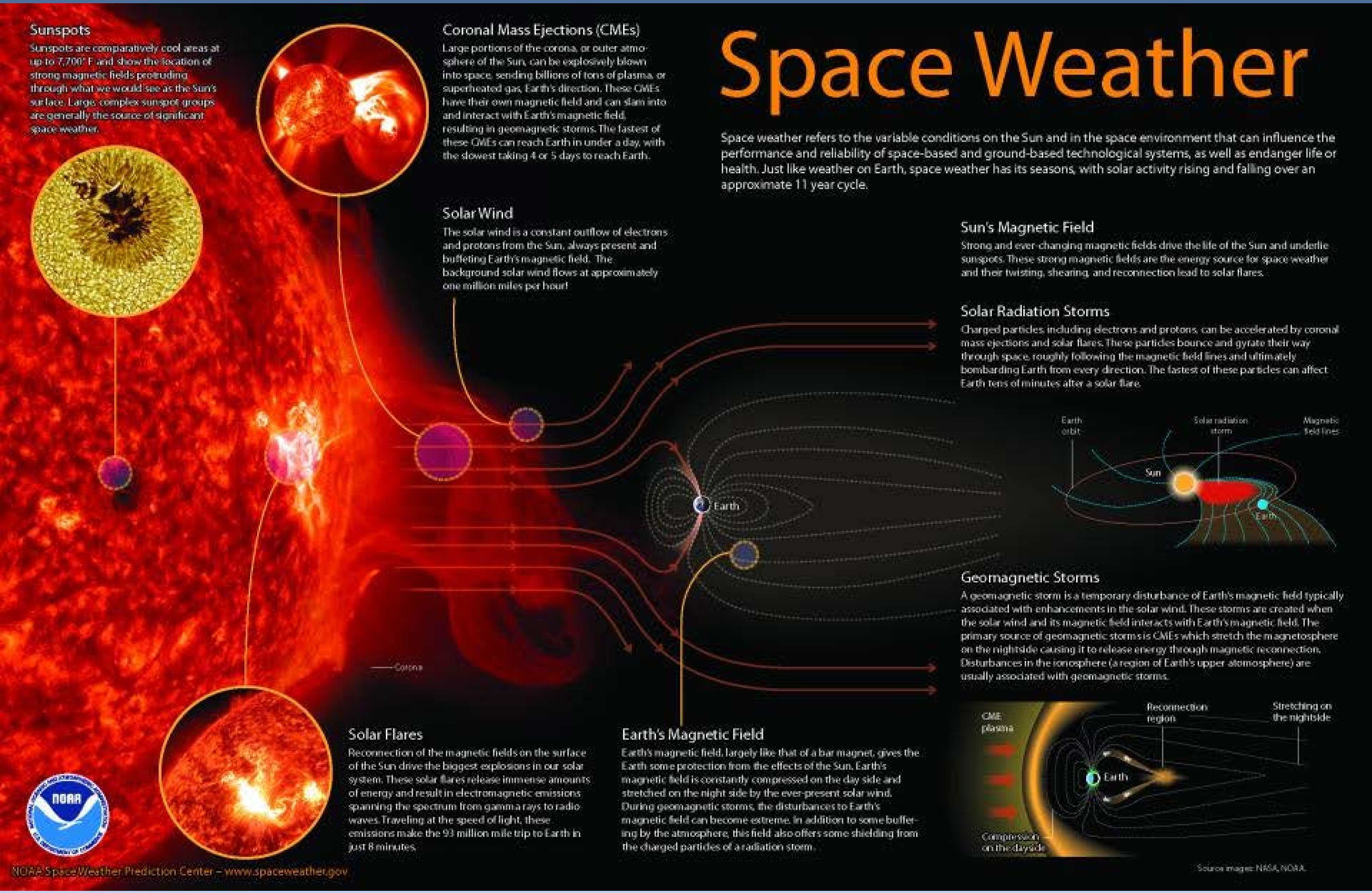
Space Weather Overview

LCDR Paul S. Hemmick
NOAA's Space Weather Prediction Center


Space Weather
Space weather refers to the variable conditions on the Sun and in the space environment that can influence the performance and reliability of space-based and ground-based technological systems, as well as endanger life or health. Just like weather on Earth, space weather has its seasons, with solar activity rising and falling over an approximate 11 year cycle.
Sunspots
Sunspots are comparatively cool areas at up to 7,700° F and show the location of strong magnetic fields protruding through what we would see as the Sun's surface. Large, complex sunspot groups are generally the source of significant space weather.
Coronal Mass Ejections (CMEs)
Large portions of the corona, or outer atmosphere of the Sun, can be explosively blown into space, sending billions of tons of plasma, or superheated gas, Earth's direction. These CMEs have their own magnetic field and can slam into and interact with Earth's magnetic field, resulting in geomagnetic storms. The fastest of these CMEs can reach Earth in under a day, with the slowest taking 4 or 5 days to reach Earth.
Solar Wind
The solar wind is a constant outflow of electrons and protons from the Sun, always present and buffeting Earth's magnetic field. The background solar wind flows at approximately one million miles per hour!
Sun's Magnetic Field
Strong and ever-changing magnetic fields drive the life of the Sun and underlie sunspots. These strong magnetic fields are the energy source for space weather and their twisting, shearing, and reconnection lead to solar flares.
Solar Radiation Storms
Charged particles, including electrons and protons, can be accelerated by coronal mass ejections and solar flares. These particles bounce and gyrate their way through space, roughly following the magnetic field lines and ultimately bombarding Earth from every direction. The fastest of these particles can affect Earth tens of minutes after a solar flare.
Earth orbit
Solar radiation storm
Magnetic field lines
Sun
Earth
Corona
Geomagnetic Storms
A geomagnetic storm is a temporary disturbance of Earth's magnetic field typically associated with enhancements in the solar wind. These storms are created when the solar wind and its magnetic field interacts with Earth's magnetic field. The primary source of geomagnetic storms is CMEs which stretch the magnetosphere on the nightside causing it to release energy through magnetic reconnection. Disturbances in the ionosphere (a region of Earth's upper atomosphere) are usually associated with geomagnetic storms.
CME plasma
Reconnection region
Stretching on the nightside
Earth
Compression on the dayside
Solar Flares
Reconnection of the magnetic fields on the surface of the Sun drive the biggest explosions in our solar system. These solar flares release immense amounts of energy and result in electromagnetic emissions spanning the spectrum from gamma rays to radio waves. Traveling at the speed of light, these emissions make the 93 million mile trip to Earth in just 8 minutes.
Earth's Magnetic Field
Earth's magnetic field, largely like that of a bar magnet, gives the Earth some protection from the effects of the Sun. Earth's magnetic field is constantly compressed on the day side and stretched on the night side by the ever-present solar wind. During geomagnetic storms, the disturbances to Earth's magnetic field can become extreme. In addition to some buffering by the atmosphere, this field also offers some shielding from the charged particles of a radiation storm.
NOAA Space Weather Prediction Center – www.spaceweather.gov
Source images: NASA, NOAA.

SPACE WEATHER CONDITIONS on NOAA Scales

24-Hour Observed Maximums: R none | S none | G none

Latest Observed: R none | S none | G none

Predicted 2015-08-03 UTC: R1-R2 5% | R3-R5 1% | S1 or greater 1% | G none

Solar Wind Speed: **491** km/sec | Solar Wind Magnetic Fields: Bt **4** nT, Bz **1** nT | Noon 10.7cm Radio Flux: **102** sfu

21st Century Blue Marble
published: Tuesday, July 21, 2015 16:56 UTC
The NASA EPIC instrument on the NOAA/DSCOVR satellite snapped this picture of the day-lit side of the Earth, the 'Blue Marble,' on July 6, 2015.

New Website Q&A
published: Wednesday, January 14, 2015 00:42 UTC
If you have questions about the new website, we likely answer them here.

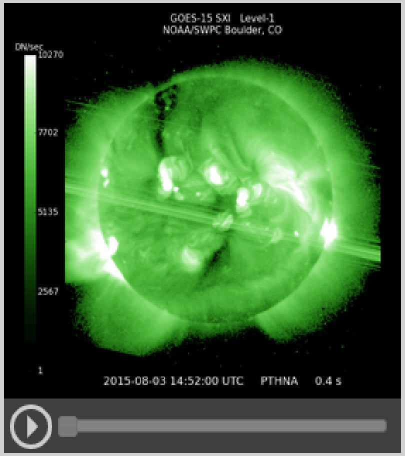
What's that bright spot in the Coronal Mass Ejections Image?
published: Tuesday, July 28, 2015 13:16 UTC
What are those bright spots that appear in the CME Image, people often ask.

Receive SWPC alerts and warnings
published: Thursday, October 09, 2014 22:31 UTC
Sign up for e-mail alerts via the Product Subscription Service.

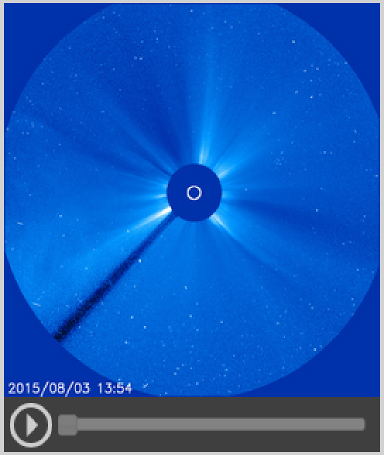
SERVING ESSENTIAL SPACE WEATHER COMMUNITIES

Aviation | Electric Power | Emergency Management | Global Positioning System (GPS)
Radio Communications | Satellites | Space Weather Enthusiasts

