Space Weather, Flares and their Impact

FLARECAST First Stakeholders Workshop

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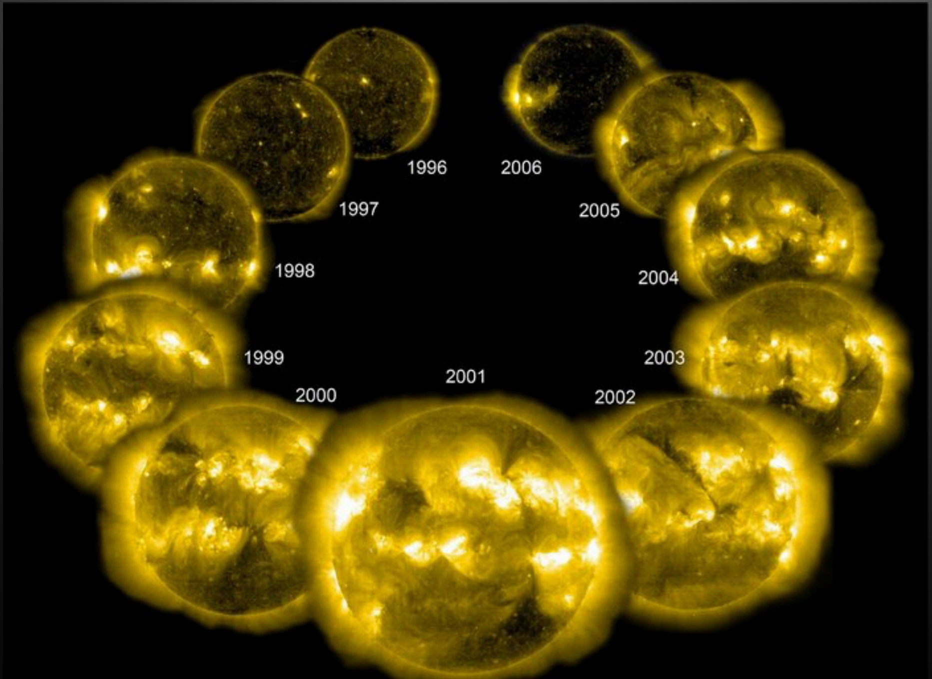
Outline

- ❑ Space Weather vs. Space Climate
- ❑ Main SWx agents
- ❑ Solar flare occurrence and properties
- ❑ Solar flare impact
    - ❑ Biological
    - ❑ Technological
    - ❑ Societal
    - ❑ Financial
- ❑ Predicting flares: why do we need prediction?
- ❑ Can flares be predicted, really?
- ❑ Conclusions

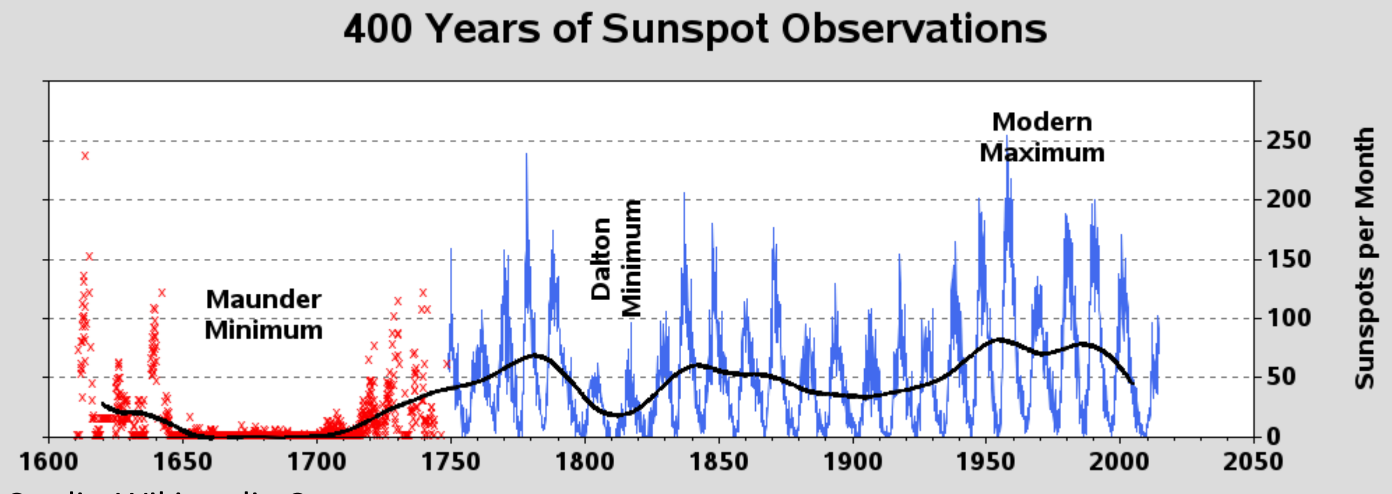
The solar (coronal) activity cycle



Credit: ESA / SOHO

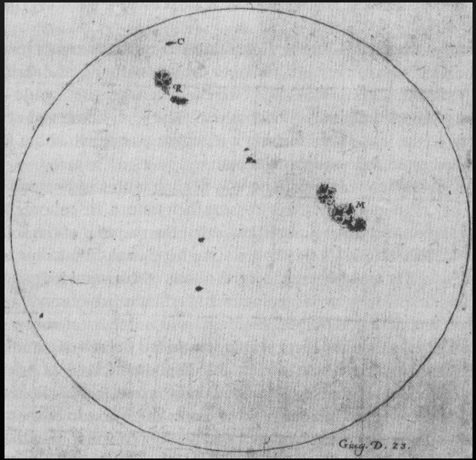
- The appearance of the solar corona changes nearly periodically, with a periodicity of ~11 years
- So does the occurrence of sunspots in the Sun's visible surface, the photosphere
- The solar cycle is conventionally measured via the sunspot number
- Sunspots and overall coronal activity are dominated by magnetic fields

