
Space Weather for Beginners



A quick-fact guide to the Sun's flares, solar wind and storms, and what they do to Earth, satellites, power grids and the sky.

Seven sections. Plain-language facts, tables and short rules.
Image: the Sun in extreme ultraviolet light, NASA/SDO.

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HOW TO USE THIS BOOK

- Read Sections 1 to 6 in order. They follow a storm from the Sun to Earth. Section 7 has the case files, the NOAA scales and a one-page cheat sheet.
- Each section opens with a boxed rule, then short bullets and tables. Orange boxes are key rules. Blue boxes are things to remember.
- Image credits: NASA, NOAA and other public-domain images are marked with their source.

SECTION 1

Meet the Sun and Space Weather

Space weather is the Sun's light, particles and magnetic fields reaching Earth. Most of the time it is quiet. When the Sun erupts, it can light up the sky, jam radios, confuse GPS and knock out power grids.

What the Sun sends us

- **Light.** The Sun gives off every kind of light: radio, infrared, visible, ultraviolet (UV), X-rays and gamma rays. Light reaches Earth in about **8 minutes**.
- **Particles.** The **solar wind** is a stream of charged particles (mostly hydrogen) blowing out from the Sun in every direction, all the time. It reaches past Pluto.
- **Magnetic fields.** The Sun's magnetic field stretches through the whole solar system and links the Sun to the planets.
- **Visitors from deep space.** **Cosmic rays** are fast particles from the galaxy. They hit Earth all the time too.



The Sun in ultraviolet light. The bright swirls are magnetic fields. Image: NASA/SDO

Remember: Sun makes it, wind carries it, field steers it, Earth takes it.

Layers above your head

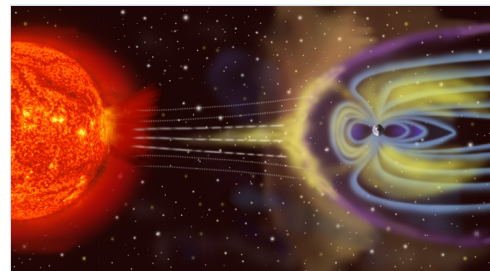


Earth's layers and how high they reach.

- **Troposphere** (under 10 miles): where weather happens.
- **Stratosphere** (10-30 miles): thin air; small changes matter.
- **Mesosphere** (30-50 miles): charged particles start to rise.
- **Ionosphere** (50-600 miles): an electric layer. Radio and GPS signals pass through it.
- **Magnetosphere** (past 1,000 miles): Earth's magnetic bubble and shield.

The cast of characters

Name	What it is	Where
Sunspot	Dark patch of strong magnetic field	Section 2
Solar flare	X-ray flash above a sunspot	Section 2
Filament	A rope of plasma above the Sun	Section 2
CME	Giant plasma cloud thrown out	Section 3
Coronal hole	A gap that blasts out fast wind	Section 3
Proton storm	Fast particles, arrive in minutes	Section 4
Geomagnetic storm	Earth's magnetic bubble shaken	Section 5
Solar cycle	The Sun's ~11-year ups and downs	Section 6



The Sun's wind squeezing Earth's magnetic bubble (artist's view, not to scale). Image: NASA

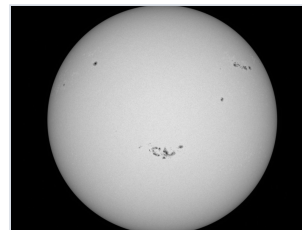
SECTION 2

Sunspots, Flares and Filaments

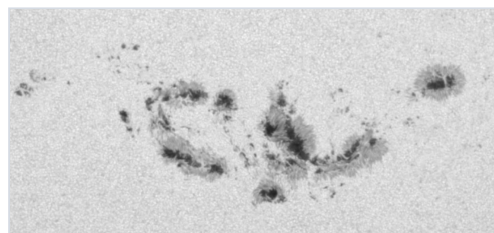
Sunspots are the trouble spots. Flares are the flashes. Filaments are the ropes. Together they start almost every space weather event. Flares and filament eruptions are the two things that launch CMEs (Section 3).

Sunspots

- Sunspots are places where magnetic field comes up out of the Sun's surface and goes back in. Humans have been counting them for centuries.
- The dark center is the **umbra**. The hairy ring around it is the **penumbra**.
- The Sun turns left to right as we see it. The right-hand spot in a group is the **leading spot**. The ones on the left are **trailing spots**.
- Field loops connect spot to spot, Sun to Sun.
- More sunspots means a denser, rougher solar wind across the whole solar system.

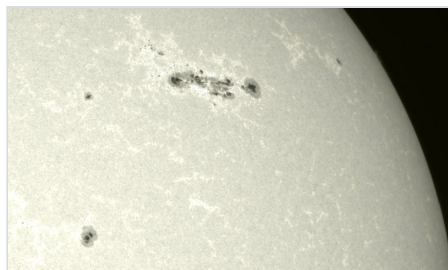


Sunspot groups on the Sun's face. Image: NASA/SDO

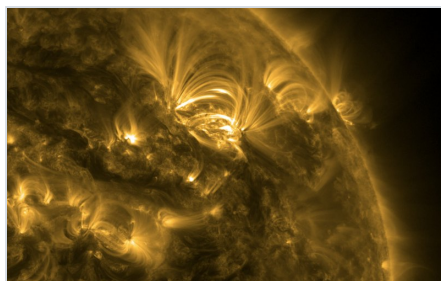


Close-up: dark umbra cores, fuzzy penumbra. Image: NASA/SDO

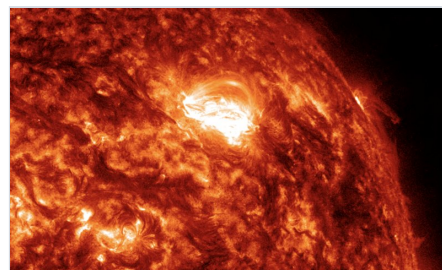
The three-look test: is this group dangerous?



1. Spots (visible light)



2. Field loops (171 Å)



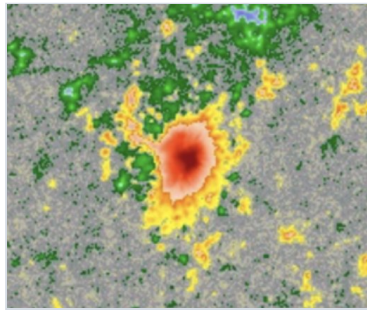
3. Helium glow (304 Å)

The same two groups in three views. The group on the right is the risky one. Image: NASA/SDO

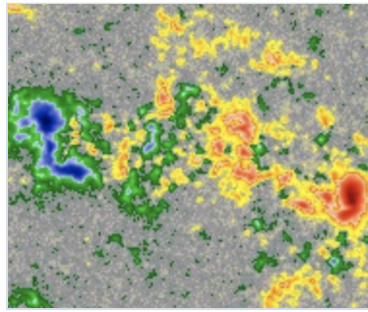
- **Look 1:** many spots of different sizes packed together is unstable.
- **Look 2:** short, crowded field loops are unstable. One big spot reaching out with long loops is calmer.
- **Look 3:** a group that glows bright in the red 304 Å view is active and interacting.

Magnetic class: the flare risk label

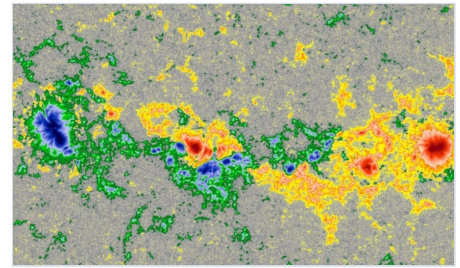
Class	What it means	Flare risk
Alpha	One polarity only. All the loops connect to magnetism outside the group.	Low
Beta	Both positive and negative spots in the group.	Moderate
Gamma	A beta group where no single line can separate the two polarities.	High
Delta	Positive and negative spots share one penumbra, crammed together.	Highest



Alpha: one red core



Beta: blue and red cores

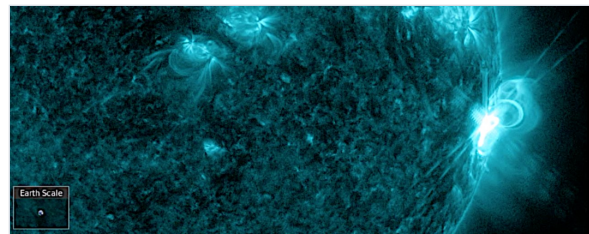


Beta-gamma-delta: mixed and crowded in the middle

Magnetic maps of sunspot groups. Blue is positive, red is negative. Image: NASA/SDO

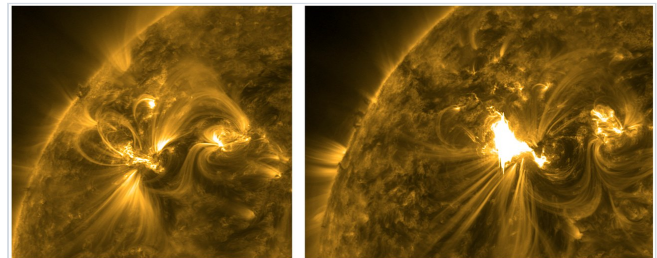
- A quiet alpha group can turn into a gamma or delta group in just a few hours.