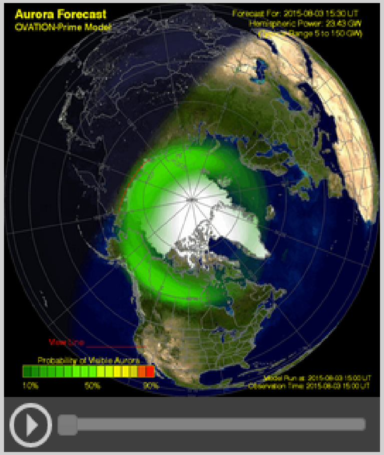
THE SUN'S X-RAYS



CORONAL MASS EJECTIONS

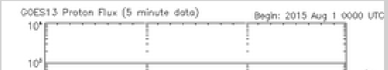


THE AURORA



GOES X-RAY FLUX

GOES PROTON FLUX



ESTIMATED PLANETARY K-INDEX

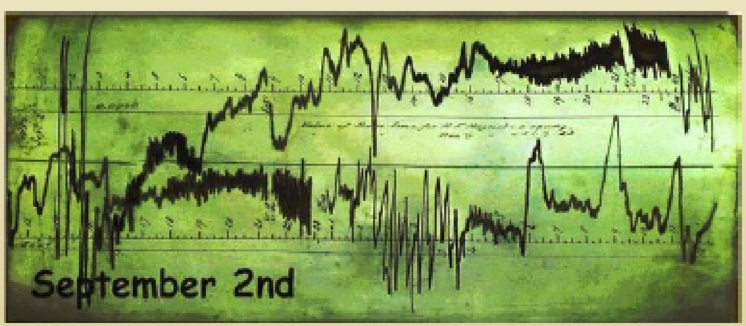
Space Weather Forecasting

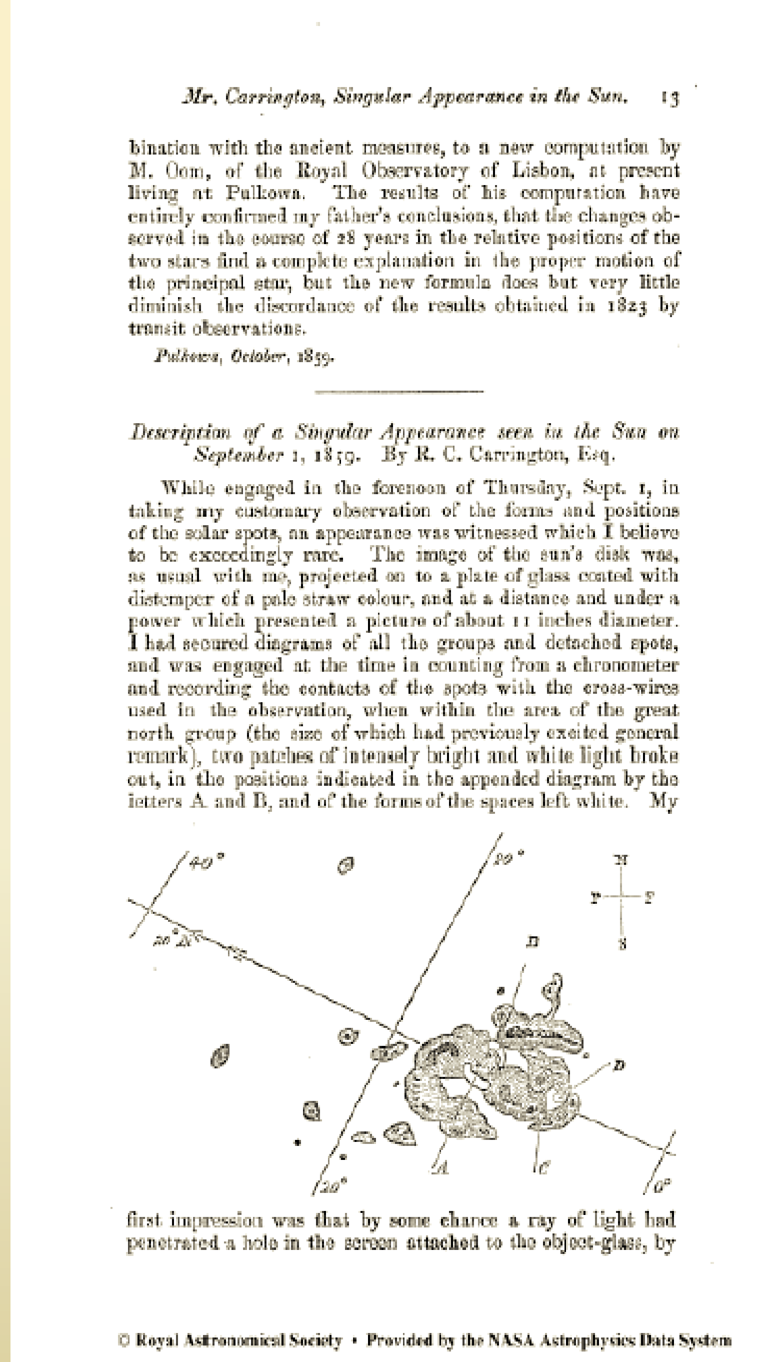
SWPC (Boulder, CO)

https://www.facebook.com/NWSSWPC

Carrington Event - 1859

- Thought to be the most energetic solar eruption in the last 150+ years
- This magnitude of event is very worrisome for FEMA, EU, et al
- Could have destructive impact to critical infrastructure





bination with the ancient measures, to a new computation by M. Oom, of the Royal Observatory of Lisbon, at present living at Pulkowa. The results of his computation have entirely confirmed my father's conclusions, that the changes observed in the course of 28 years in the relative positions of the two stars find a complete explanation in the proper motion of the principal star, but the new formula does but very little diminish the discordance of the results obtained in 1823 by transit observations.

Pulkowa, October, 1859.

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My first impression was that by some chance a ray of light had penetrated a hole in the screen attached to the object-glass, by

- Church, 1865, painting of aurora from South Seas.
- Electrical current induced in telegraph wires, so strong that it burned down a few telegraph offices.

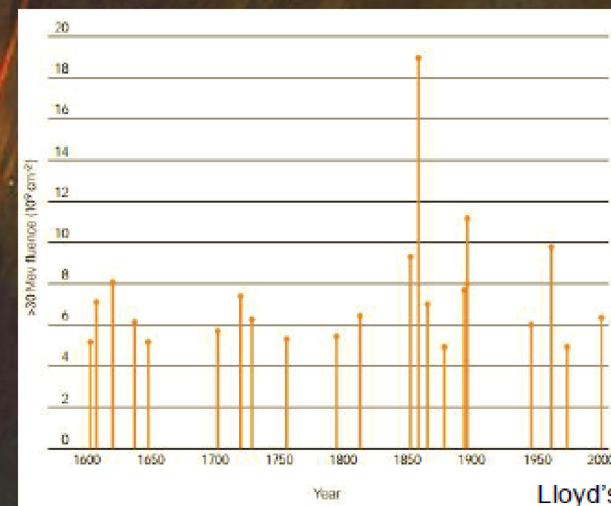
"…it was found utterly impossible to communicate…" – Quebec

"…pieces of paper were set on fire by the sparks…" – Christiania, Norway

"…intensity of current which gave a severe shock when testing…" – Philadelphia

"…worked more steadily when the batteries were off than attached." – Pittsburgh

Estimated global economic impact: $300,000 [Green et al., 2006]



Estimated satellite revenue loss today: $30 bln

Carrington Event – Most extreme space weather event on record

1859

That was a close one! Study: Massive solar storm barely missed us in 2012

By Carter Maguire, CNN
Updated 4:16 PM ET, Fri July 25, 2014

Science news

Star Trek legend became NASA's 'secret weapon'

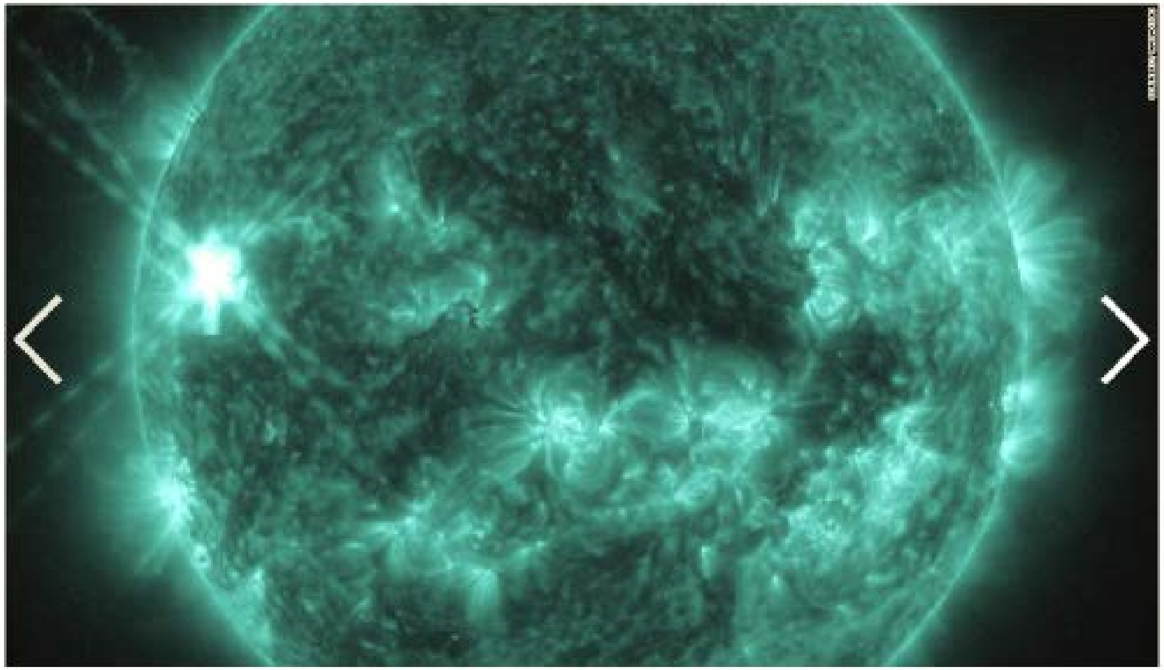
Nichelle Nichols has spent her whole life going where no one has gone before, and at 81 she's still as sassy and straight-talking as you'd expect from an interstellar explorer.

World's largest aquatic insect specimen found in China

The world's largest flying aquatic insect, with huge, nightmarish pincers, has been discovered in China's Sichuan province.

