

# Space Weather Super Storm: Not *if* But *When*

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**NASA Headquarters, Science Mission Directorate**

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“Conversation about the weather is the last refuge of the unimaginative.”

-Oscar Wilde

“Don’t knock the weather; nine-tenths of the people couldn’t start a conversation if it didn’t change once in a while.”

-Kin Hubbard

“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 endanger human life and health. Adverse conditions in the space environment can cause disruption of satellite operations, communications, navigation, and electronic power grids, leading to a panoply of socio-economic losses.

National Space Weather Program  
Strategic Plan (March 1995)

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# Magnetism

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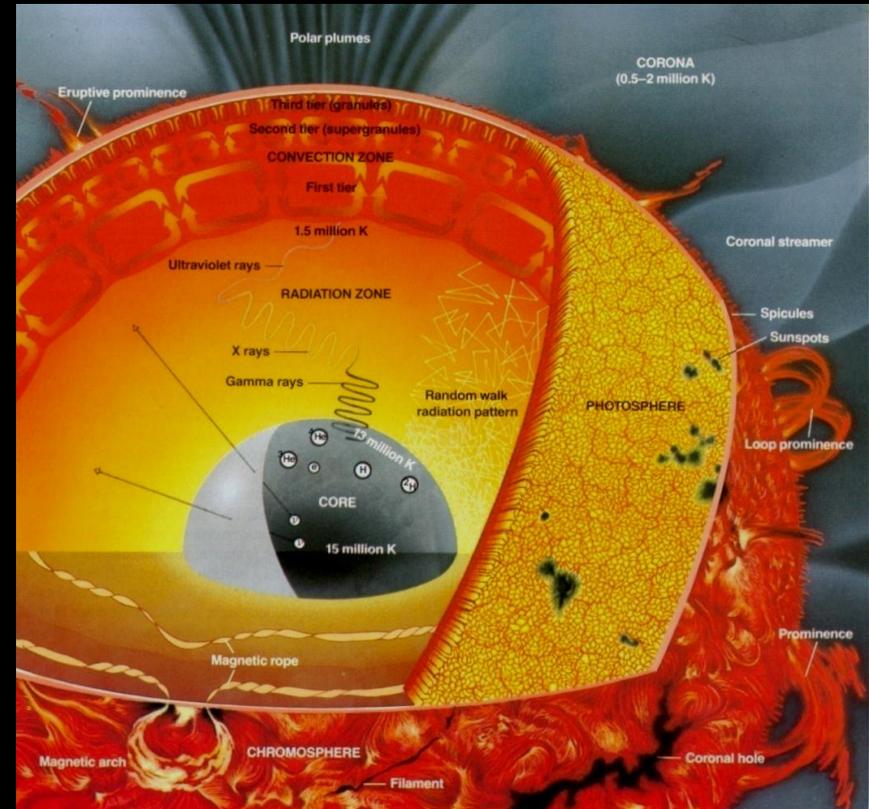
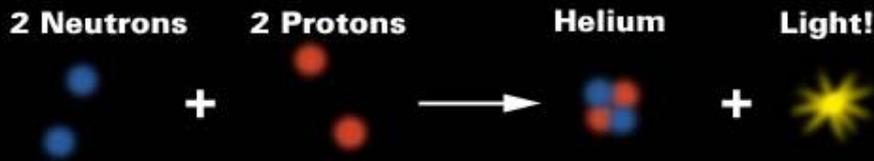
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**The Outer Limits (1964)**

# The Sun's Structure

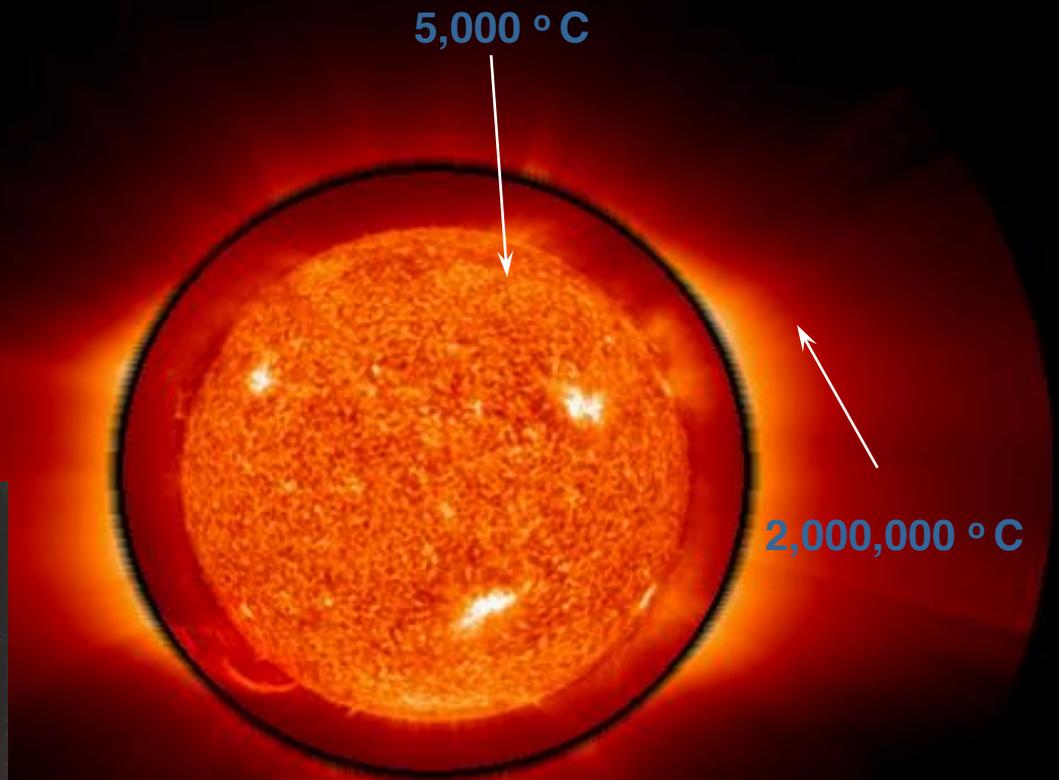
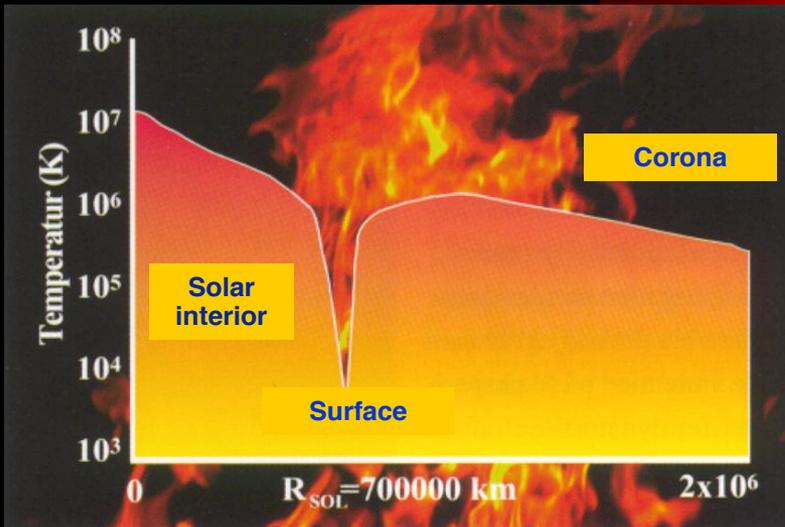
- **Core**

- Where the energy is created.
- Nuclear reactions burn every second about 700 million tons of hydrogen into helium.
- Inside the core the particles are packed so tightly, and the temperature is so hot, that individual atoms ram into each other, forming heavier helium atoms and releasing energy



# The Solar Corona

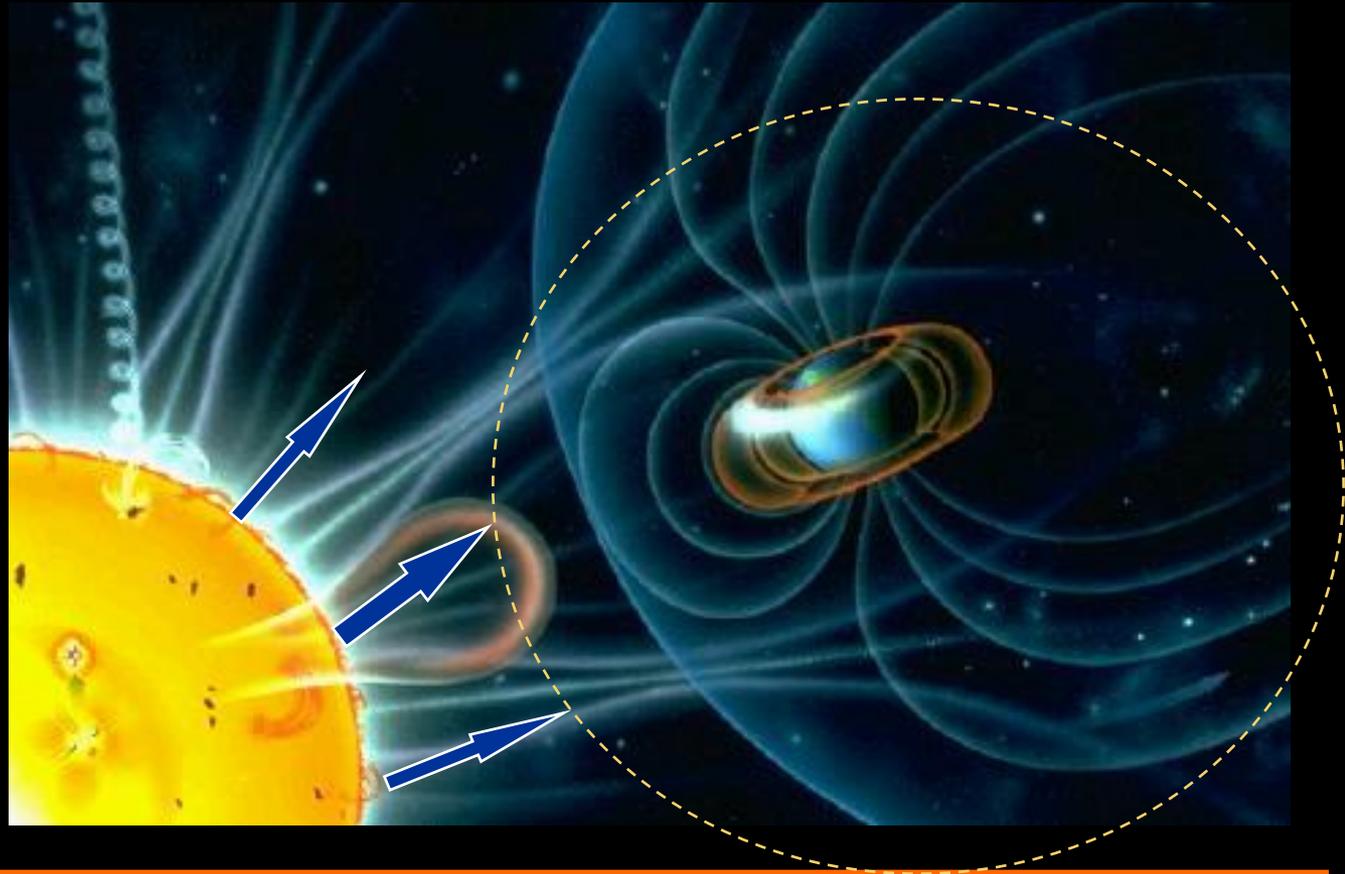
- The corona is the area just above the surface. While the surface is about  $5,000^{\circ}\text{C}$ , the temperature in the corona reaches about 2 million degrees Celsius. What causes this rapid increase in temperature is still one of the big mysteries in solar physics.



*The black circle divides two images.*

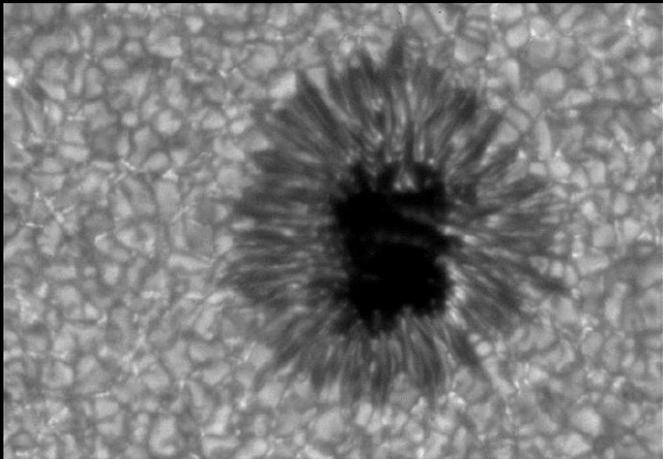
# What is the Solar Wind?

- A constant stream of particles flows from the Sun's corona, with a temperature of about a million degrees and with a velocity of about 450 km/s. The solar wind reaches out beyond Pluto's orbit (about 5900 million kilometers). The drawing shows how it pushes on and shapes the Earth's magnetosphere (the dotted line).

