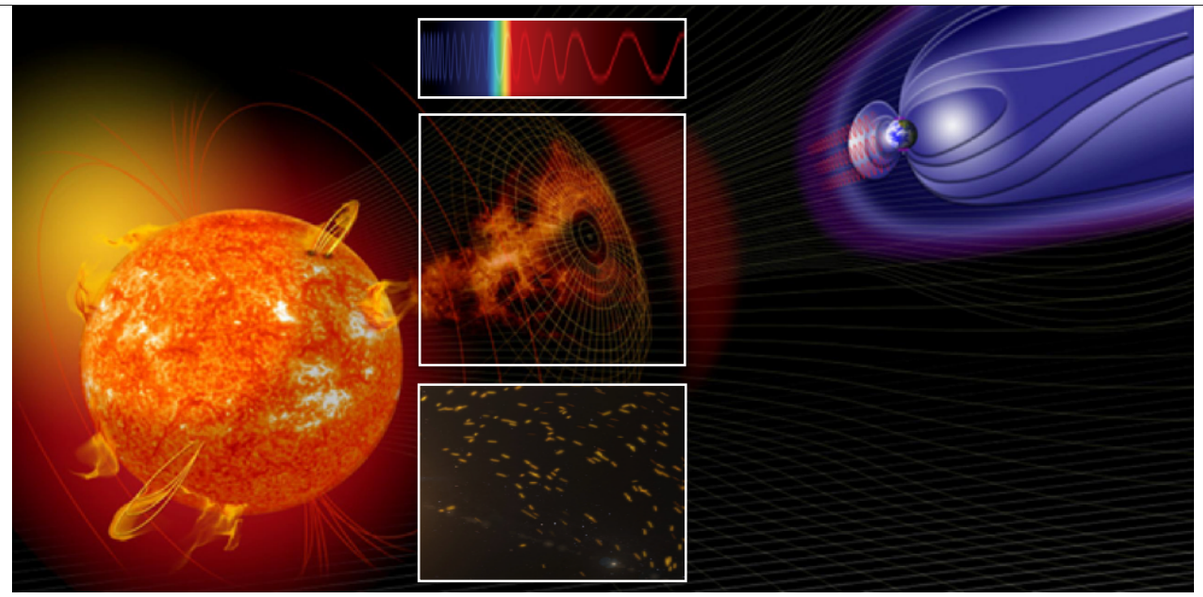


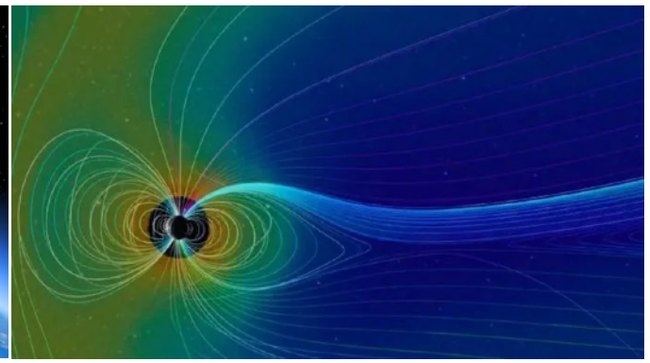
SPACE WEATHER

Introduction

Petra Vanlommel

Space Weather

The Sun's energy impacting earth's atmosphere and magnetic shield.



As we go out into space, the atmosphere becomes very thin, until by the time we are in space, it has almost vanished. Almost, but not quite. Even in space there are some atoms which are often moving very quickly. Many forms of energy also move through **space** and it is the **interaction of energy and atoms that produces what we refer to as space weather**. In particular, space weather is the changes that occur in the space environment.

The **sun** is the source of 'normal' terrestrial weather. It is also the **primary (but not the only) source of space weather**. Most aspects of space weather affect us to some extent. The more our society becomes dependent on technology and the more we utilize space, the more we are affected by space weather. Some aspects of space weather are benevolent, and allow activities not otherwise possible such as long range radio communications. Some aspects are benign but fascinating such as the Aurora, and some are malevolent. **Like terrestrial weather, it depends on the situation and the event.**

THE SUN AS A BALL OF ENERGY

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

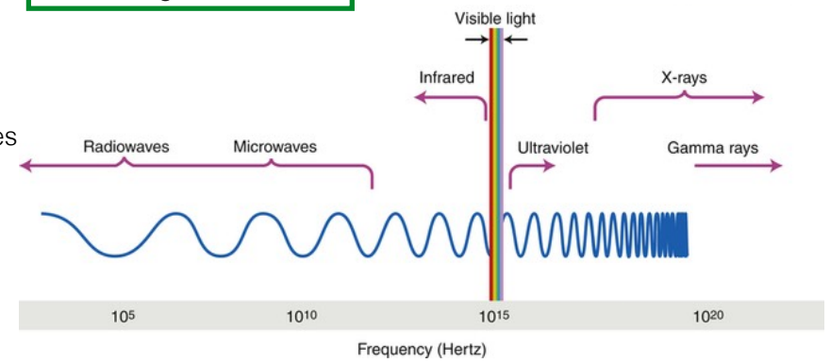
This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

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

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.

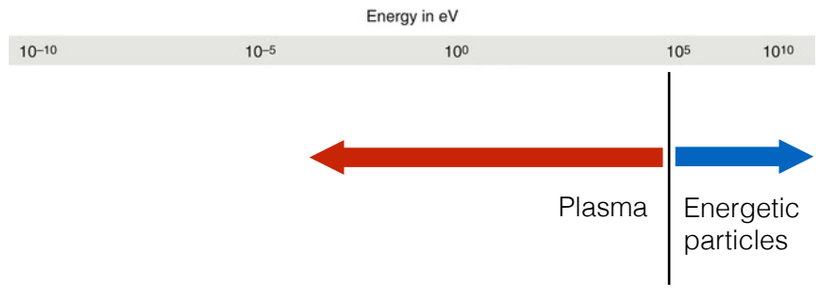
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



Particles

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

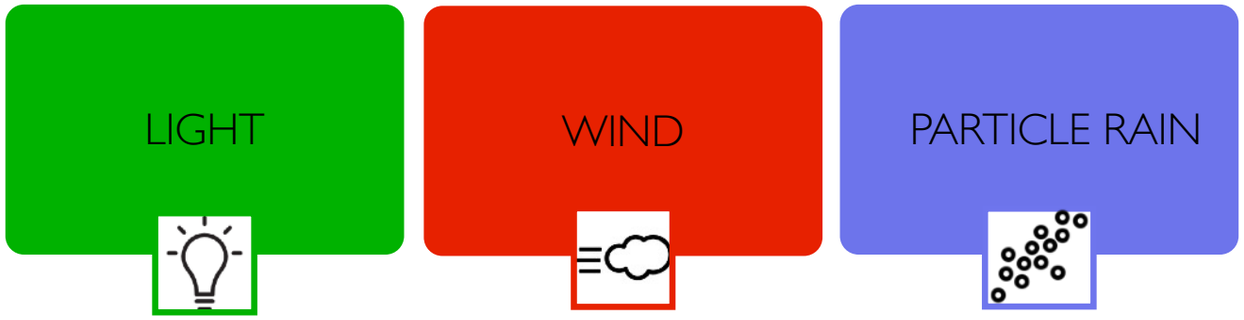


100 kEV

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

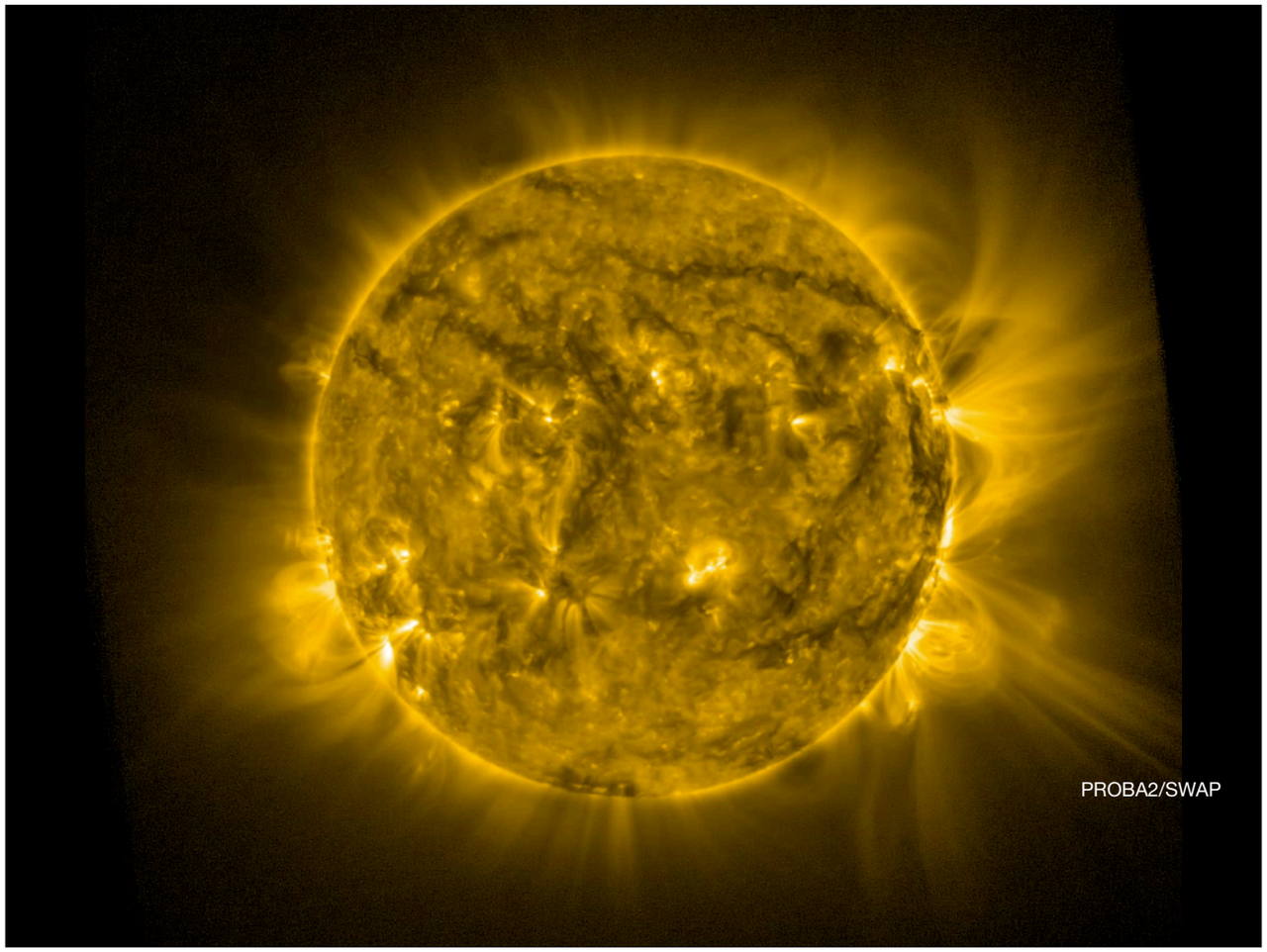
Particle precipitation - energy transmitted in the form of fast-moving atomic or sub-atomic particles —> drizzle

Energy expressed in eV= 1.602 10^-19 J

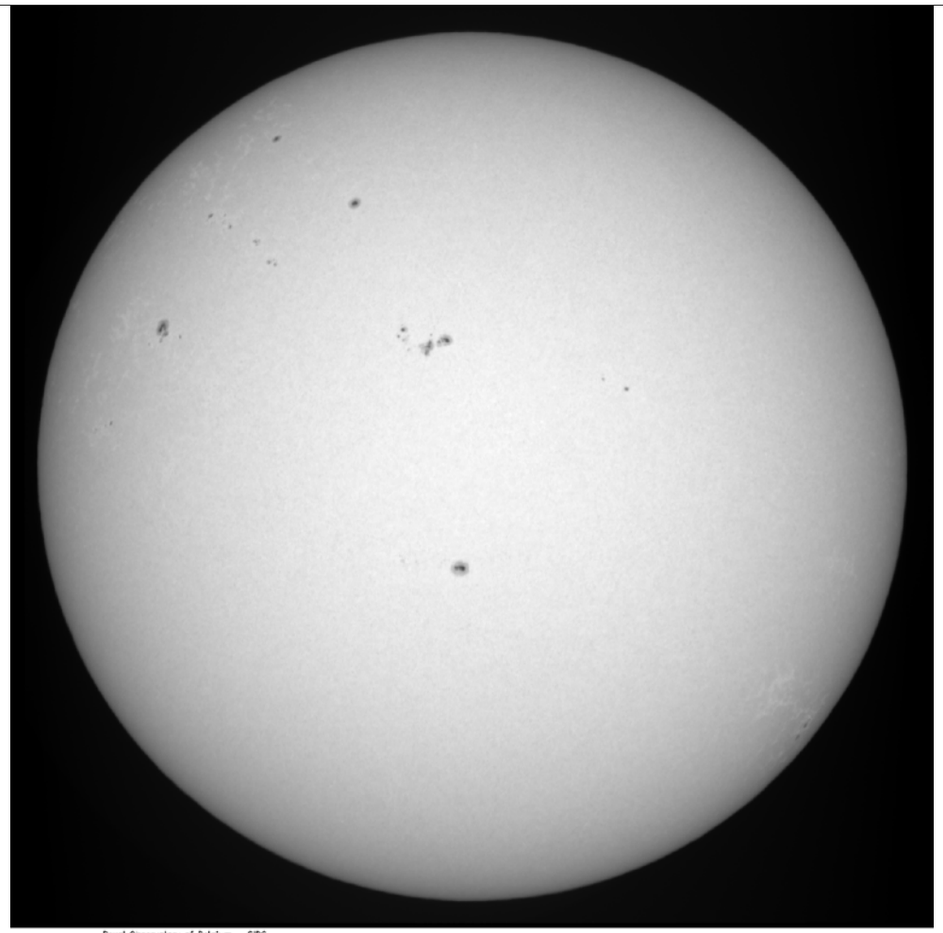
https://lasp.colorado.edu/home/mag/research/energetic-particle-precipitation/

Focus on solar energetic particles

Magnetism drives space weather and the sun’s dynamics.