Solar flares



A big flare (bright spot, right) during the September 2017 flurry. The Earth-size box shows the scale. Image: NASA/SDO

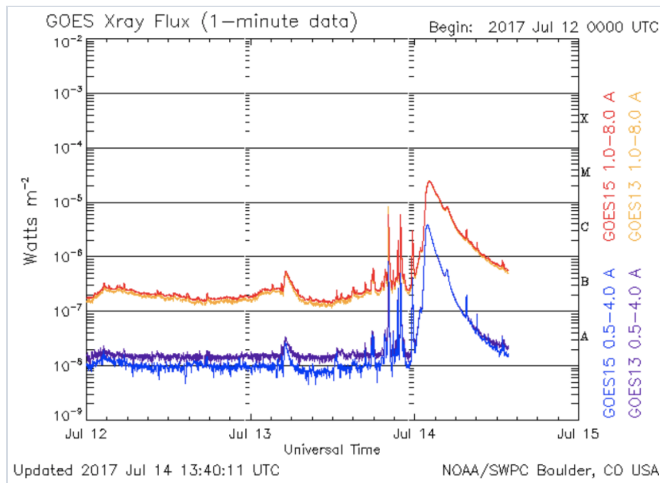
- A flare is a planet-sized flash of X-rays. The strongest also give off gamma rays. The light reaches Earth in about **8 minutes**.
- The X-rays electrify the upper atmosphere. This blocks shortwave (HF) radio on the sunlit side of Earth. It is called a **radio blackout**. It fades the moment the flare ends.
- Flares last from a few minutes to a few hours.
Impulsive flares look like spikes on a chart. **Long-duration** flares look like mountains, and they are more likely to launch a CME.



Minutes apart: field loops over a sunspot group (left), then the flare flash (right). The X-ray area is bigger than Jupiter. Image: NASA/SDO

The flare scale: A, B, C, M, X

- Each letter is **10 times** stronger than the one before. A1, B1, C1, M1, X1 climb by 10x each step.
- X is the top letter, so the numbers keep counting up: **X10 is ten times an X1, and X20 is twice an X10.**
- Flares below M-class rarely matter. The exception is a long-duration C-class flare (over 2 hours).
- X-class is exciting. X10 is a big deal. At X20 it gets scary. An X30 aimed at Earth means a very bad week.



Three days of flares on a GOES X-ray chart (July 12-15, 2017). The letters A to X run up the right side. Spikes are impulsive flares; the hill at the end is a long-duration flare. Image: NOAA SWPC

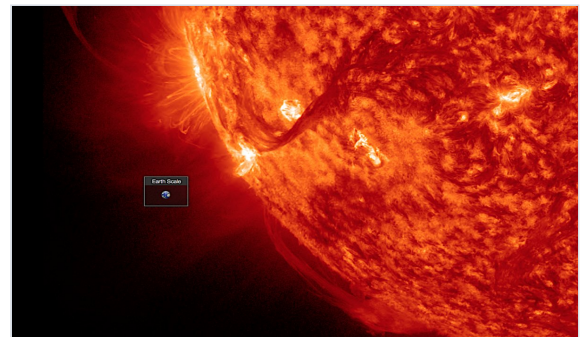
The biggest flare chart

How often	Flare size	What it threatens
Every ~11 years	X10	Satellites
Every ~250 years	X50+	Ground technology
Every ~1,000 years	X200+	The ozone layer
Every ~3,000 years	X500+	The ice caps
Every ~6,000 years	About X1000	Everything

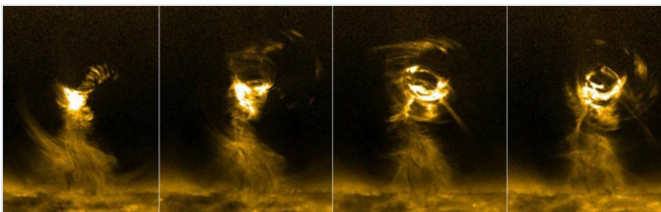
Why you should care: during the big flares of October-November 2003 and September 2017, satellite sunlight readings (TSI) dropped while X-rays and particles surged. Climate models lean on TSI, so the Sun's real energy is missed. More in the *Solar Climate Forcing Cheatbook*.

Plasma filaments

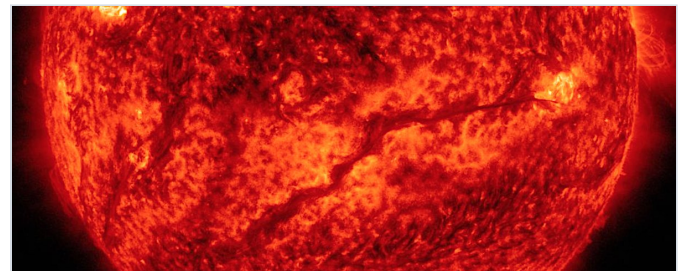
- A filament is a long rope of plasma that hangs above the Sun's surface. On the Sun's face it shows up as a **dark line**. Filaments are also called **prominences**.
- Same stuff as the rest of the Sun: hydrogen, plasma, ionized helium and ionized iron. It is calmer and lower energy.
- They hold billions to trillions of tons and still defy the Sun's gravity, held up by magnetic forces.
- Many are 10, 20 or 30 Earth-widths long, or more.
- Some stand straight up like a tornado.
- One filament stretched halfway across the Sun, more than **700,000 km** end to end.



A filament arching at the Sun's edge, with an Earth-size box for scale. Image: NASA/SDO



A filament standing up like a tornado. Image: NASA/SDO



A filament stretching across the Sun's face. Image: NASA/SDO

Remember: below M-class, ignore it. Gamma and delta groups flare most. Long flares and erupting filaments launch CMEs.

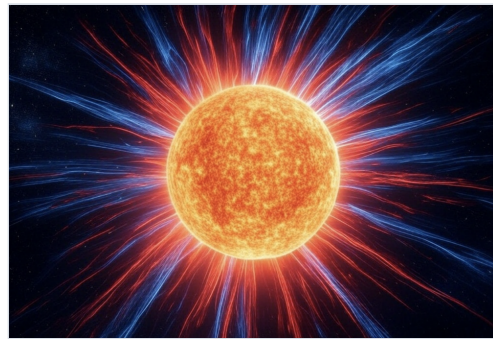
SECTION 3

Solar Wind, CMEs and Coronal Holes

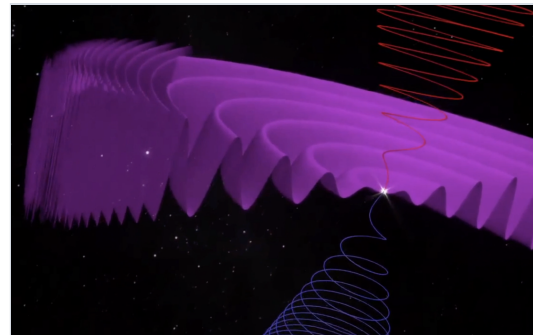
The solar wind is the Sun's steady breeze. CMEs and coronal holes are the gusts that cause storms. A CME hits all at once. A coronal hole stream builds up in two steps. The timing tells you which one you are looking at.

