Seminars on Space Weather
Panamá 2018

Extreme Events
What is it and How does it affect us?

Eventos extremos.
¿Qué es y cómo nos afecta?

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What is an Extreme Event ?

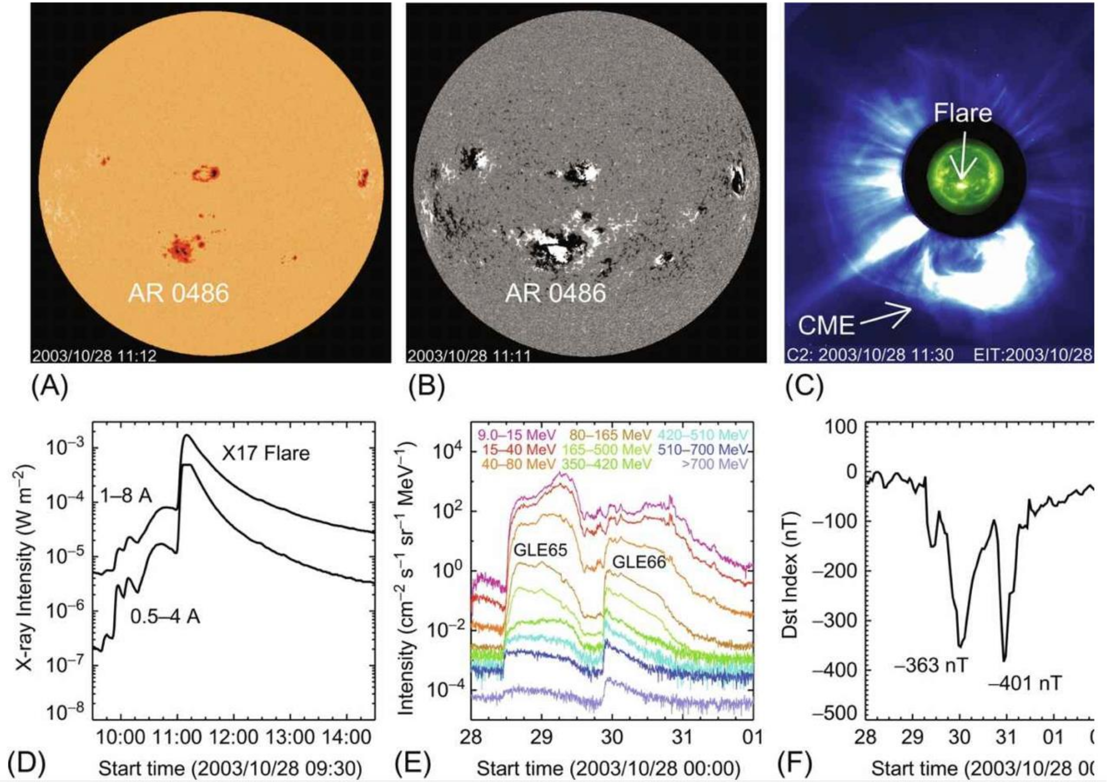
The consequences of a space weather event can be **extreme** only if certain conditions occurs at Earth environment.

- Example: a CME that has an extreme speed can be considered an extreme event if such an occurrence is extremely rare. Among the thousands of CMEs observed by the Solar and Heliospheric Observatory (SOHO) from 1996 to 2015, only a couple have speeds exceeding 3000 km s^{-1}.
- How big can be the speed of a CME? The magnetic field ?

The Halloween Event (Oct 28-29, 2003)

To our knowledge, this is an extreme event that impacted Earth recently!

- Very soon after the flare and CME, the society took actions to safeguard the technological systems.
- Two super intense geomagnetic storm was produced

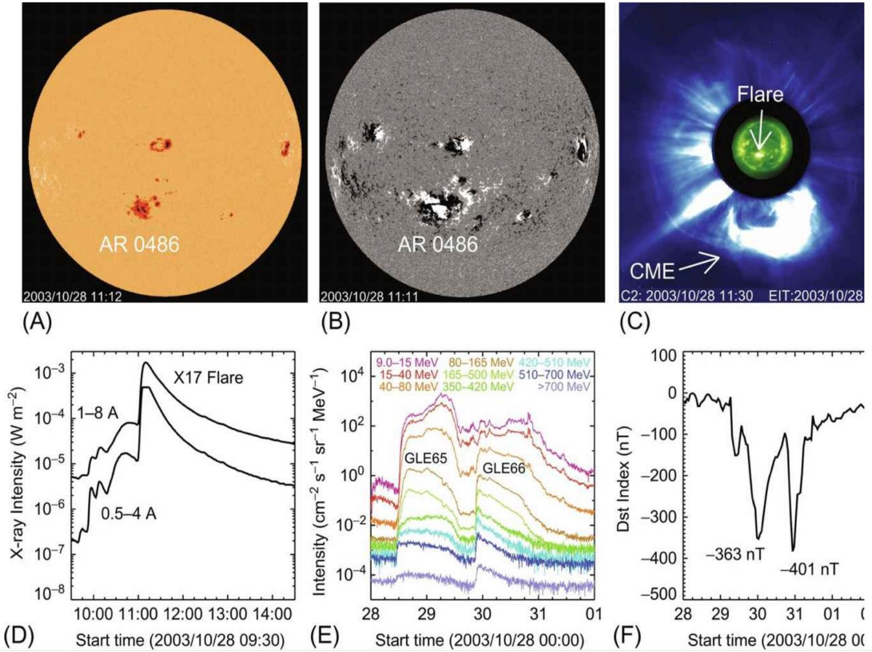


Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1

What we learned from the Halloween

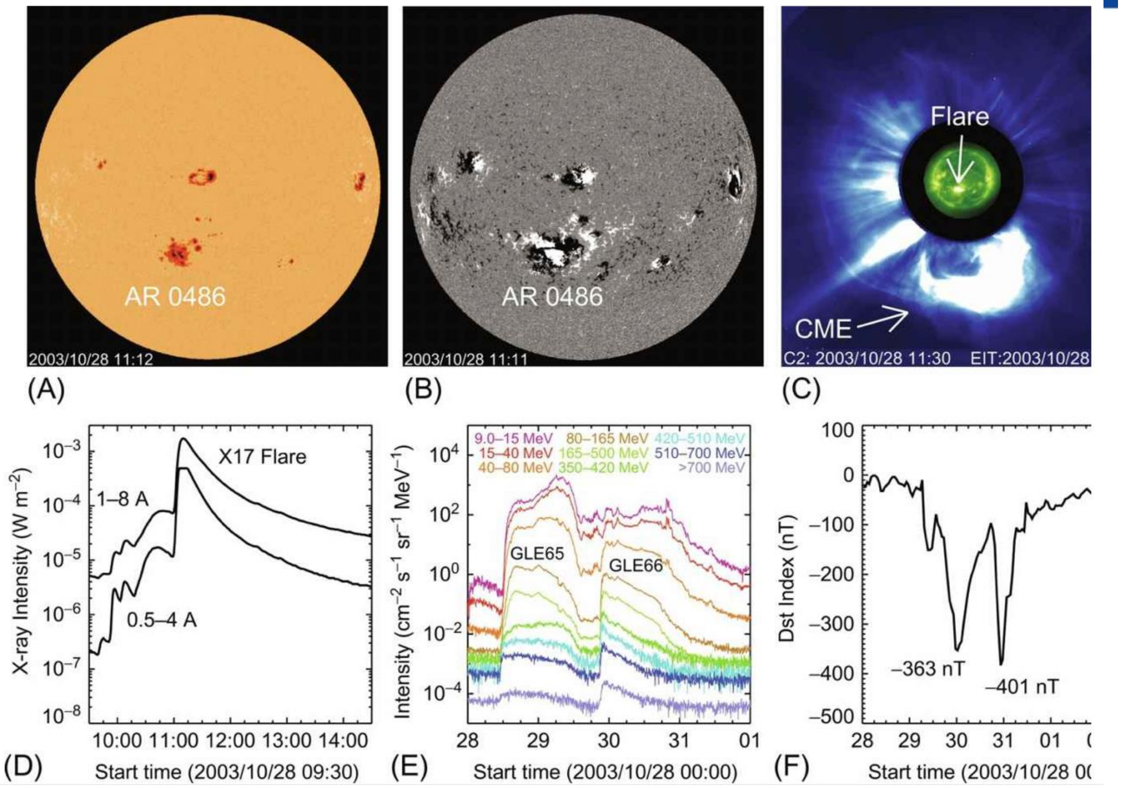
The space weather service is not yet standardized and the impact on the many sectors of the technologies and the Society is not known!

- The Halloween events were documented in about seventy articles published during 2004–05 (see Gopalswamy et al., 2005a for the list of the articles).
- The solar active region (10486) from which the CMEs originated was also very large and had the potential to launch energetic CMEs.
-

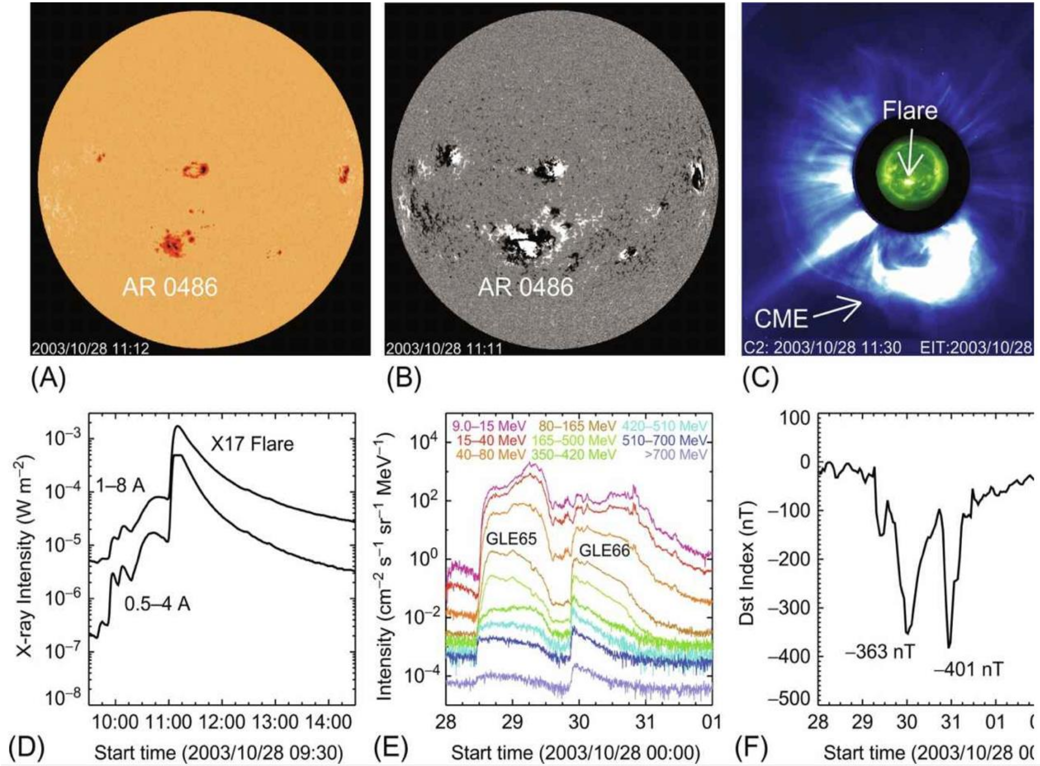


The active region with sunspots and its complex magnetic structure as observed by the Magnetic and Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO).

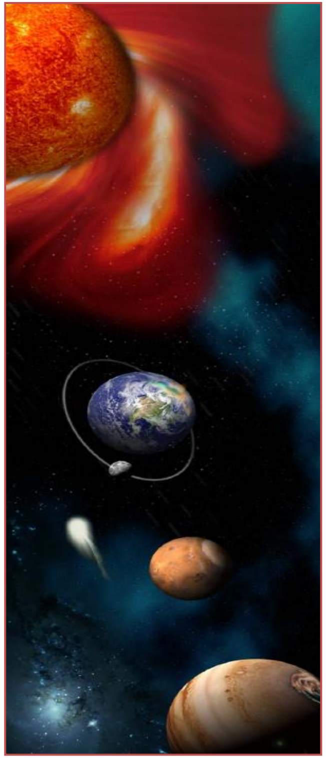
The region produced two of the Halloween events that are of historical importance. The first eruption on October 28, 2003 was seen bright in EUV wavelengths and had the soft X-ray flare size of X17.



