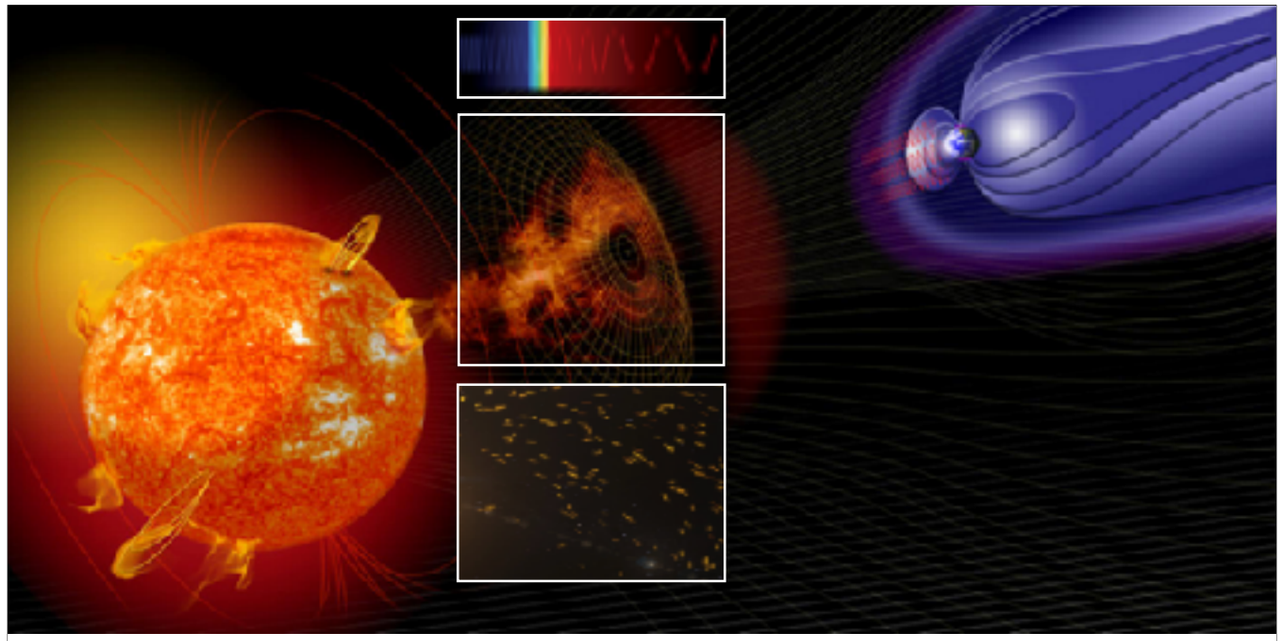
Role of the Ionosphere & SPWx in Military Communications

Solar-Terrestrial
Centre of
Excellence

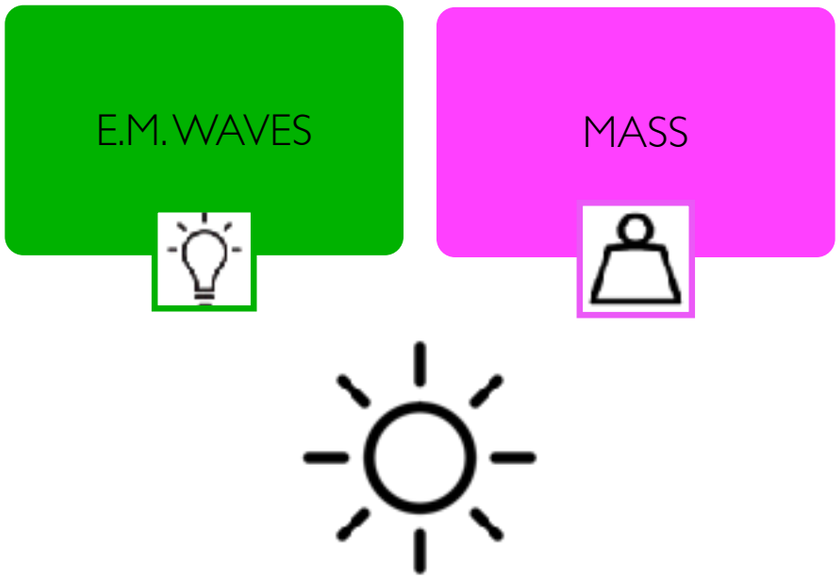


SOLAR DRIVERS

Petra Vanlommel
Solar-Terrestrial Centre of Excellence (STCE)

THE SUN AS A BALL OF ENERGY

The sun emits continuously energy which is expelled to outer space in the form of electromagnetic waves and moving plasma.



The sun is a gigantic ball of energy: magnetic energy, heat, moving plasma, …

This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

This energy is expelled, leaves the Sun to outer space and is carried away by electromagnetic waves and plasma.

Note: the solar plasma is hot. The plasma particles bump on each other. These collisions changes their kinetic energy. This change is emitted in the form of thermal radiation, light photons. Once these photons are at the solar surface, they can escape and move freely.
Thermal radiation is electromagnetic radiation generated by the thermal motion of particles in matter. You have thermal motion as soon as the temperature is above absolute zero.

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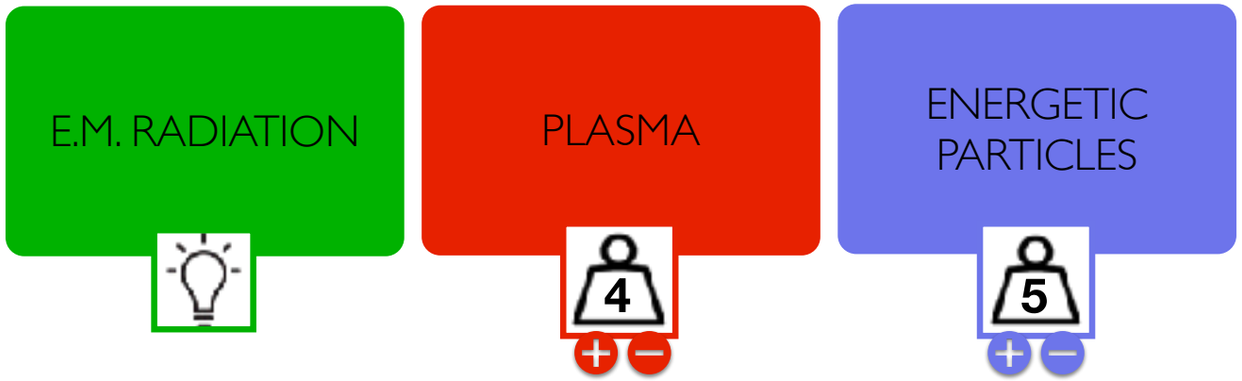

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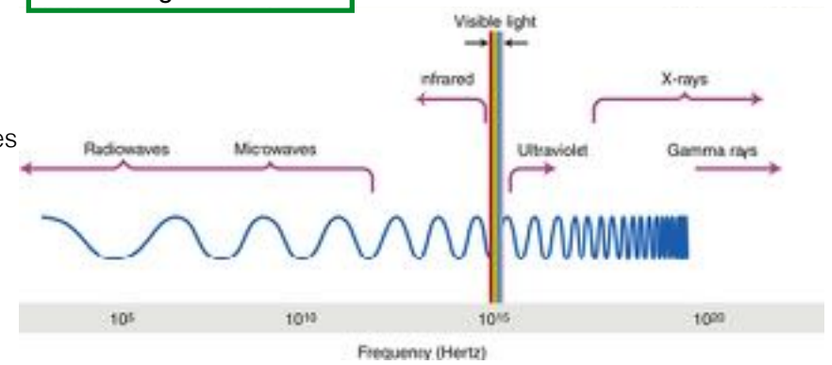
Thermal radiation is electromagnetic radiation generated by the thermal motion of particles in matter. You have thermal motion as soon as the temperature is above absolute zero.

Solid is distinguished by a fixed structure. Has a define shape and volume. In a solid, atoms are tightly packed together in a fixed arrangement.
Liquid is distinguished by its in define shape, but constant volume. In a liquid, atoms are close together but not in a fixed arrangement.
Gas is made up of atoms that are separate. A gas has no fixed shape and volume.

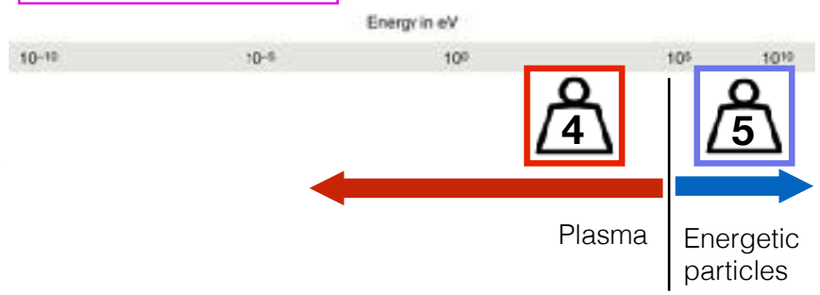
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



Particles

- Atomic & sub-atomic particles
- m/s to fractions of speed of light

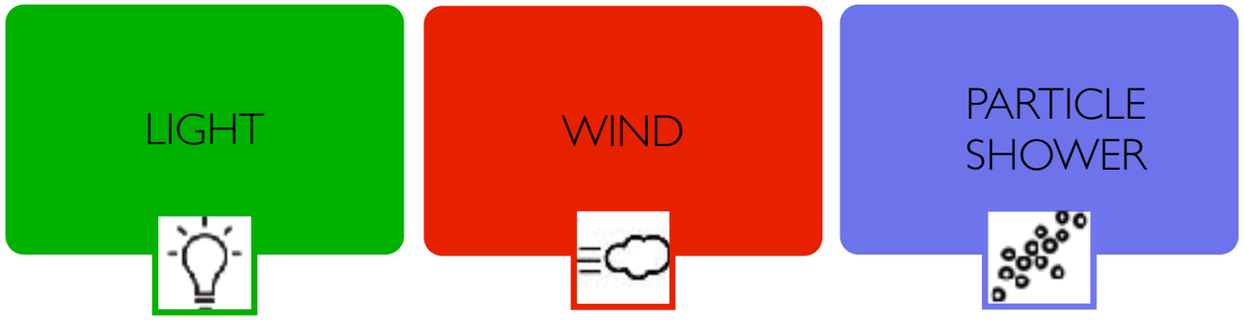


100 kEV

3 SPACE WEATHER PHENOMENA

The sun's energy reaches the earth in 3 forms: light, moving gas and particle precipitation. This energy interacts with the magnetosphere and the atmosphere of the earth. This is space weather.

How and where the interaction occurs depends on the type of energy.



light= electromagnetic waves, energy transmitted in the form of photons/ EM waves

Wind= moving gas, in this case moving plasma

EPP = particle has high energy and precipitates along the geomagnetic field.