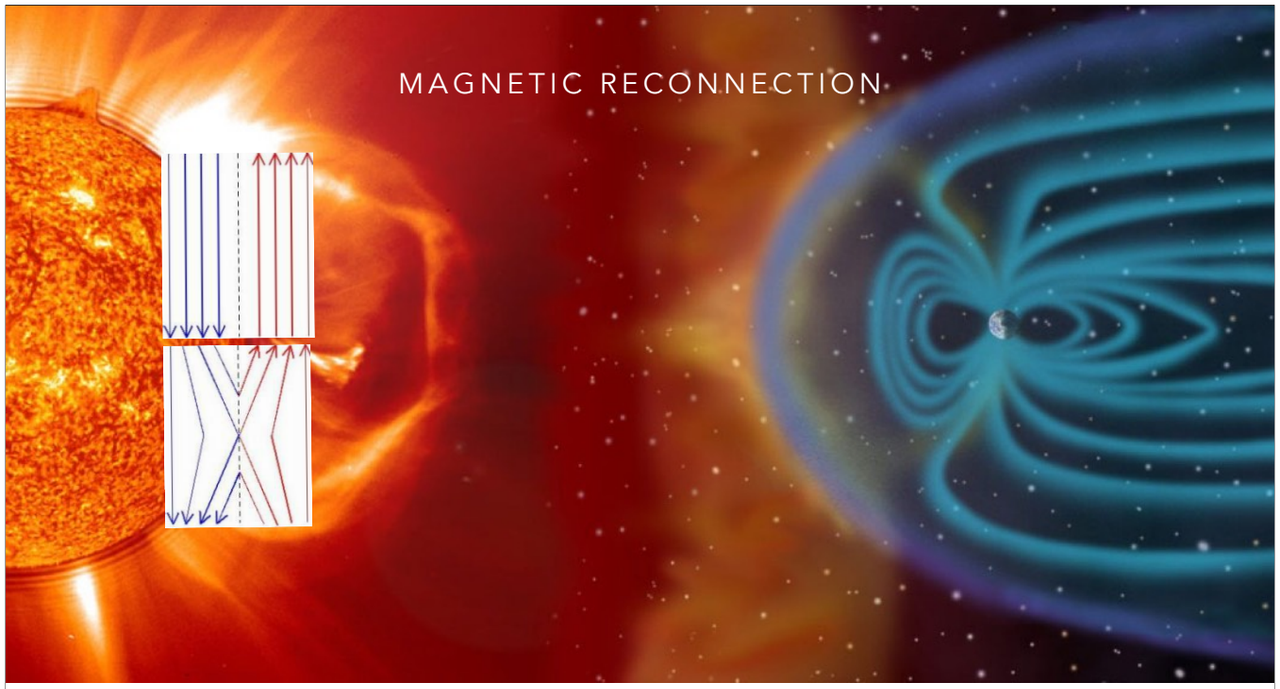


In the EUV it looks like this!
The sun doesn’t only rotate but it is also tangled with loops which move, shake back and forth, restructure and do all sorts of electric and magnetic magic.
It is a turbulent plasma ball where magnetic fields are moving, shake, connect with other other, ….



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

At the controle room of the solar dome, you saw also H Alpha and Ca II images: they represent the chromosphere, a layer on top of the photosphere.
You saw plages, filaments.
When a filament erupts, it might be watched by LASCO onboard of SOHO as a CME, a coronal mass ejection.



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

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.

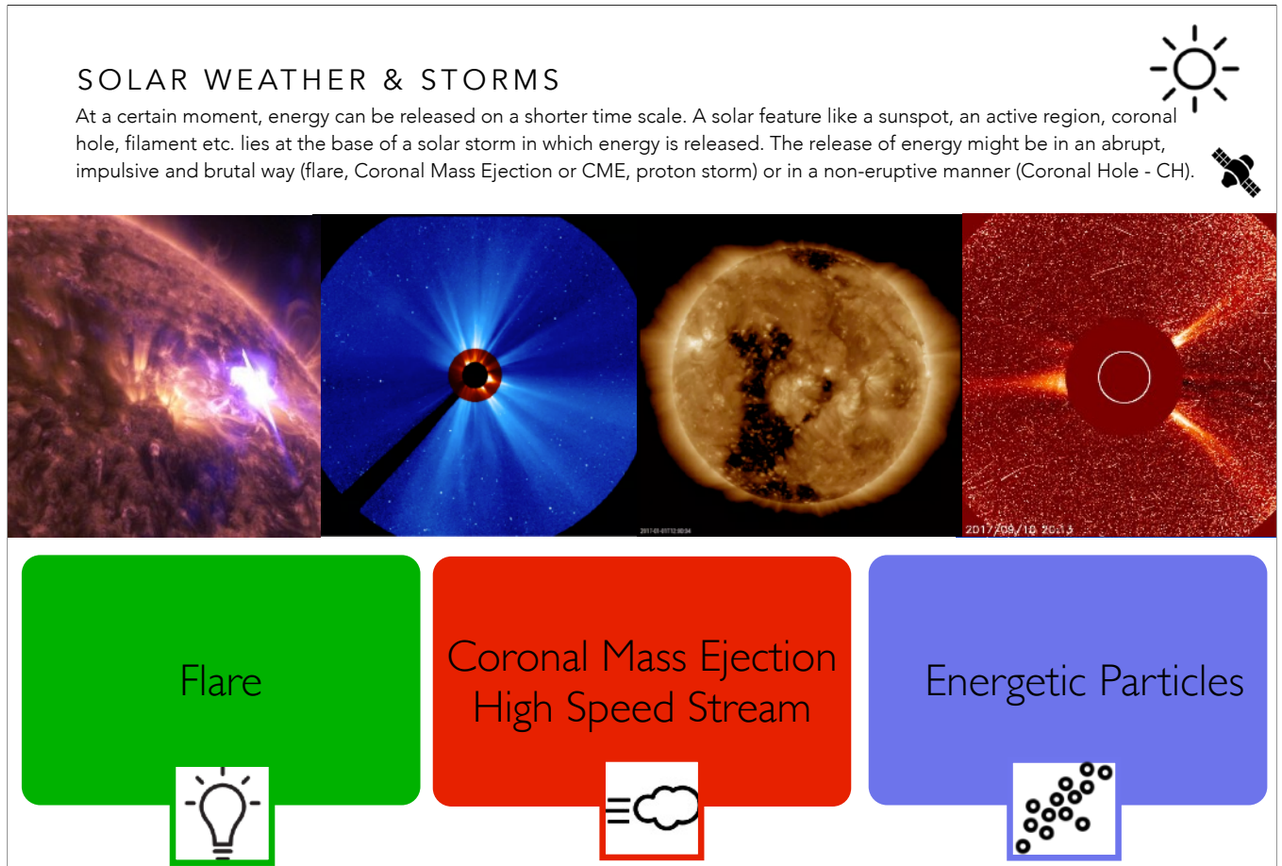
In the case of a speed boat, the boat moves through the water.
In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

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



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)

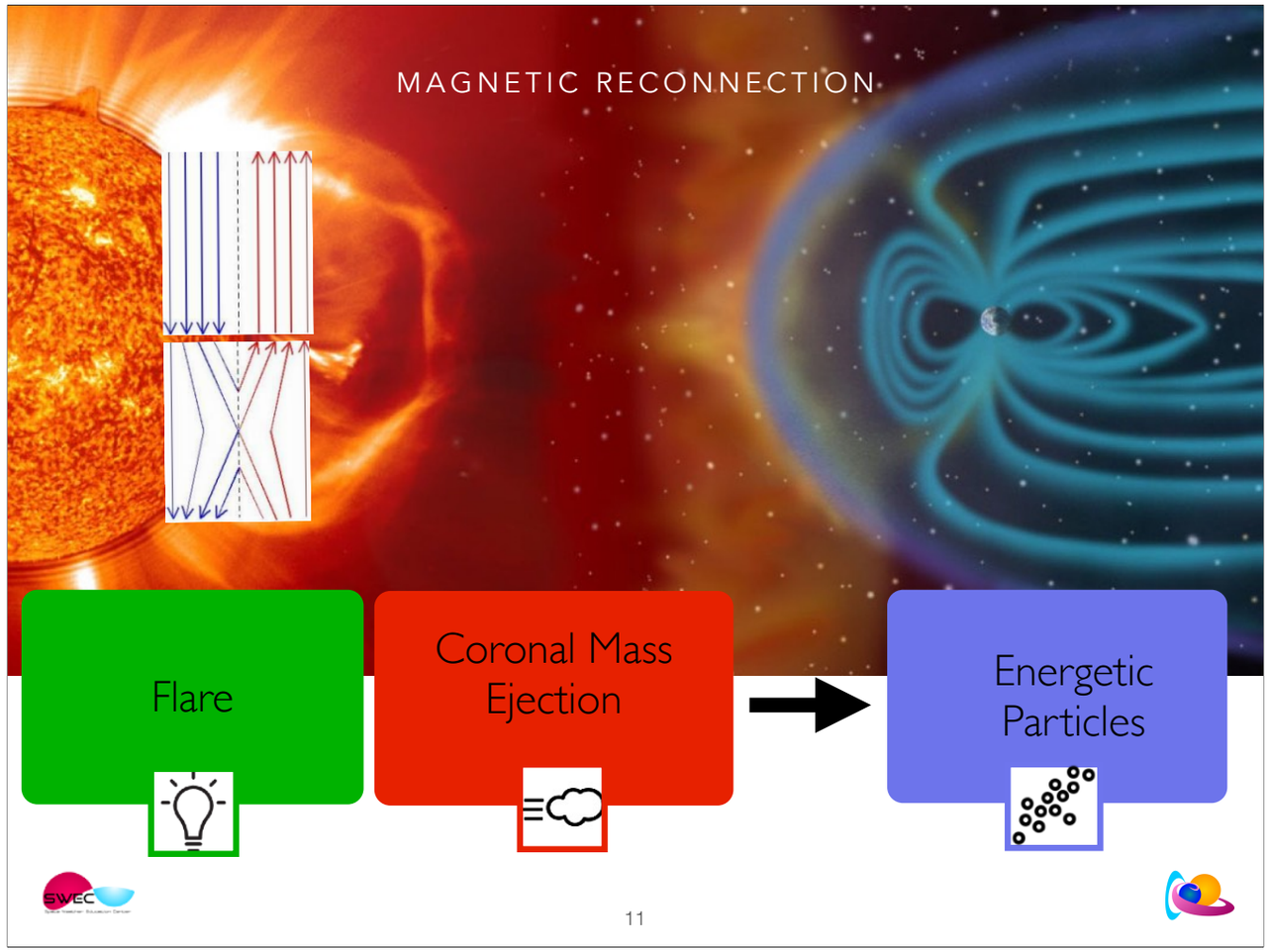
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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



Flares and coronal mass ejections are the result of magnetic reconnection. The stored magnetic energy is released in the form of thermal e.m. radiation (flare) and/or of kinetic energy as the plasma is being ejected (coronal mass ejection).

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.

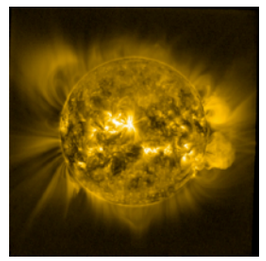
The blue magnetic field lines are imbedded in the solar wind.
The red magnetic field lines represent the earth magnetosphere.
The blue and the red magnetic region have to face each other. Opposite magnetic field lines can reconnect easily and 'open'. This causes geomagnetic storms. Magnetic field lines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

0.3 T - solar sunspot

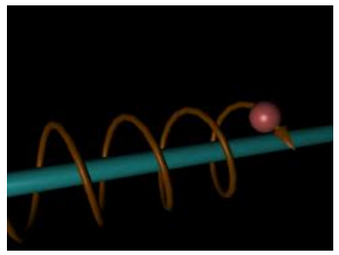
5mT – strength of a typical refrigerator magnet
31.869 μT (3.1×10^{-5} T) – strength of Earth's magnetic field at 0° latitude (North/South), 0° longitude (west/east)
1 to 5 nT – IMF at L1

SOLAR SEASONS

The sun has 2 seasons: an active and a low season with the typical variations in the three space weather phenomena. This seasonal variation is called the solar cycle and takes around 11 years.



PROBA2/SWAP



E.m. Radiation
Flares

Solar Wind
CME - HSS

Energetic Particles

The energy expelled in the form of plasma takes two forms: solar wind and solar particles.