Progression of sunspot cycles



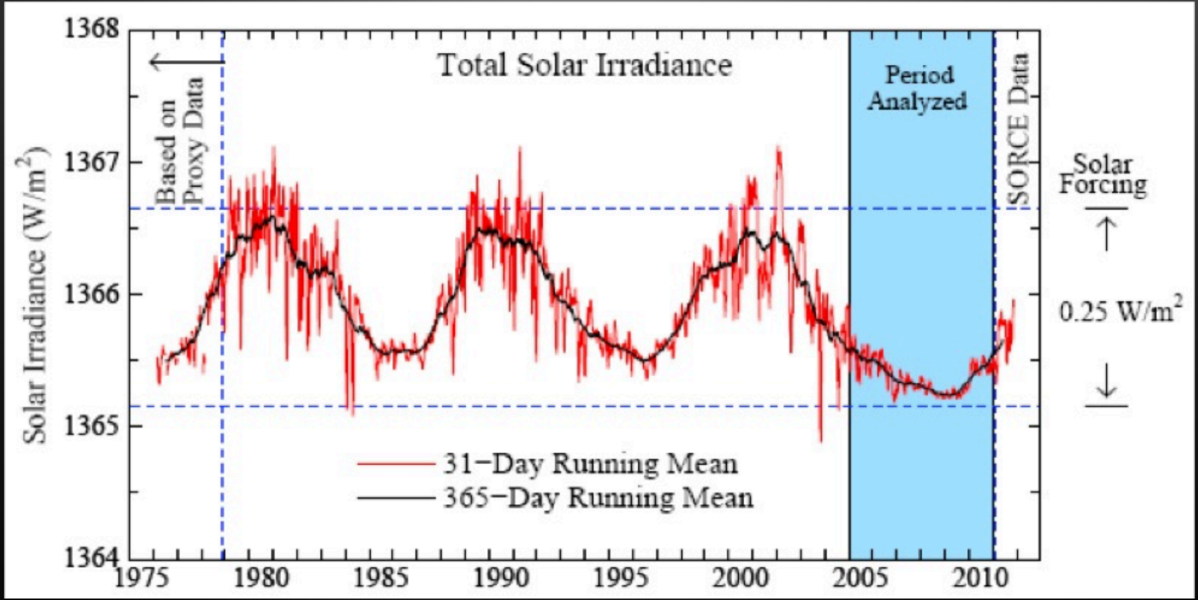
Credit: Wikimedia Commons

Galileo drawing, June 23, 1612



- Solar cycles succeed each other with an apparently aperiodic amplitude
- However, lack of sunspots (cycle minima) does not imply a lack of solar activity

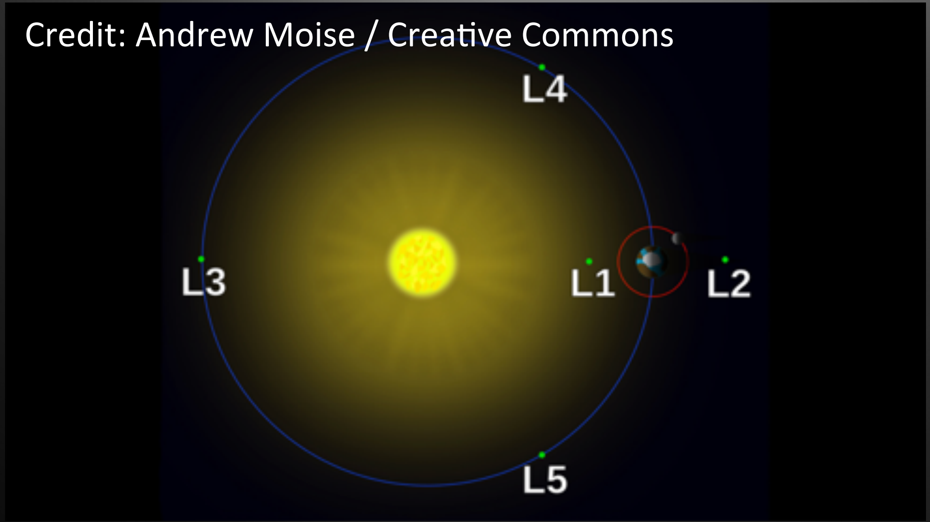
Total solar output (aka solar constant)

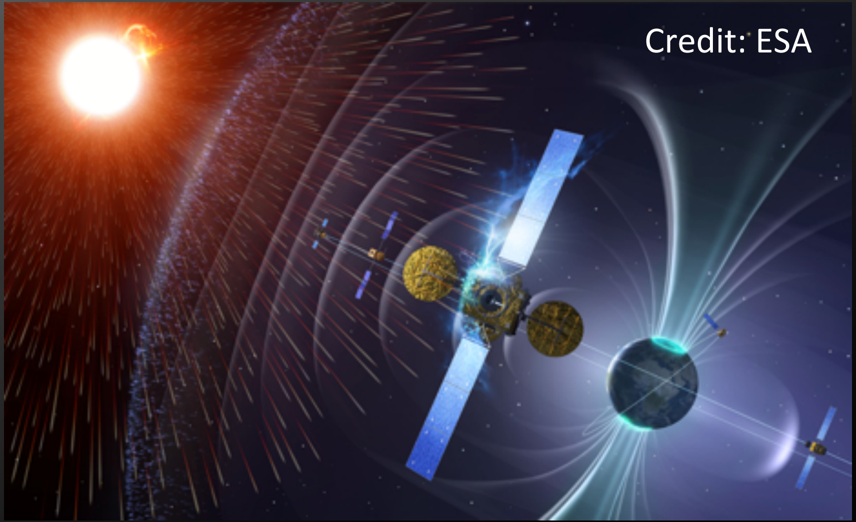


Credit: NASA / James Hansen

- The mean total (bolometric) solar irradiance at the top of Earth's atmosphere amounts to ~ 1,366 W/m^2
- Solar-cycle-related (magnetic) modulations amount to ~0.25 W/m^2, or ~0.02% of the mean

Space Weather and Space Climate

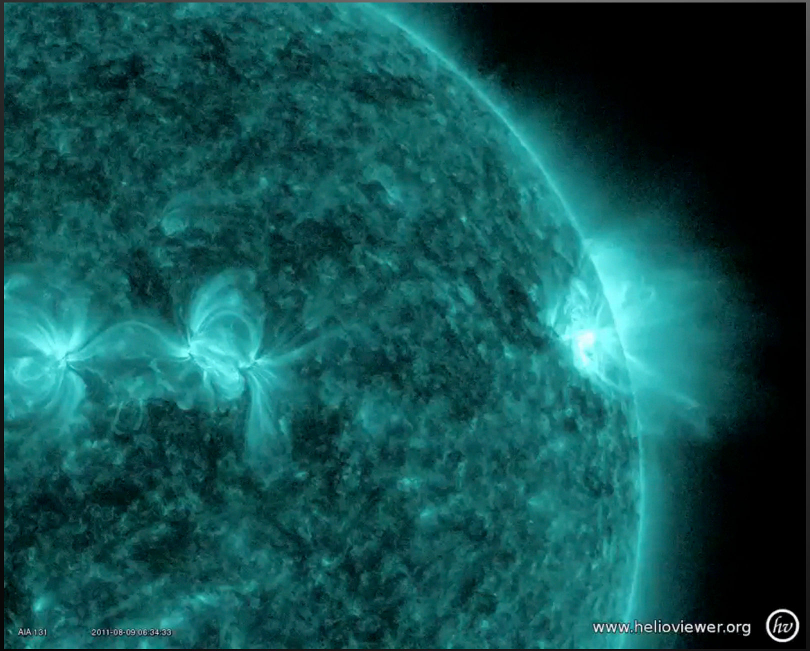




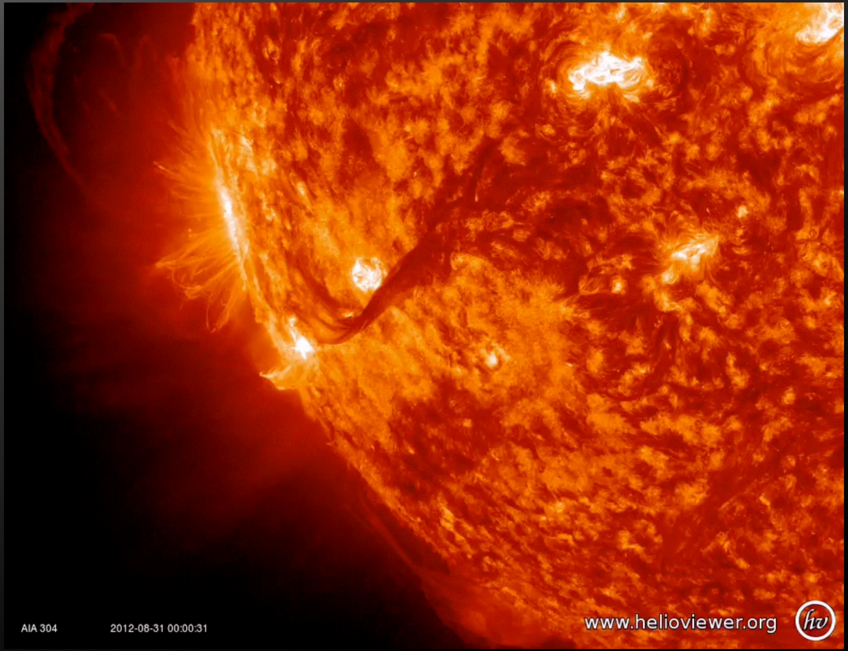
Space Climate: variability due to the solar constant (~99.98% of the Sun's total output) and its potential variations. Characteristic timescales of decades – millennia