The solar wind

- The solar wind is charged particles (mostly hydrogen) streaming away from the Sun in every direction, all the time. It streams out past Pluto, then slows and stops.
- Nearly every known element has been found in it, but most only in tiny amounts.
- Outer space is not a true vacuum. It is filled with this thin electric plasma.
- The Sun's magnetic field rides along with the wind. This field, the **IMF**, is the link between the Sun and every planet.
- The wavy boundary between the Sun's north and south magnetic fields is the **heliospheric current sheet**. The Sun spins in about **27 days**, so the sheet sweeps past the planets much faster than they orbit. The Sun's field flips every 11 years.



The Sun's magnetic field streaming out into space.



*The current sheet, a wavy boundary between north and south field.
Image: NASA*

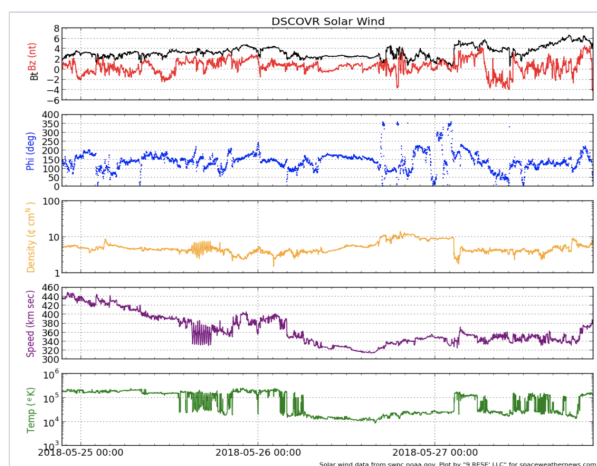
Solar wind speed and density at Earth

Wind type	Speed	Density (protons per cm ³)
Quiet	200-275 miles per second (300-400 km/s)	0.1 to 10
Fast	Over 600 km/s	Varies
Intense stream	Over 800 km/s, 10 to 100 times hotter	Dozens to hundreds
Big events	Over 600 miles per second, more than 2 million mph	High

The Bz rule: the one magnetic rule to learn

- **Bz** is the up-down direction of the wind's magnetic field.
- **Negative Bz (south-facing)** links up with Earth's field and lets energy in. That is when trouble starts.
- **Positive Bz (north-facing)** gets pushed away by Earth's magnetic bubble.
- Strength is not the whole story. Direction matters just as much.

How to read a solar wind chart



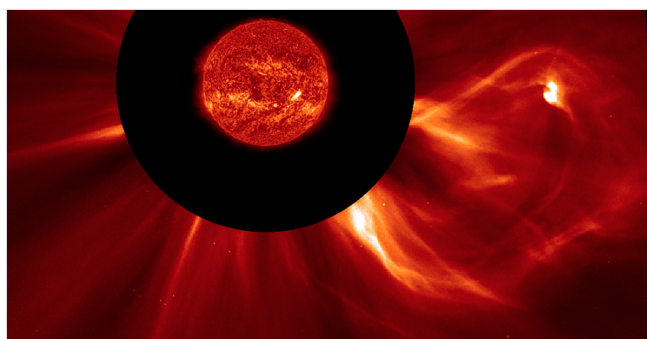
Solar wind readings from the DSCOVR satellite, May 25-27, 2018. Image: NOAA data

Panel	What it shows
1 (top)	Field strength (black) and Bz (red). Dips below zero are south-facing.
2	Field direction (Phi). Big jumps act like a dense, fast stream.
3	Density
4	Speed
5	Temperature

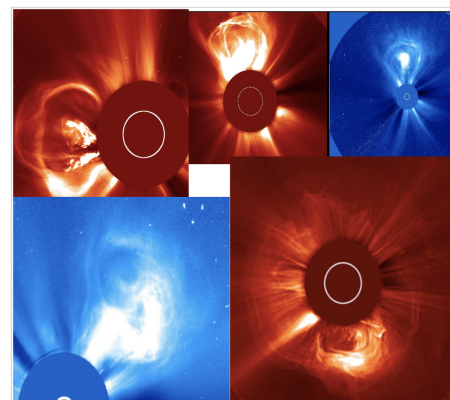
This example: speed slid from about 450 to 350 km/s. A mild fast stream was ending and things were returning to calm. Over 600 km/s counts as fast. This stream barely cleared the normal ceiling of 400.

Coronal mass ejections (CMEs)

- A **CME** is a giant cloud of plasma and magnetic field blown off the Sun. A flare is the lightning. A CME is the thunder.
- CMEs are the main producers of big space weather events on Earth.
- Flares and erupting filaments launch them, and they often come together.
- A CME can grow bigger than the Sun within **1 hour**, as wide as Mercury's orbit within a **day**, and within a **week** big enough to fit millions of Suns.
- It takes a few days to reach Earth. CME wind is fast, dense and hot.
- The **SOHO coronagraph** blocks the Sun's glare with a disk so the faint plasma shows. Without it every picture would be white.
- A CME aimed at Earth looks like a ring around the Sun, a **halo**. CMEs that go off to the side miss us.



A big CME, with the Sun's image placed in the blocked-out center for scale. Image: NASA/SOHO and SDO

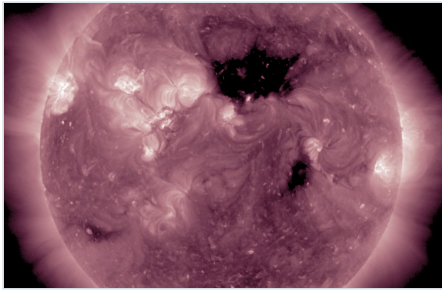


Five CMEs seen by SOHO. Bottom right: a halo CME. Image: NASA/ESA SOHO

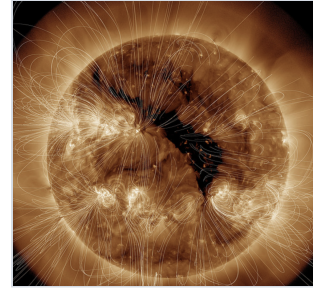
Coronal holes

- A **coronal hole** is a dark patch in the Sun's atmosphere (the corona) that is nearly empty of plasma. It is bigger and blockier than a filament.
- The Sun's magnetic field is **open** there. It runs straight out into space and carries the plasma away with it.
- That makes a **fast, hot, thin** stream of wind.

- The fast stream catches up with slow wind ahead of it and piles it up, like snow on a shovel blade. The pile-up works like a CME shockwave, so coronal holes can cause storms too.



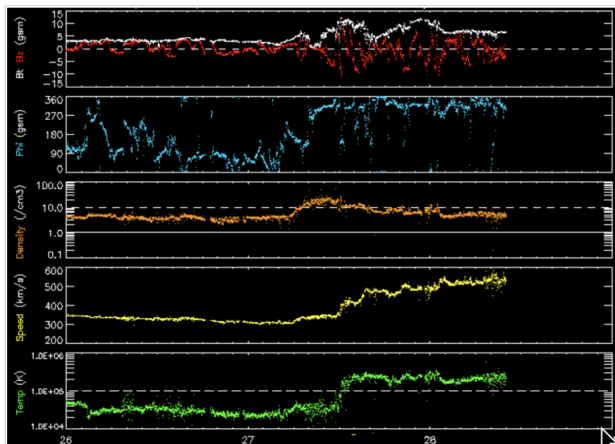
Coronal holes: the black patches on the Sun. Image: NASA/SDO



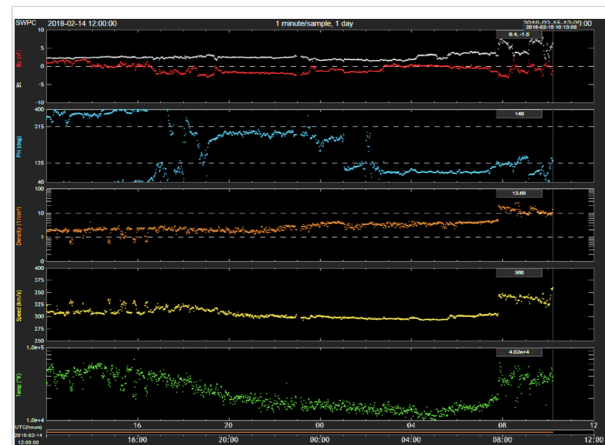
Open field lines streaming out of the hole, while sunspot loops stay closed. Image: NASA/SDO

CME or coronal hole? It is all about timing

What you see	What it is
Density jumps first, then speed and temperature rise later	Coronal hole stream
Everything changes at once	CME



Coronal hole stream: density (orange) rises first, then speed and temperature. Image: NOAA data



CME: every panel jumps at the same moment. Image: NOAA data

Remember: both can cause geomagnetic storms. Negative Bz makes either one worse.