<100 kEV : plasma

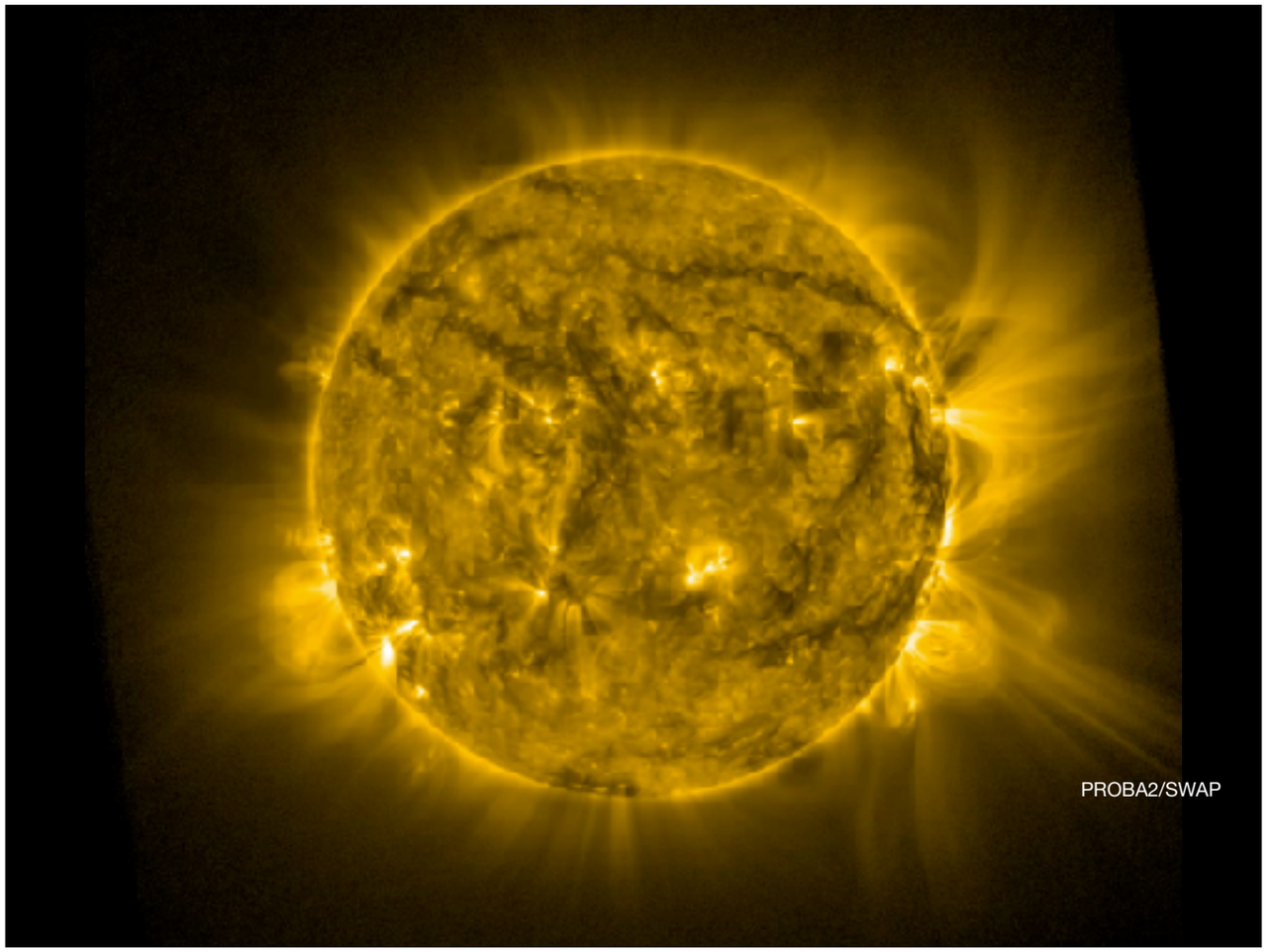
Particle precipitation - energy transmitted in the form of fast-moving atomic or sub-atomic particles —> drizzle

Energy expressed in eV= 1.602 10^-19 J

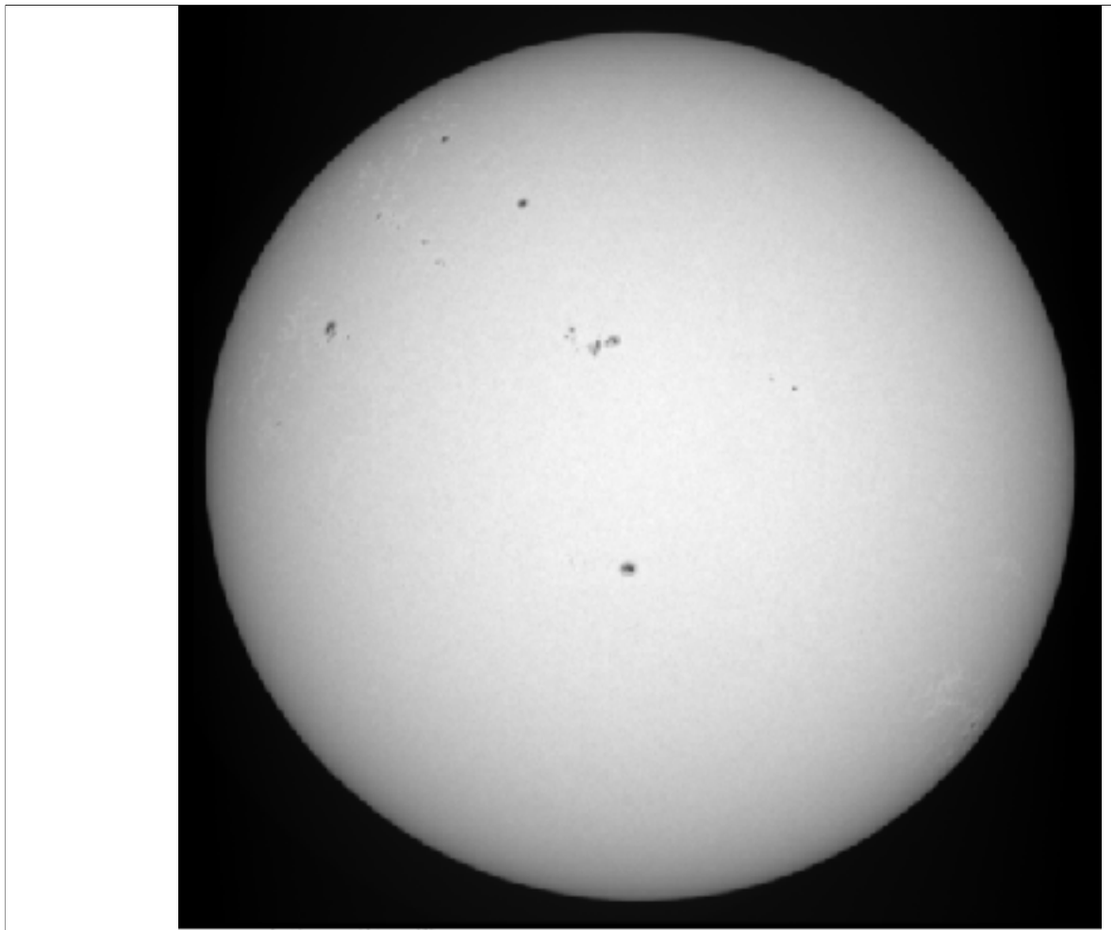
https://lasp.colorado.edu/home/mag/research/energetic-particle-precipitation/

Focus on solar energetic particles

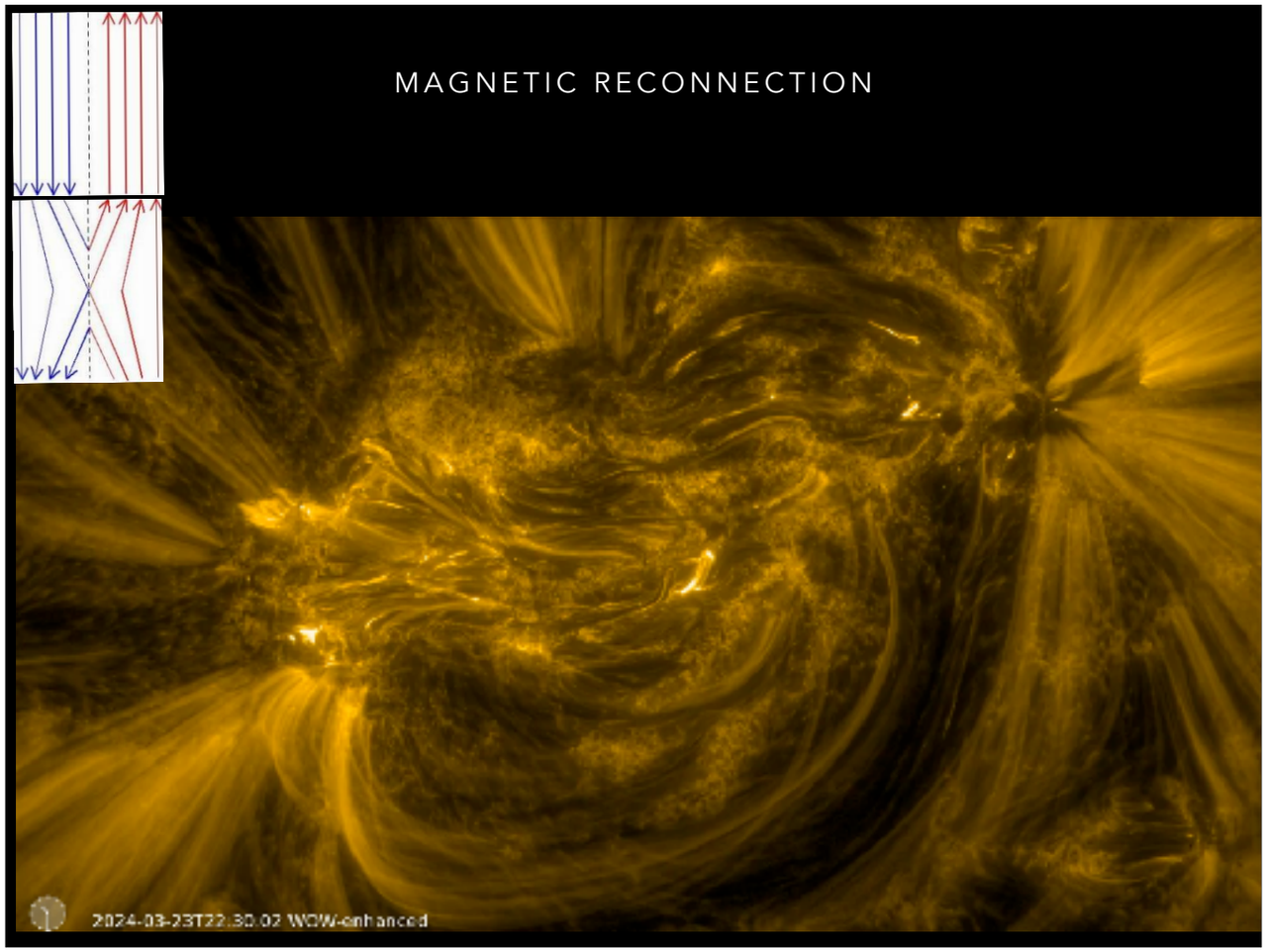
Magnetism drives space weather and the sun’s dynamics.



In the EUV it looks like this!
The sun doesn’t only rotate but it is also tangled with loops which move, shake back and forth, restructure and do all sorts of electric and magnetic magic.
It is a turbulent plasma ball where magnetic fields are moving, shake, connect with other other, ….



Sunspots are bundles of magnetic fields.
This is the photosphere of the Sun, in the visible light.

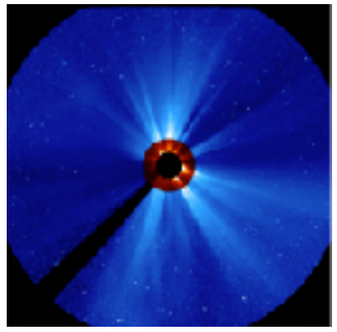


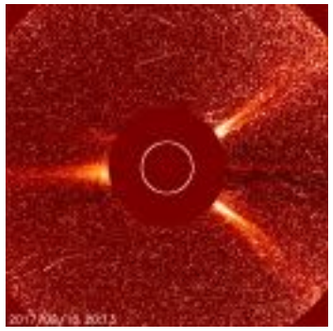
The more sunspots, the higher the chance for magnetic reconnection.

0.3 T – solar sunspot
5mT – strength of a typical refrigerator magnet
31.869 μT (3.1×10^{-5} T) – strength of Earth's magnetic field at 0° latitude (North/South), 0° longitude (west/east)
1 to 5 nT – IMF at L1

SOLAR WEATHER & STORMS

Energy can be released on a shorter time scale. A solar feature like a sunspot, an active region, coronal hole, filament etc. lies at the base of a solar storm in which energy is released. The release of energy might be in an abrupt, impulsive and brutal way (flare, Coronal Mass Ejection or CME, proton storm) or in a non-eruptive manner (Coronal Hole - CH).





Flare

Coronal Mass Ejection

Particle Storm

Change in energy output on the scale of minutes, hours, days.

Remote sensing (seeing) - in situ (taste and touch the ambient space)

Space weather is the change of energy that occur in the space environment.

A Flare is a sudden strong increase of the solar e.m. radiation. The light flash is localised on the solar surface.
SDO/AIA

A Coronal Mass Ejection is a plasma cloud that is ejected into space. You consider it as a cloud and not as a bunch of individual particles. It is superimposed on the background solar wind. You can see a CME as a complex magnetic bag with different magnetic layers with plasma in it that travels as a tsunami through space. It can go faster/as fast as/slower than the background solar wind. When it is faster, you will see a shock in front of the cloud. This is exactly the same as the shock you see in front of a speed boat.
A CME is visible as a white cloud in corona graphic images like the one on the slide. A coronagraph is a telescope that creates an artificial eclipse and makes pictures in the visible light of the region around the sun.
SOHO/LASCO C2 (red) and LASCO C3 (blue)

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SDO/AIA

Particle shower
A particle storm is a bunch of electrically charged particles that are accelerated in the solar atmosphere to very high velocities by a large-scale magnetic eruption often causing a CME and/or solar flare. They follow the IMF
They may impact telescopes. They are seen as white stripes and dots: this are particles that fall into the lens and blind the pixel(s). During that particular moment, the telescope can't see anymore through the impacted pixels. You can say that the dots and stripes represent a sort of in situ measurement.