Space Weather: variability due to the magnetically dominated solar cycle (~0.02% of the Sun's total output). Characteristic timescales of minutes – days, in case of intense activity

Main SWx agents. I. Solar eruptions

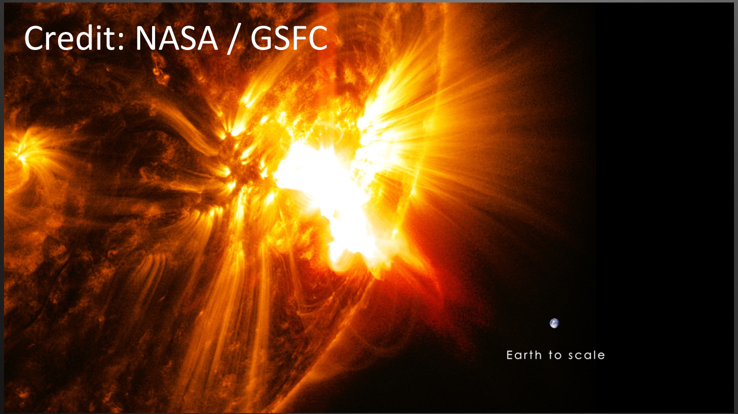


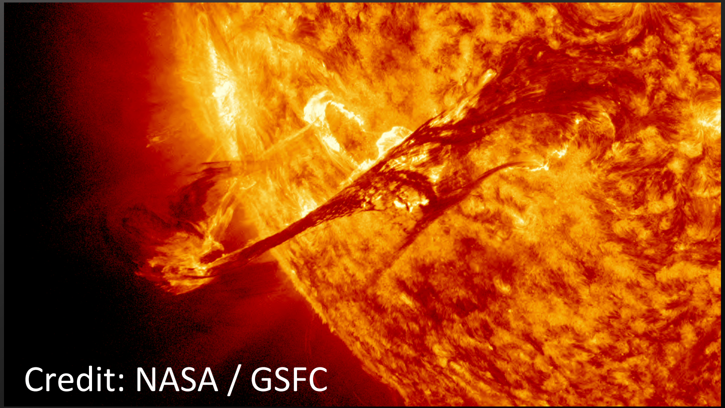
Solar flares



Coronal mass ejections (CMEs)

Main SWx agents. I. Solar eruptions and associated particle events





Solar Flare: *"A sudden eruption of magnetic energy released on or near the surface of the sun, usually associated with sunspots and accompanied by bursts of electromagnetic radiation and* *<u>particles.</u>"*, American Heritage Dictionary

Coronal Mass Ejection (CME): *"A massive, bubble-shaped burst of plasma expanding outward from the Sun's corona, in which large amounts of superheated* *<u>particles</u>* *are emitted at nearly the speed of light."*, American Heritage Dictionary

Main SWx agents. Solar energetic particles (SEPs)

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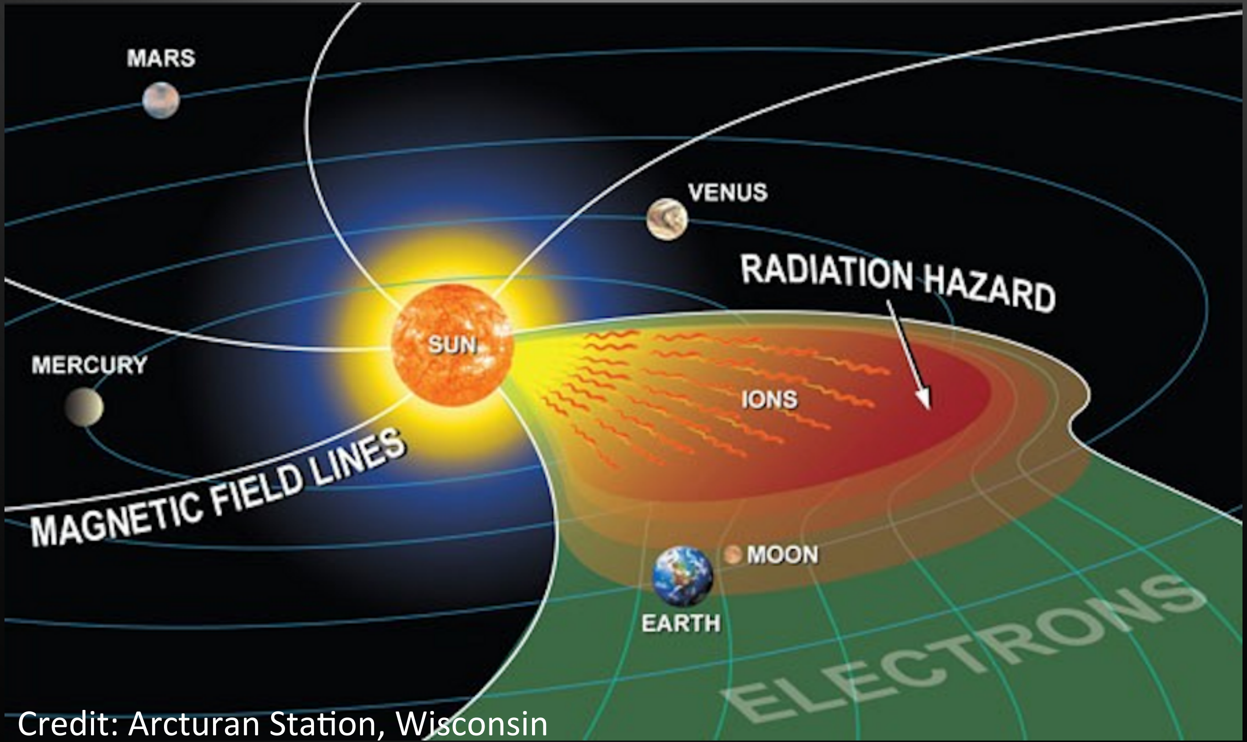
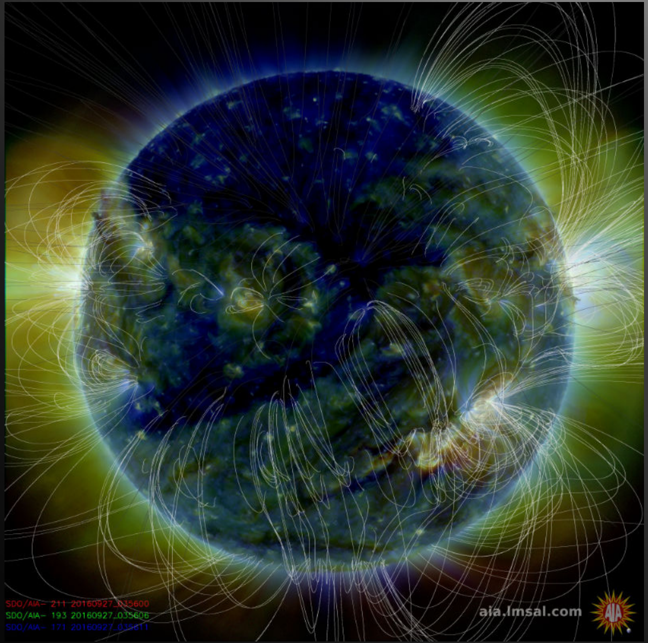