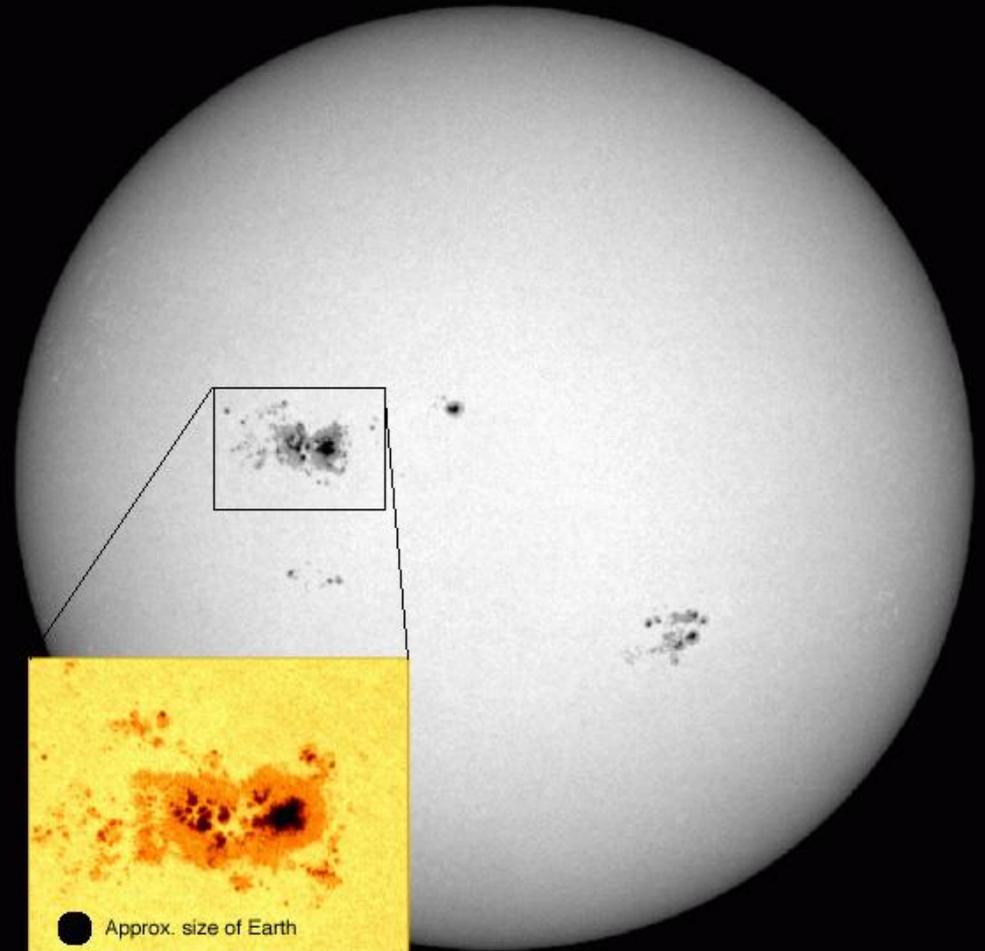


# Sunspots

- **Dark areas (umbra, penumbra)**
- **Strong magnetic fields**
  - Inhibit energy transport from solar interior
  - Cooler areas, and therefore darker
  - Frequency varies with the 11-year cycle



*Close-up of sunspots*

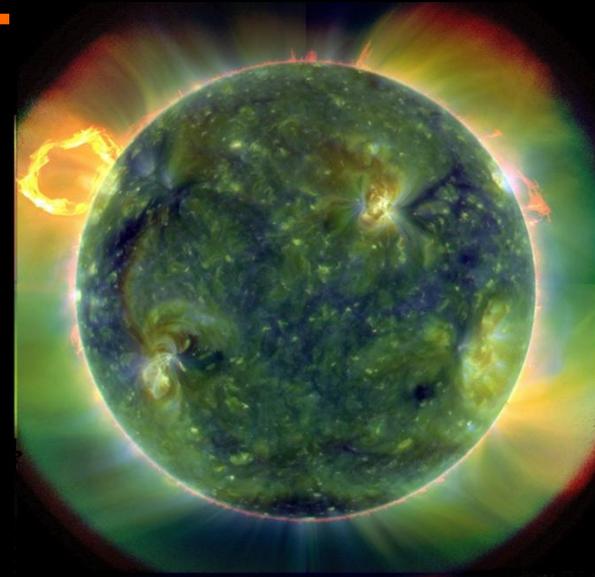


# Heliophysics

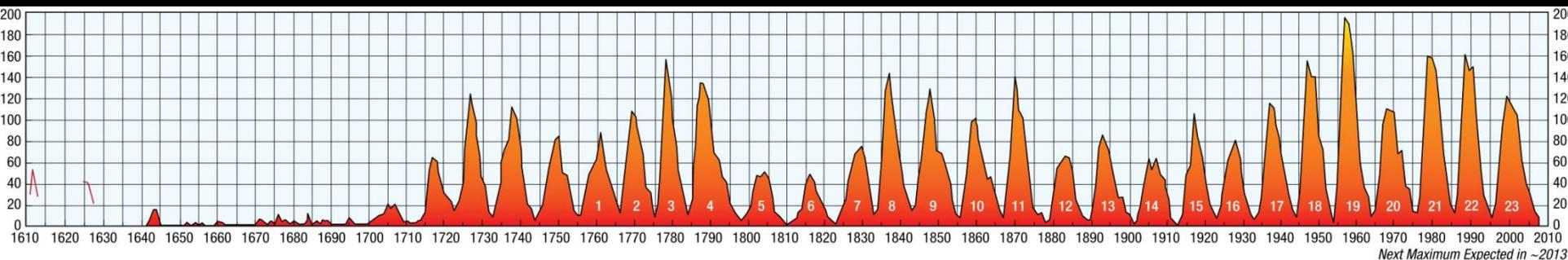
Heliophysics is an environmental science, a unique hybrid between meteorology and astrophysics. It comprises a ~~body of data and a set of paradigms (general laws~~ perhaps mostly still undiscovered) specific to magnetized plasmas and neutrals in the heliosphere interacting with themselves and with gravitating bodies and their atmospheres

## *with the Earth and the Solar System*

- Determine the origins of the Sun's activity and predict the variations of the space environment.
- Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.
- Determine the interaction of the Sun with the solar system and the interstellar medium.
- Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.



*The Solar Cycle: The observed year-to-year variation in the sunspot number spanning the period from the earliest use of the telescope. Evident is the well-known solar cycle of about eleven years. The period of suppressed activity between the mid-1600s and about 1715 is known as the Maunder Minimum.*



*First light SDO image from March 30, 2010*

Credit: NASA/GSEC/ATIA

# Electromagnetic Radiation

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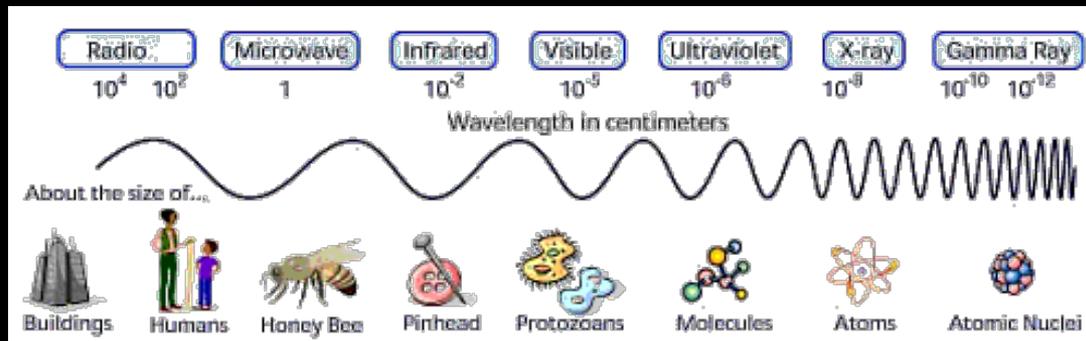
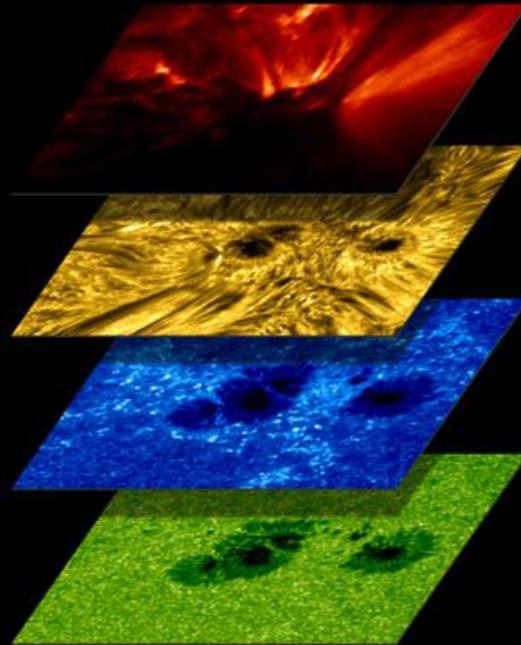
Ultraviolet  
Light



X-rays



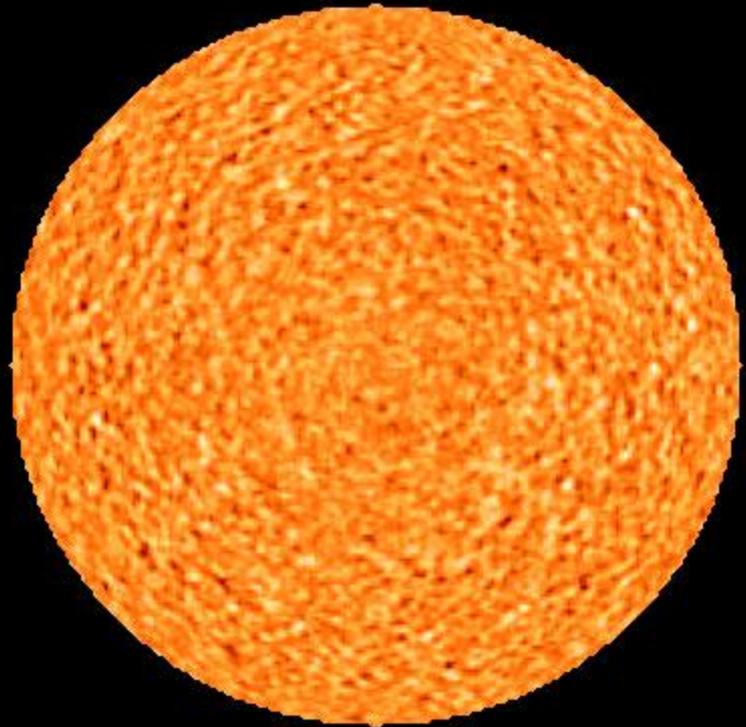
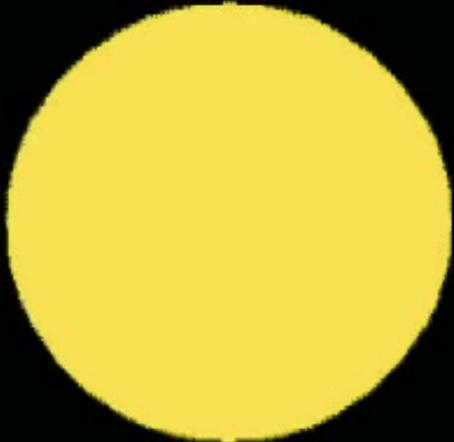
# Electromagnetic Radiation - Filters



# Helioseismology

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- The entire Sun vibrates from a complex pattern of acoustic waves
- The Sun's acoustic waves bounce from one side of the Sun to the other, causing the Sun's surface to oscillate up and down
- The sound waves are influenced by conditions inside the Sun
- By observing these oscillations on the surface we can learn about the structure of the solar interior



**Hear the Sun sing!**

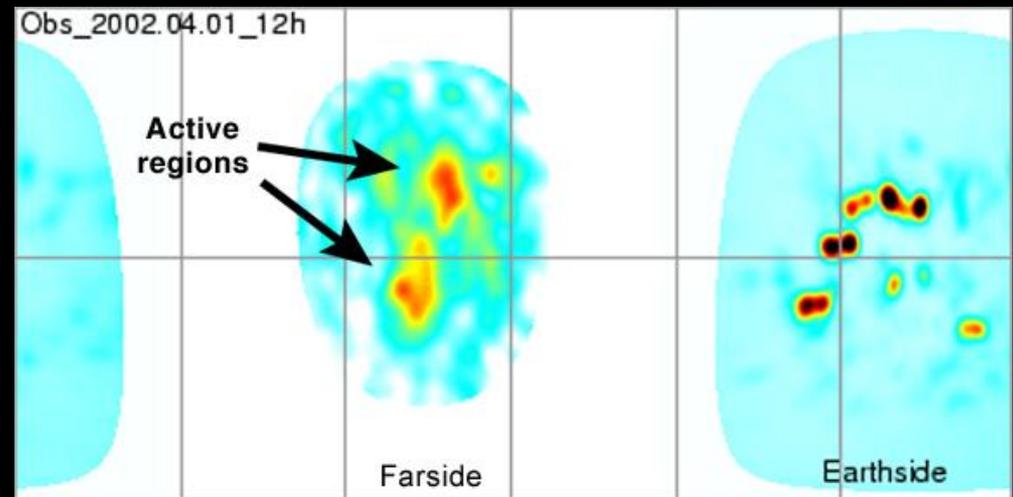
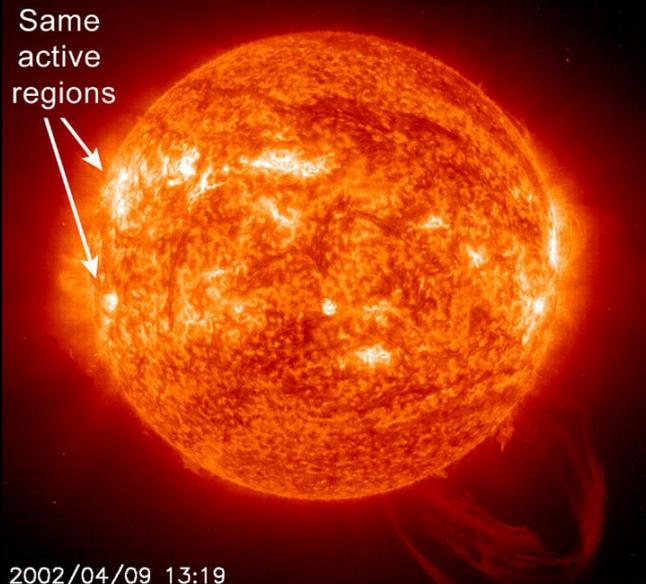
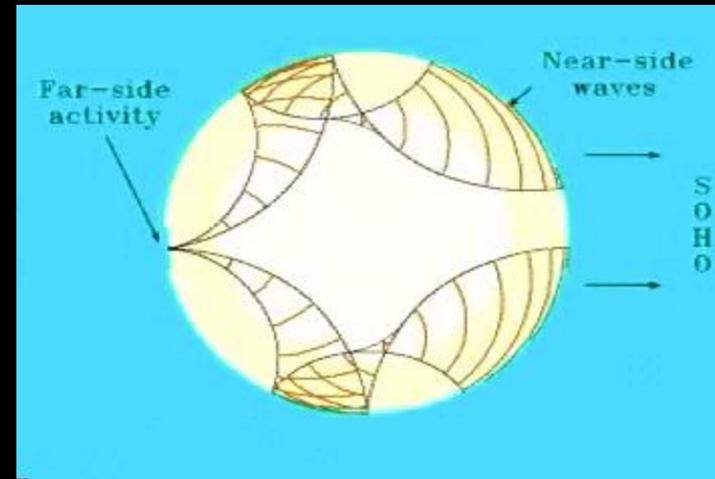


Sound waves speeded up 42,000 times

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# SOHO and SDO sees through the Sun