In situ means that you measure a parameter local. Remote sensing means that you look at something from a distance.

Near Earth, the IMF still controls the solar wind and its movement. If we would go much much further, the CME magnetic bag with solar plasma would be almost empty (all the solar material is spread

over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

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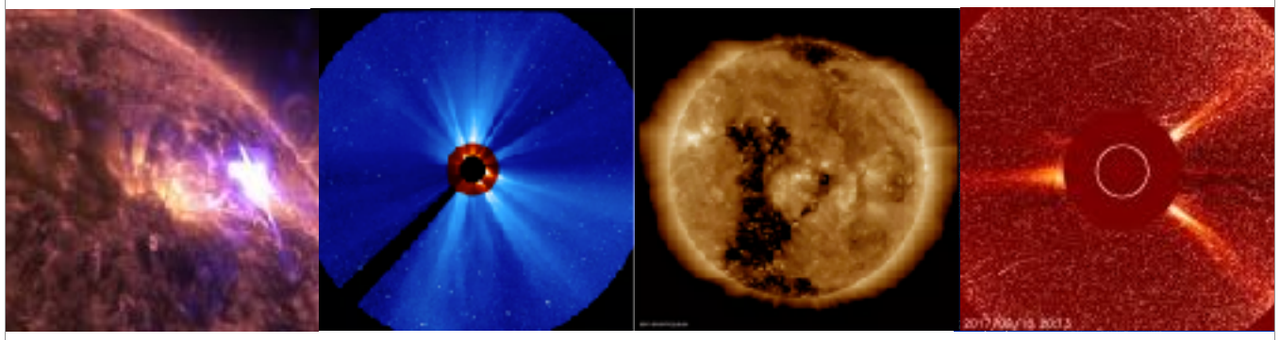

Flare

Coronal Mass Ejection
HSS

Particle Storm

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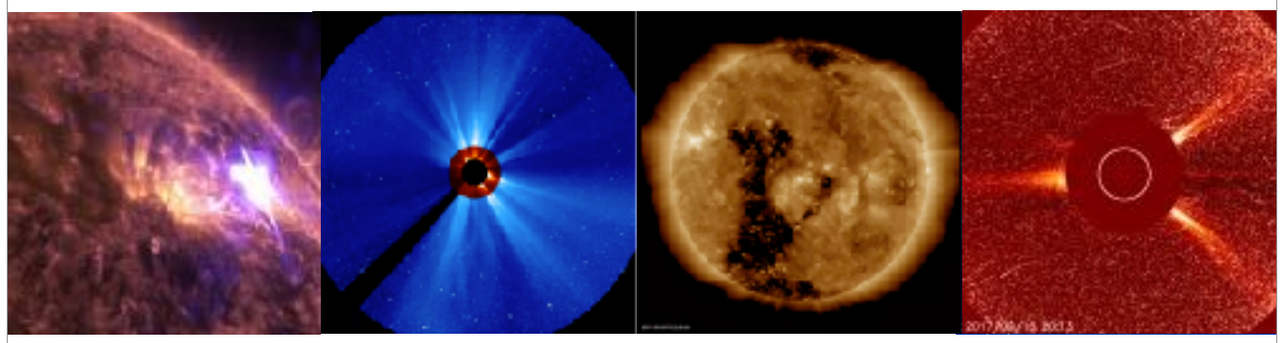

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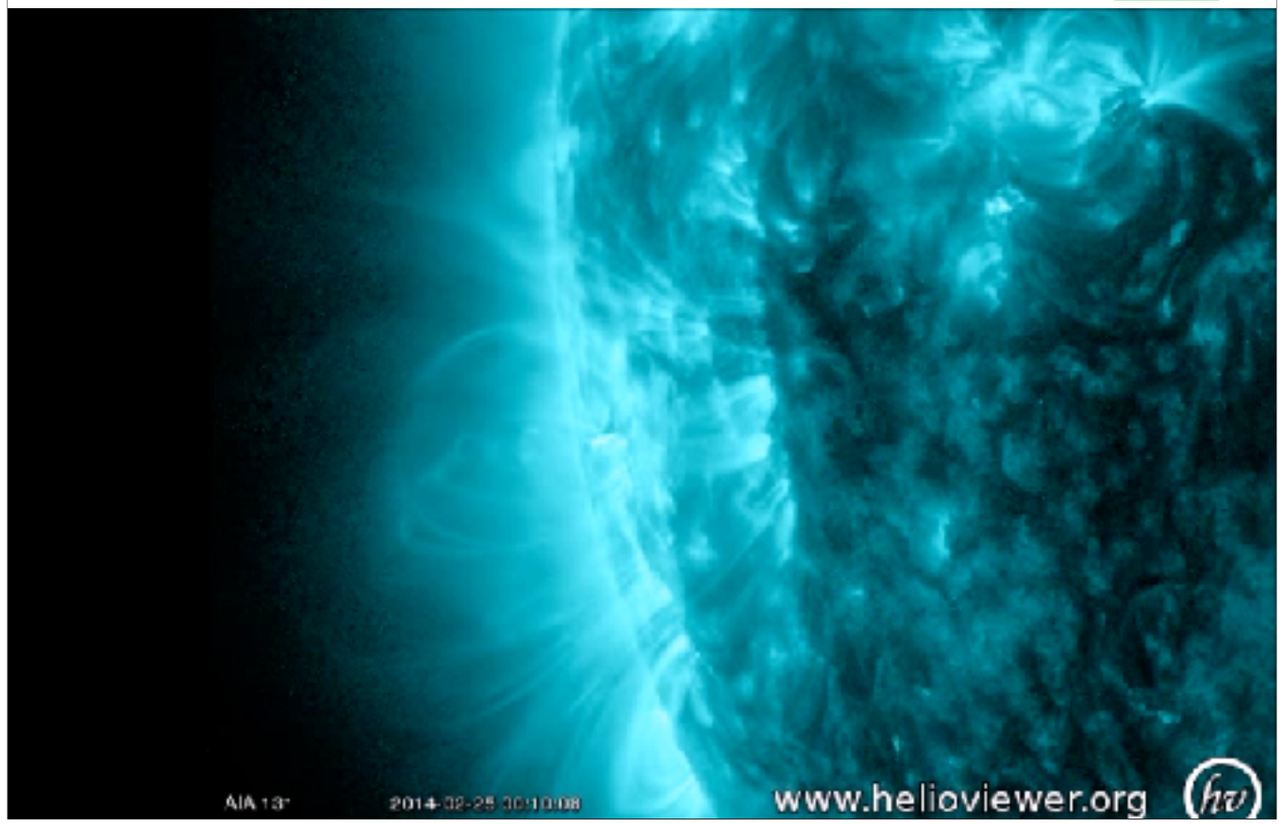
Transit time

On earth
Storm scale – strength
duration
Area of impact

A flare is a light flash near an active region. A volume of plasma is suddenly heated and therefore lights up.



Light storms

During a flare, an area in the solar corona lights up. This is a movie from the EUV imager AIA onboard of SDO.

AU TRANSIT TIME

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8 MIN

STORM SCALE

A,B,C,M,X

https://www.swpc.noaa.gov/products/goes-x-ray-flux

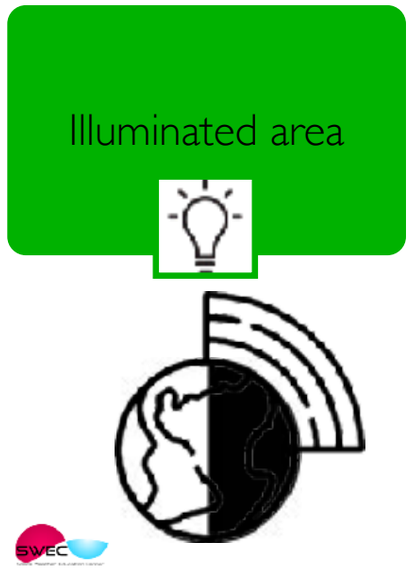
The scale of a flare is defined by it’s X-ray flux. The X-ray flux is measured by the geostationary satellite GOES.

DURATION

MINs to HOUR

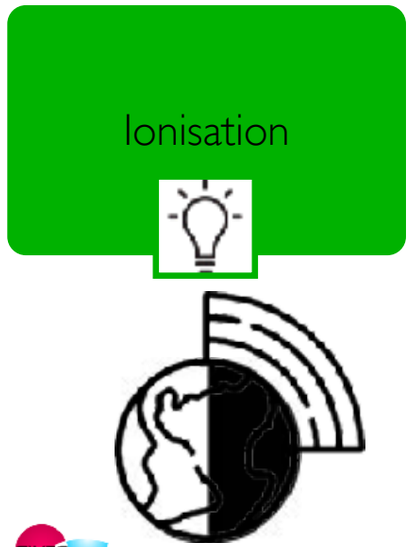
AREA OF IMPACT

AREA OF IMPACT



The icon represent the Earth. White is the day-side, black is the night side.
When you ‘see’/detect a flare, you can be impacted.

IMPACT



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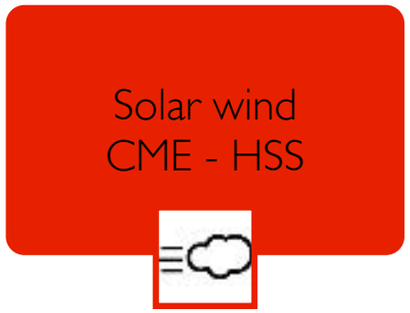

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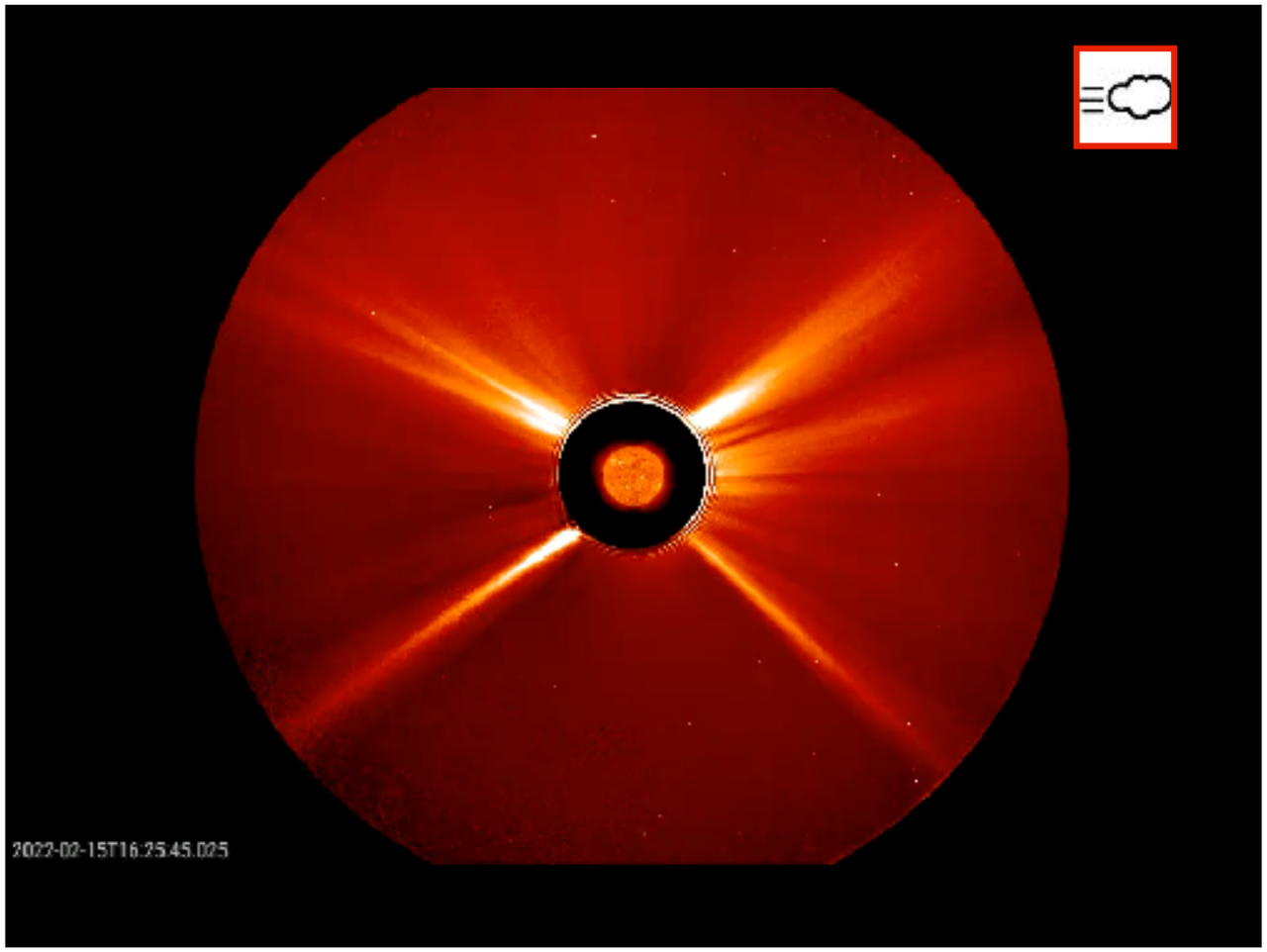

