CTU Presents

The Wonderful World of Space Weather

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The Aerospace Corporation

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Who is Impacted by Space Weather?

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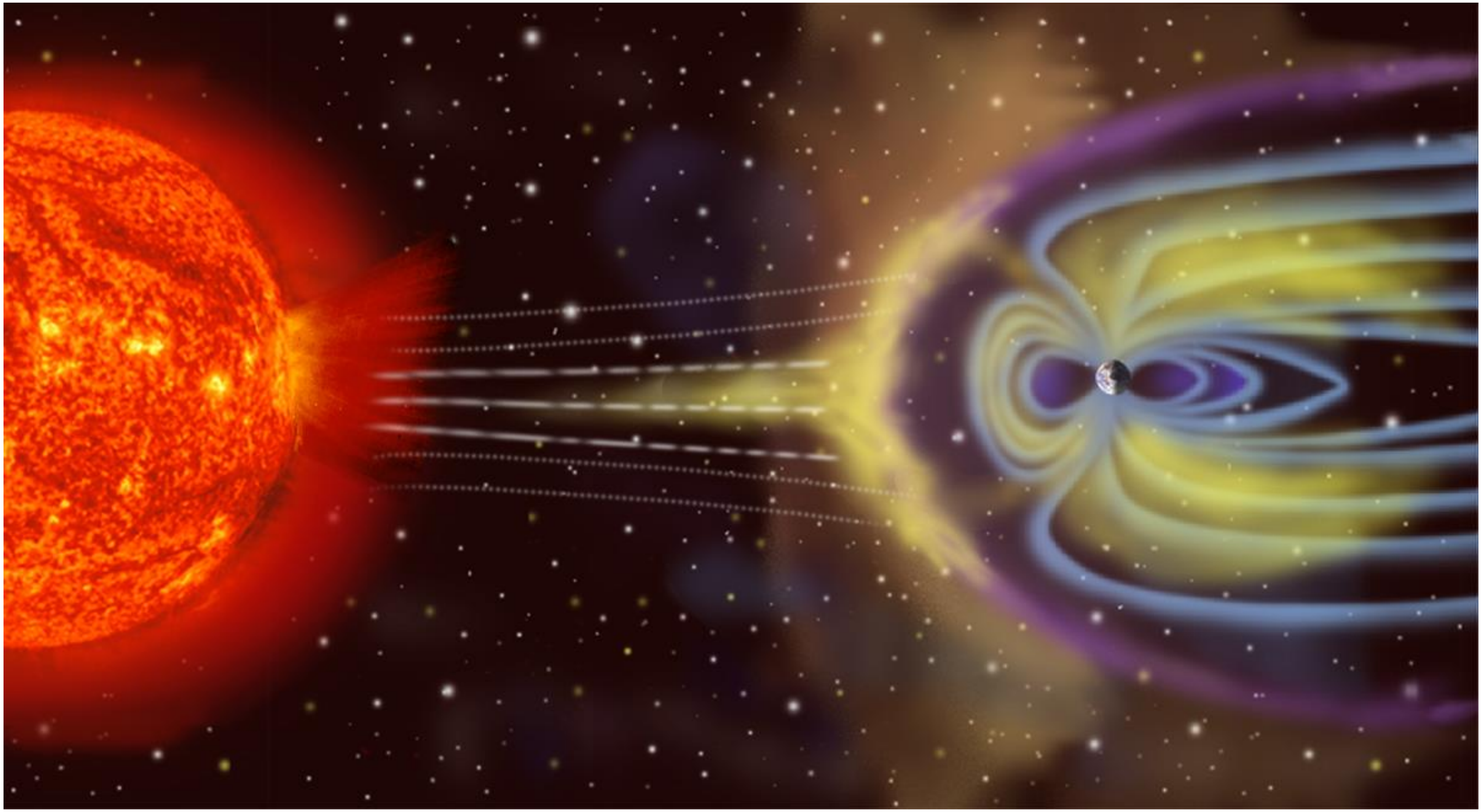
What is Space Weather?

Essentially Space Weather is:
A planet's interaction with its host star and the surrounding space environment.



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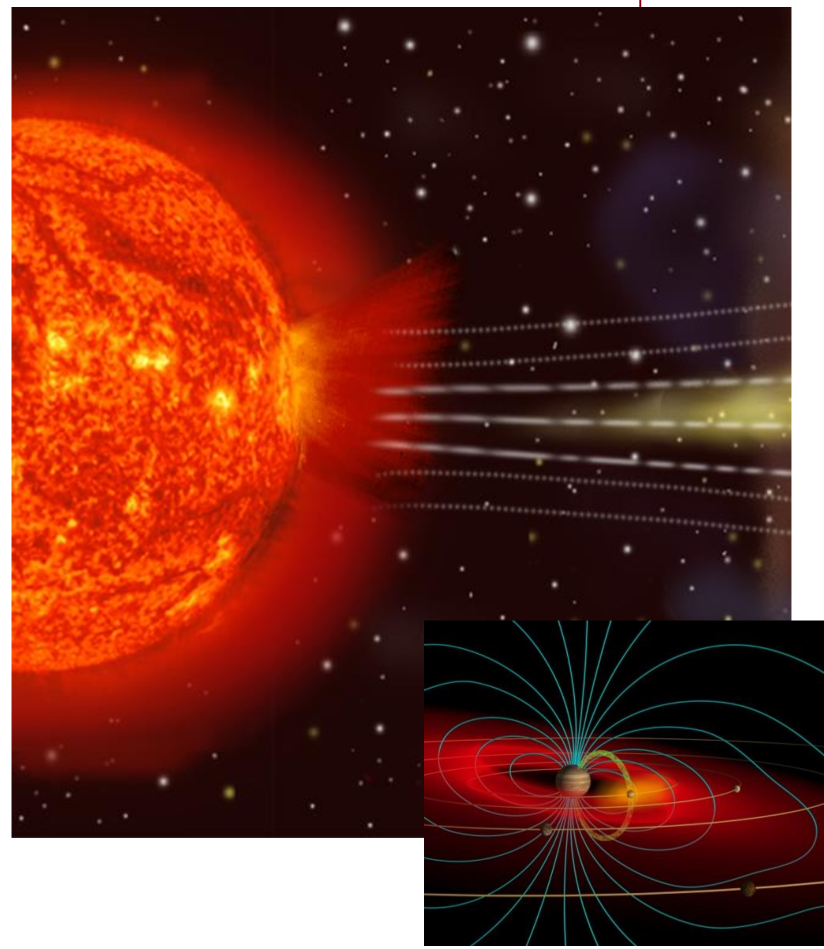
What is Space Weather?

