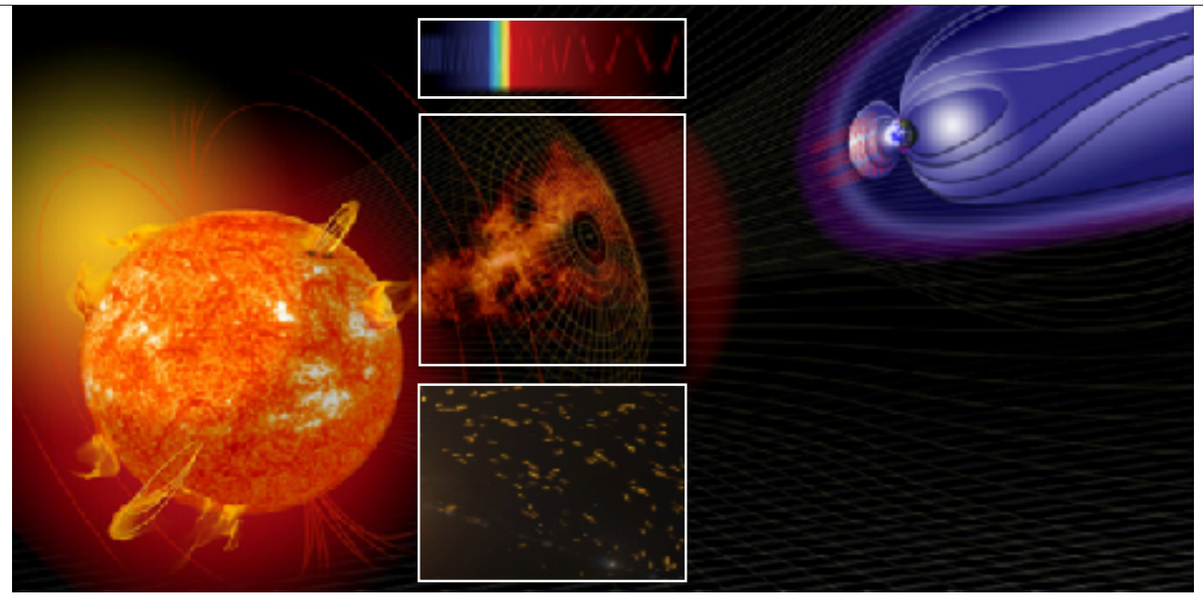


SPACE WEATHER

Introduction

Petra Vanlommel

We are all familiar with **terrestrial tropospheric weather.** It is what we experience all around us; our atmospheric environment. It may be fine, cloudy, stormy or sunny. It may rain or hail. We know about temperature and pressure and humidity. This is all about weather in the **lowest 10 km of our atmosphere.**

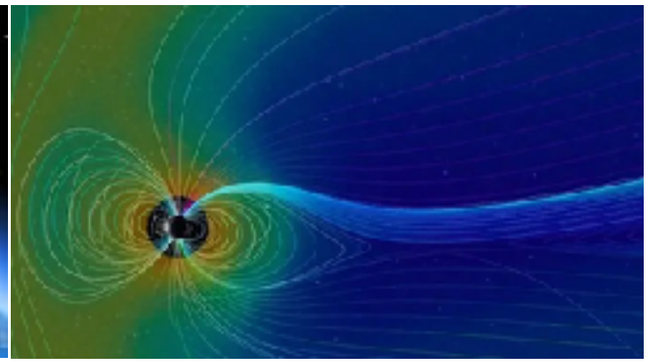
Wikipedia
Weather is the state of the atmosphere, to the degree that it is hot or cold, wet or dry, calm or stormy, clear or cloudy.
Most weather phenomena occur in the lowest level of the atmosphere, the troposphere, just below the stratosphere. **Weather refers to day-to-day** temperature and precipitation **activity**, whereas climate is the term for the averaging of atmospheric conditions over longer periods of time.

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.**

Space Weather

The Sun's energy impacting earth's atmosphere and magnetosphere



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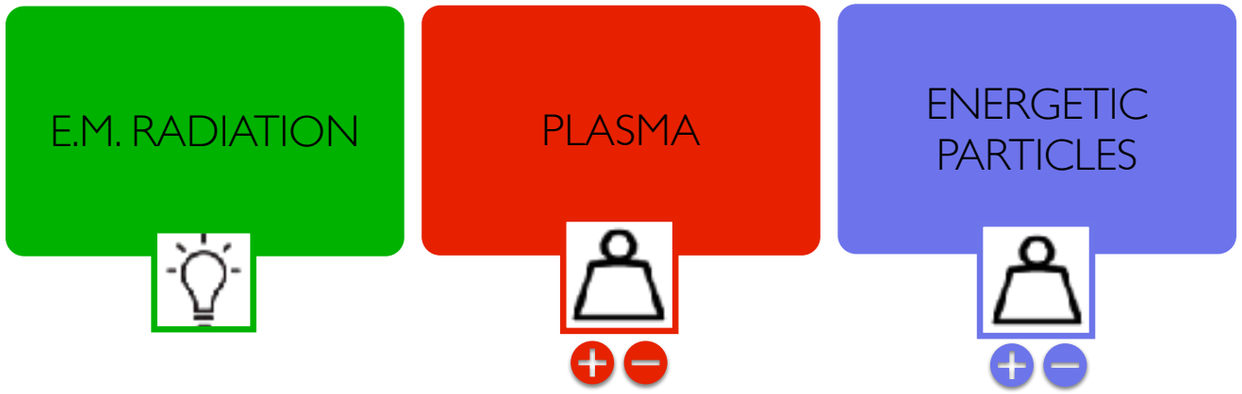
THE SUN AS A BALL OF ENERGY

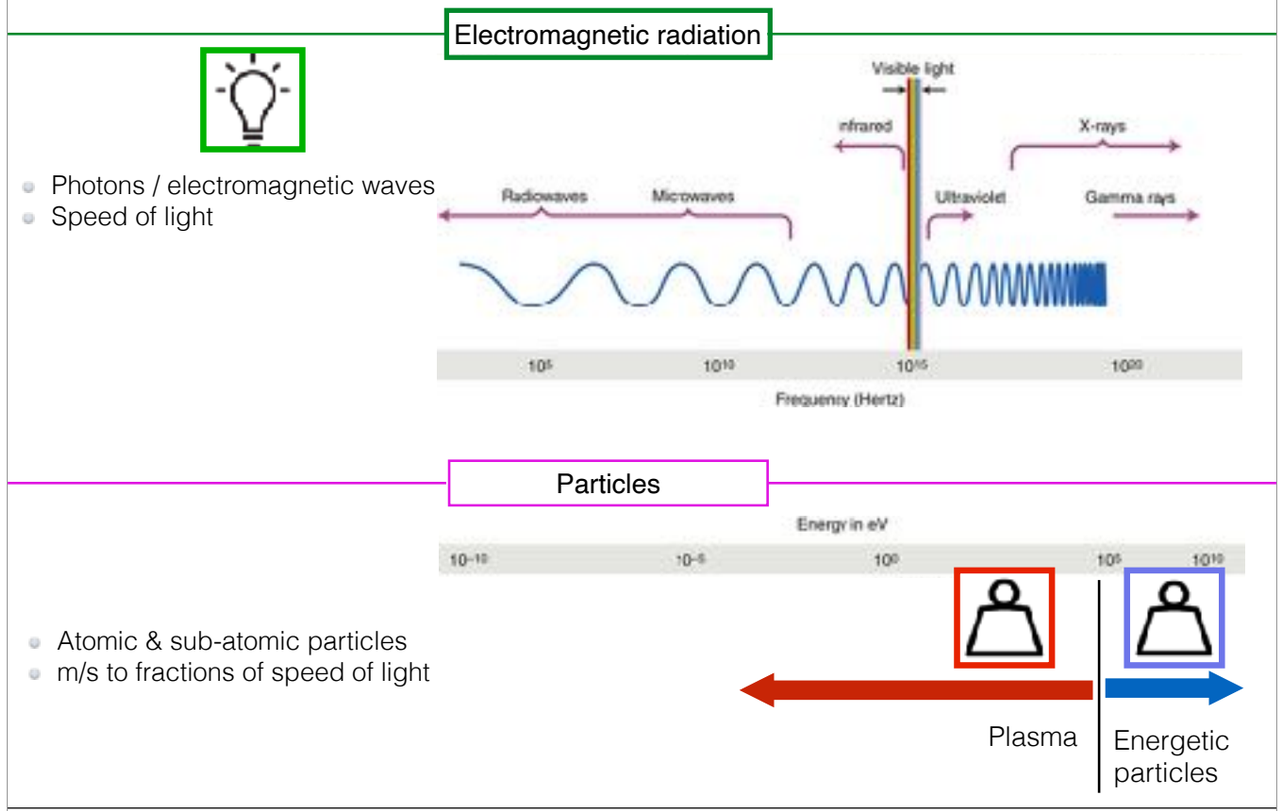


The sun is a gigantic ball of energy: magnetic energy, heat, moving plasma, …

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.



