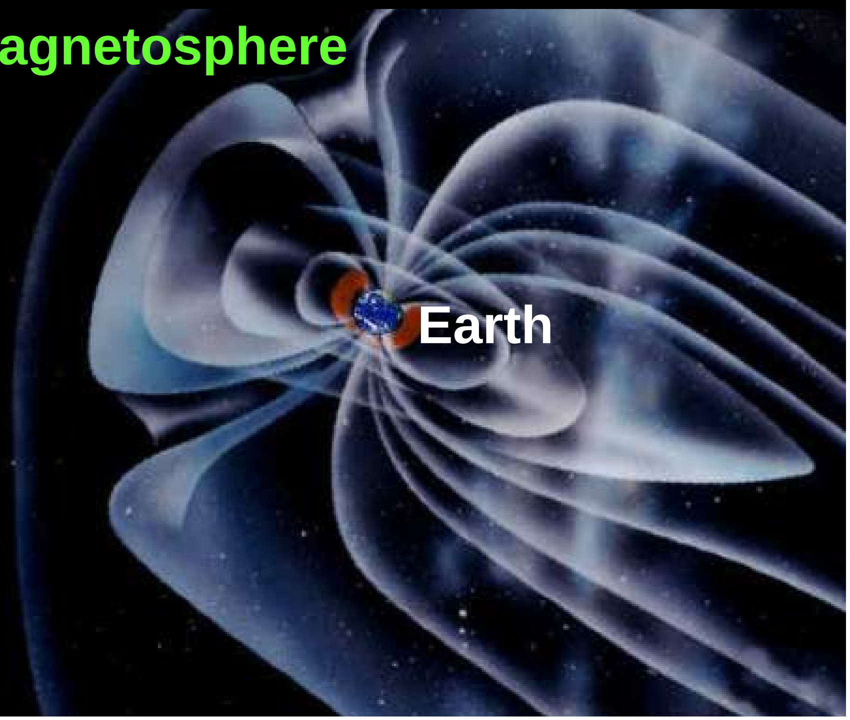
Interplanetary Space:

- Solar Wind
  - Mostly electrons and protons
  - very tenuous, a few per cm**3
  - very hot, >10^4 K
  - Magnetic field, a few nano-T
  - high velocity, 250-2000 km/sec
- Disturbances from the sun make shocks and waves in the solar wind



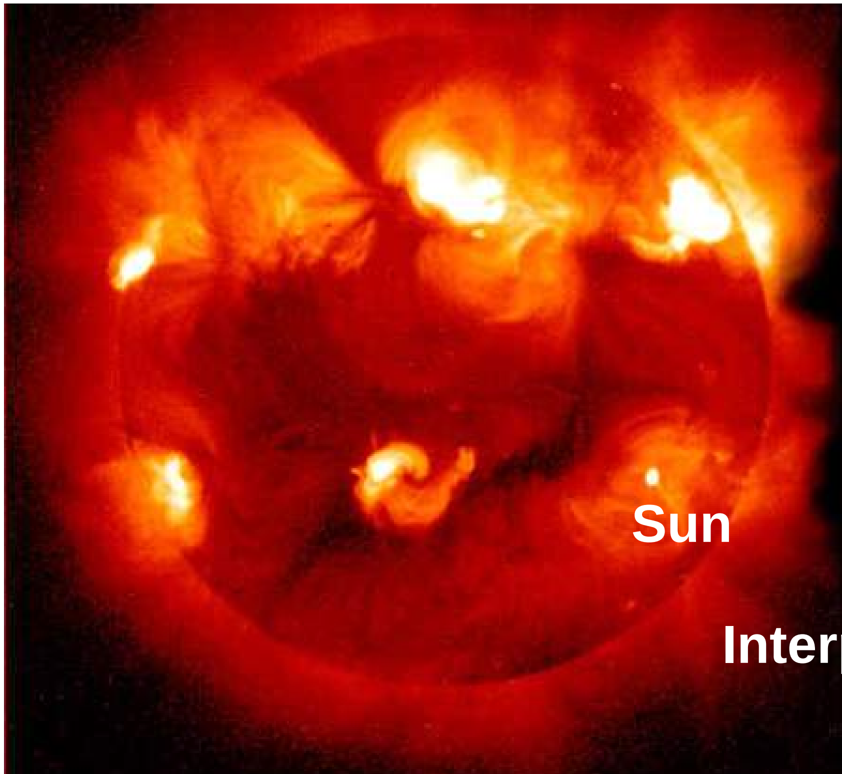
Interplanetary Space



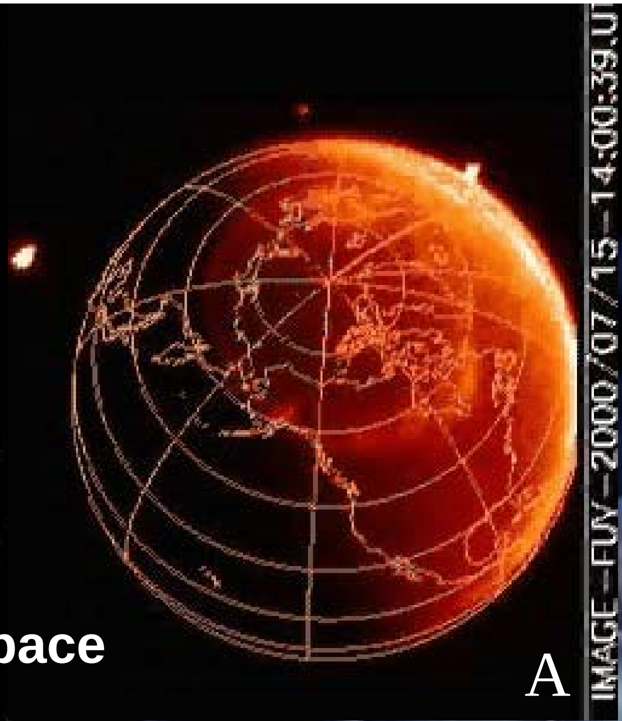


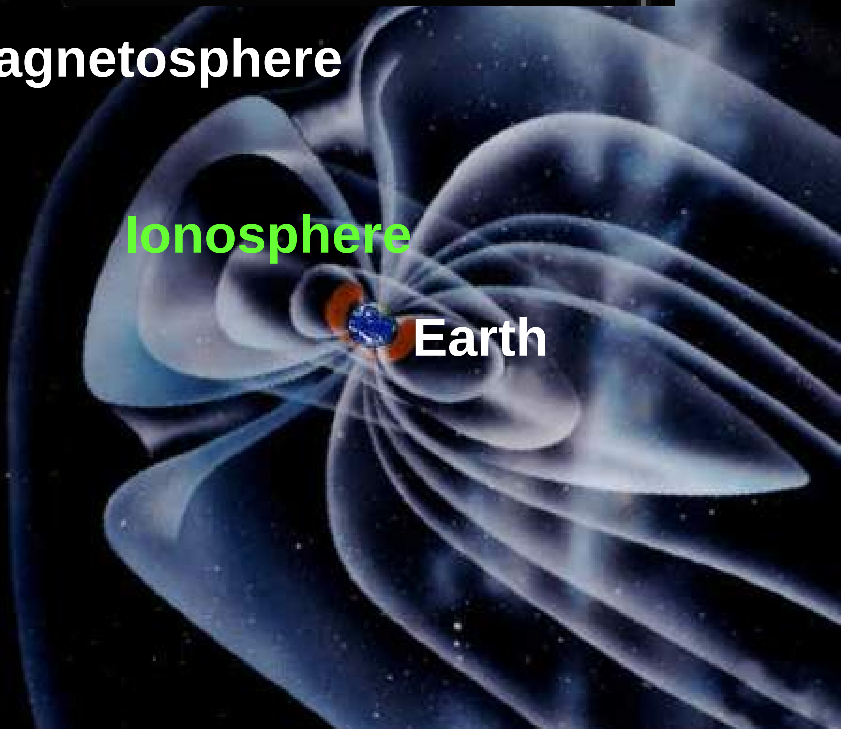
Magnetosphere:

- **Created by Earth’s magnetic field**
- **Deformed by the Solar Wind**
  - **Particles (mostly electrons and protons) trapped on magnetic field lines**
  - **Polar regions are magnetically open**