The outward flow of solar particles and magnetic fields from the Sun. Typically at 1 AU, solar wind velocities are near 375 km/s and proton and electron densities are near 5 cm-3. The total intensity of the interplanetary magnetic field is nominally 5 nT.

TSI, e.m. radiation is not linked to the IMF. It doesn't follow the magnetic field lines.
PROBA2/SWAP, the sun in the EUV.

However, plasma containing ions and electrons has to follow the magnetic field lines. Or you can also say that the magnetic field lines guide the plasma.
The solar wind plasma is glued to the IMF - or the IMF is glued to the plasma.
The plasma in the solar wind is considered as a gas, a group of particles behaving and moving in group. You don't speak about that particular particle in the solar wind, you speak about the solar wind, a whole bunch together.
Cartoon

Electrically charged particles have to follow the IMF. These electrically charged particles are considered as individuals and behave as individuals.
Cartoon

Near Earth, the IMF still controls the solar wind and its movement. Much much further away from the Sun, the IMF becomes very weak and doesn't control the solar wind anymore. But, this is not important for us. At 1AU, the IMF influences the plasma and the plasma the IMF.

About the animated gif:
Conceptual animation (not to scale) showing the sun's corona and solar wind.
Credits: NASA's Goddard Space Flight Center/Lisa Poje

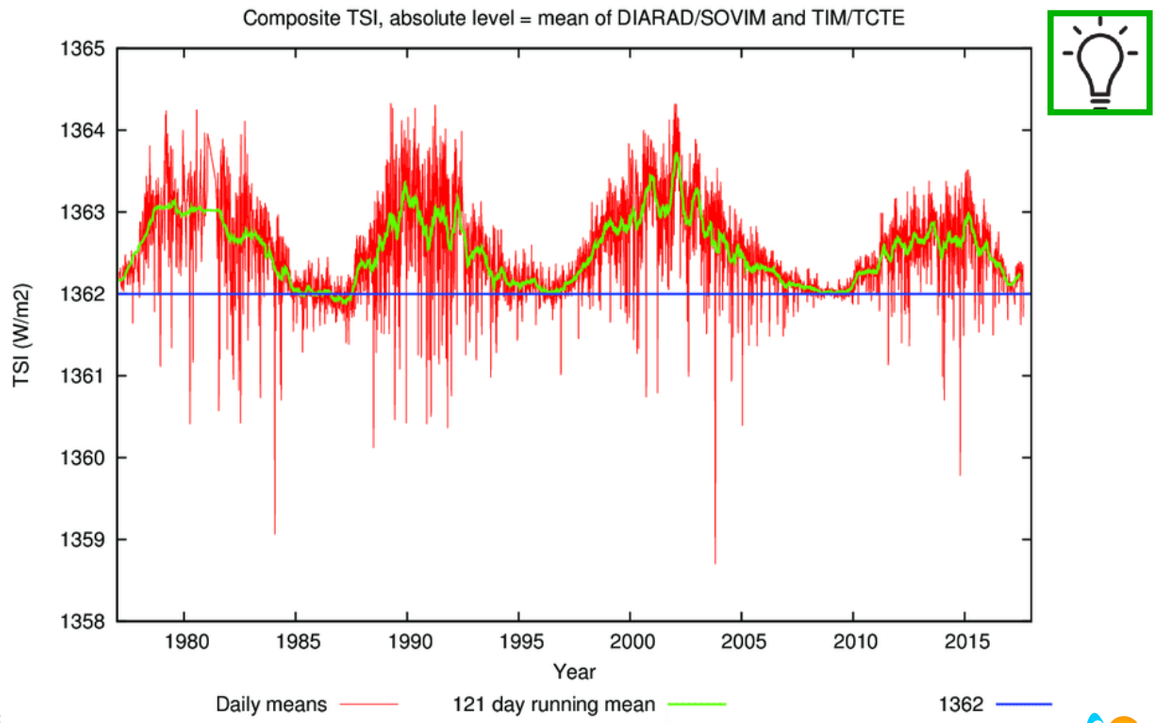
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you have solar weather. Outside the heliosphere, you have the rest of the galaxy. Earth is in the heliosphere.

A nice movie is found on
https://www.nasa.gov/feature/goddard/2016/images-from-sun-s-edge-reveal-origins-of-solar-wind

https://youtu.be/QYM2_ytkjQo

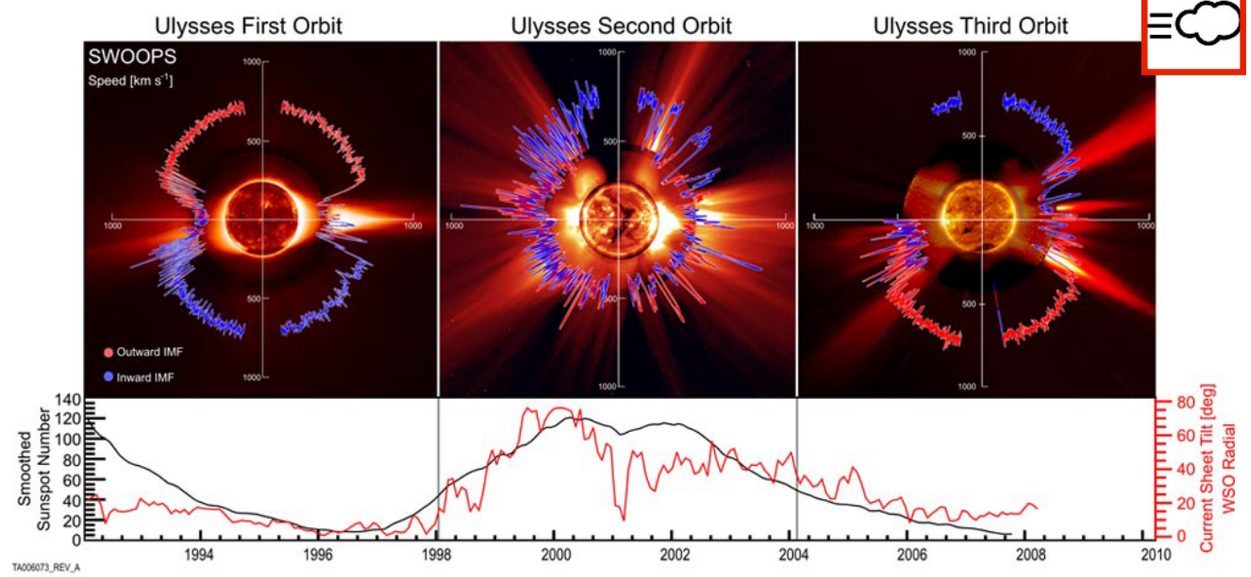
SEASONAL BEHAVIOUR OF LIGHT

The solar irradiance, i.e. all the solar light, varies over the solar seasons.
The sun radiates stronger in the high season compared to the low season.



SEASONAL BEHAVIOUR OF THE SOLAR WIND

The solar wind varies over the solar seasons. The variation depends on the solar latitude. In the low season, the solar wind is slower near the equator compared to the higher latitudes and is more nicely structured. In the high season, the solar wind varies over all latitudes.



Ulysses passing all latitudes measuring the solar wind speed. Ulysses made 3 orbits around the Sun.

It seems that the solar wind is not the same on all places of the solar disk, it depends on the latitude.

During solar minimum: more structured. Only near the equator, it looks like a mess.

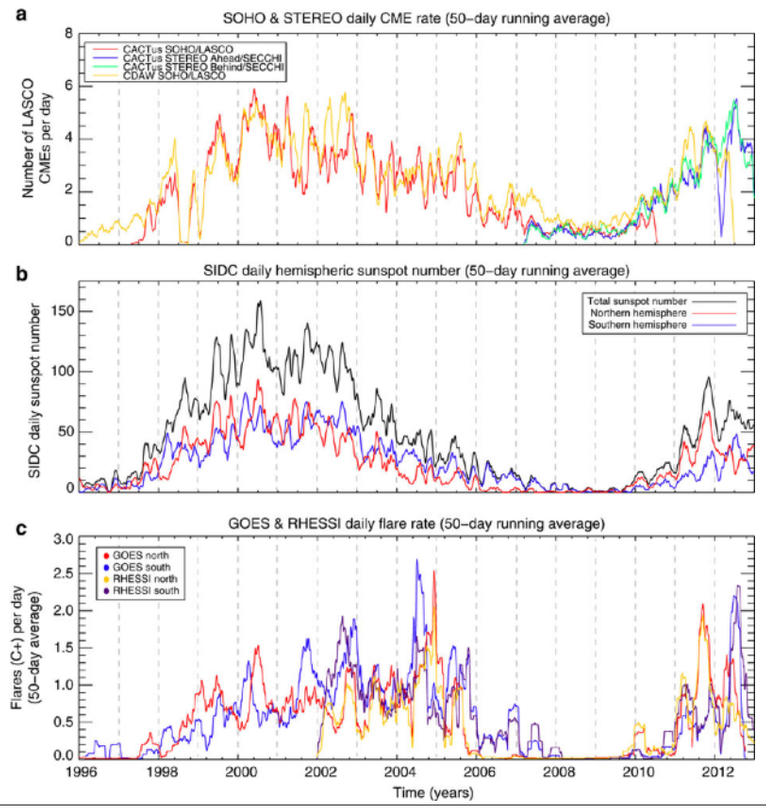
During solar maximum: global and local magnetic field mingle strongly. The solar wind looks more like a mess.

Larger areas with fast solar wind streams. Fast solar wind streams are associated with coronal holes. These are regions with open magnetic field regions of the corona. While slow streams are associated with closed field regions primarily concentrated near the equatorial (or streamer) belt.

Solar minimum is the season of polar coronal holes extending to low latitudes.

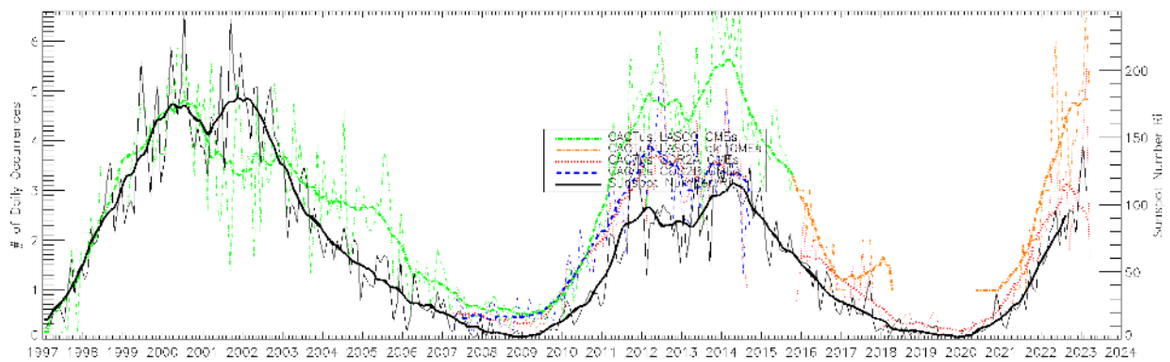
SEASONAL BEHAVIOUR OF SOLAR LIGHT & WIND STORMS

The seasonal behaviour is also visible in the variability of the Sun's eruptive output. You see here a comparison of the variation in the CME and flare rates over solar cycle 23 with the sunspot number.



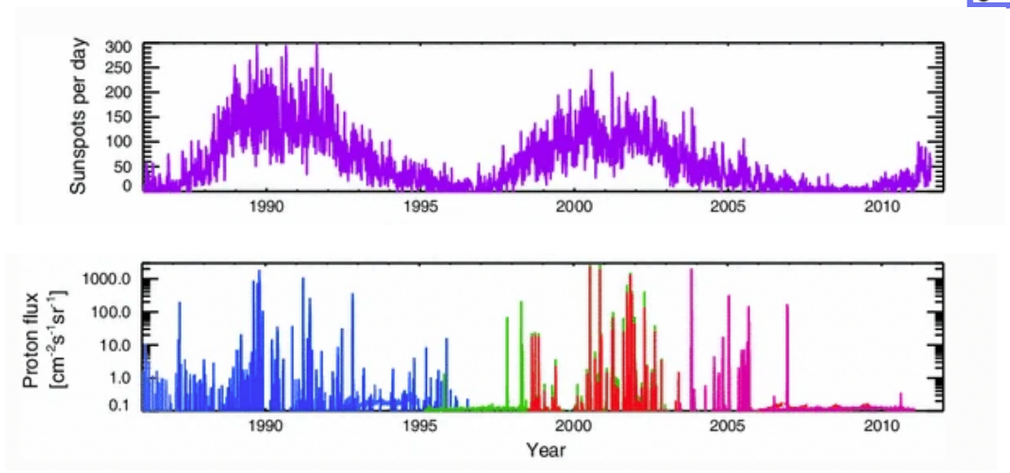
From https://www.researchgate.net/publication/274697133_The_solar_magnetic_activity_band_interaction_and_instabilities_that_shape_quasi-periodic_variability

Variability of the Sun's eruptive output over solar cycle 23. Comparison of the variation in the CME and flare rates over solar cycle 23 with the modulation in the (daily) sunspot number. (a) Variation in the (whole Sun) daily CME rates as detected by the CACTus44 and CDAW13 methods for the SOHO (red—CACTus; orange—CDAW) and the twin STEREO (blue—'ahead'; green—'behind') coronagraphic data sets. (b) SIDC- Solar influences data center. Total (black) and hemispheric (red—north; blue—south) daily sunspot numbers—compare with the monthly counterpart in . (c) Variation of the hemispheric daily rate of flares larger than 'B' magnitude in the GOES (red—north; blue—south) and RHESSI (orange—north; purple—south) records. As in , there is considerable lag between (total) sunspot maximum with the CME and flare series—occurring late in the descending phase. Almost every bump and wiggle in the sunspot number shows a corresponding surge in CME and flare activity—these surges can be as large amplitude as a doubling of the sunspot number or flare/CME rate over the course of only a few months before recovering. The panels of the figure show a set of dashed fine vertical lines that are 12 months apart and act as a timescale reference. Each timeseries shown in these panels is a 50-day running average over the original. The CME timeseries are not separated by hemisphere due to the uncertainty in determining the actual CME location from only plane-of-the-sky coronagraphic observations.