More generally, it occurs at planets, moons, comets, asteroids, and other celestial bodies in the universe.

In our solar system

- We see aurora at Jupiter, Saturn, and recently at Uranus and Mars
- Effects are studied at Io, Europa, Ganymede, and Titan to name a few
- Highlight **Sun-driven processes**
- Will not cover other sources of space weather
  - Galactic and anomalous cosmic rays
  - Micrometeroids & interstellar dust
  - Space junk



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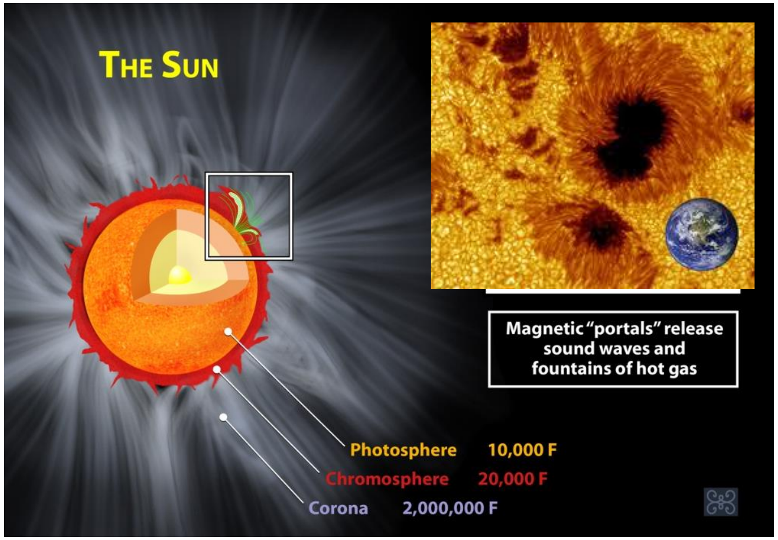
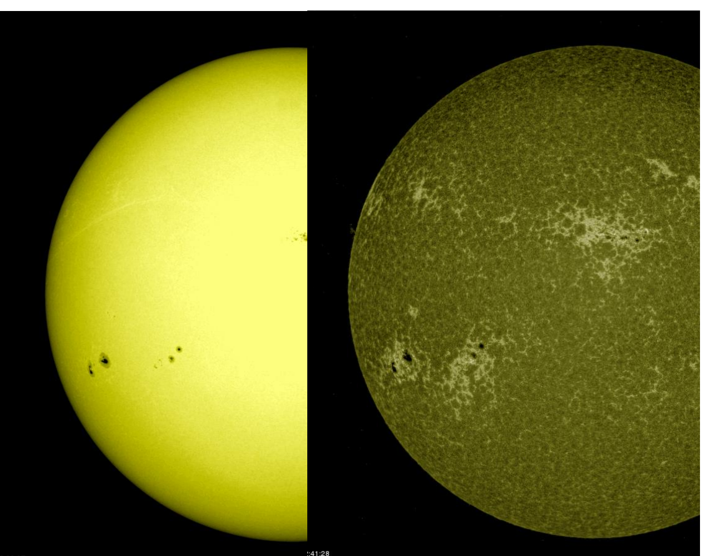
Our Star

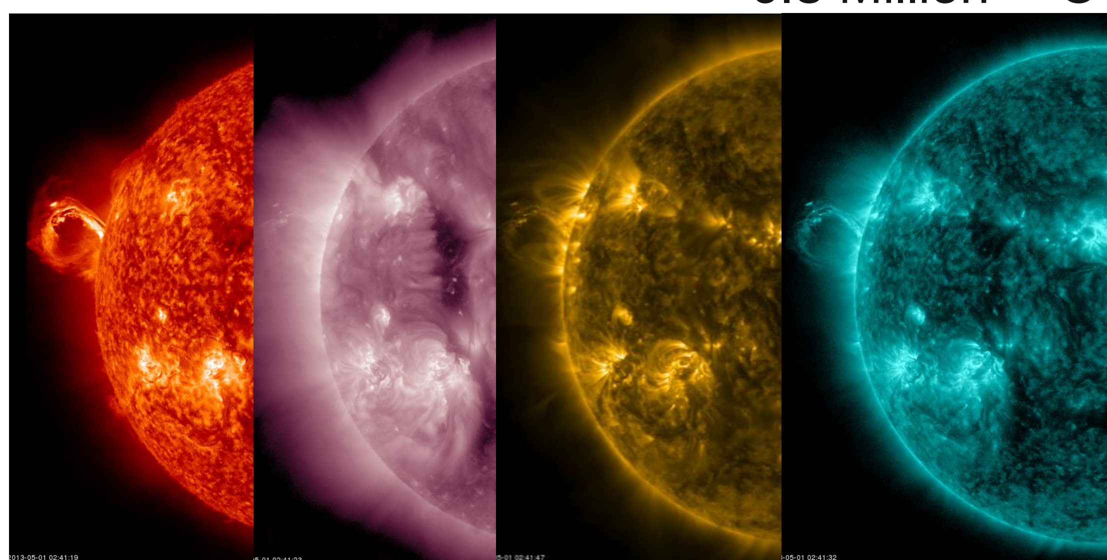


- Giant fusion reactor: Drives Space Weather
- Energy output in the form of:
  - Electromagnetic radiation (from X-rays through radio)
  - Solar wind plasma & magnetic fields
  - Flares
  - Solar Energetic Particles (SEPs) (aka solar radiation storms)
  - Coronal Mass Ejections

What do Space Telescopes See?