- **First images of active regions on the far side of the Sun, from applying a new technique, called two-skip far-side seismic holography, to high quality MDI data.**
- **Acoustic waves speed up in areas of strong magnetic field (active regions)**
  - The delay of the sound waves is about 12 sec in a total travel time of 6 hours



Real-time farside images: <http://soi.stanford.edu/data/farside/index.html>

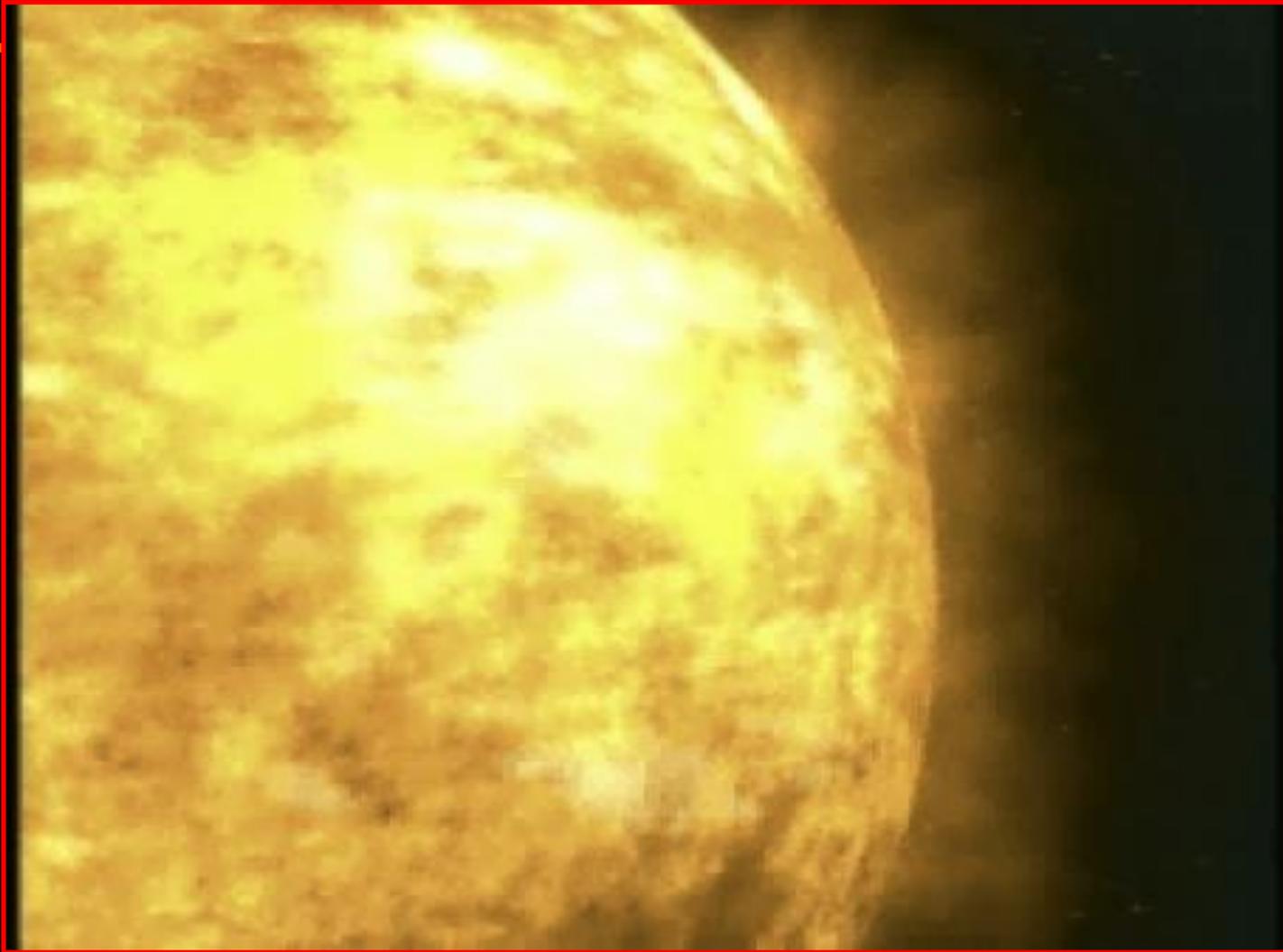
# Three Years of SDO

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# What is Space Weather?

( Courtesy of NASA )



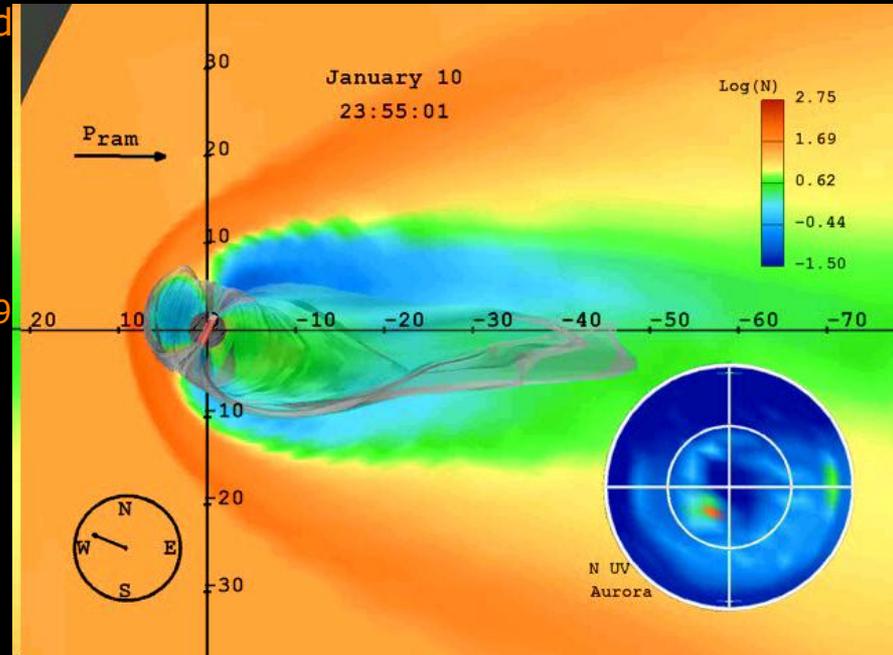
Impact of an Earth directed CME

# What is Space Weather?

**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 born and ground-based technological systems and that can affect human life or health.

## “Space Weather” effects on installations on Earth not a new phenomena

- 17 November 1848: Telegraph wire between Pisa and
- September 1851: Telegraph wire in New England disrupted
- Induced currents made it possible to run the telegraph lines without batteries. The following is a transcript between Portland and Boston (1859)
  - Portland: “Please cut off your battery, let us see if we can work with the auroral current alone”
  - Boston: “I have already done so! How do you receive my writing?”
  - Portland: “Very well indeed - much better that with batteries”



# International Aurorae...



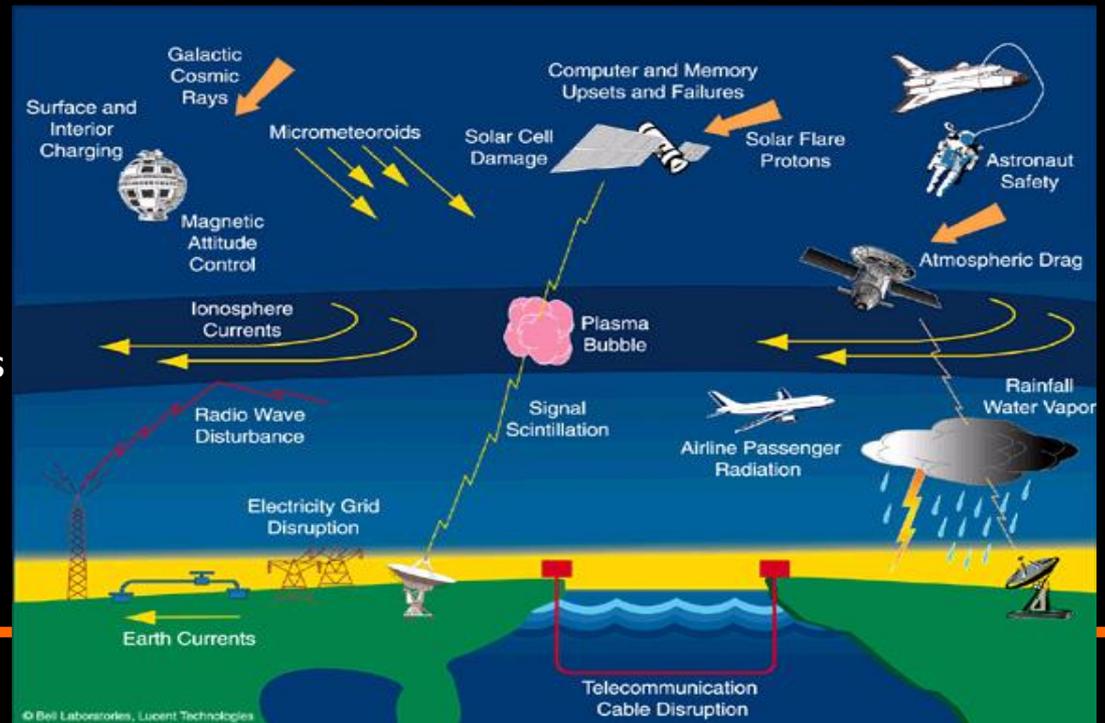
# Space Weather: Why should we care?

- **Our society is much more dependant on technology today compared to in 1989**
- **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
  - 250 million users if GPS
- **Change in 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.**

**Damages: estimated to 200 M\$ per year**

- 100 M\$ - satellites
- 100 M\$ - powergrids
- 10 M\$ - communication



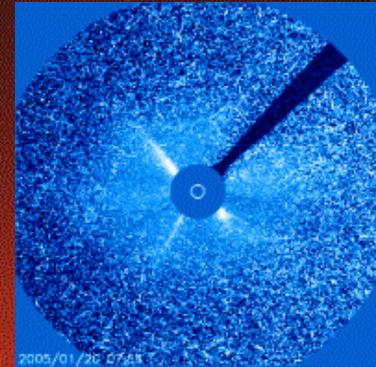


# ***Satellite Industry***



## **Needs Solar storm warnings and alerts:**

- Instruments and/or spacecraft turned off or safed
- Maneuver planning
- Anomaly assessments
- Orbit determination accuracy
- Increased spacecraft and instrument monitoring for health and safety during solar storms



# GPS

Global Positioning System used: In-vehicle navigation systems, railway control, highway traffic management, emergency response, commercial aviation, and much more...

GPS Global Production Value—expected growth:

2003 - \$13 billion

2008 - \$21.5 billion

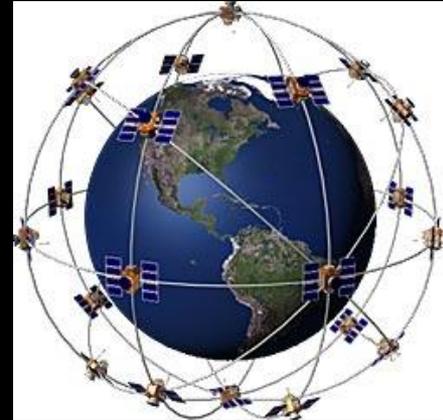
2017 - \$757 billion

Industrial Technology Research Institute (ITRI) – Mar 2005

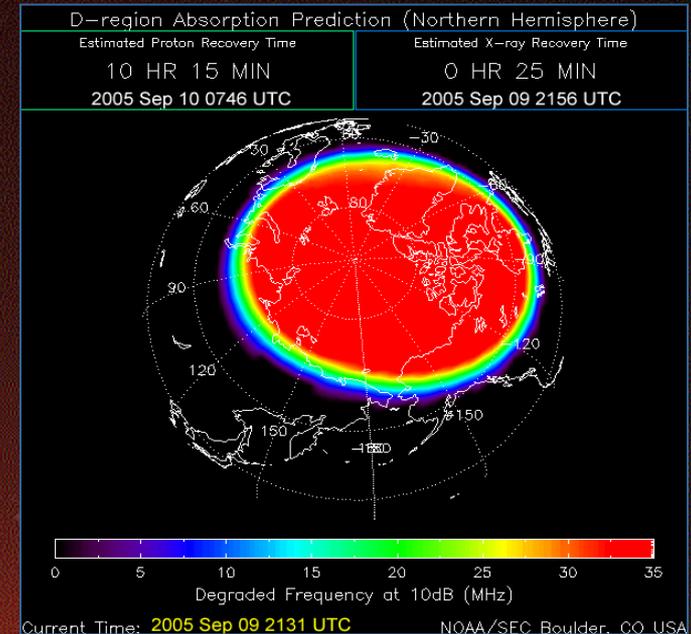
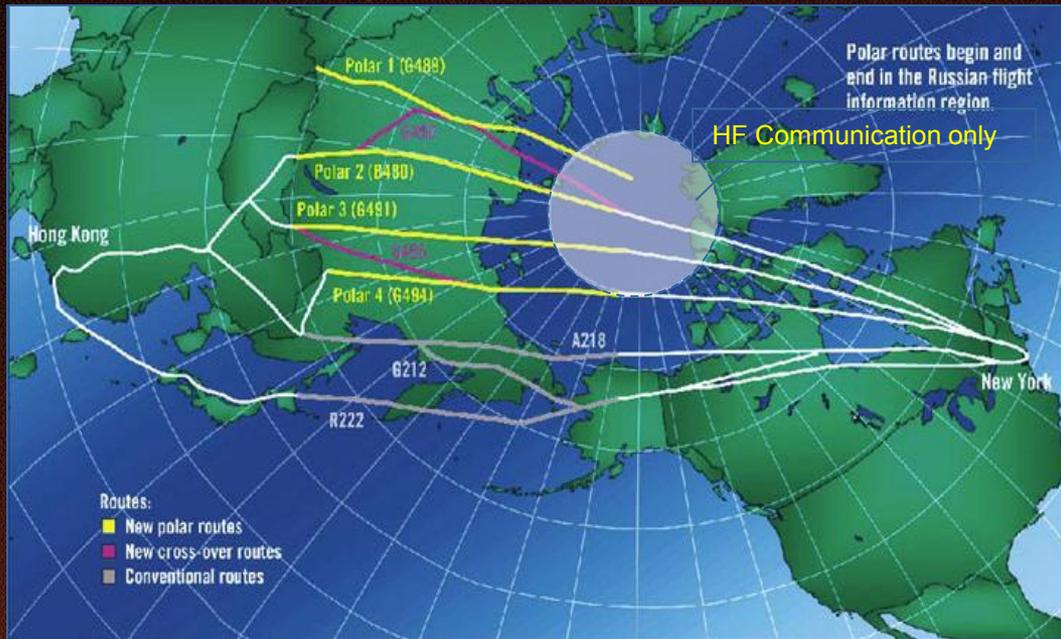
Space weather creates positioning errors larger than 50 meters

—A mid-latitude problem (where most users reside!)