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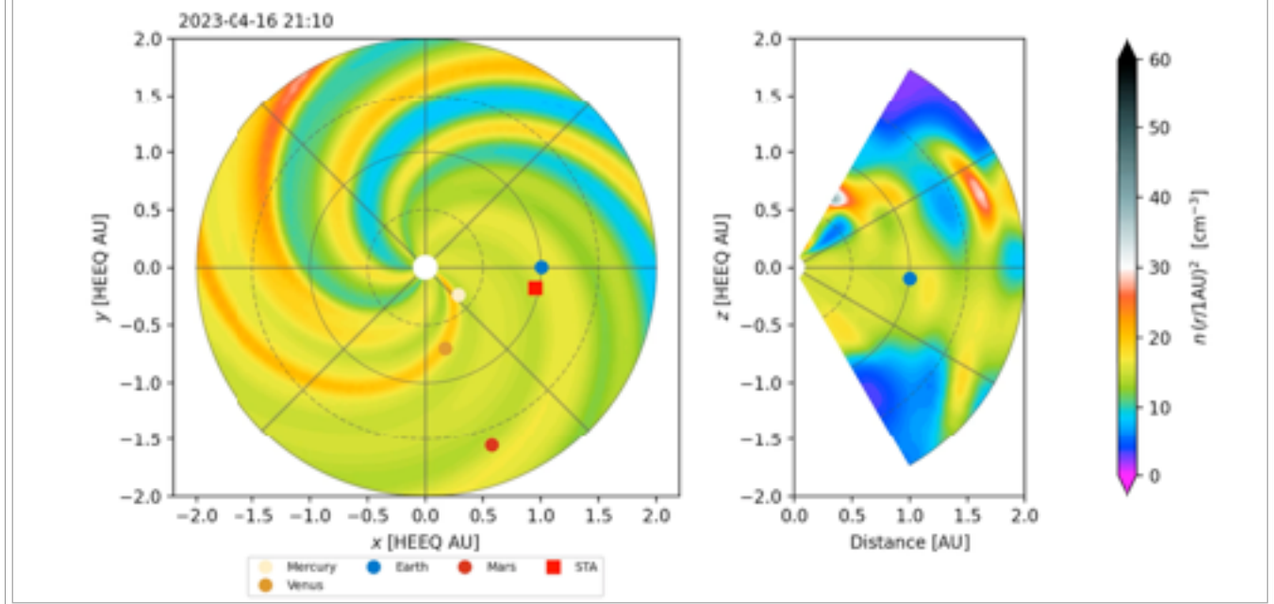
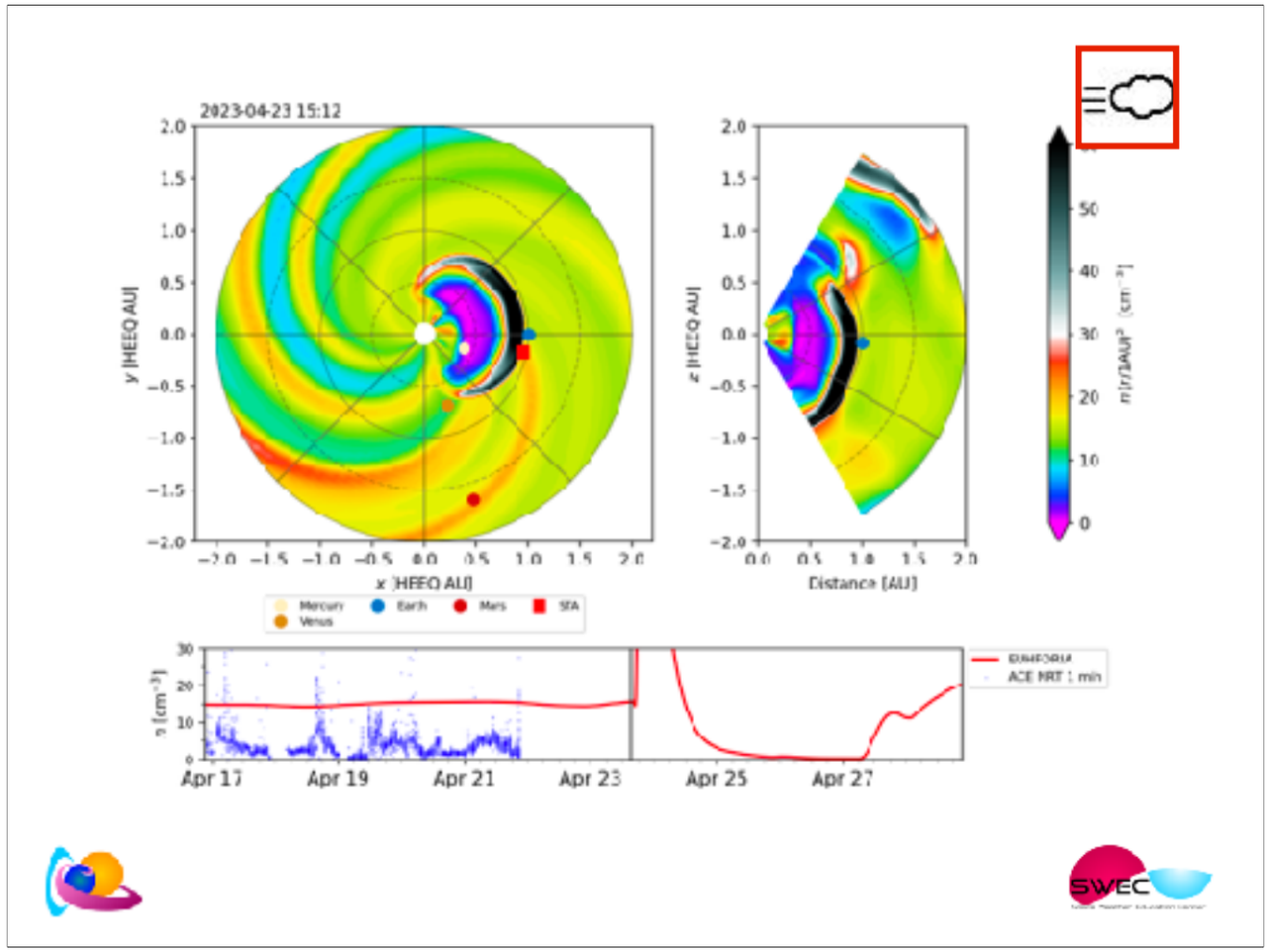


A CME moving through the heliosphere



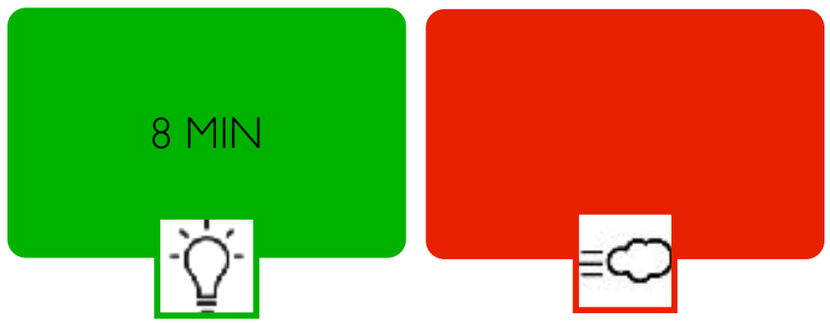
A CME reaches Earth

Next, the forecaster will run a model simulation to have a better estimate of the arrival time. This resulted in an arrival time prediction for late evening on April 23. This is slightly earlier than the first estimation, which was purely based in a projected (and thus underestimated speed).

The picture is the output of a simulation by EUHFORIA of the cloud propagation in the heliosphere. Left is a 'top' view of the sun (white dot) and the earth (blue dot). The black structure is the front of the magnetic cloud (purple) that reaches the earth. On the right is a side view of space. At the bottom, you see that the density curve goes through the roof at the time of arrival.

AU TRANSIT TIME

The energy released during a solar storm moves through space, each with its own typical speed: speed of light, order of a few 100 km/s,….



AU TRANSIT TIME

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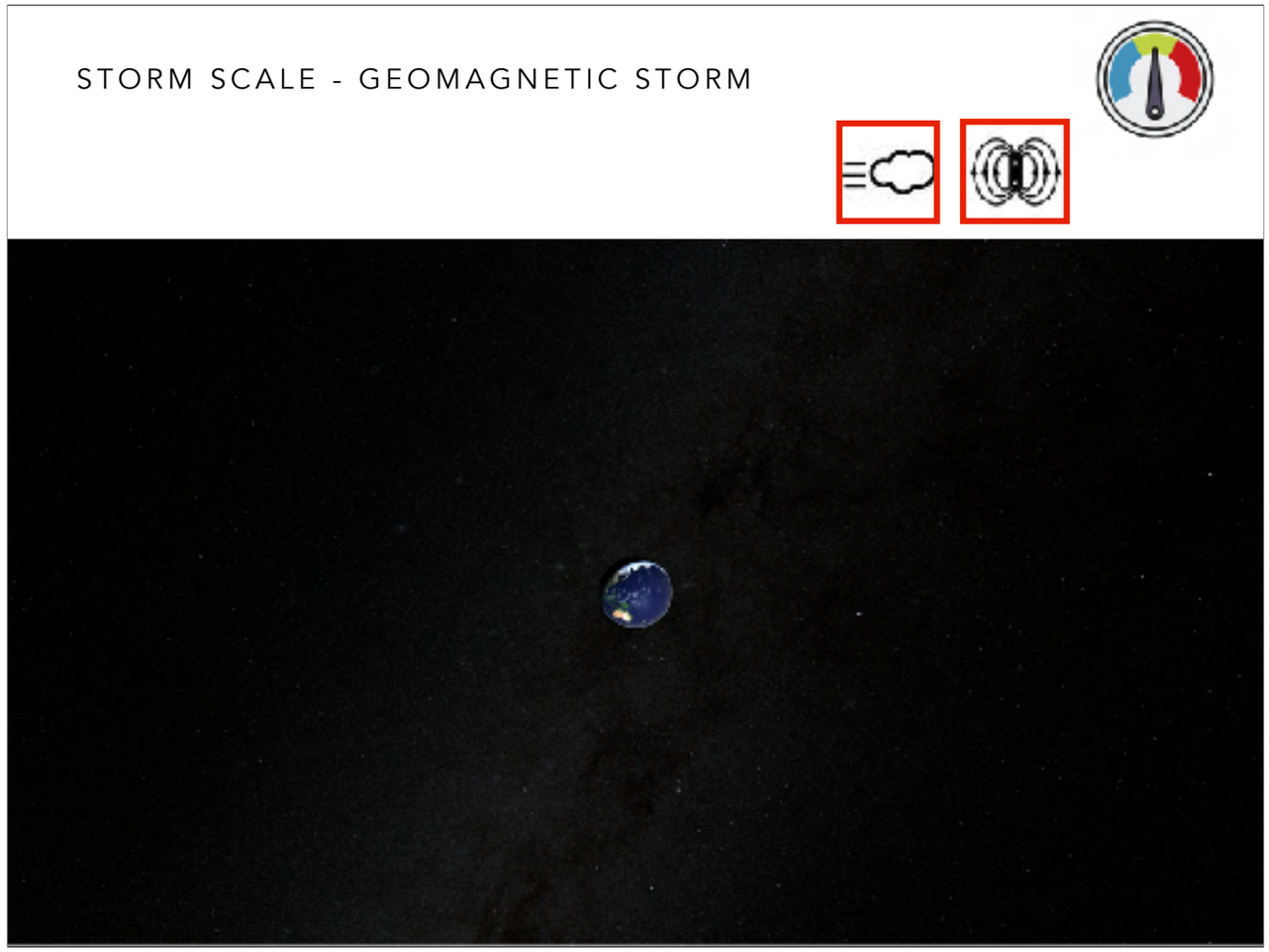
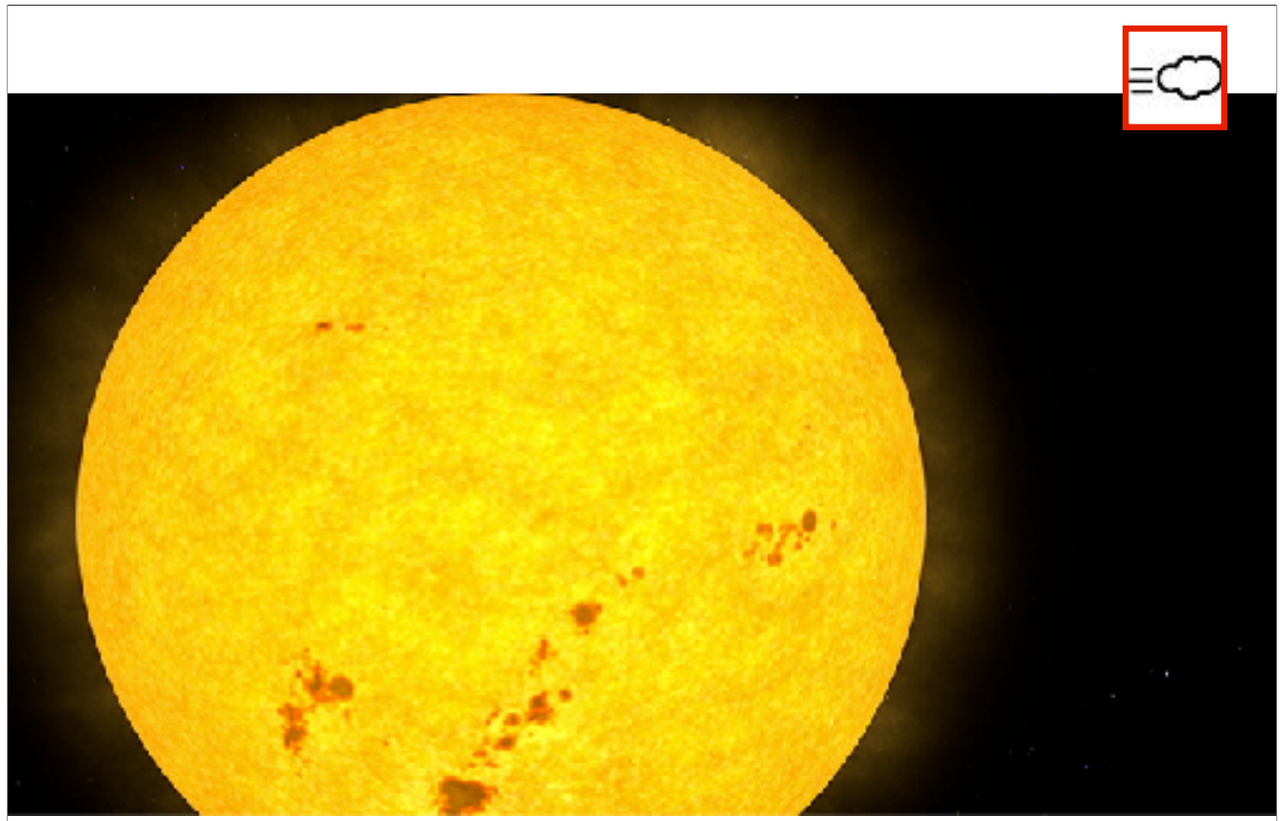