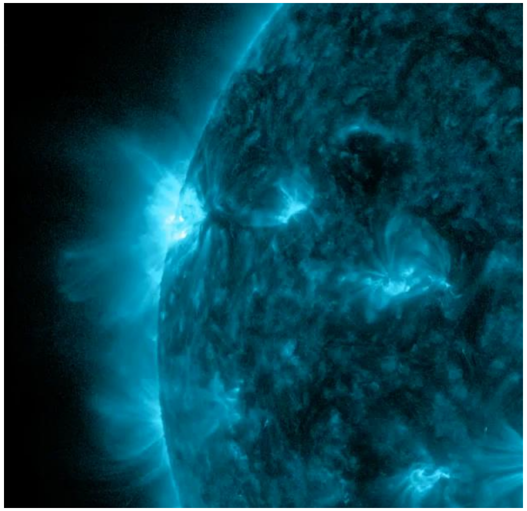
5700 ° C → 6.3 Million ° C



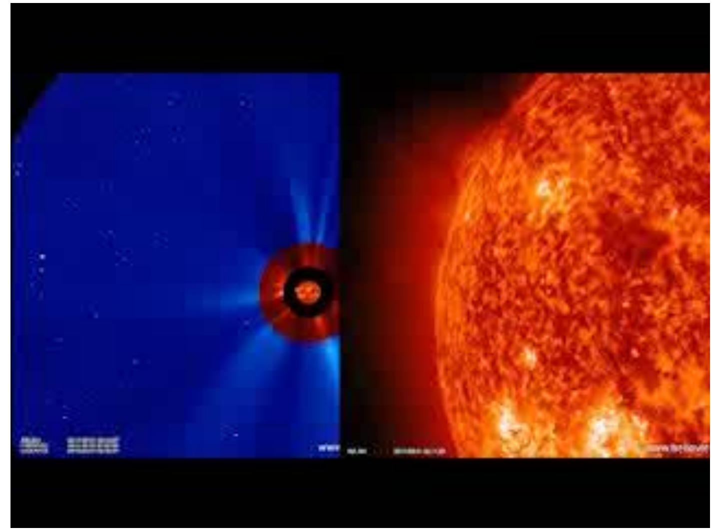


Four Basic Types of Solar Phenomena Affecting Earth

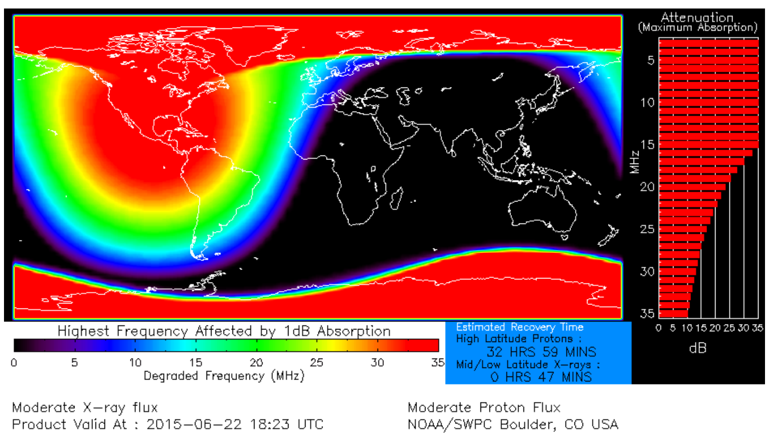
Solar Flares



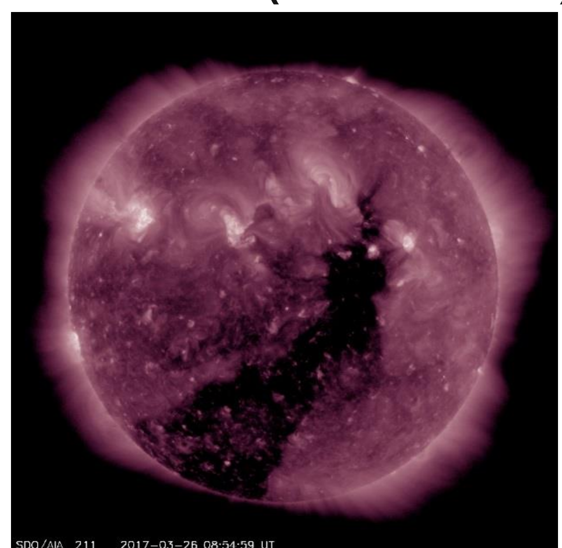
Solar Storms (a.k.a. CMEs)



Solar Radiation Storms



Coronal Holes (Fast Solar Wind)



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…So how bad can Space Weather be?

3 Categories:

- Geomagnetic Storms
(CMEs and fast solar wind)
- Solar Radiation Storms
(Particle Events)
- Radio Blackouts
(Solar Flares)

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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)

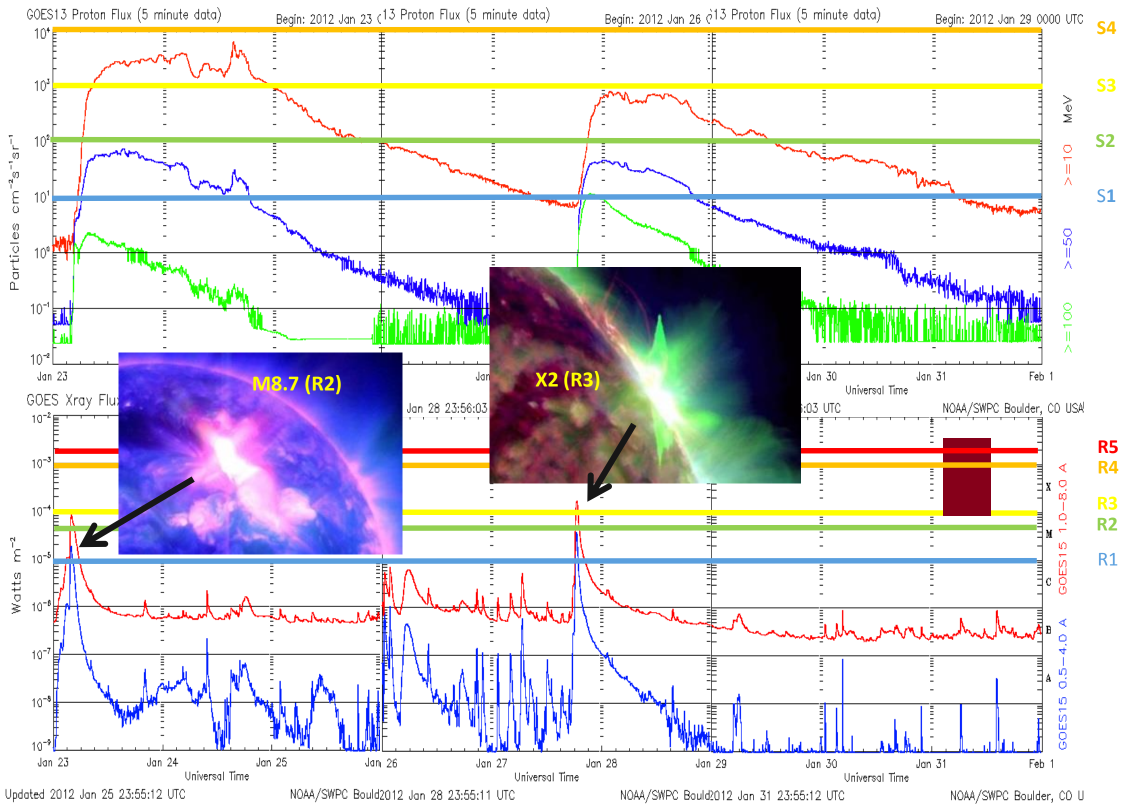
Scale	Descriptor	Solar Radiation Storms	Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high 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.