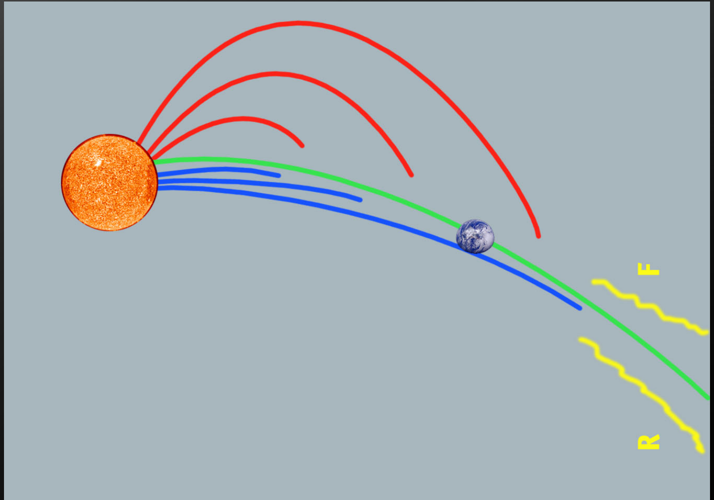
Credit: Arcturan Station, Wisconsin

Solar flare and CME relativistic particles reach Earth if suitable magnetic connection exists. However, the disturbance caused by CMEs in the inner heliosphere is such that by far the most SEPs at Earth vicinity can be attributed to CME shock acceleration

Minor SWx agents. II. Coronal Holes, CIRs



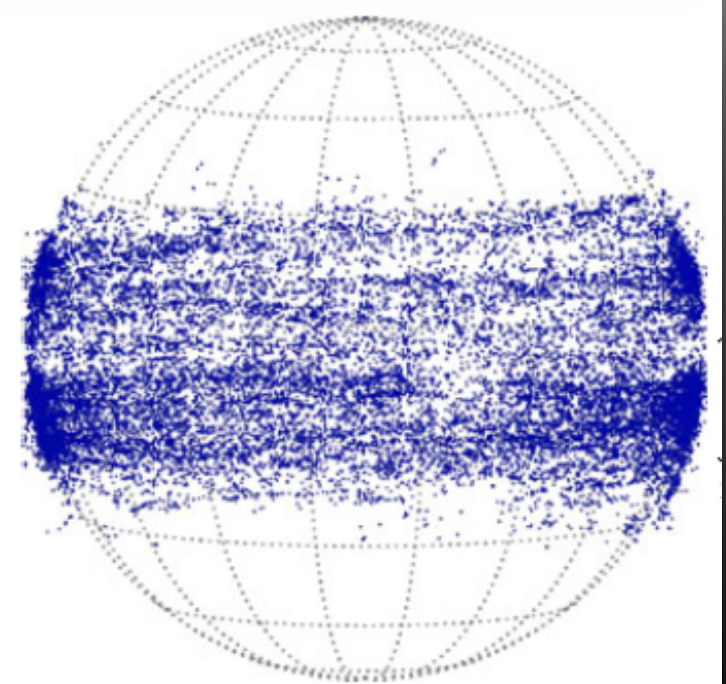
Geoeffective coronal holes: at right magnetic-connectivity locations, they channel high-energy particles toward Earth in a “sprinkler-type” fast-streamer effect



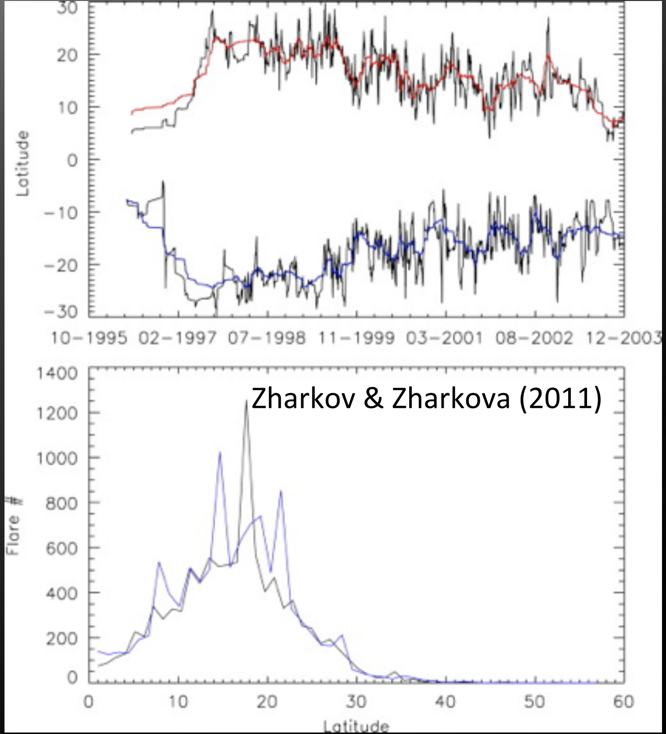
Credit: High-Altitude Observatory

Co-rotating interaction regions: shearing between fast, CH-generated and slower solar wind streamers

Occurrence locations of solar flares



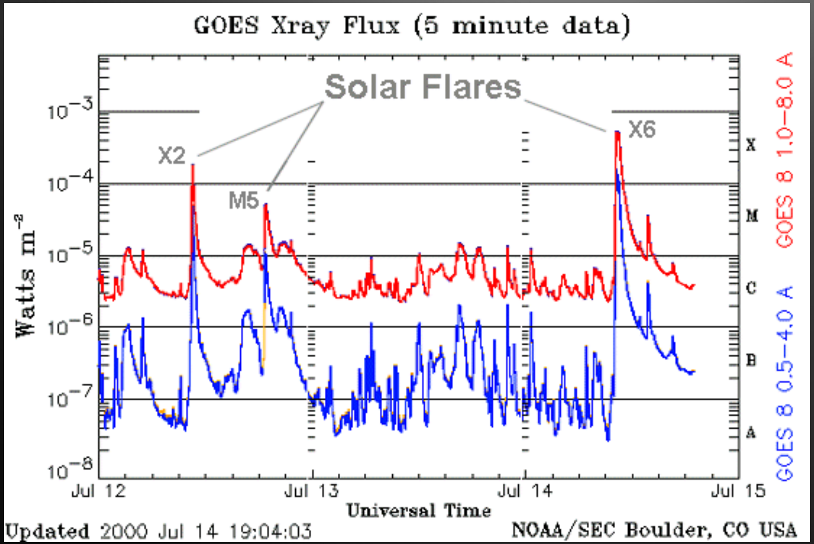
Hannah et al. (2011)