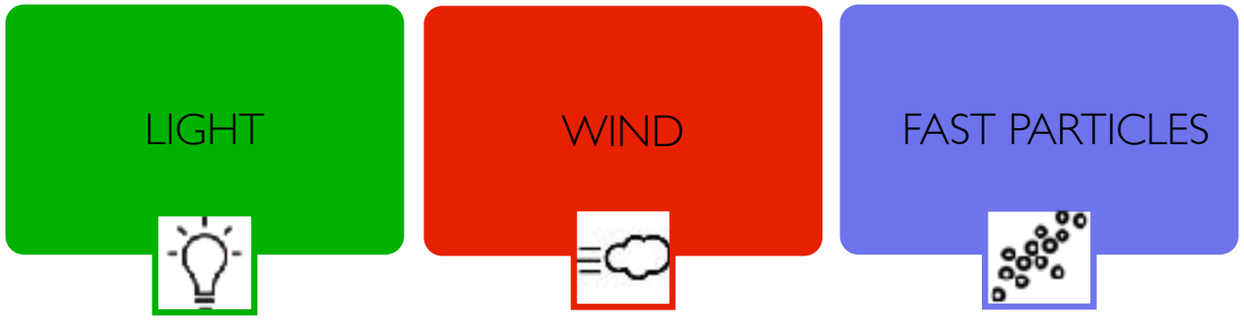
100 kEV
Energetic particles detach from the plasma and move on their own

Energetic subatomic particles are individual constituents of atoms, such as electrons, protons, and neutrons, that are moving at high speeds or have high kinetic energy. Plasma, in contrast, is a distinct state of matter consisting of a superheated, ionized gas where these subatomic particles (now called ions and free electrons) are separated and move freely, rather than being bound within neutral atoms. Therefore, energetic subatomic particles are the fundamental building blocks, while plasma is the collective, highly energized, and ionized state formed by these particles.

THE SUN AS A BALL OF ENERGY

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

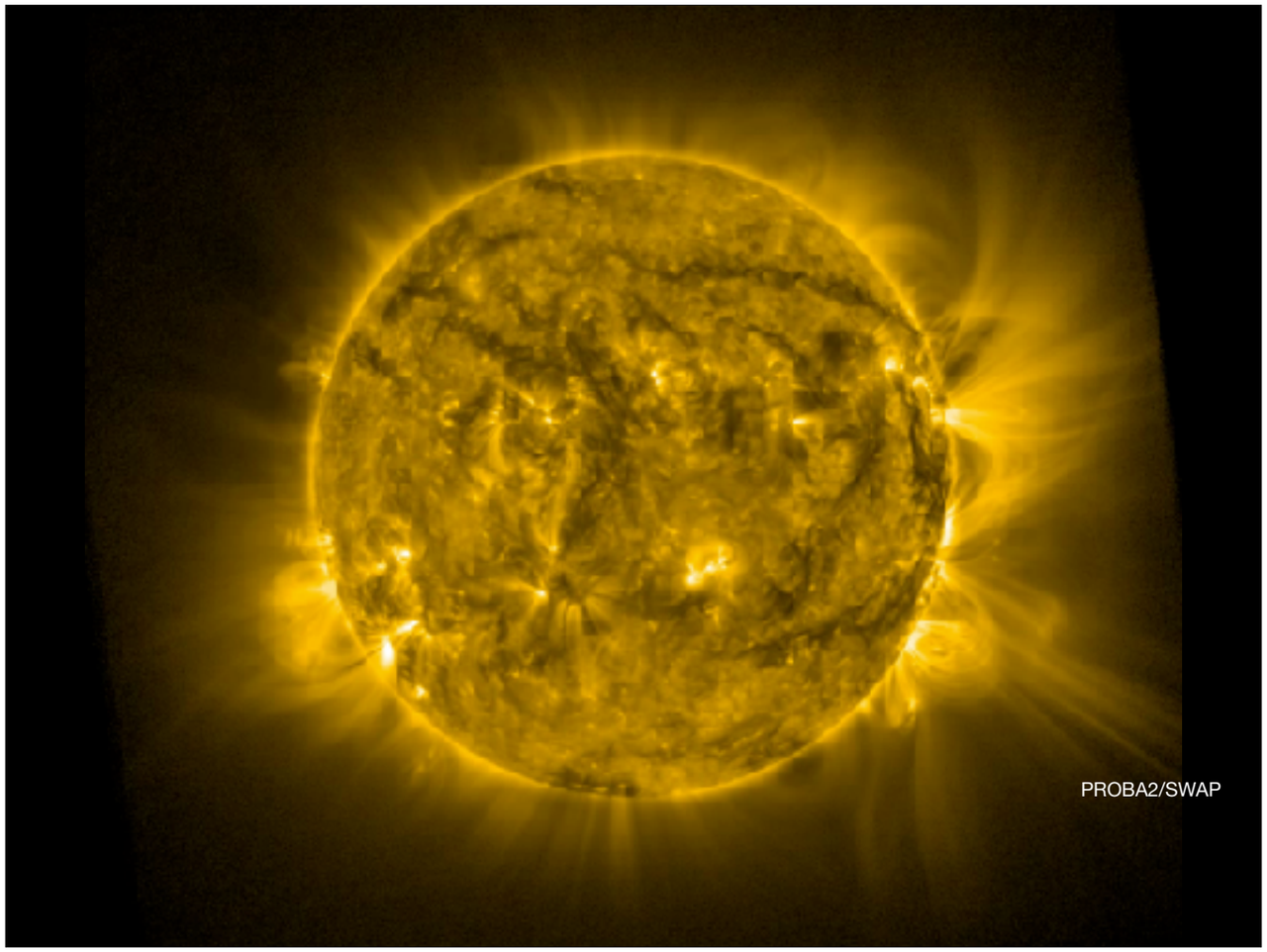
Particle precipitation - energy transmitted in the form of fast-moving atomic or sub-atomic particles —> drizzle