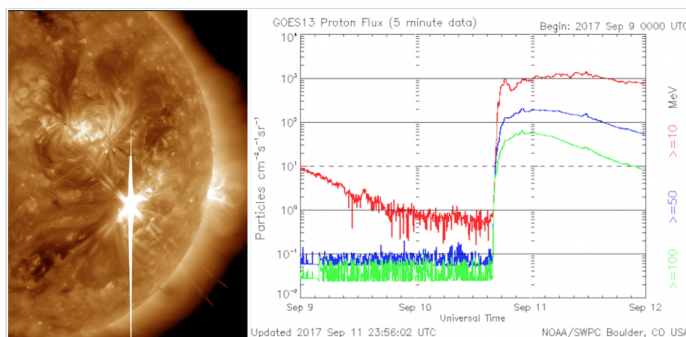
SECTION 4

Proton Storms and Cosmic Rays

Protons from a big flare reach Earth within minutes to hours. The CME takes days. Cosmic rays are a different kind of fast particle. They come from deep space, and the Sun's magnetic bubble holds them back.

Proton storms (SEP events)

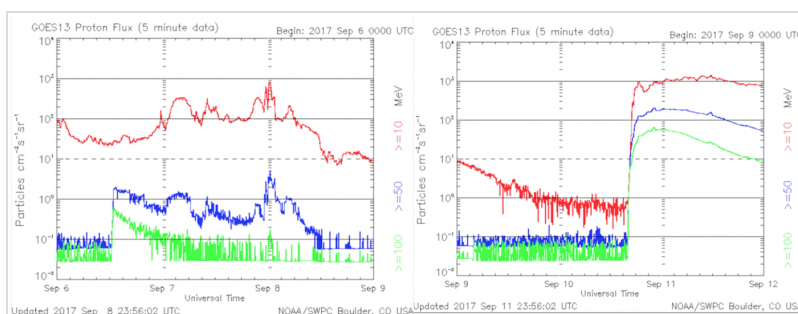
- A **proton storm** is also called a **solar energetic particle (SEP) event**. A strong flare blasts protons toward Earth at a large fraction of the speed of light.
- They arrive within minutes to a few hours. The CME that comes with the flare needs a few days.
- The count can jump about **1,000 times** in minutes. Here it went from about 1 to about 1,000.
- The protons ride the Sun's magnetic link (the IMF) and slip around Earth's magnetic shield. They pour in near the **north and south poles**.
- The main protection on the ground is the **air**. Astronauts and passengers on polar flights are most at risk. Space stations have shielded safe rooms. Airlines reroute polar flights during big flares.
- Radiation storms are rated on the NOAA **S scale** (Section 7).



A flare on the Sun (left, SDO) and the proton surge it set off minutes later (right). Red, blue and green lines are protons of three different energies. Image: NASA/SDO and NOAA SWPC

How to read a proton plot

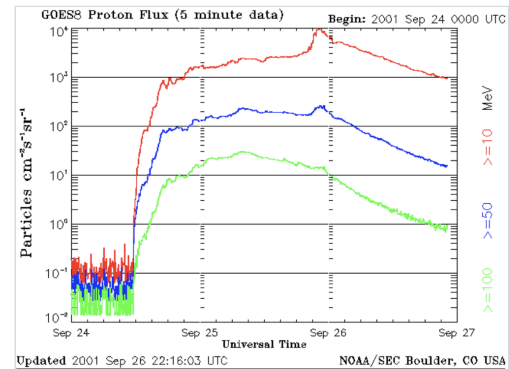
What the line does	What it means
Messy bumps	More flares keep adding fuel. Every new bump is a new eruption. Sept 6-9, 2017 had seven separate proton events in almost three days.
Sharp rise, then flat top	One flare, and the stream limit was reached. The CME shockwave is magnetic. It holds back any more increase.
A second, bigger spike	The punch . A stronger burst of protons rides in with the CME, but only if the CME hits Earth.



Left: messy bumps, Sept 6-9, 2017. Right: sharp rise and flat top from one flare, Sept 9-12, 2017. The CME missed Earth, so there was no punch. Image: NOAA SWPC GOES-13 proton plots

Example: the stream limit and the punch, September 2001

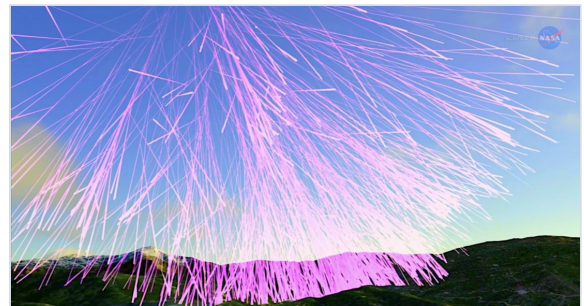
- A powerful flare and CME erupted on **Sept 24, 2001**.
- Red protons started below 1, then shot up to a stream limit of about **2,000** that night. They stayed there into the 25th.
- The CME hit Earth late on the 25th. The punch took the count to nearly **10,000**.
- The punch was about 4 to 5 times the stream limit. It looks small only because the chart scale goes up by tens. In all, a jump of more than **10,000 times**. That is rare.



Proton flux, Sept 24-27, 2001. Red is protons above 10 MeV, blue above 50 MeV, green above 100 MeV. Image: NOAA SEC

Cosmic rays

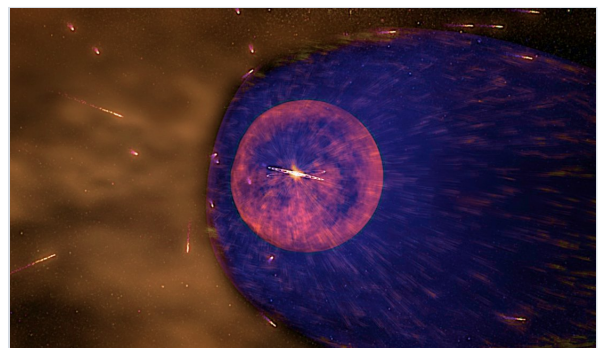
- **Cosmic rays** are atomic nuclei stripped of their electrons. They come from the galaxy and beyond, not from the Sun. Most are protons.
- Earth's magnetic field blocks a great deal of them. Enough get through to hit **every square meter of the upper air every second**.
- Each one smashes into an air molecule and sprays a **cascade** of particles. One low energy cosmic ray can shower a few acres.
- The rarest, highest energy particles hit only about once a year per square kilometer. They can reach the Earth's mantle or core.
- Cascades cover the ground all the time. About **33 particles pass through your body every second**. Most go straight through. You have lived in this shower your whole life.



A cosmic ray cascade: one particle strikes the upper air and sprays a shower of particles toward the ground. Image: NASA

Two shields against cosmic rays

- Cosmic rays are charged, so magnetic fields push them aside.
- **Shield 1:** Earth's magnetosphere.
- **Shield 2:** the Sun's magnetic bubble, the **heliosphere**. It is the solar wind and magnetic field streaming out past Pluto.
- Sunspots up means a stronger shield and **fewer** cosmic rays. A quiet Sun means a weaker shield and **more** cosmic rays. They move in opposite directions.



The Sun's magnetic bubble, the heliosphere, turning cosmic rays away from the solar system. Image: NASA/SVS

Sun	Solar wind shield	Cosmic rays
Active (solar maximum)	Strong	Low
Quiet (solar minimum)	Weak	High

Forbush decrease: a sudden drop in cosmic rays just before and during a CME hit. Earth sits inside the CME cloud, which is a magnetic shield of its own. The same cloud can cause a geomagnetic storm.