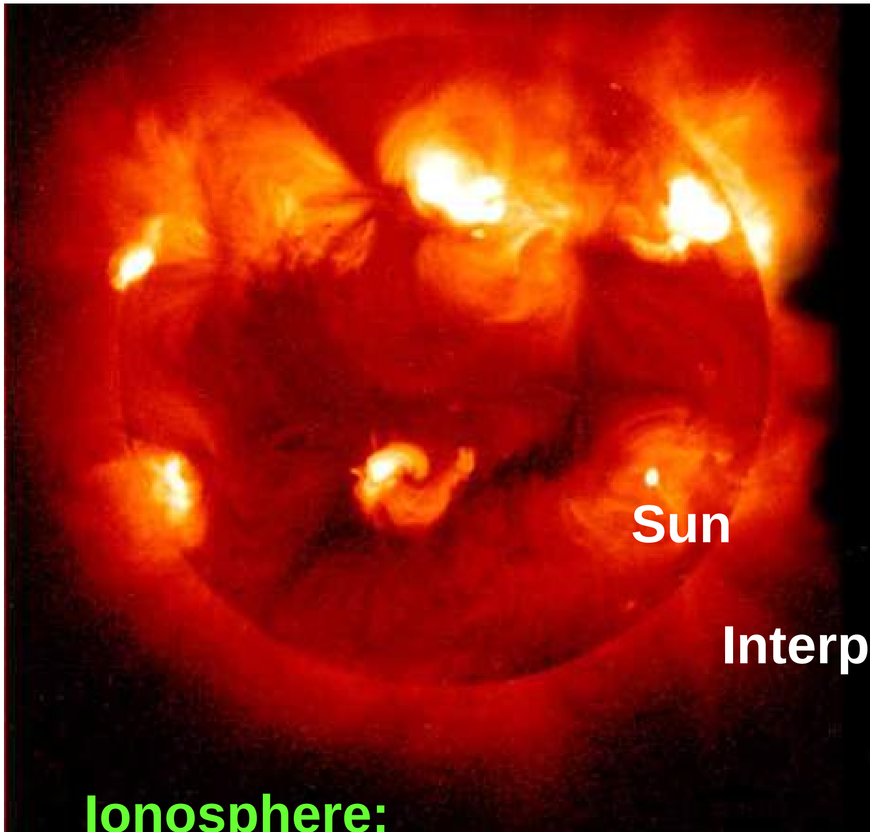
Interplanetary Space

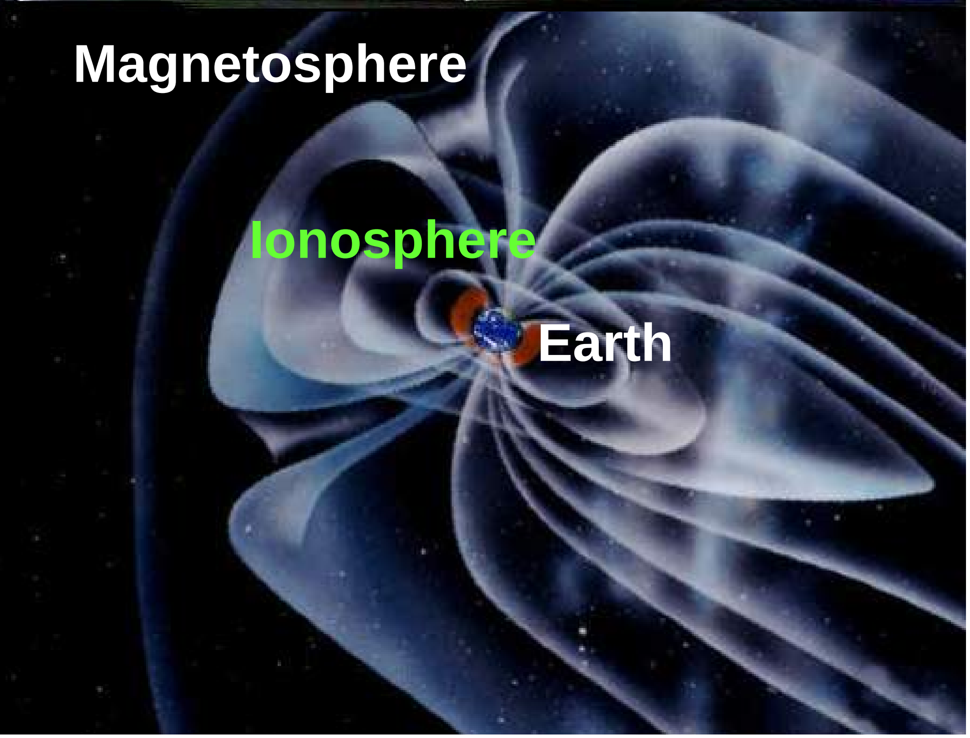




Ionosphere:

- **Layer of electrons and ions at the top of the atmosphere (100 – 300 km and up)**
- **Formed when extreme ultraviolet light from the sun impinges on Earth's atmosphere**
- **Critical in the reflection and transmission of radio waves**





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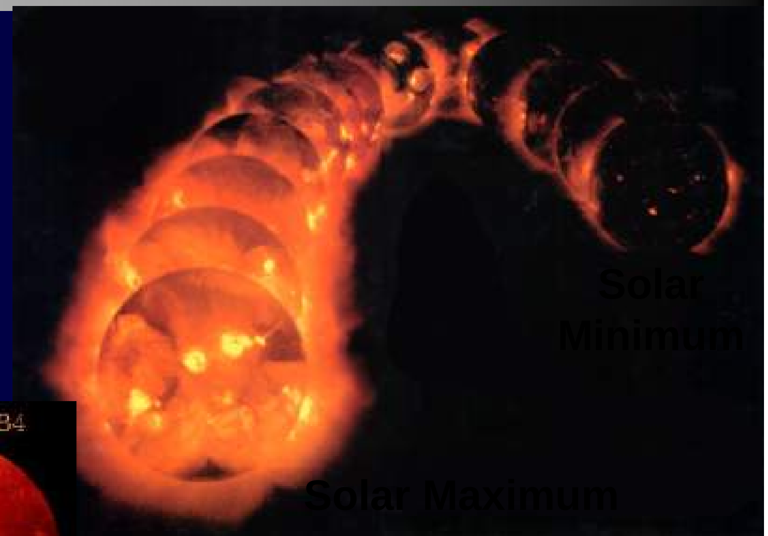
- Formed when extreme ultraviolet light from the sun impinges on Earth's atmosphere
- Critical in the reflection and transmission of radio waves

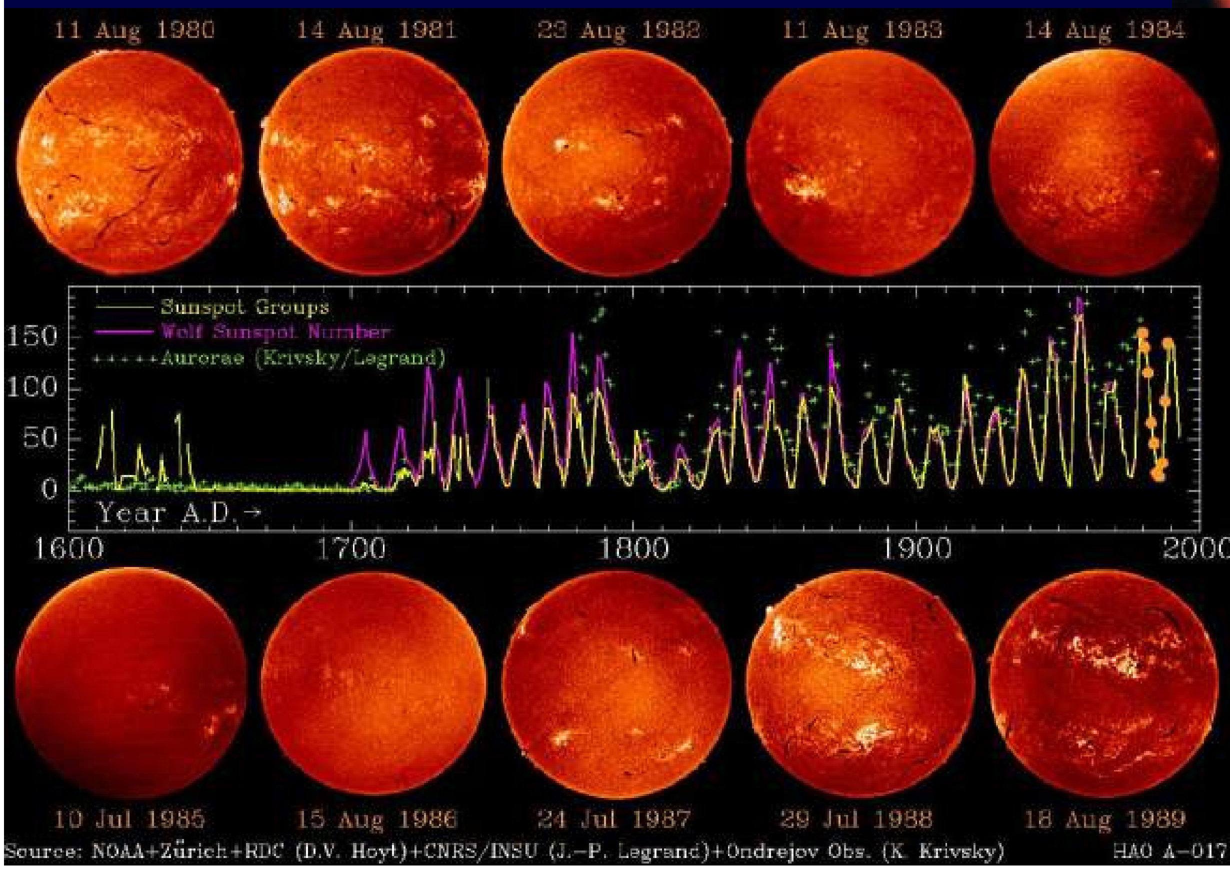
Sun to Earth

- **An animation of a space weather event as it starts at the sun and ends up at Earth**
  - **Solar Flare**
    - **Light**
    - **Particles**
  - **CME**
    - **Particles and Fields**
  - **Magnetosphere**
    - **Deflects the solar wind**
    - **Energy transfer from solar wind to magnetosphere when interplanetary field opposite direction of Earth's field**
    - **Accelerates particles**
  - **Ionosphere**
    - **Accelerated particles collide with the atmosphere producing the aurora**