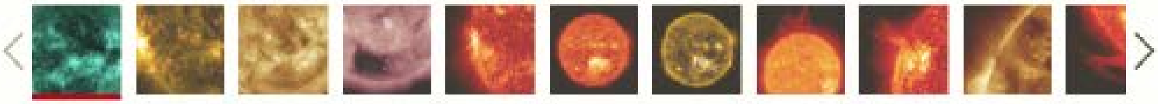
Cheating death through 'suspended animation'

As fans of "Grey's Anatomy," "ER" and any other hospital-



1 of 12

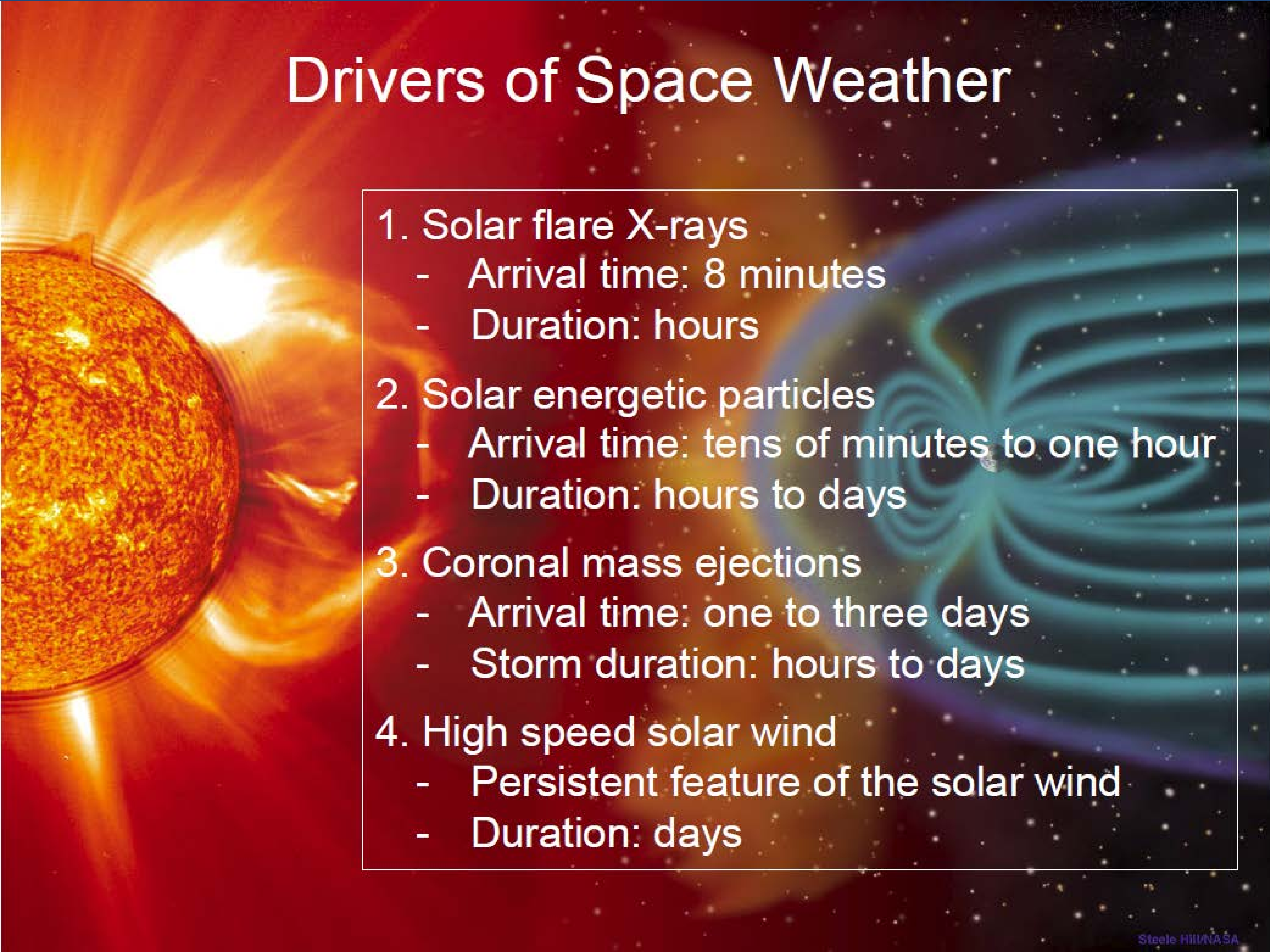
Show Caption



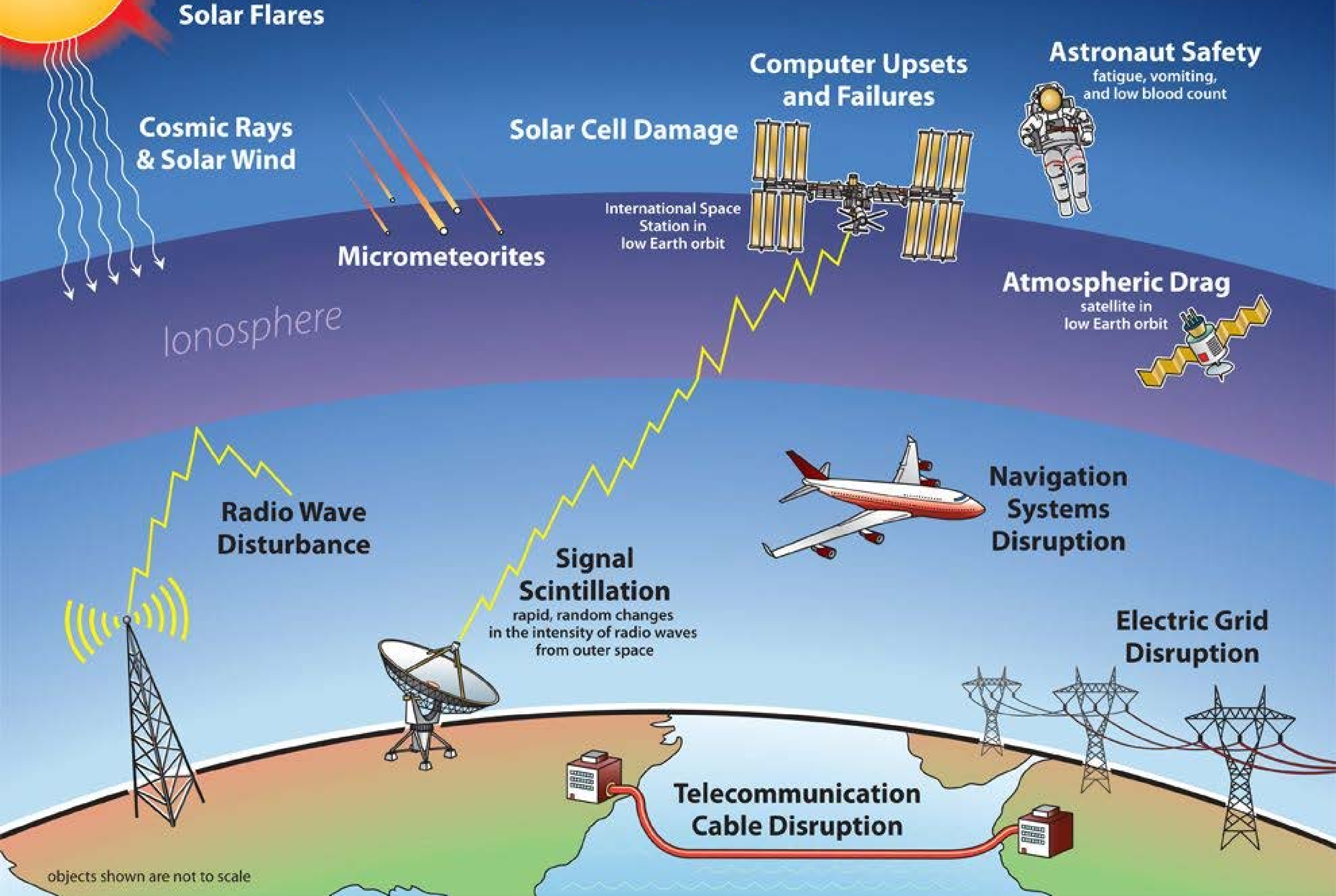
How Space Weather Impacts Earth

- Geomagnetic Storms
  - Coronal Mass Ejections (CME)
  - Coronal Holes
- Solar Radiation Storm
  - Solar Energetic Particles
- Radio Blackouts (Solar Flares)

Relativistic Electrons


Drivers of Space Weather
1. Solar flare X-rays
- Arrival time: 8 minutes
- Duration: hours
2. Solar energetic particles
- Arrival time: tens of minutes to one hour
- Duration: hours to days
3. Coronal mass ejections
- Arrival time: one to three days
- Storm duration: hours to days
4. High speed solar wind
- Persistent feature of the solar wind
- Duration: days
Steele Hill/NASA

Impacts of Space Weather



Space Weather Scales

- 3 Categories
  - Geomagnetic Storms

    (CMEs)
  - Solar Radiation Storms

    (Particle Events)
  - Radio Blackouts

    (Solar Flares)

http://swpc.noaa.gov

NOAA Space Weather Scales

Category: Scale	Category: Descriptor	Effect (Duration of event will influence severity of effects)	Physical measure	Average Frequency (1 cycle = 11 years)
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)

Category: Scale	Category: Descriptor	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
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); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** 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; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** 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 high-flying aircraft at high latitudes may be exposed to radiation risk.*** 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: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: 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.
*** High energy particle measurements (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

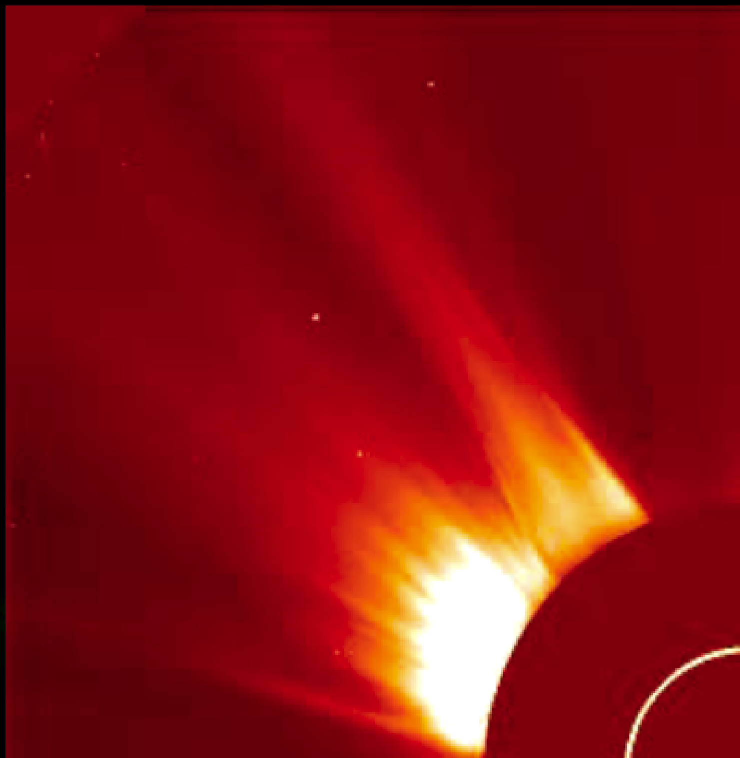
Category: Scale	Category: Descriptor	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on 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·m^{-2}. Based on this measure, but other physical measures are also considered.
** Other frequencies may also be affected by these conditions.