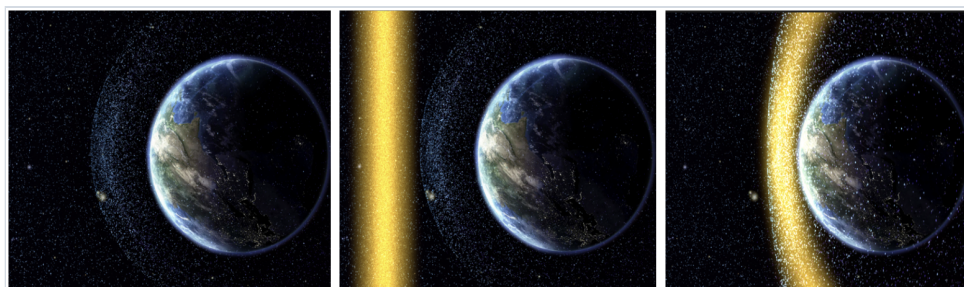
SECTION 5

Earth Fights Back: Magnetosphere, Belts, Storms, Auroras and the Ionosphere

A CME or fast stream squeezes Earth's magnetic bubble, and some of its energy gets in. That is a **geomagnetic storm**. It reaches every layer, from the radiation belts to your GPS.

Earth's magnetic bubble

- The **magnetosphere** is Earth's magnetic bubble. It starts more than 1,000 miles up. The solar wind pushes it into a comet shape: squeezed on the Sun side, with a long tail on the night side.
- When a CME shockwave hits, the bubble is **compressed**. The shock is steered around the planet, and part of its energy **couple**s into the field.
- The squeeze forces that energy through a smaller, tighter loop. It pushes particles into the ionosphere and upper air and induces electric currents in the air and in the ground.
- Earth's field connects to the planet at the poles, so the particles are guided to the poles.
- A geomagnetic storm acts on every layer. Flares and proton storms do not reach as far.

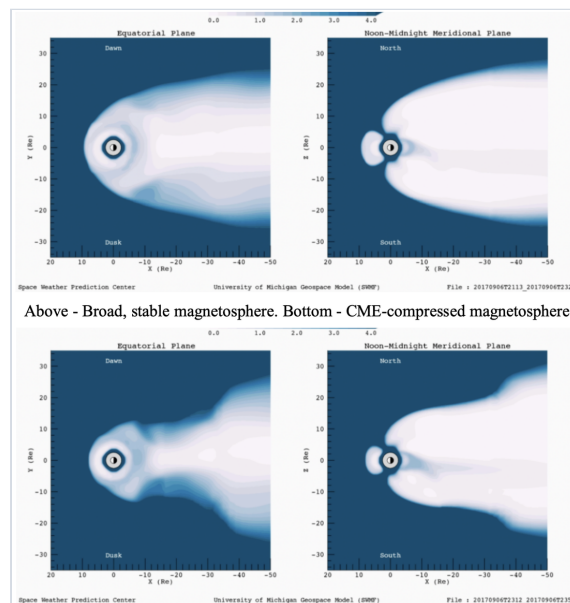


A CME shockwave (yellow) hits Earth's magnetic field and is steered around the planet. Left to right: before impact, impact imminent, compression.

The Kp scale: how shaken is the bubble?

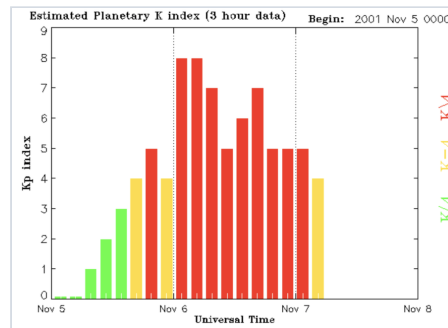
Kp	Conditions	NOAA scale
0-3	Calm	-
4	Unsettled	-
5	Storm	G1
6	Storm	G2
7	Storm	G3
8	Severe storm	G4
9	Extreme storm	G5

- Kp is the total disruption of the magnetosphere. It takes complete silence to get Kp 0. Kp 3 is slightly above average wind.
- Kp 5 gives beautiful auroras near the poles. The scarier effects are for **Kp 8 and up**, which can be **1,000 to 10,000 times more powerful**.



Computer model of Earth's magnetic bubble on Sept 6, 2017. Top: stable and broad. Bottom: squeezed after a CME hit. Left: from above the equator. Right: side view. Sun is on the left. Image: NOAA SWPC and U. Michigan model

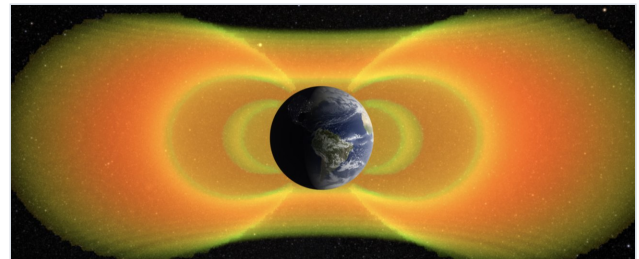
A real storm in Kp



Kp every 3 hours, Nov 5-7, 2001. Green is calm, yellow is Kp 4, red is storm. This storm hit Kp 8 twice. Image: NOAA SEC

The Van Allen belts

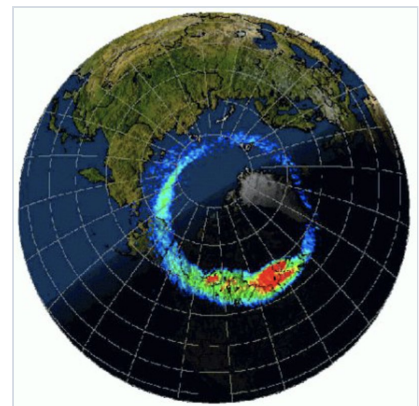
- Two doughnut-shaped rings of fast particles trapped by Earth's magnetic field. They were found in **1958** by James Van Allen's team, using Explorer 1, the first US satellite.
- **Inner belt:** about 1,000 to 8,000 miles above the equator. Mostly protons.
- **Outer belt:** about 12,000 to 25,000 miles up. Mostly electrons. It can swell out to about 37,000 miles.
- Both belts reach to about 65° north and south latitude.
- A solar storm can swell the belts with energy and create "killer electrons" that damage satellites. When a CME squeezes the bubble, it can force belt particles down toward the air on the Sun side.



The two Van Allen belts around Earth. Image: NASA

Auroras

- The magnetic field funnels storm particles to the poles. Auroras form in a ring, the **auroral oval**.
- Big storms push the ring toward the equator. On a day with exceptional auroras, a CME or fast stream has hit.
- The bigger the storm, the farther south you can see them (table below).



The auroral oval seen from space over the north pole. Image: NASA

Storm	Kp	Aurora has been seen as far south as
G1	5	Northern Michigan and Maine
G2	6	New York and Idaho
G3	7	Illinois and Oregon
G4	8	Alabama and northern California
G5	9	Florida and southern Texas



Aurora over the North Atlantic, seen from the International Space Station. Image: NASA

Electrojets: rivers of current in the sky

- A ring of electric current called the **auroral electrojet** sits over each pole. The particles guided down the field feed it.
- When a storm energizes the electrojets, they induce strong electric currents in the air and in the ground. Those ground currents are what hit power lines and pipelines.
- A third ring, the **equatorial electrojet**, sits over the tropics. The squeeze strengthens it, but it rarely makes auroras.

The ionosphere: radio, GPS and satellite drag

The **ionosphere** is an electric layer about 50 to 600 miles up. Shortwave (HF) radio bounces off it. GPS signals pass through it.

Effect	What happens
HF radio	Flare X-rays (sunlit side), proton storms (polar caps) and aurora electrons (night-side poles) all disturb the ionosphere and block HF radio.
GPS	The ionosphere bends GPS signals like a lens. In a storm the correction is wrong, so position errors grow. A normal receiver is accurate to about a meter in calm conditions and can be off by tens of meters or more in a severe storm. High-precision receivers (farming, surveying, construction) can lose their lock entirely.
Satellite drag	An active Sun and storms heat and swell the upper air. Satellites in low orbit slow down and fall. When the Sun is quiet, satellites reboost about 4 times a year. At solar maximum, every 2 to 3 weeks.

The whole chain at a glance

#	What happens	What you get
1	A CME or fast stream hits and squeezes the bubble	The Kp number climbs (G1 to G5)
2	Energy couples in; the Van Allen belts swell	Killer electrons that hurt satellites
3	Particles are guided to the poles	Auroras that spread toward the equator
4	The electrojets surge	Currents in the ground, in power lines and in pipelines (Section 7)
5	The ionosphere is disturbed	HF radio blackouts and GPS errors
6	The upper air heats and swells	Low-orbit satellites slow down and fall

Remember: the bigger the Kp number, the farther every one of these effects reaches. Kp 8 and up is the one to fear.