The CME was a symmetric halo as seen by the Large Angle and Spectrometric Coronagraph (LASCO) on board SOHO. The October 28 and 29, 2003, eruptions were responsible for intense SEP events that had ground level enhancements (GLEs) numbered GLE 65 and GLE 66, respectively. The CMEs had speeds exceeding 2000 km s − 1 and produced super magnetic storms (Dst < − 200 nT) when they arrived at Earth. The Halloween solar eruptions thus turned out to be extreme events both in terms of their origin at the Sun and their consequences in the heliosphere.



Which sectors were impacted?



- ***Electric Power***
- ***Aviation***
- ***GPS Applications***
- ***Satellite Operations***
- ***Deep Space Missions***
- ***Manned Space Flight***

All

The Haloween Event (Oct. 28 and 29 2003)

- **The ionospheric total electro**n content over the U.S. mainland increased tenfold during the period of October 30– 31, 2003.
- **In Malmoe**, a southern of Sweden, about 50,000 people experienced a blackout (9h) when the transformer oil heated up by 10 ° C.
- **About 59%** of the reporting spacecraft and about 18% of the onboard instrument groups were affected by these events.
- In order to protect **Earth-orbiting spacecraft** from particle radiation, they were put into **safe mode** (Webb and Allen, 2004).
- **The high-energy particles** from the CMEs penetrated Earth's atmosphere, causing significant depletion of stratospheric ozone.

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

The Haloween Event (Oct. 28 and 29 2003)

- **Significant enhancement of the density** in the magnetosphere also coincided with the arrival of the CMEs at Earth.
- **In addition to the Earth's space environment**, the impact of the CMEs was felt throughout the heliosphere, all the way to the termination shock.
- **The detection of the impact** was possible because there were space missions located near Mars (Mars Odyssey), Jupiter (Ulysses), and Saturn (Cassini) as well as at the outer edge of the solar system (Voyager 1 and 2).
- **The MARIE instrument** on board the Mars Odyssey mission was completely damaged by the energetic particles from these CMEs.

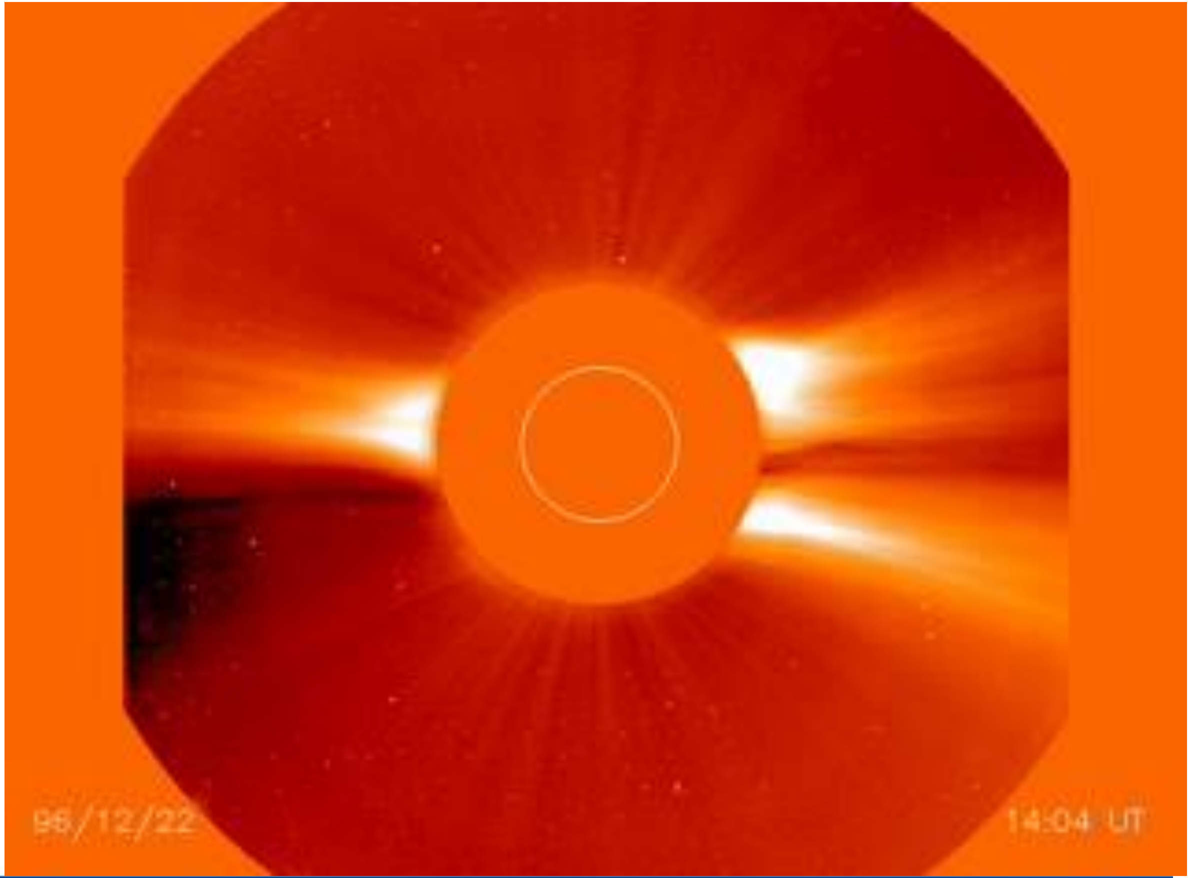
Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

CMEs

For sure the main driver for disturbances is the CME!

When the CME is ejected from the Sun it release a Shock front that can accelerate particles in space. These particles can reach velocities near the light velocity.

- CME takes 2 to 3 days to impact.
- SEP take only 30 minutes (they travel near the light velocity



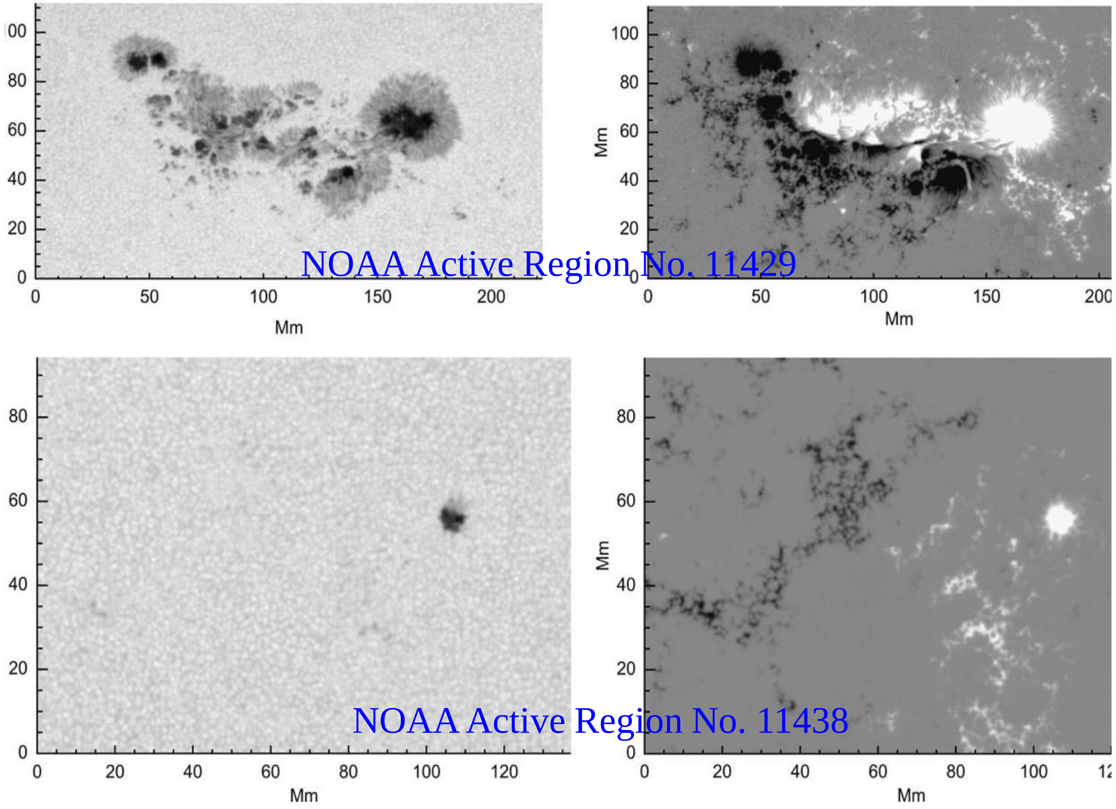
Sunspot and Magnetic field

CME and Flares originates over sunspots.
Important parameters measured are:

- Sunspot area
- Magnetic field intensity and complexity

Top: The very complex, very large group of sunspots designated that produced many large flares

Bottom: A very small, very simple group of sunspots, which was almost completely flare-quiet.



NOAA Active Region No. 11429

NOAA Active Region No. 11438

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

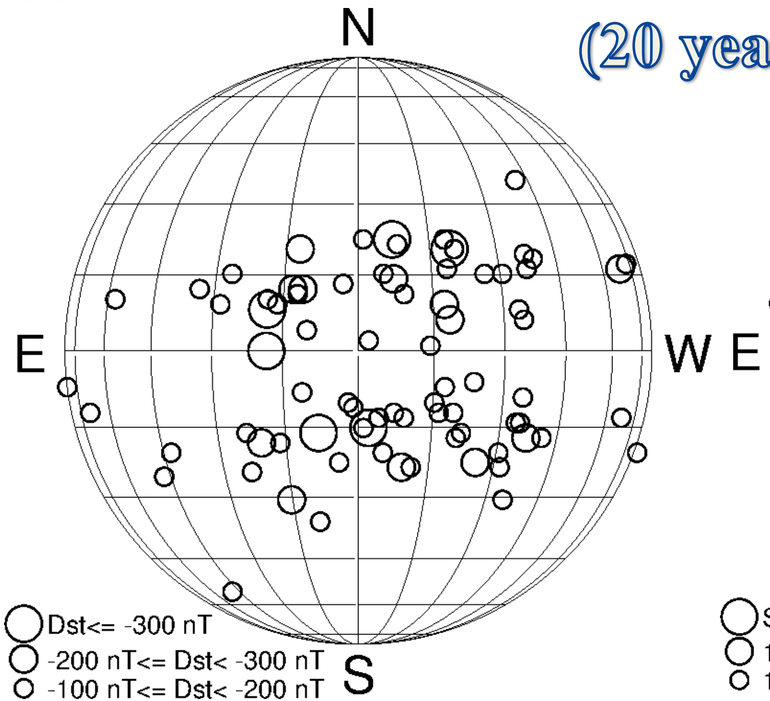
Types of CME's

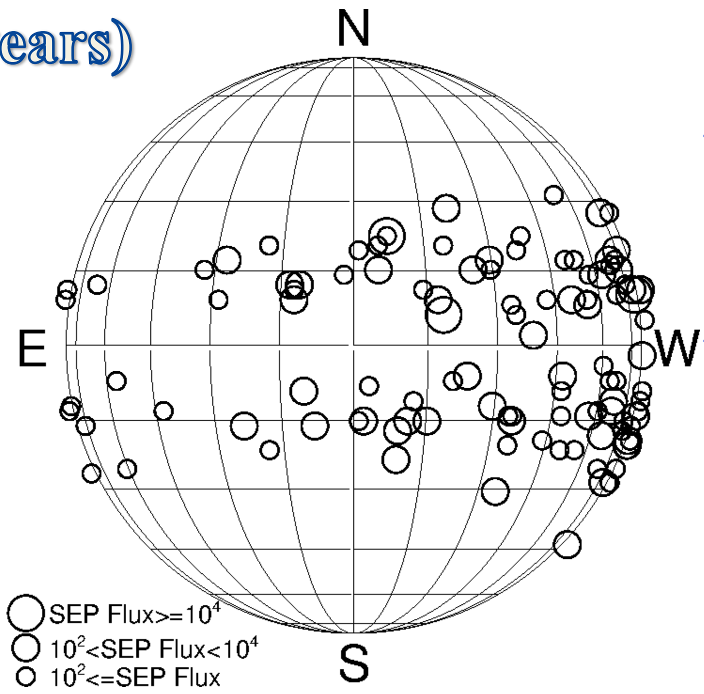
- **m2 - metric type II radio bursts (m2**) due to shocks in the corona at heliocentric distances < 2.5 Rs
- **MC - magnetic clouds (MC**), which are the inter planetary CMEs (ICMEs) with flux rope structure;
- **EJ** - ICMEs lacking flux rope structure and hence named as **ejecta (EJ)**;
- **S - interplanetary shocks (S**) detected in the solar wind;
- **GM - geomagnetic storms (GM)** caused by CME magnetic field or shock sheath;
- **Halo - halo CMEs (Halo)** that appear to surround the occulting disk of the coronagraph and propagating Earthward or anti-Earthward;
- **DH - decameter-hectometric (DH) type II bursts** indicating electron acceleration by CME-driven shocks in the interplanetary medium;
- **SEP - SEP events caused by CME**-driven shocks;
- **GLE - ground level enhancement (GLE**)