NAVSTAR - USA  
GLONASS - Russia  
Galileo - Europe



# Airlines and the Polar Routes



- Flights rely on HF (3 – 30 MHz) communication inside the 82 degree circle.
- Federal Aviation Regulation Sec. 121.99 – aircraft must have two-way radio communication over the entire route with dispatch office and air traffic control.
- Airlines will often re-route flights away from polar routes during radiation and geomagnetic storms at a cost that can exceed \$100,000 per flight.

# Electrical Power Grid...

**The grid is becoming increasingly vulnerable to space weather events** *Future Directions in Satellite-derived Weather and Climate Information for the Electric Energy Industry – Workshop Report Jun 2004*

**"...blackouts could exceed even that of the very large blackout that occurred in August 14, 2003. And there is no part of the U.S. power grid that is immune to this... we could impact over 100 million population in the worst case scenario."** John Kappenman - before U.S. House Subcommittee on Environment, Technology & Standards Subcommittee Hearing on *"What is Space Weather and Who Should Forecast It?"*



Transformer winding failure

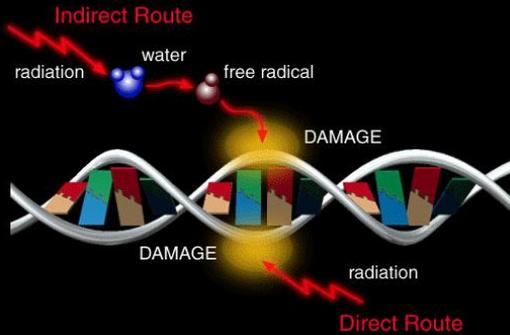


Transformer exit lead overheating



ervat

# High Energy Particles Hazards to Humans



- **Humans in space**

- Space Shuttle, International Space Station, missions beyond low earth orbit to asteroid, moon, mars...

- **Crew/Passengers in high-flying jets and polar routes**

- Some airlines carry radiation detectors
- Passengers may receive radiation doses equivalent to several chest X rays.



# When the Sun went Crazy

Active regions 10484 & 10486 produced, together:

**11** X-Class Flares  
**36+** M-Class Flares  
Countless C-Class

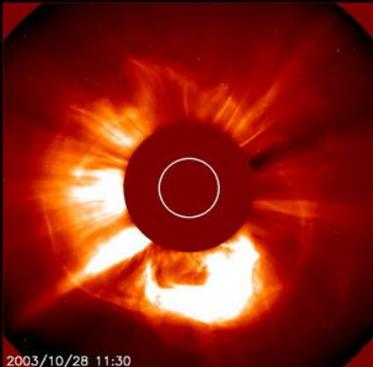
At least **15** "halo" CMEs  
Many other small CMEs and jets.



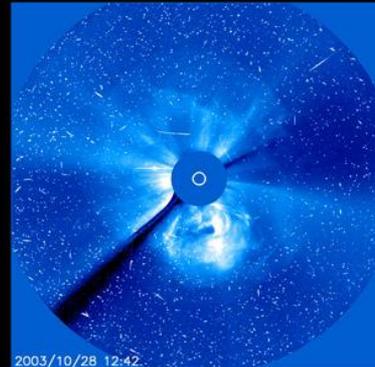
2003/10/28 06:24



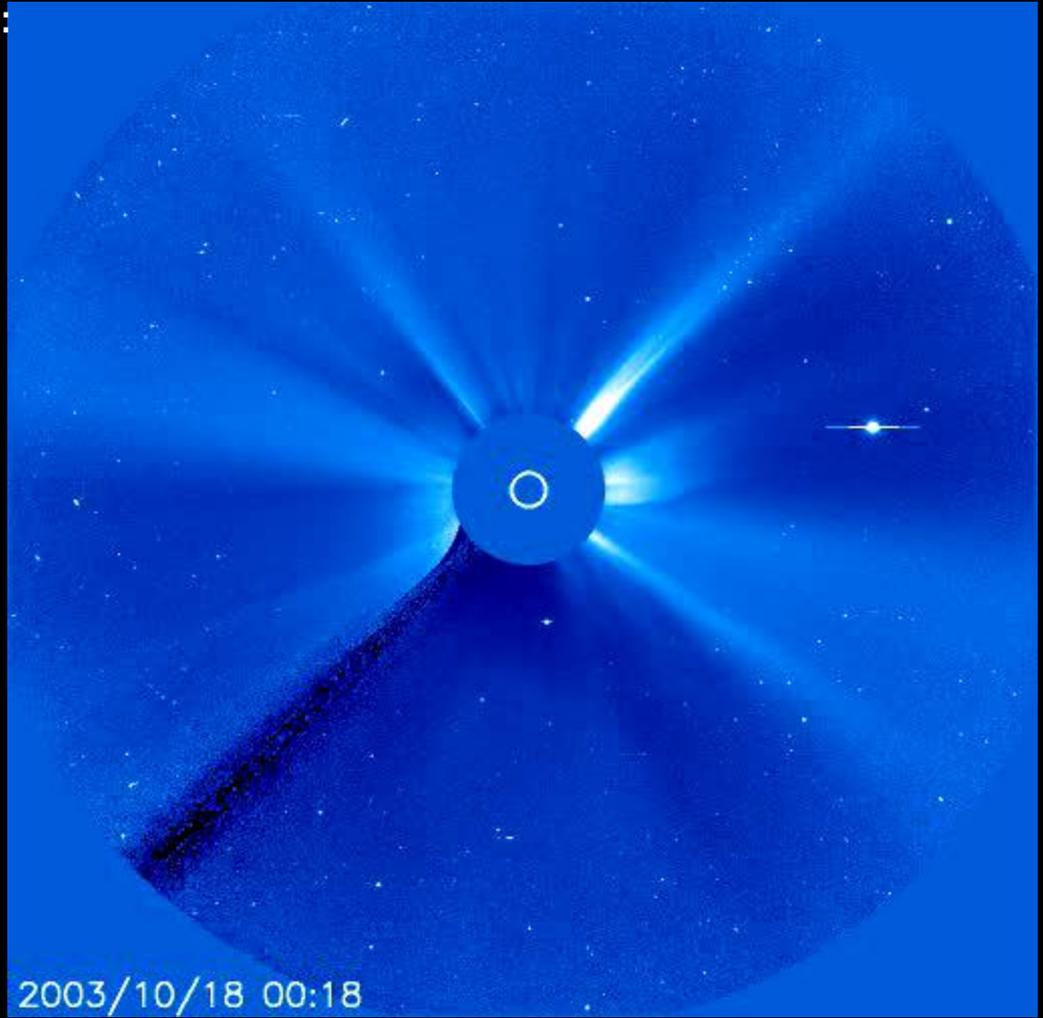
2003/10/28 11:12



2003/10/28 11:30



2003/10/28 12:42



2003/10/18 00:18

# So What Do We Mean by Extreme SWx?

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From Cliver & Svaalgard (Solar Physics, 2004)

The biggest geomagnetic storm occurred in March 1989.

The biggest solar particle event occurred in Sept. 1859.

The lowest latitude auroras were observed in Feb. 1872.

The fastest CME on record crossed the sun-Earth divide in only 14 hours in August 1972.

The most intense SID occurred during the Halloween storms of 2003.

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# Solar Flares – EMP from the Sun

Corresponding NOAA space weather scale: Radio Blackout

Extreme (R5) = X20

Frequency: Happens less than once per cycle.

Consequence: Complete HF radio blackout on the entire sunlit side of the Earth lasting for a number of hours, loss of HF contact with mariners and aviators.

Other effects: Direct radio interference with GPS signals. Accelerated orbital decay of satellites.

## Strongest X-ray Flares since 1976

- |     |                   |       |
|-----|-------------------|-------|
| 1.  | November 4, 2003  | X28+  |
| 2.  | April 2, 2001     | X20.0 |
| 3.  | August 16, 1989   | X20.0 |
| 4.  | October 28, 2003  | X17.2 |
| 5.  | September 7, 2005 | X17   |
| 6.  | March 6, 1989     | X15.0 |
| 7.  | July 11, 1978     | X15.0 |
| 8.  | April 15, 2001    | X14.4 |
| 9.  | April 24, 1984    | X13.0 |
| 10. | October 19, 1989  | X13.0 |

SOURCE: IPS Radio & Space Services and Spaceweather.com

# Geomagnetic Storms

Corresponding NOAA  
Space Weather Scale:  
Geomagnetic Storm

Extreme (G5) = K9

All of the top storms  
saturate the K-index scale  
at K9.

**Frequency:** 4 per cycle

**Consequences:** low-  
latitude auroras,  
transformer damage,  
power outages , pipeline  
currents reach hundreds  
of amps

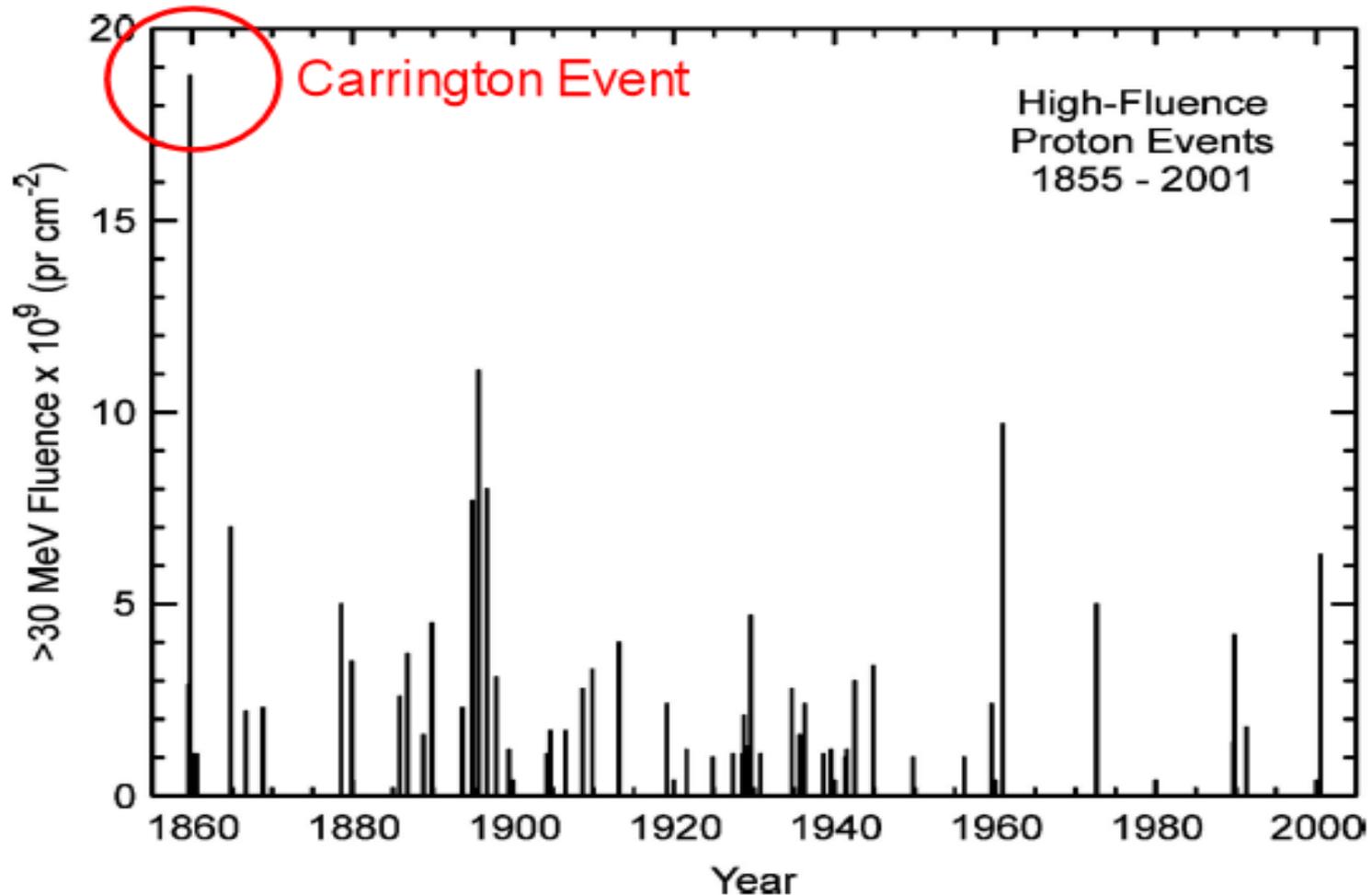
## Top Geomagnetic Storms 1932-2000 (Dst)

1. March 14, 1989	-548 nT
2. July 5, 1941	-453 nT
3. March 28, 1946	-440 nT
4. July 15, 1959	-434 nT
5. February 11, 1958	-428 nT
6. September 13, 1957	-426 nT
7. May 26, 1967	-391 nT
8. March 31, 2001	-383 nT
9. March 1, 1941	-382 nT
10. November 9, 1991	-375 nT

**“[Several lines of evidence suggest] the Carrington storm ranks among, but not significantly beyond, the greatest storms observed since.”** – Cliver and Svalgaard (2004)

# Solar Energetic Particles – A Hail of a Problem

SEPs are subatomic particles (mostly protons) accelerated to almost-light speed by explosions on the sun and subsequent shock waves. They pepper spacecraft and Earth's upper atmosphere like a cosmic hailstorm. In this category, the Carrington event is ~twice as strong as any other event of the past 150 years.



# Solar Energetic Particles – A Hail of a Problem

NOAA Space Weather Scale:  
Solar Radiation Storm

Extreme (S5) = 10,000\*

**Frequency:** Happens less than once per cycle on average, but more often recently.

**Consequences:** Radiation hazard to astronauts on EVA and people in high-flying aircraft at high latitudes; some satellites rendered useless; complete blackout of HF communications in polar regions.