Energy expressed in eV= 1.602 10^-19 J

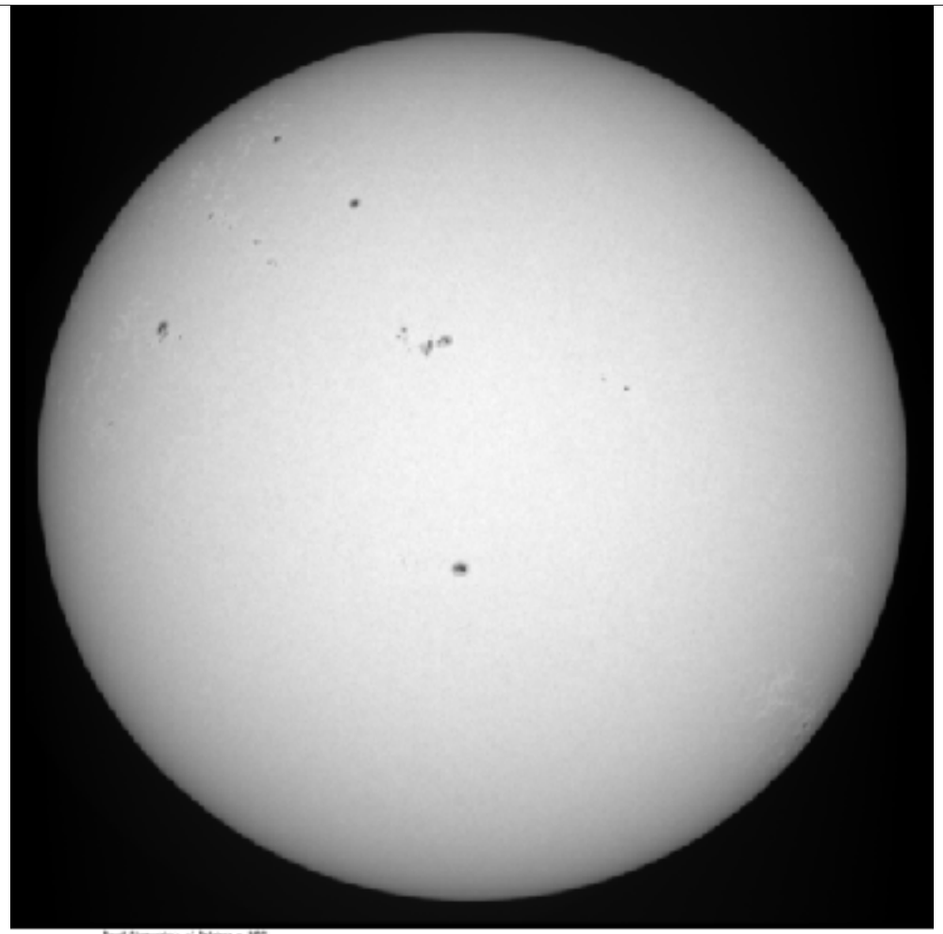
https://lasp.colorado.edu/home/mag/research/energetic-particle-precipitation/

Focus on solar energetic particles

Magnetism drives space weather and the sun’s dynamics.

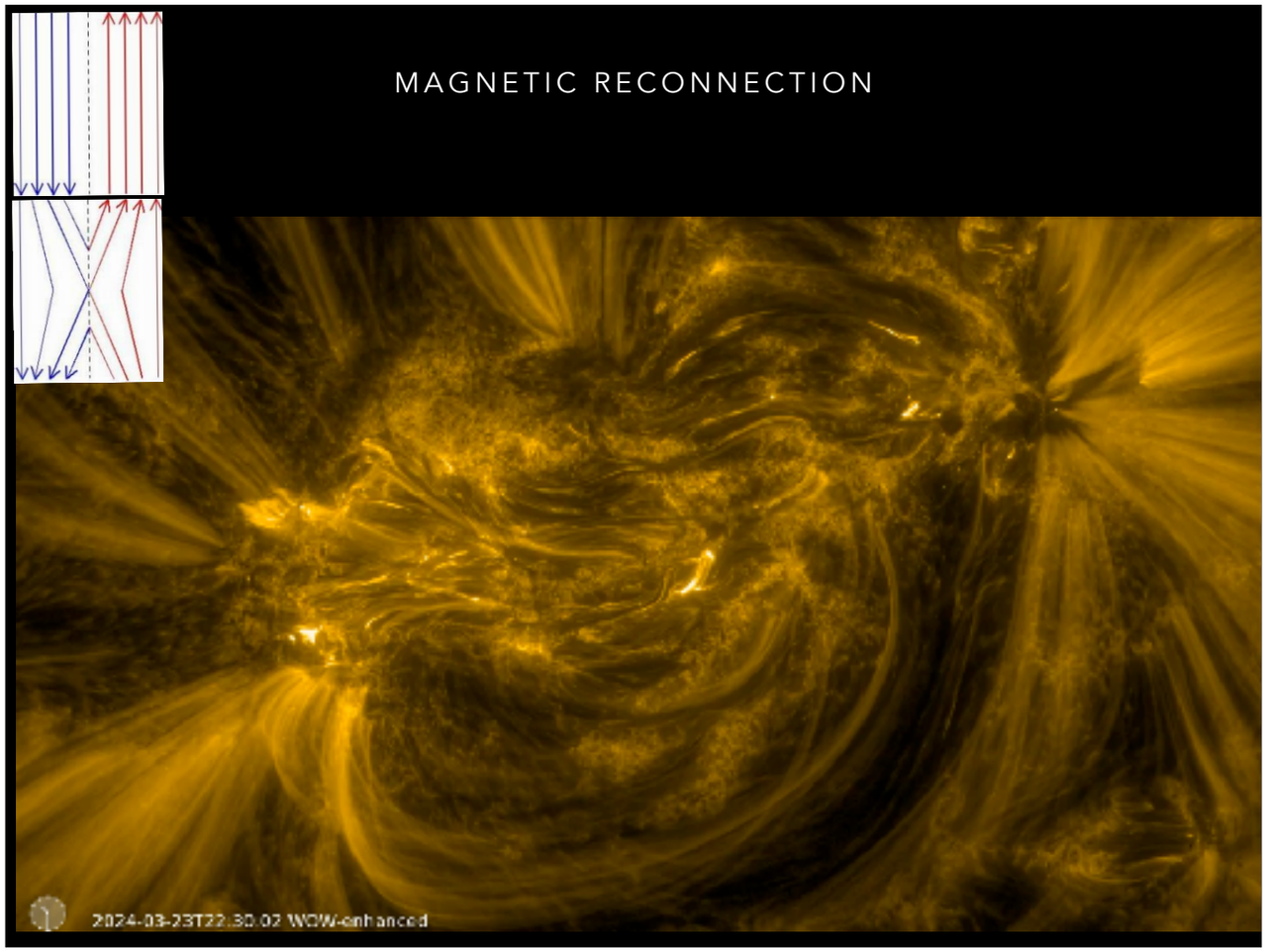


In the EUV it looks like this!
The sun doesn’t only rotate but it is also tangled with loops which move, shake back and forth, restructure and do all sorts of electric and magnetic magic.
It is a turbulent plasma ball where magnetic fields are moving, shake, connect with other other, ….



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.

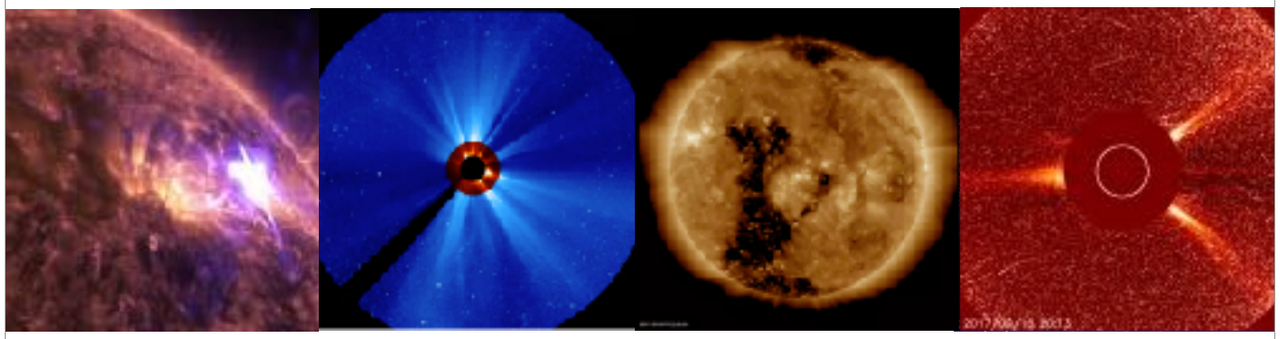


The more sunspots, the higher the chance for magnetic reconnection.