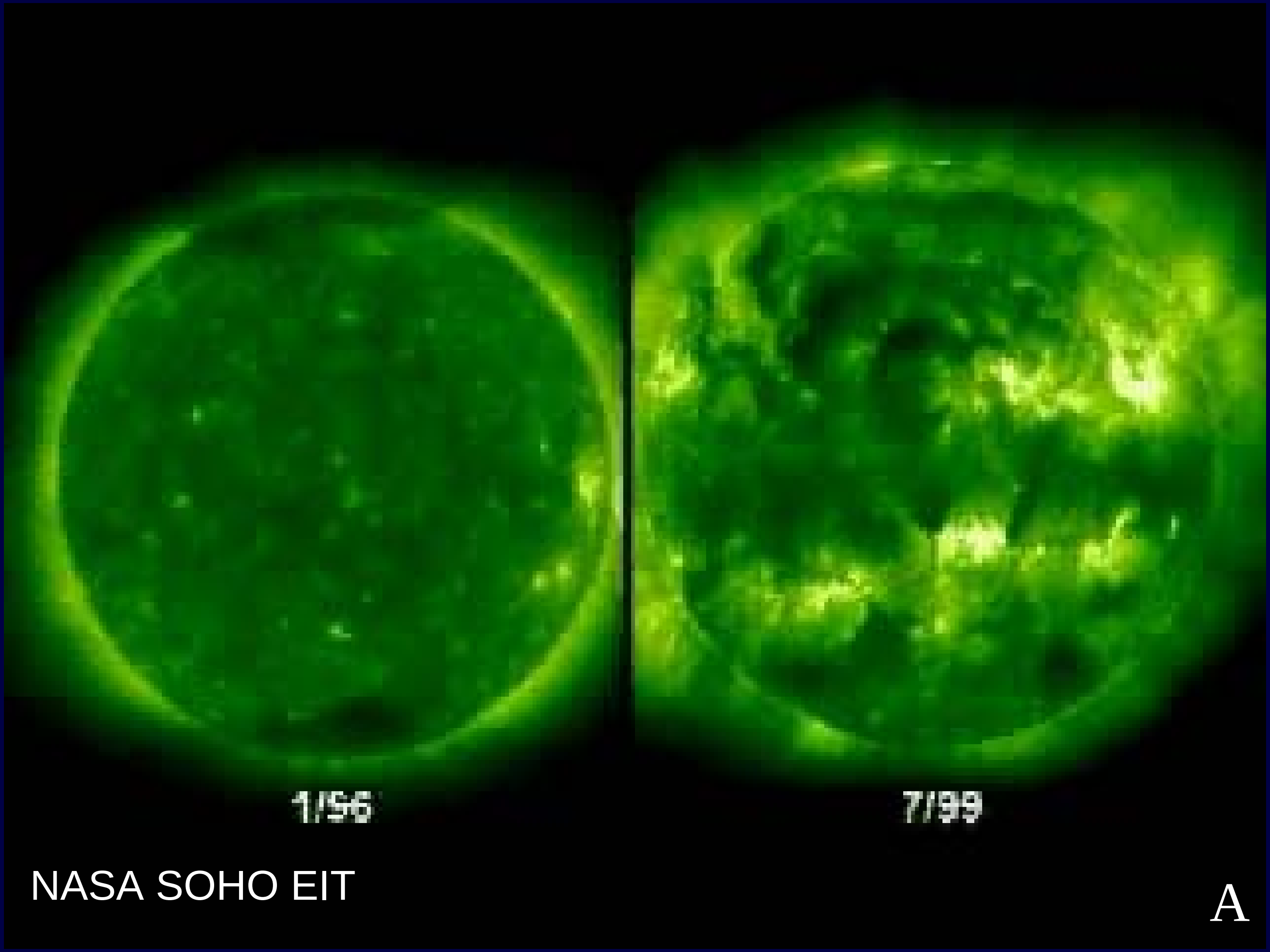
The Solar Cycles of the Past

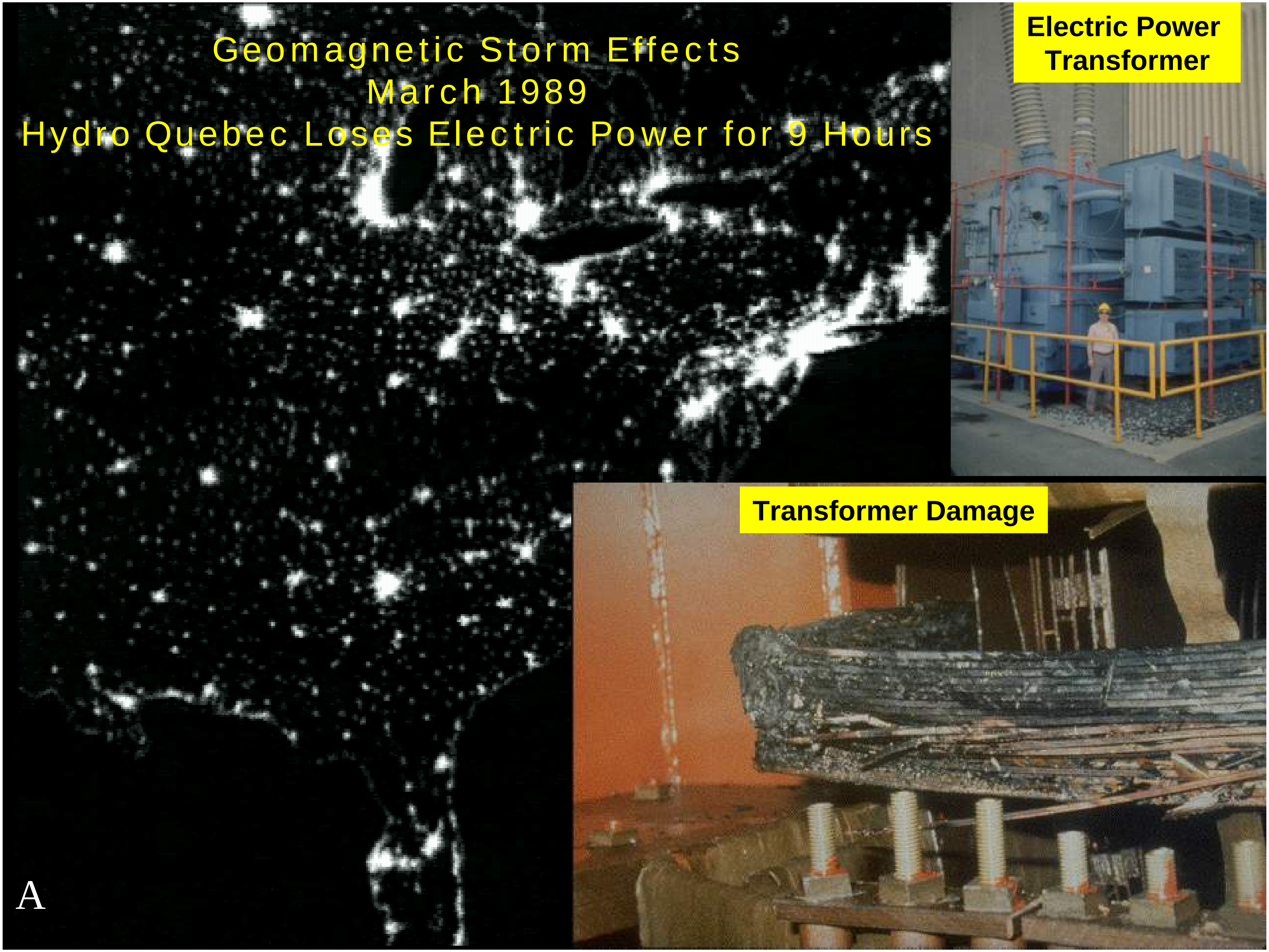
- **Climatology**
- **Sunspots have been recorded for the last 400 years**
- **Note that there were no sunspots for nearly 60 years after 1640**
- **During the same period, it was very cold in Europe. This is a period called "The Little Ice Age"**
- **Is there a Connection?**





Solar Minimum – 1996/7 Solar Maximum – 2000/1




Geomagnetic Storm Effects
March 1989
Hydro Quebec Loses Electric Power for 9 Hours
Electric Power Transformer
Transformer Damage
A

Energetic Particle Effects

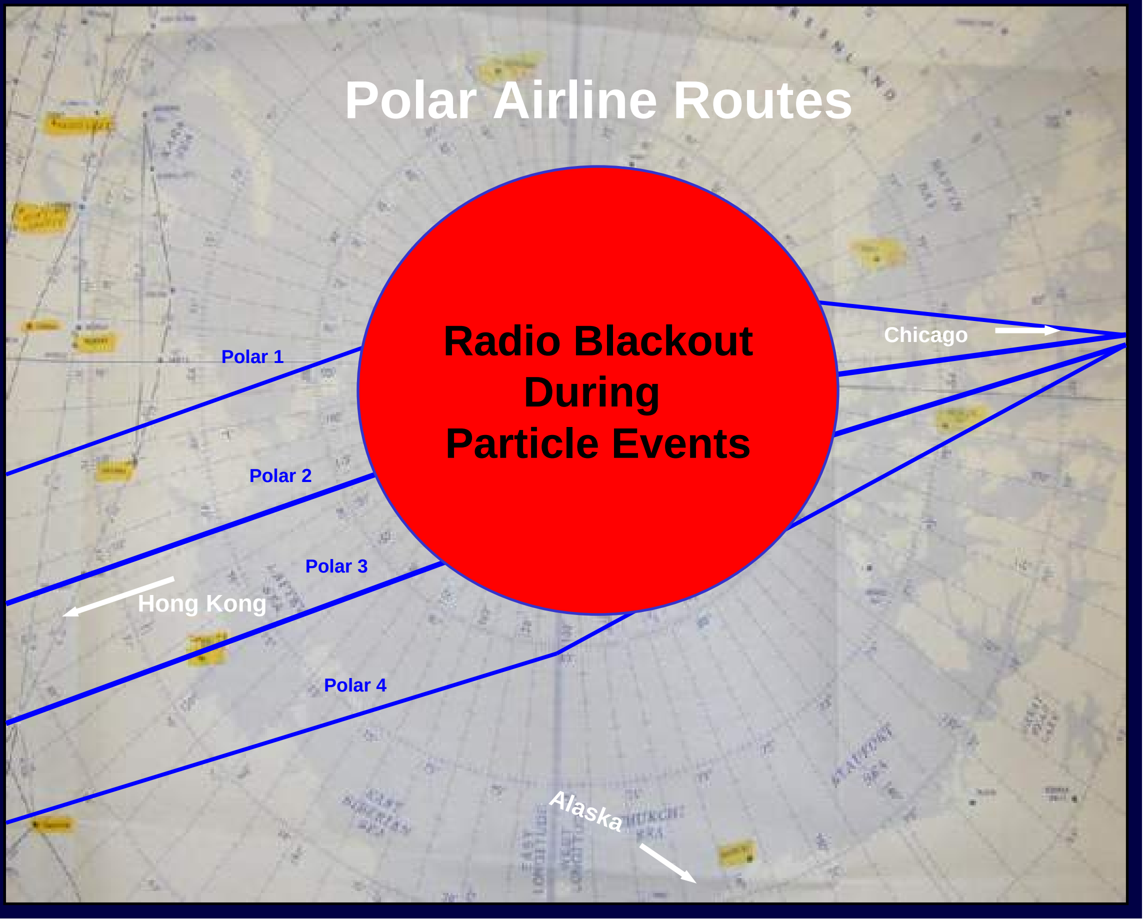
High Latitude HF Communications

Polar airline routes loose ground communications

- Alternate routes required
- Uses more fuel
- Flight delays

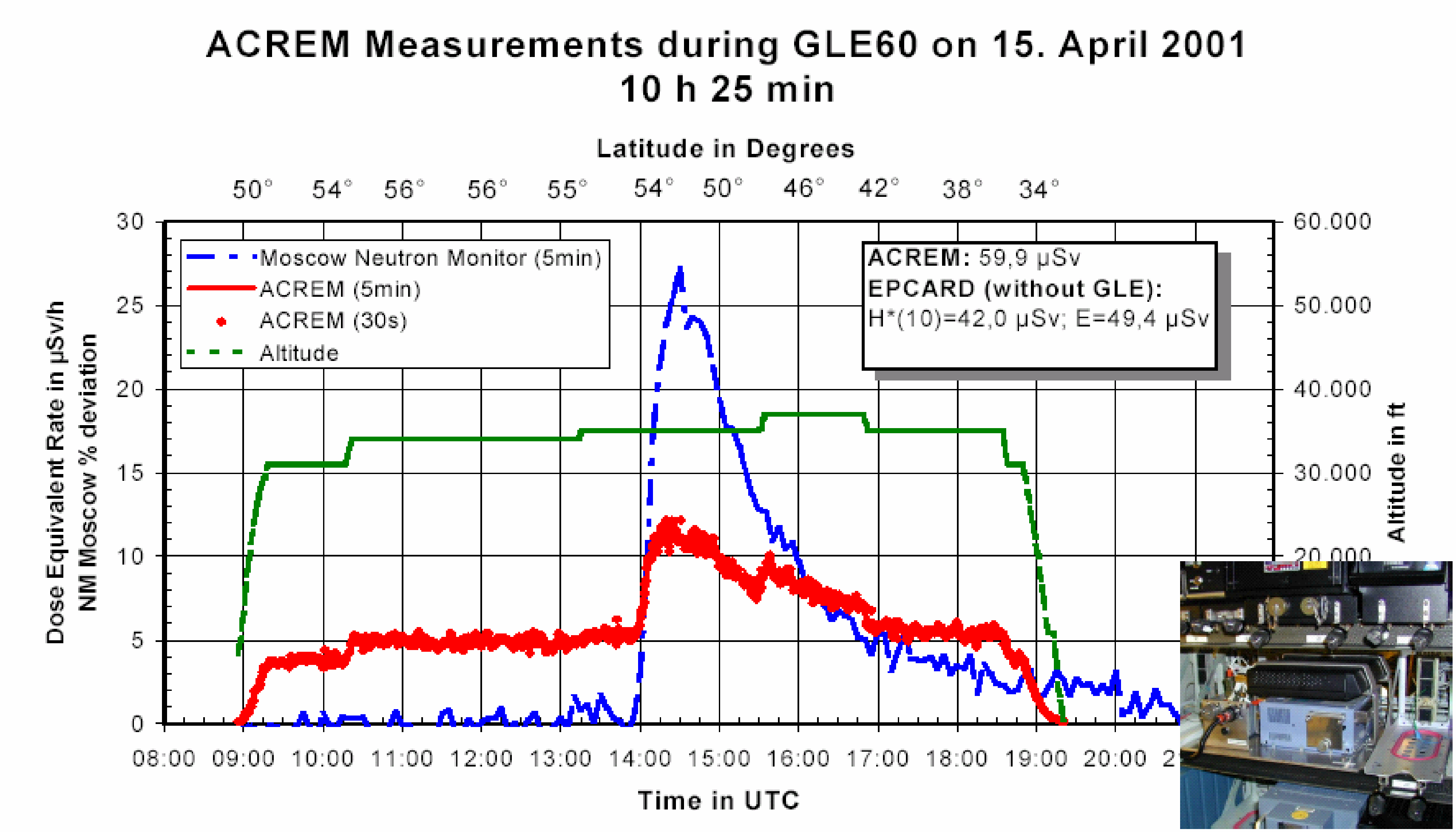
Sample of Flights Affected:

- **10/26/00: Lost of HF prior to 75N, re- route off Polar route with Tokyo fuel stop. 15:00 flight now 20:30**
- **11/10/00: Due to poor HF, ORD to HKG flown non-polar at 47 minute penalty**
- **3/30/01-4/21/01: 25 flights operated on less than optimum polar routes due to HF disturbances resulting in time penalties ranging from 6 to 48 minutes**
- **11/25/00: Polar flight re-route at 75N due to Solar Radiation, needed Tokyo fuel stop**
- **11/26/00: Operated non-polar at 37 minute penalty due to solar radiation**
- **11/27/00: Operated non polar at 32 minute penalty due to solar radiation.**
- **11/28/00: Operated non-polar at 35 minute penalty due to solar radiation**



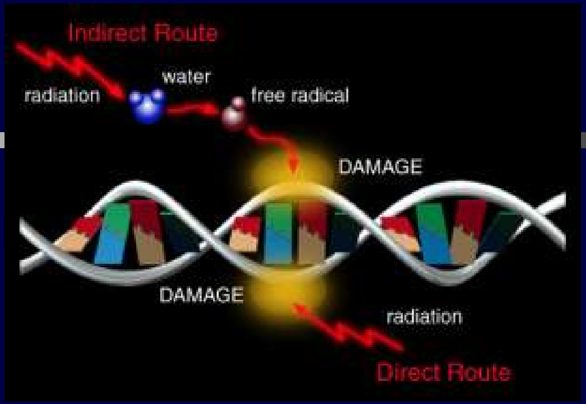
Cosmic Ray and Solar Proton Radiation Effects on Airline

ARCS - Health Physics Division



Energetic Particles Effects

Radiation Hazard



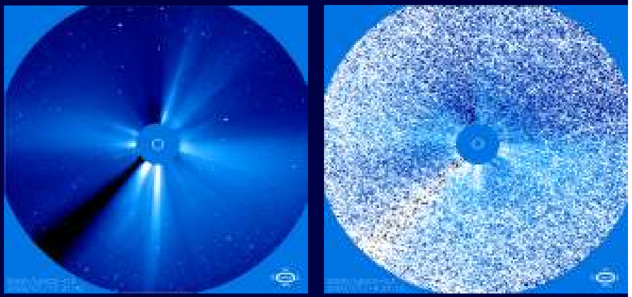
Health Hazards from Energetic Particles

- Humans in space
  - Space Shuttle, International Space Station, missions to Mars
- Crew/Passengers in high-flying jets
  - Concorde carries radiation detectors
  - Exposure limits set for European flight crews

Spacecraft Systems

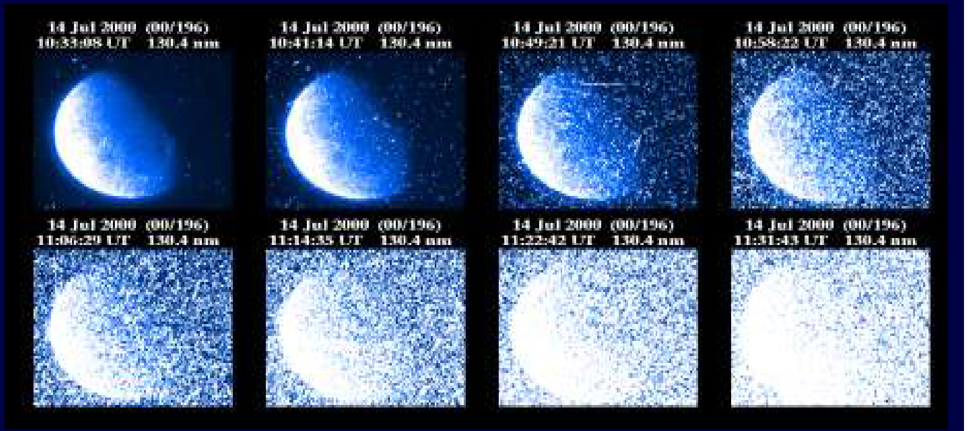
- Systems affected
  - Spacecraft electronics
    - Surface Charging and Discharge
    - Single Event Upsets (SEU)
    - Deep Dielectric Charging
    - USAF attributes 35% of SEU to space weather
  - Spacecraft imaging and attitude systems

SOHO Satellite Image Degradation

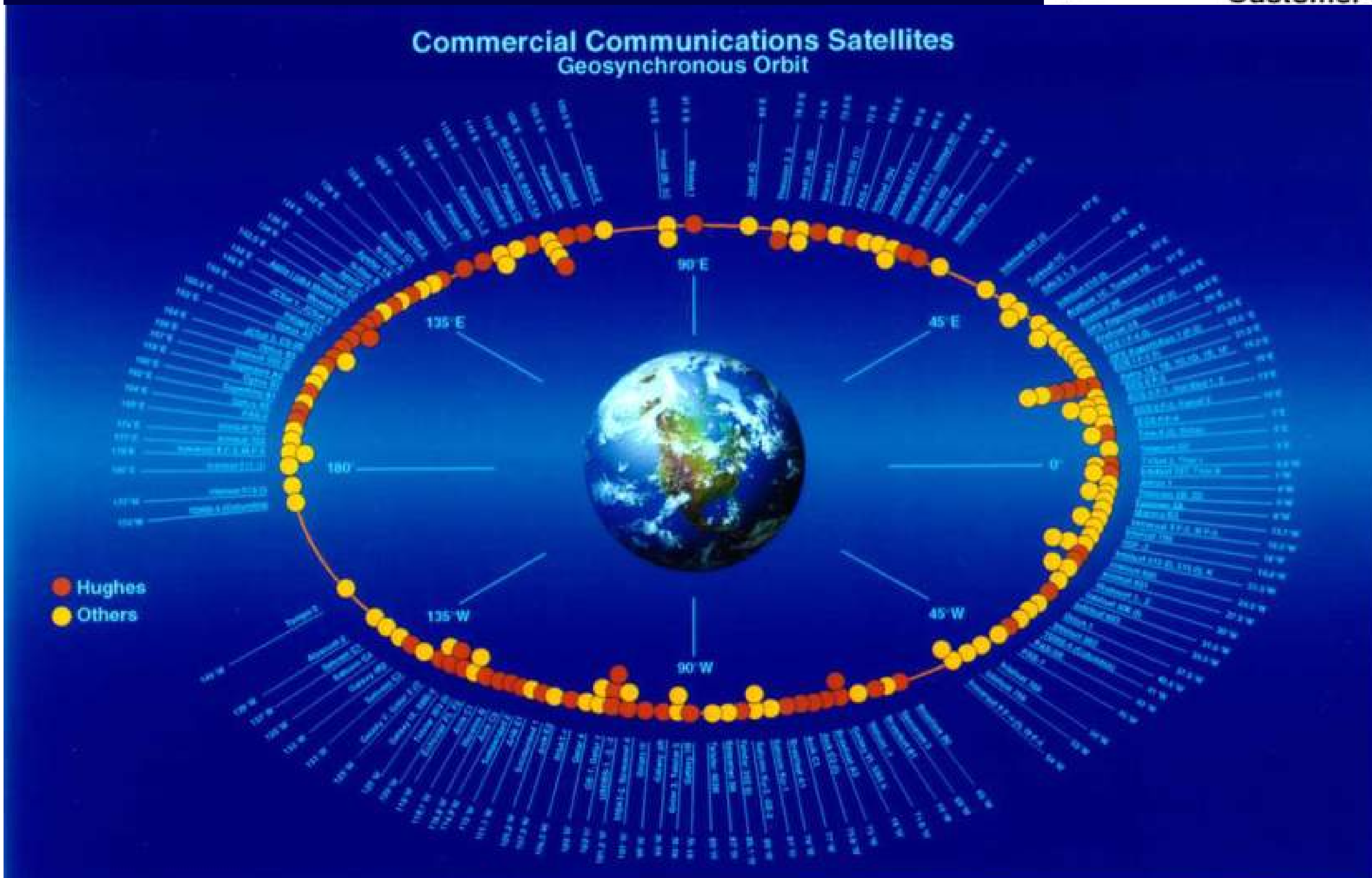


Spacecraft Surface Charging (animation)

Polar Satellite Image Degradation



GEOSYNCHRONOUS COMMUNICATIONS SATELLITES



CUSTOMER NEEDS

SPACE WEATHER OPERATIONS AT NOAA SEC

- Nation's official source of Space Weather alerts, warnings, and forecasts
- Synthesis of space environment data and information
- Works together with Research and Development to bring new understanding, models, and data into operations

Space Weather Scales

Similar to hurricane (C1-C5) and tornado (F1-F5) scales

- 3 Categories
  - Geomagnetic Storms (CMEs)
  - Solar Radiation Storms (Particle Events)
  - Radio Blackouts (Solar Flares)

http://sec.noaa.gov

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.sec.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: none. Satellite operations: infrequent single-event upsets possible. Other systems: small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