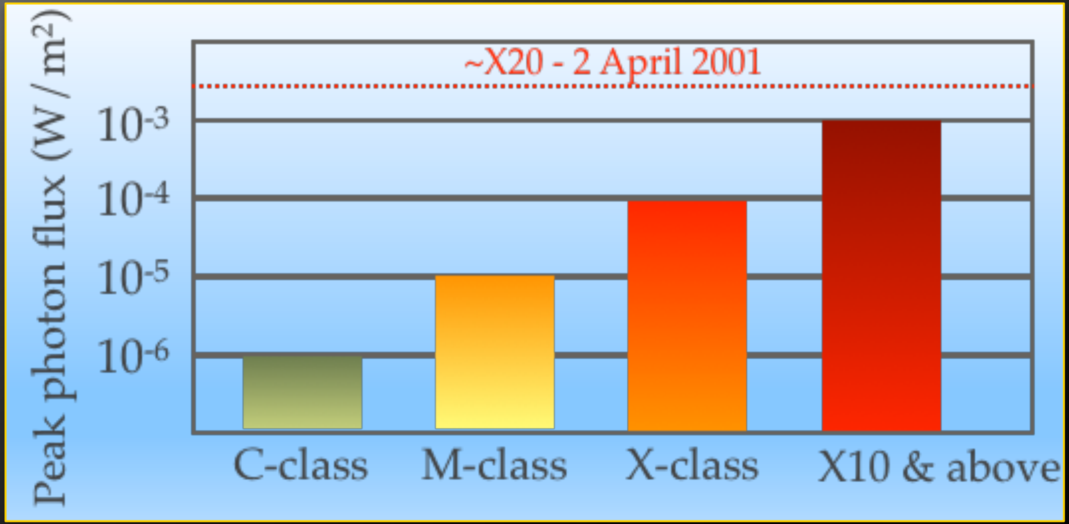
Zharkov & Zharkova (2011)

Major flares occur almost exclusively in solar active regions, or opposite polarity sunspot complexes

NOAA / GOES solar flare classification

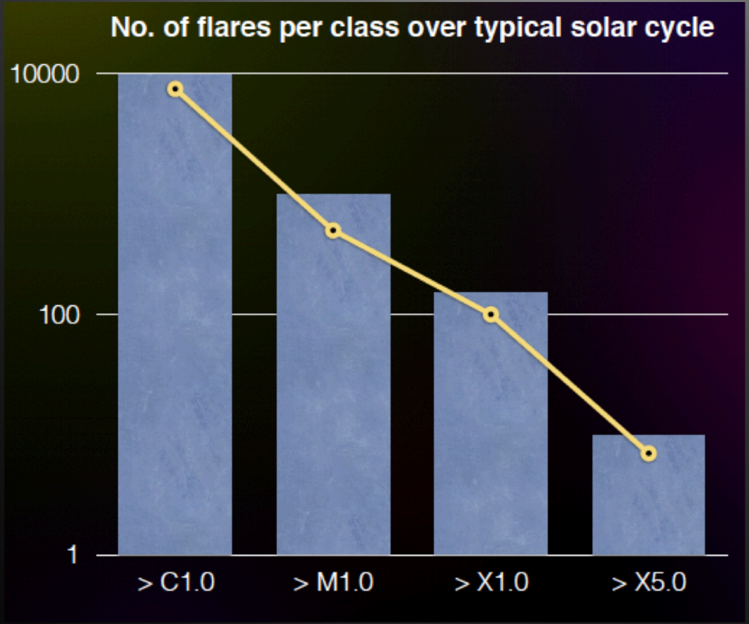


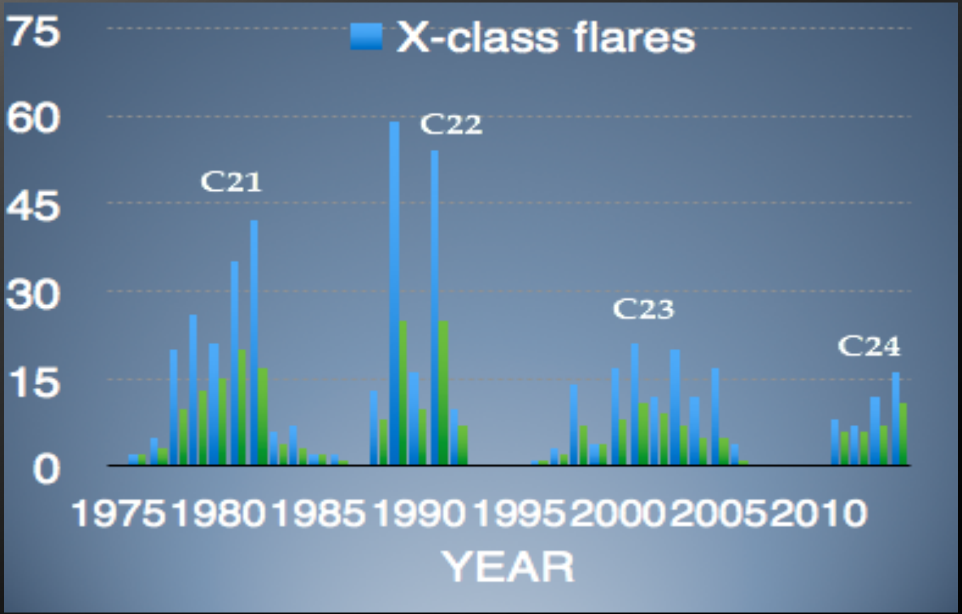
Active solar conditions in July 2000



Logarithmic scale, measured in soft X-rays (1 – 8 Å) at flares' peak

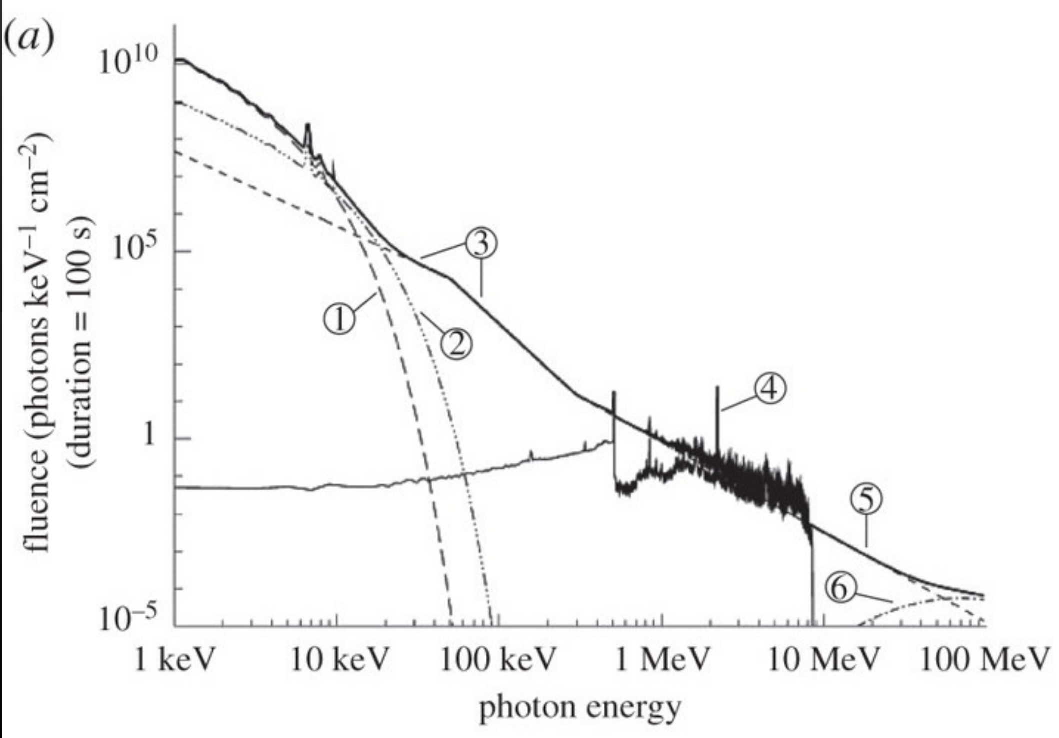
Occurrence frequency of flares





- < 2% of solar active regions will ever host an X-class flare
- <10% of solar active regions will ever host an M-class flare