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

At a certain moment, 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
High Speed Stream

Energetic Particles

Day to day situation

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

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

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SDO/AIA

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

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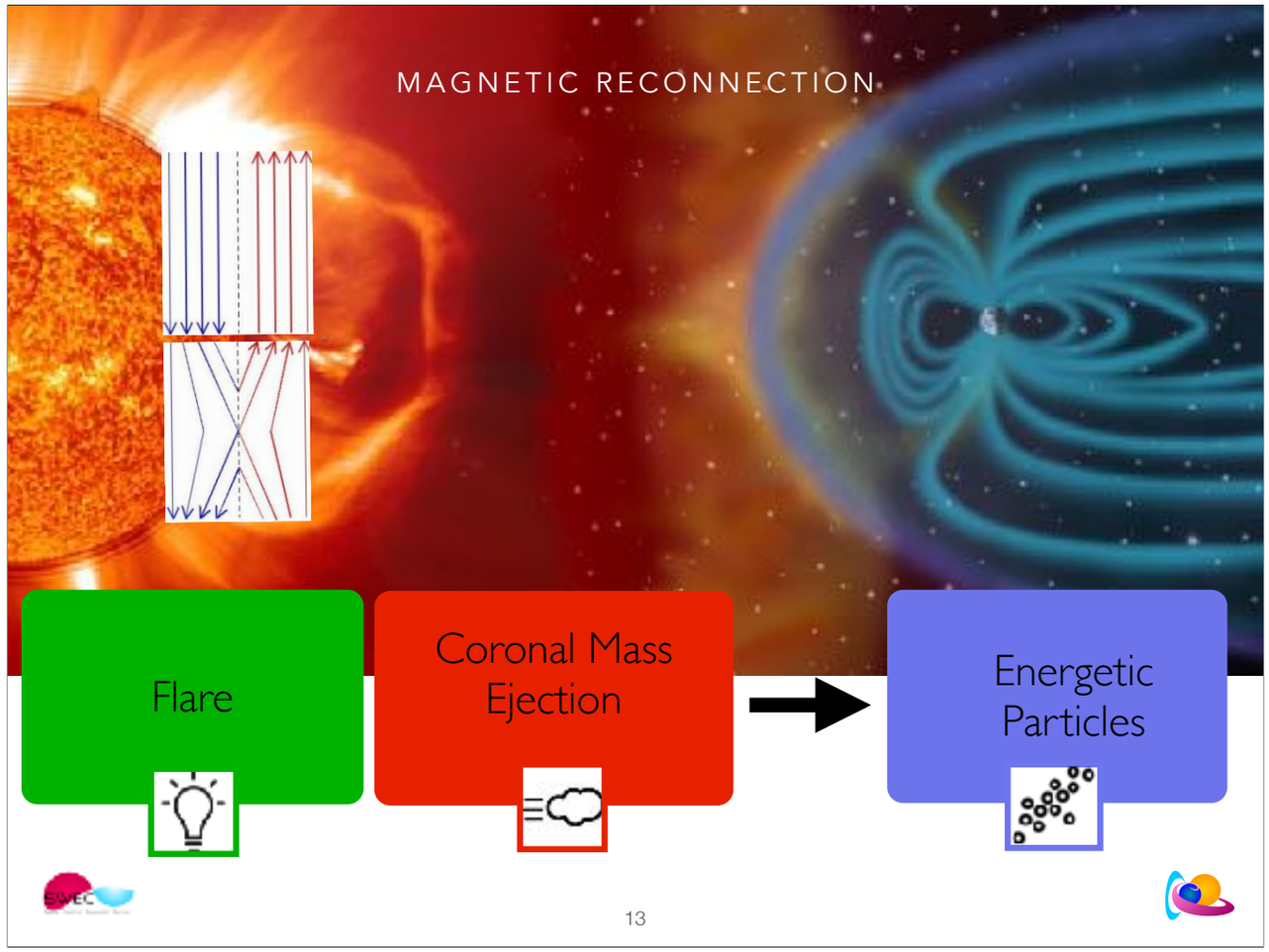

Flares and coronal mass ejections are the result of magnetic reconnection. The stored magnetic energy is released in the form of thermal e.m. radiation (flare) and/or of kinetic energy as the plasma is being ejected (coronal mass ejection).

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

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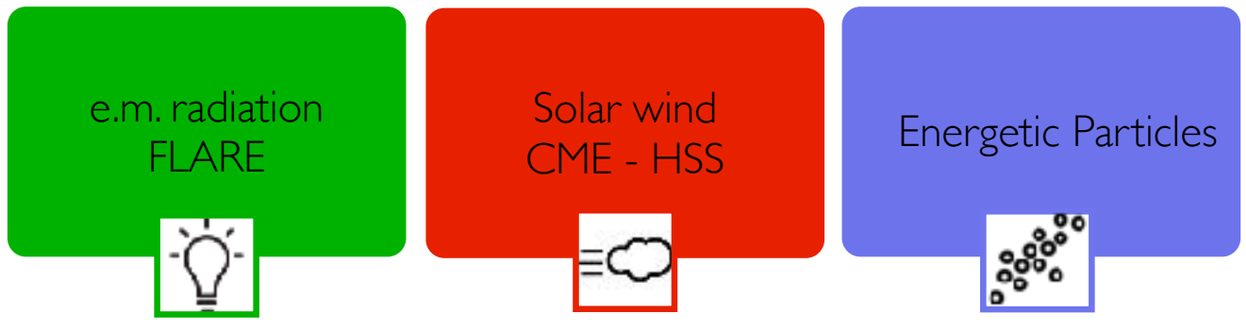
SOLAR WEATHER & STORMS



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

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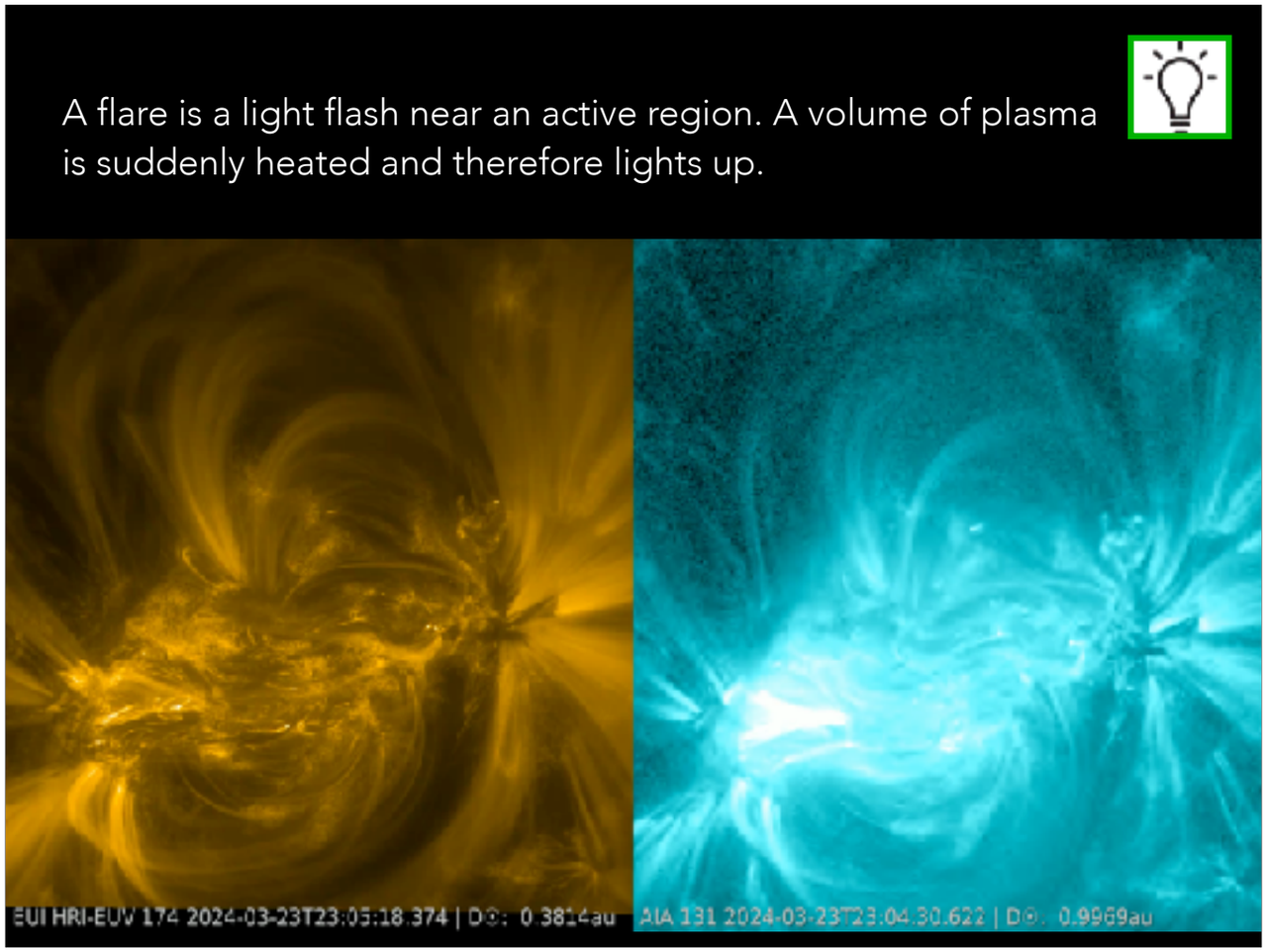
Transit time