CACTus LASCO CMEs
CACTus LASCO vs TGMEs
CACTus SOHO CMEs
CACTus SOHO TGMEs
SIDC Number
# of Daily Occurrences
Sunspot Number
0
1
2
3
4
5
6
50
100
150
200
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

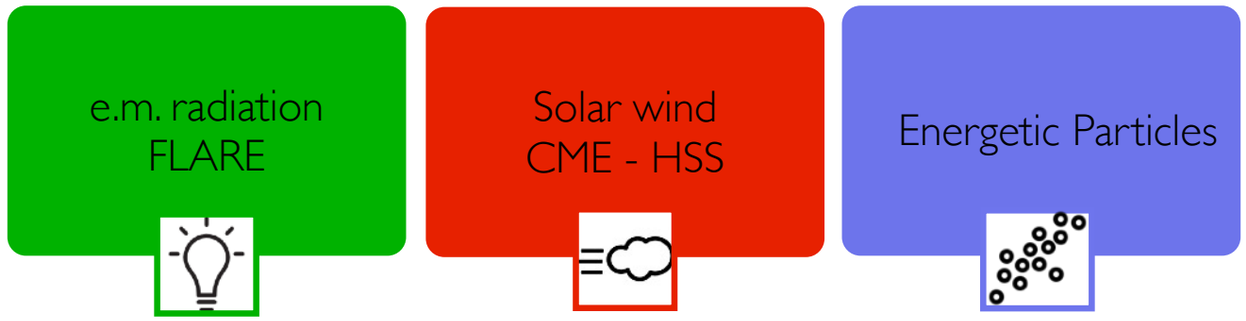
SEASONAL BEHAVIOUR OF SOLAR PARTICLE STORMS

The seasonal behaviour is also visible in the variability of the Sun's eruptive output. You see here a comparison of the variation of the proton flux over solar cycle 23 with the sunspot number.



Less/More flares,CME's —> Less/More proton storms

From https://link.springer.com/article/10.1007/s10712-012-9201-3
Different indices for solar activity and energetic particle precipitation throughout the last 2 1/4 solar cycles. From top to bottom sunspot number per day, a proxy for solar activity; the Ap index, a proxy for geomagnetic activity linked to the precipitation of auroral particles; fluxes of relativistic electrons of energies >2 MeV in the radiation belts, merged data set using different GOES satellites; and fluxes of protons of energies >50 MeV as observed by particle counters onboard different GOES satellites (light blue GOES-6; dark blue GOES-7; green GOES-8; light red GOES-10; dark red GOES-11). Data are from the National Geophysical Data Center (http://www.ngdc.noaa.gov)



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)

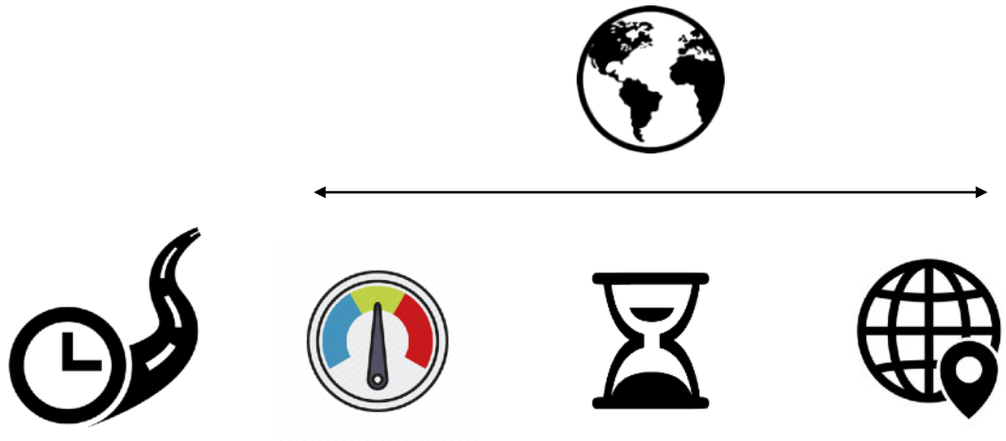
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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

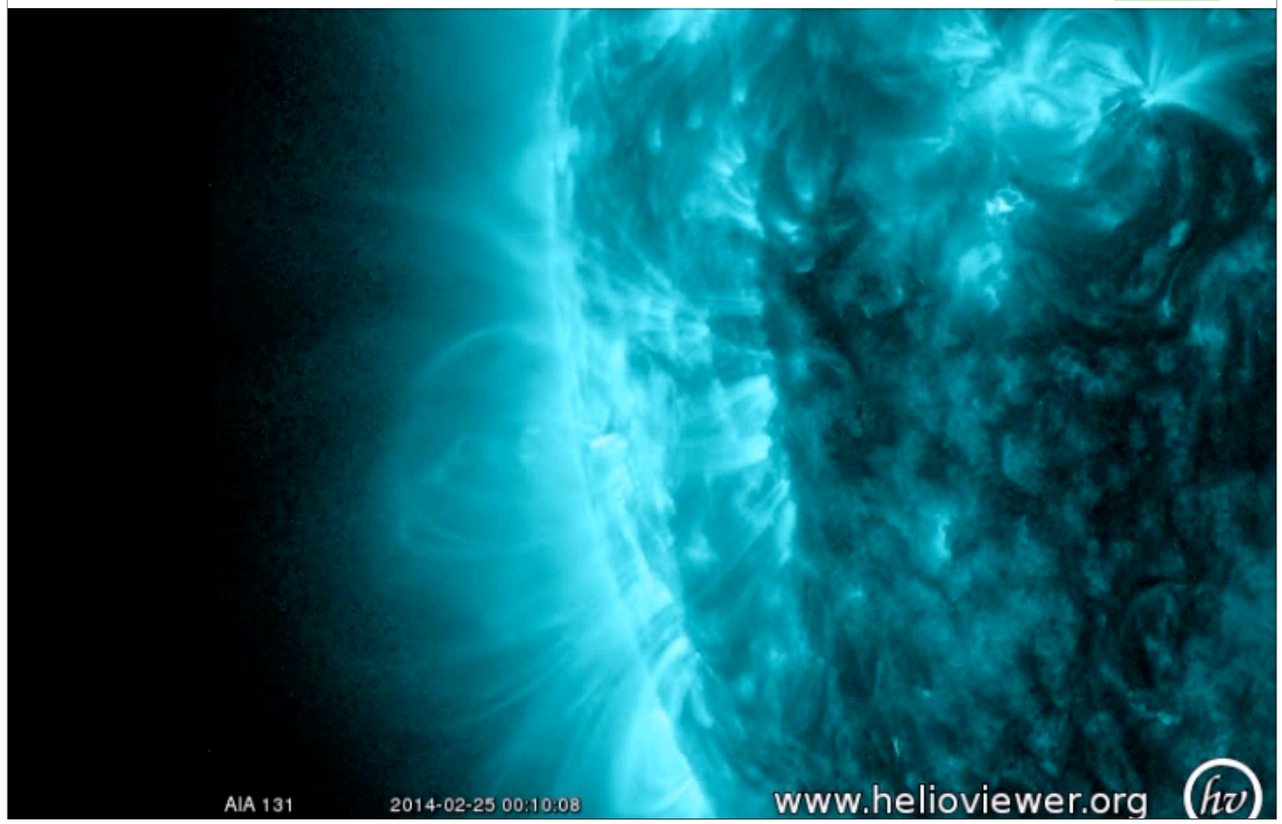
over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.



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.

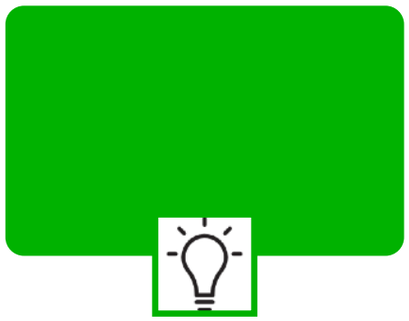


Light storms

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

The energy released during a solar storm moves through space, each with its own typical speed: speed of light, ….



AU TRANSIT TIME

The energy released during a solar storm moves through space, each with its own typical speed: speed of light, …

8 MIN

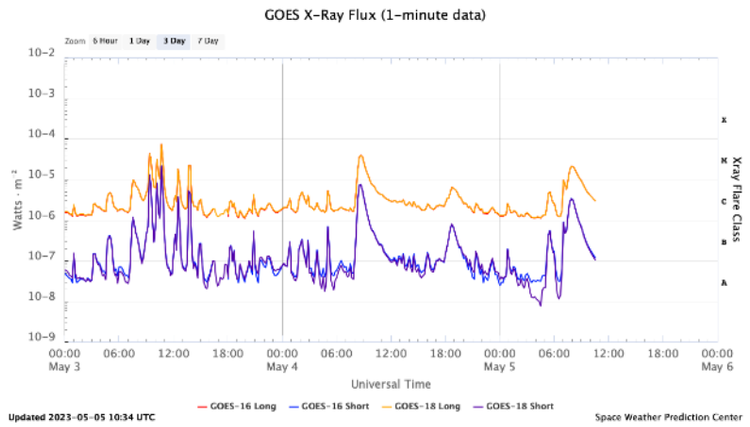
STORM SCALE

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.

STORM SCALE

A,B,C,M,X

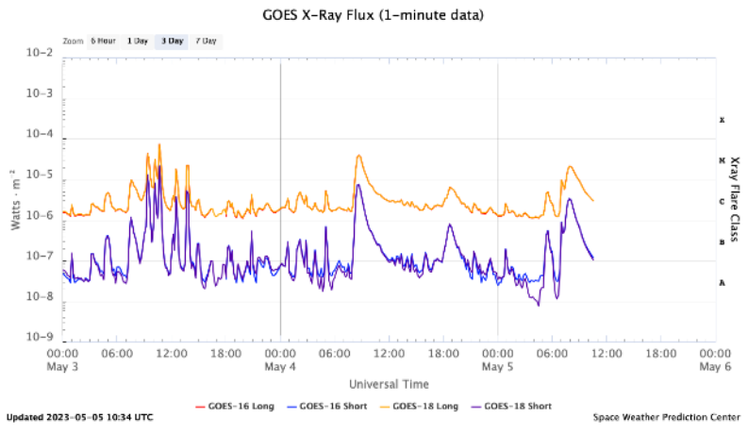


https://www.swpc.noaa.gov/products/goes-x-ray-flux

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

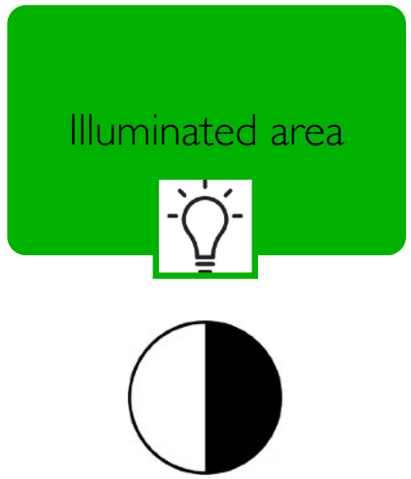
DURATION

MINs to HOUR

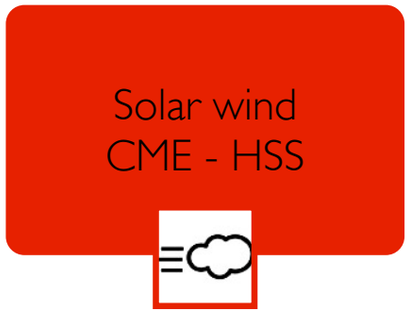


AREA OF IMPACT

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.