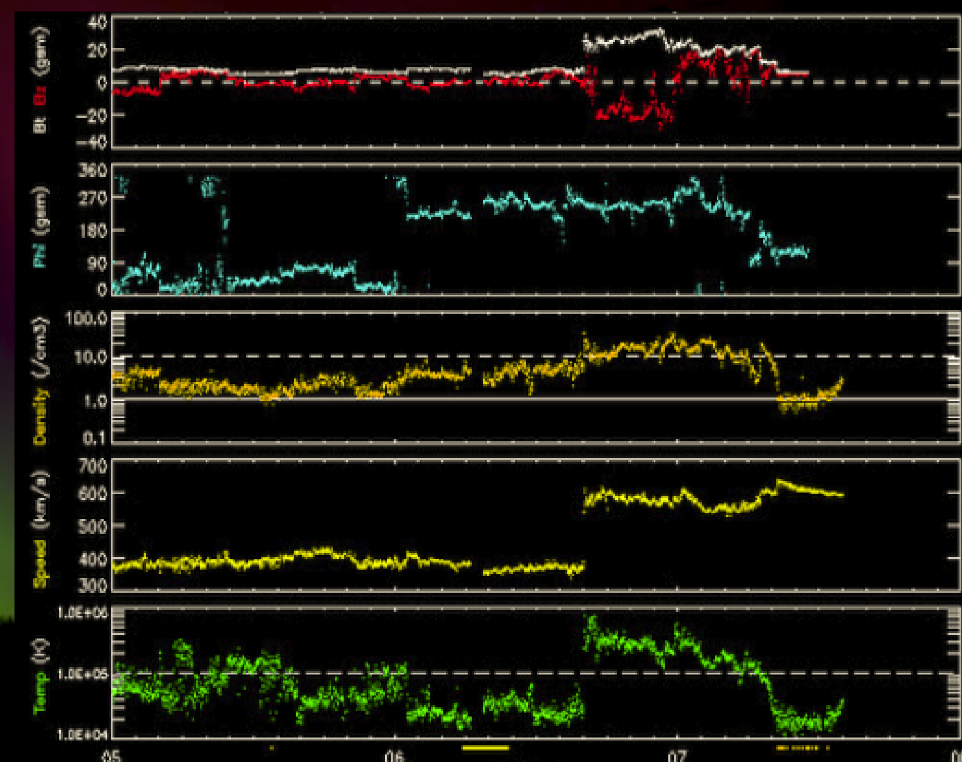
URL: www.sec.noaa.gov/NOAAScales

March 1, 2005

Geomagnetic Storms *(G Scale)*

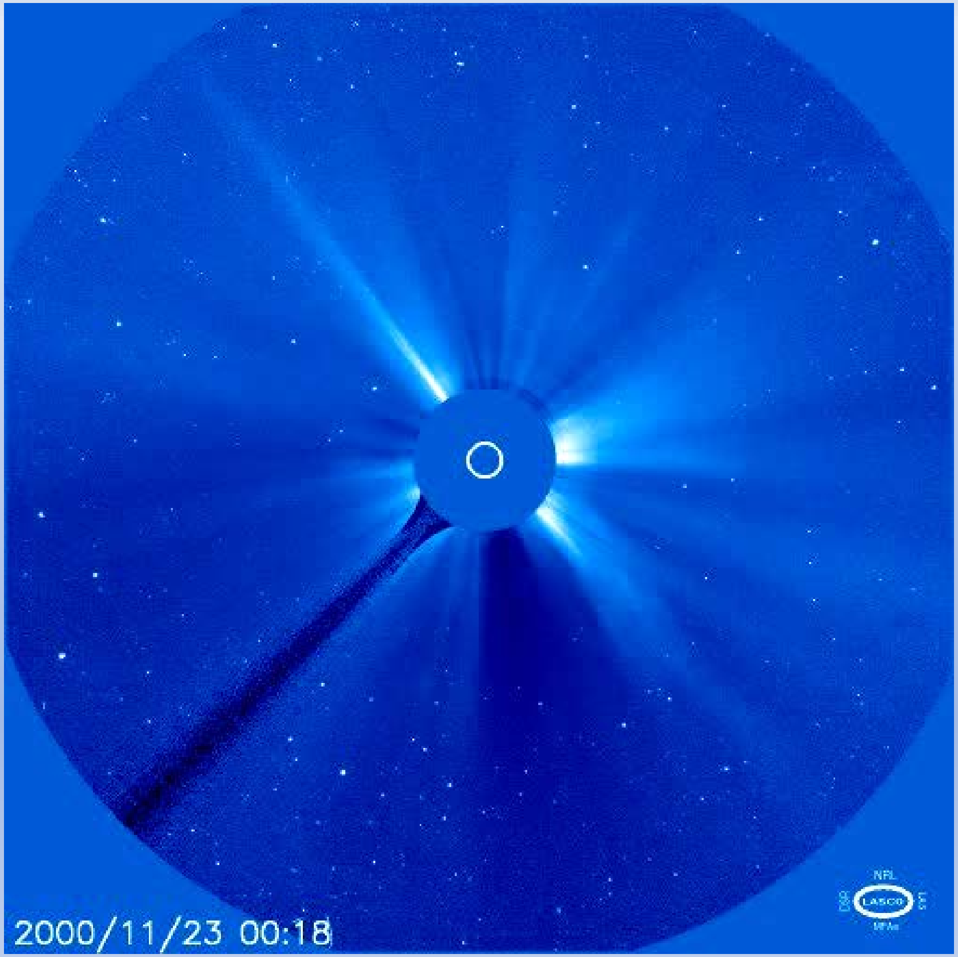


- Coronal Mass Ejections (CMEs) create geomagnetic storms
- Arrival: ~18 – 96 hours
- Duration: Hours to a day or two
- Creates ionospheric storms, geomagnetically induced currents, aurora

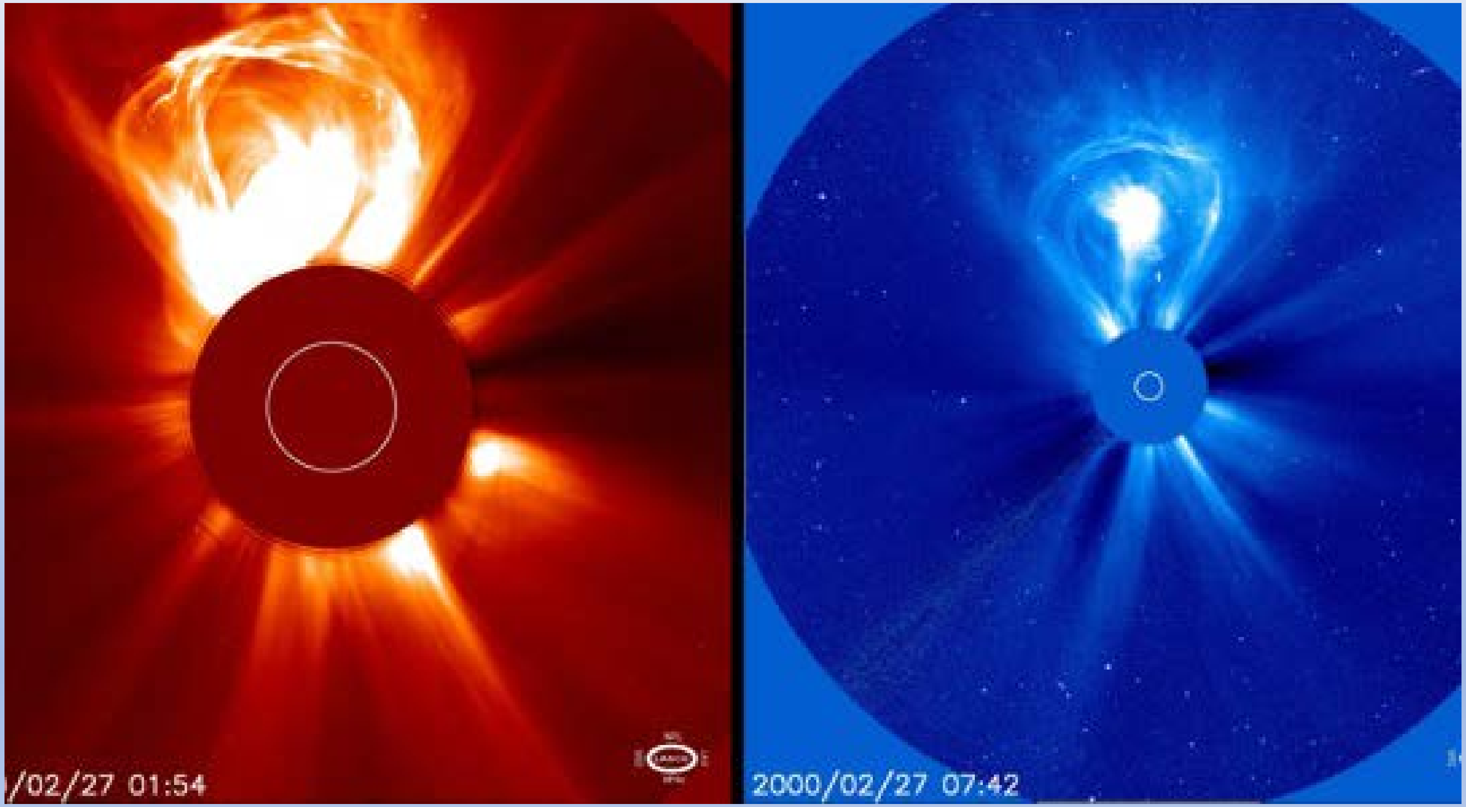


- 1-2 Day watch products based on coronagraph observations and modeling
- Short-term (15 -60 min) warnings based on measurement at ACE spacecraft

Coronal Mass Ejection (CME)



Coronal Mass Ejection (CME)