Scale	Descriptor	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.

What Can a Typical Solar Storm Event Do?



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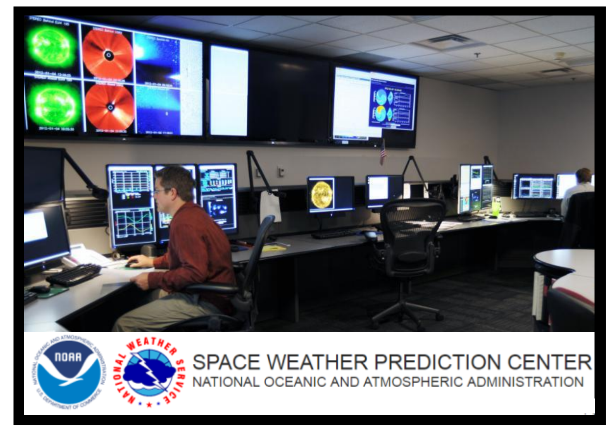
Source of all official forecasting data is the NOAA Space Weather Prediction Center (SWPC)



January 23-30, 2012 solar storm series of events caused

- 2 radio blackouts
- 2 radiation storms
- 1 geomagnetic storm

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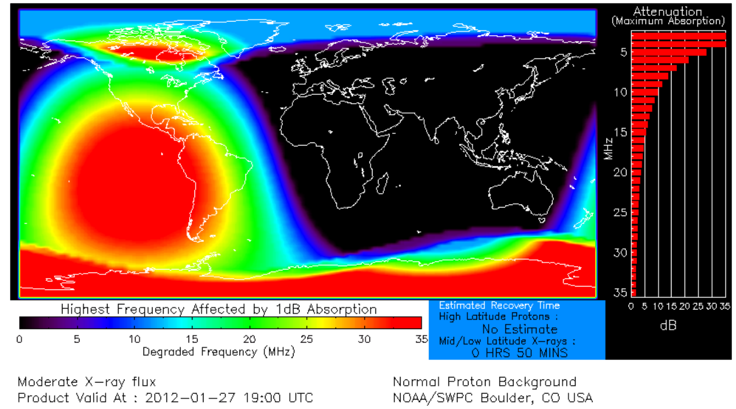
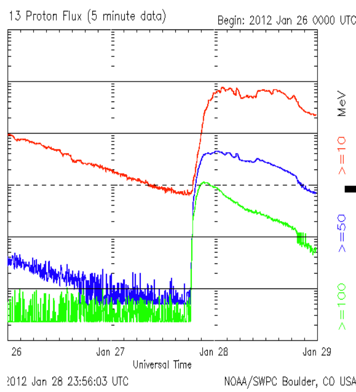
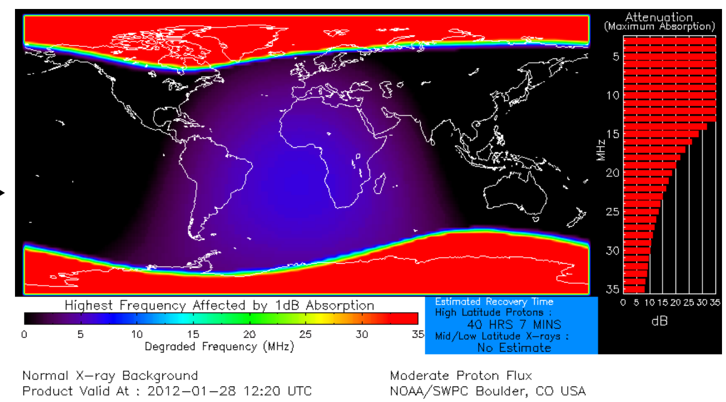
HF Band Communications Disruptions

FAA Radio Communications Center reported that the CEP (Central East Pacific) and CWP (Central West Pacific) regions were: “impacted severely by solar activity between 1830Z and 1930Z on 27 Jan due to the R3 solar flare radio blackout. Thirteen requests were received from ATC for overdue position reports.”



Several polar flights altered due to S3 Radiation Storm (23-25 Jan)





Major airline report: “…some of our polar flights (but not all) have reported HF comm outages/issues over the past 3 nights.”