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)

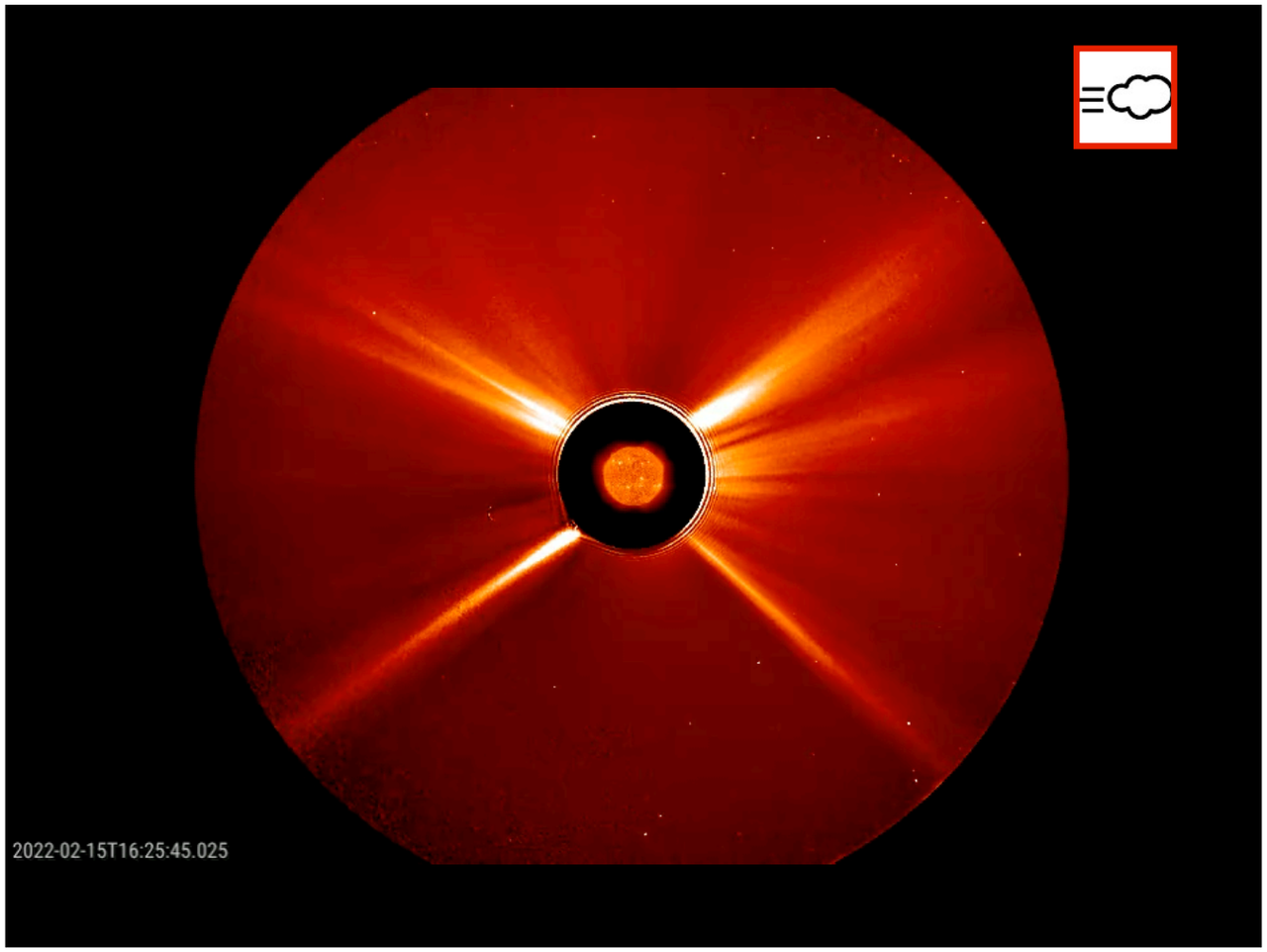
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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

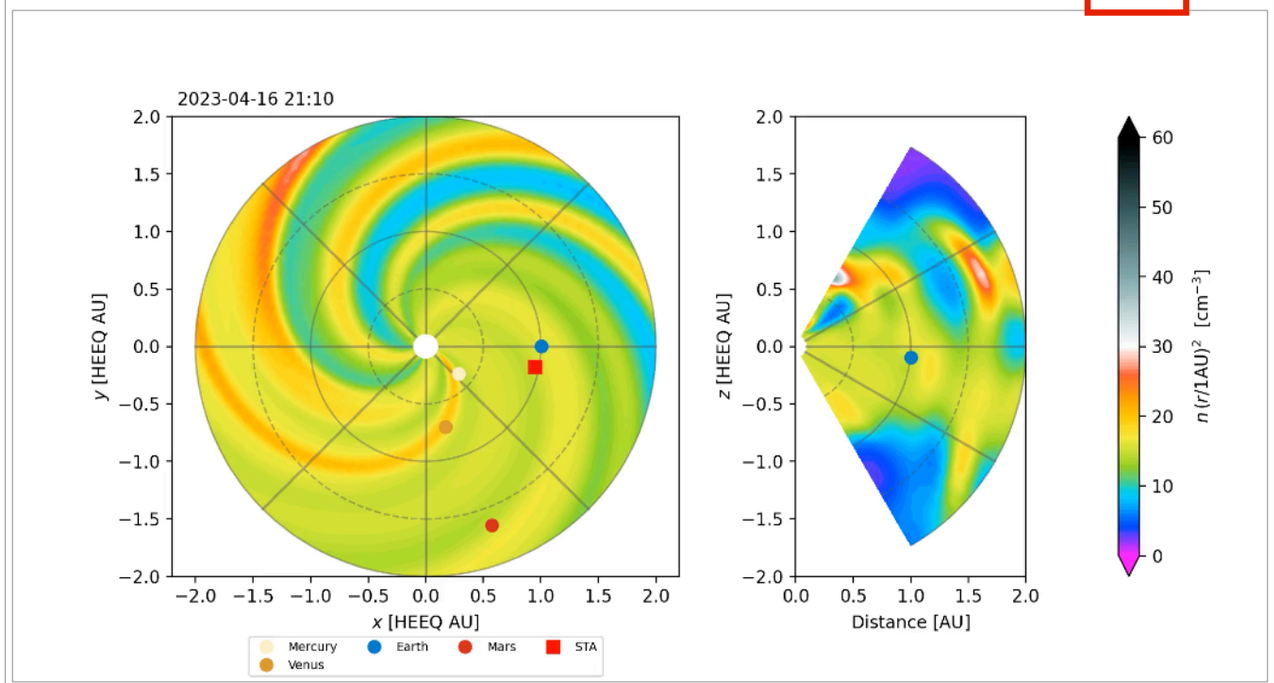
In situ means that you measure a parameter local. Remote sensing means that you look at something from a distance.

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

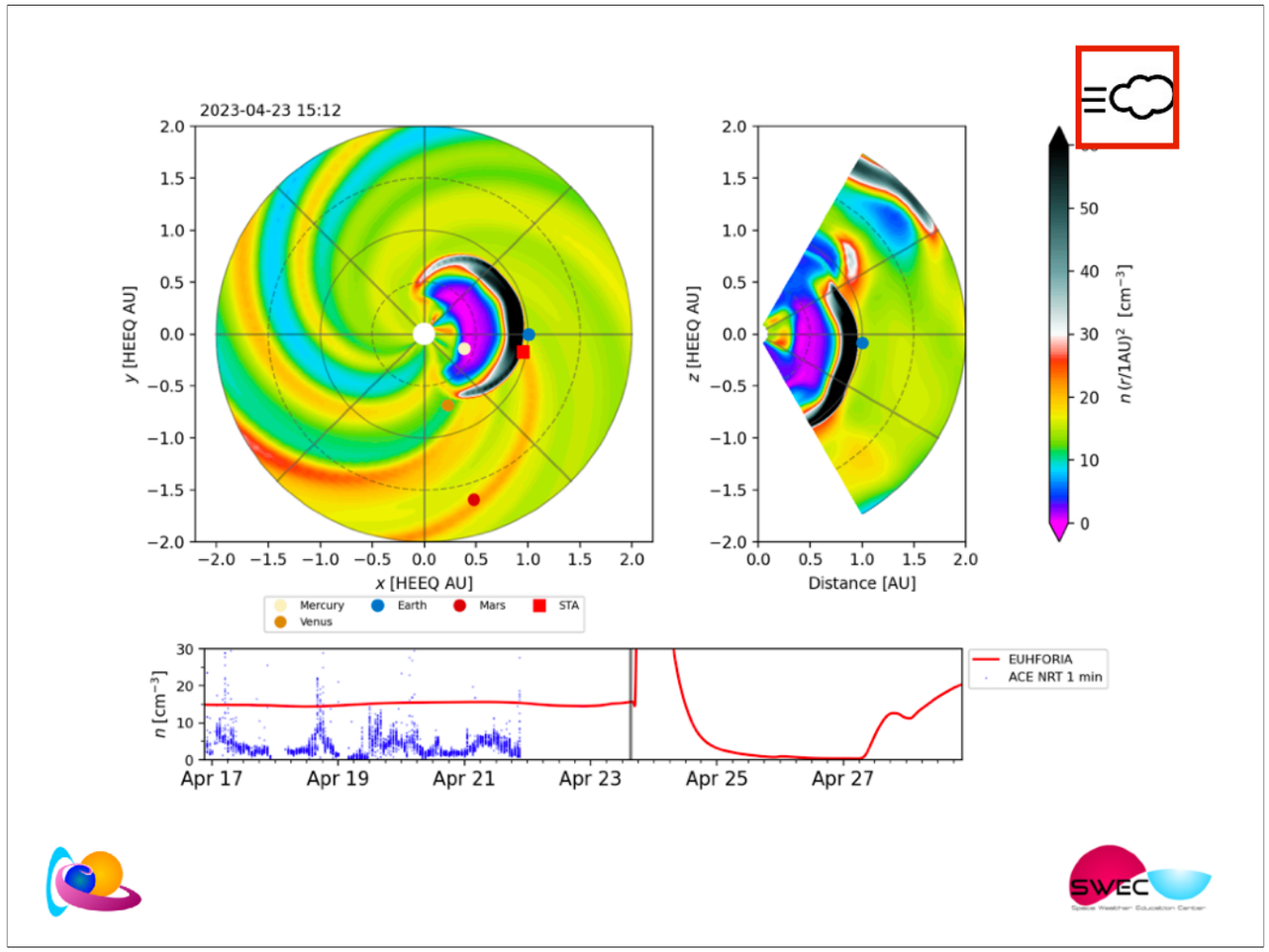
over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.



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



A CME moving through the heliosphere



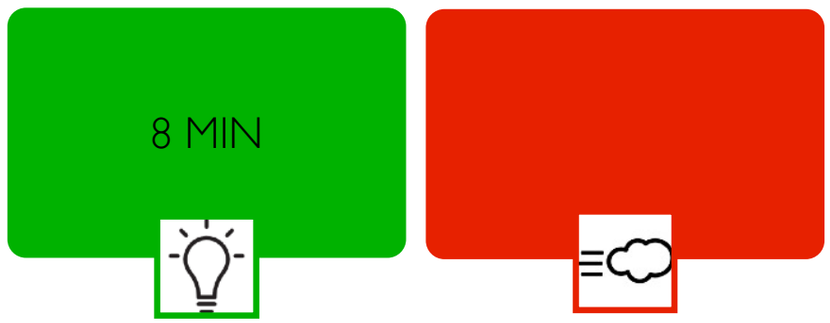
A CME reaches Earth

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.

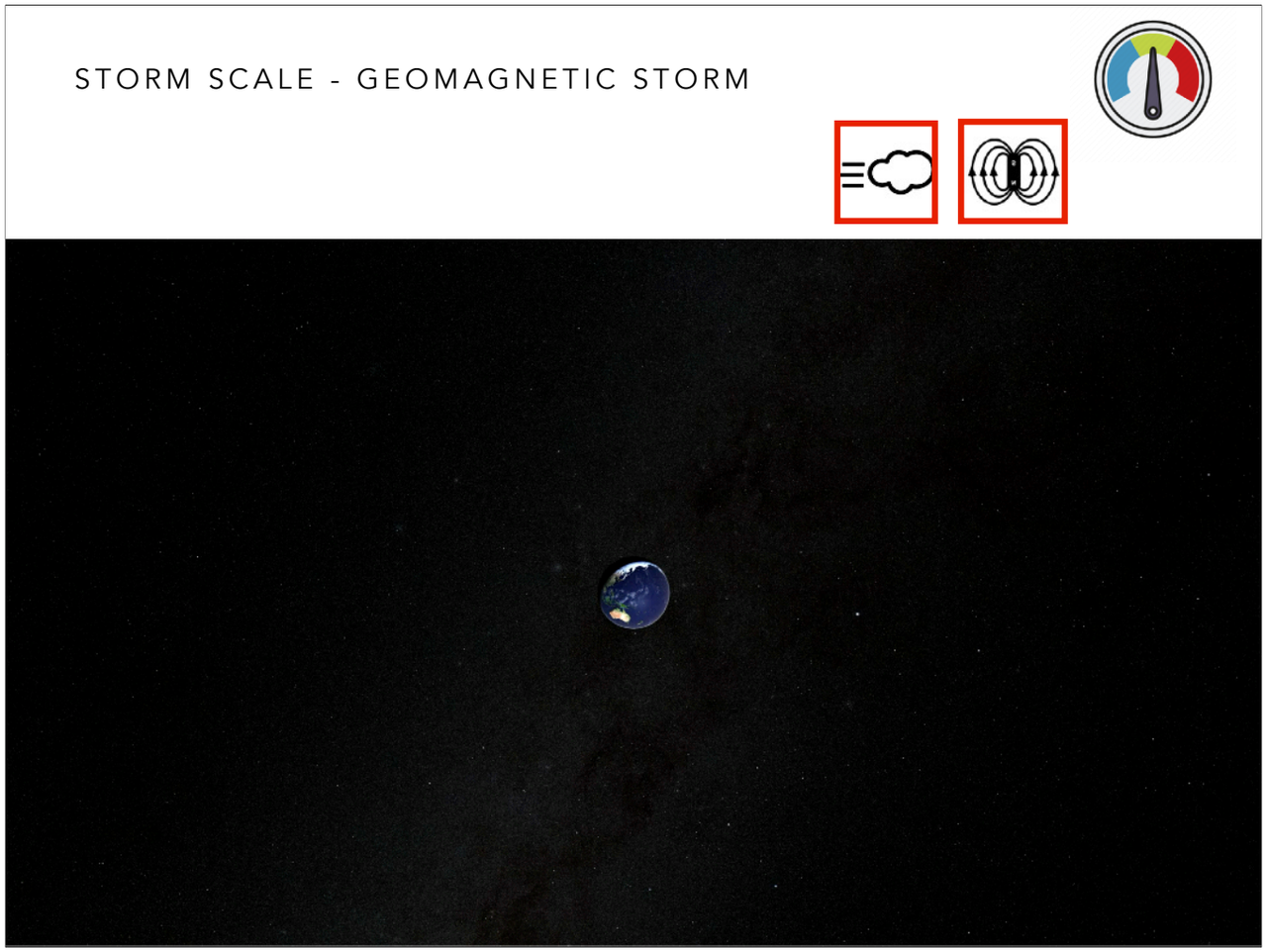
AU TRANSIT TIME

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,….