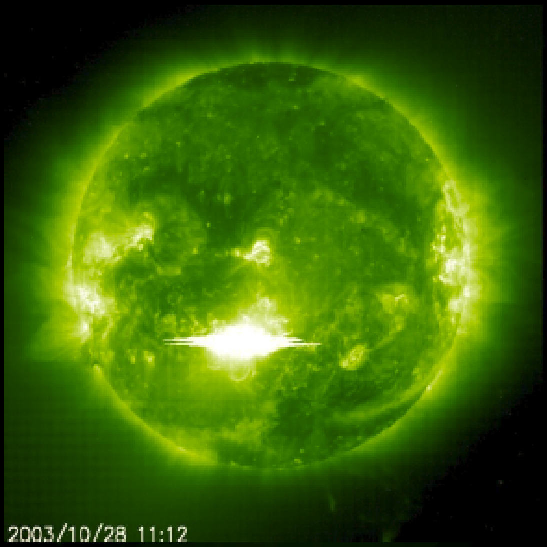


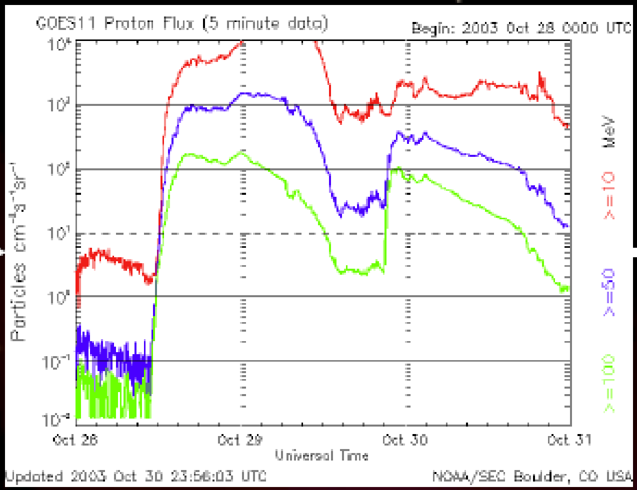
Aurora

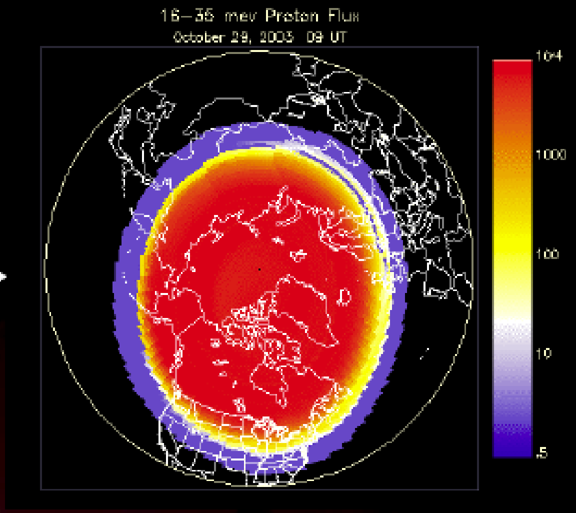
(viewed from ISS)

Formed by a complicated process involving collisions between energetic particles carrying the field-aligned currents.

Solar Radiation Storms (S Scale)

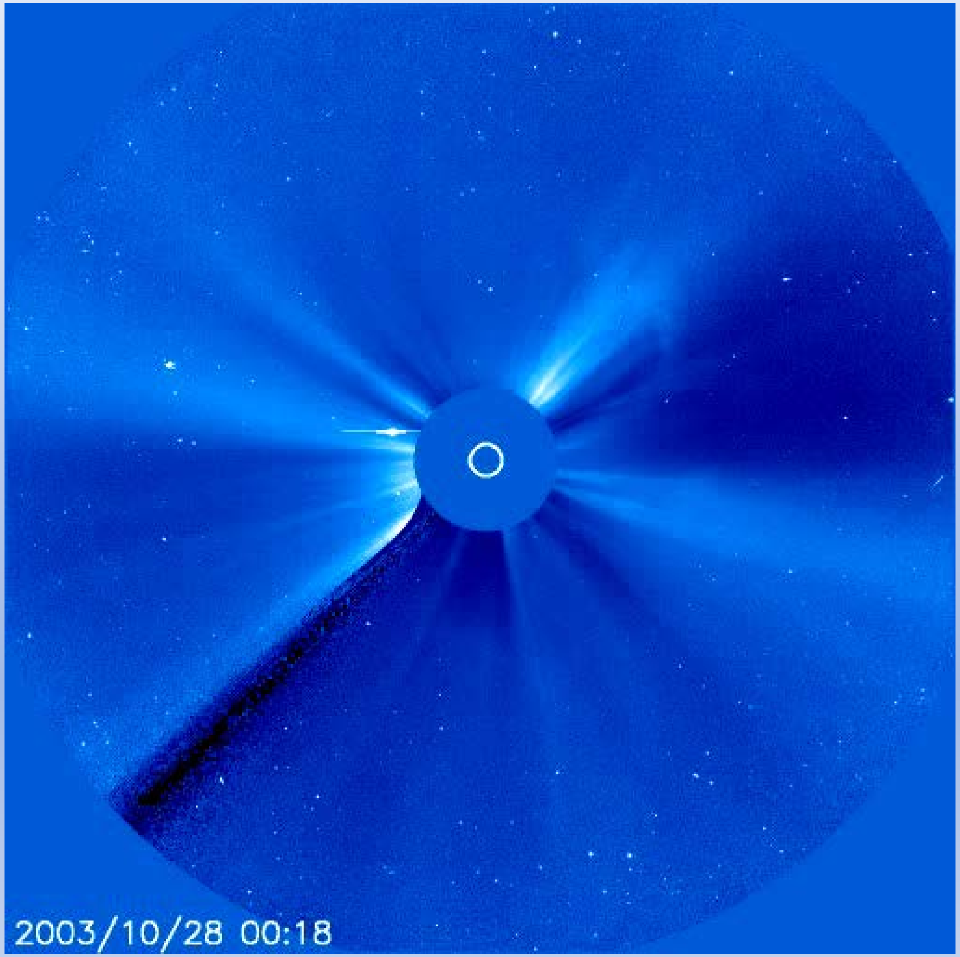




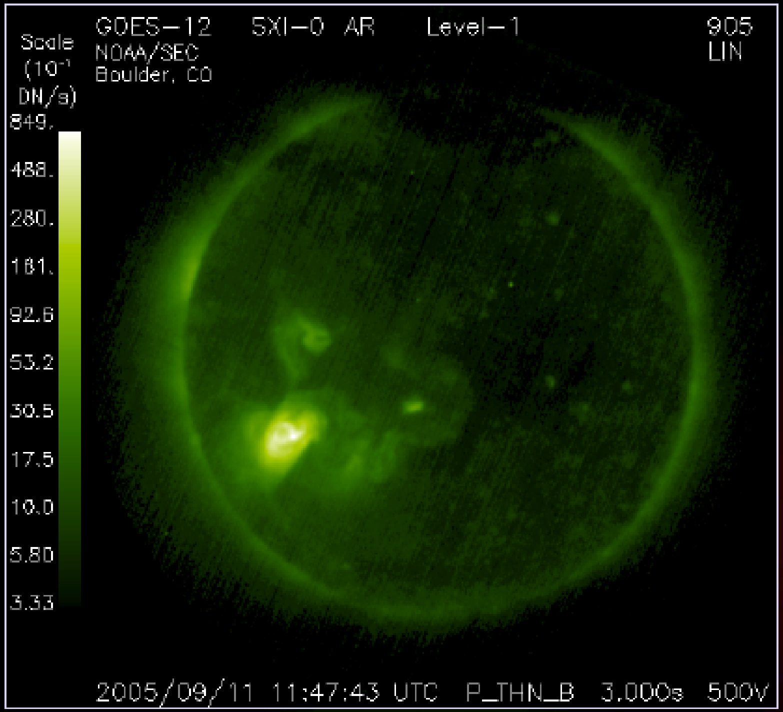


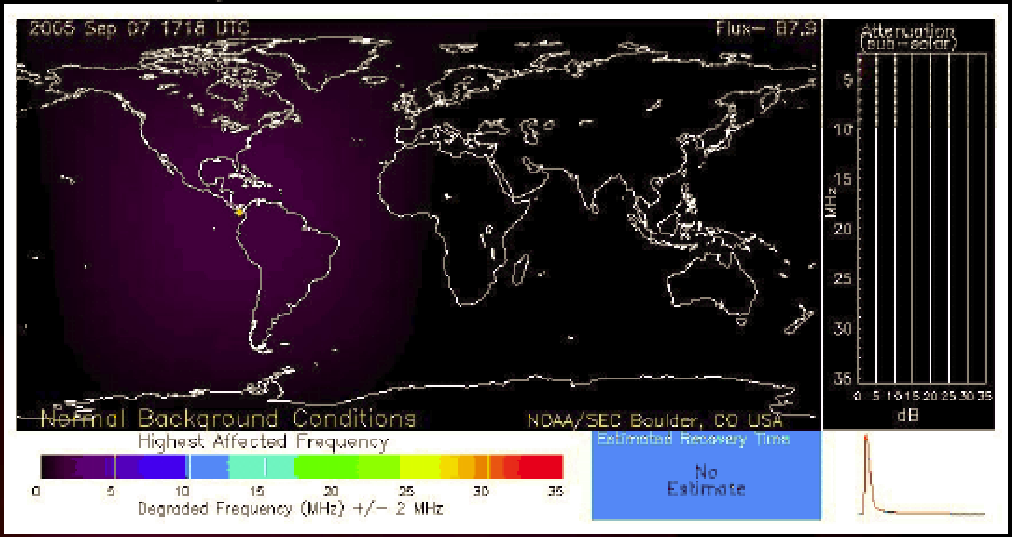
- Arrival: 10's of minutes to several hours
- Duration: hours to days
- Short-term warnings pre-onset
- Alert for threshold crossing
- Summary post-event