CME's -> intense geomagnetic storms

Dst < -100 nT **1996-2016 (20 years)** **SEP > 10 pfu**

CMEs need to arrive at Earth
CMEs must contain Bz South
Similar to MC and Halo CME sources

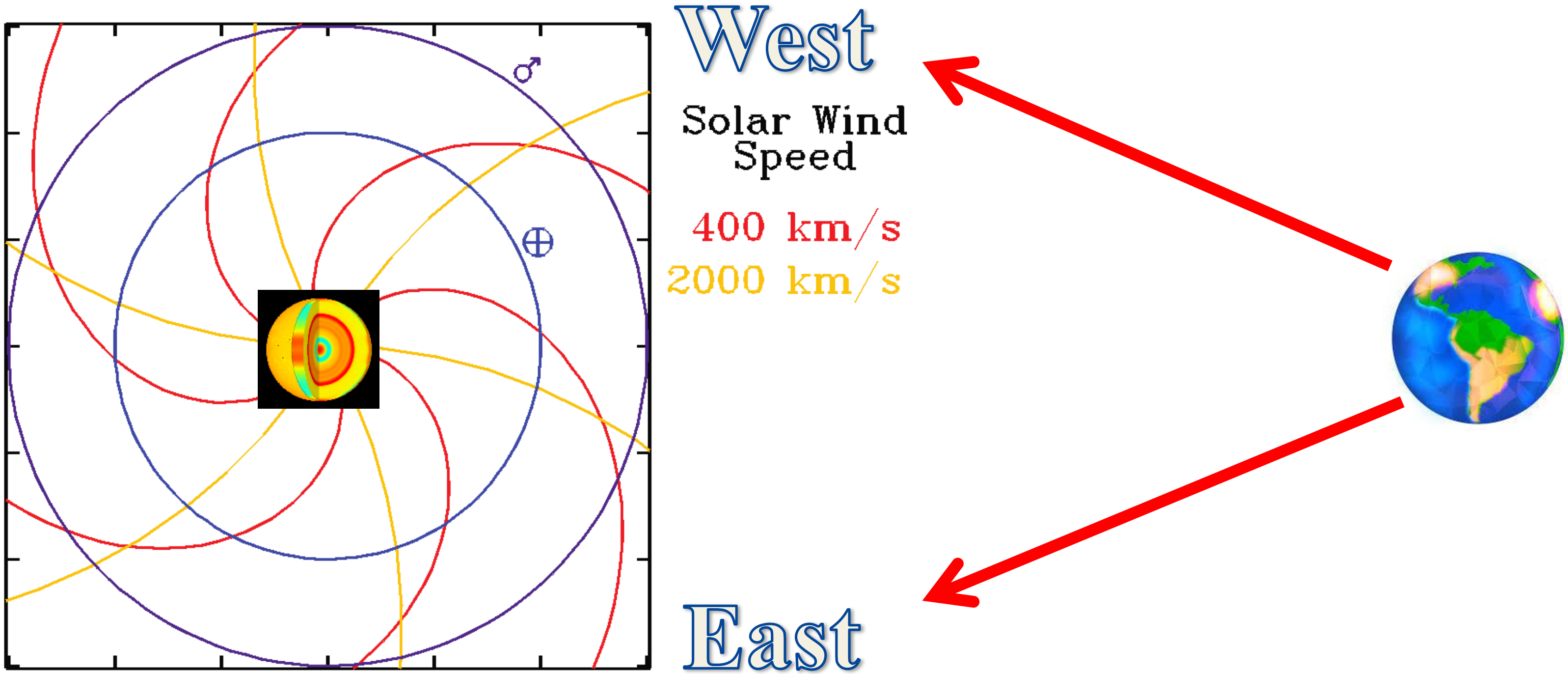




CMEs need to drive shocks
Source region needs to be magnetically connected to Earth

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

Parker Spiral (no straight line)

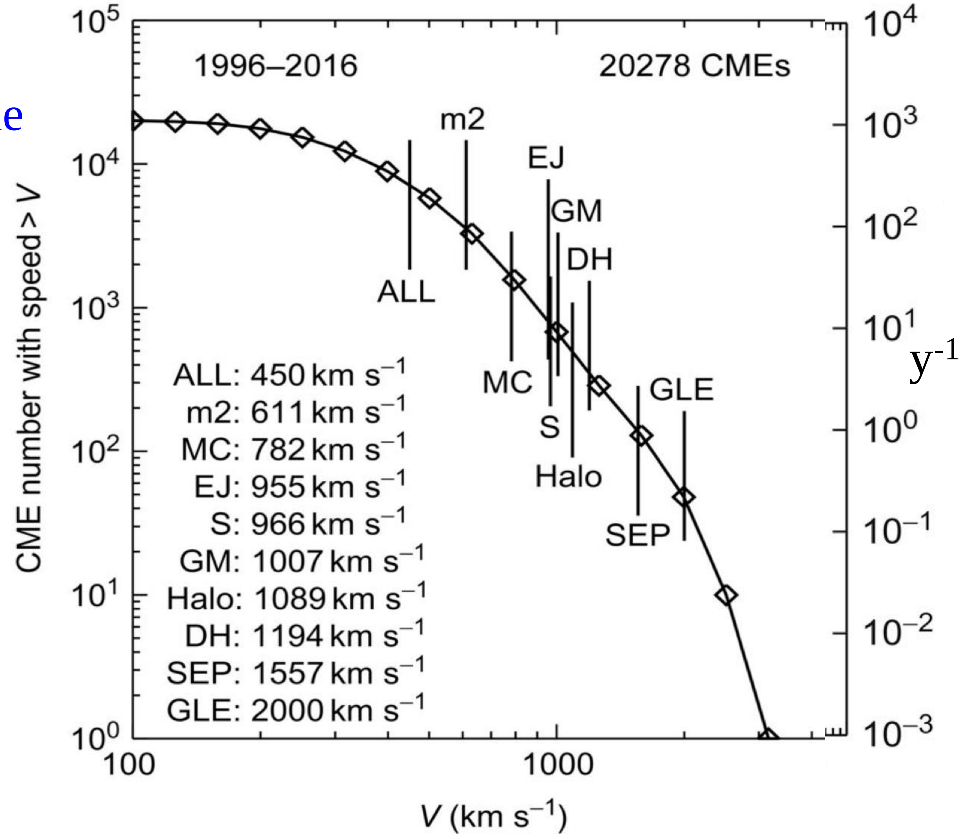


Parker Spiral for different plasma velocity

Distribution of CME vs speed

Cumulative distribution of CME speeds measured in the FOV of SOHO's Large Angle and Spectrometric Coronagraph (LASCO).

The average speed of every one of these populations is significantly greater than the average speed of the general population (450 km s^{-1}).
It must be noted that MC, EJ, GM, and Halo are related to the internal structure of CMEs in the solar wind, while the remaining are all related to the shock-driving capability of CMEs.



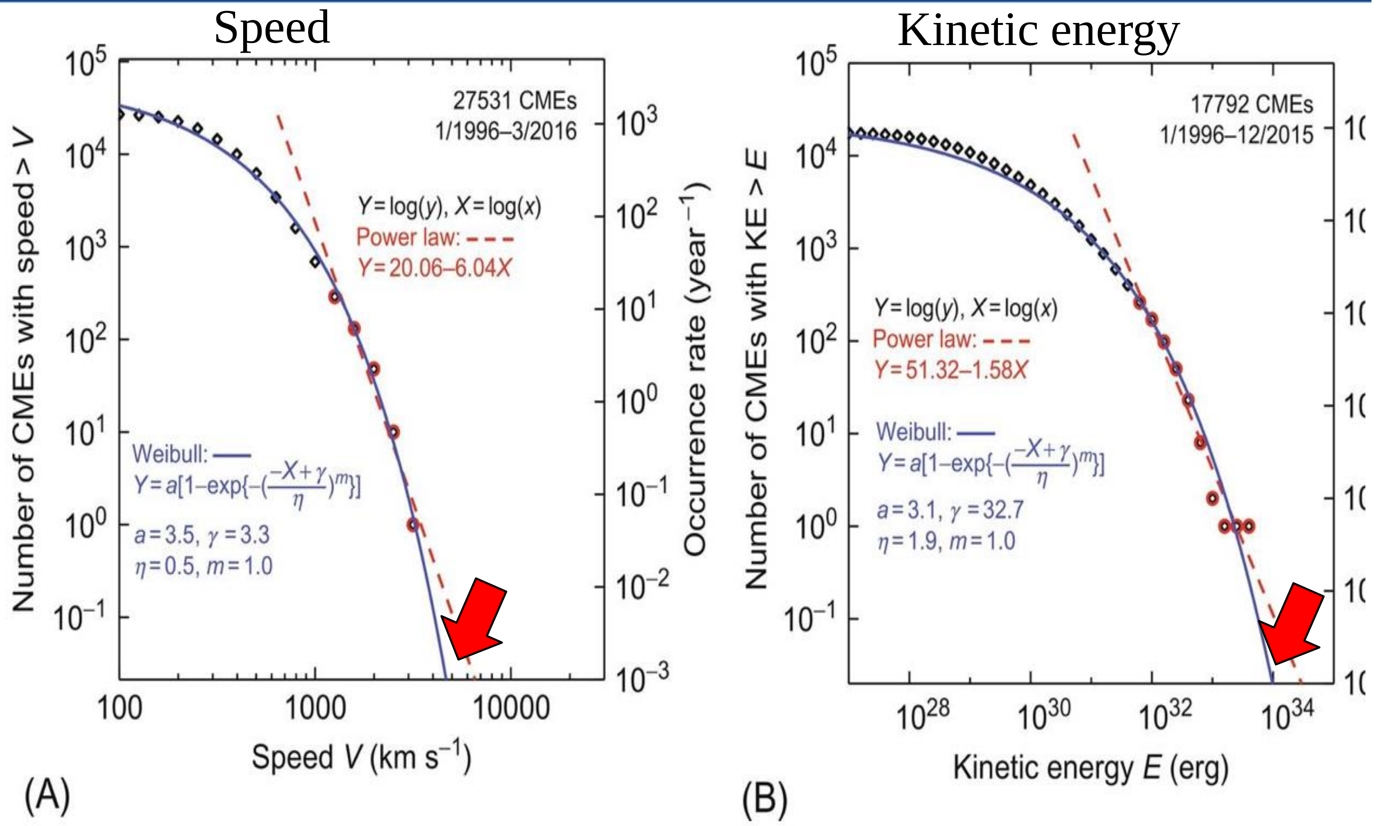
Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

What is the maximum speed and Energy?

Weibull distribution:

CME occurs once in 100 years with a speed of 3800 km s^{-1} and once in 1000 years with a speed of ~ 4700 km s^{-1}.

CME occurs in100-year and 1000-year kinetic energies as 4.4×10^{33} and 9.8×10^{33} erg, respectively.