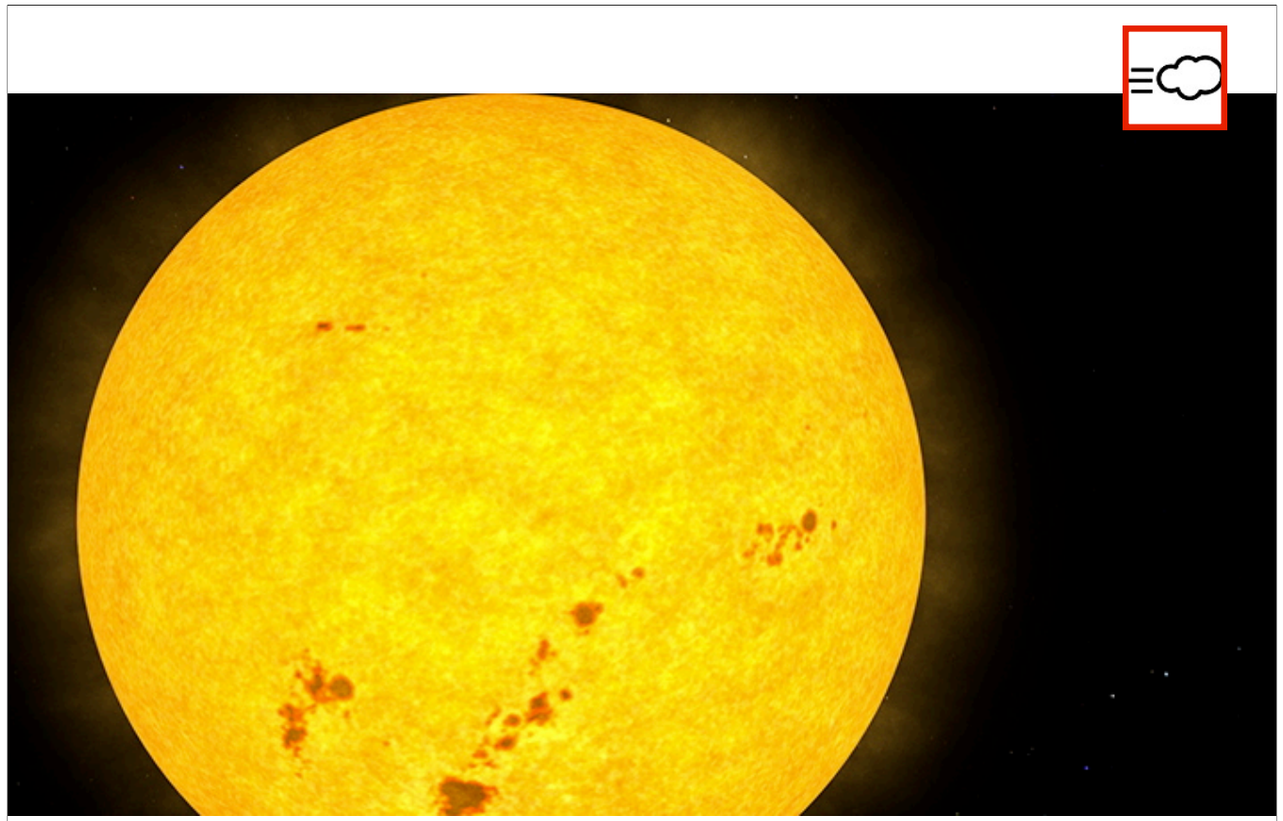
AU TRANSIT TIME

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.



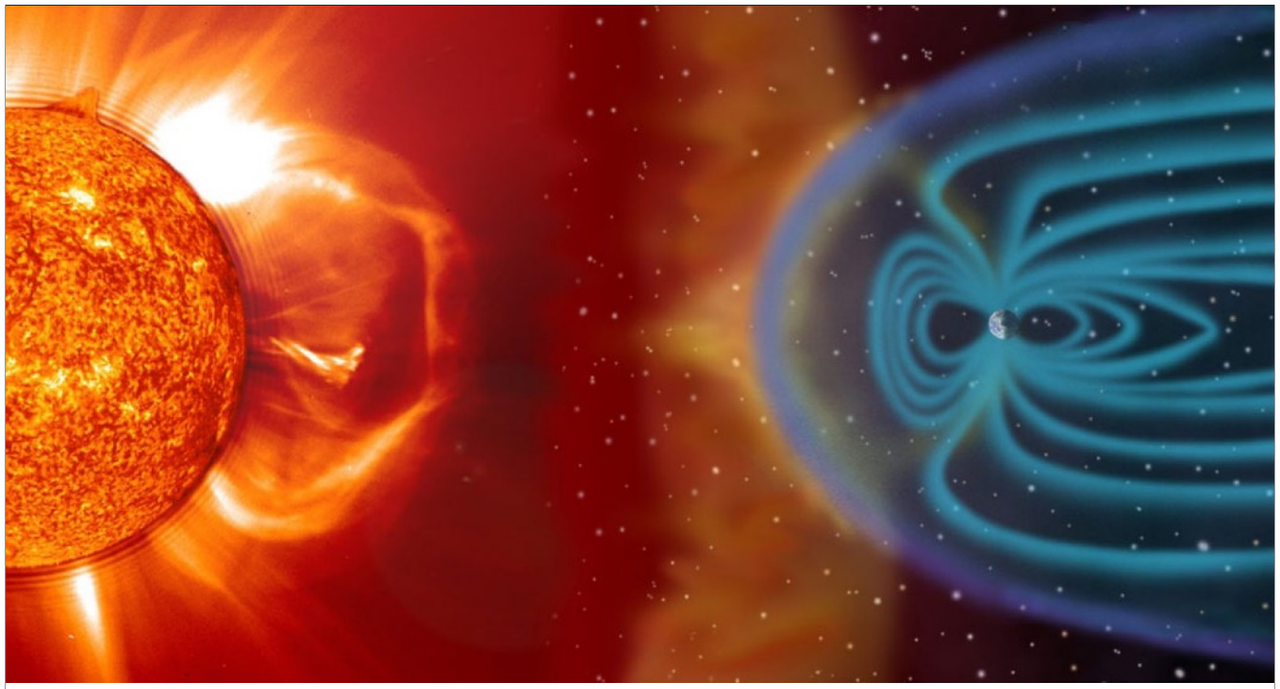
https://svs.gsfc.nasa.gov/5193/
This animation demonstrates the Earth's magnetosphere being hit by a geomagnetic storm on February 3, 2020, simulated by MAGE during the storm that caused the loss of commercial satellites.

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.

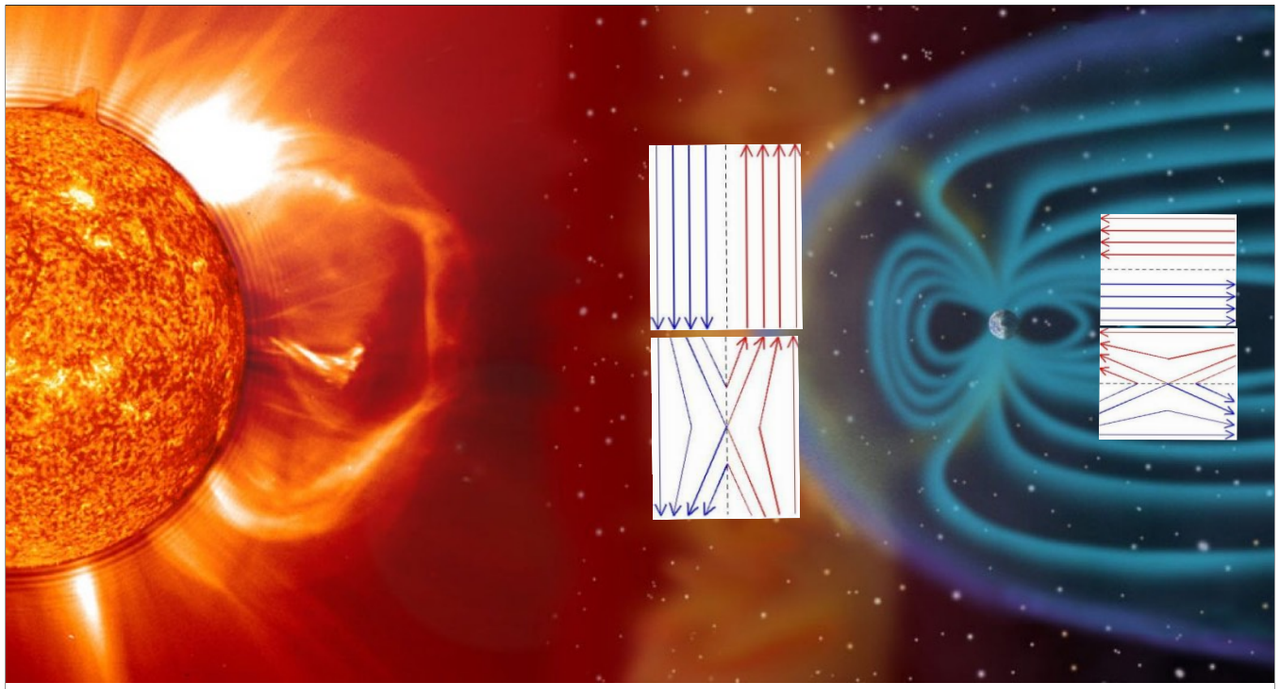
This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiate are slower compared to the speed of the boat. The boat is super-water wave.
When a plane is super-sonic, there is also a shock in front of it. The pressure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

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



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.

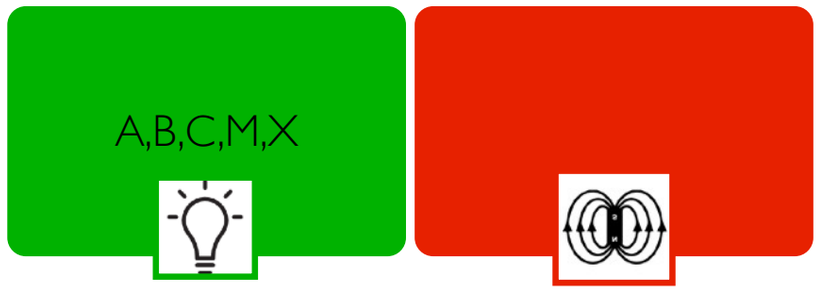
A magnetic field is imbedded in the solar wind. This magnetic field can interact with the magnetic field of the earth at the boundaries of the earth magnetosphere. This interaction is called reconnection. It happens when 2 magnetic regions are confronted with each other.

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

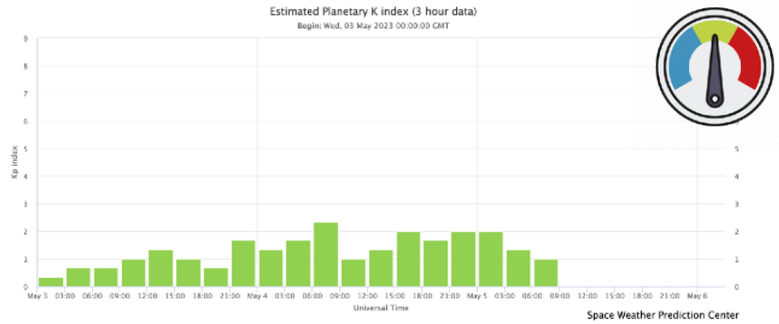
STORM SCALE

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



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.