Proton Event

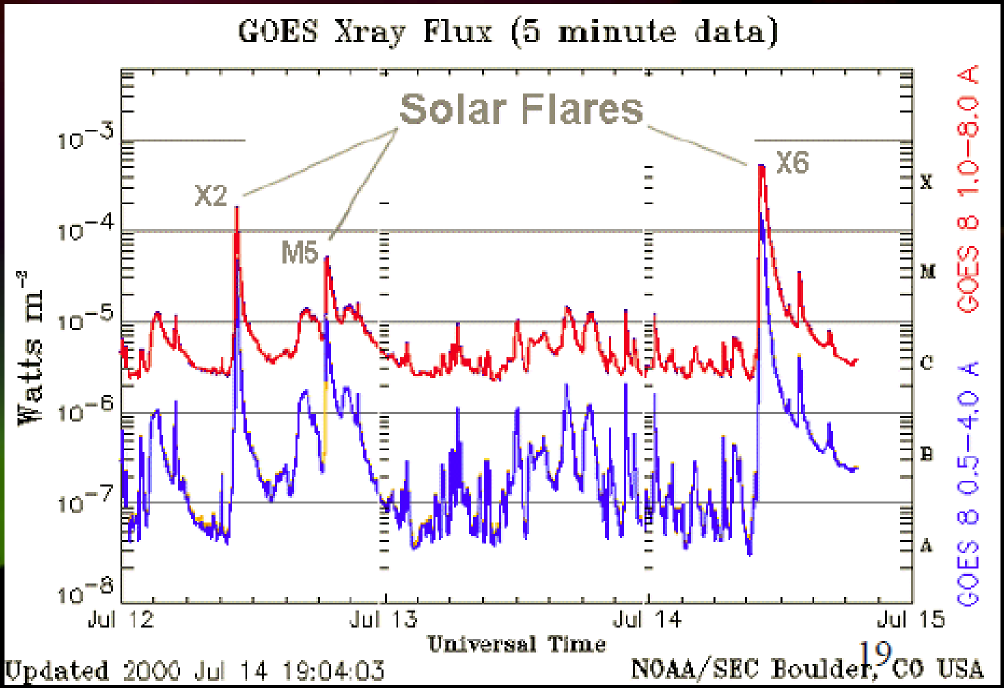


Solar Flares *(Radio Blackouts – R Scale)*

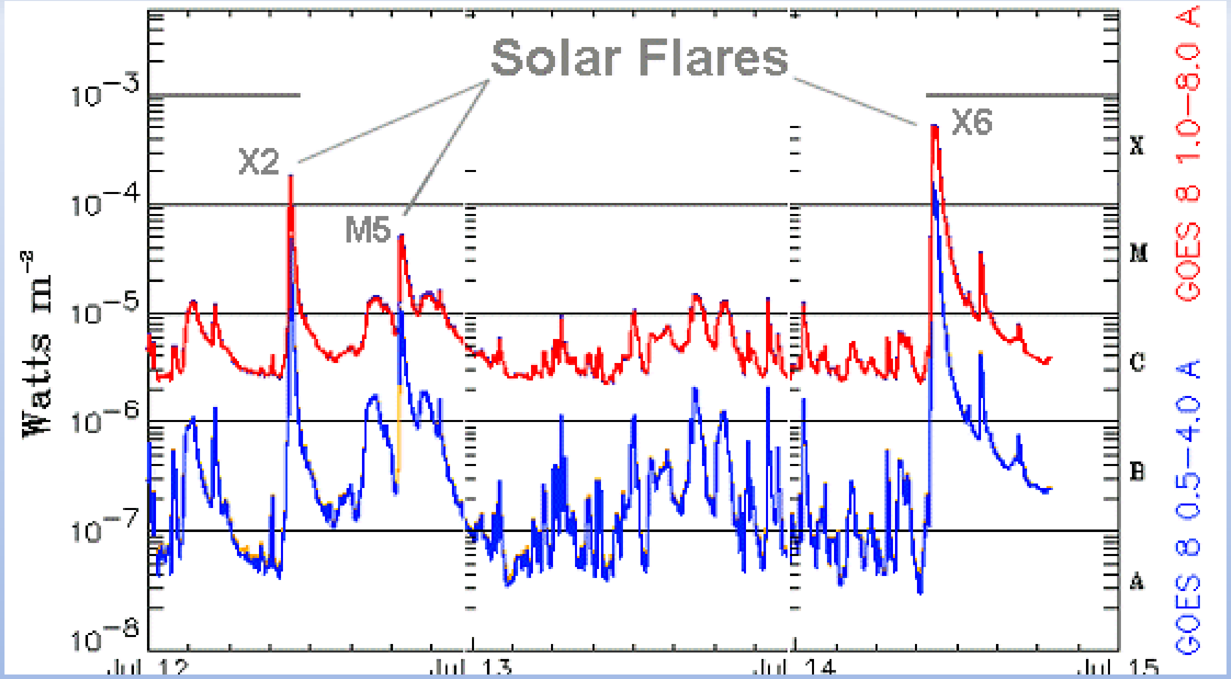




- Arrival: 8 minutes, photons
- Duration: Minutes to 3 hours
- Daylight-side impacts
- Probabilistic 1, 2, 3-day forecasts
- Alerts for exceeding R2 (only)
- Summary messages post-event



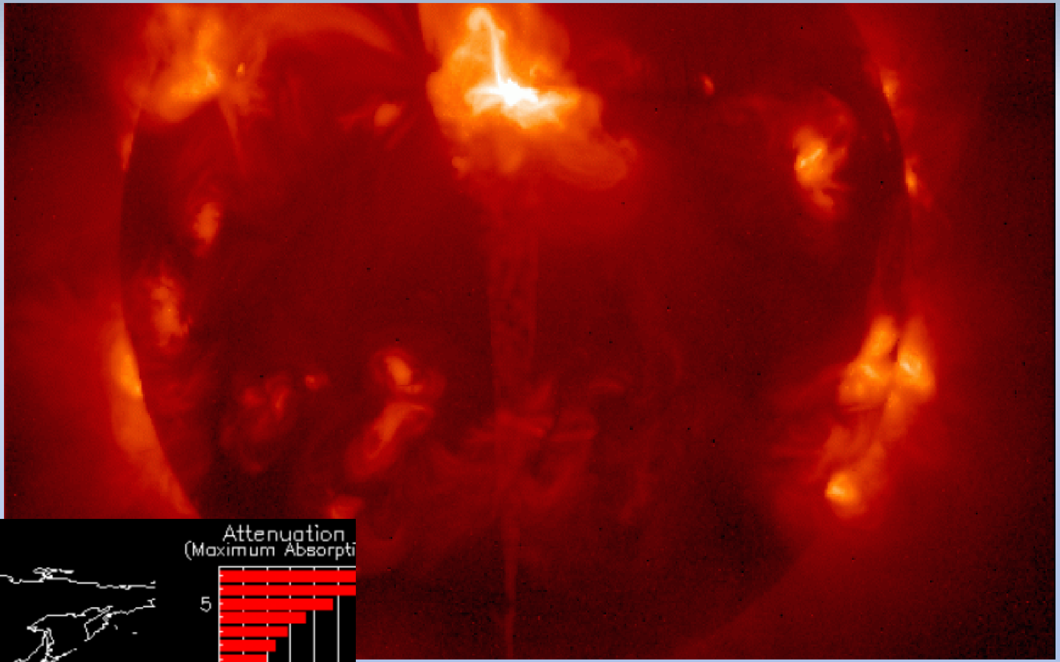
Solar Flare Categories



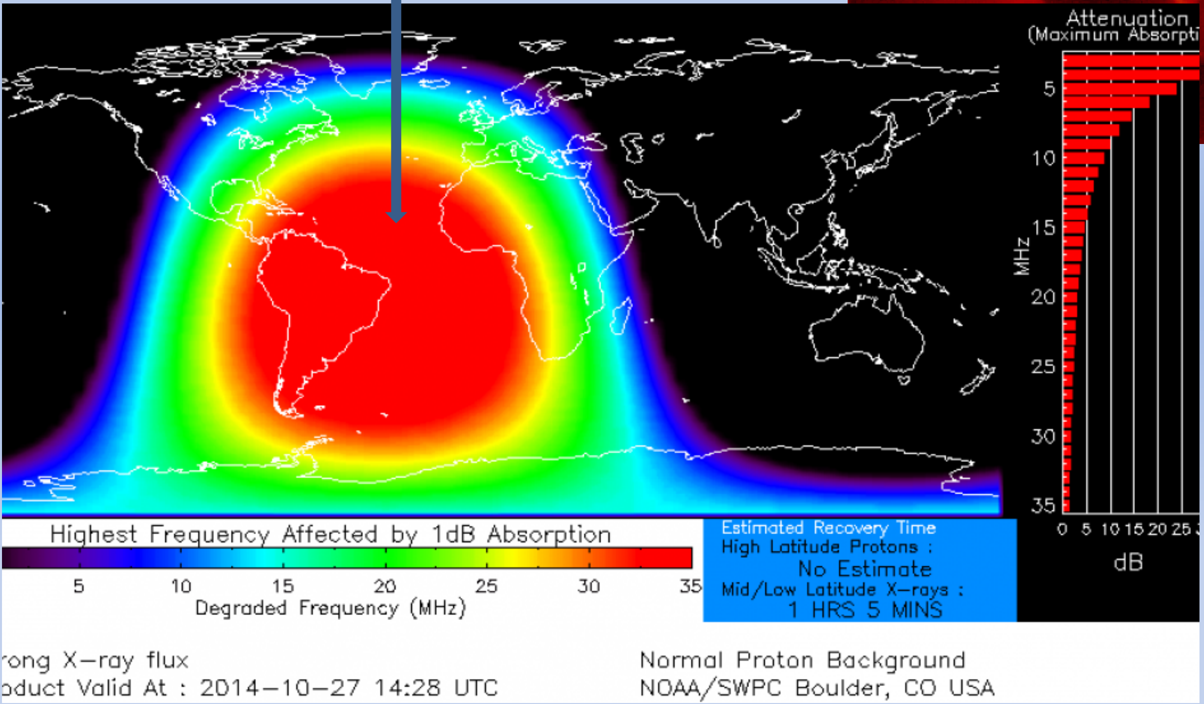
Classified according to their x-ray brightness in the wavelength range 1 to 8 Angstroms

- X-Class: major events that trigger planet-wide radio blackouts, long lasting radiation storms
- M-Class: medium size, brief radio blackouts affecting polar regions, minor radiation storms
- C-Class: small with few noticeable consequences on Earth.