## Top Solar Proton Events since 1976

Based on data from the NOAA Space Weather Prediction Center

1. March 23-34, 1991	43,000 (X9)
2. Oct. 19-20, 1989	40,000 (X13)
3. Nov. 4-6, 2001	31,700 (X1)
4. Oct. 28-29, 2003	29,500 (X17)
5. July 14-15, 2000	24,000 (X5)
6. Nov. 22-24, 2001	18,900 (M9)
7. Nov. 8-9, 2000	14,800 (M7)
8. Sep. 24-45, 2001	12,900 (X2)
9. Feb. 20-21, 1994	10,000 (M4)

\*Flux level of  $\geq 10$  MeV particles

# Busting the Scales

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NOAA Space Weather Scales for solar radiation storms and radio blackouts make sense. S5- and R5-level events are truly seldom, and it is possible to make a short, finite list of all the extreme events of the Space Age.

NOAA's Space Weather Scale for geomagnetic activity is less useful. This is because of limitations in the K-index, which is easily saturated. In the historical record, dozens of storms with a wide range of consequences would all be described as G5 or "extreme."

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# What Makes the Carrington Event Special?

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Other solar storms have exceeded the Carrington Event in narrow categories: geomagnetic intensity, X-ray flare power, the spread of auroras, and so on. The Carrington Event is special because it is near the top of all categories at once.

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Jackpot! The Perfect Solar Storm



# But Wait...There's More: 1859 Carrington Event

- Three days of intense aurora below 50 degrees latitude
  - As far south as 10 degrees latitude
- Significant portions of the world's telegraph lines were adversely affected
  - Telegraph rooms caught fire
  - Some stations were out of operation for eight hours
- The largest solar particle event on record
  - From Ice Core data covering over 500 years
  - May have reduced ozone by 5 percent for 4 years



**While the 1859 event has close rivals or superiors in each of the above [five] categories of space weather activity, it is the only documented event of the last ~150 years that appears at or near the top of all of the lists.**

**THE 1859 SOLAR–TERRESTRIAL DISTURBANCE  
AND THE CURRENT LIMITS OF  
EXTREME SPACE WEATHER ACTIVITY,**

E. W. CLIVER and L. SVALGAARD  
Solar Physics (2004) 224: 407–422

# Estimated Impacts

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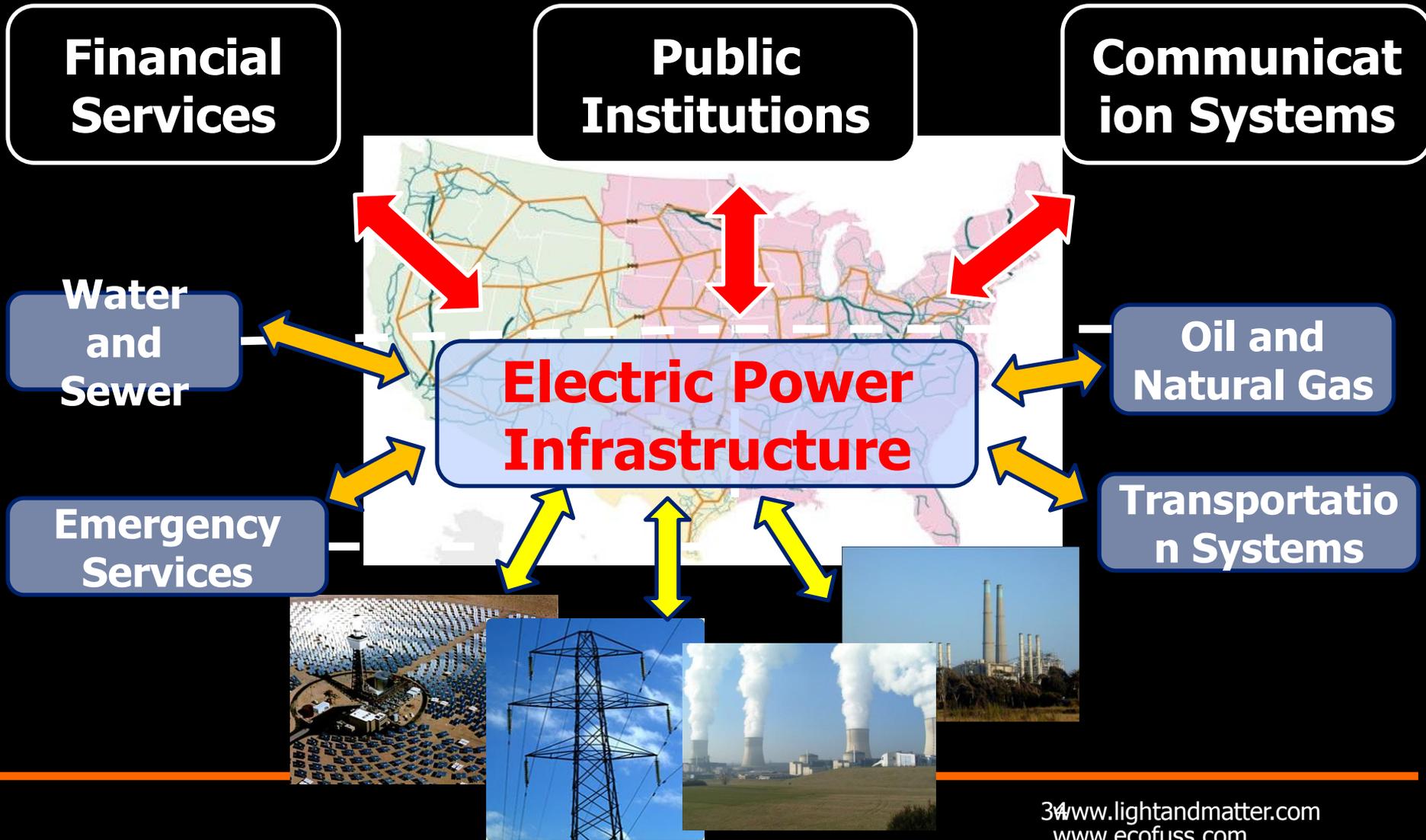
According to a study by the Metatech Corporation, the occurrence today of an event like the May 1921 superstorm, [*less intense than the Carrington Event*] would result in large-scale blackouts affecting more than 130 million people and would expose more than 350 transformers to the risk of permanent damage.

NRC Workshop Report, 2008

**Transformers in general are “one-of-a-kind” design, take months to build, and would take months to replace**

**Most Emergency Power system backups rely on gasoline or other fuel, and reserves-on-hand are limited to a few days at best**

# Electric Power is the Backbone of the Nation's Critical Infrastructure





# But we are not Defenseless (1/3)

## National Space Weather Program

The NSWP is a federal interagency initiative established in 1995 to improve our capability to make timely and reliable predictions of significant disturbances in space weather and to provide this information in ways that are tailored to the specific needs of those who are potentially affected by them.

### GOAL:

- I. Discover and understand the physical conditions that produce space weather and its effects.
- I. Develop and sustain necessary observational capabilities.
- II. Provide tailored and accurate space weather information where and when it's needed.
- III. Raise national awareness of the impacts of space weather.
- IV. Foster communication among government, commercial, and academic organizations.



# But we are not Defenseless (2/3)

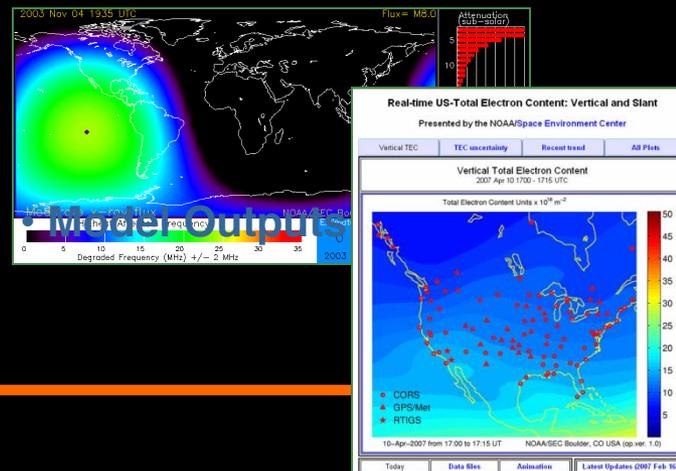


## NOAA SWPC

### Space Weather Products and Services

- **Watches:** The conditions are favorable for occurrence
- **Warnings:** disturbances that are imminent, expected in the near future with high probability
- **Alerts:** observed conditions meeting or exceeding thresholds
- **Forecasts and other routine products**

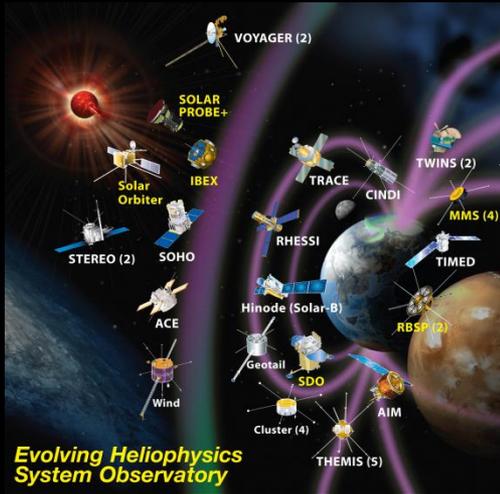
NOAA Scale	Range 1 (minor) to 5 (extreme)	Past 24 hours	Current
Geomagnetic Storms		none	none
Solar Radiation Storms		none	none
Radio Blackouts		none	none



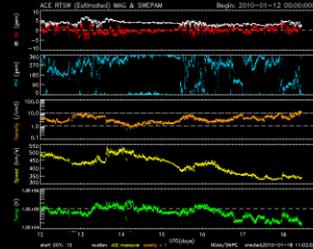
# But we are not Defenseless (3/3)



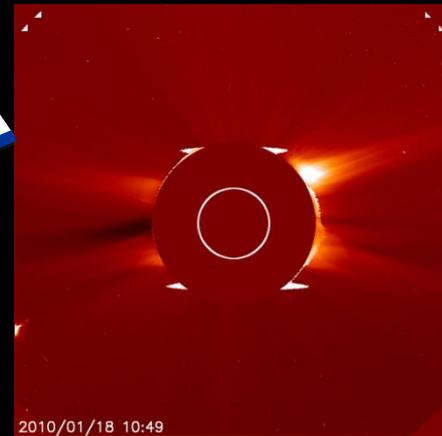
NASA Heliospheric System Observatory (HSO): SWx



HSO

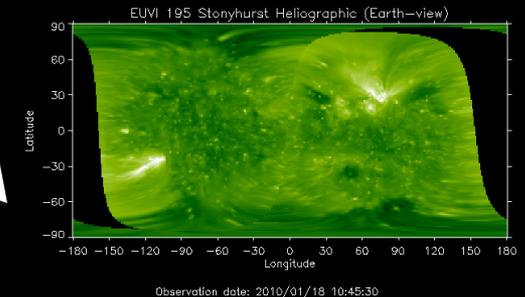


ACE



SOHO

STEREO



CCMC data  
Models+Theory

SWx Users



# Need Exists Today to Plan for Tomorrow

NASA STEREO (Ahead)

## •Ground Sites

- Magnetometers (NOAA/USGS)
- Thule Riometer and Neutron monitor (USAF)
- SOON Sites (USAF)
- RSTN (USAF)
- Telescopes and Magnetographs
- Ionosondes (AF, ISES, ...)
- GPS (CORS)

## •SOHO (ESA/NASA)/ SDO (NASA)

- Solar EUV Images
- Solar Corona (CMEs)

## •ACE (NASA)

- Solar wind speed, density, temperature and energetic particles
- Vector Magnetic field

ESA/NASA SOHO



NASA ACE

NOAA GOES

## •SDO (NASA)

- Launch 2009
- Solar UV/EUV Images

NOAA POES

## •STEREO/SDO

- Solar Corona
- Solar EUV Images
- Solar wind
- Vector Magnetic field

## •GOES (NOAA)

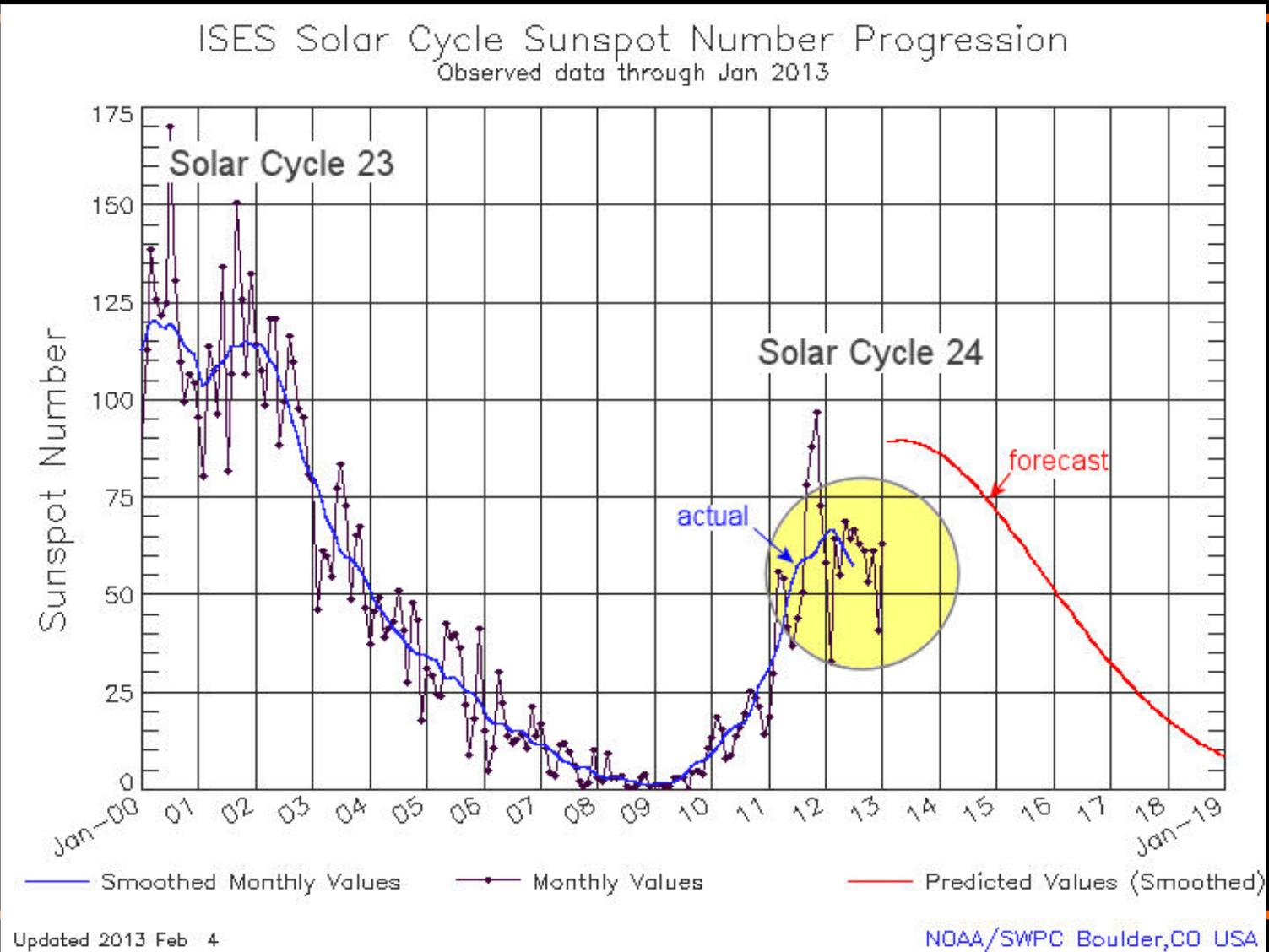
- Energetic Particles
- Magnetic Field
- Solar X-ray Flux
- Solar EUV Flux
- Solar X-Ray Images

## •POES (NOAA)

- High Energy Particles
- Total Energy Deposition
- Solar UV Flux

NASA STEREO (Behind)

# Just When You Thought it was Safe to Predict the Solar Cycle....



# When is Winter, Again?

Terrestrial weather forecasters often have trouble predicting the timing and intensity of winter storms. We've learned to live with the uncertainty of wind and snow. It could be worse, though. What if weather forecasters had trouble predicting the timing and intensity *of winter itself*?