STORM SCALE

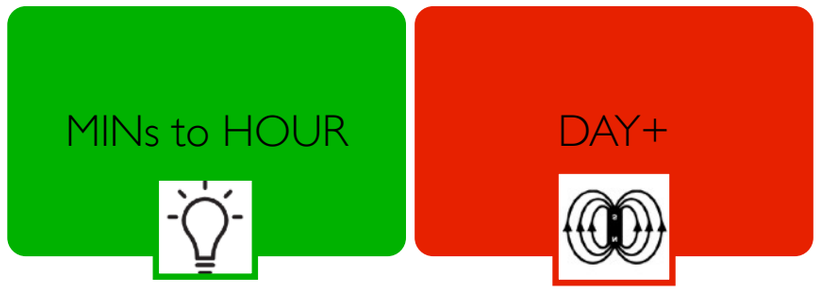


A,B,C,M,X

Kp
0 - 9

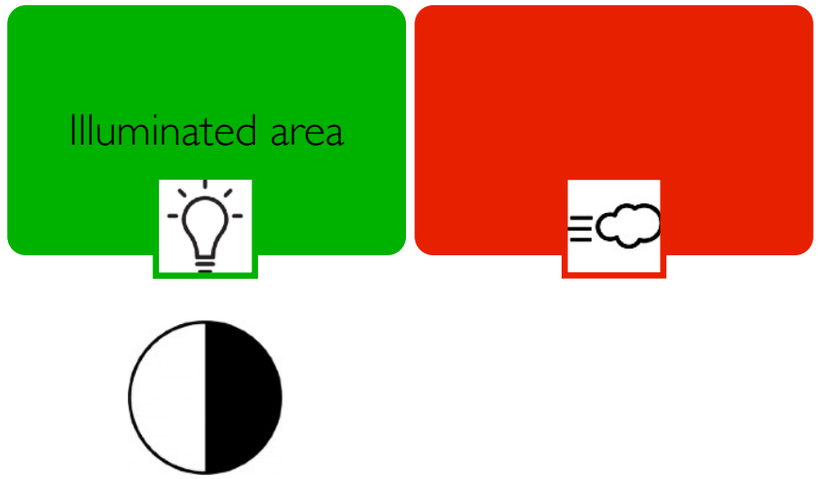
The Kp index is an index that quantifies the disturbance of the magnetic field of Earth. It ranges between 0 and 9, with 0 no disturbance and 9 an extreme disturbance.

DURATION

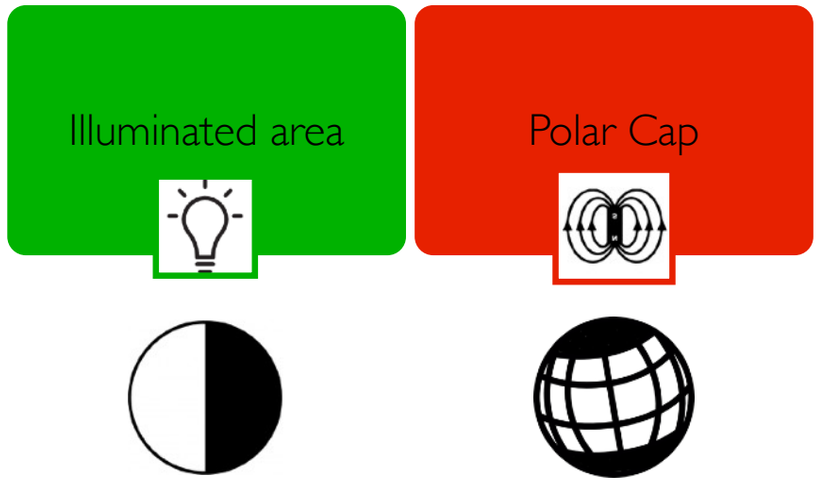


Day or more

AREA OF IMPACT



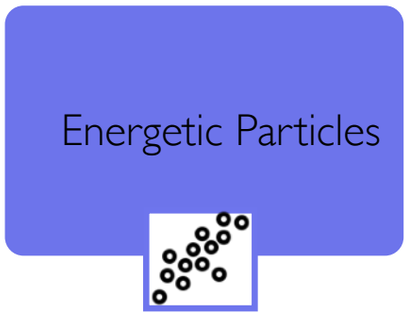
AREA OF IMPACT



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.



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)

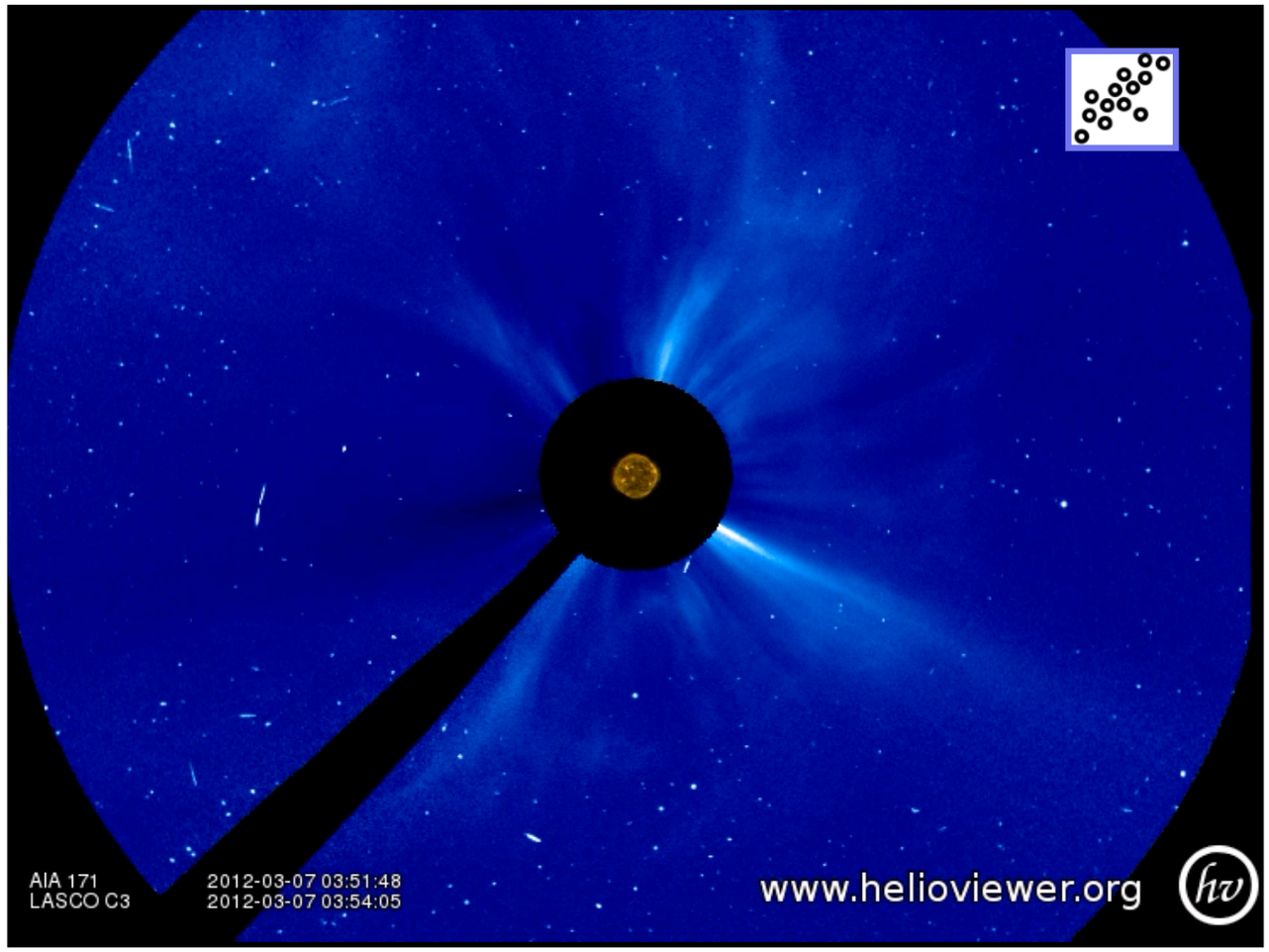
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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

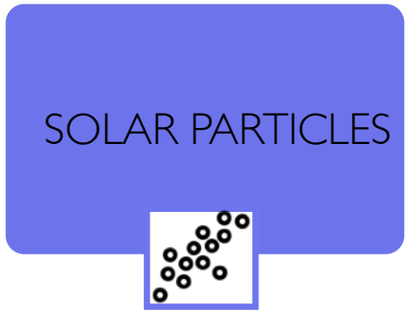
over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

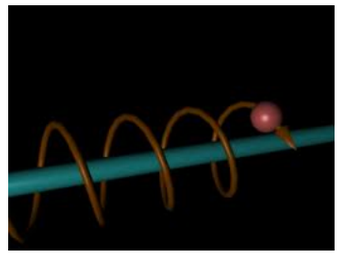


Particle showers

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.

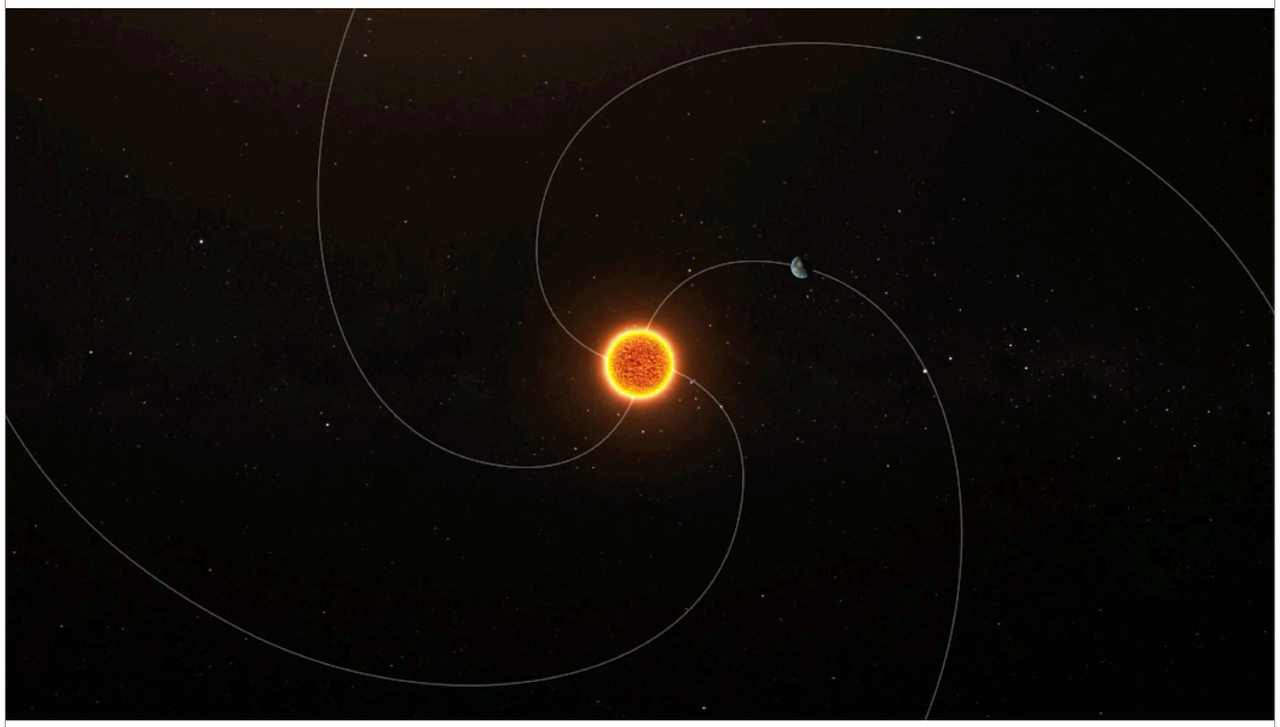
(The image in the middle of the occulter is an EUV image from the instrument AIA onboard of SDO.)





Solar energetic particles follow magnetic field lines.

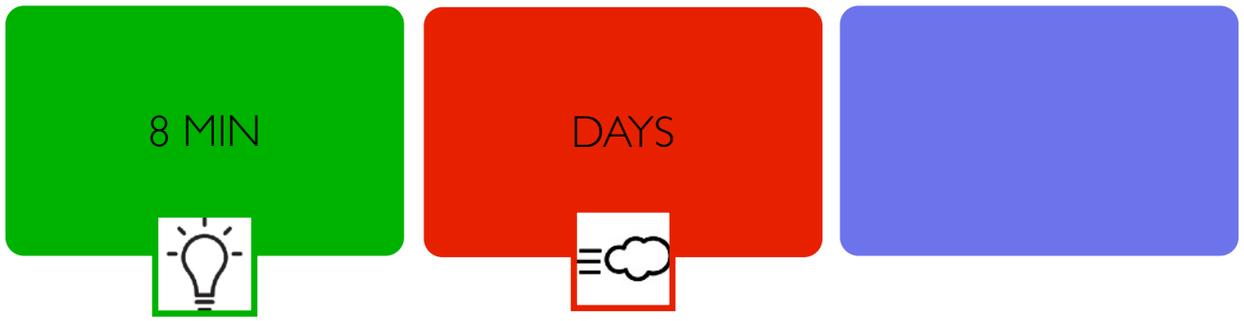
They have to go where the magnetic field takes them.



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.

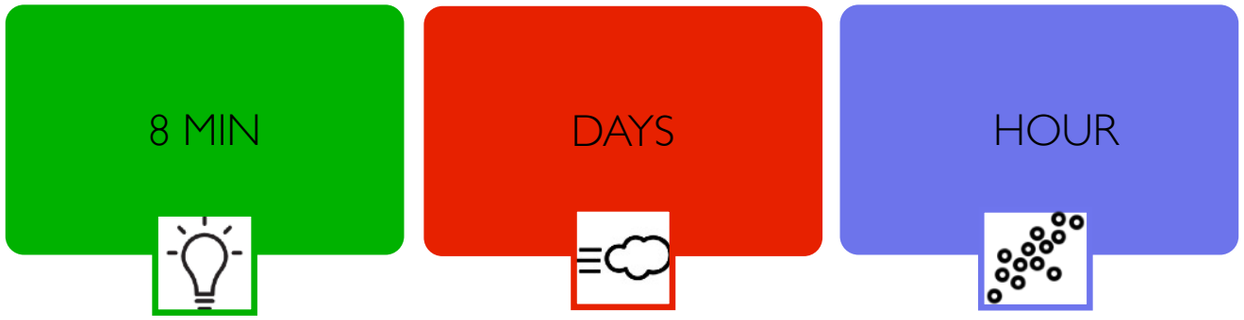
AU TRANSIT TIME

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.