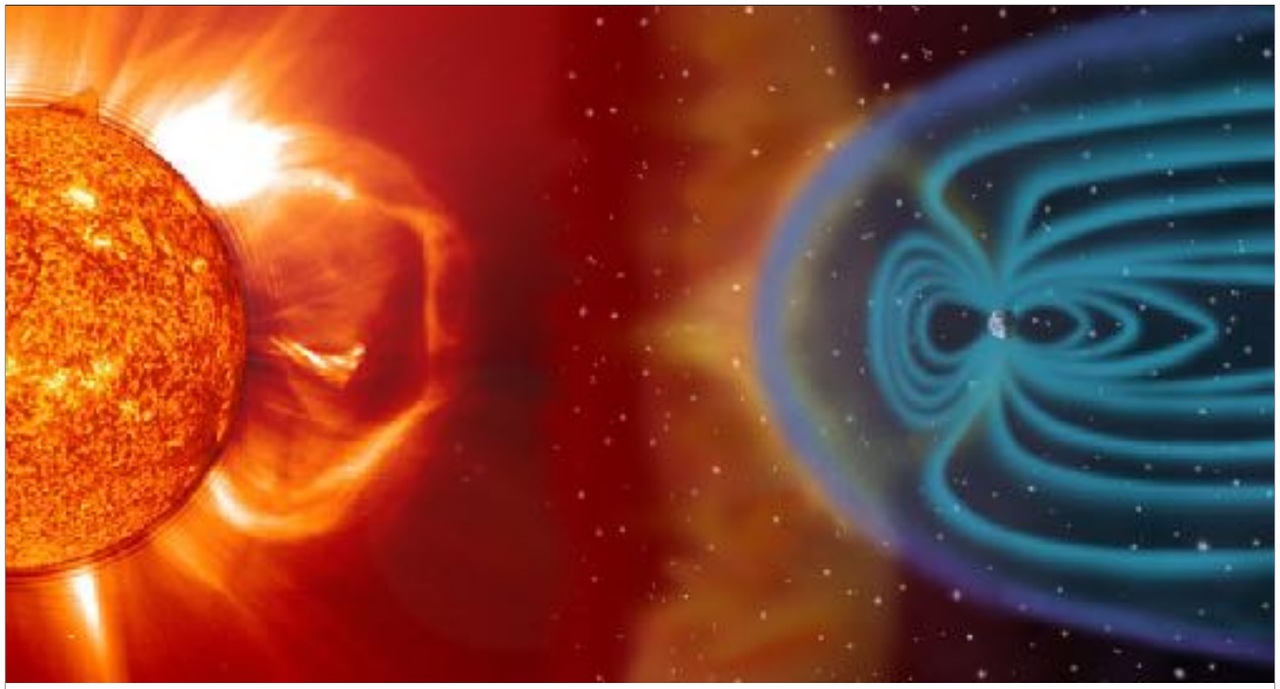
https://svs.gsfc.nasa.gov/5193/
This animation demonstrates the Earth's magnetosphere being hit by a geomagnetic storm on February 3, 2020, simulated by MAGE during the storm that caused the loss of commercial satellites.

The green current density shows where magnetic current is strong. Lines tracing out the magnetic field are purple in regions of weaker magnetism, and orange-yellow where the magnetic field is strongest. Blue tracers in the velocity field represent the solar wind, and they have been calibrated to appear brightest when they are moving toward the Earth.



A CME that hits the Earths magnetosphere.
Precipitating electrons coming from the tail of the magnetosphere gyrate along the earths magnetic field and drop into the atmosphere in the auroral oval.

These electrons have no solar origin, they are present in the plasmasphere of the Earth.



RECONNECTION

The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.

This is the earths magnetosphere. The sun is somewhere far away in the right top corner.
The earth is a giant dipole - similar as the sun. Except, the solar magnetic dipole field reverses every 11 year. The Earths magnetic poles don't. They are already for ages like this.
The part of the earths dipole facing the sun/solar wind is pushed more together, while the part behind the earth is stretched and forms a tail. In front of the magnetic structure, you have a shock.

This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiate are slower compared to the speed of the boat. The boat is super-water wave.
When a plane is super-sonic, there is also a shock in front of it. The pressure waves that the moving plane creates move much slower than the plane.

In the case of a speed boat, the boat moves through the water.
In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

A magnetic field is imbedded in the solar wind. This magnetic field can interact with the magnetic field of the earth at the boundaries of the earth magnetosphere. This interaction is called reconnection. It happens when 2 magnetic regions are confronted with each other.

The blue magnetic field lines are imbedded in the solar wind.
The red magnetic field lines represent the earth magnetosphere.
The blue and the red magnetic region have to face each other. Opposite magnetic field lines can reconnect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.
Therefore, it is very important to know how strong the

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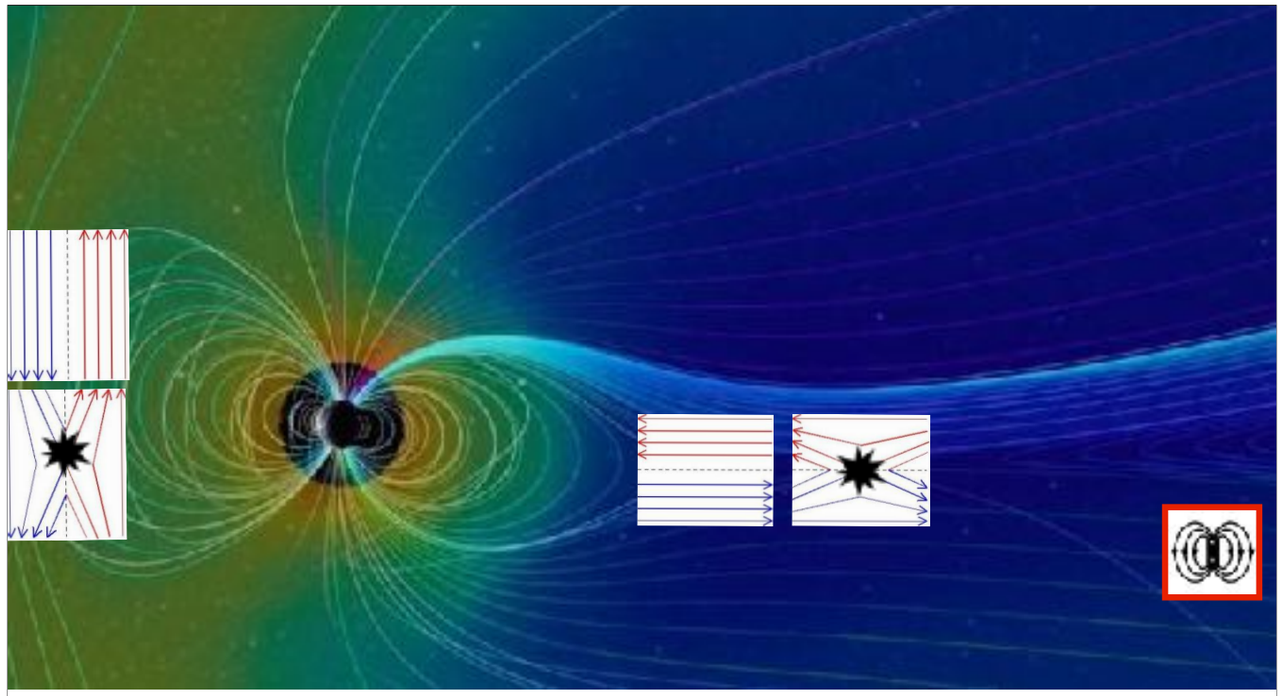


RECONNECTION

The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.

This is the earths magnetosphere. The sun is somewhere far away in the right top corner.
The earth is a giant dipole - similar as the sun. Except, the solar magnetic dipole field reverses every 11 year. The Earths magnetic poles don't. They are already for ages like this.
The part of the earths dipole facing the sun/solar wind is pushed more together, while the part behind the earth is stretched and forms a tail. In front of the magnetic structure, you have a shock.

This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiate are slower compared to the speed of the boat. The boat is super-water wave.
When a plane is super-sonic, there is also a shock in front of it. The pressure waves that the moving plane creates move much slower than the plane.

In the case of a speed boat, the boat moves through the water.
In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

A magnetic field is imbedded in the solar wind. This magnetic field can interact with the magnetic field of the earth at the boundaries of the earth magnetosphere. This interaction is called reconnection. It happens when 2 magnetic regions are confronted with each other.