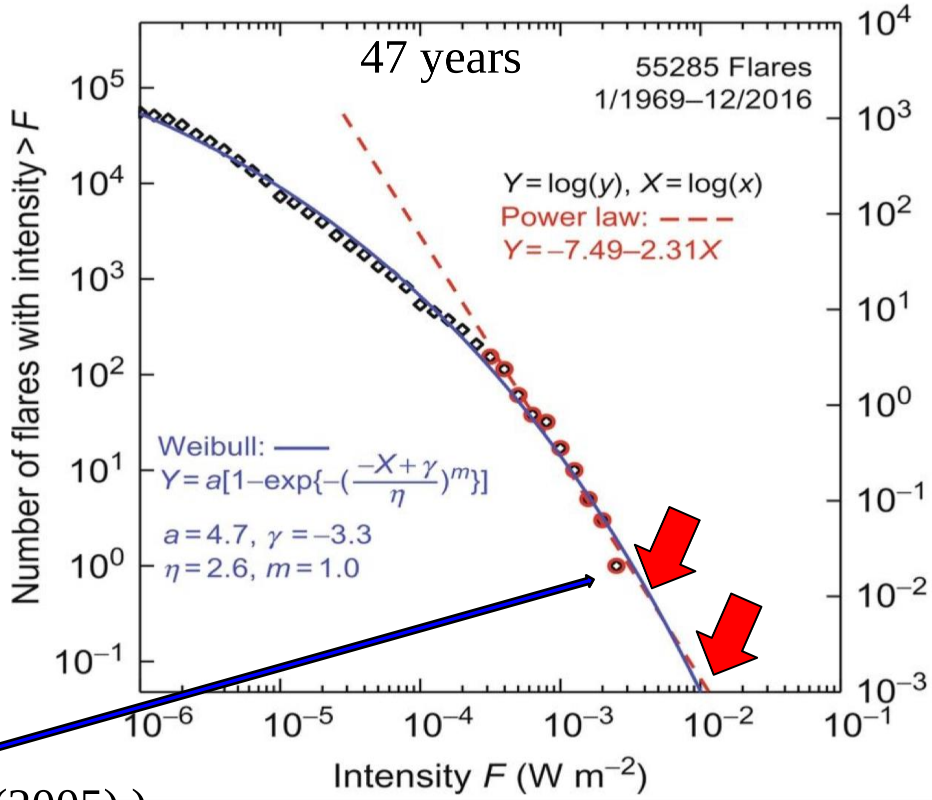


Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

What is the maximum flare intensity?

Weibull distribution:
X flare occurs once in 100 years and 1000 years with an intensity of X44 and X101, respectively.

Power law distribution:
X-flares occurs in100-year and 1000-year, with an intensity of X42 and X115, respectively.

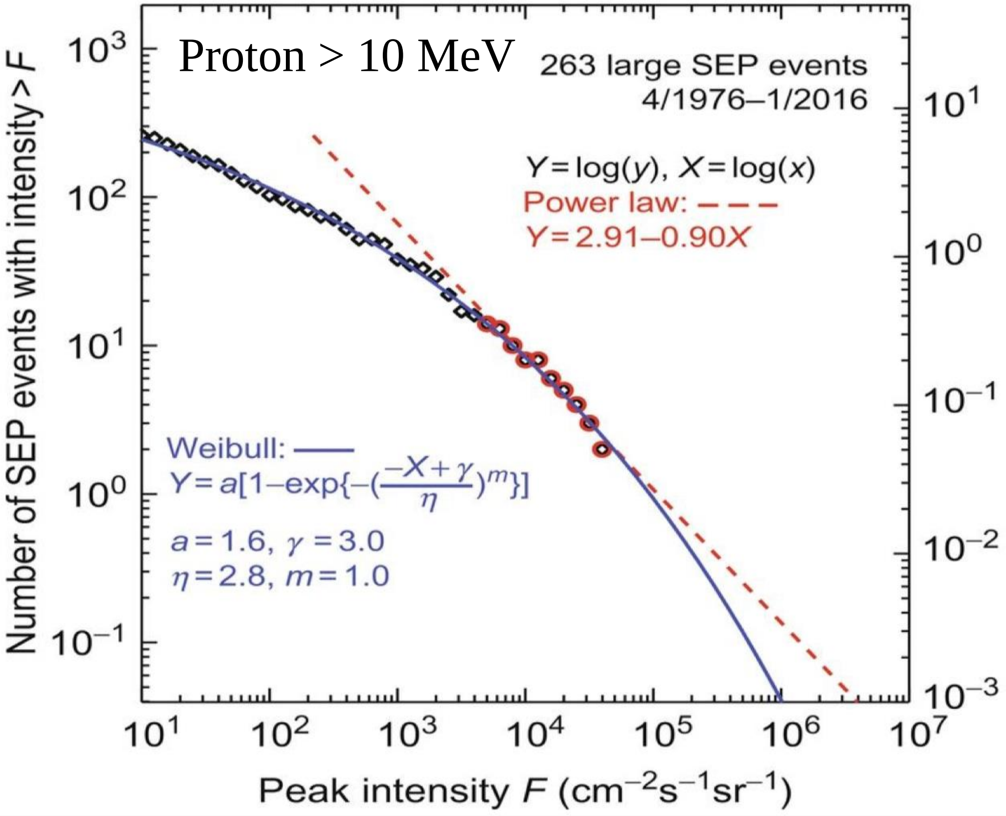


Nov 4, 2003 after Halloween
X17.4 => ~X40 (Brodrick et al. (2005))

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

What is the maximum SEP flux?

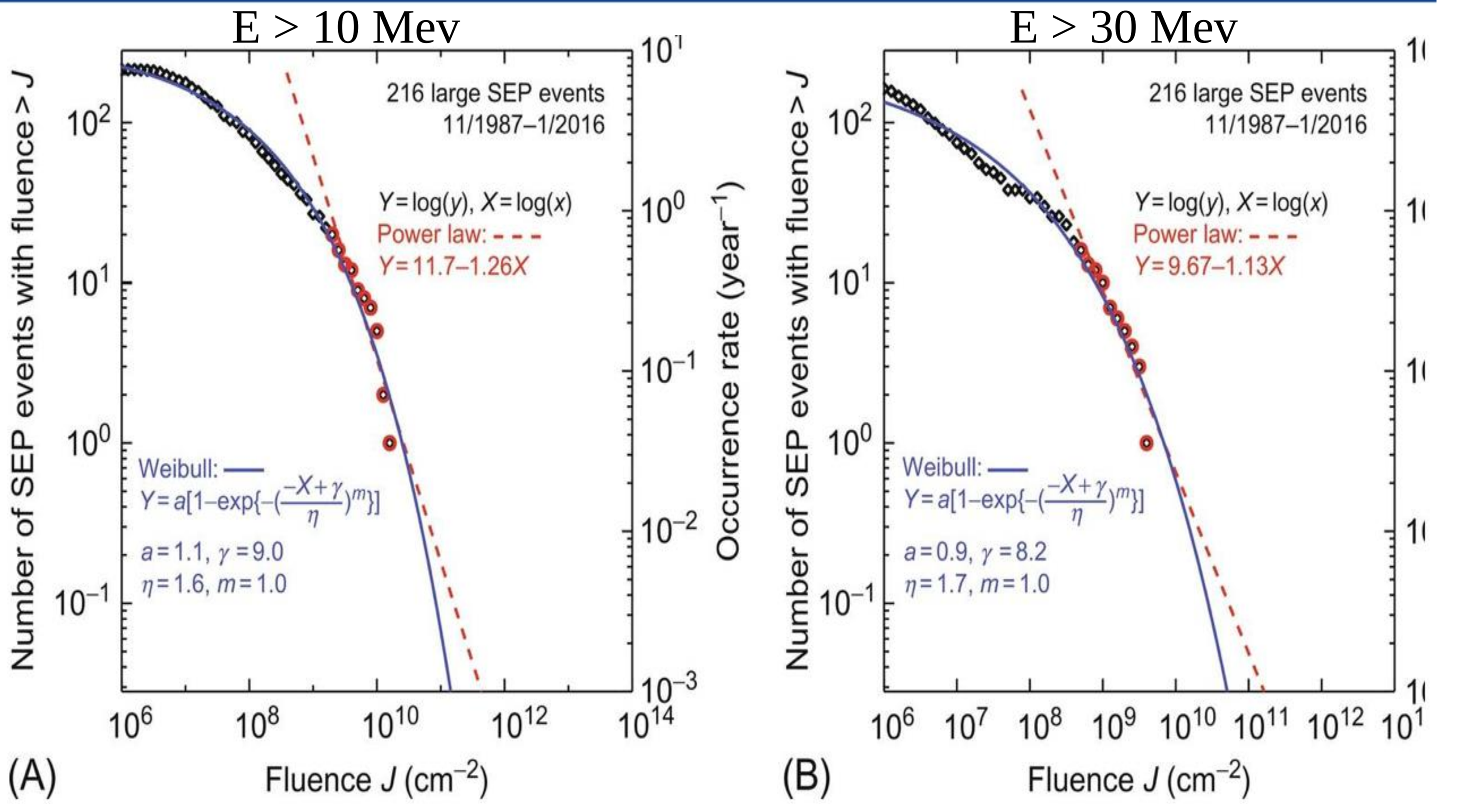
Weibull distribution:
SEP event occurs once in 100 years and 1000 years with an intensity of 2.04×10^5 and 1.02×10^6 pfu, respectively.



Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

What is the maximum fluences?

Weibull distribution: SEP fluence of protons >10 MeV occurs once in 100 years and 1000 years with an intensity of 5.11×10^{10} and 1.4×10^{11} pfu, respectively.



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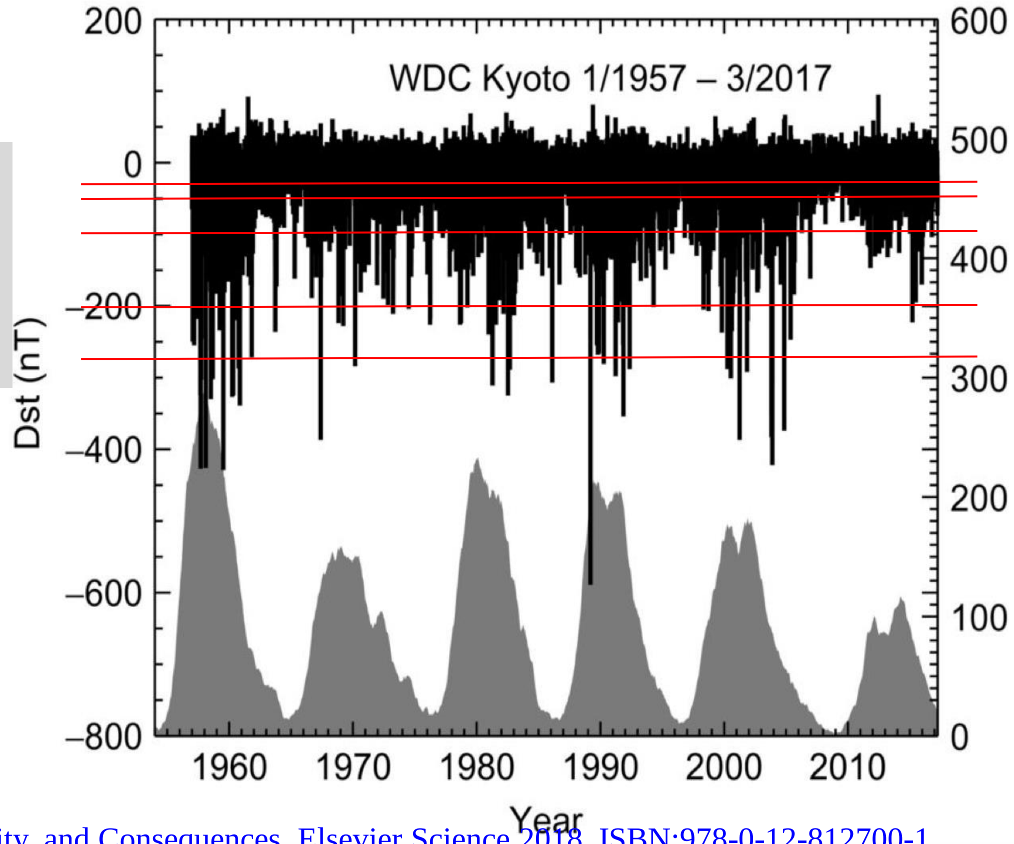
Geomagnetic variation by Dst

The **strength of the CME magnetic field component in opposition that of Earth's horizontal magnetic field Bz** is critically important in causing intense storms along with the speed (**V**) with which the CME magnetic field impinges on the magnetosphere.
Wu and Lepping, 2002; Gopalswamy et al., 2008.