On earth
Storm scale – strength
duration
Impact
Area of impact



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

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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

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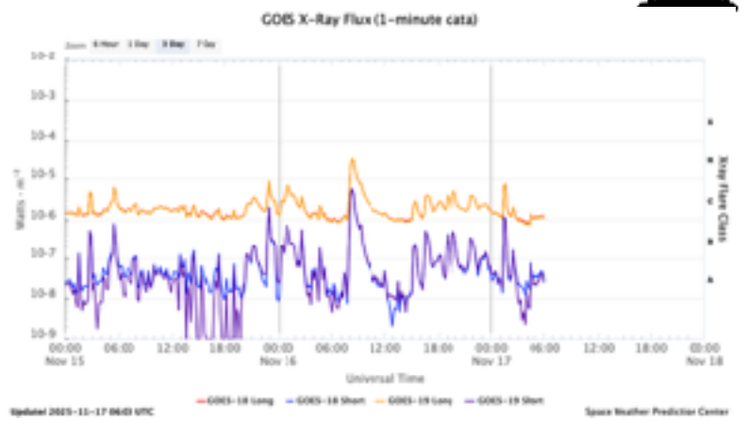
DURATION

MINs to HOUR



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.

Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light

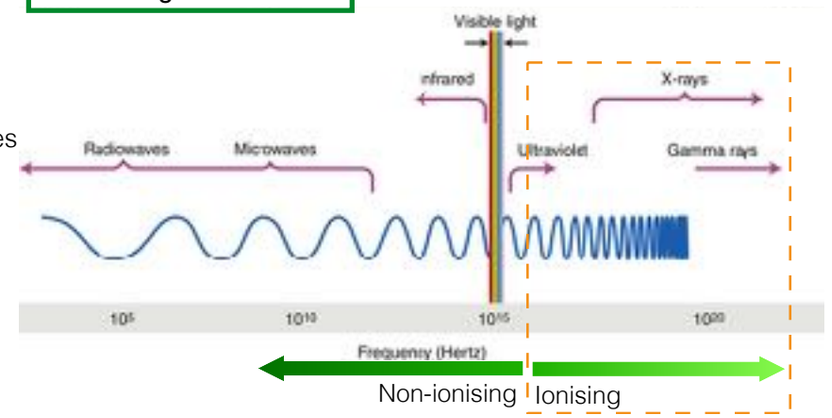


Photo-ionisation — green

Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

Ionizing radiation (or ionising radiation), including nuclear radiation, consists of subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules by detaching electrons from them.[1] Some particles can travel up to 99% of the speed of light, and the electromagnetic waves are on the high-energy portion of the electromagnetic spectrum.

Gamma rays, X-rays, and the higher energy ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, nearly all types of laser light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and non-ionizing radiation in the ultraviolet area cannot be sharply defined, as different molecules and atoms ionize at different energies. The energy of ionizing radiation starts between 10 electronvolts (eV) and 33 eV.

IMPACT

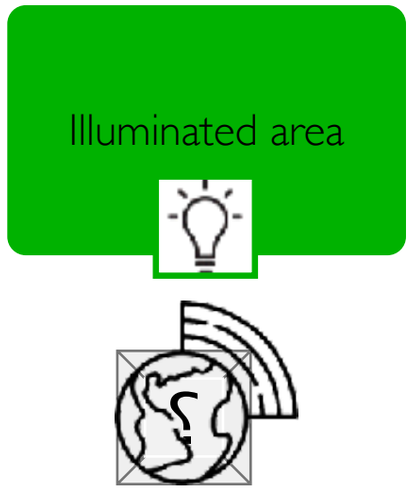
Ionisation

The icon represent the Earth + atmosphere with the ionosphere
Ionisation of atoms and molecules due to photons -

The light smashes atomic particles into pieces. Those pieces are electrically charged.

AREA OF IMPACT

AREA OF IMPACT



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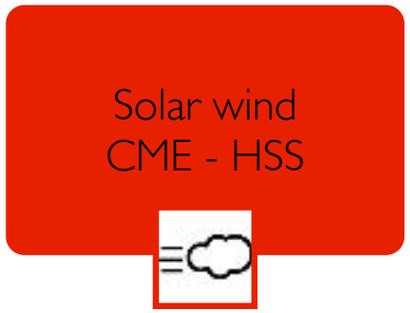

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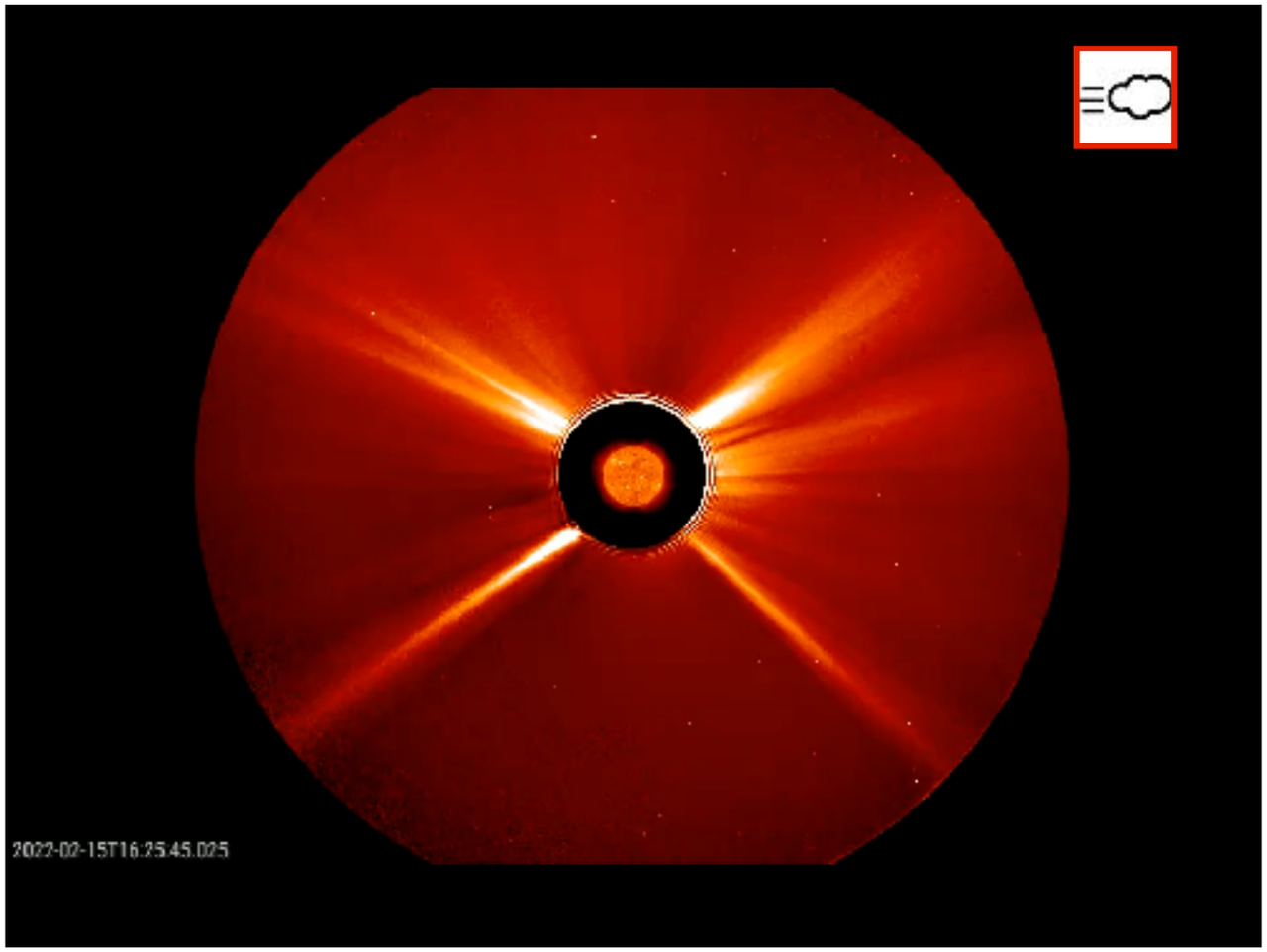