Geomagnetic Storm Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
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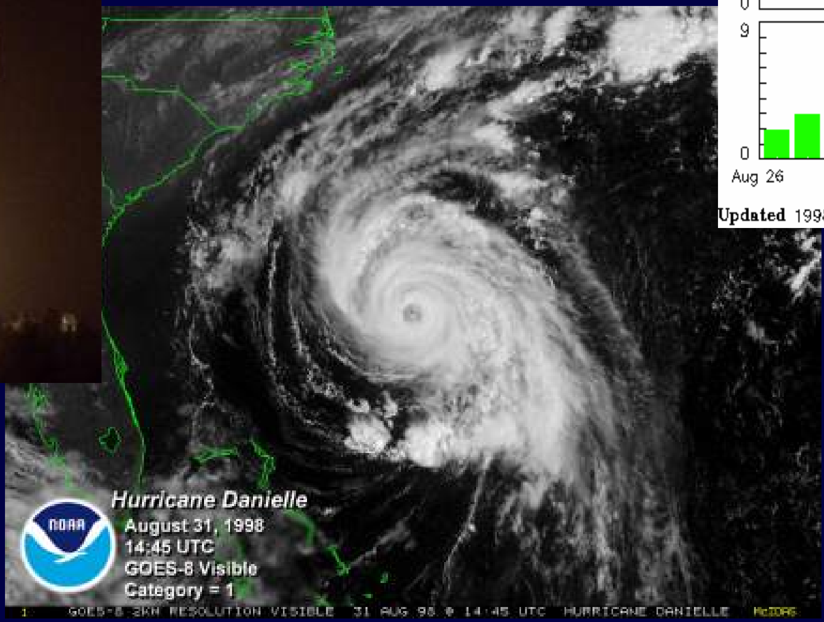
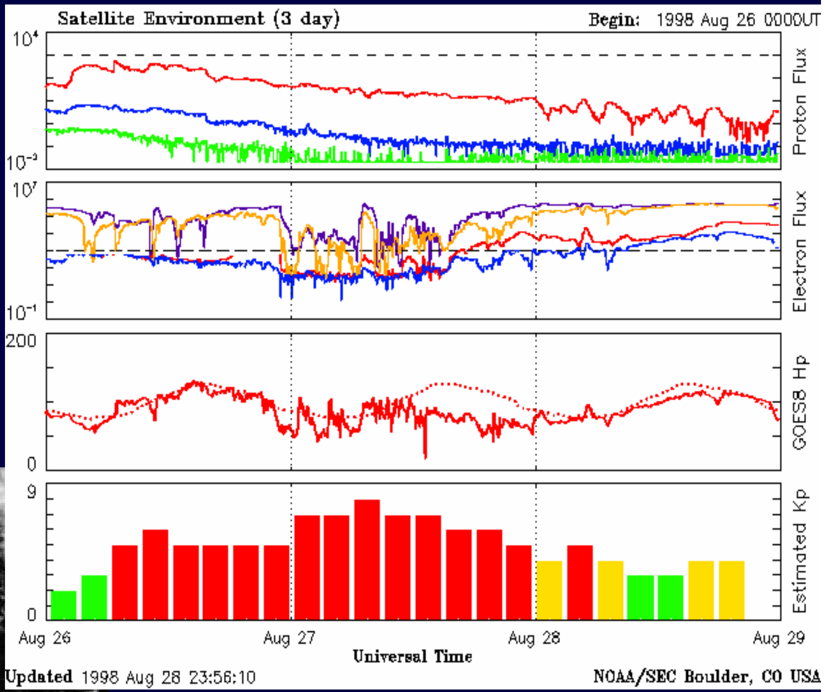
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.sec.noaa.gov/Aurora)

NOAA GOES Simultaneous Monitoring of Tropospheric Weather and Space Weather





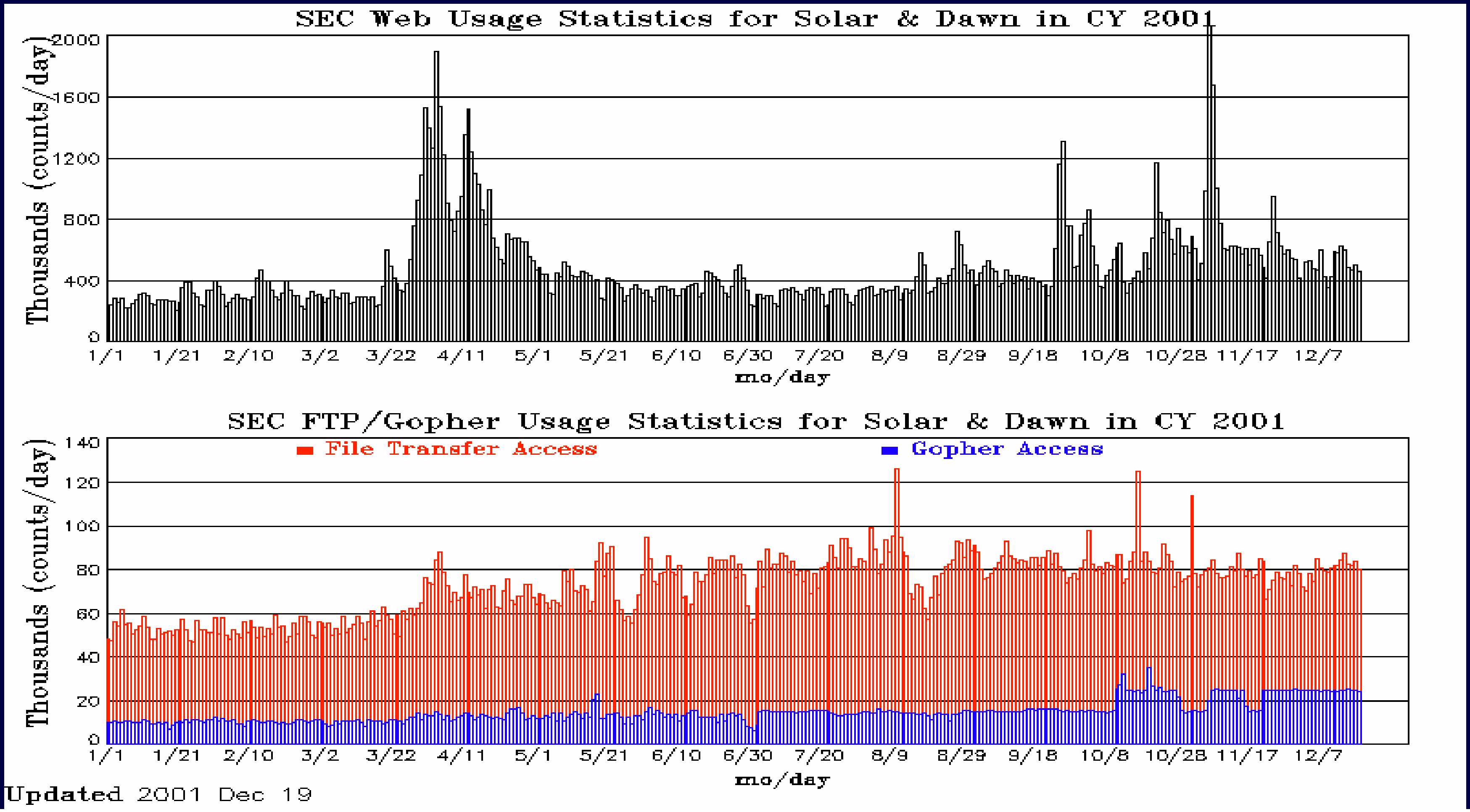
August 1998: Hurricane Danielle and a Geomagnetic Storm at the same time!

H. J. Singer
NOAA/SEC

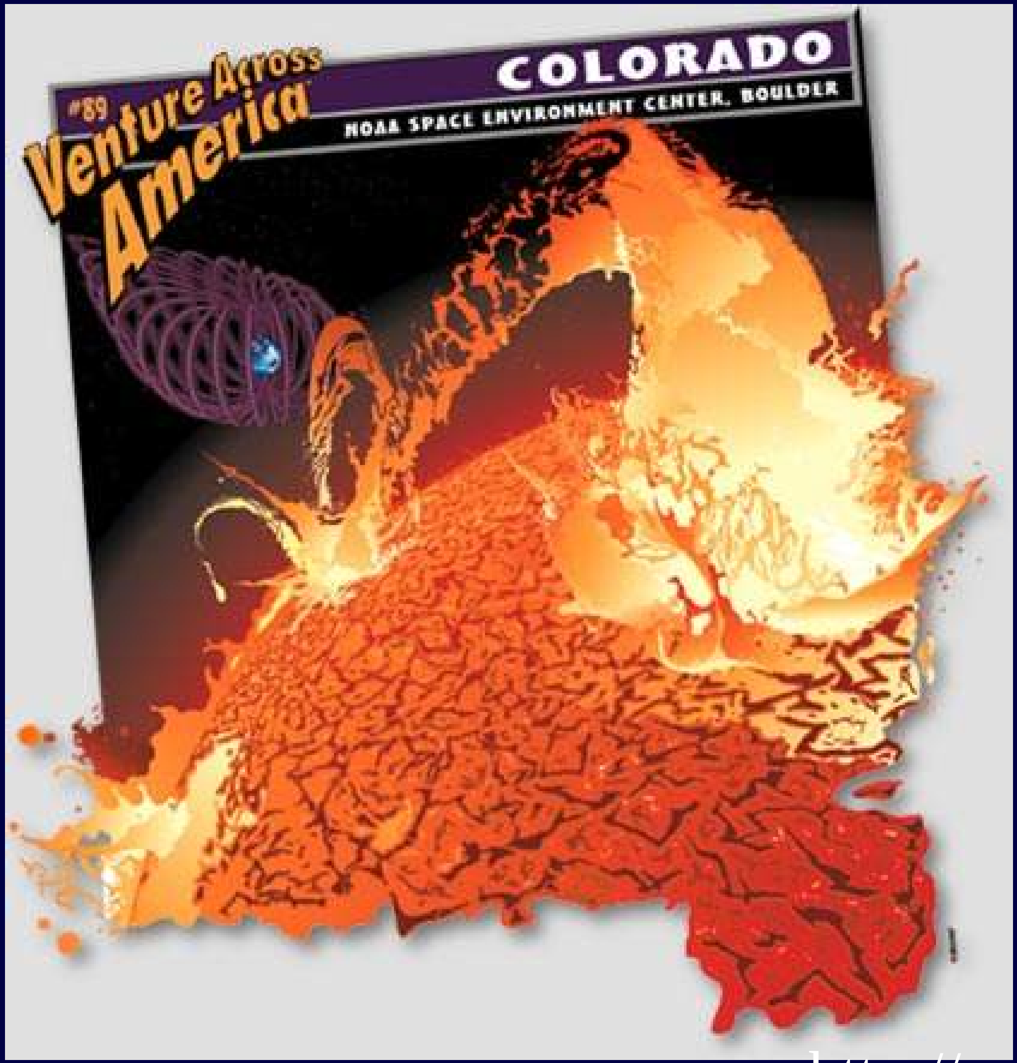
SPD Summer School, UNH, June 2006

Public Response

- NOAA Space Environment Center Web hits go from 400,000 hits per day to more than 2,000,000 hits per day during times of peak solar activity



Unveiling of U-Haul Truck Supergraphic Representing Colorado at Space Weather Week 2001



Did you know...
Scientists monitor the Earth's magnetic field, the sun and the solar wind to forecast the effect of space weather on our planet.