Solar flare impact: “hard“ photons



Composite X-ray/γ-ray spectrum from 1 keV to 100 MeV for a large flare (Lin et al., 2007 – see also Vilmer 2012 for details)

Issues with X- and γ-rays (> 100 keV; ~10^{19} Hz):

- **Biological**: cell and DNA impact or even destruction (astronauts in EVA)
- **Technological**: saturation issues in Sun-observing telescopes (attenuators must be deployed) and, possibly, sensitive electronics

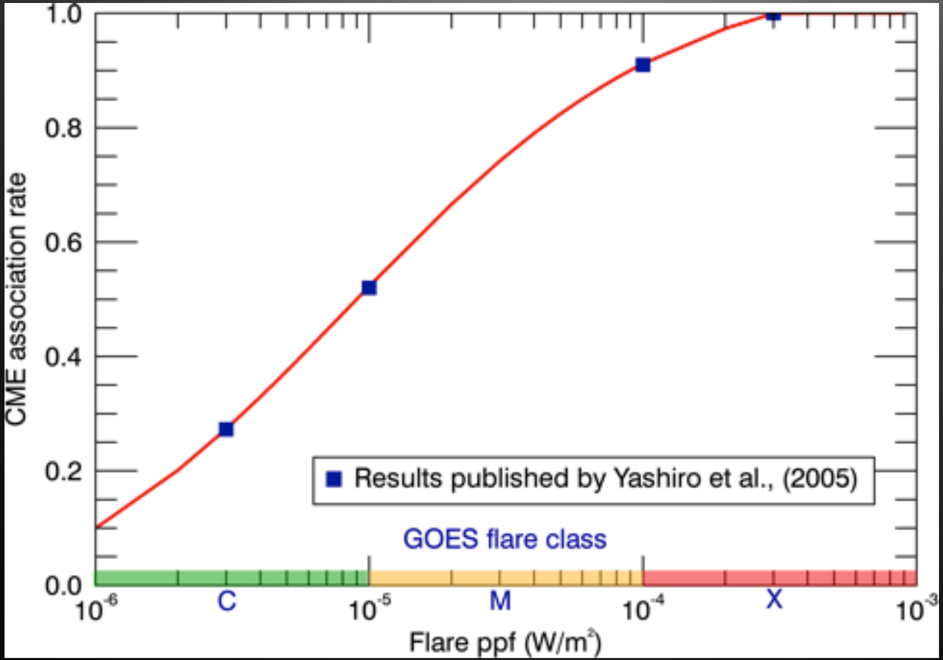
Solar flare impact: radio blackouts

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
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 (2×10^{-3})	Less 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 (5×10^{-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)

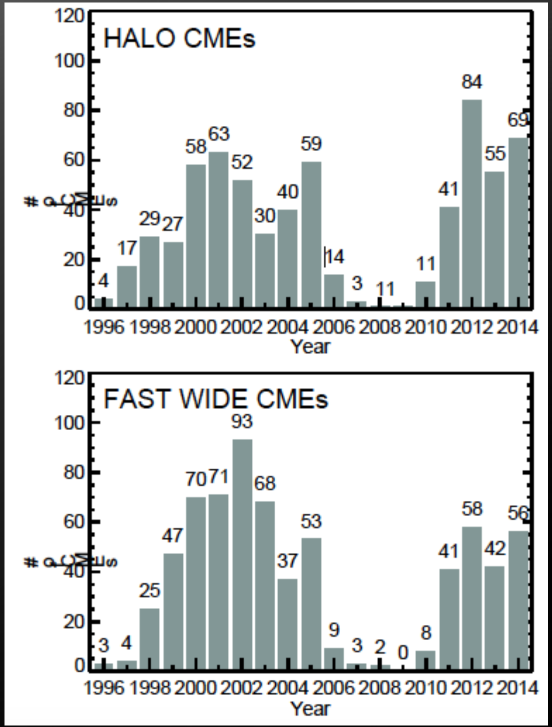
Source: NOAA / SWPC

- At least a few (< 10) severe (R4+) radio bursts are expected during a typical solar cycle.
- At least one extreme (R5) burst is expected in two consecutive cycles

The flare – CME connection



Flares >X3 are one-to-one correlated to fast CMEs



Gopalswamy et al. (2015)

Combined flare – CME impact: (particle) radiation storms

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Source: NOAA / SWPC

Scale	Description	Effect	Physical measure (Flux level of >= 10 MeV particles)	Average Frequency (1 cycle = 11 years)
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.	105	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.	104	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.	103	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:** Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	102	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

Flares > X10

Flares ~X10

Flares ~X4

Flares ~X3

Flares ~X2

Contrary to radio bursts, such effects can be lasting for days!

Combined flare – CME impact: geomagnetic storms

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Source: NOAA / SWPC

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
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)