The connection between solar eruption and the geomagnetic storm has an average delay of ~1 day.

WeaStor
ModSto
StrStor
SevSto
GreSto

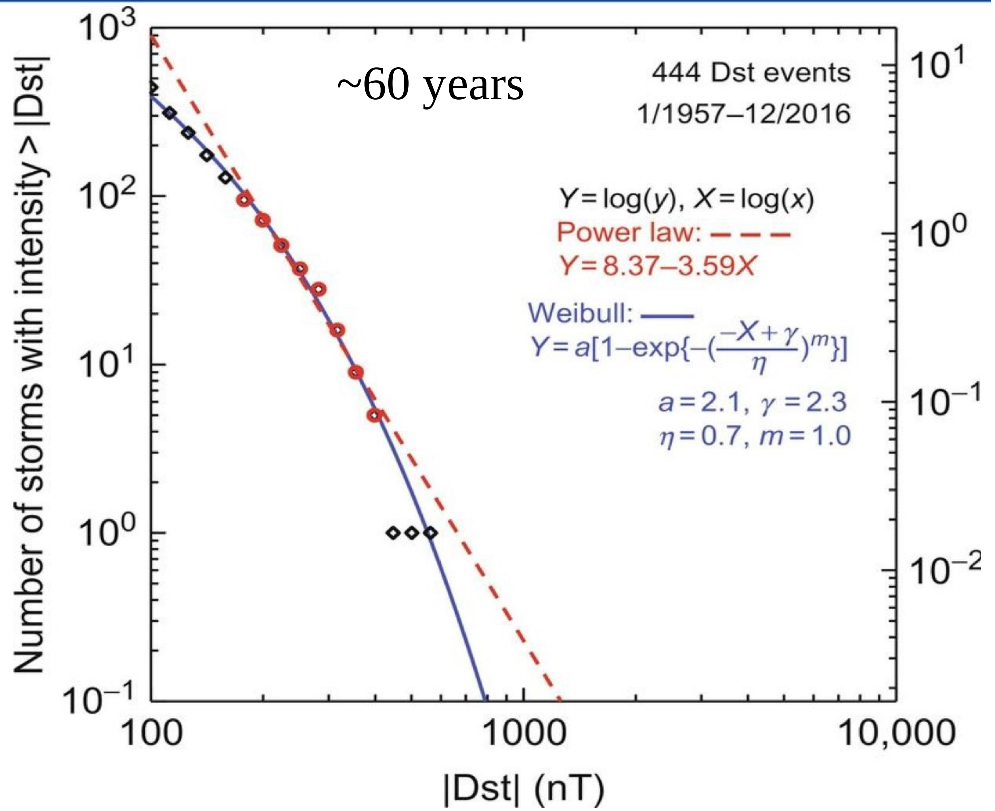


Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

What is the maximum Dst?

Weibull distribution:
Dst occurs once in 100 years and 1000 years with an intensity of -603 nT and -845, respectively.

Power law distribution:
X-flares occurs in100-year and 1000-year, with an intensity of X42 and X115, respectively.



Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

Extreme specs

	100-Year		1000-Year	
	Weibull	Power Law	Weibull	Power Law
AR Area (msh)	5780	7090	8200	13,600
CME Speed (km s^{-1})	3800	4484	4670	6564
CME KE (10^{33} erg)	4.40	6.85	9.76	29.5
Flare Size (X1.0 = 10^{-4} W m^{-2})	X43.9	X42.4	X101	X115
Bolometric Flare Energy (10^{32} erg)	4.39	4.24	10.1	11.5
SEP Intensity (10^5 pfu)	2.04	3.03	10.2	39.6
> 10 MeV SEP Fluence (10^{10} cm^{-2})	5.11	7.07	14.3	43.7
> 30 MeV SEP Fluence (10^{10} cm^{-2})	1.58	2.12	5.09	16.30
Dst (nT)	− 603	− 774	− 845	− 1470

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

A long time series of observation

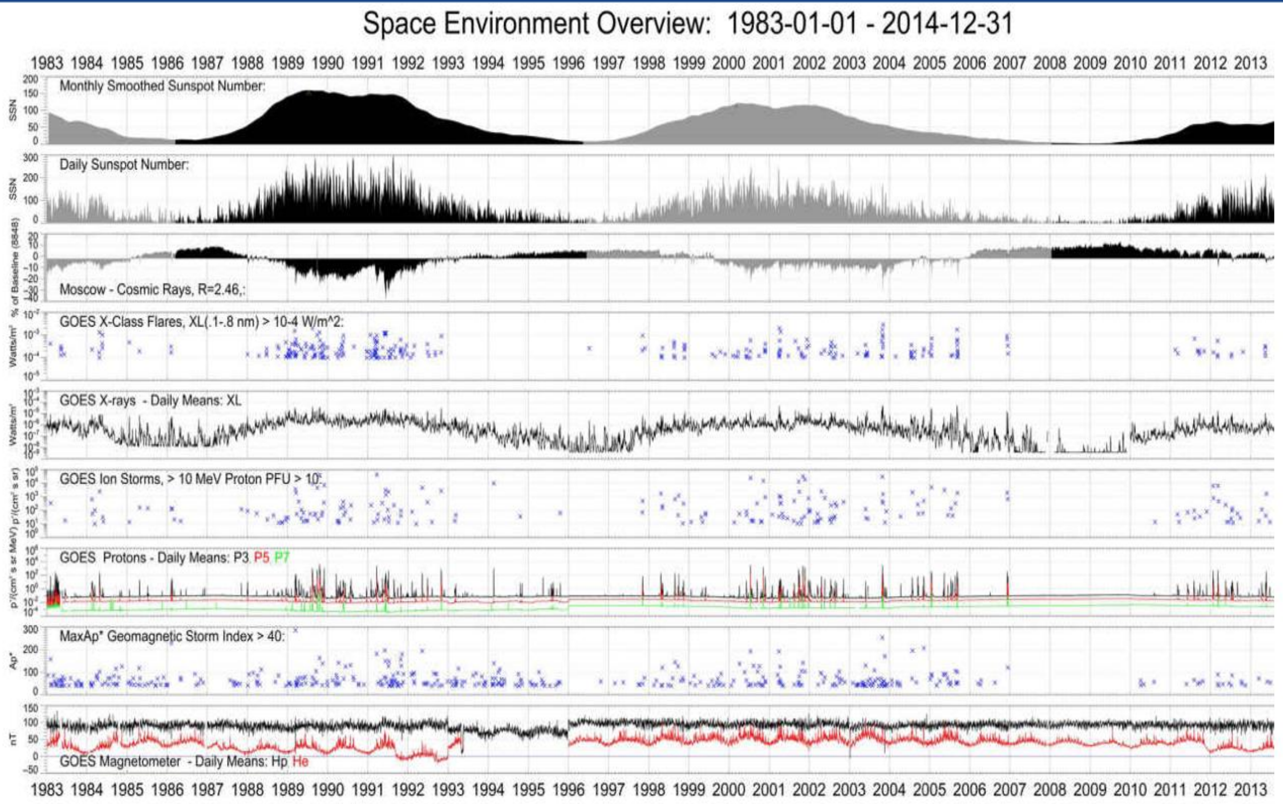
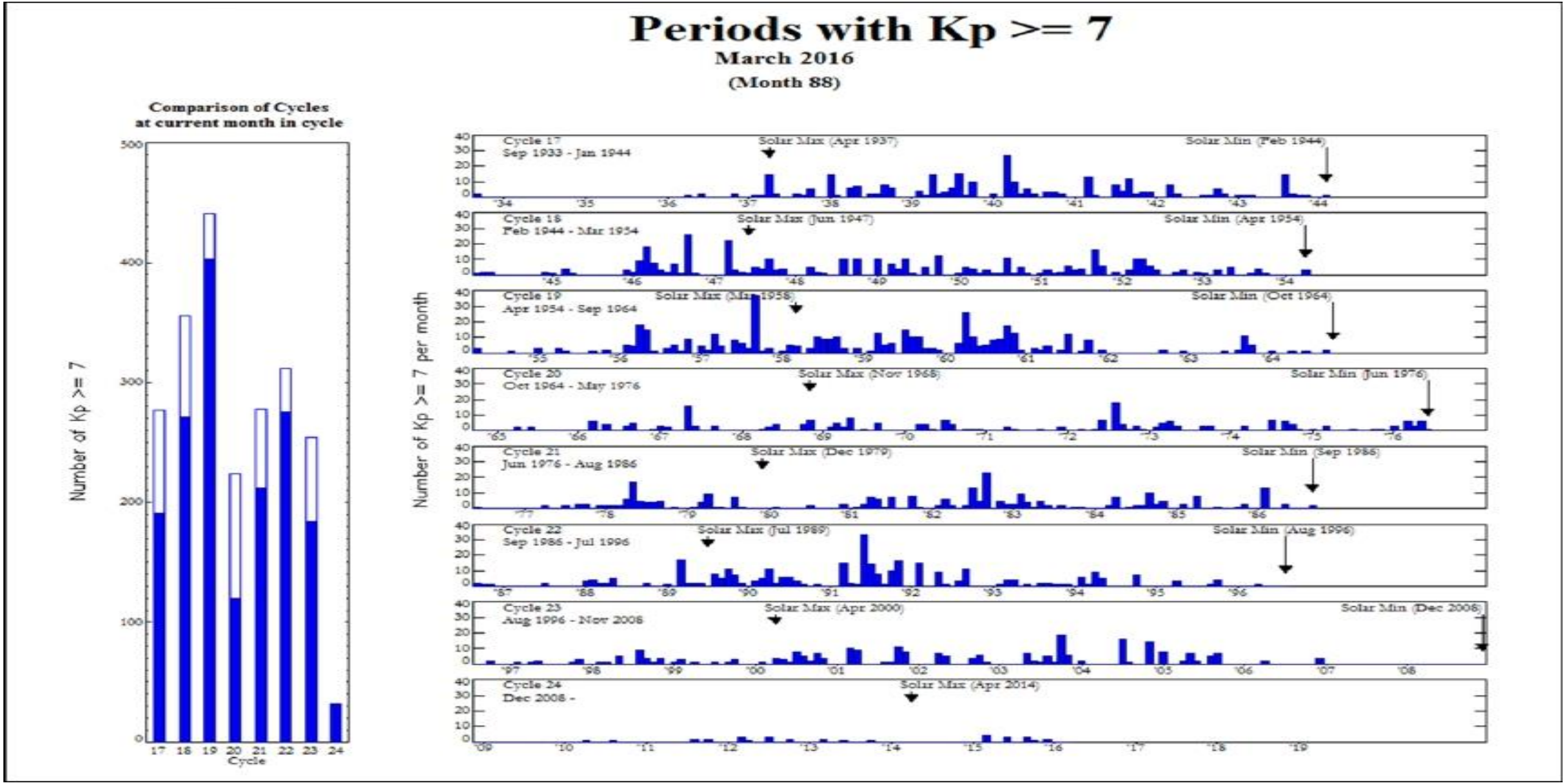