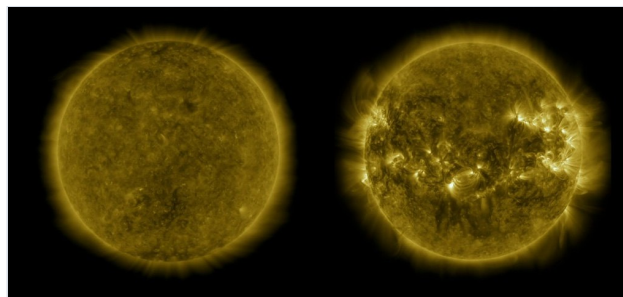
SECTION 6

Solar Cycles

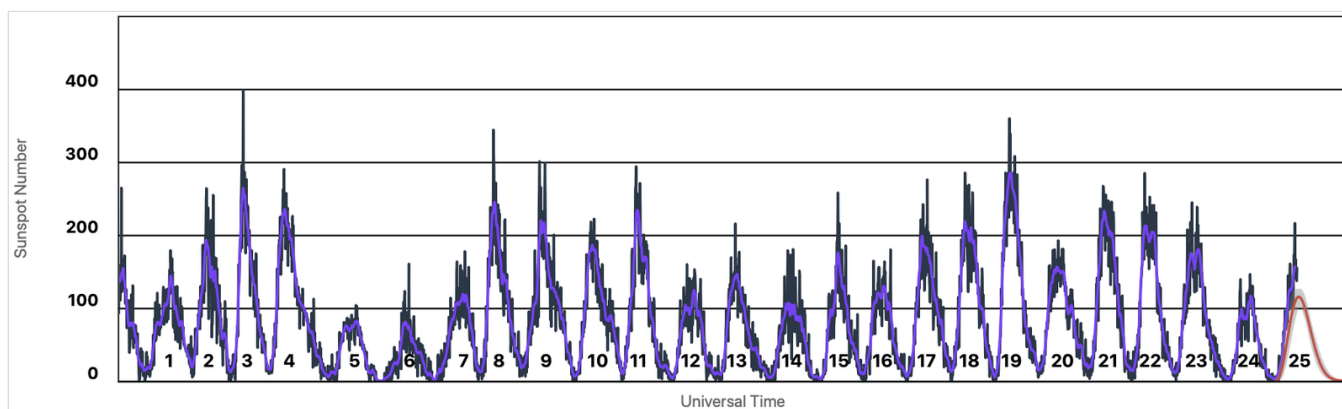
The Sun runs on clocks. The big one is the 11-year sunspot cycle. Flares, CMEs, proton storms and geomagnetic storms all rise and fall with it. Cosmic rays go the other way.

The 11-year sunspot cycle

- The sunspot cycle is about **11 years** long. It can run from 9 to 13 years.
- Sunspots, flares, CMEs, proton storms and geomagnetic storms all rise and fall together on this cycle.
- At **solar minimum** the Sun is often spotless. At **solar maximum** it is covered with active regions.
- Cycles differ a lot in **strength** and a little in **length**.
- It is called the sunspot cycle because for centuries sunspots were what people could watch.



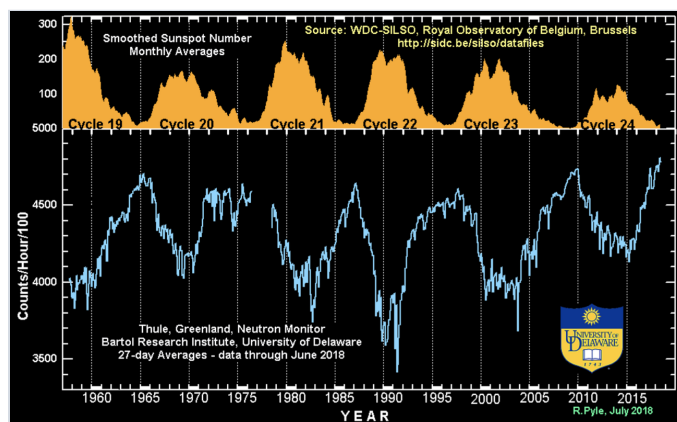
The Sun at solar minimum (December 2019, left) and solar maximum (May 2024, right), in extreme ultraviolet light. Image: NASA/SDO



Sunspot number, cycles 1 to 25. The thin line is monthly, the thick line is smoothed. Image: NASA/NOAA data

Cosmic rays and the polar fields run opposite

- Cosmic rays peak at sunspot **minimum** and drop to their lowest at sunspot **maximum**.
- The Sun's magnetic field **flips** every cycle. North and south swap places. It happens around solar maximum.
- The polar fields are weakest when they flip, at sunspot maximum. They are strongest at sunspot minimum, when cosmic rays are highest.
- Solar physicists use the polar fields to forecast how many sunspots the next cycle will have.
- The polar fields also decide where coronal holes and filaments appear on the Sun.



Sunspots (orange, top) and cosmic rays (blue, bottom) from 1957 to 2018. Each time sunspots peak, cosmic rays dip. Data: WDC-SILSO (Royal Observatory of Belgium) and Bartol Research Institute (University of Delaware)

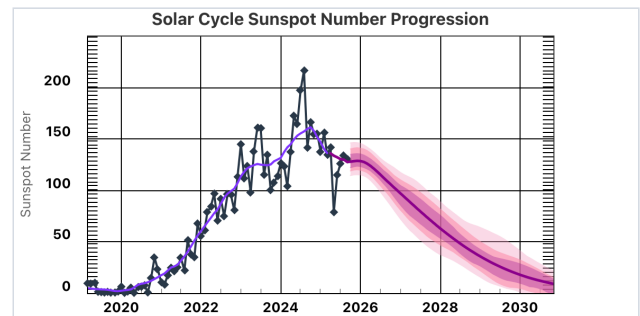
The Sun's clocks

Clock	Name	What it is
About 27 days	Solar rotation	One spin of the Sun.
About 6 months	Equinox effect	Earth takes more hits from geomagnetic storms around the equinoxes (March and September) than around the solstices.
About 11 years	Sunspot cycle	Sunspots, flares and storms rise and fall. The polar fields flip.
About 22 years	Hale cycle	Two 11-year cycles make one full magnetic cycle. An odd-numbered cycle is usually stronger than the even-numbered cycle before it.
About 80 to 88 years	Gleissberg cycle	A slow swing in solar activity over about 80 years.
About 200 years	Radiocarbon cycle	Seen in radiocarbon data.
About 400 to 440 years	Grand solar cycle	Long peaks (grand maxima) and long lows (grand minima) in activity. The last grand minimum ended about 1700. The Little Ice Age (about 1400 to 1700) fell in a very low activity time.

Where we are now

When	What
Dec 2008	Cycle 24 begins.
Sept 6, 2017	An X9.3 flare, the biggest of Cycle 24.
Dec 2019	Solar minimum. Cycle 25 begins.
Oct 15, 2024	NASA and NOAA announce the Sun has reached solar maximum. The active phase could run about another year.

- The exact peak month can only be named after activity has fallen for a long while.



Cycle 25 sunspot number from late 2019, with NOAA's forecast (pink) sliding toward the next minimum around 2030. Chart updated Oct 2, 2025. Image: NOAA SWPC

Remember: an active Sun means more flares, CMEs and storms, and fewer cosmic rays. A quiet Sun is the opposite. Big storms can still hit as the cycle declines.

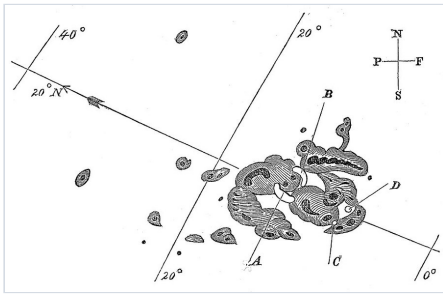
Want the weather and climate side? This book stops at the edge of the atmosphere. How these storms and cycles push the jet stream, rain, hurricanes, the global electric circuit and ozone is in the *Solar Climate Forcing Cheatbook*.