Graphic on the side of several thousand U-Haul Trucks

http://www.uhaul.com/supergraphic

How to predict Space Weather

Simulation of CME Propagation in the heliosphere

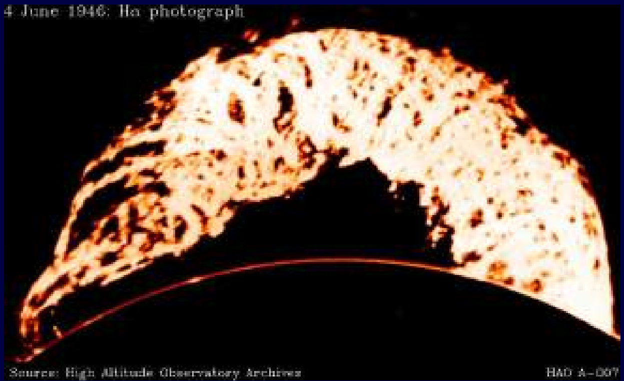
QuickTime™ and a BMP decompressor are needed to see this picture.

extras

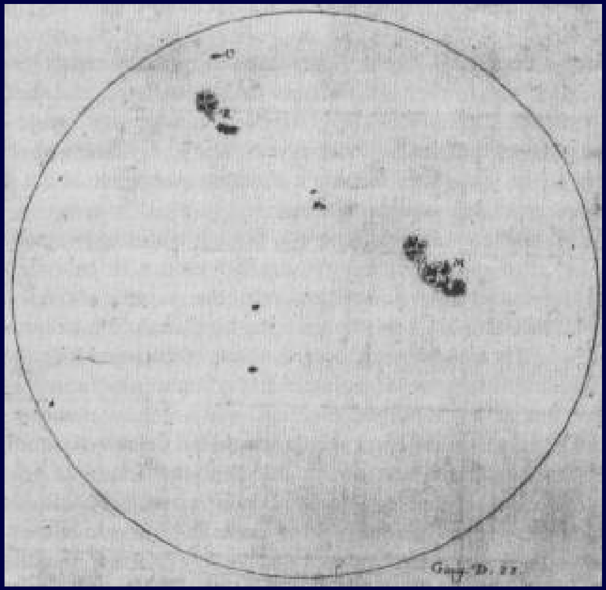
Brief History of Solar - Terrestrial Discoveries

- 800 B.C. : First plausible observation of sunspots recorded in China
- 200 B.C. : Aristarchos of Samos measures Earth-sun distance (wrong by a factor of 20, but he got the scale).
- 968: First mention of the solar corona (Leo Diaconus, Byzantine)
- 1128: First sunspot drawing

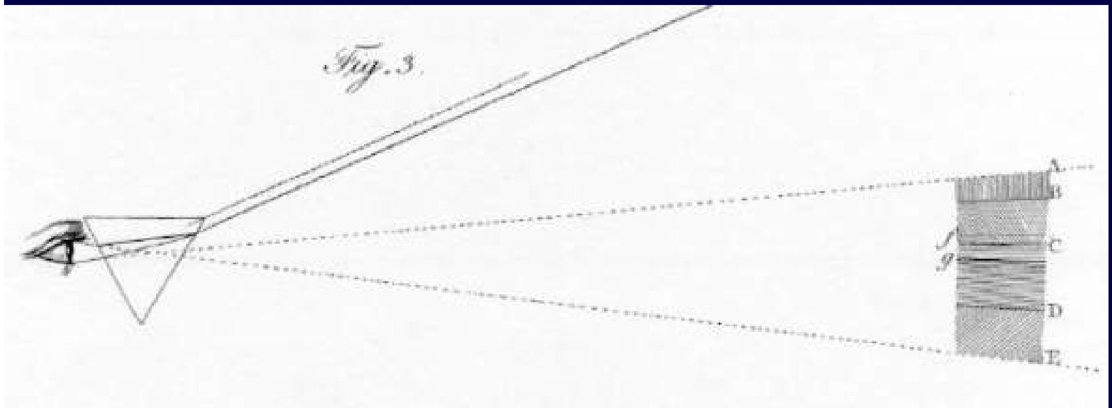
- 1185: First description of a prominence

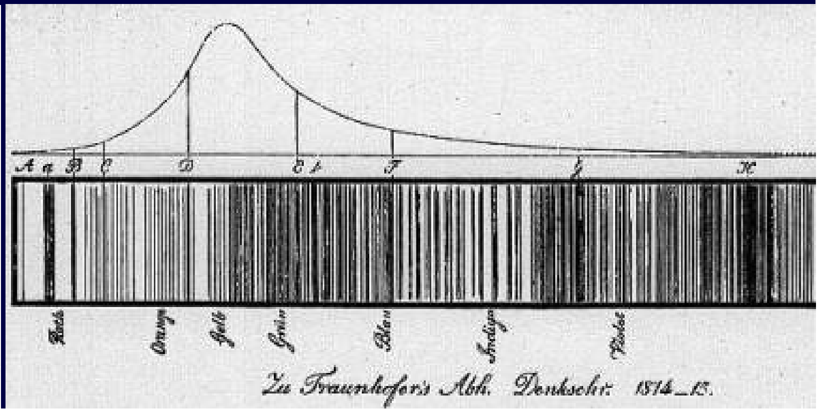


- 1543: Copernicus puts the sun into center stage
- 1609: Kepler finds the laws of planetary motion
- 1610: First telescopic sunspot observations (Goldsmid, Harriot, Galileo, Scheiner)

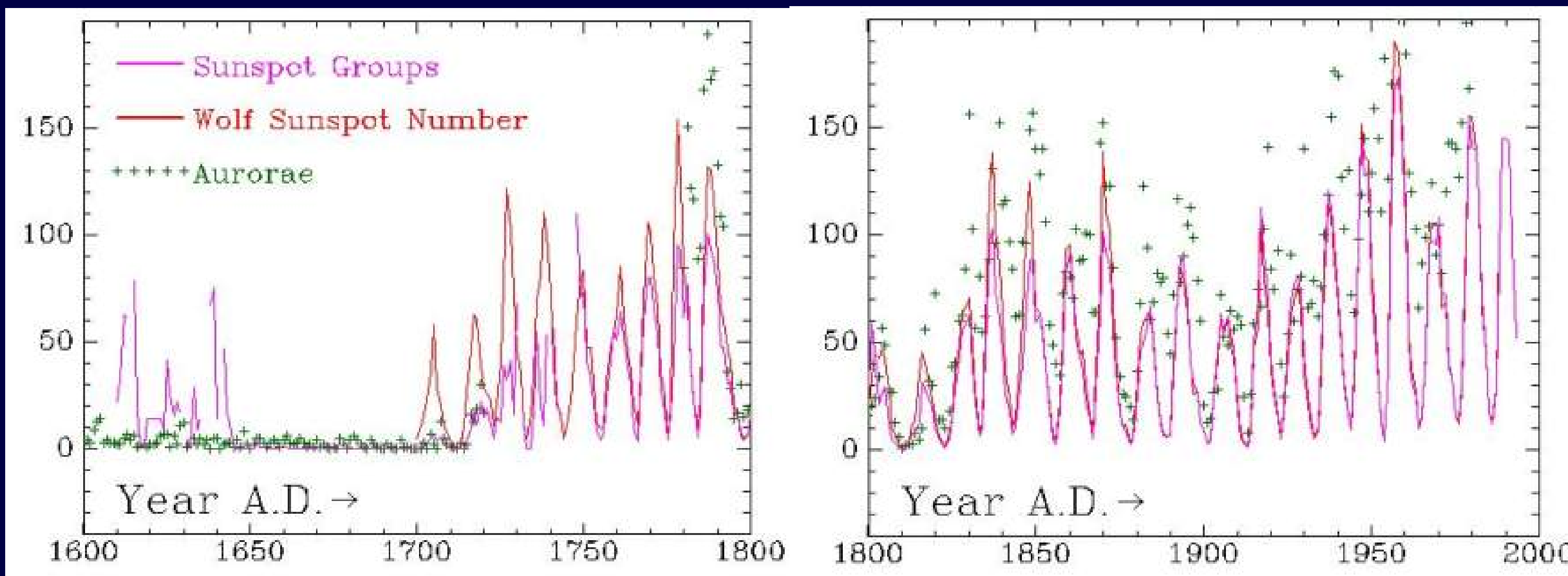


- 1645-1715: sunspots disappear
- 1817: First solar spectroscopy (Wollaston, Fraunhofer)