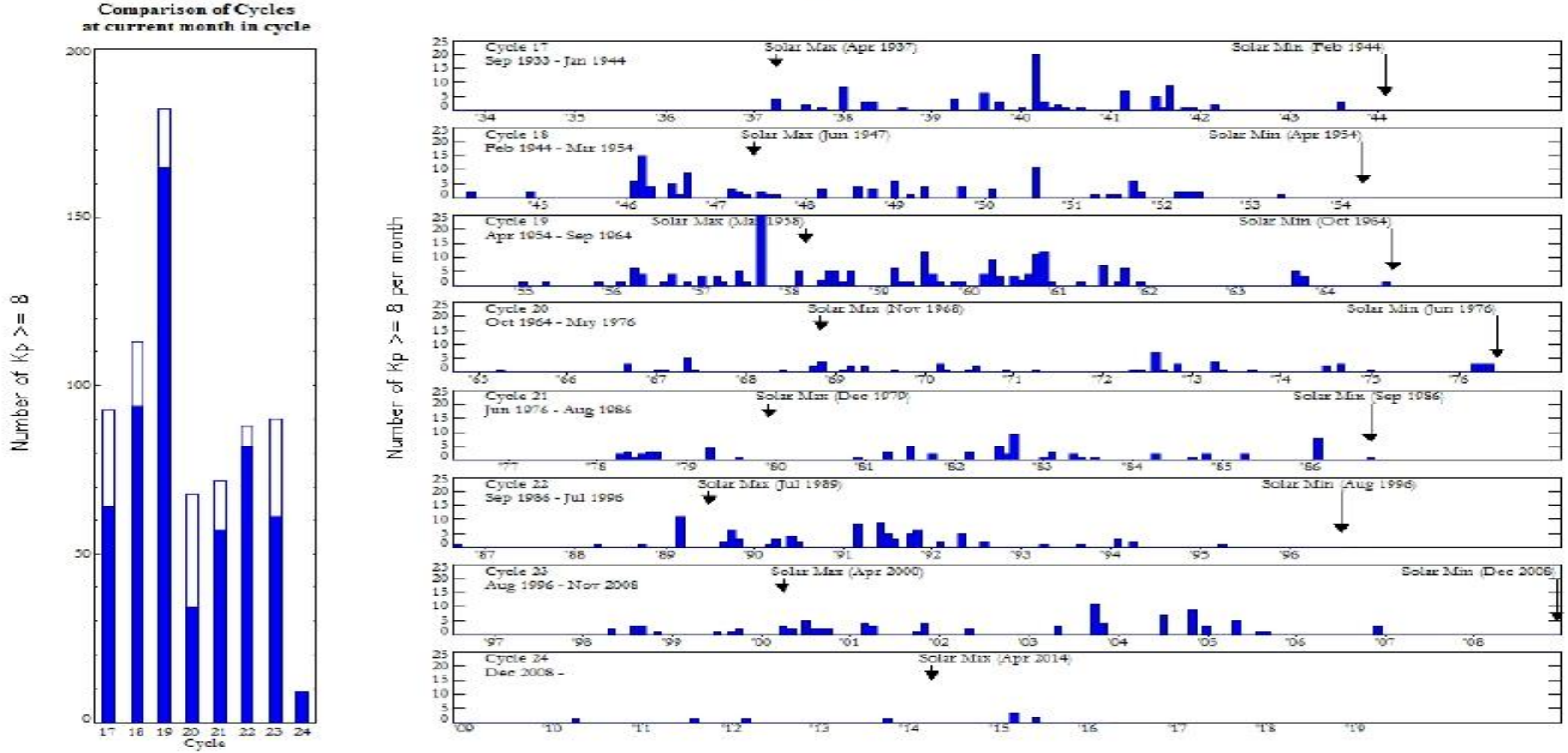
FIG. 1 Overview of the space environment for 1983–2014.

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

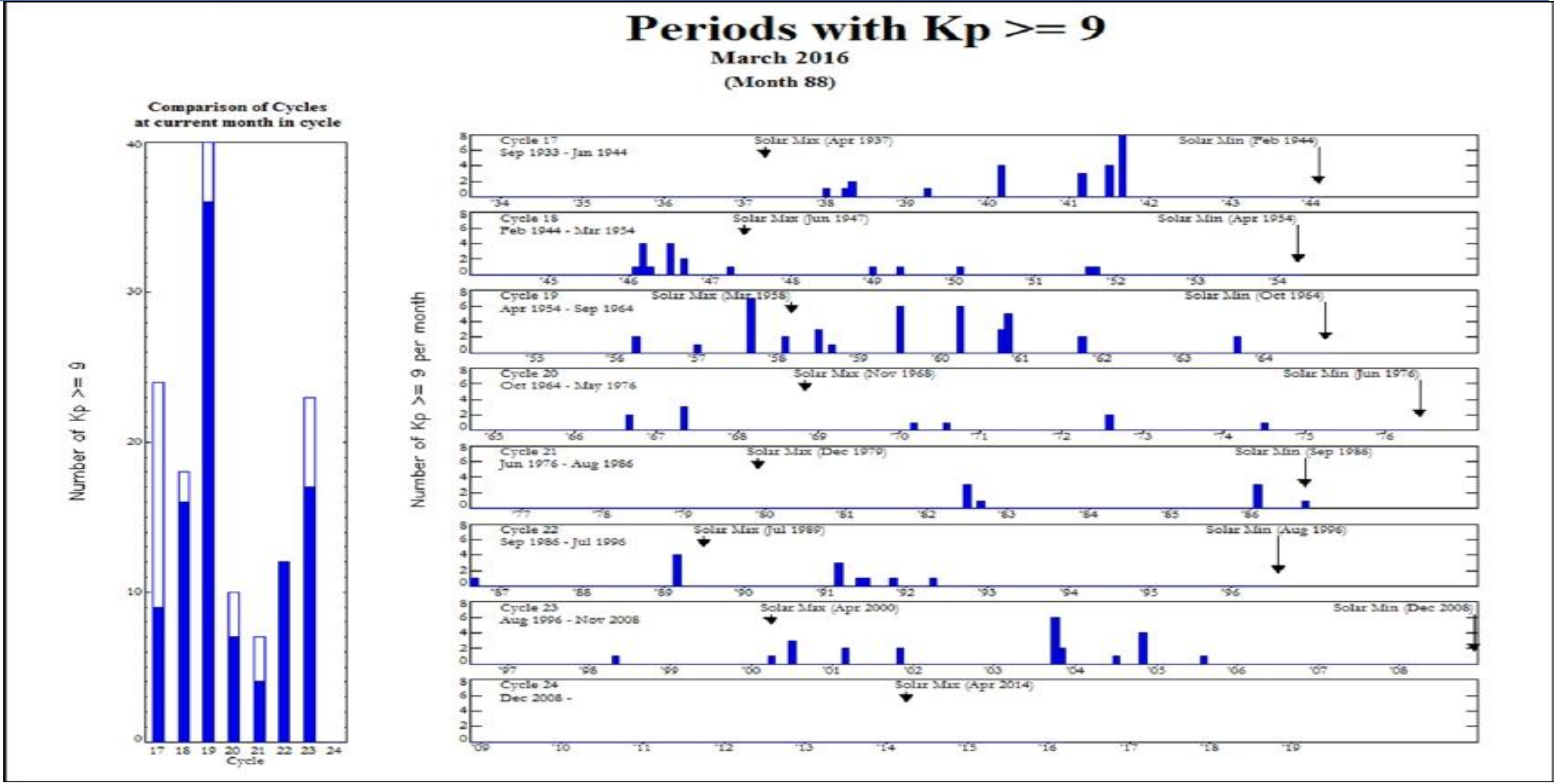


Source: Bob Rutledge (NOAA Space Weather Prediction Center). In: Boulder, Colorado, April 26th, 2016

Periods with Kp >= 8



Source: Bob Rutledge (NOAA Space Weather Prediction Center). In: Boulder, Colorado, April 26th, 2016



Source: Bob Rutledge (NOAA Space Weather Prediction Center). In: Boulder, Colorado, April 26th, 2016

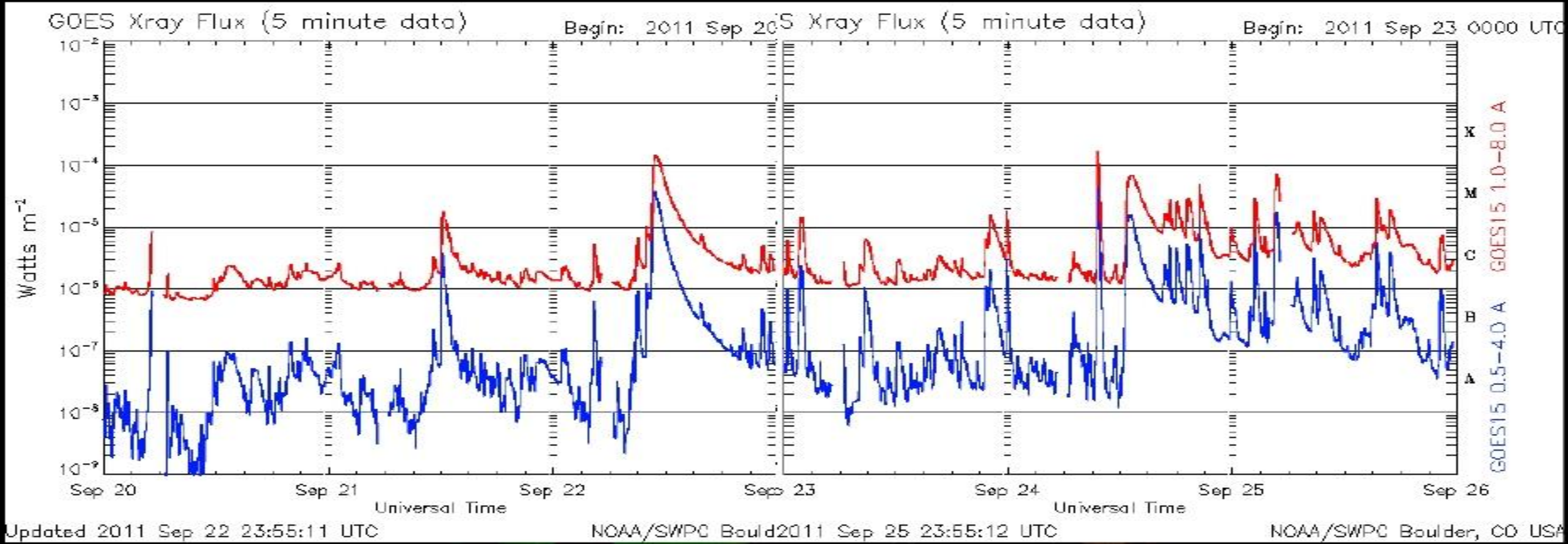
Extreme in radio background

Although ionizing radiation such as UV and X-rays define the amount of ionization that disturbs radio propagation (remember Scale R), the radio radiation is directly produced by solar flares with intensities more than 100,000 times the quiet flux.
And varies in milliseconds!

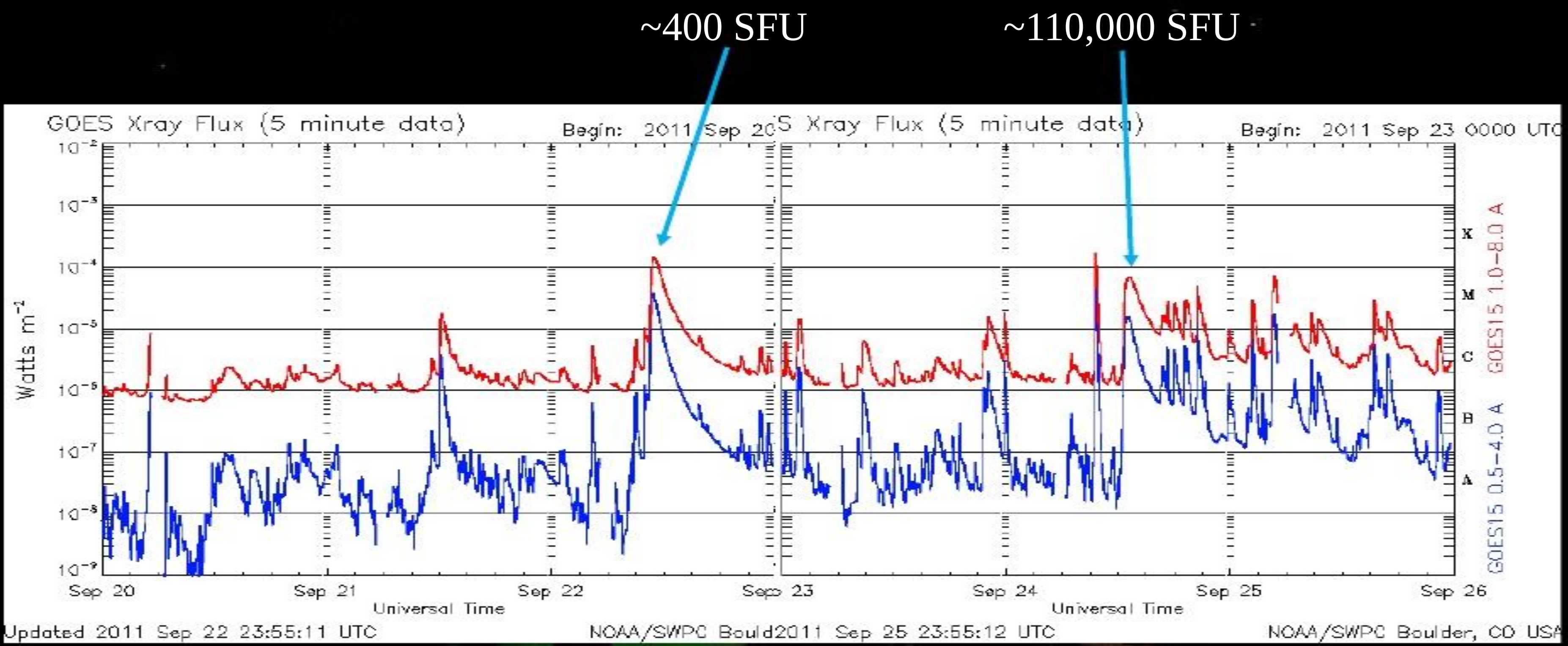
How are we quantifying the extremeness of the radio peak flux?