Flares > X10+

Flares ~M7 – X1

Flares ~M4

Flares ~M2

Flares ~C5

An inter-connected societal fabric: an avalanche impact

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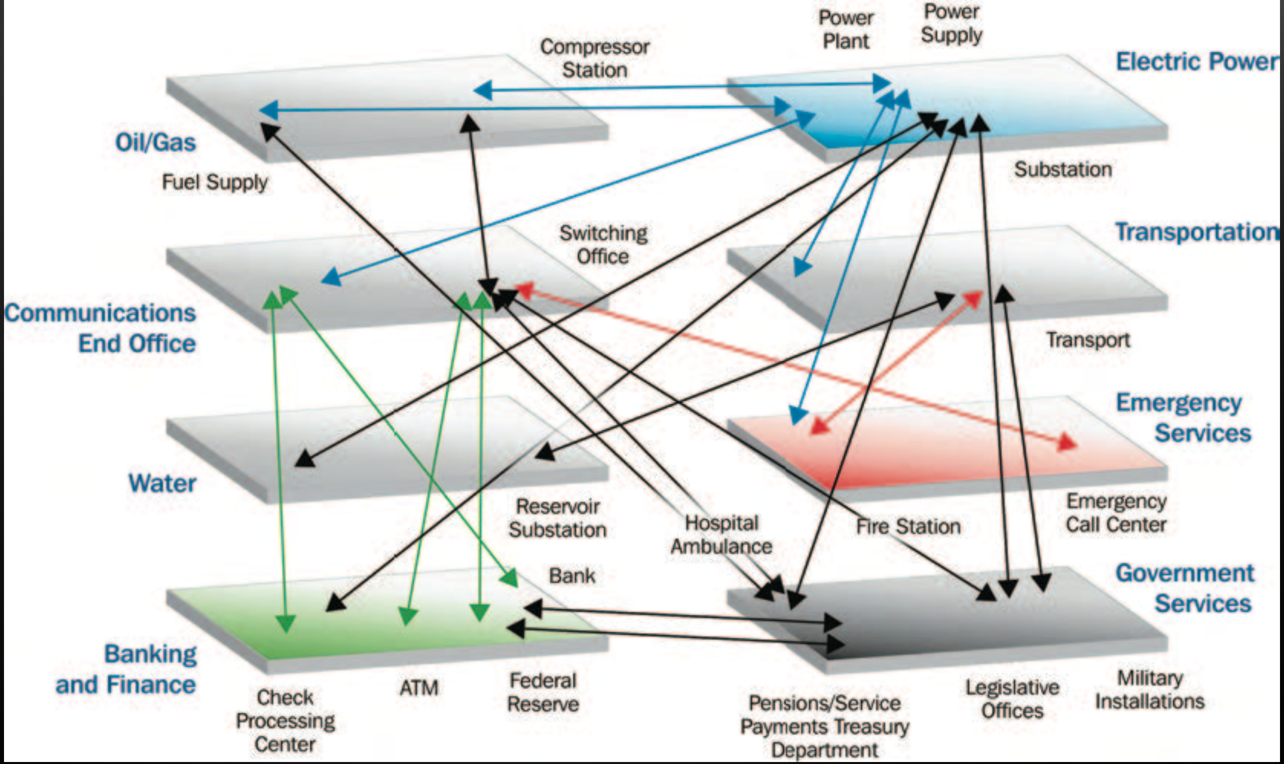
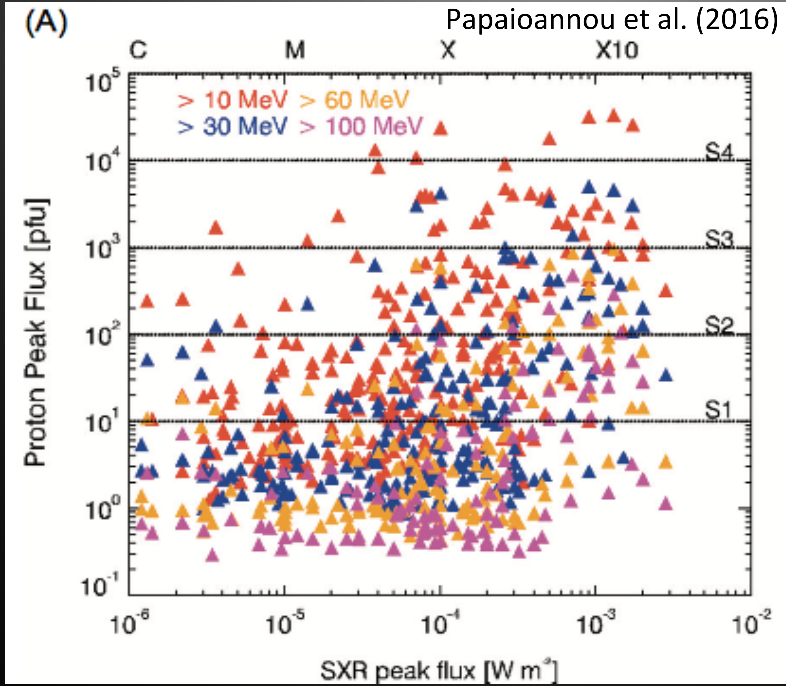


Source: Severe Space Weather Events: Understanding Societal and Economic Impacts, US NRC Workshop Report, NAS Press, 2008

A price tag of a catastrophic SWx event (surely related to an extreme flare) is hard to assign: however, it can be projected to GEUR, up to TEUR in the long run(!)

A question of when, not whether



1984 – 2013: tens of extreme flares (X10+); at least 8 severe radiation storms (S4)

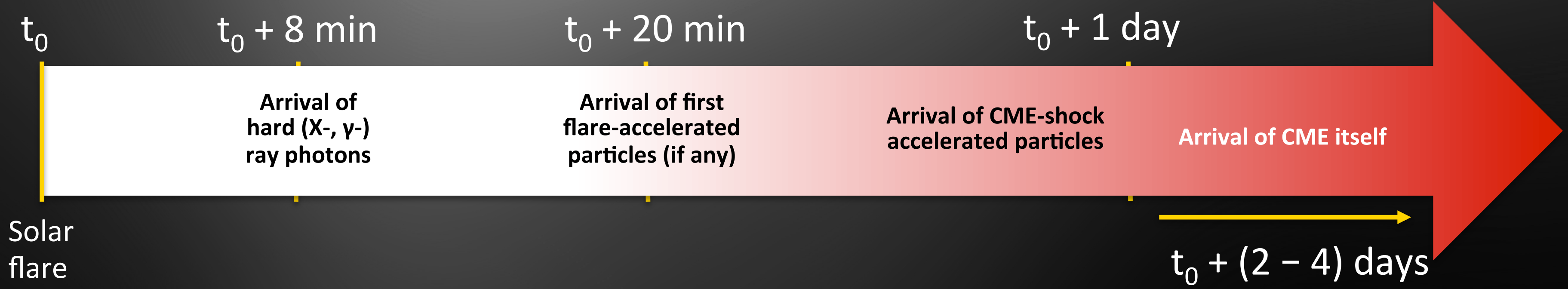
Probability for a Carrington-type flare (estimated at ≳ X45 by Cliver [2013]):

- 10.3% over the next 10 yrs (>95% CI) – Riley & Love (2017)
- 4 – 6 % over the next 10 yrs – Kataoka (2013)
- 1 event very 500 yrs – Yermolaev et al. (2013)
- STEREO-B claimed an allegedly Carrington-type event detection in July 2012 (reached S/C in 19 hours only!)

Governmental actions:

- Jul 2015: Space Weather Preparedness Strategy, Cabinet Office, Dept. of Business Innovation & Skills, UK Government
- Oct 2015: National Space Weather Action Plan, National Science and Technology Council, US Government
- Governments of China, Japan, Australia, South Korea, South Africa and India are possibly moving toward this direction

So… Why do we need advance flare prediction?



- There is no early warning for flare X- and γ-ray photons
- There is a slim (few min) early-warning window for possible flare-only particulate
- From the flare class, one can effectively proceed to CME prediction for major flares
- Flares are the primary agents for solar radio bursts
- Dot-connecting exercises (from predicted flare location, surroundings, orientation) can be made to assess possible eruption impact and combine with other SWx prediction efforts (CMEs, SEPs)

But can major flares be predicted, really?