The blue magnetic field lines are imbedded in the solar wind.
The red magnetic field lines represent the earth magnetosphere.
The blue and the red magnetic region have to face each other. Opposite magnetic field lines can reconnect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.
Therefore, it is very important to know how strong the

0.3 T - solar sunspot
5mT - strength of a typical refrigerator magnet
31.869 μT (3.1×10^{-5} T) - strength of Earth's magnetic field at 0° latitude (North/South), 0° longitude (west/east)
1 to 5 nT - IMF at L1

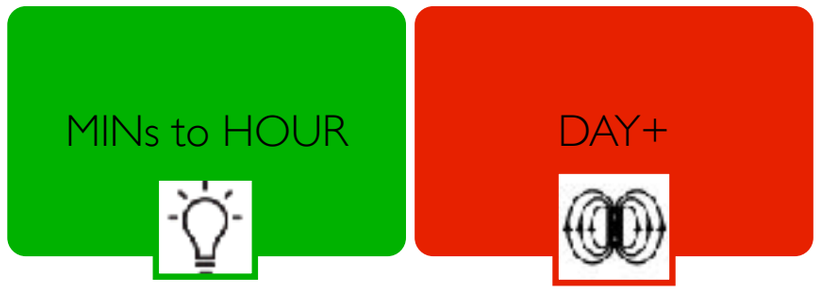
STORM SCALE

A,B,C,M,X

Kp
0 - 9

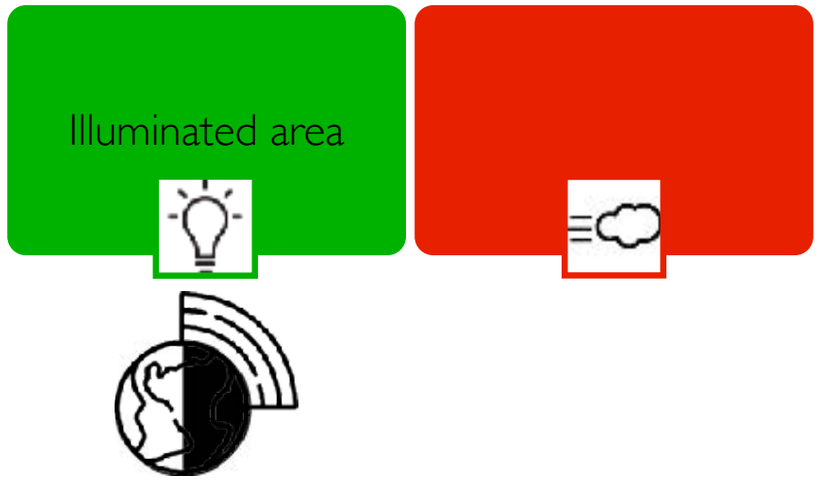
The Kp index is an index that quantifies the disturbance of the magnetic field of Earth. It ranges between 0 and 9, with 0 no disturbance and 9 an extreme disturbance.

DURATION

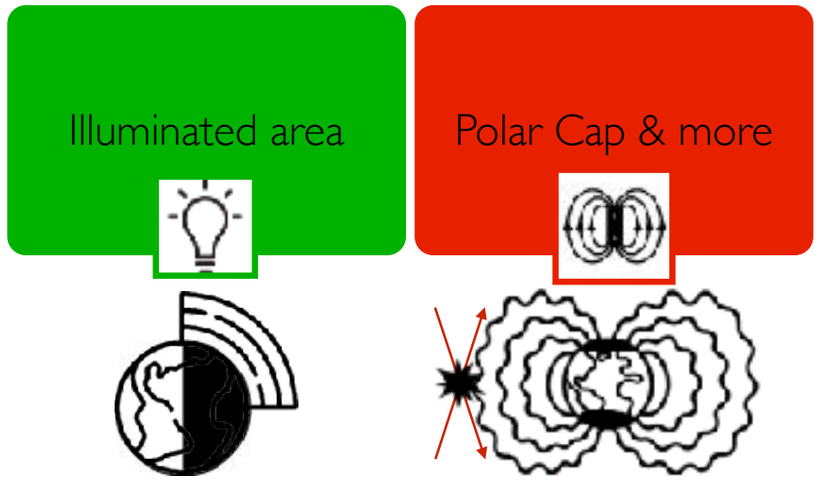


Day or more

AREA OF IMPACT



AREA OF IMPACT

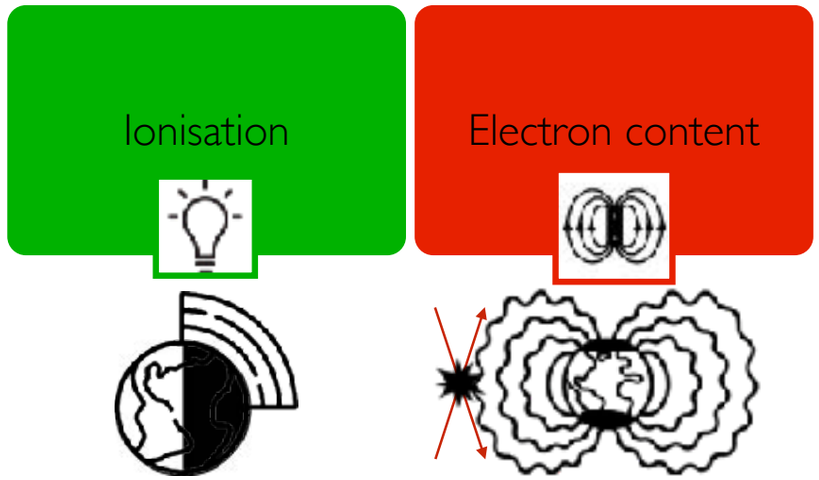


The magnetic field carried by the solar wind can reconnect on the day side with the magnetic field of Earth.
On the night side, magnetic reconnection between opposite magnetic field of the magnetosphere of Earth. (No solar magnetic field involved.)

The icon of the dipole represents the Earth dipolar field.

The result is that the Earth’s magnetic field is disturbed and most strong in the polar regions.

IMPACT



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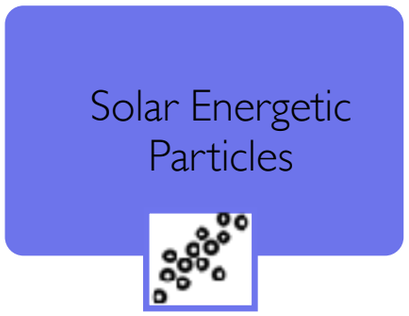


Change in energy output on the scale of minutes, hours, days.

Remote sensing (seeing) - in situ (taste and touch the ambient space)

Space weather is the change of energy that occur in the space environment.

A Flare is a sudden strong increase of the solar e.m. radiation. The light flash is localised on the solar surface.
SDO/AIA

A Coronal Mass Ejection is a plasma cloud that is ejected into space. You consider it as a cloud and not as a bunch of individual particles. It is superimposed on the background solar wind. You can see a CME as a complex magnetic bag with different magnetic layers with plasma in it that travels as a tsunami through space. It can go faster/as fast as/slower than the background solar wind. When it is faster, you will see a shock in front of the cloud. This is exactly the same as the shock you see in front of a speed boat.
A CME is visible as a white cloud in corona graphic images like the one on the slide. A coronagraph is a telescope that creates an artificial eclipse and makes pictures in the visible light of the region around the sun.
SOHO/LASCO C2 (red) and LASCO C3 (blue)

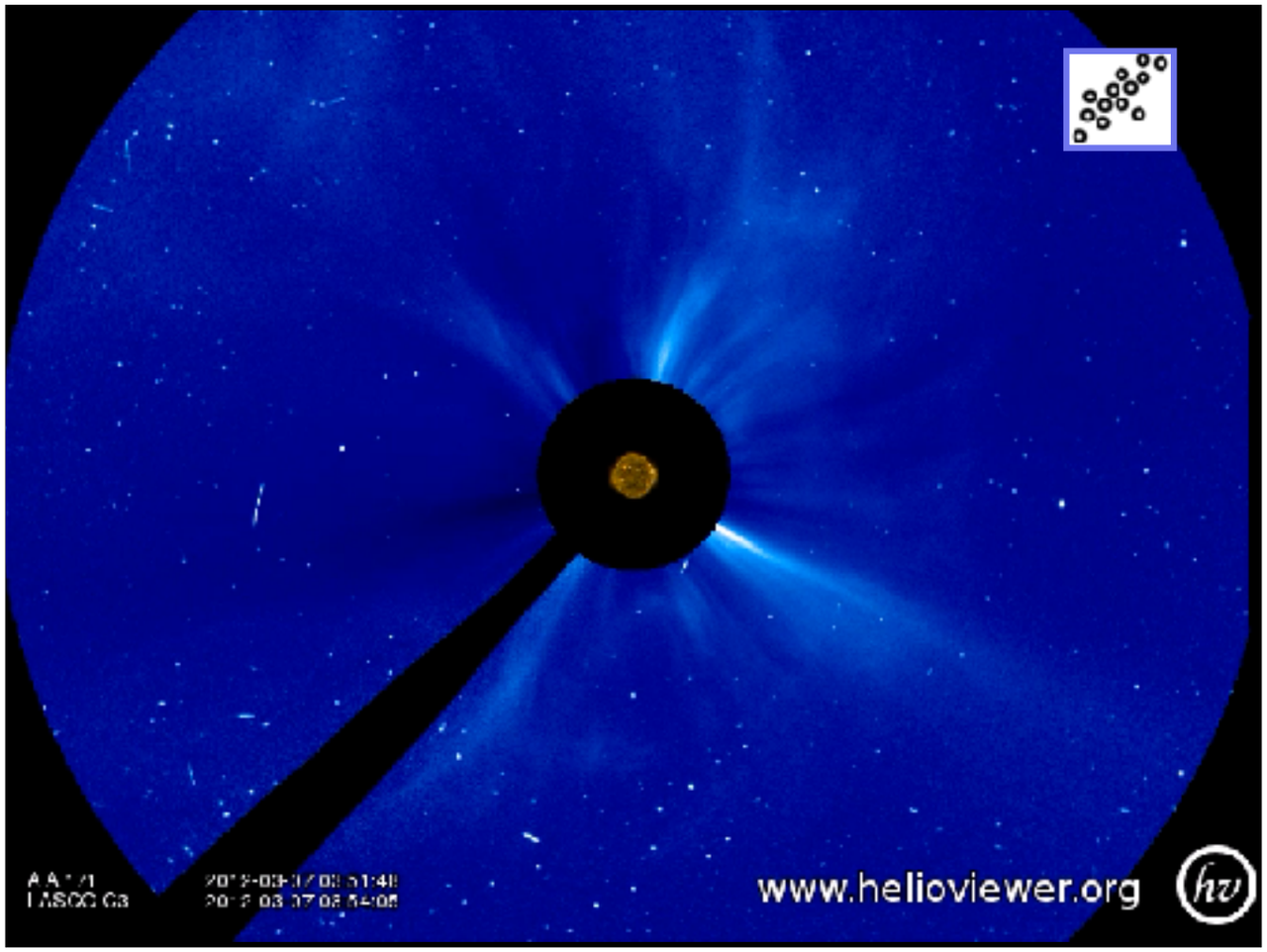
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating from a CH is faster compared to the usual solar wind.
SDO/AIA

Particle shower
A particle storm is a bunch of electrically charged particles that are accelerated in the solar atmosphere to very high velocities by a large-scale magnetic eruption often causing a CME and/or solar flare. They follow the IMF
They may impact telescopes. They are seen as white stripes and dots: this are particles that fall into the lens and blind the pixel(s). During that particular moment, the telescope can't see anymore through the impacted pixels. You can say that the dots and stripes represent a sort of in situ measurement.

In situ means that you measure a parameter local. Remote sensing means that you look at something from a distance.

Near Earth, the IMF still controls the solar wind and its movement. If we would go much much further, the CME magnetic bag with solar plasma would be almost empty (all the solar material is spread

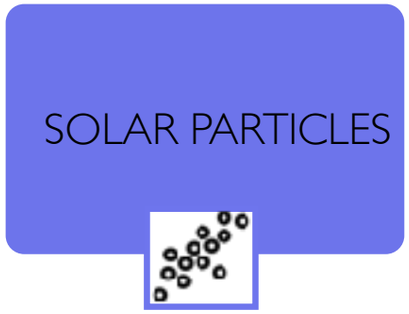
over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

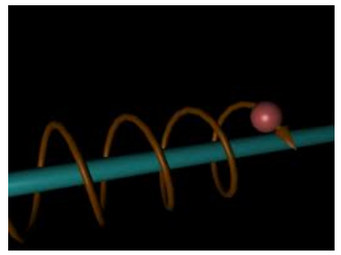


Particle showers

You see energetic particles that impact the telescope LASCO/C3 onboard of SOHO. They are seen as white stripes and dots: these are particles that fall into the lens, hit a pixel or more pixels. The impacted pixel in blinded. The dots and stripes represent an in situ measurement.