"NOAA forecasters say there is a 40% chance that winter will begin in December this year, and a 20% chance that it will last for at least 3 months."

This is, essentially, the state of forecasting the underlying rhythms of the sun.



# The Sun is never boring

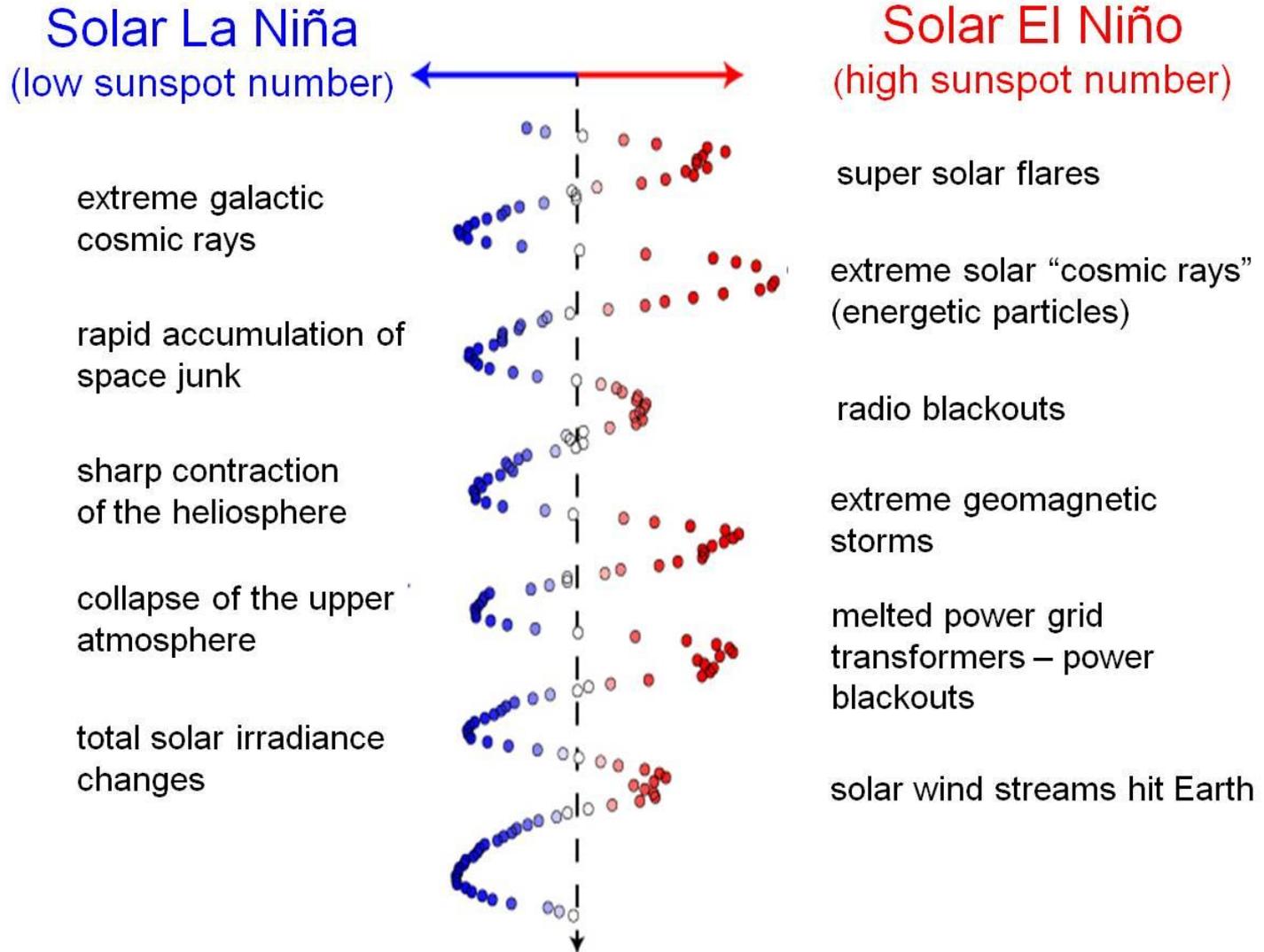


Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right, low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather impacts experienced at Earth (doi: 10.1002/swe.20039).

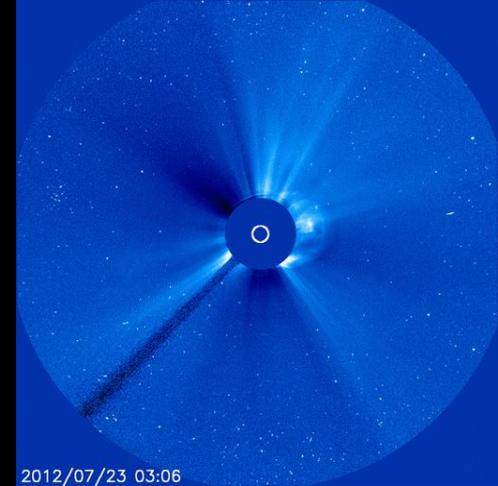
“Nature, at its most fantastic...”



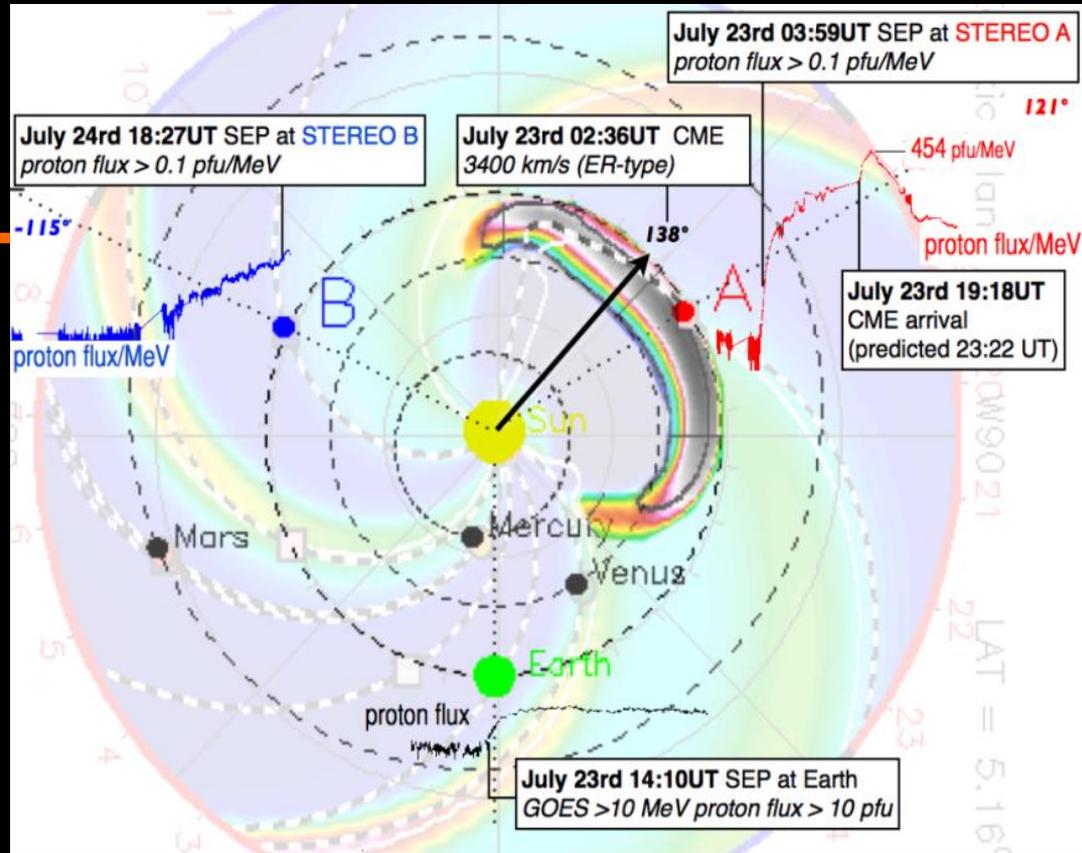
Anderson  
Cooper  
360

DISCOVERY GOING TO SMITHSONIAN

LIVE  
CNN



July 23, 2012, one of the fastest CMEs of the Space Age rocketed away from the western limb of the sun travelling 3500 km/s.



From <http://stereo.gsfc.nasa.gov/gallery/item.php?id=selects&iid=66>  
 Surrounding the sun has allowed us to detect major storms that otherwise we might have missed.

What would this storm have done to our planet?



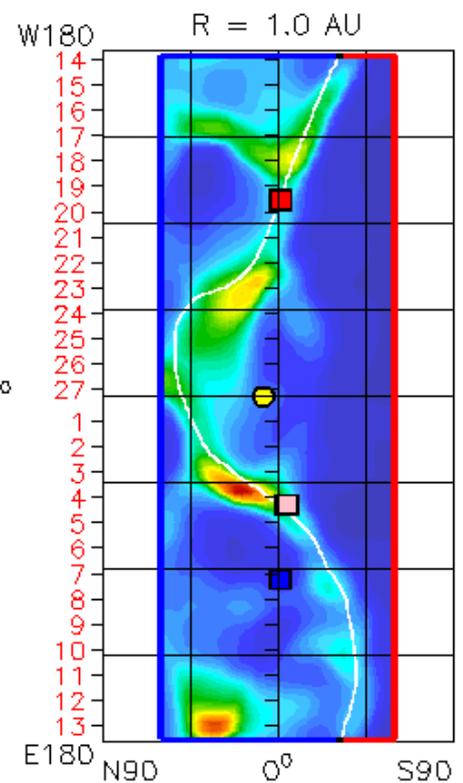
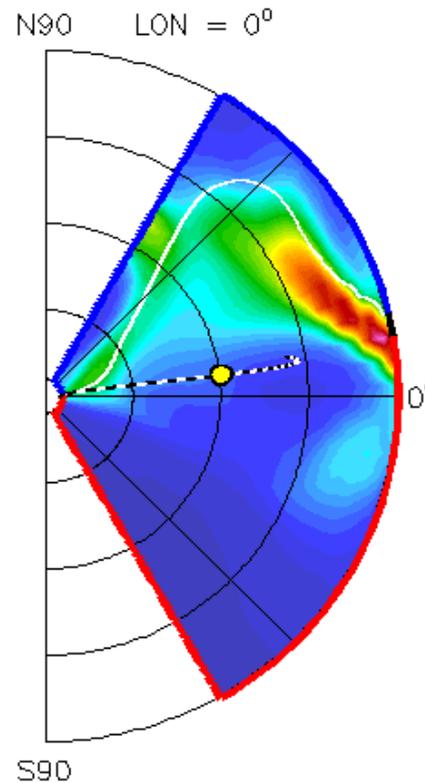
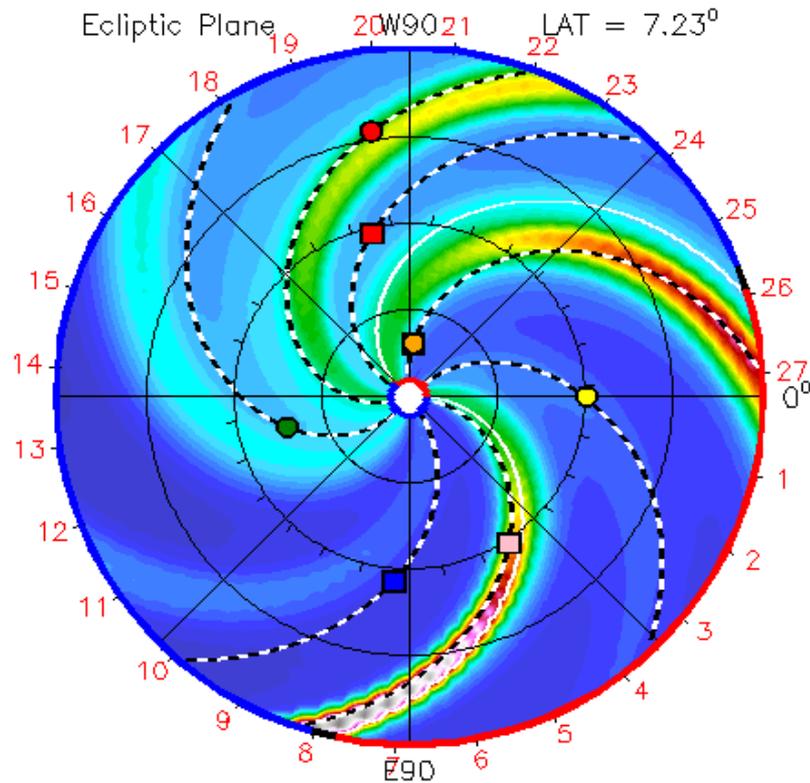
STEREO-A was in the line of fire, and the spacecraft was hit by a severe solar radiation storm. It was stronger than any proton event observed since 1976. Without STEREO-A, this major event would have passed unnoticed

# Interplanetary Space Weather: A New Paradigm

2011-09-07T00:00

2011-09-07T00 +0.00 day

● Earth    ● Mars    ● Mercury    ● Venus    ■ Messenger    ■ Spitzer    ■ Stereo\_A    ■ Stereo\_B