Storm Case Files, Tech Effects, NOAA Scales, Monitoring and Cheat Sheet

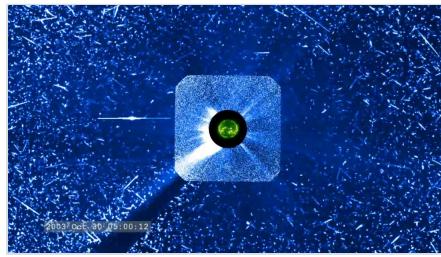
Big space weather has happened before, and it will happen again. Here are the case files, what storms break, the NOAA scales for rating them, the satellites that watch the Sun, and a one-page cheat sheet.

Storm case files

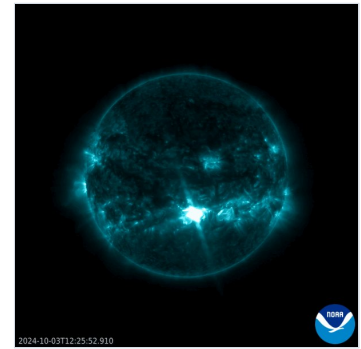
When	What happened
1859 Carrington event	Sept 1: Carrington and Hodgson each saw a white-light flare over a giant sunspot group. The CME hit the next day. Auroras reached Cuba, the Bahamas, Jamaica, El Salvador and Hawaii and were bright enough to read a newspaper by. Telegraph wires shocked operators and set paper on fire. Some lines sent messages with the batteries unplugged. Many lines were down for 8 hours or more. It is the biggest geomagnetic storm on record.
About 775 AD	The Charlemagne event, seen in ice-core records. About 3 to 10 times the Carrington event. Events like this come about once every 1,000 to 2,000 years.
1921 New York Railroad storm	May 13-15: on May 15 at 7:04 a.m., New York Central railroad signals below 125th Street failed and a control tower at 57th Street caught fire. A station burned in Brewster, NY. A telephone station burned in Sweden. The storm was about 10 times stronger than the 1989 storm.
1967	May 23: a giant solar radio burst jammed U.S. and U.K. radar and radio at the poles. The U.S. Air Force Strategic Air Command began readying its bombers, thinking the Soviets had jammed them. Air Force space weather forecasters told them it was the Sun, just in time.
1972	Aug 2-4: huge flares and CMEs. Auroras were bright enough to cast shadows. Radio blackouts and TV breakup. U.S. nuclear detection devices gave a false alert of a bomb going off. Magnetic sea mines off Vietnam exploded. Long-distance phone lines in Illinois went down, and AT&T redesigned the power system of its transatlantic cables.
1989 Quebec	March 13: within 90 seconds, 6 million people lost power for 9 hours , many for days. A transformer was destroyed, and transformers melted in New Jersey. Some people feared a nuclear attack. A NASA satellite, the Solar Maximum Mission, "dropped as if it hit a brick wall" from drag.
2003 Halloween storms	Oct 19-Nov 5: three huge sunspot groups fired 17 big flares, including an X17 on Oct 28. On Nov 4 came the biggest flare ever measured: the sensor maxed out at X17, and later estimates put it near X45. Sweden lost power. The ISS crew took shelter. About 59% of deep space missions and satellites had trouble. The ADEOS-2 satellite was lost. Mars Odyssey's radiation experiment was destroyed. Polar flights lost radio. Antarctic bases lost communications for over 5 days. GPS failed for surveyors and drillers. Aurora reached Florida and Texas.
2012	March 7: a flare, a CME and a proton storm hit together. The SkyTerra-1 satellite, used by emergency responders, went offline that afternoon. It was recovered by early April.
2015	June 22-23: three CMEs hit and drove a Kp 8 (G4) storm.
Sept 2017	Sept 6-10: four X-class and 27 M-class flares. The X9.3 on Sept 6 was the biggest of Cycle 24. Seven proton events in almost three days. Its CME hit Sept 7-8 and drove a Kp 8 (G4) storm. HF radio was badly disrupted.
Feb 2022	A launch put 49 Starlink satellites into a low orbit on Feb 3. A moderate storm the next day swelled the air. 38 of the 49 fell from orbit.
May 2024 Gannon storm	May 8-11: a sunspot cluster 17 times the width of Earth threw at least 8 Earth-bound CMEs. A G5 storm, the top of the scale. Auroras reached the tropics. Large numbers of satellites had to maneuver at once because of drag. There were about 25 stronger solar wind hits in the last 50 years, but only two matched this magnetic disturbance and none matched the aurora spread. Only 1859 matched the aurora spread, and it was 40 to 100 times stronger.
Oct 2024	Oct 3: an X9.0 flare. Oct 10-11: a modest solar event caused a G4 storm and auroras across most of the U.S. There have been 20 low-latitude aurora events since March 2023. Before that there were 1 or 2 per decade.



Carrington's sketch of the sunspots, Sept 1, 1859. Image: public domain

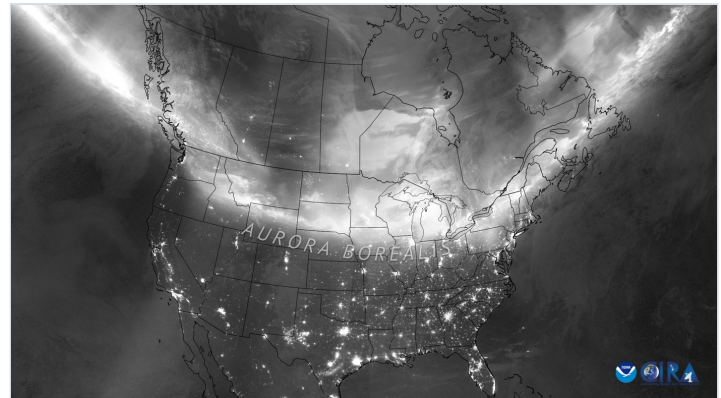


SOHO coronagraph, Oct 30, 2003. The speckles are fast protons hitting the camera. Image: NASA/ESA SOHO



The X9.0 flare of Oct 3, 2024, seen by GOES-19. Image: NOAA

If a Carrington storm happened today: it could cost nearly **\$2 trillion** and knock out communications, banking, GPS and the grid (National Academies of Sciences). An estimated 20 to 40 million Americans could lose power for 16 days up to 1 to 2 years. Carrington is the biggest storm in the 160-year record. In 500 years of ice-core records it was nearly twice as big as the runner-up.



Aurora glowing over North America from satellite, May 11, 2024. Image: NOAA/CIRA (JPSS satellite)

What storms break

System	What a storm does
Power grid	Storm currents flow through power lines and saturate transformers. Protection trips. Transformers can be damaged and blackouts follow. A grid already near peak demand is most at risk.
Pipelines and rail	Pipeline currents can reach hundreds of amps in a G5 storm. Railway signals can fail (1921).
Satellites	Surface charging, memory errors, drag, and damaged solar panels in big proton storms. Some are lost.
GPS and navigation	Errors of meters to tens of meters, and lost lock.
Radio	HF blackouts. Low-frequency navigation outages.
Flights and space	Polar routes lose radio and are rerouted. Astronauts take shelter.

The solar killshot. In the biggest solar storms, the induced currents would fry transformers, melt copper wires, destroy circuits and basically eliminate all modern technology. **The U.S. government estimates that if a storm like that happened today, in six months 90% of humans could be dead** from lack of water, heat, food, energy, banking, communication and transportation. All of them run on electricity. This is the **solar EMP**, the "solar killshot."

NOAA space weather scales

NOAA rates three kinds of storms from 1 (minor) to 5 (extreme). Each is rated by a number you can measure. "Per cycle" is how often it happens in one 11-year sunspot cycle.