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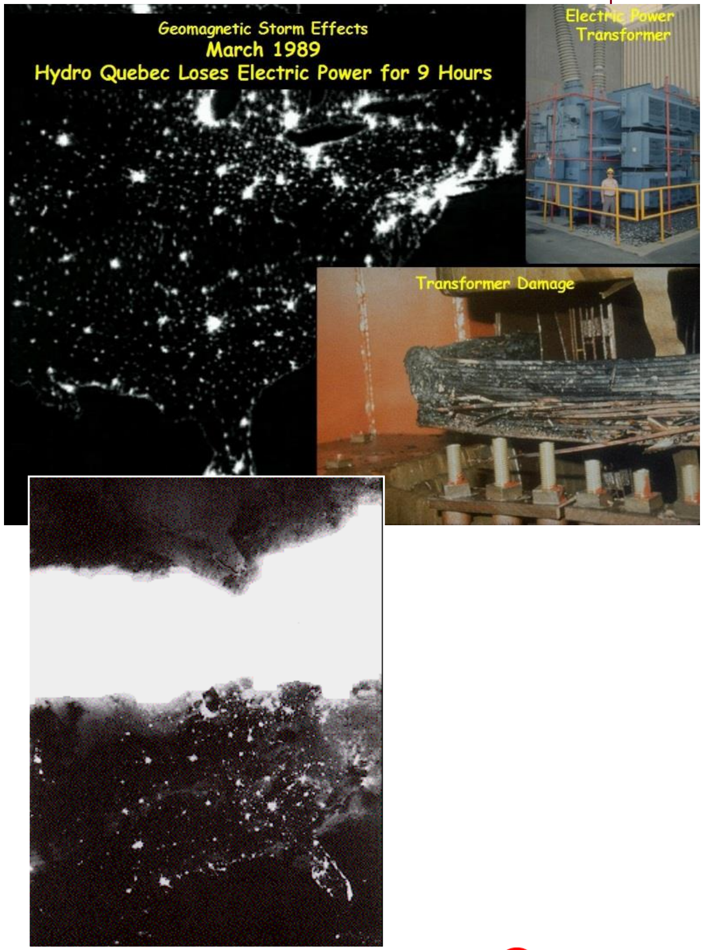
What Can a Super Solar Storm Event Do?

- **March 6-15, 1989**
  - X-15 Flare followed by a CME
  - Weather Satellites lost images for hours
  - TDRS-1 com sat had over 250 anomalies
  - Space Shuttle Discovery fuel sensor failed
  - Radio Free Europe disrupted thinking it was Soviet Jam Event
  - Quebec Hydro-Quebec Power Grid shutdown
  - James Bay Network, serving 6 million people, offline for 9 hours
  - Caused Toronto Stock Market to close
  - Brilliant Auroral Displays as far at Texas and Florida (aurora pic by DOD F9 weather sat)



- Many other examples of super storms in space age: 1998 Telstar 401, Anik 1,2, “Halloween Events” 2003

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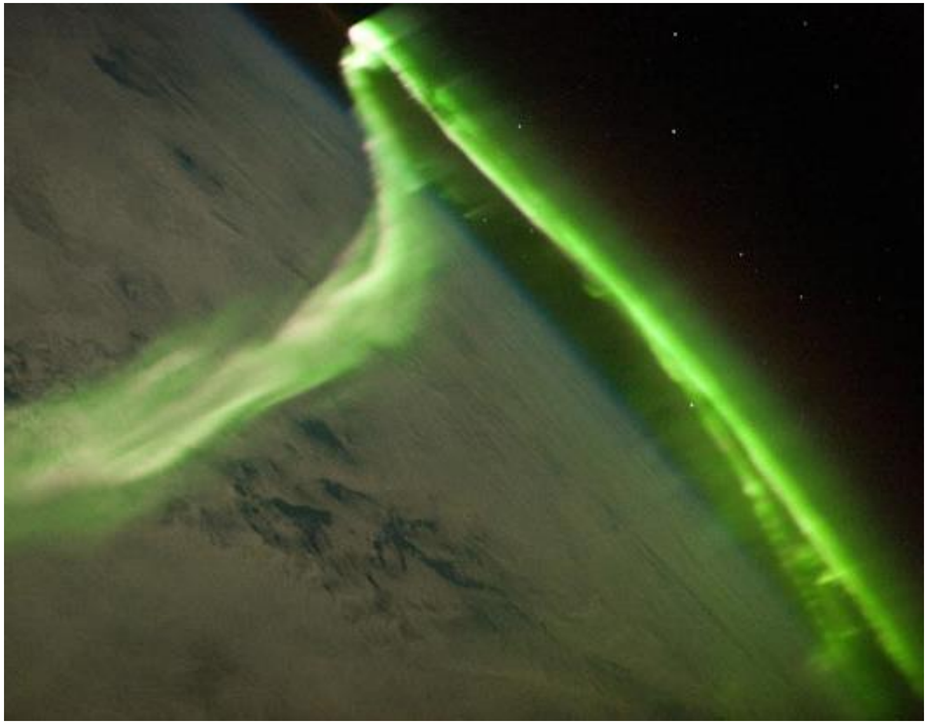
What is the Ionosphere?

- Ionosphere is a charged plasma layer above the atmosphere comprised of ions and electrons
- It would be neutral but it gets charged from exposure mainly to the Sun's UV radiation
- This charged nature facilitates radio propagation
- During geomagnetic storms, extra energy caught in the Earth's magnetic shield gets dumped into the ionosphere
- This energy (flow of charged particles) lights-up the plasma in the Earth's ionosphere similar to a fluorescent lamp or neon sign
- Result is the aurora borealis (northern lights) and aurora australis (southern lights)