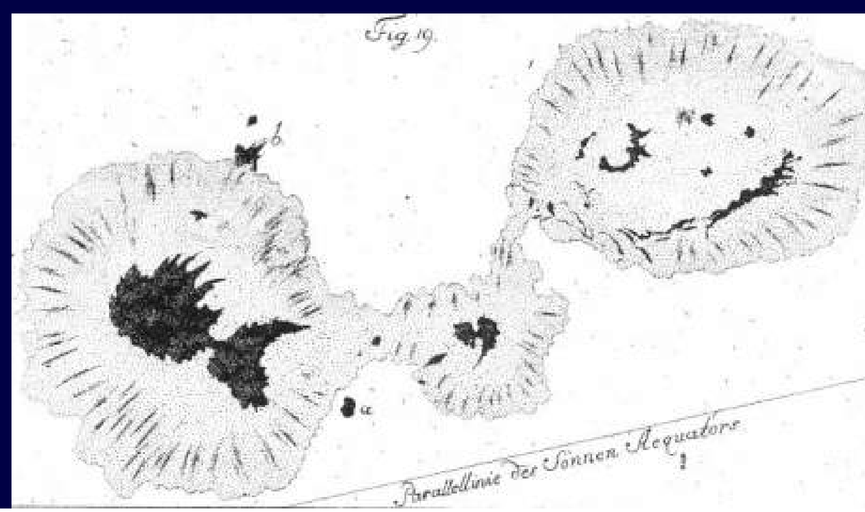




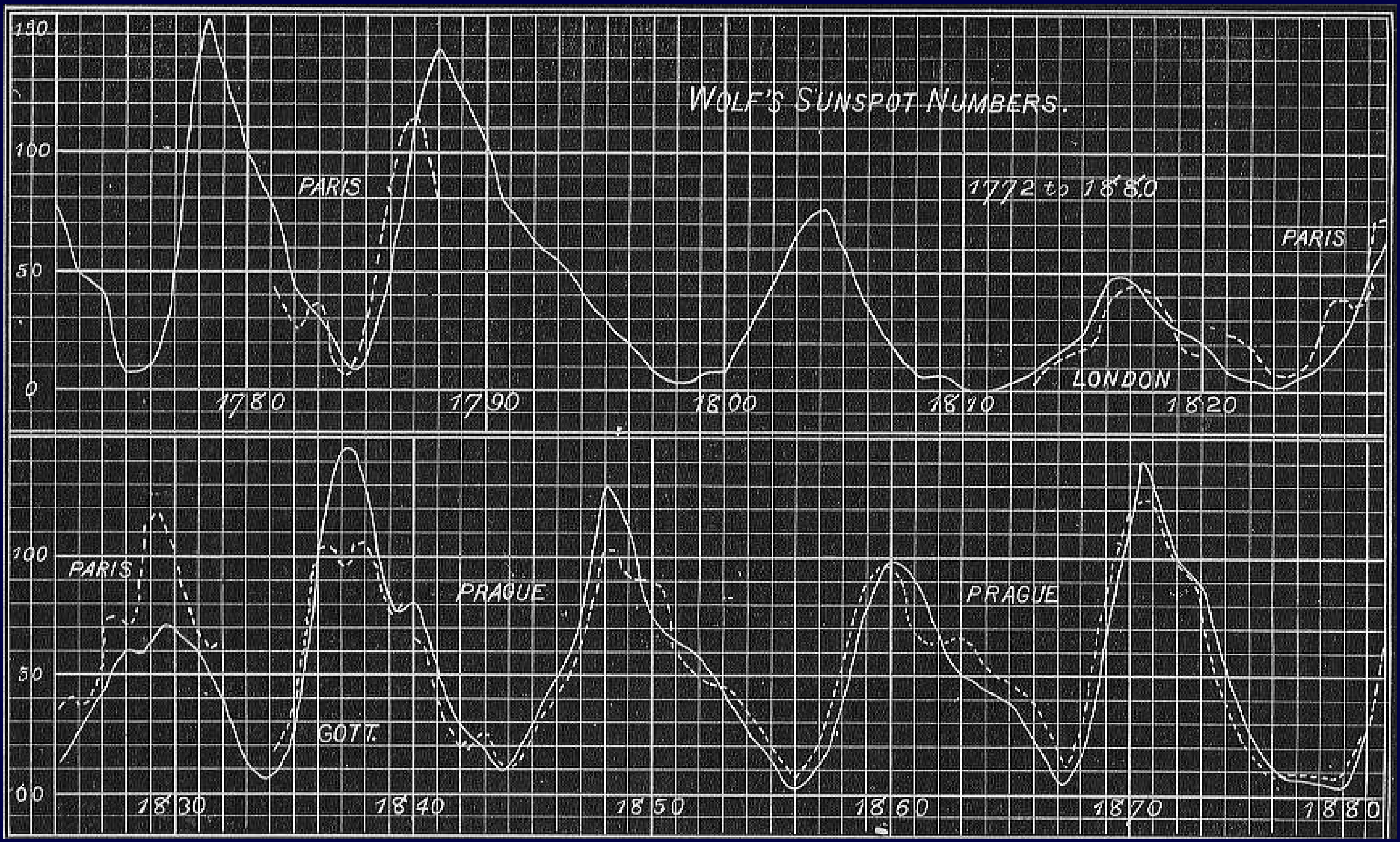
- 1830: Discovery of the sunspot cycle (Heinrich Schwabe)
- 1645-1715: Sunspots vanish, the so-called Maunder minimum
- coincides with `little ice age' in Europe



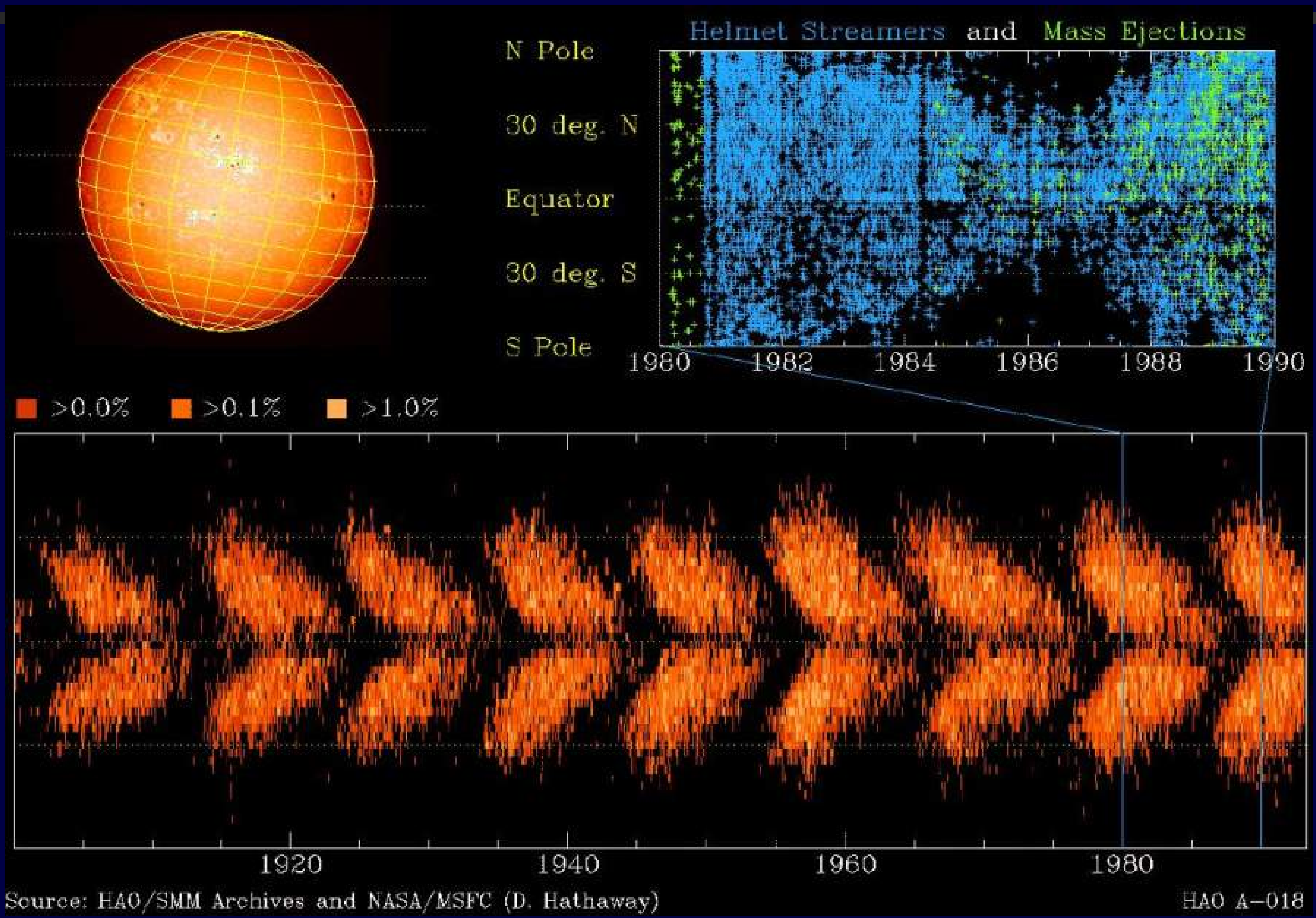
- 1850: Wolf defines the sunspot number, the 1755-1766 cycle is named cycle 1



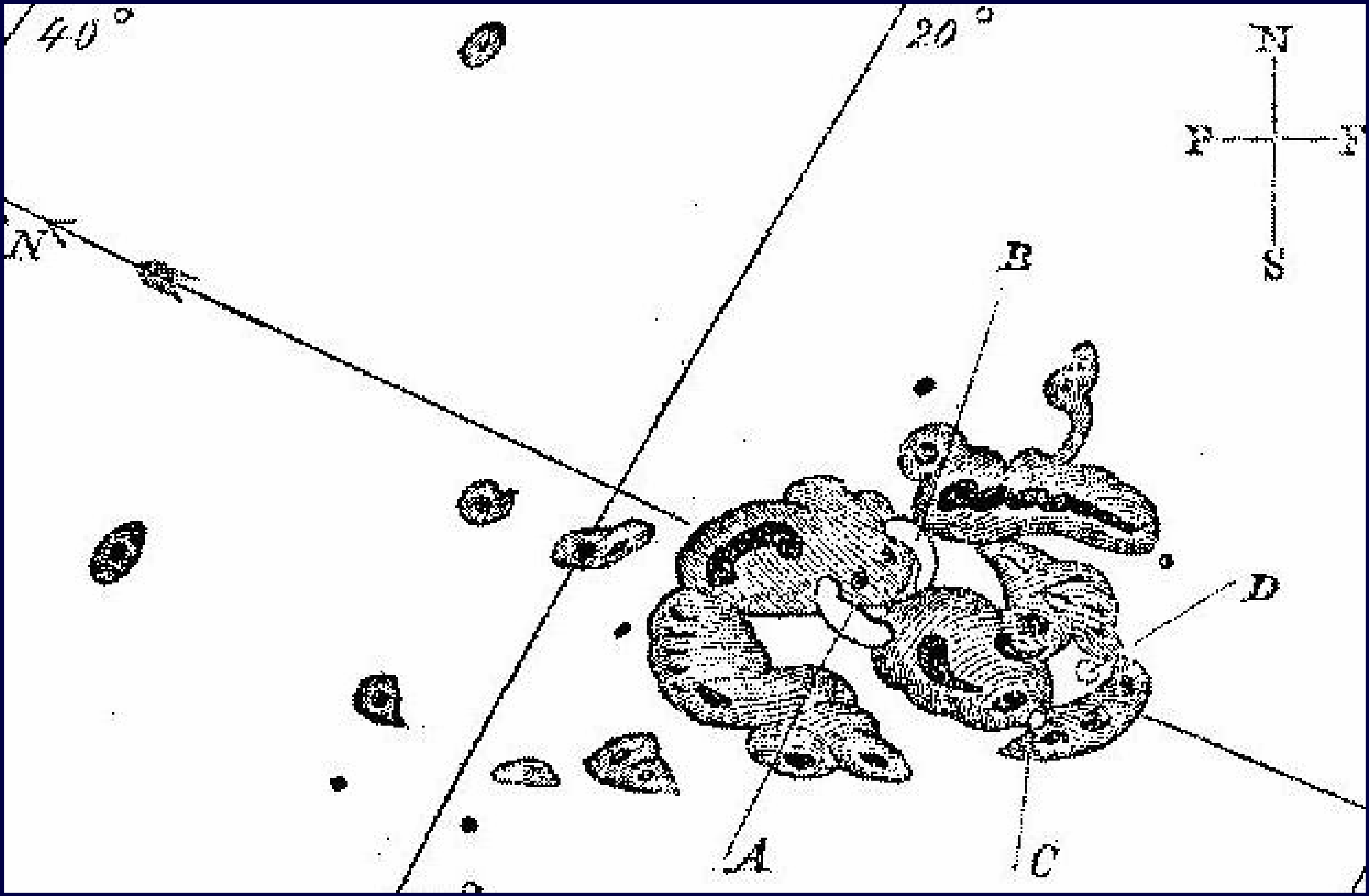
- **1852: sunspot cycle is linked to geomagnetic activity (Sabine, Gautier, Wolf)**