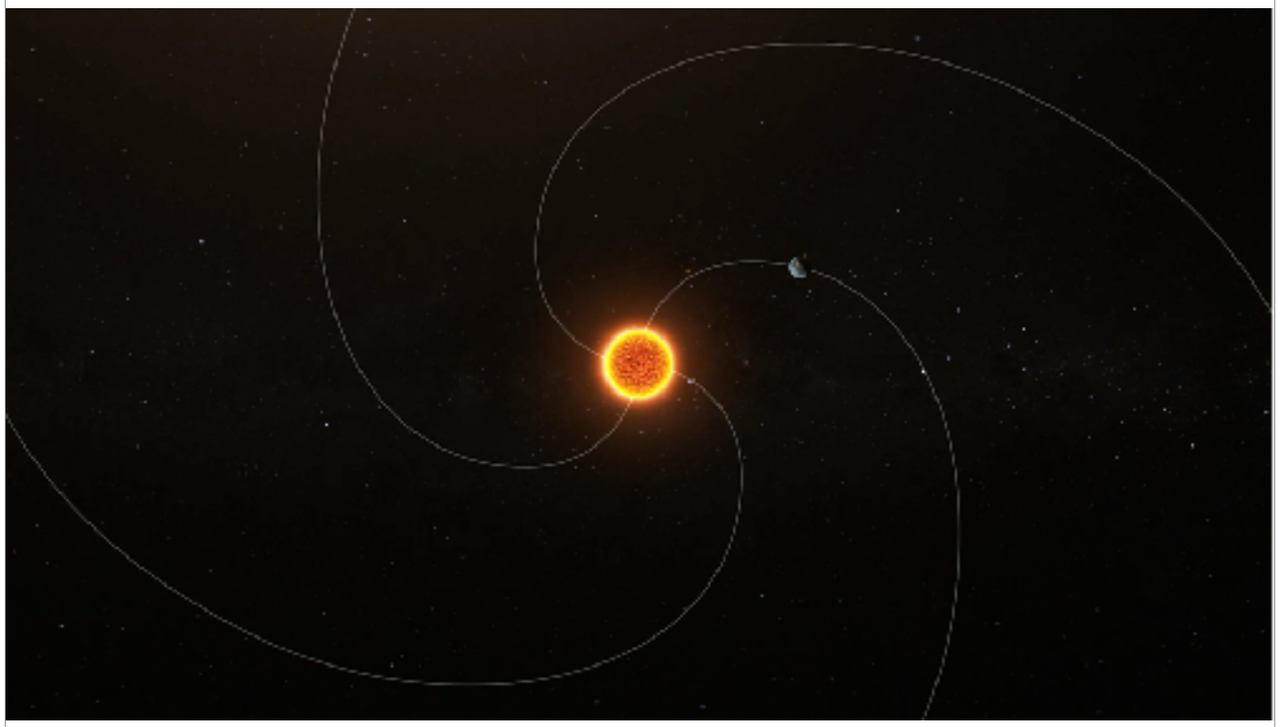
(The image in the middle of the occulter is an EUV image from the instrument AIA onboard of SDO.)





Solar energetic particles follow magnetic field lines.

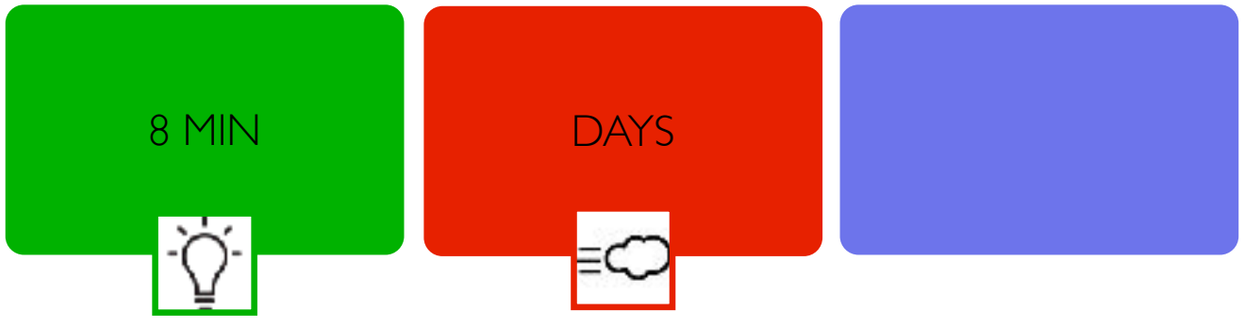
They have to go where the magnetic field takes them.



https://svs.gsfc.nasa.gov/20320
An intense solar eruptive event has many parts. This animation starts with a solar flare, which sends light and energy in straight paths, traveling at the speed of light. A coronal mass ejection, or CME, appears next – this is a giant cloud of solar particles that also expands in a straight direction with speeds up to two thousand miles an hour. The eruption also generates solar energetic particles, with speeds nearly reaching the speed of light, following the spiral shape of the solar wind's magnetic fields into interplanetary space.

AU TRANSIT TIME

The energy released during a solar storm moves through space, each with its own typical speed: speed of light, order of a few 100 km/s, relativistic speeds.



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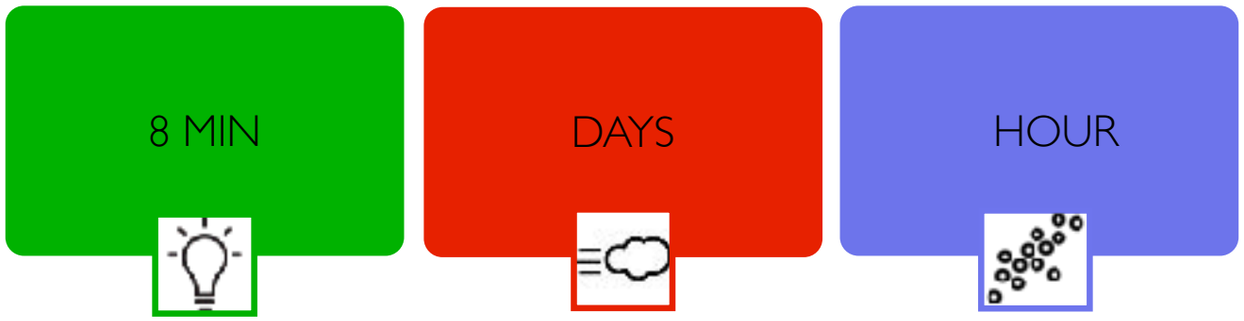


STORM SCALE

A,B,C,M,X

Kp
0 - 9

Storm - major storm

The GOES satellite measures the proton flux.
Storm: 10 pfu (proton flux units) for >10MeV
Major storm: 100 pfu for >100MeV

DURATION

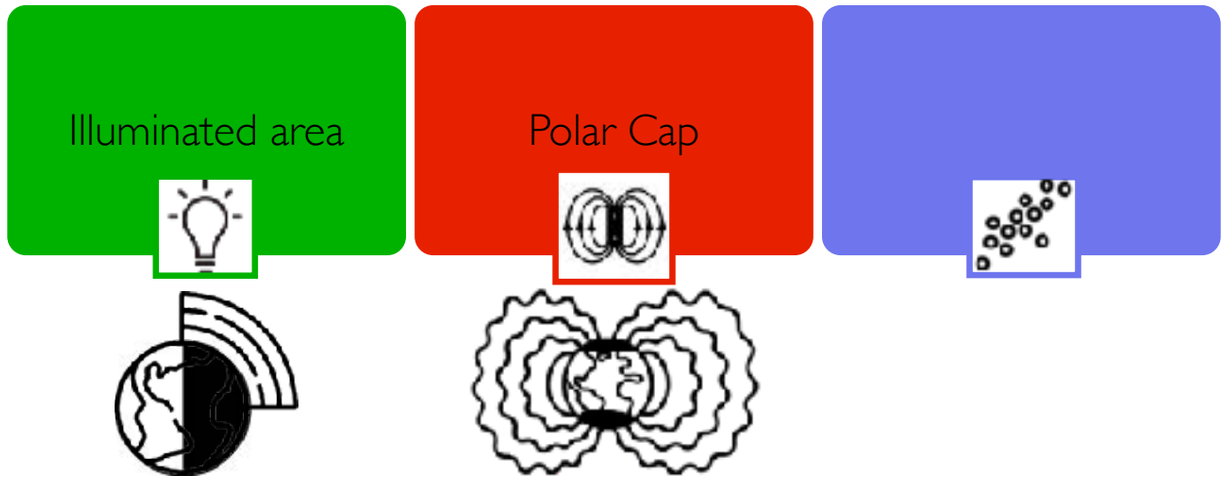
MINs to HOUR

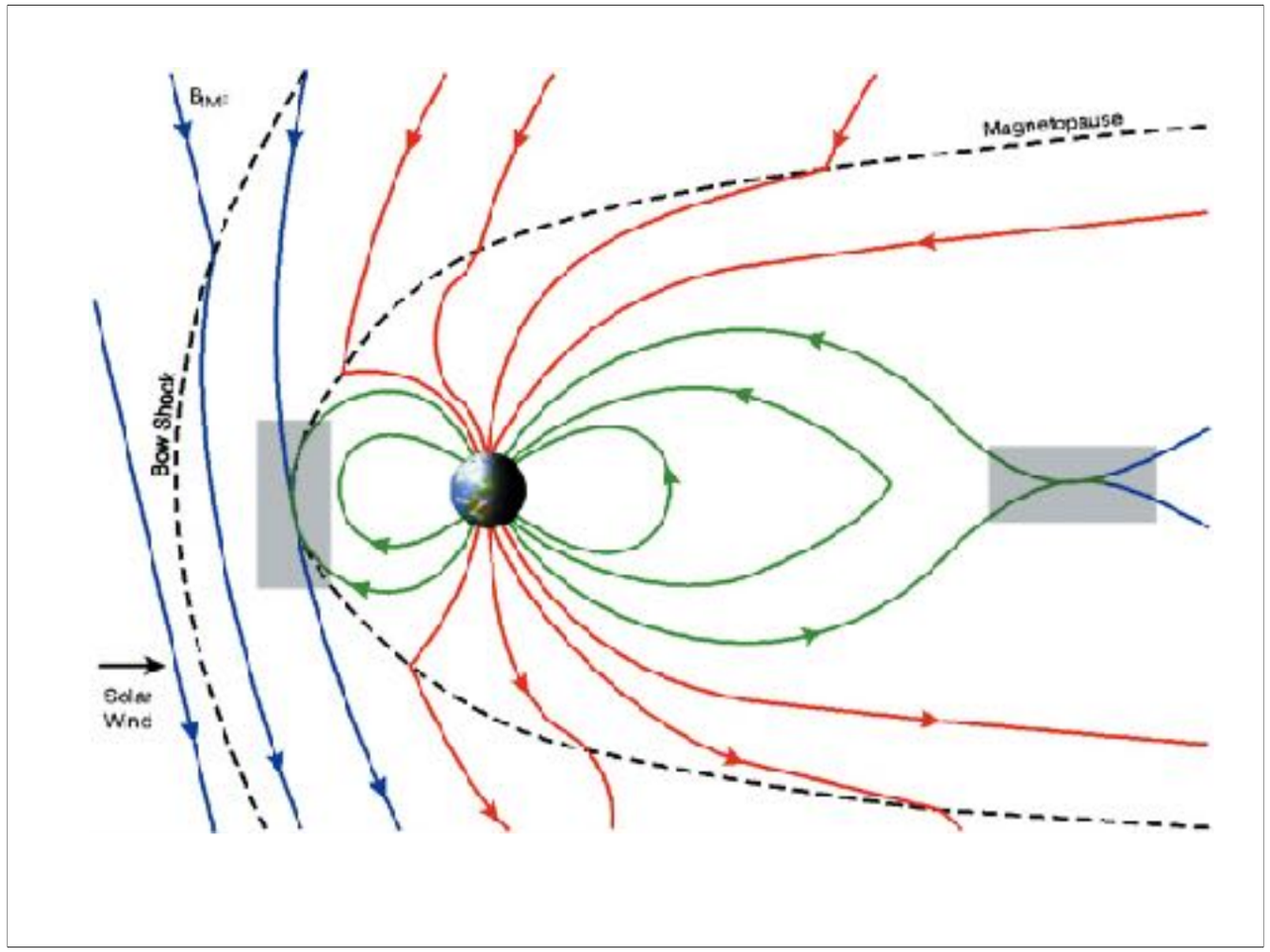
DAY+

HOURS to DAYS

It takes in the order of an hour to reach Earth but the particle shower on Earth can last for days