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SOHO/LASCO C2

AU TRANSIT TIME

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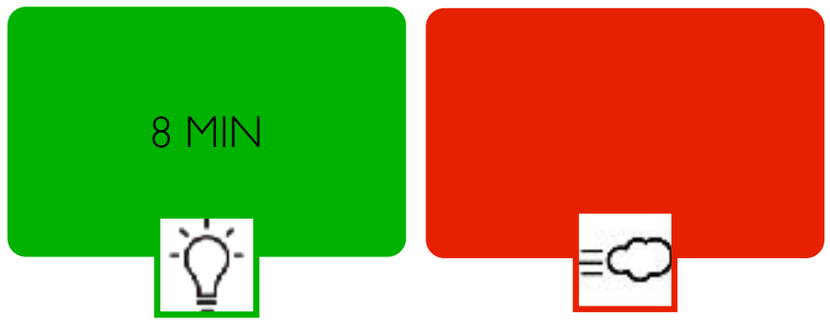

AU TRANSIT TIME

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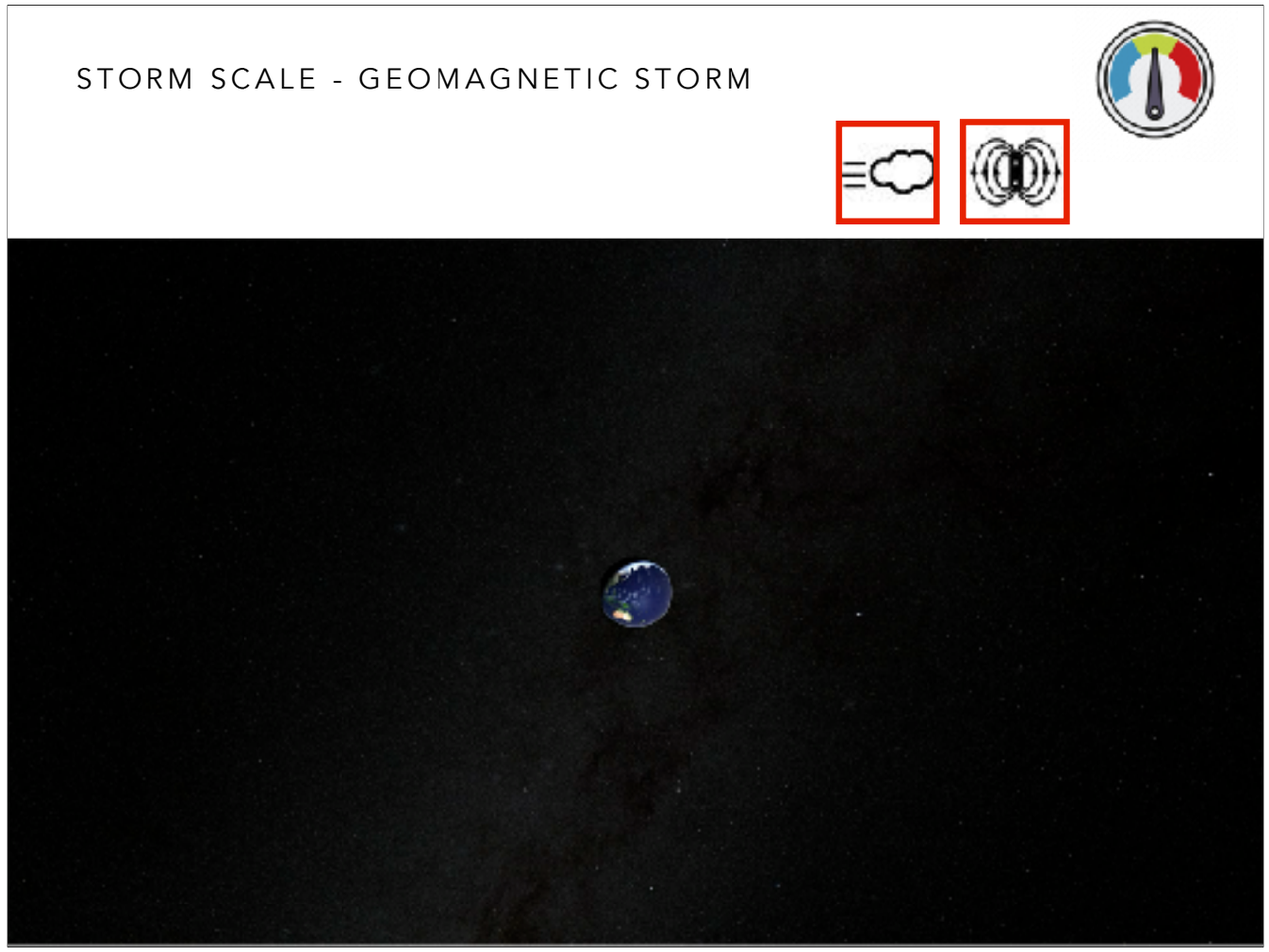
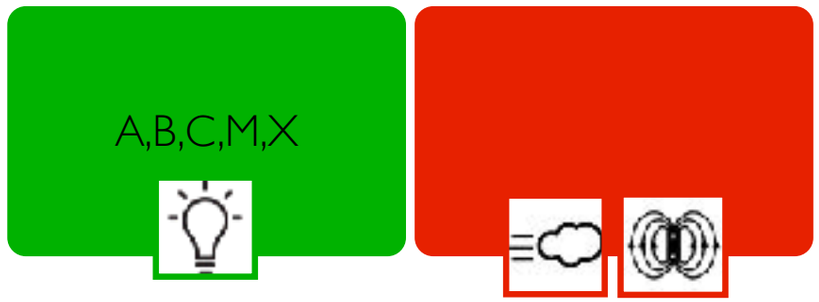


https://svs.gsfc.nasa.gov/5193/
This animation demonstrates the Earth's magnetosphere being hit by a geomagnetic storm on February 3, 2020, simulated by MAGE during the storm that caused the loss of commercial satellites.

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.