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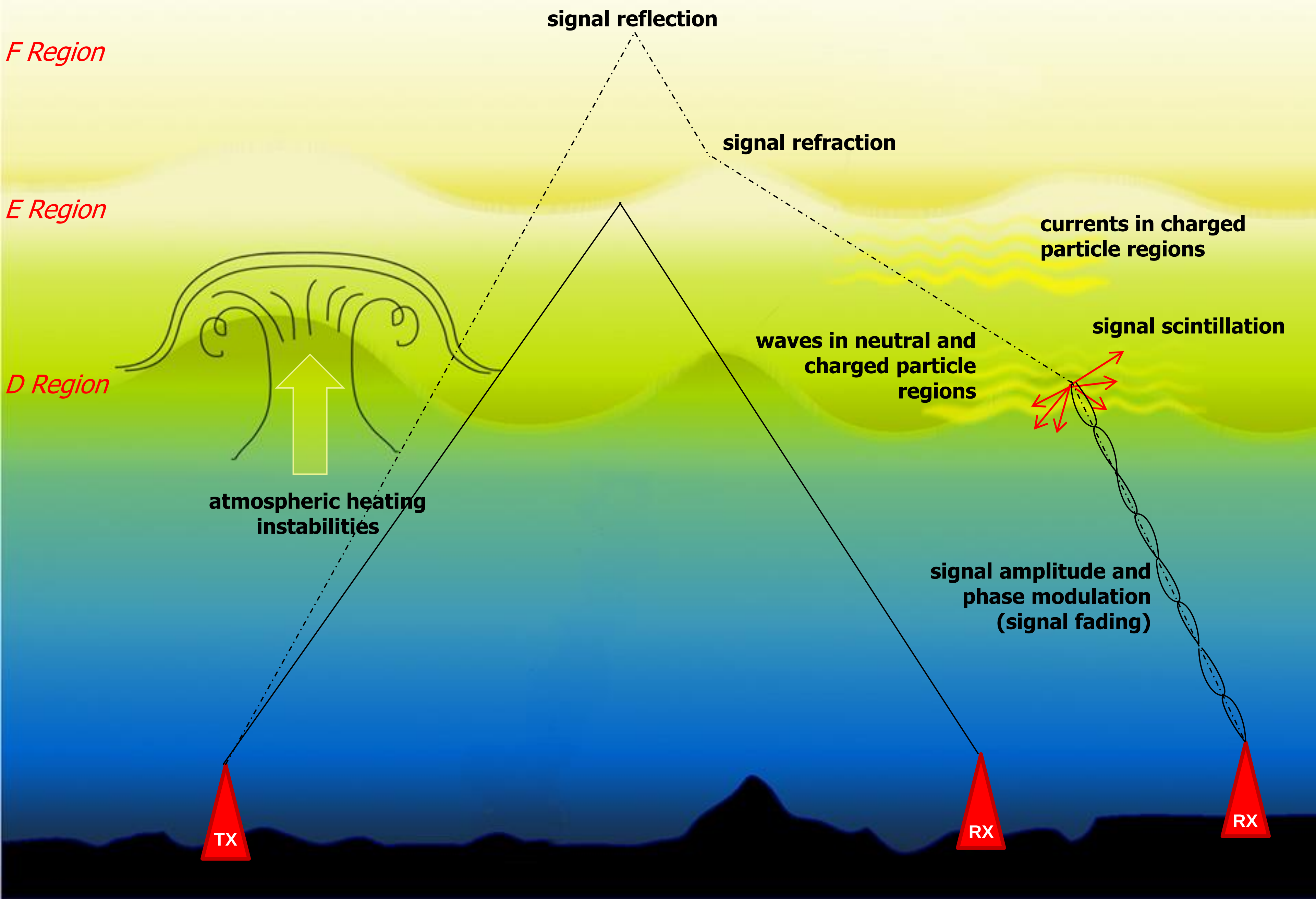
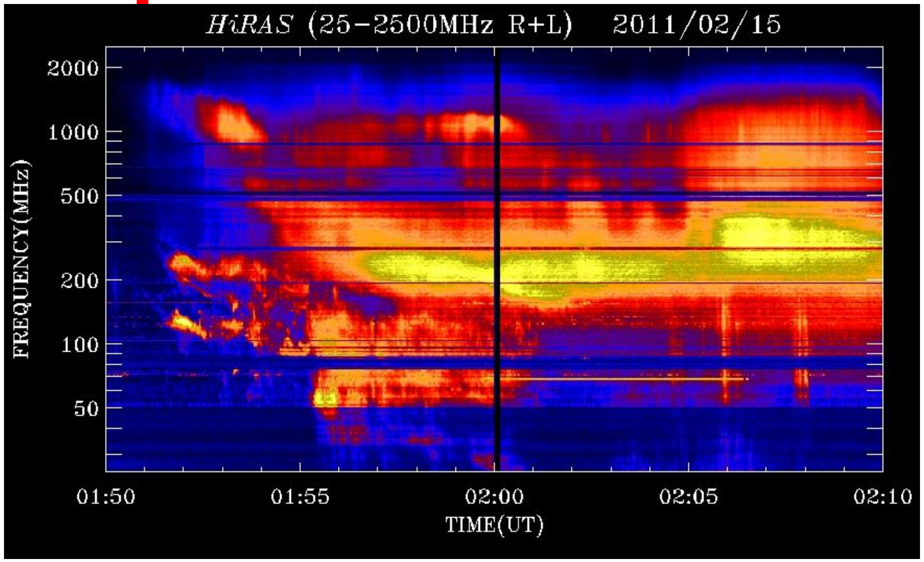
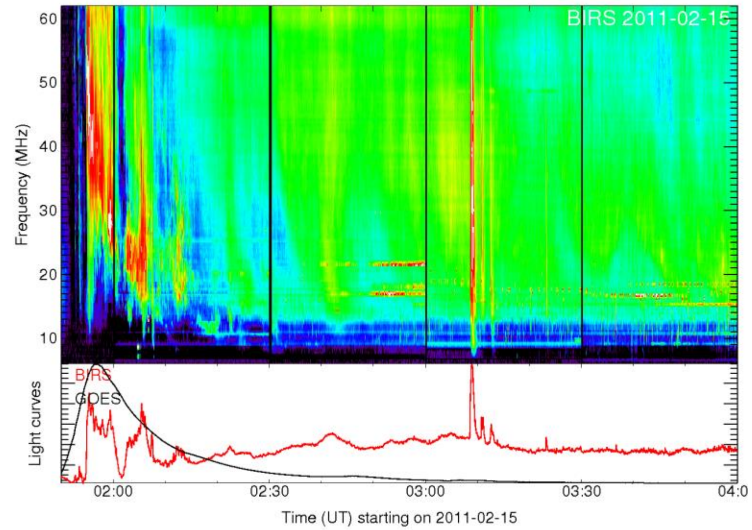
Space Weather Effects on Propagation



Space Weather Audible Interference





Solar flare: Solar radio bursts cause radio blackouts over a wide frequency range
https://www.wired.com/2013/02/radio-solar-outburst/

Dawn Chorus: Radio Waves due to energetic particles in the magnetosphere
https://www.nasa.gov/mission_pages/rbsp/news/emfisis-chorus.html#.VVWFy_lVikp

Sferics and Tweeks: Radio waves caused by lightning nearby
http://www.spaceweather.com/glossary/inspire.html

Whisters: Radio waves caused by lightning far away
http://www.spaceweather.com/glossary/inspire.html