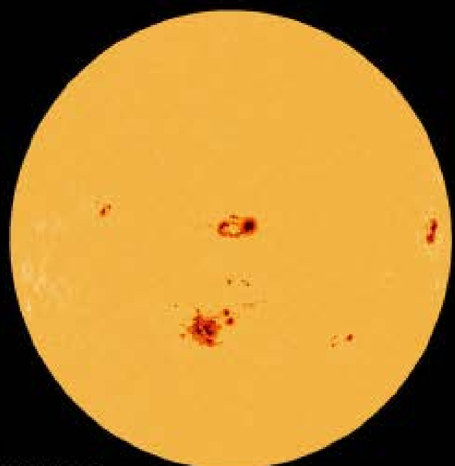
Solar Flares

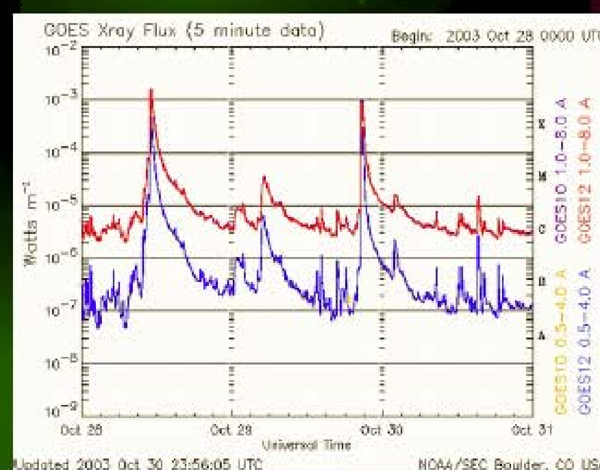


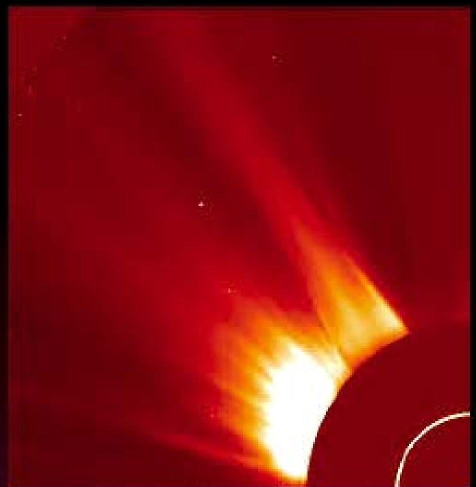
Radio Blackout!

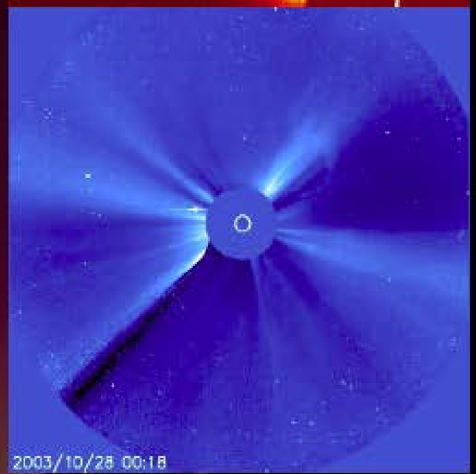


State of Forecasting Today









Conditions are Favorable for Activity (Probabilistic Forecasts) → Event Occurs → Coronal Observations

NOAA SPACE WEATHER PREDICTION CENTER

Geomagnetic Storm Warning issued upon detection of CME at L1 on ACE

- 15-45 MIN forecast

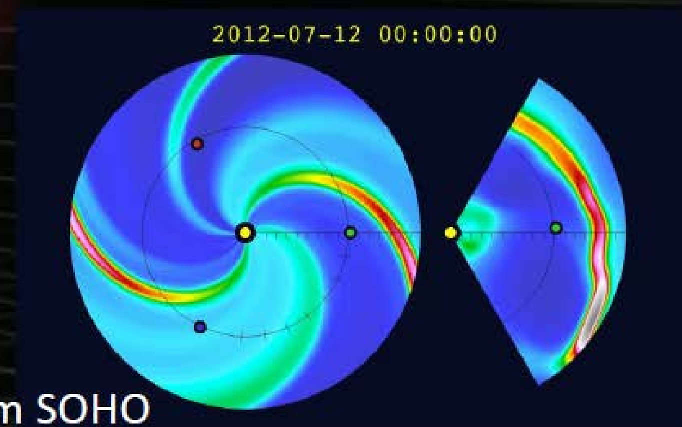
L1

Geomagnetic Storm Alert issued upon onset of geomagnetic storm using USGS magnetometers

- Current condition

Geomagnetic Storm Watch issued upon detection of Earth-directed coronal mass ejection (CME) on SOHO LASCO and STEREO coronagraphs

- 1-3 day forecast



CME measurements from SOHO and STEREO drive the Enlil model which predicts arrival time

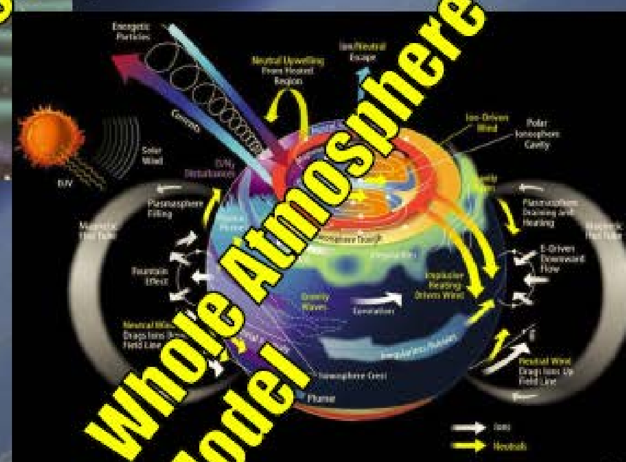
Modeling at NOAA – A Sun to Earth Continuum

Partnerships with the Space Weather Research Community

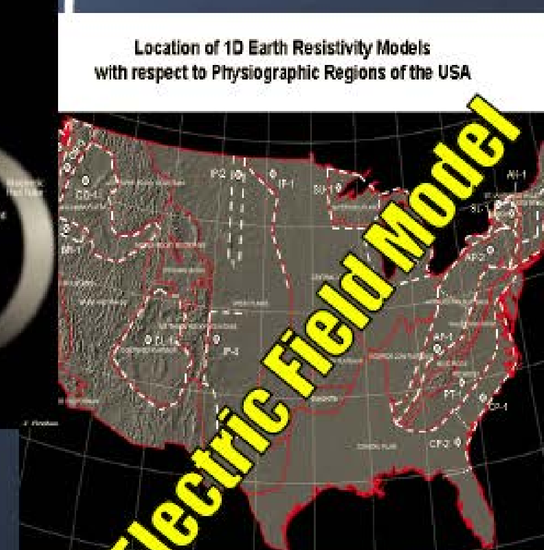
Solar /Solar Wind

Magnetosphere/
Ionosphere

Ionosphere/
Atmosphere



Earth's surface



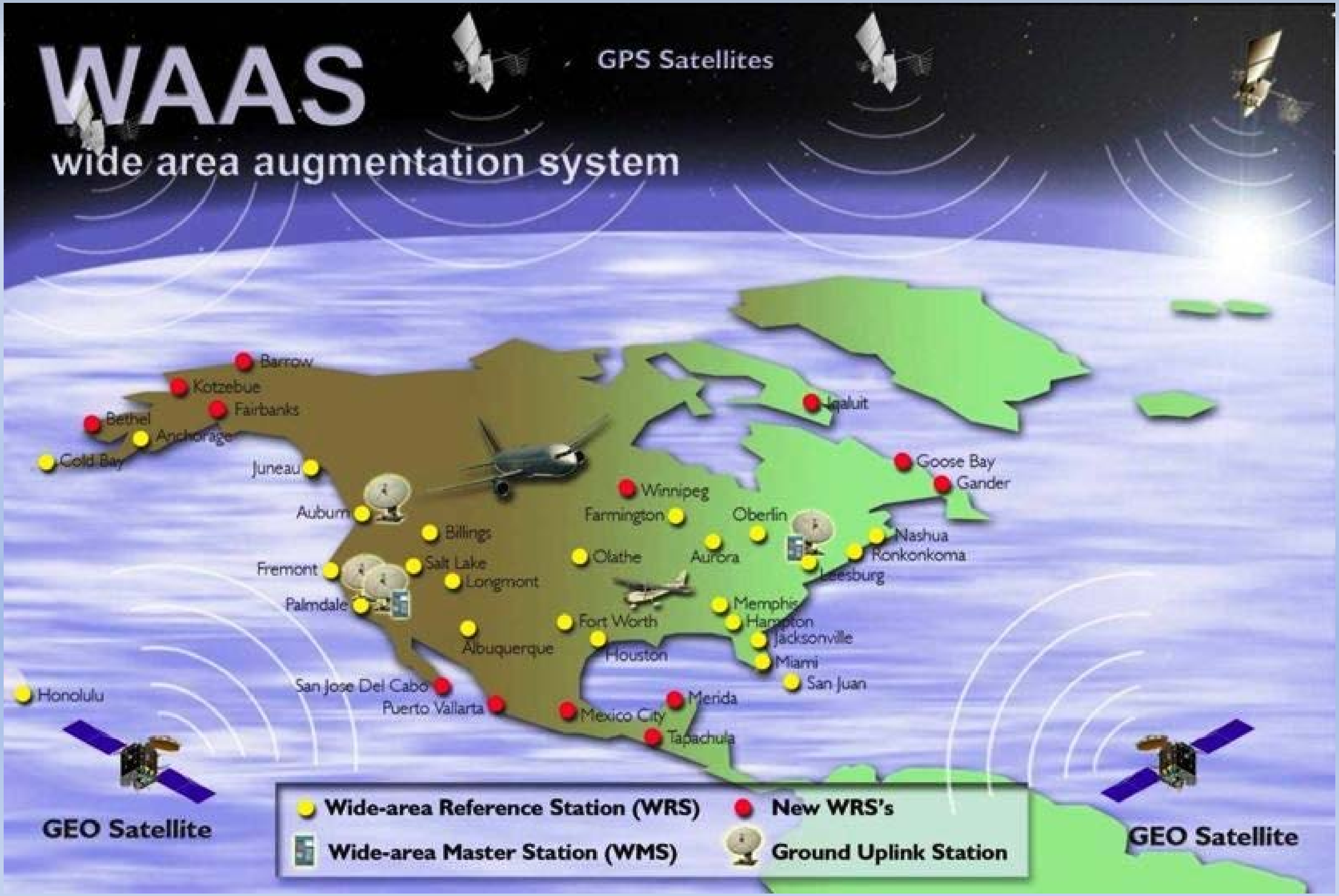
GPS/GNSS System Impacts

- There are several ways in which space weather impacts GPS function. GPS radio signals travel from the satellite to the receiver on the ground, passing through the Earth's ionosphere. The charged plasma of the ionosphere bends the path of the GPS radio signal similar to the way a lens bends the path of light. In the absence of space weather, GPS systems compensate for the "average" or "quiet" ionosphere, using a model to calculate its effect on the accuracy of the positioning information. But when the ionosphere is disturbed by a space weather event, the models are no longer accurate and the receivers are unable to calculate an accurate position based on the satellites overhead.
- In calm conditions, single frequency GPS systems can provide position information with an accuracy of a meter or less. During a severe space weather storm, these errors can increase to tens of meters or more. Dual frequency GPS systems can provide position information accurate to a few centimeters. In this case the two different GPS signals are used to better characterize the ionosphere and remove its impact on the position calculation. But when the ionosphere becomes highly disturbed, the GPS receiver cannot lock on the satellite signal and position information becomes inaccurate.
- Geomagnetic storms create large disturbances in the ionosphere. The currents and energy introduced by a geomagnetic storm enhance the ionosphere and increase the total height-integrated number of ionospheric electrons, or the Total Electron Count (TEC). GPS systems cannot correctly model this dynamic enhancement and errors are introduced into the position calculations. This usually occurs at high latitudes, though major storms can produce large TEC enhancements at mid-latitudes as well.