Why is this important?

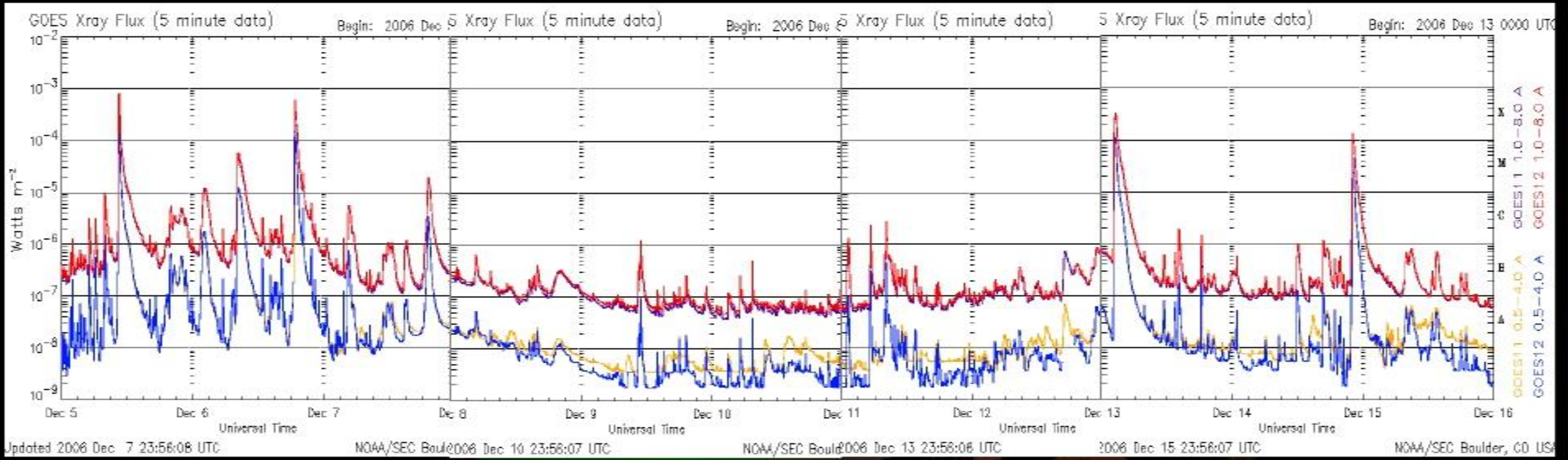
September 2011 – 1415MHz Radio Bursts



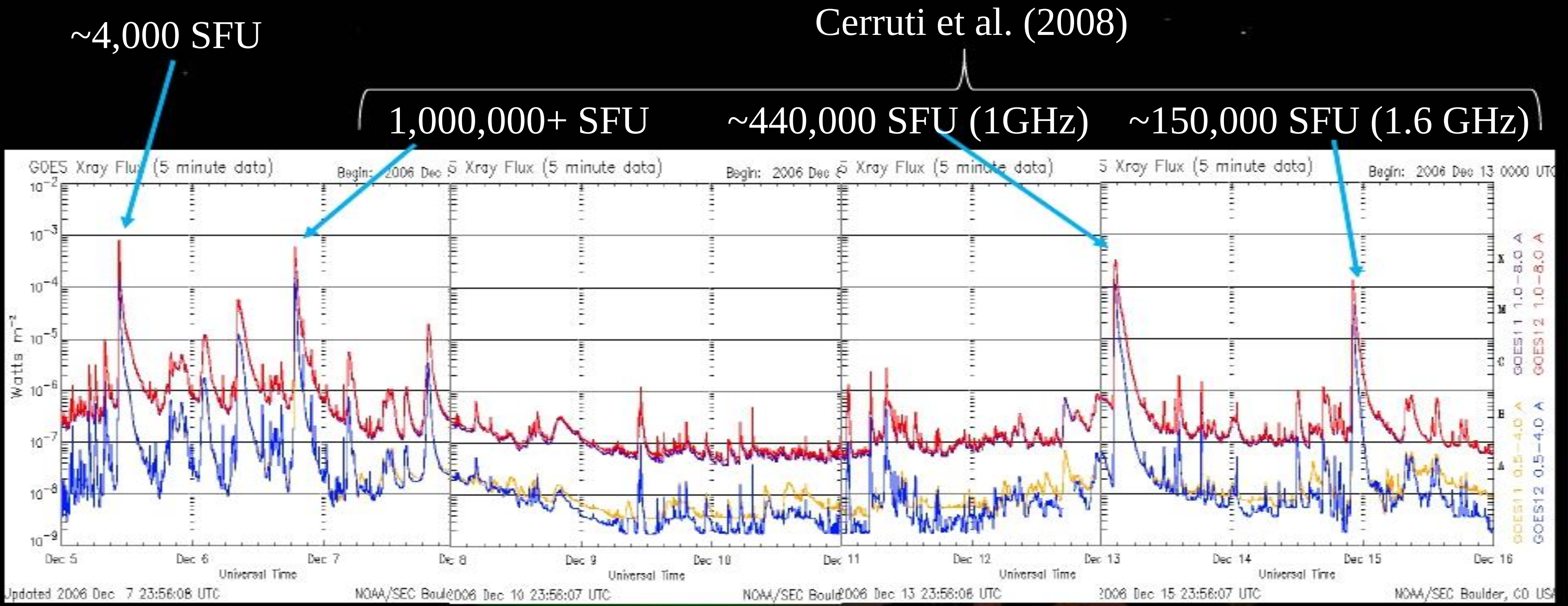
September 2011 – 1415MHz Radio Bursts



December 2006 – 1415MHz Radio Bursts



December 2006 – 1415MHz Radio Bursts



November 2015 Radio Burst

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Solar storm knocks out flight control systems in Sweden, grounds planes

Flights disappeared from radar screens

The Associated Press Posted: Nov 04, 2015 3:38 PM ET | Last Updated: Nov 04, 2015 3:40 PM ET

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Aviation officials say a solar storm knocked out the air traffic control systems in Sweden on Wednesday, prompting them to close the country's airspace for more than an hour.

The civil aviation authority said the solar storm created disturbances in the Earth's magnetic field, which affected radar installations in southern Sweden. No such pro[blems] were reported in neighbouring countries.

Parked aircraft are seen at at Stockholm Arlanda Air[port in a] photo from March 2015. Swedish airspace was close[d for an] hour Wednesday after a solar storm knocked out air [traffic] control systems. (Johan Nilsson/Associated Press)

http://www.dn.se/nyheter/sverige/solstorm-bara-en-del-av-forklaringen-till-radarstopp/

What we could see was how it appeared **rows of unfamiliar echoes on the screens, these echoes were incorrect identification numbers and incorrect heights and they came and went all the time**, says AndersAndersson, Systems for monitoring infrastructure LFV. - The problems meant that our older stations were overloaded, while the newer ones are not affected in the same way. According to AndersAndersson, two things that indicate that solstormen is one of the causes of the accident: • **All the stations affected are located in the part of Sweden where the sun was above the horizon when the problems occurred. •All false echoes appeared over a nine degrees narrow sector on the radar in the direction that was facing the sun.**

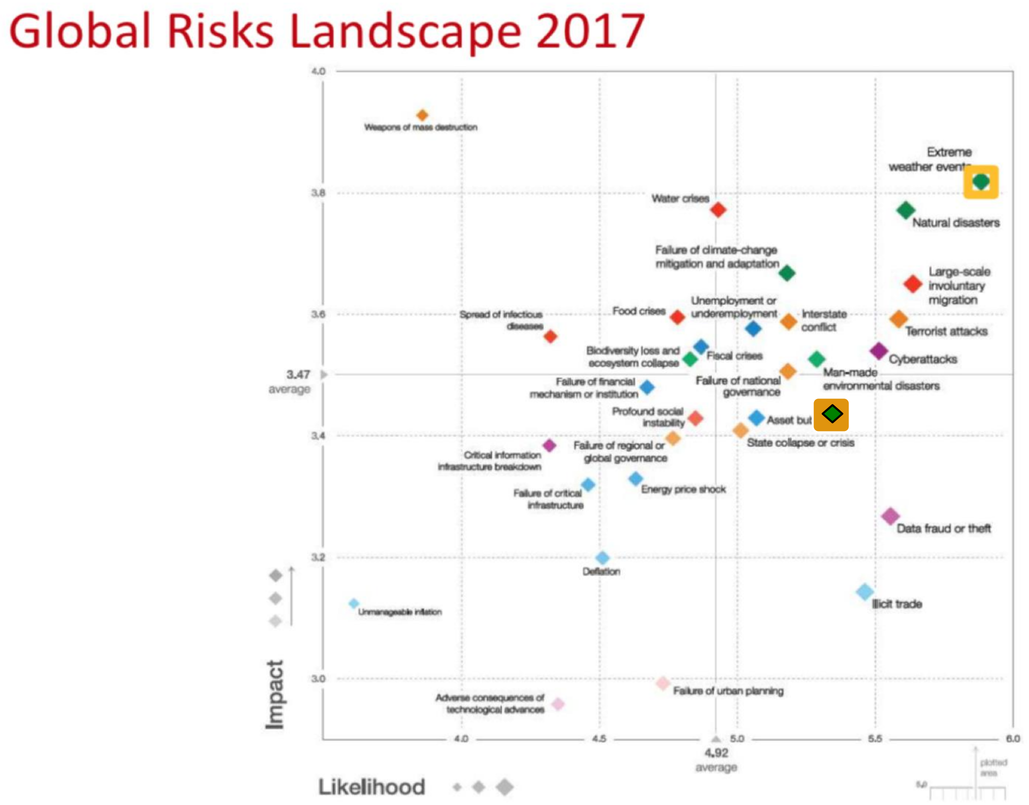
Source: Bob Rutledge (NOAA Space Weather Prediction Center). In: Boulder, Colorado, April 26th, 2016

The follow up

- In Malmoe (Sweden) 50.000 people experienced blackout (a transformer heated)
- 59% of spacecraft and 18% of onboard instruments were affected (US report)
- High energy particles penetrate Earth atmosphere and caused large depletion of the stratospheric Ozone.
- The ionospheric TEC was increased over U.S. by ten times during October 30-31.
- The event also impacted space missions near Mars (Odyssey), Jupiter (Voyager 1 and 2).
- The instrument MARIE on Mars Odyssey was damaged by the energetic particles

Two CME's produced shocks that accelerated particles up to GeV energy that reached Earth in 19 hours!

Recent report from Economic Forum Davos



Sunspot Specs

NOAA Region Number	Date (at 21:48 TAI)	Size (μH)[a]	Magnetic Class[a]	McIntosh Class (Modified Zurich)[a]	Flare Index[b] Before	Flare Index[b] After
11429	March 8, 2012	950	$\beta\gamma\delta$	Ekc	922.42	243.77
11430	March 8, 2012	180	β	Dao	134.7	13.1
11433	March 16, 2012	100	β	Dso	3.96	0.55
11438	March 25, 2012	20	α	Hsx	1.01	2.54

[a] As listed for 2400 UT in the NOAA Solar Region Summary.