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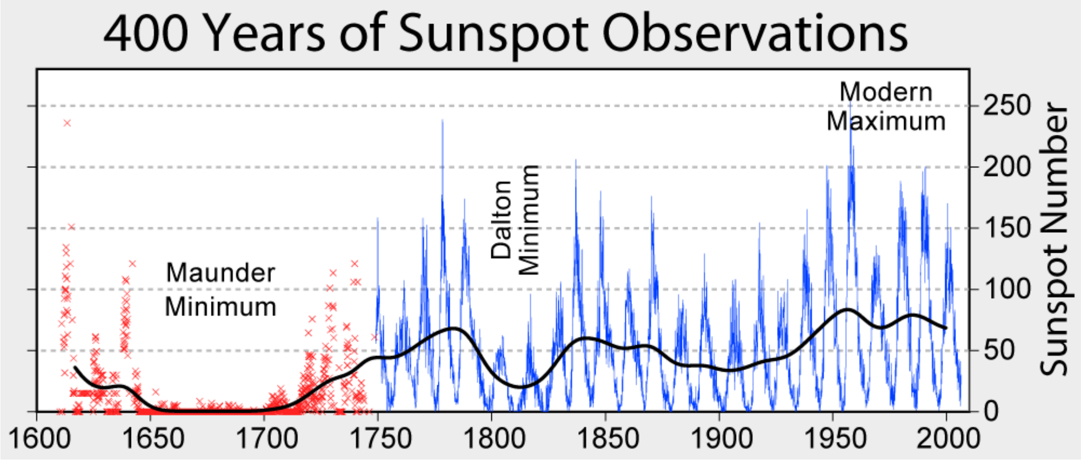
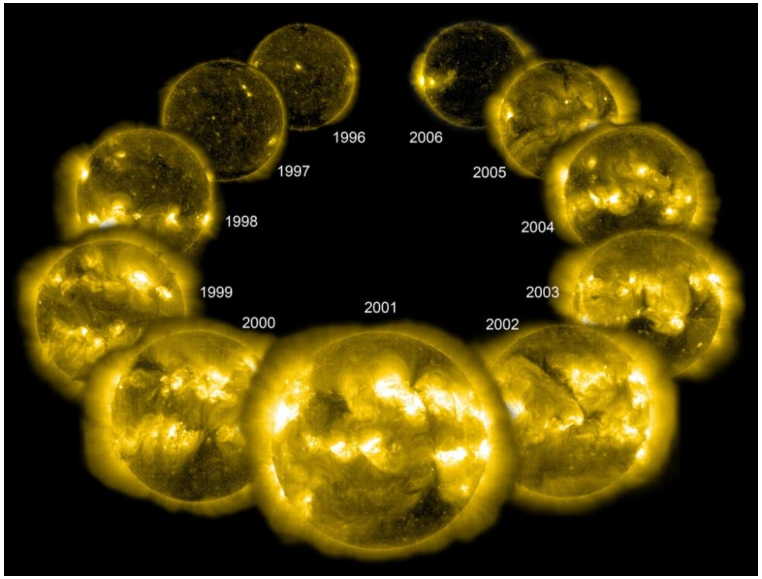
What about Solar Variability?

- Sun's activity cycle has a quasi 11-year periodicity
- Solar magnetic field constantly reversing orientation
- Activity increases for few years around field reversal (solar maximum) and decreases when field becomes ordered again (solar minimum)
- Other competing cycles cause deviations from 11-years and modulate the strength of the cycle over the long-term
- Sunspot numbers are used as a proxy for solar activity





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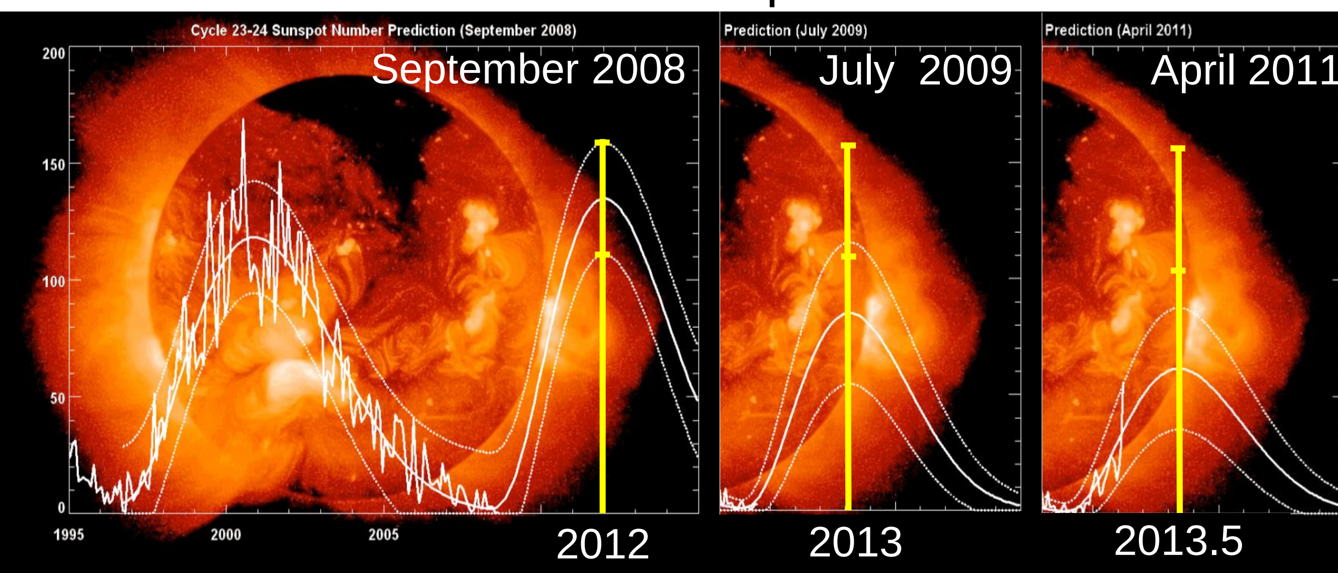
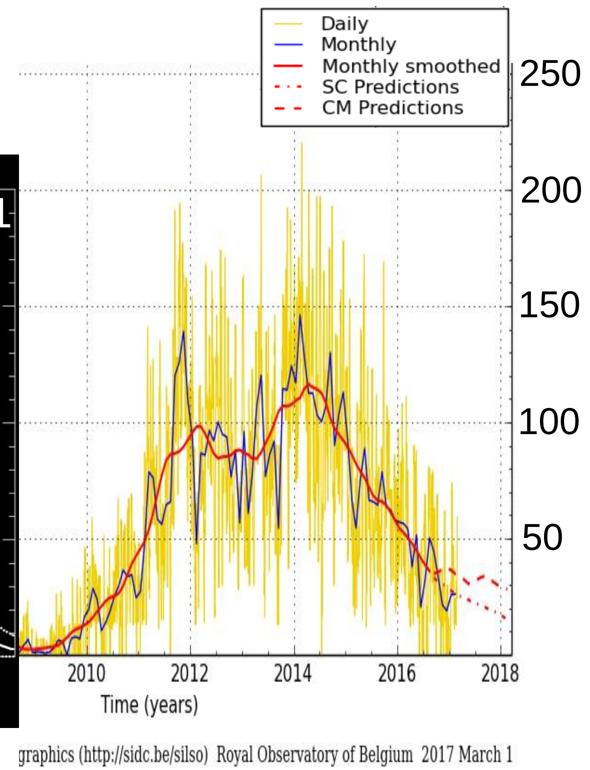
Solar Cycle: Where are We Now?