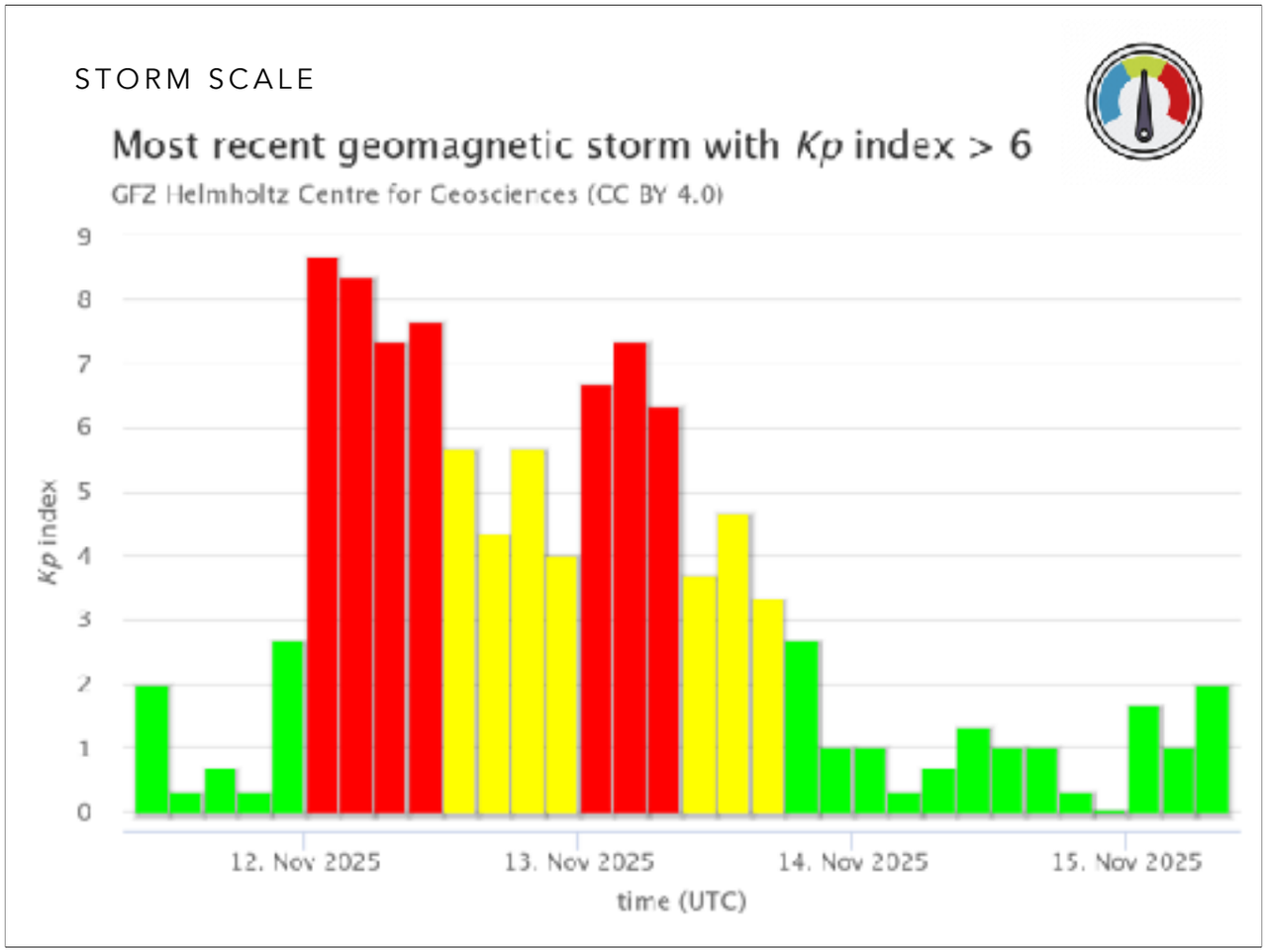
STORM SCALE

https://kp.gfz.de/en/



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



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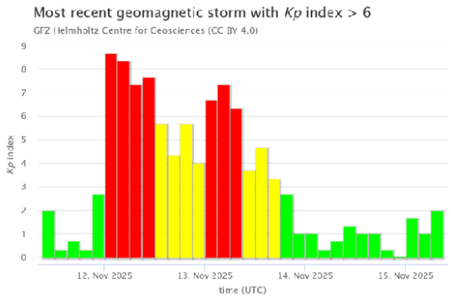

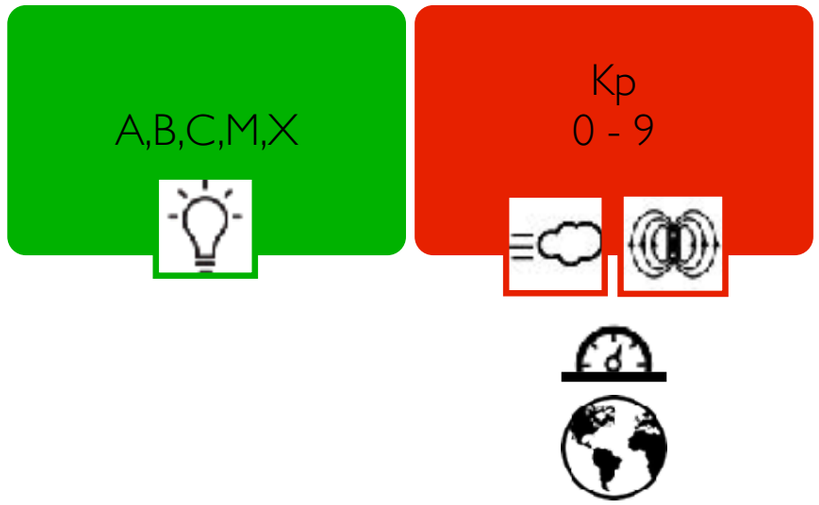

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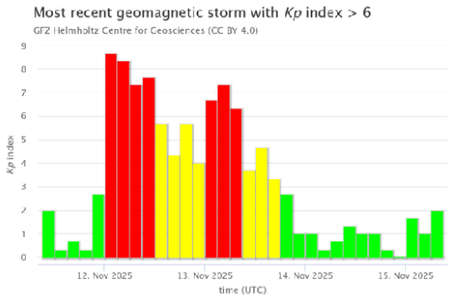
DURATION