G: geomagnetic storms

Level	Kp	What it does	Per cycle
G1 Minor	5	Weak grid wobbles. Auroras at high latitudes.	1,700
G2 Moderate	6	High-latitude grid alarms. HF radio fades. Long storms can damage transformers.	600
G3 Strong	7	Grid voltage fixes. Satellite drag. GPS and radio come and go.	200
G4 Severe	8	Grid protection trips. Satellite navigation down for hours.	100
G5 Extreme	9	Possible grid collapse and transformer damage. Pipeline currents. GPS bad for days. HF radio gone for 1 to 2 days.	4

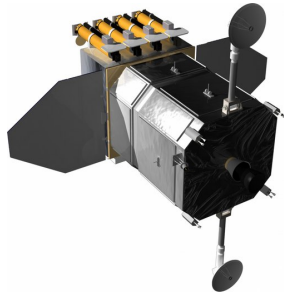
S: solar radiation (proton) storms

Level	Protons (10 MeV+)	What it does	Per cycle
S1 Minor	10	Small effects on polar radio.	50
S2 Moderate	100	Rare satellite upsets. More radiation for high-flying polar flights.	25
S3 Strong	1,000	Satellite upsets. Polar radio degraded. Astronauts should avoid spacewalks.	10
S4 Severe	10,000	Polar radio blackout. Satellite memory trouble. Unavoidable radiation hazard on spacewalks.	3
S5 Extreme	100,000	Spacewalk hazard cannot be avoided. Satellites can be rendered useless. Polar HF radio can black out completely.	Fewer than 1

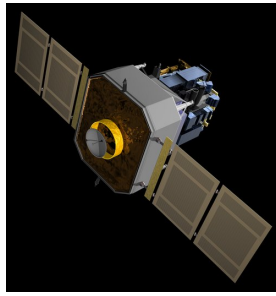
R: radio blackouts (from flares)

Level	Flare	What it does	Per cycle
R1 Minor	M1	Brief HF radio loss on the sunlit side.	2,000
R2 Moderate	M5	Tens of minutes of HF radio loss.	350
R3 Strong	X1	About an hour of HF radio loss.	175
R4 Severe	X10	1 to 2 hours of HF radio loss on most of the sunlit side.	8
R5 Extreme	X20	Hours of complete HF blackout on the whole sunlit side. X20 is twice X10.	Fewer than 1

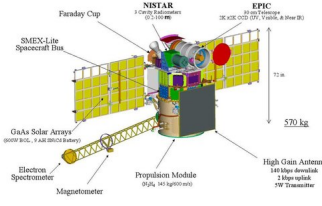
Eyes on the Sun



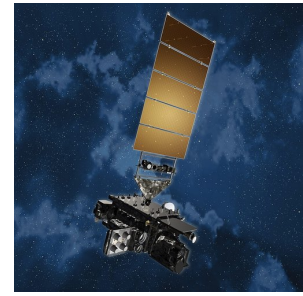
SDO



SOHO



DSCOVR

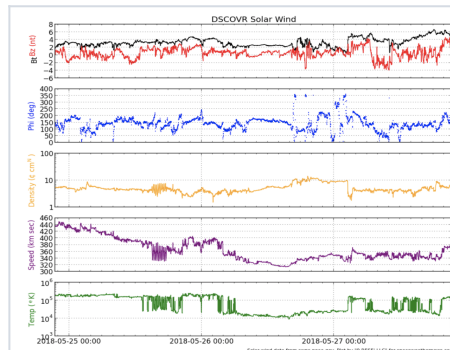


GOES-R series

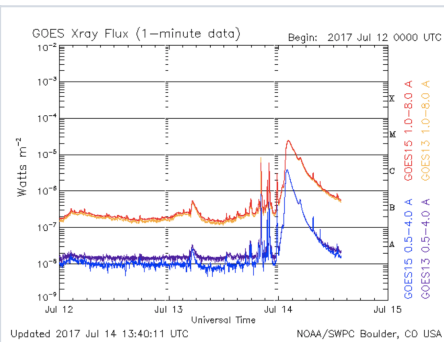
Spacecraft artwork. Images: NASA and NOAA

Satellite	Owner, launch	Job
SDO	NASA, Feb 11, 2010	Watches the Sun in 10 colors of ultraviolet light every 10 to 12 seconds (AIA) and maps its magnetic fields (HMI). Source of most Sun pictures in this book.
SOHO	ESA and NASA, Dec 2, 1995	Sits about 1.5 million km sunward of Earth. Its LASCO camera blocks the Sun to show CMEs.
DSCOVR and ACE	NOAA (DSCOVR, Feb 2015) and NASA (ACE)	Sit about a million miles out and measure the solar wind. DSCOVR gives 15 to 60 minutes of warning before a CME hits. New satellites SOLAR-1 and IMAP take over starting in 2026.
GOES	NOAA	X-ray sensors rate flares. Particle sensors rate proton storms. SUVI takes Sun pictures. CCOR-1 on GOES-19 (launched June 25, 2024) is NOAA's first operational CME camera.

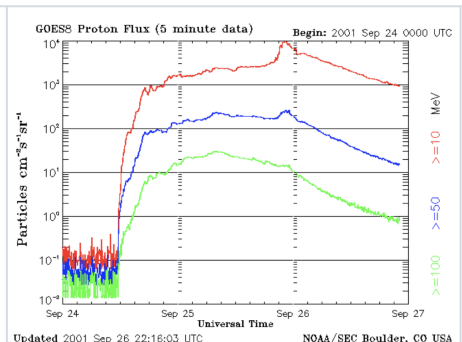
The dashboard: five plots to know



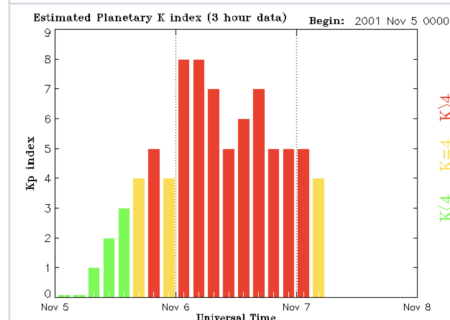
1. Solar wind (DSCOVR). Over 600 km/s is fast. Bz below zero is trouble. Everything at once is a CME.



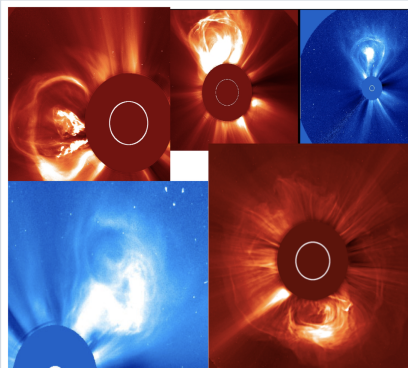
2. Flare X-rays (GOES). Each letter is 10 times the one before. X20 is twice X10.



3. Protons (GOES). Up and flat is the stream limit. Watch for the punch.



4. Kp bars. Green is calm, yellow is Kp 4, red is a storm (5 and up).



5. SOHO. A ring around the Sun is a halo CME aimed at Earth.

Images: NOAA SWPC, NASA/ESA SOHO

One-page cheat sheet

The timeline of a big storm

#	When	What happens
1	Flare: 8 minutes	X-rays and light reach Earth. HF radio fades on the sunlit side.
2	Protons: minutes to hours	Proton storm. Radiation near the poles.
3	CME: a few days	The cloud arrives. Watch DSCOVR for Bz and speed.
4	Storm: hours to days	The magnetic bubble is squeezed. Kp rises.
5	During the storm	Auroras, grid currents, GPS errors, radio loss, satellite drag.
6	Along the way	Cosmic rays dip (Forbush decrease).

Ten quick rules

1. Flares below M-class are quiet. Ignore them.
2. Each flare letter is 10 times the one before. **X20 is twice X10.**
3. **Negative Bz** (south-facing) means trouble.
4. Wind over **600 km/s** is fast.
5. **Density first** is a coronal hole. **Everything at once** is a CME.
6. A **halo** around the Sun is a CME aimed at Earth.
7. Protons come in minutes to hours. The CME takes days.
8. **Up and flat** protons mean the stream limit. The punch comes only if the CME hits.
9. **Kp 5 and up** is a storm. Kp 8 and up is the one to fear.
10. Sunspots up means cosmic rays down.

Twelve terms

Sunspot	Dark patch of strong magnetic field	Magnetosphere	Earth's magnetic bubble
Flare	Flash of X-rays above a sunspot	Geomagnetic storm	The bubble shaken by a CME or fast stream
CME	Giant cloud of plasma and magnetic field	Kp	Scale of how shaken the bubble is (0 to 9)
Coronal hole	Dark gap that blasts out fast wind	Ionosphere	Electric layer 50 to 600 miles up
Solar wind	Stream of particles from the Sun	Van Allen belts	Rings of trapped fast particles
Bz	Up-down direction of the wind's magnetic field	Cosmic rays	Fast particles from deep space

Remember: flare light first, protons next, CME last. Negative Bz and a high Kp are what to watch.