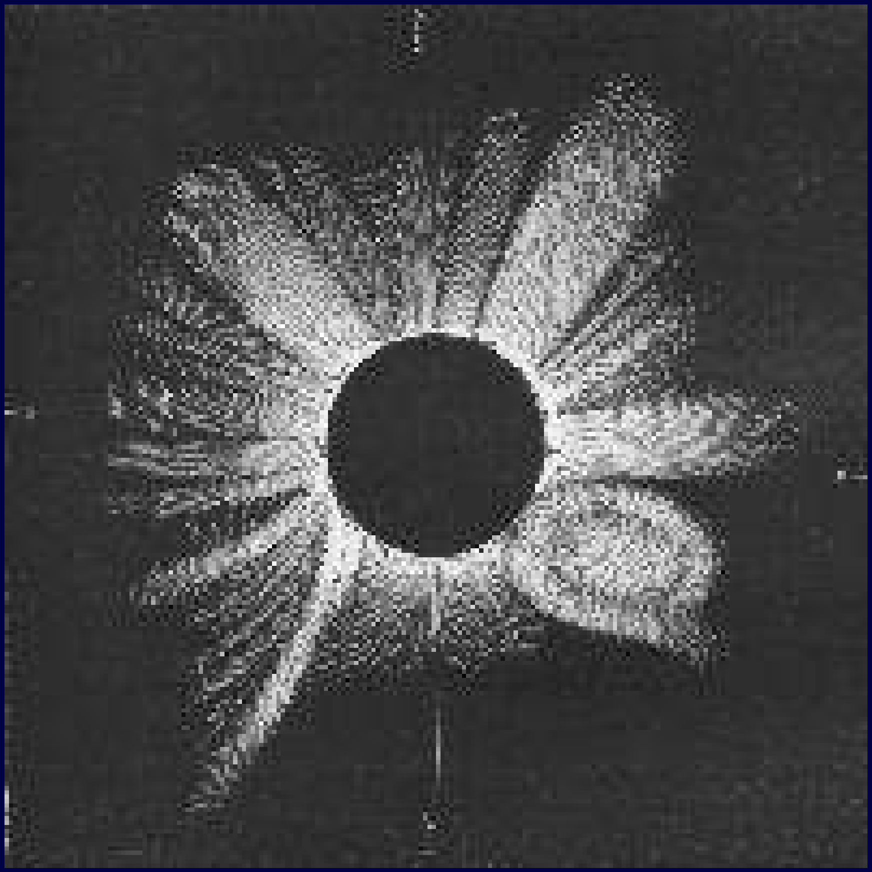
- **1858: discovery of sun's differential rotation (Carrington)**
- **1880: Spoerer discovers sunspot migration**



- **1859: First observation of a flare (Carrington)**

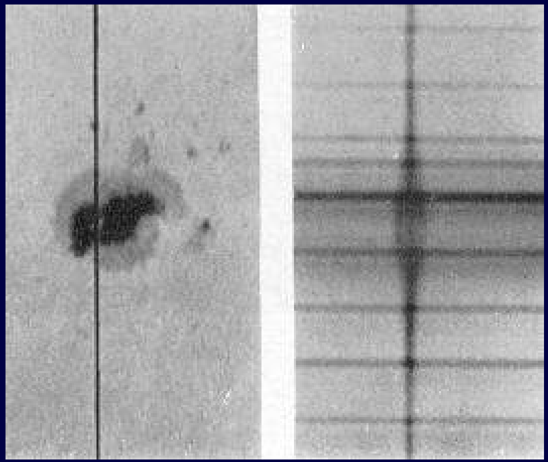


- **1860: First observation of Coronal Mass Ejection (CME)**

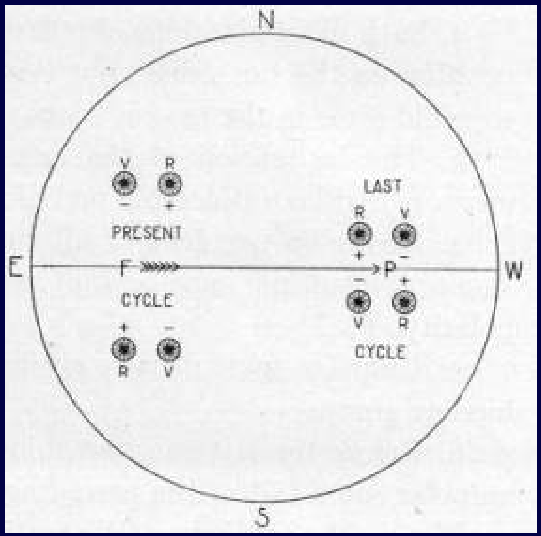


Drawing by G. Tempel during the 1860 eclipse

- **1919: Discovery of the magnetic nature of sunspots and the magnetic cycle (G. E. Hale)**

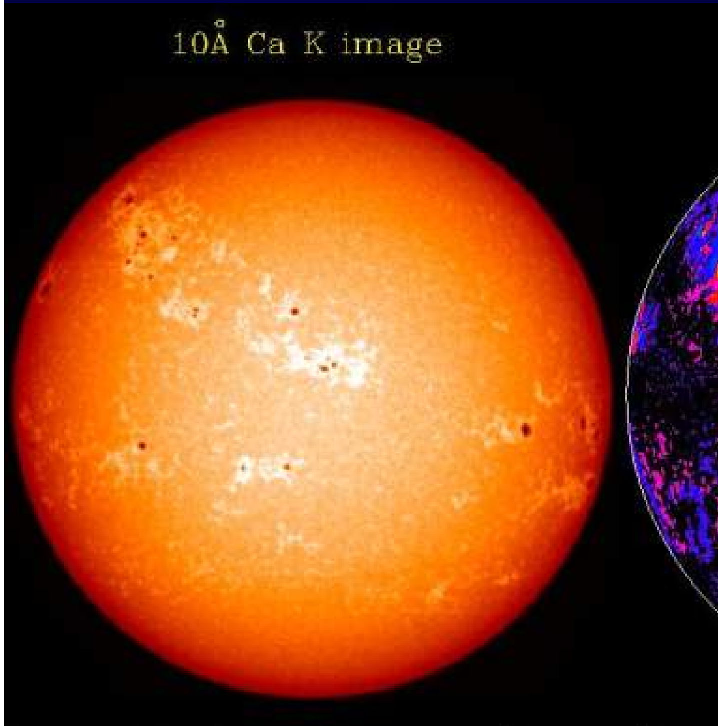


Sunspot spectrum with Zeeman effect (line splitting due to the magnetic field)

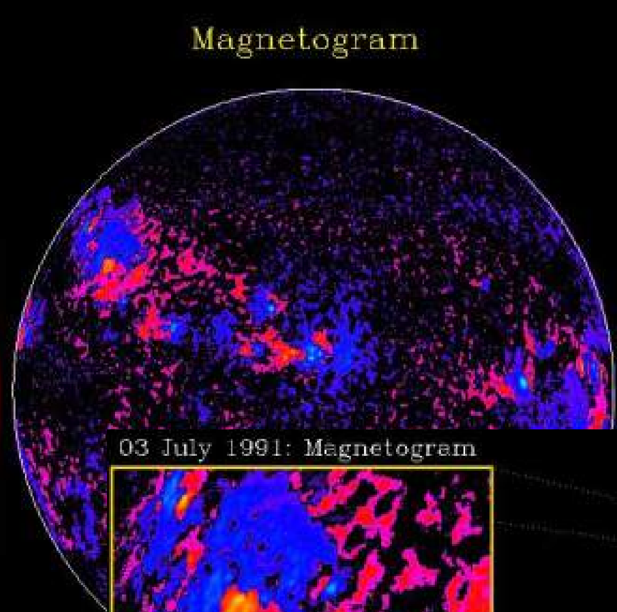


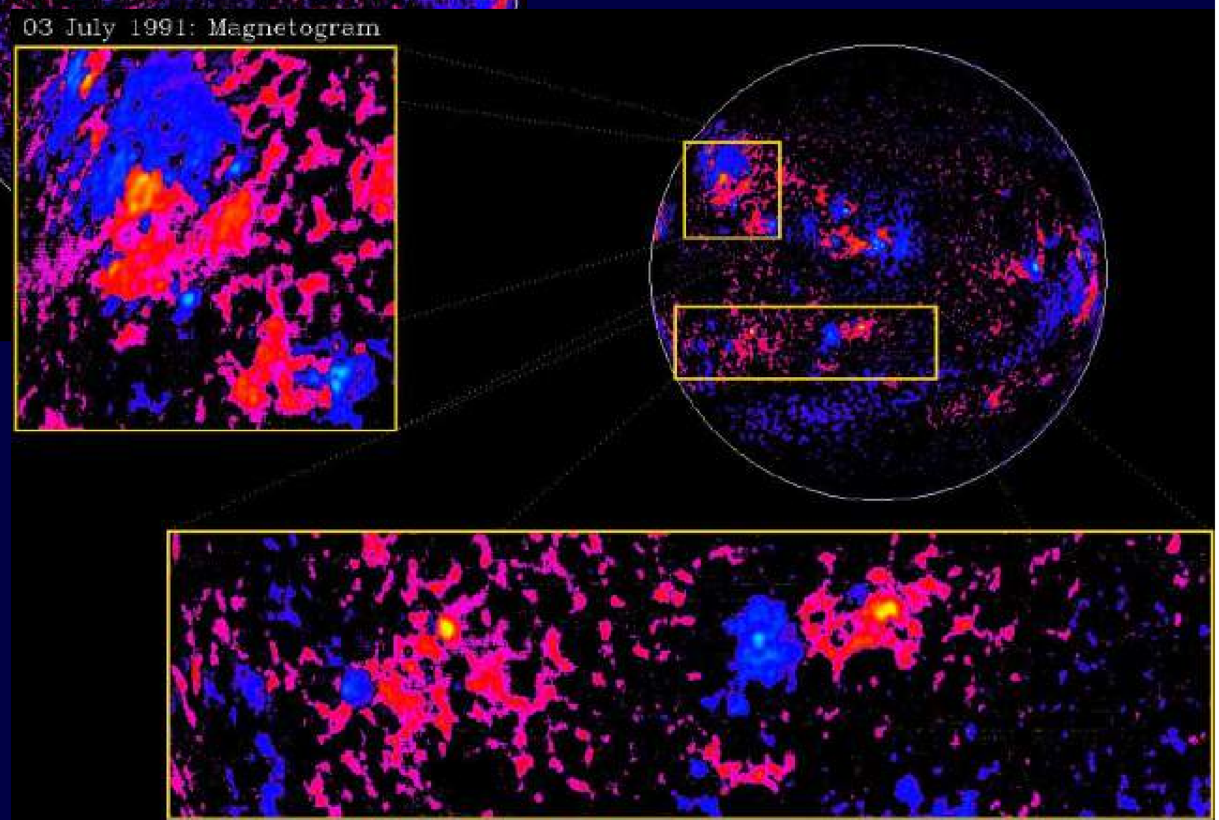
The sun’s magnetic field switches polarity every sunspot cycle (11 years)

- **Now: Magnetic maps (magnetograms)**



Source: National Solar Observatory (J. Harvey)





Source: National Solar Observatory (J. Harvey)

The color shows the magnetic polarity (in/out of the surface) at the photosphere. Note the dual polarity of sunspots.

- **Now: SOHO coronograph**

QuickTime™ and a Cinepak decompressor are needed to see this picture.

- **Now: TRACE**

QuickTime™ and a Photo decompressor are needed to see this picture.

- **Now: TRACE sunspot motion**

QuickTime™ and a Photo decompressor are needed to see this picture.

- **Now: TRACE: developing arcade**

QuickTime™ and a Photo decompressor are needed to see this picture.

- **Now: TRACE: magnetic loops on the limb**

QuickTime™ and a Photo decompressor are needed to see this picture.

- **Now: TRACE: flare and slinky**

QuickTime™ and a Cinepak decompressor are needed to see this picture.

- **When it hits the magnetosphere: substorm**

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

- **When it hits the magnetosphere: storm**

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

- **Upcoming: THEMIS**

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

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