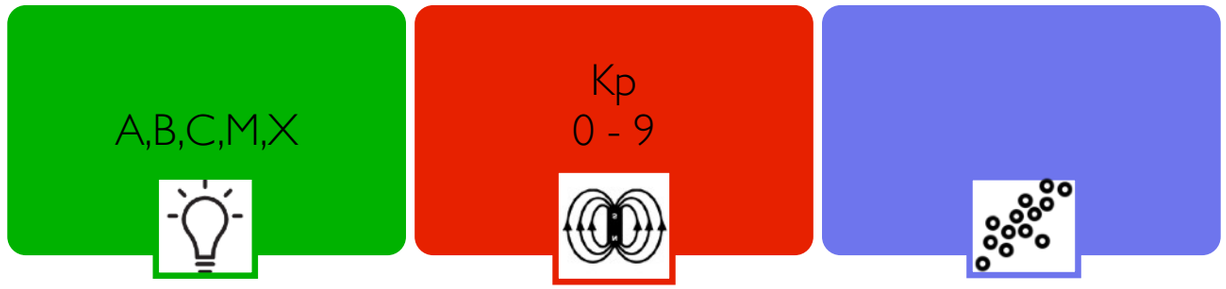
AU TRANSIT TIME

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.



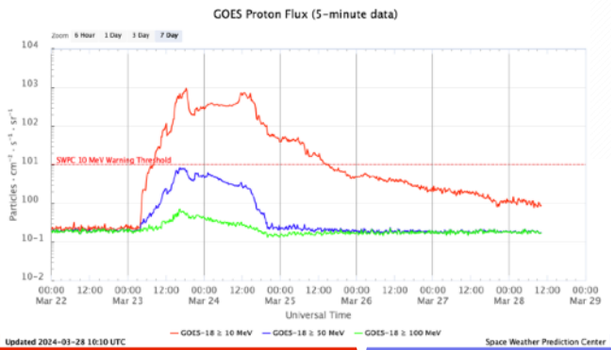
STORM SCALE

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



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

STORM SCALE



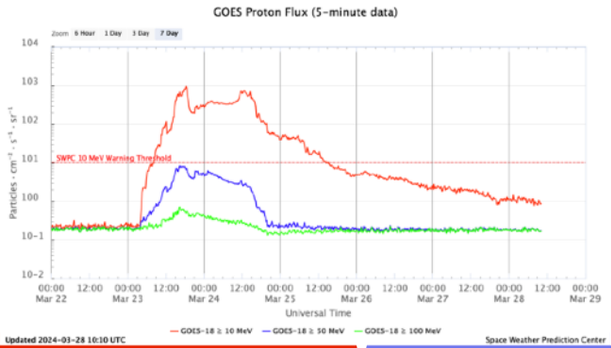
A,B,C,M,X

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



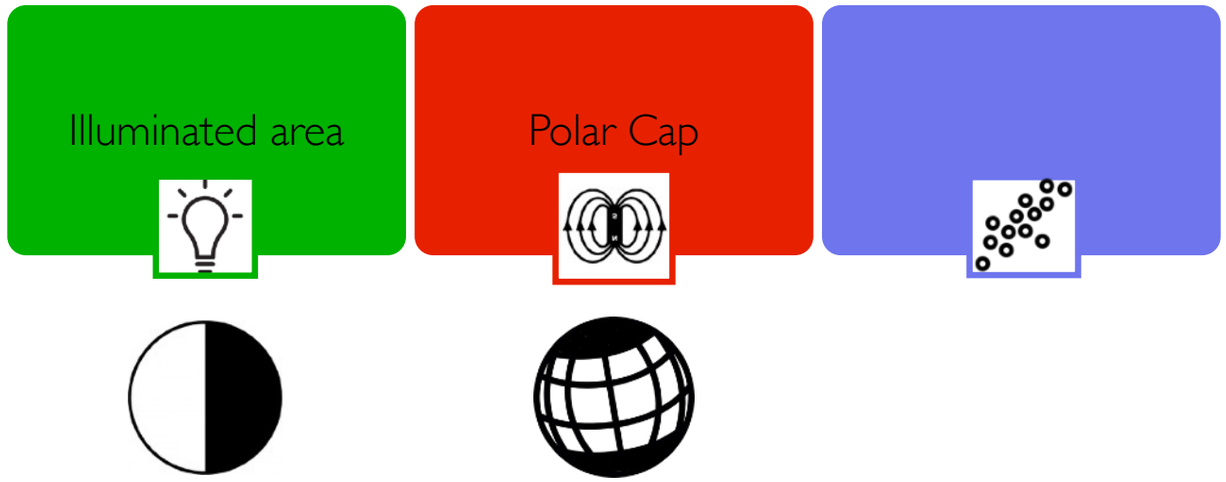
MINs to HOUR

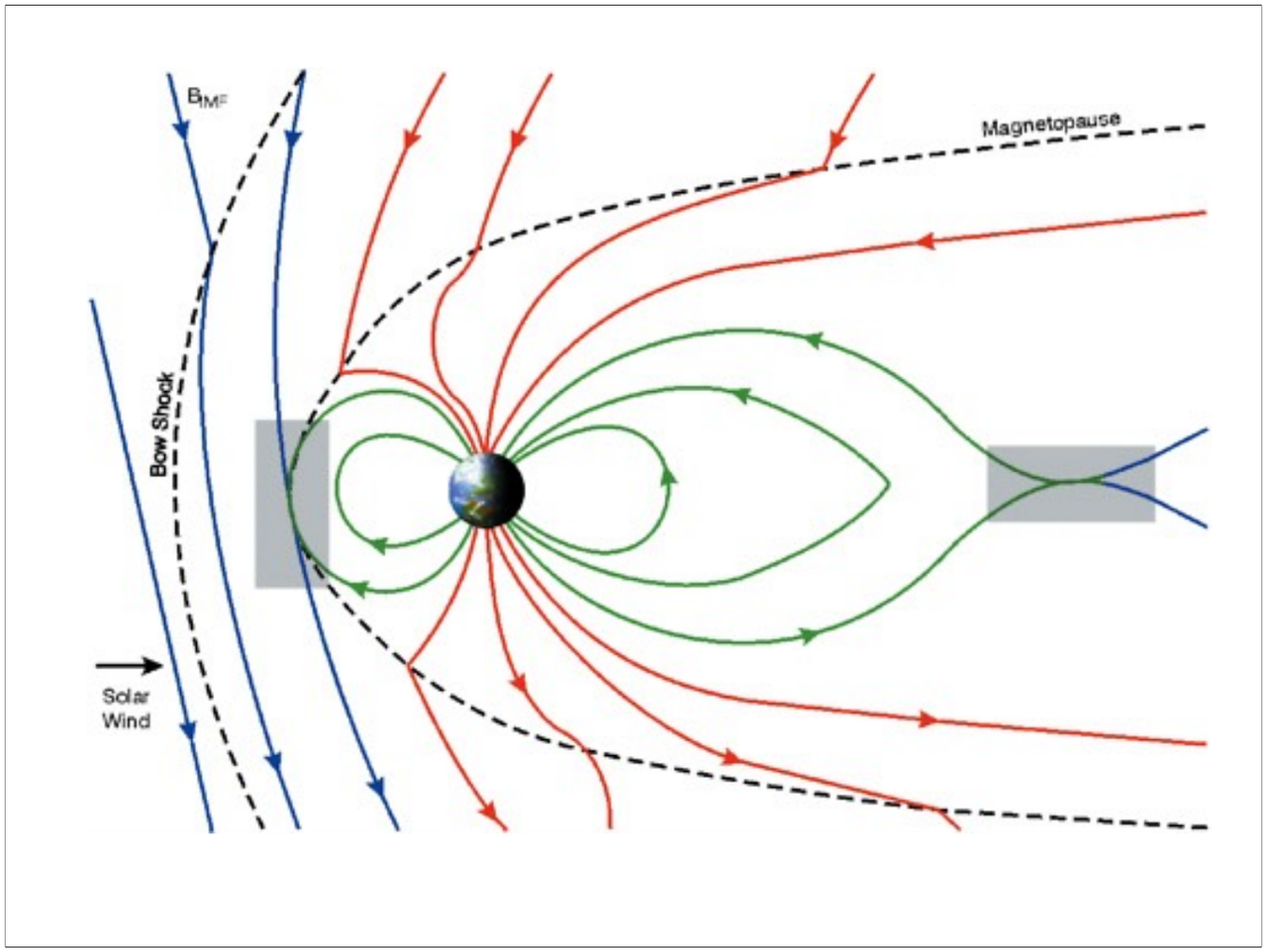
DAY+

HOURS to DAYS

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

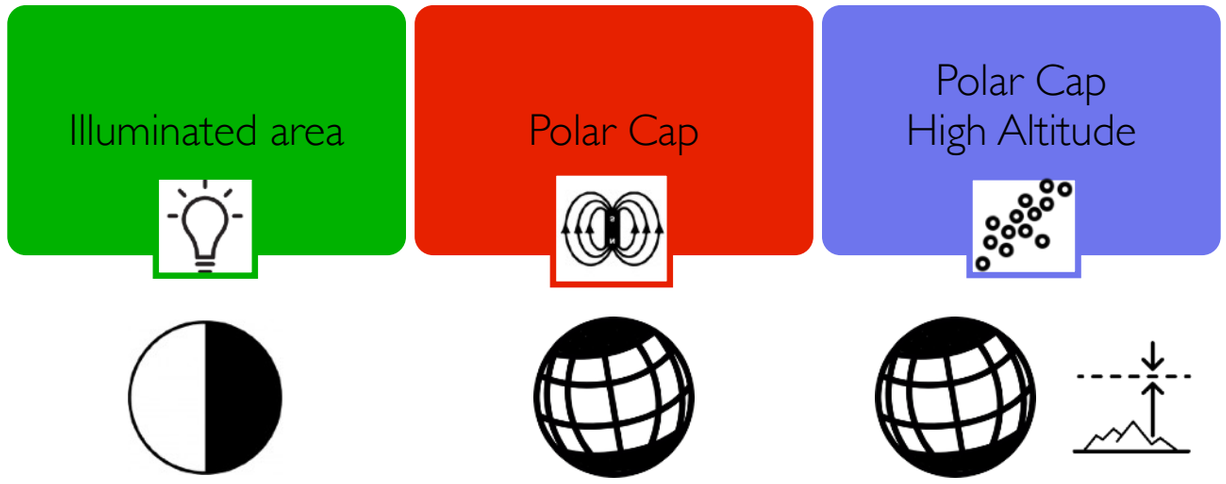
AREA OF IMPACT





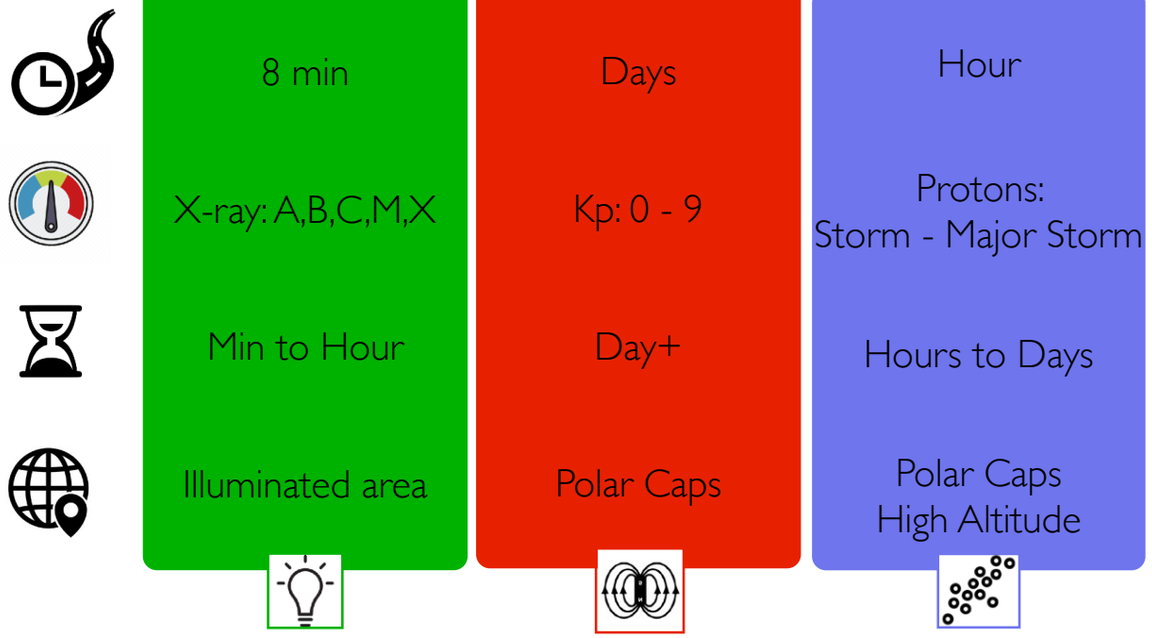
The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).

AREA OF IMPACT



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

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