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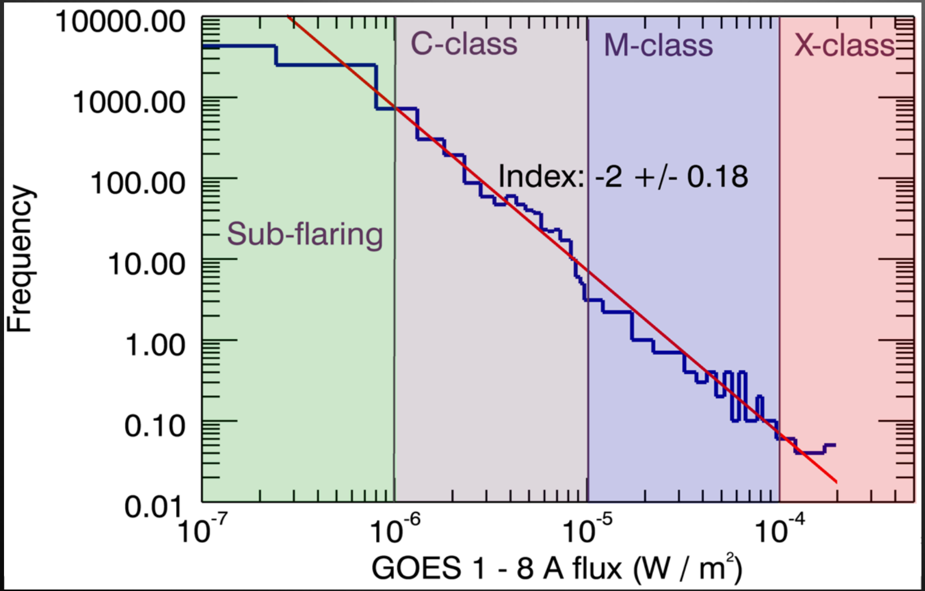

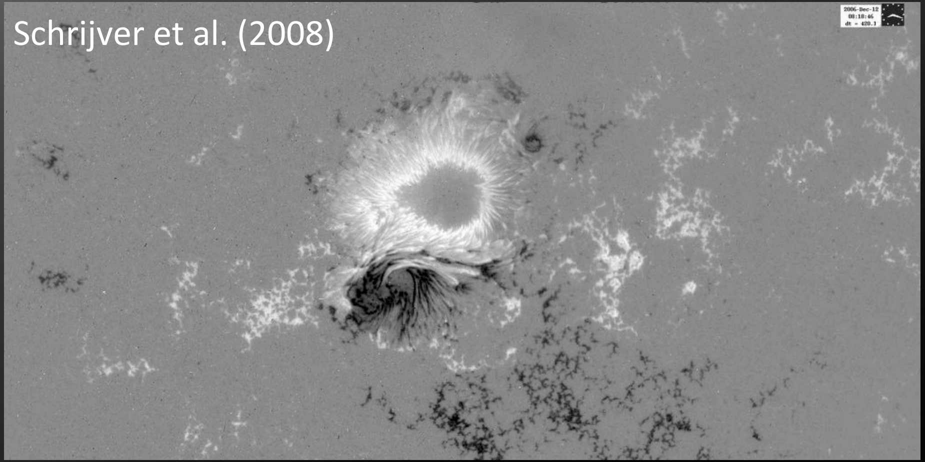

- Flares tend to cluster in active regions, show a self-similar occurrence frequency and follow a time-dependent Poisson appearance process

- Major flares are scarce and stochastic events; hence, a probabilistic forecasting seems most likely
- How effective can this be, or whether we can do any better, is up to FLARECAST to determine

Conclusions

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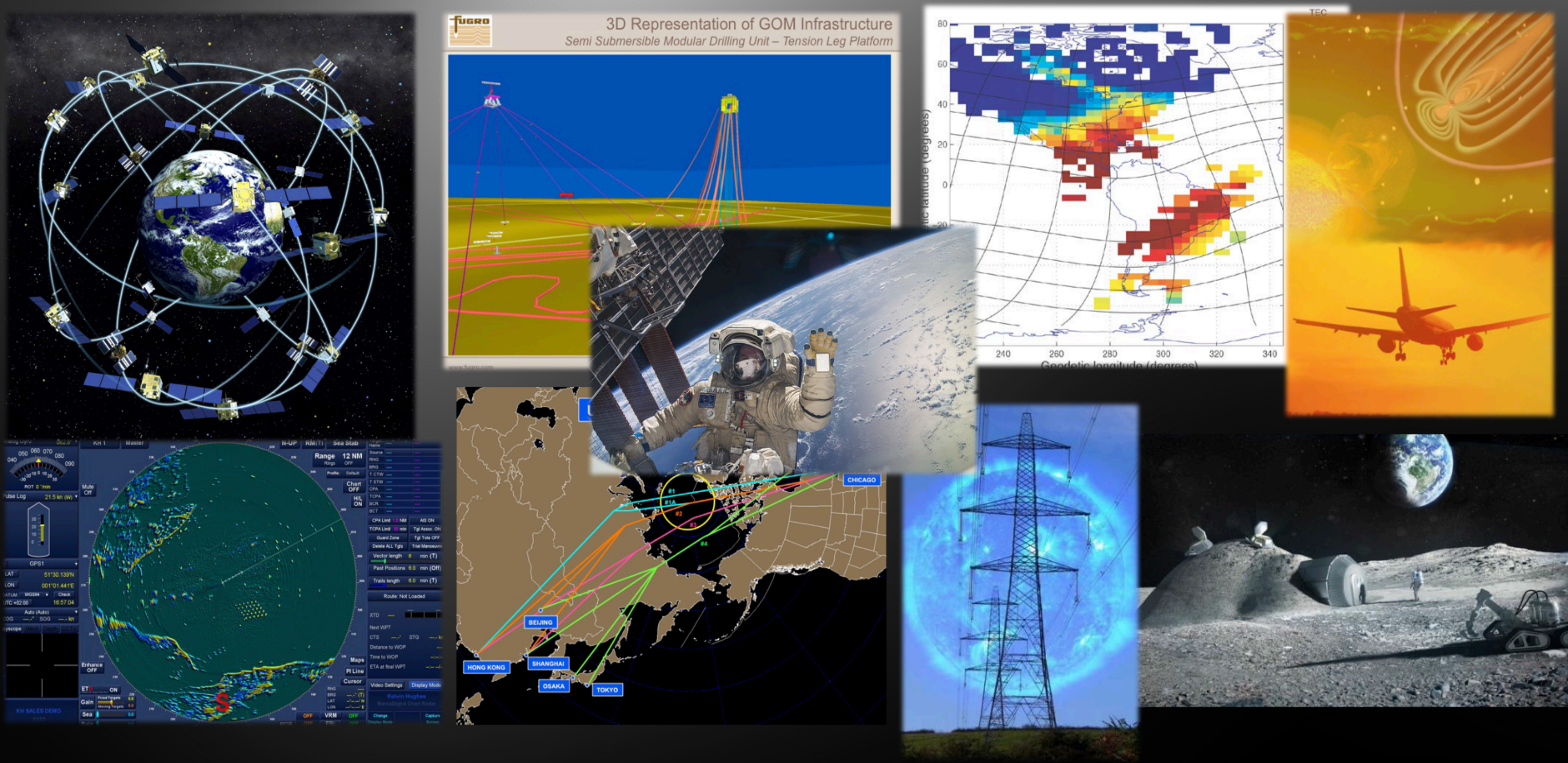
- Extreme space weather: a rarity that cannot be ignored anymore
- Solar flares: a SWx leg that must be predicted <u>before</u> its occurrence
- Issues exist with both solar flare photons and particulate
- Major or great solar flares effectively couple one-to-one with CMEs. Therefore, flare prediction might involve a notable "bonus" in this respect
- The question of flare prediction, besides practical use, is also of academic interest. We need to reach and assess our limits in predicting these events
- What is the plan in achieving flare prediction, at the same time addressing stakeholder needs? **Check out FLARECAST**



THANK YOU FOR BEING HERE!