$R^2 N$  ( $\text{cm}^{-3}$ )

0 10 20 30 40 50 60

IMF polarity

- ■ ■ +

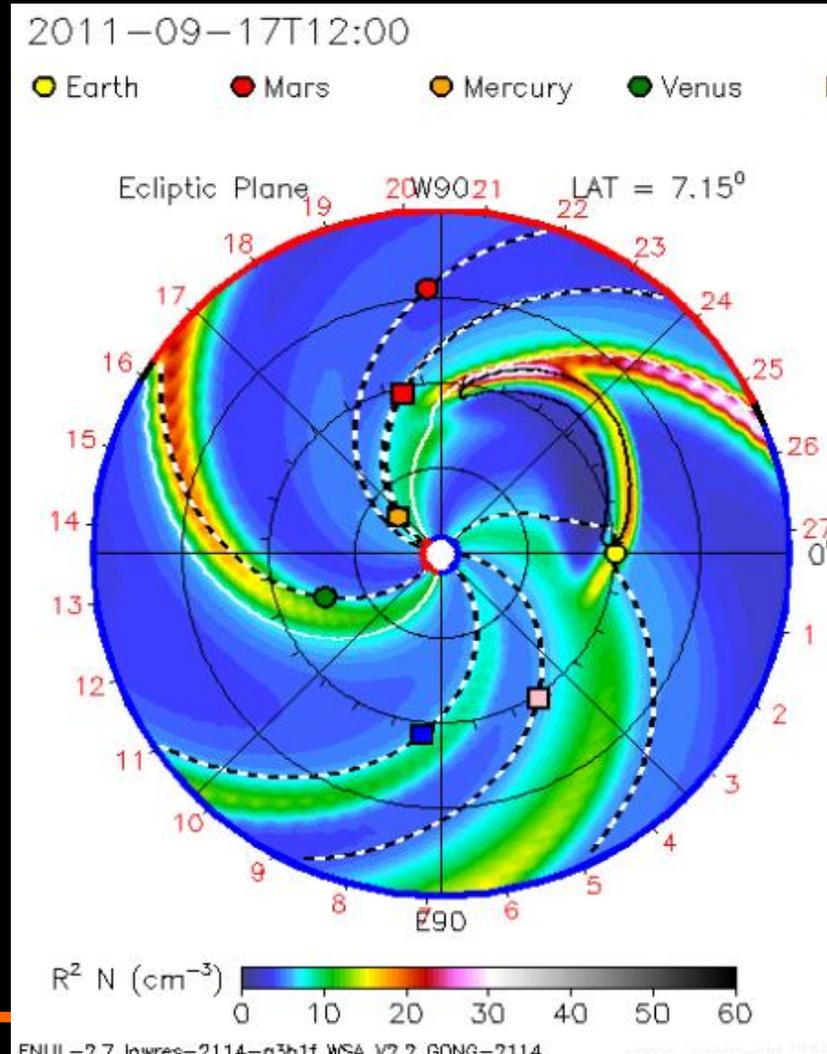
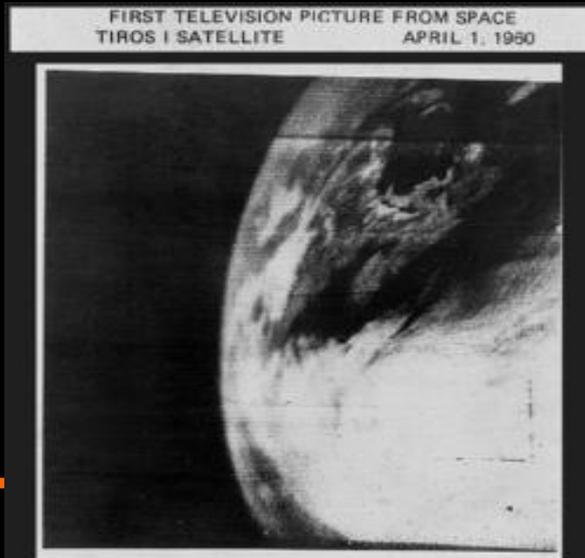
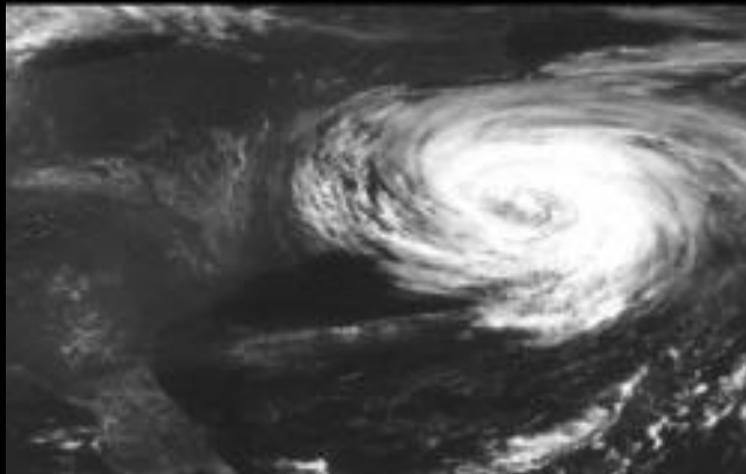
Current sheath

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3D IMF line

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# This development is akin to the first satellite images of hurricanes on Earth



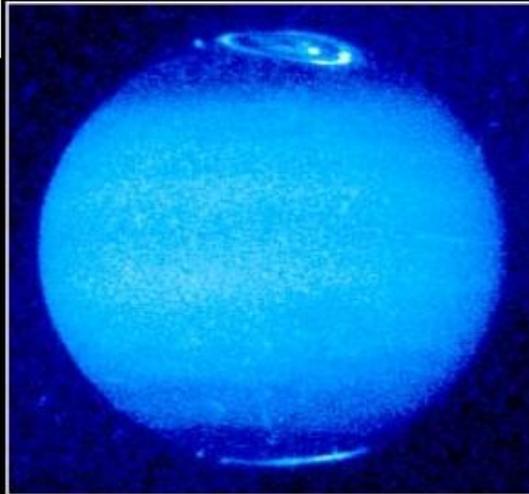
# Sun's Impact on other Planets

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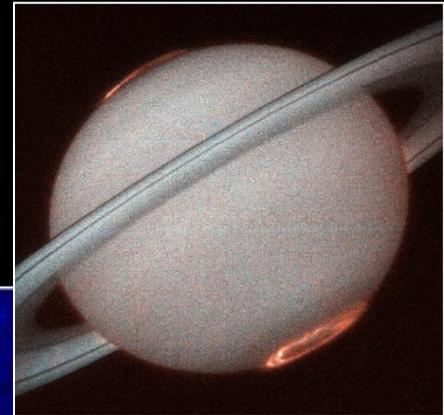


*True-color image of Earth's aurora taken from Space Shuttle*

- **Similar physical processes are evident in vastly different environments**



*Jupiter's aurora imaged with HST*



*Aurora at Saturn's poles*

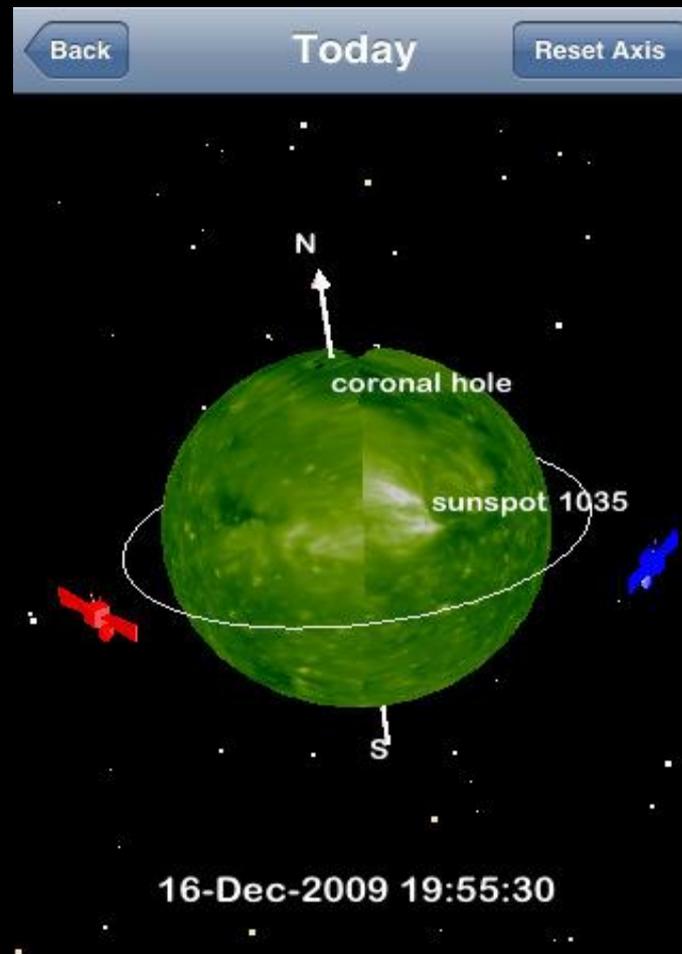
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# On the subject of Scientists



# 3D Sun: there is an app for that

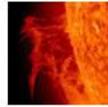
## Over a Million Users to Hold the Sun in the Palm of their Hand



Geographic distribution of the App is holding steady at 85 countries. The top 10 are:

1. United States 60483
2. Canada 6484
3. United Kingdom 6002
4. Italy 5363
5. Netherlands 3539
6. Japan 3394
7. Spain 3345
8. Germany 2589
9. Australia 2148
10. France 1224

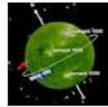
## Today's News

**Nov. 9** Solar Activity Update

Sunspot 1121 is decaying, but it still has a 'beta-gamma' magnetic field that harbors energy for M-class solar flares. NOAA forecasters estimate a 50% chance of M-flares during the next 24 hours.



## More news:

**Nov. 9** Farside Sunspot

Old sunspot 1117 is emerging from STEREO's narrow blind spot on the far side of the sun. Spin the 3D Sun and look for 'AR1117'.

**Nov. 6** Bright X-ray Flare

Active sunspot 1121 has unleashed one of the brightest solar flares in years, an M5.4-class eruption at 15:36 UT on Nov. 6th. Must-see movie from SDO.

**Nov. 5** Active Sunspot

Sunspot 1112 has returned and, as expected, it is crackling with flares. So far, the eruptions have not been geoeffective because of the sunspot's location on the eastern limb.

**Nov. 3** Farside Flares

An active region just over the sun's eastern horizon is crackling with solar flares and hurling material high above the stellar surface. Hot movies from SDO!

**Nov. 3** Northern Lights

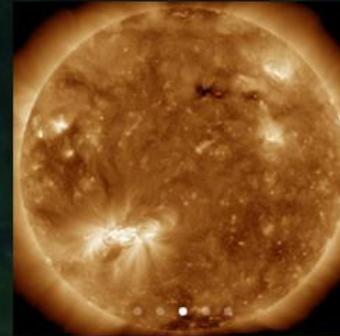
A bright outburst of auroras spread across the skies of Norway this morning. A magnetic fluctuation in



## Current Conditions

Last updated: November 10, 2010 04:06:01 UTC

**EERIE QUIET:** After unleashing the brightest X-ray flare in years on Nov. 6th, sunspot 1121 has gone quiet. Solar activity is low--for now.



There are no large coronal holes on the Earth-facing side of the sun.

<b>Sunspot Number:</b>	35
<b>Solar Wind Speed:</b>	283.0 km/s
<b>X-ray Solar Flares:</b>	6 hr max: B2 24 hr max: B3
<b>Planetary K Index:</b>	Current: Kp = 0 24 hr max: Kp = 1

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# NEWS TECHNOLOGY

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A group of students from Bishop, California, have launched a rubber chicken to an altitude of 120,000ft as part of a project.

The journey, which involved attaching the fowl to a rocket as Camilla to a helium balloon, was undertaken to measure the levels of radiation exposed to the chicken during a solar storm, last month.

Camilla is already well known among space enthusiasts as a mascot of Nasa's Solar Dynamics Observatory and has more than 20,000 followers on Twitter, Facebook, and Google+.

On the outside of her knitted space suit, she wears several badges to register radiation levels.

She flew twice - once on 3 March before the start of the solar storm and again on 10 March while the storm was in full swing - to give the students a basis for comparison.

The students now hope to repeat the mission with a different species of microbes to find out if they can live on the edge of space.

# NASA Takes Students on a Journey to the Stars

## TEACHING WITH THE SHOW

To support a class discussion after viewing *Journey to the Stars*, you may wish to review the main content points from each section of the show (bolded terms are found in the glossary) and then use the Guiding Questions (answers available at [smith.org/resources/nfl/web/starguide/questions.html](http://smith.org/resources/nfl/web/starguide/questions.html)).

### 1. Introduction

- We live on a planet that orbits a star that is one of hundreds of billions in our galaxy.
- Our star, the Sun, is a middle-aged yellow star of somewhat above average mass.
- Without nurturing light that carries energy from our Sun, life as we know it would not exist.
- And without the elements formed by stars that lived and died billions of years ago, we—and everything around us—would not exist.



Visualization of the Sun and Earth are created from observations made by satellites using Earth ground-based and space-based telescopes.

### GUIDING QUESTIONS

#### All Grades

- What have you learned about stars?
- Why are stars important to us?
- How do scientists study stars? How do they study the Sun?

#### Grades 3-5

- What is the Sun?
- How is the Sun important?
- How are stars the same? How are they different?

#### Grades 6-8

- How does the Sun affect Earth?
- How is our Sun similar to or different from other stars?
- What are star clusters?
- What is mass? How does mass relate to gravity?
- What are the stages of the life of a star?

#### Grades 9-12

- What does the Sun emit?
- How do stars form?
- Why do stars shine?
- What does the color of a star indicate?
- How does life depend on ancient stars?
- How might the Sun impact future stars?
- How does the discovery of brown dwarfs expand our understanding of stellar objects?



**NEWS UPDATE: Over 39,000 educators requested the DVD and supporting materials. Educator responses indicate that over TWO MILLION STUDENTS are being taken on a Journey to the Stars!**



Visuals are scientifically accurate and depict stars using real data from NASA spacecraft and the most advanced theoretical models modern science has to offer. *Journey* is a solid combination of science and art. Scientists were involved in the show from beginning to end, contributing to every step of the production process. *Journey* has data from about 40 different scientific research groups around the world and more than one hundred scientists contributed to the production.

Each DVD contains the show in multiple languages--English, Spanish, French, Japanese, Hindi, Chinese and others.