[b] See Eq. (1). Before/after refers to the date in column 2.

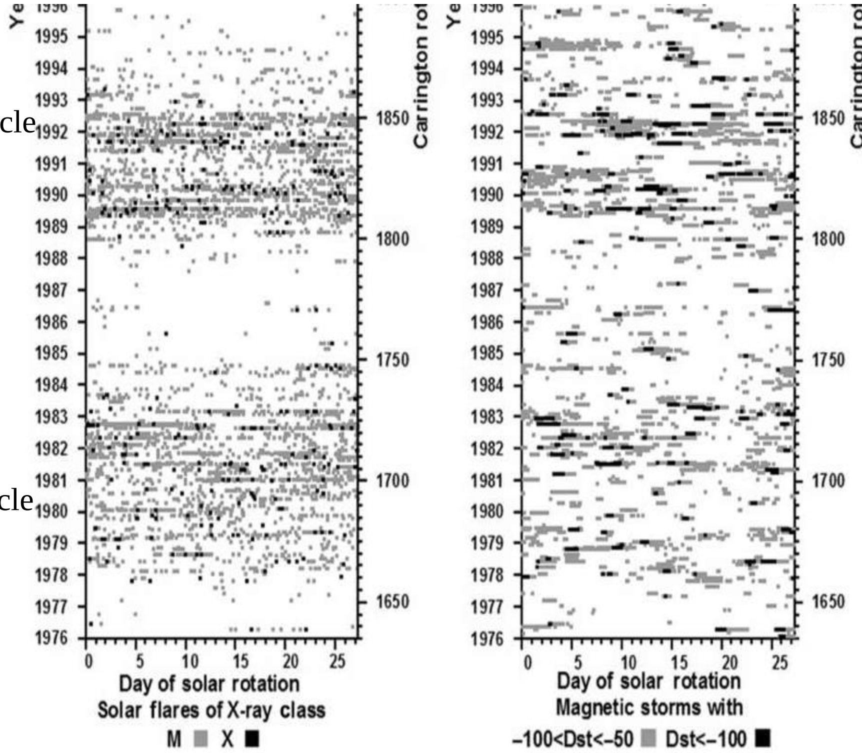
$$FI = \sum (\text{index}_C + 10 \times \text{index}_M + 100 \times \text{index}_X)$$

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

Flares and Magnetic Storms

Cycle 22

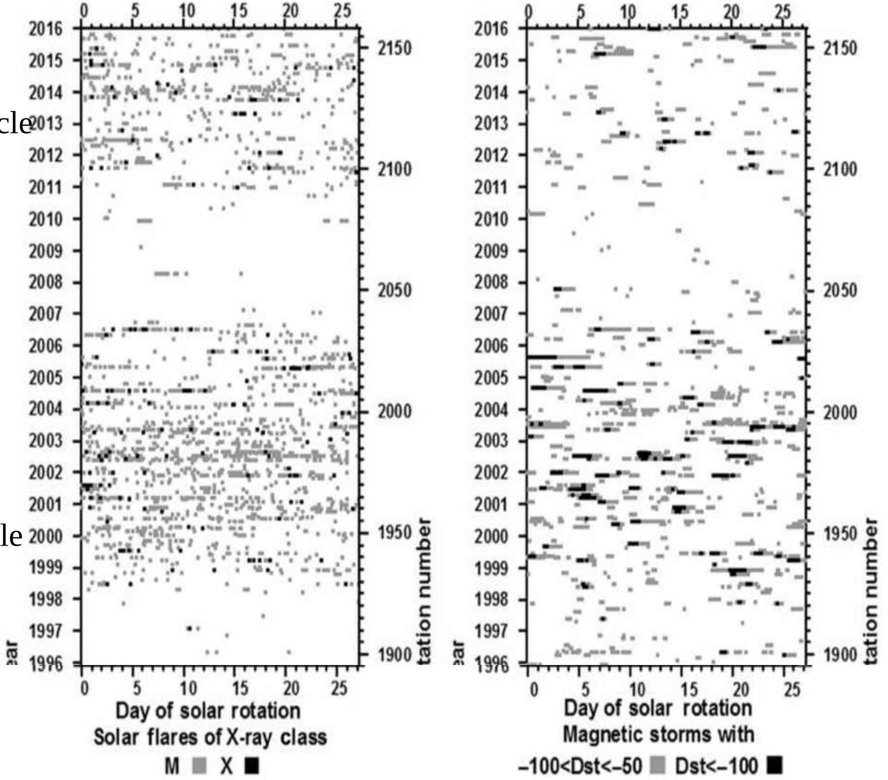
Cycle 21



Mod – Sev/Great

Cycle 24

Cycle 23



Mod – Sev/Great

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Associated Effects/Impacts

Date	Associated Effects/Impacts
March 24, 1940	Power circuit disturbances in North America. Earliest publicly reported impact on power grids (Davidson, 1940; McNish, 1940).
February 11, 1958	Blown AC power supply fuses for Finnish telecommunications cable system; Fire damage to telegraph equipment (Nevanlinna et al., 2001; Wik et al., 2009).
November 13, 1960	30 Swedish high-voltage power network line breakers tripped (Wik et al., 2009).
August 4, 1972	Communications cable system outage in mid-western United States (Boteler and Jansen van Beek, 1999).
July 13–14, 1982	Transformers and lines tripped in the Swedish high-voltage power system; Railway traffic light anomalies; Effects on telecommunications (Wik et al., 2009).
March 13–14, 1989	Hydro-Quebec blackout; New York transformer damage; Railway track anomalies (Boteler, 2001b; Bolduc, 2002; Eroshenko et al., 2010).
March 24, 1991	GIC > 100 A measured in Finland; 220 kV lines and a transformer tripped (Viljanen et al., 1999; Wik et al., 2009).
November 9, 1991	220 kV line tripping; Large pipe-to-soil voltages in an oil pipeline (Wik et al., 2009).
April 6, 2000	Largest GIC on Swedish transformer; False railway track occupations/blockages (Wik et al., 2009; Eroshenko et al., 2010).
November 6, 2001	Railway automatic system failure (Eroshenko et al., 2010).
October 29–30, 2003	Malmö blackout; Excessive transformer heating; Triggered emergency procedures at nuclear power plants in Canada and Northeastern United States; Reported damaged to high-voltage transformers in South Africa; Railway automatic system failure (Pulkkinen et al., 2005; Wik et al., 2009; Gaunt and Coetzee, 2007; Eroshenko et al., 2010).
November 20, 2003	Railway automatic system failure (Eroshenko et al., 2010).
November 8, 2004	Transformer GIC exceeding 100 A measured in southern Sweden (Wik et al., 2009).
May 14, 2005	Railway automatic system failure (Eroshenko et al., 2010).

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

Extreme cases observed

Largest Ap geomagnetic

Cycle 22

Halloween Storms

X28 in Nov 4

Cycle 23

Cycle 24

Extreme Event Cases 01 to Case 12	G-Scale G1-5	R-Scale R1-5	S-scale S1-5	*Kp*	X-ray	SEP pfu	Ap	Dst nT
Mar. 10–15, 1989	G5	R3	S3	9_o	X4.5	1860	285	−589
Sep. 26–Oct. 1, 1989	G0	~ R4	S3	4_o	X9.8	2960	52	−151
Oct. 18–31, 1989	G4	R4	S4	8_+	X13.0	42,200	162	−268
Mar. 22–28, 1991	G5	~ R4	S4	9_o	X9.4	43,500	181	−298
Jun. 1–20, 1991	G5	R4	S3	9_o	X12[a]	3000	196	−223
Jul. 14–16, 2000	G5	R3	S4	9_o	X5.7	24,000	192	−301
Nov. 4–8, 2001	G5	R3	S4	9_o	X1.0	> 10,000	141	−292
26-Oct.—06-Nov. 2003	G5	R4	S4	9_o	X17.2[b]	29,500	252	−383
15-Jan.—24-Jan. 2005	G4	R3	S3	8_o	X7.1	5040	91	−97
06-Sep.—16-Sep. 2005	G4	R4	S3	8_-	X17.0	1880	101	−139
05-Dec.—17-Dec. 2006	G4	~ R3	S3	8_+	X9.0	1980	120	−159
08-Mar.—17-Mar. 2012	G4	R3	S3	8_o	X5.4	6530	90	−131

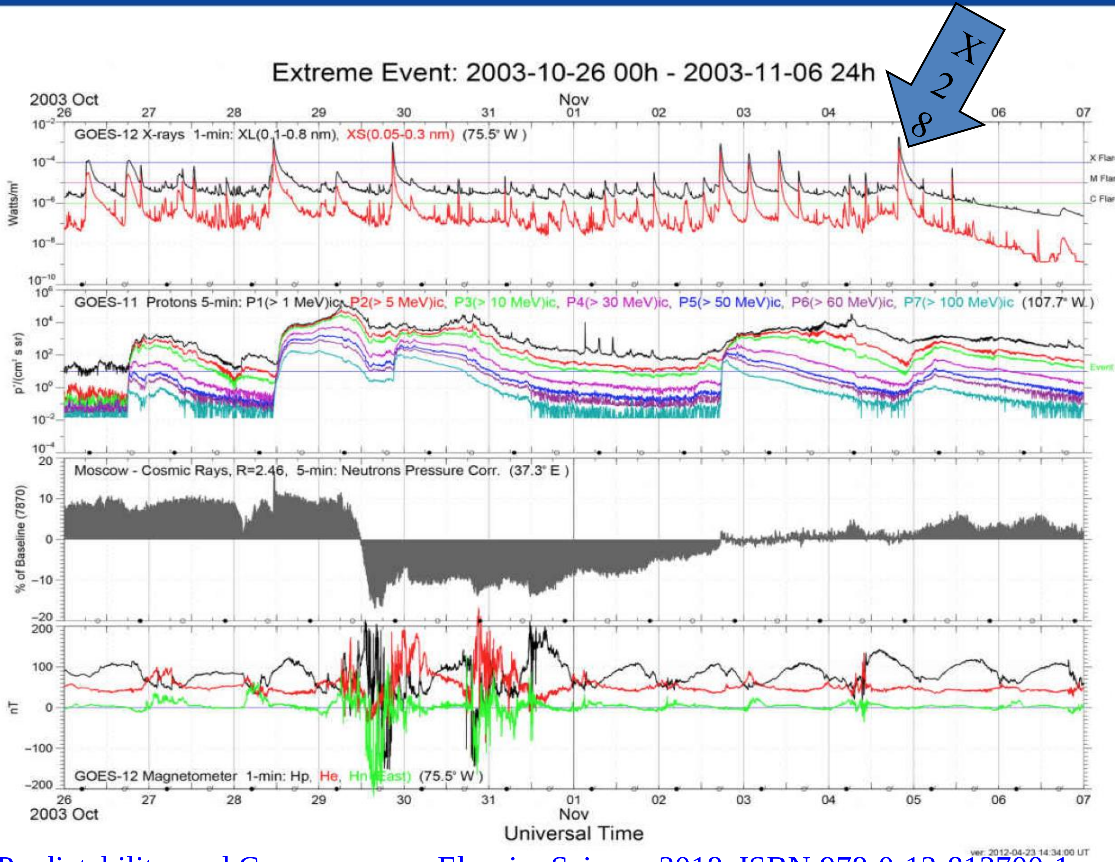
[a] Saturated. [b]X28 (estimated) flare on 04-Nov-2003 was the largest during the 26-Oct.–06-Nov. 2003 interval although the space weather impacts from this flare were limited (Balch et al., 2004).

Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

Halloween Event

Oct. 26– Nov. 6, 2003 Notable Features {G5/ R4/ S4}

- Severe compression/ reconfiguration of the van Allen radiation belts.
- Severe SPE on Oct. 20 was the third largest during the GOES lifetime.
- SPE impacts persisted for months in the composition of the middle atmosphere.
- First event with reported GPS interference due to SRB.



Source: Extreme Events in Geospace: Origins, Predictability, and Consequences. Elsevier Science 2018. ISBN:978-0-12-812700-1.

A very scary event: Superstorm

July 23, 2012
~01:00 UT

Thank you

Gracias

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