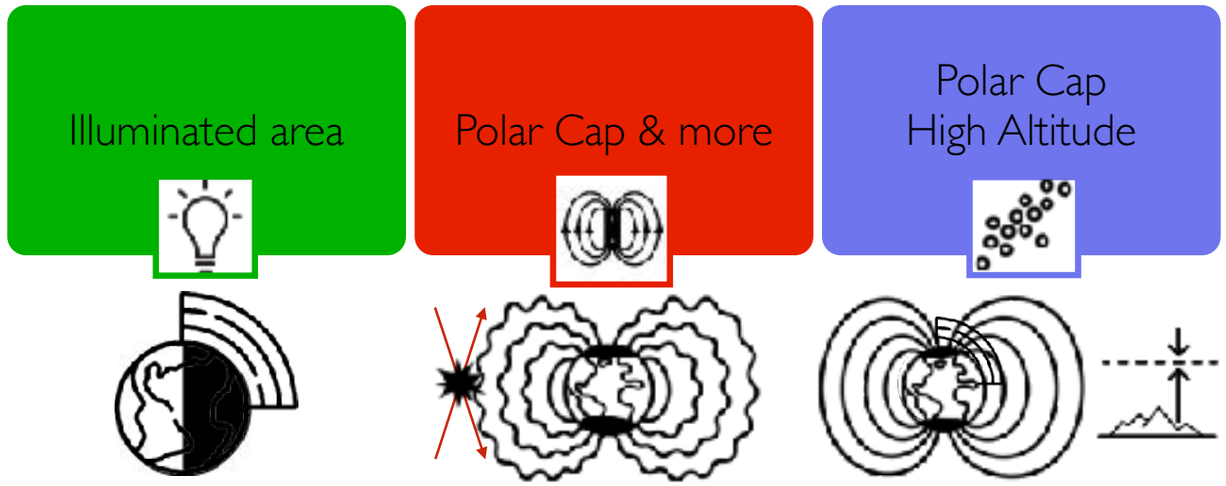
AREA OF IMPACT





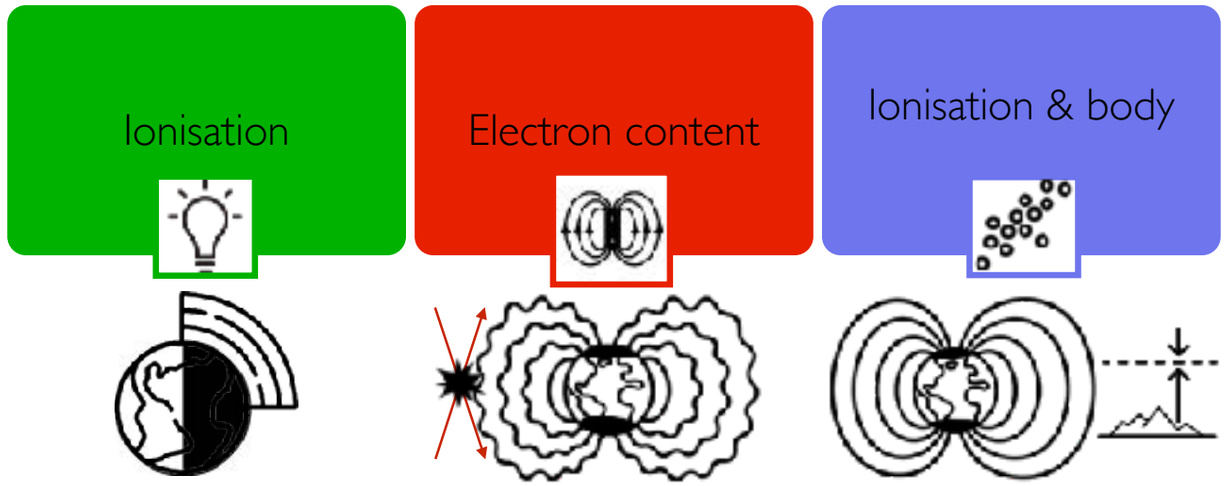
The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).

AREA OF IMPACT



The higher the energy, the deeper they can penetrate into the Earths atmosphere.

IMPACT



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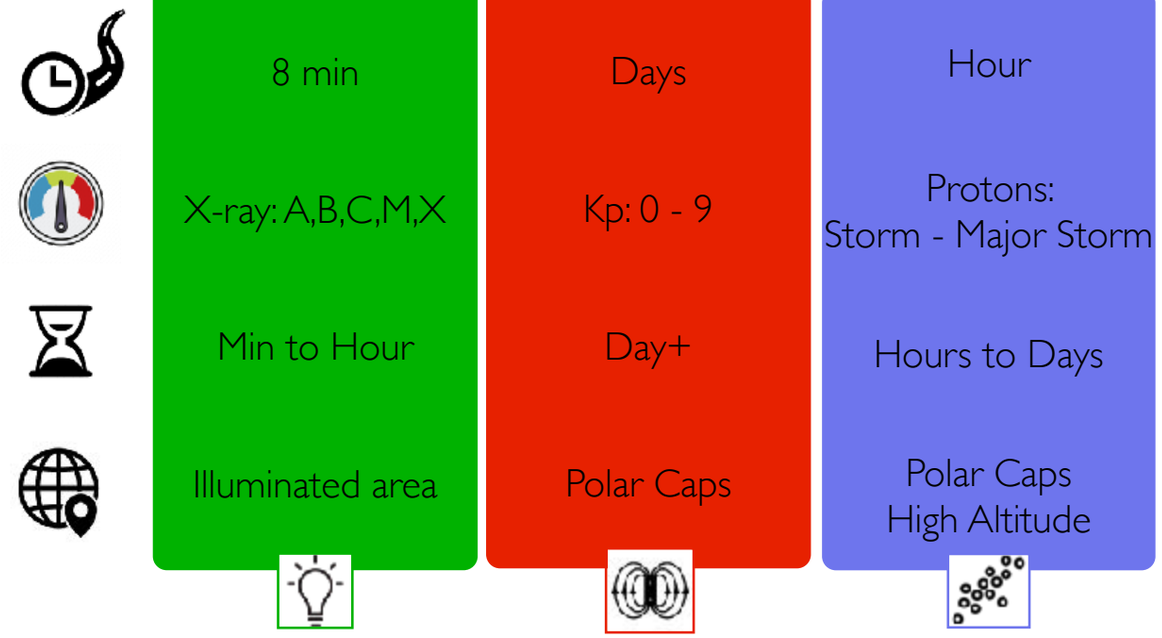
Overview


8 min
X-ray: A,B,C,M,X
Min to Hour
Illuminated area
Days
Kp: 0 - 9
Day+
Polar Caps
Hour
Protons:
Storm - Major Storm
Hours to Days
Polar Caps
High Altitude

X-ray Flux Passport

Type

X-ray output (0.1-0.8 nm and 0.05-0.4 nm) of the solar spectrum versus time.

Use

To quantify solar flares happening on the side of the Sun facing Earth.

Units

$W \cdot m^{-2}$
Integrated over 1 min

Sensor

GOES-16 satellite
GOES-18 satellite

Sensor location

Geostationary orbit

Cadence

Integrated over 1 min

Data location

https://www.swpc.noaa.gov/products/goes-x-ray-flux

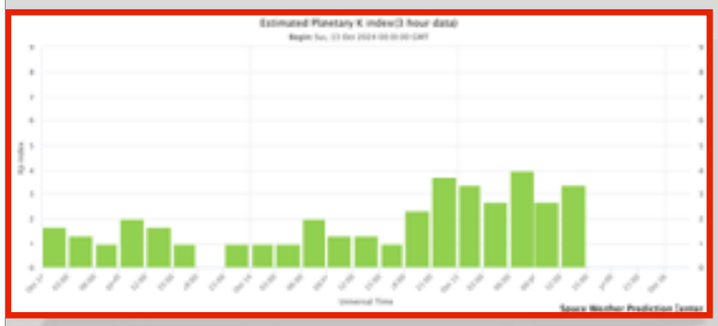
Plot

X-axis: time in UTC
Y-axis: X-ray flux in W/m^2, i.e. how much energy (Joule) passes in 1 sec (W=Watt=J/s) through 1 square meter at geostationary height.

Classes

The long wavelength (0.1-0.8 nm, red and orange) is the reference for identification of the class. The red is measured by GOES 18, orange by GOES 16.
The flare classes are indicated on the right of the graphs. When the peak of the red/orange curve is in blue/green/yellow/orange/red, it is a A/B/C/M/X-class flare.

Kp-index Passport



What

Kp-index (NOAA) represents the planetary geomagnetic condition or the state of the magnetic field of Earth. It is a planetary index and is valid for the globe.

Use

To quantify the disturbance of the magnetic field of Earth. The scale ranges from 0 to 9, with 0 indicating no disturbance and 9 the highest disturbance of the Earth magnetic field .

Plot

X-axis: data and time in UTC, time stamp every 3 hours.
Ranges from 3 days in the left (left) to now (right).
Y-axis:
coloured bars of 3 hours wide, height= Kp-index (NOAA)
Height of a bar represents a number: 0, 0+, 1-,1,1+, 2-,2,2+, … 8-,8,8+, 9-,9.
With e.g. 2- = 1,70 and 2+ = 2,30 etc.

Definitive

The values become definitive after calculation and confirmation by the German Research Centre for Geosciences, Potsdam.

Magnetometers

The calculation is based upon the measurements done by magnetometers.

Observatories

Thirteen (13) Geomagnetic Observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude.

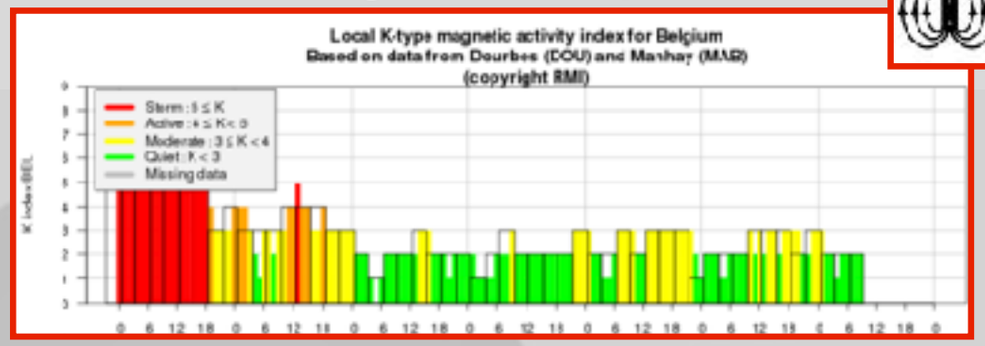
Estimated

by NOAA, US

Data location

https://www.swpc.noaa.gov/products/planetary-k-index

K Belgium Passport



What

K Belgium represents the geomagnetic conditions or the state of the magnetic field of Earth above Belgium. It is an index for Belgium.

Use

To quantify the disturbance of the magnetic field of Earth. The scale ranges from 0 to 9, with 0 indicating no disturbance and 9 the highest disturbance of the Earth magnetic field .

Plot

X-axis: data and time in UTC. Ranges from 7 days in the left (left) to now (right).
Y-axis: coloured bars of 1 hour wide, height= K Belgium.
Height of a bar represents a natural number: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

Sensors

The calculation is based upon the measurements done by the Royal Meteorological Institute of Belgium based on the measurements done in Dourbes and Manhay, Belgium.

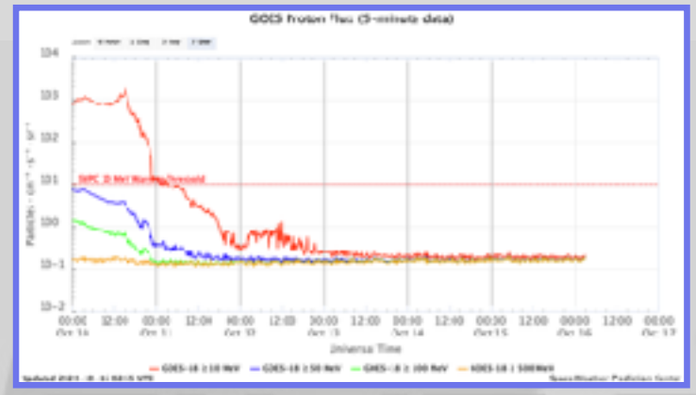
Provider

Royal Meteorological Institute of Belgium

Data location

http://ionosphere.meteo.be/geomagnetism/K_BEL/

Proton Flux Passport



Type

Graph, flux of solar protons versus time.

Sensor

GOES-18 satellite

Use

To quantify proton events impacting Earth.

Sensor location

Geostationary orbit

Units

Particles/(cm^2*s*sr) with s=second and sr=steradian

Cadence

Integrated over 5 min

Data location

https://www.swpc.noaa.gov/products/goes-proton-flux

Plot

X-axis: time in UTC
Y-axis: Particles/(cm^2*s*sr), i.e. how many solar protons with a particular energy (eV) pass in 1 sec through 1 square centimeter from a cone with the Sun at the apex. The count is done at geostationary height.
The 4 colours represent 4 energies.