# Because we all share the same fate

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The End

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Those  
movies  
were, of  
course,  
from the  
“old days”  
before we  
could see  
“all the Sun,  
all the time”  
Solar  
Dynamics  
Observatory



# Satellite Failures due to Space Weather Effects

## More recent satellite failures:

- **Telestar 401 (Jan 11 1997)**
- **Galaxy IV (1998) – a 250 million USD satellite**
  - silenced 80% of pagers in North America
  - PC-Direct (internet)
  - CBS's radio and television feeds
  - CNN's Airport Network
- **More than 12 satellites lost due to Space Weather Effects**

**Last 4 years space losses may have exceeded \$500 million**

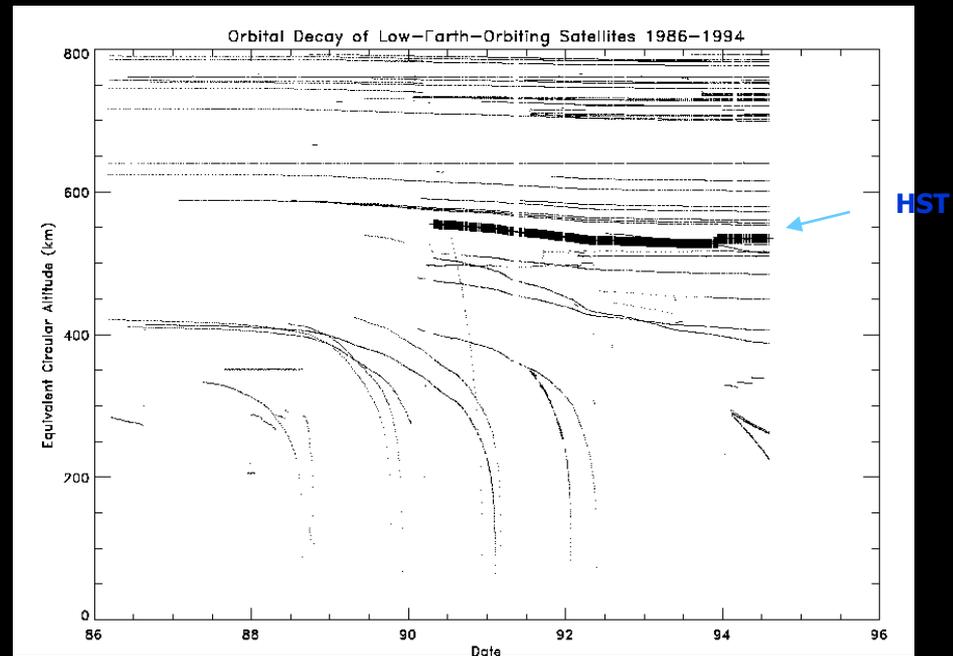
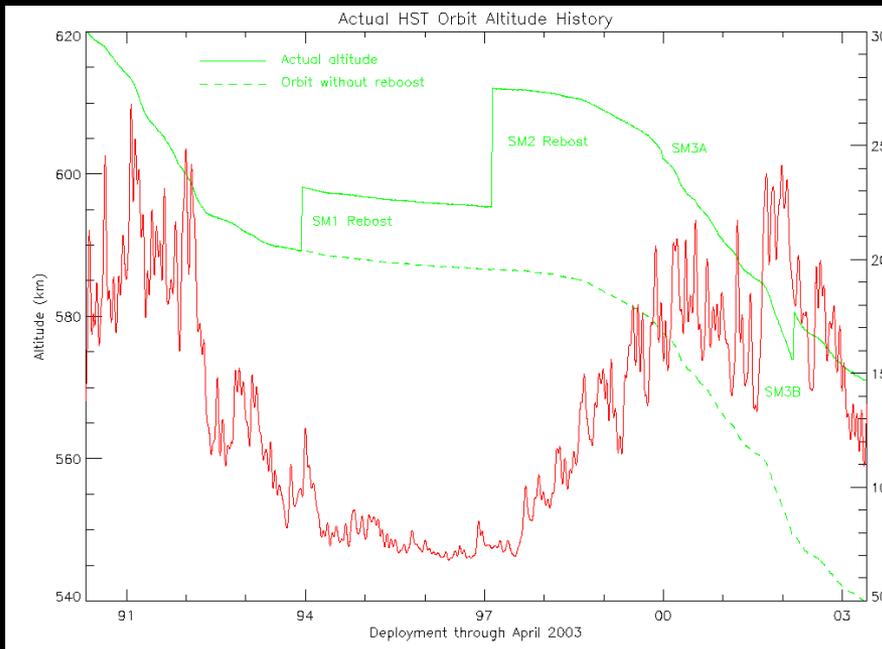


Figure courtesy of The Solar Data Analysis Center

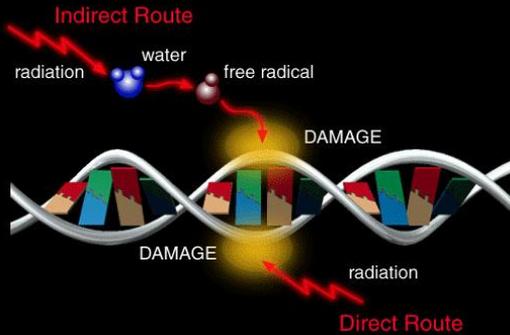
# Increased Drag on Satellites

The expanding atmosphere causes an increased drag on low orbit satellites. In addition to loose altitude they can also start tumbling since the satellites in most cases are non-symmetrical

- Skylab re-entered several years earlier than planned
- XMM dropped 5 km during the March 89 storm
- Hubble Space Telescope drops 10-15 km per year
  - Re-boosted by the Shuttle



# High Energy Particles Hazards to Humans

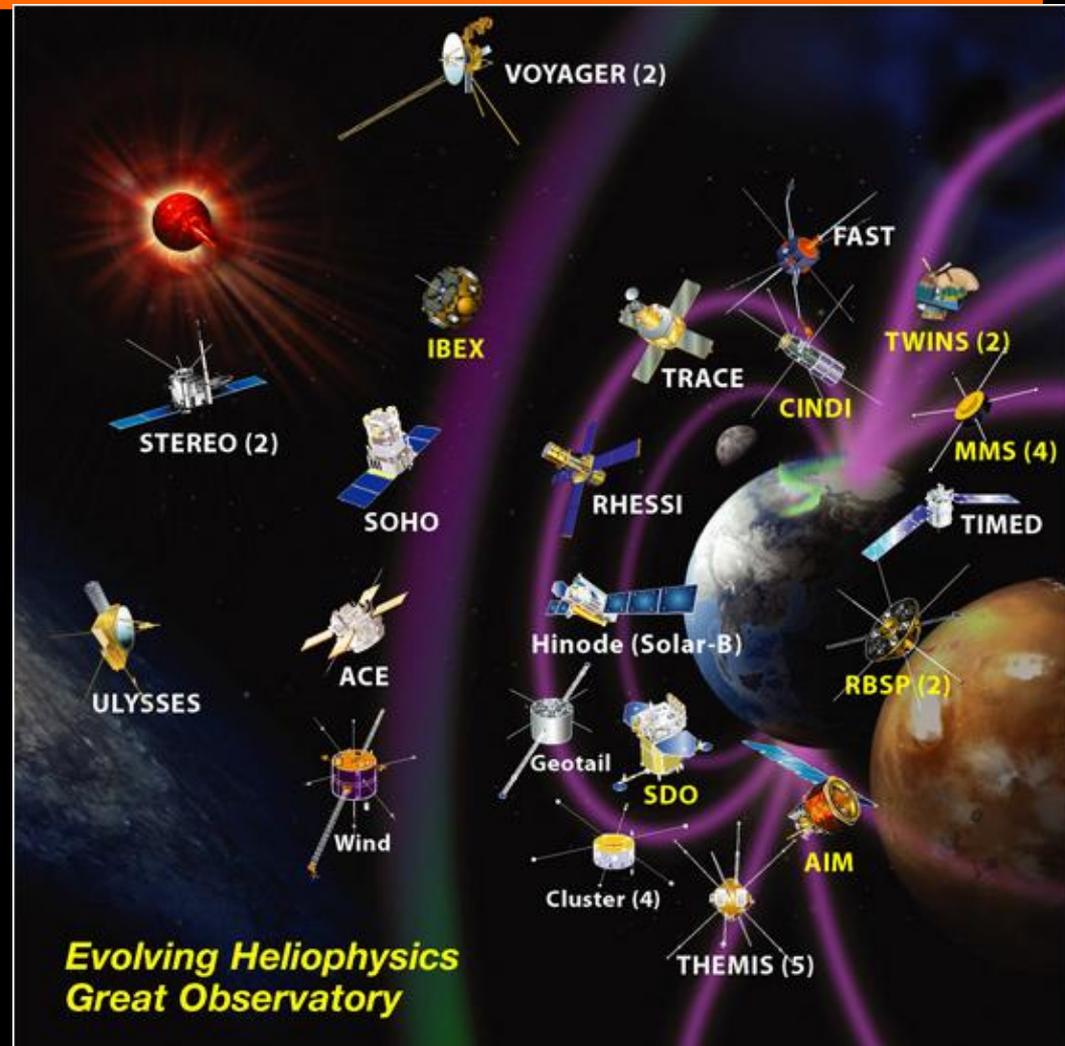


- **Humans in space**
  - Space Shuttle, International Space Station, missions to Mars
- **Crew/Passengers in high-flying jets and polar routes**
  - Concorde carries radiation detectors
  - Passengers may receive radiation doses equivalent to several chest X rays.



# Heliophysics Great Observatory

NASA Short Term Approach:  
Research program with existing NASA assets to create space weather prediction capability at the moon, Mars and Beyond



# Sun's Impact on other Planets

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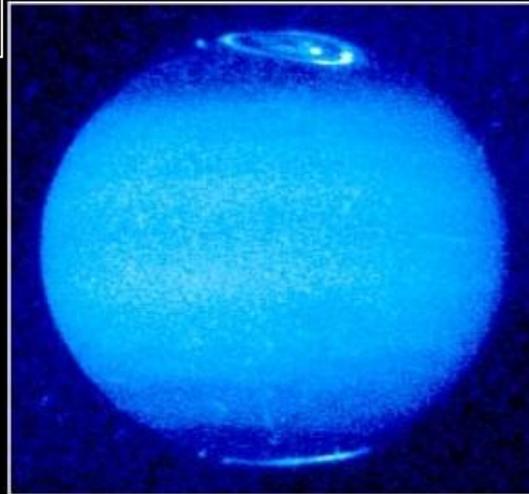


*True-color image of Earth's aurora taken from Space Shuttle*



*Aurora at Saturn's poles*

- Similar physical processes are evident in vastly different environments



*Jupiter's aurora imaged with HST*

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# Effects on Civil Aviation

- **Aircrew radiation exposure**
- **Effects on aircraft avionics, communications and GPS navigations systems**

## Recent effects on polar routes

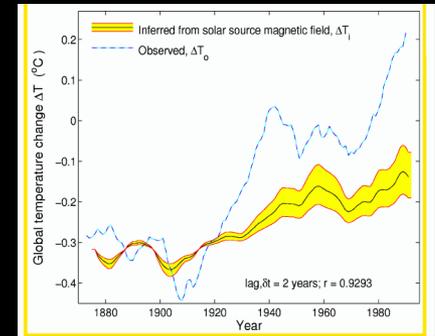
**Northwest Airlines:** diverted a Detroit-Beijing flight to a non-polar route due to both HF communication problems (radio blackout) and a solar radiation storm, forcing an unscheduled stop at Fairbanks for fuel. This caused a 3 hour delay and an estimated \$100,000 cost to NWA.

**Re-routing and delays are costly to the airlines:**  
fuel cost/ crew delays/ additional crews



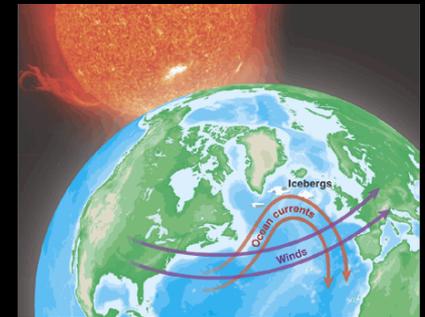
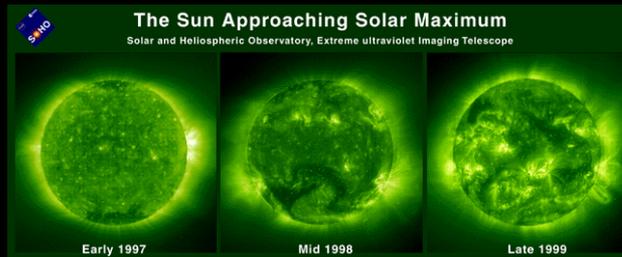
# The Sun and global warming

- Long term variations in total irradiance ("total energy")

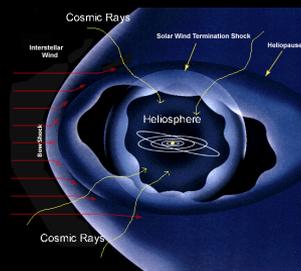
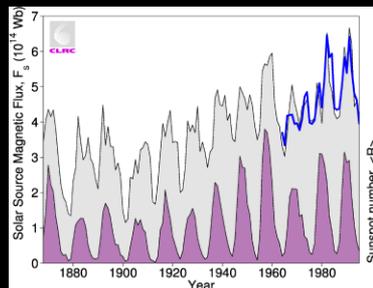
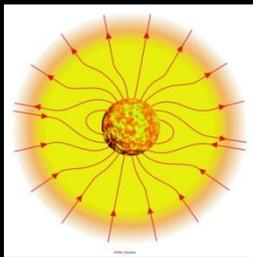


- Long term variation in UV/EUV radiation:

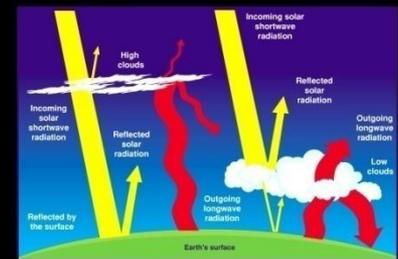
- Changes in chemistry (ozone), temperature etc.



- Long term variation in the solar wind and the magnetic field



Cloud Effects On Earth's Radiation



## Impacts on animals

- The navigational abilities of homing pigeons are affected by geomagnetic storms
- Pigeons and other migratory animals, such as dolphins and whales, have internal biological compasses composed of the mineral magnetite wrapped in bundles of nerve cells.