- Recent solar cycles are showing dramatic changes, making predictions more complicated
- Consensus is we are in a new Dalton-like Minimum
  - Cycle is slower, up to 14 years
  - Lower luminosity, slower currents beneath Sun's surface, lower magnetic field
  - lower activity at maximum
- Solar maximum double-peaked
  - First peak in 2011-2012, second peak 2014-2015

Recent Sunspot Number Predictions





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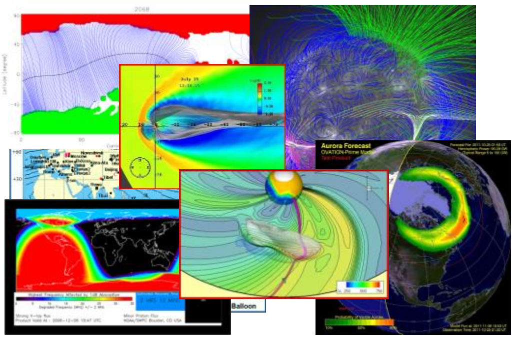
Space Weather Forecasting: A Return to the Sixties



Space Weather Prediction Centers

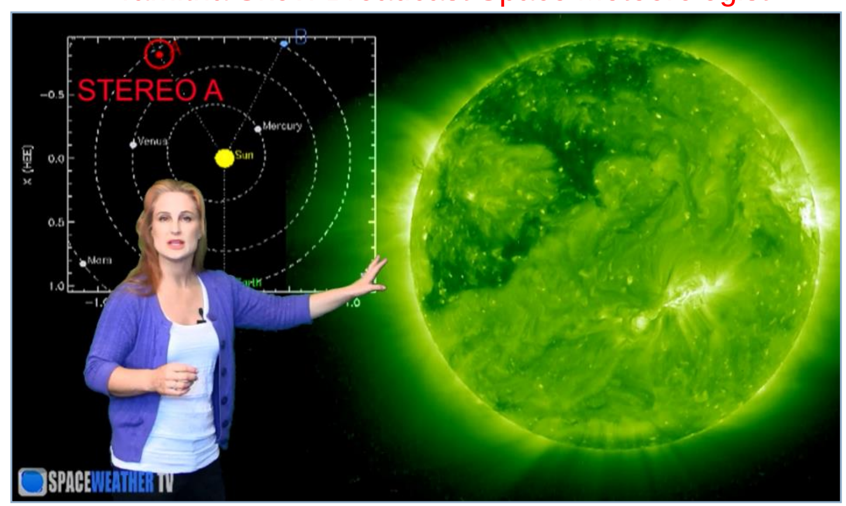
- Developed mainly as a response to super storms
- Models that predict solar fields, CME transit, magnetospheric responses→ solar storm alerts
- Radio blackouts, solar radiation storms→ FAA alerts
- Space and ground telescopes for 24/7 monitoring of Sun, even on the backside
- “Spaceship Earth” networks

~1960

Harry Volkman: Broadcast Meteorologist

Today

Tamitha Skov: Broadcast Space Meteorologist



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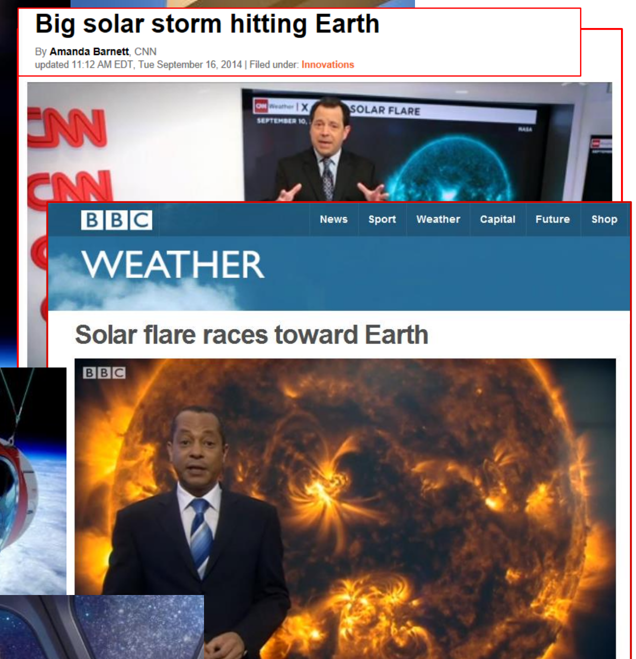
Space Weather Forecasting: A Return to the Sixties

Our Future Relies on Predicting Space Weather

Reliance on Space is advancing:

- Wireless technologies
  - 6 Billion mobile phones in world today
  - GPS/GNSS receivers
  - Satellite service providers exploding
- Self-driving cars
  - CA law passed in 2012 Google car can share public roads
- Unmanned Aerial Vehicles (UAVs)
  - FAA allows GPS/GNSS enabled drones to share commercial airspace in 2015
- Space Tourism
  - World View to launch manned balloon test flights in 2017
- National Power Grids



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