Consequences of Space Weather

- Aviation
  - Disruption of communication and radiation risk
  - The Next Generation Air Transportation System will depend on GNSS
- GNSS
  - Degradation of accuracy or availability
  - Strong growth in applications – surveying, drilling, precision agriculture, navigation, aviation
- Space Systems
  - Degradation or loss of satellite capabilities
  - Commercial space and astronaut safety
- Electric Utilities
  - Potential for significant disruption of service with $Billion consequences

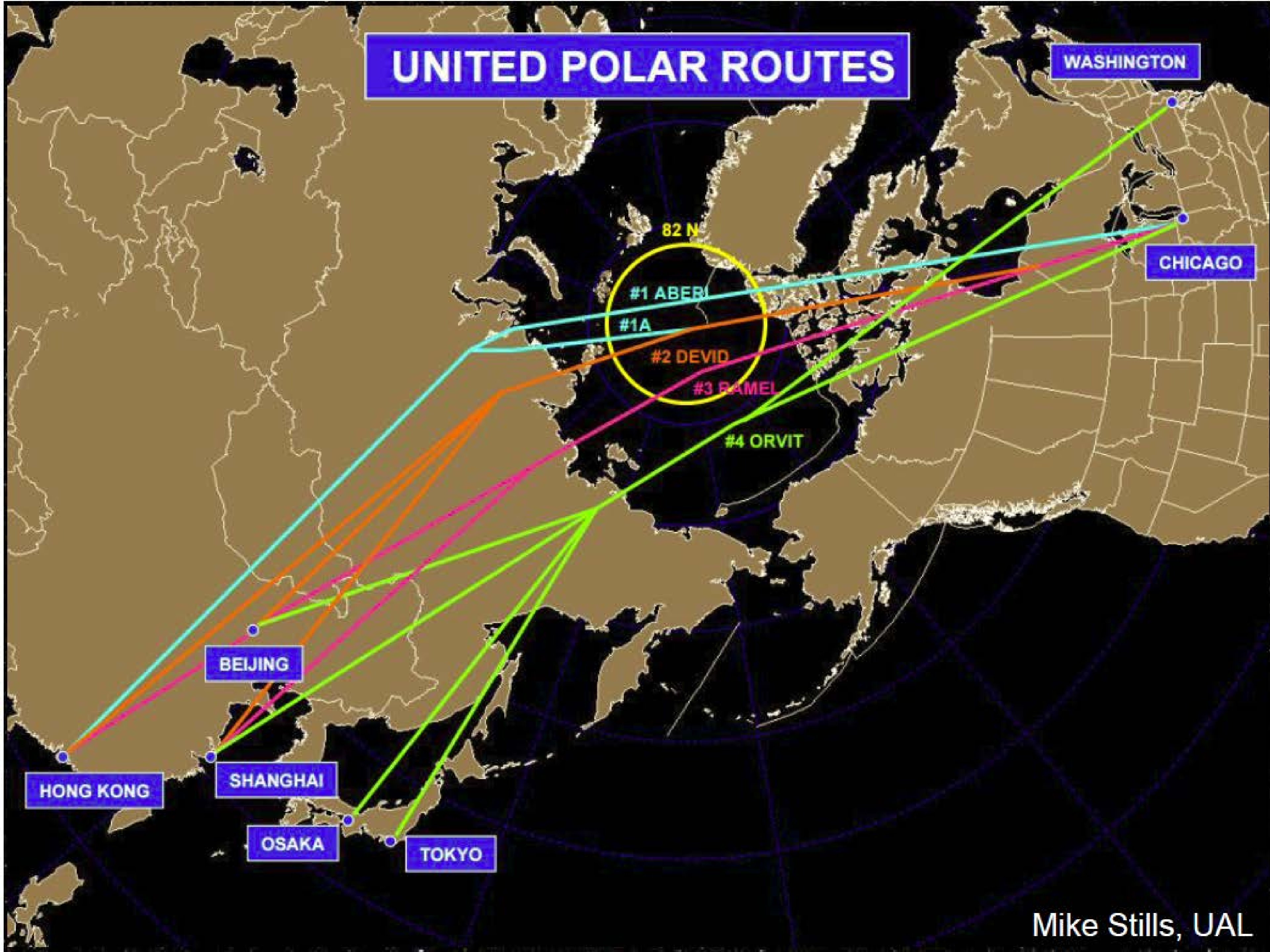
Aviation



WAAS
wide area augmentation system
GPS Satellites
Barrow
Kotzebue
Fairbanks
Bethel
Anchorage
Cold Bay
Juneau
Auburn
Billings
Fremont
Salt Lake
Longmont
Palmdale
Albuquerque
Honolulu
San Jose Del Cabo
Puerto Vallarta
Mexico City
Merida
Tapachula
Winnipeg
Farmington
Olathe
Oberlin
Aurora
Fort Worth
Houston
Memphis
Hampton
Jacksonville
Miami
San Juan
Leesburg
Ronkonkoma
Nashua
Iqaluit
Goose Bay
Gander
GEO Satellite
GEO Satellite
Wide-area Reference Station (WRS)
New WRS's
Wide-area Master Station (WMS)
Ground Uplink Station

HISTORICAL PERSPECTIVE

- 1999-UNITED OPERATED 12 POLAR DEMO FLIGHTS
- 2000-UNITED OPERATED 253 POLAR FLIGHTS
- 2001-UNITED OPERATED 466 POLAR FLIGHTS
- 2002-UNITED OPERATED 471 POLAR FLIGHTS
- 2003-UNITED OPERATED 578 POLAR FLIGHTS
- 2004-UNITED OPERATED 1096 POLAR FLIGHTS
- 2005-UNITED OPERATED 1402 POLAR FLIGHTS
- 2006-UNITED OPERATED 1484 POLAR FLIGHTS
- 2007-UNITED OPERATED 1832 POLAR FLIGHTS


UNITED POLAR ROUTES
WASHINGTON
CHICAGO
82 N
#1 ABERI
#1A
#2 DEVID
#3 RAMEL
#4 ORVIT
BEIJING
HONG KONG
SHANGHAI
OSAKA
TOKYO
Mike Stills, UAL

SOLAR EVENTS and RESPONSE

<u>January 2005</u>

26 FLIGHTS OPERATED ON LESS THAN OPTIMUM POLAR ROUTES DUE TO SOLAR ACTIVITY

<u>CHICAGO TO HONG KONG</u>

STOP IN ANCHORAGE ON 4 CONSECUTIVE DAYS

PENALTY 180 TO 210 MINUTES

<u>CHICAGO TO BEIJING</u>

PENALTIES 18 TO 55 MINUTES

<u>BEIJING TO CHICAGO</u>

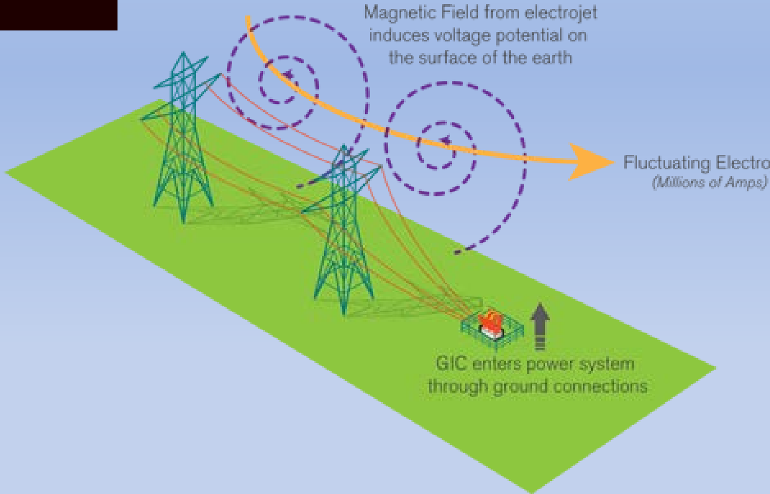
PENALTIES 55 MINUTES TO 80 MINUTES

UNITED

Precision Agriculture / Grading

Geomagnetically Induced Currents (GICs)

- Rapid geomagnetic field variation lead to induction of electric currents in Earth's Crust
- Ex. March 1989 – Hydro-Quebec power grid
- Loss of power to 6 million people



YEAR	Event
1940	Power distribution disturbances in US and Canada
1946	Transformers trip in Ontario, Canada
1957 – 1972	Numerous disturbances in trans-Atlantic submarine cables
1989	Transformer failure in Quebec, Canada results in blackout affecting 6m people, lasting up to 9 hours
2001	Transformer failure in New Zealand
2003	Several transformers damaged in South Africa
2003	Power outage in Malmo, Sweden
2004	Geomagnetically induced currents affect power distribution networks in Europe, Africa, North America a China

Power distribution problems due to space weat

Ref: Oldenwald, 2012

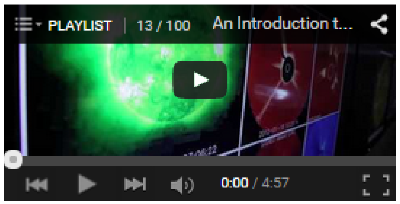
Electricity transformer damage

CURRENT SPACE WEATHER CONDITIONS on NOAA Scales

R none | S none | G none

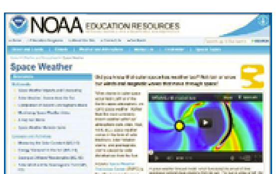
EDUCATION AND OUTREACH

Featured Videos

An Introduction to Space Weather and SWPC	Space Weather Impacts: Power
	
Space Weather Impacts: GPS	Space Weather Impacts: Communications
	

Space Weather Information

- NOAA's Space Weather Prediction Center – Education & Outreach Resources
- Space Weather Primer
- Space Weather FAQ
- Space Weather Glossary
- NOAA Space Weather Scales
- NOAA Space Weather Education Resources
- Service Assessment: Intense Space Weather Storms October 19 – November 07, 2003



Space Weather and its Impacts Poster	Space Weather: Storms from the Sun Booklet

Questions?