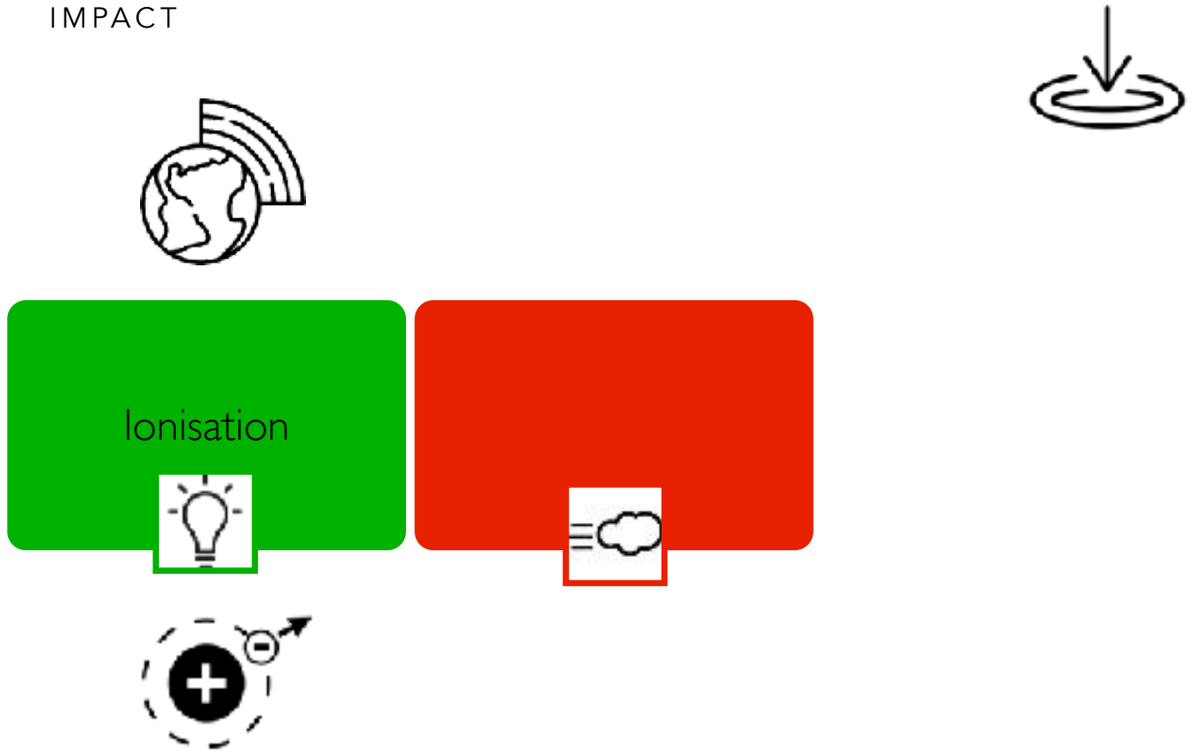


MINs to HOUR

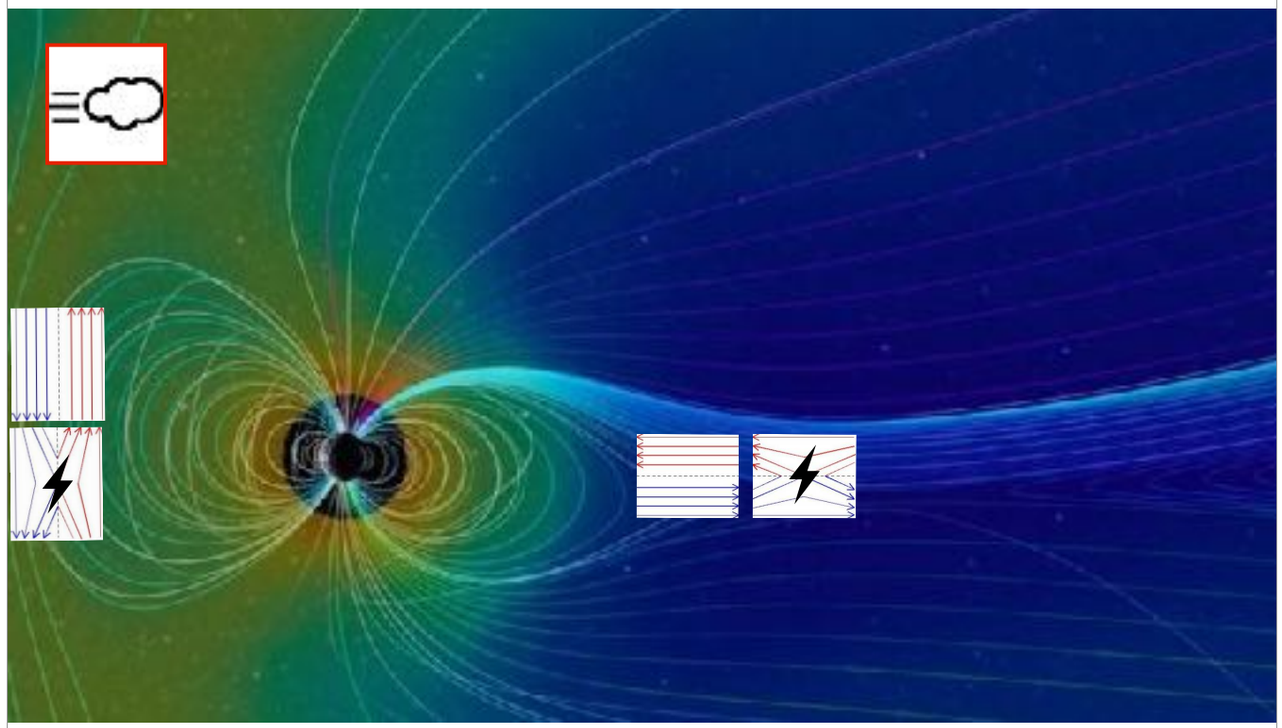
DAY+

Day or more

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.

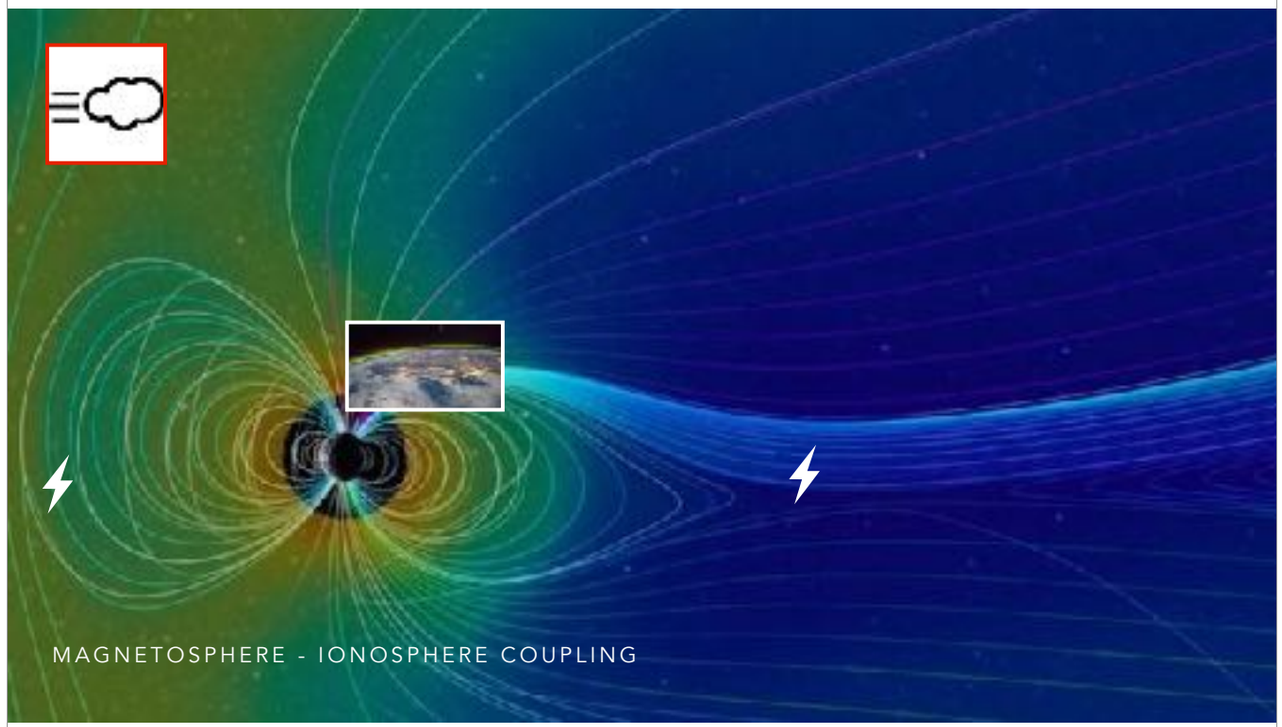


- Ampères law : circulation of magnetic field = enclosed electric current —> sheet current

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 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.

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 connect easily and ‘open’. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.

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



currents

- Ampères law : circulation of magnetic field = enclosed electric current —> sheet current
- Magnetopause current, neutral sheet current, magnetotail current
- can propagate to the ionosphere (field aligned currents)

Ionosphere: a region with free electrons due to ionisation - conductive system

Magnetosphere-ionosphere coupling
The gas-system of the ionosphere is connected with magnetic system of Earth. Both systems intersect and interact with each other.
(Magnetopause current couples to pedderson and hall currents in low ionosphere (E and D-layer))
—> due to the coupling with a magnetic dipolar structure, the ionospheric behaviour is different at low, middle and high latitudes.

Field aligned currents along the magnetic field lines, connect the magnetospheric currents with ionospheric currents. The Pedersen and Hall currents are two main currents in the lower ionosphere. They are localized in the ionospheric D and E regions.

Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an “image” in the ionosphere, and conversely. We identify the following regions:

Magnetopause ↔ footpoints of the cusps
Tail lobes ↔ polar caps
Plasma sheet ↔ auroral oval
Plasmasphere ↔ ionosphere at low latitude

The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. ionospheric structures and peak densities in the ionosphere vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes,

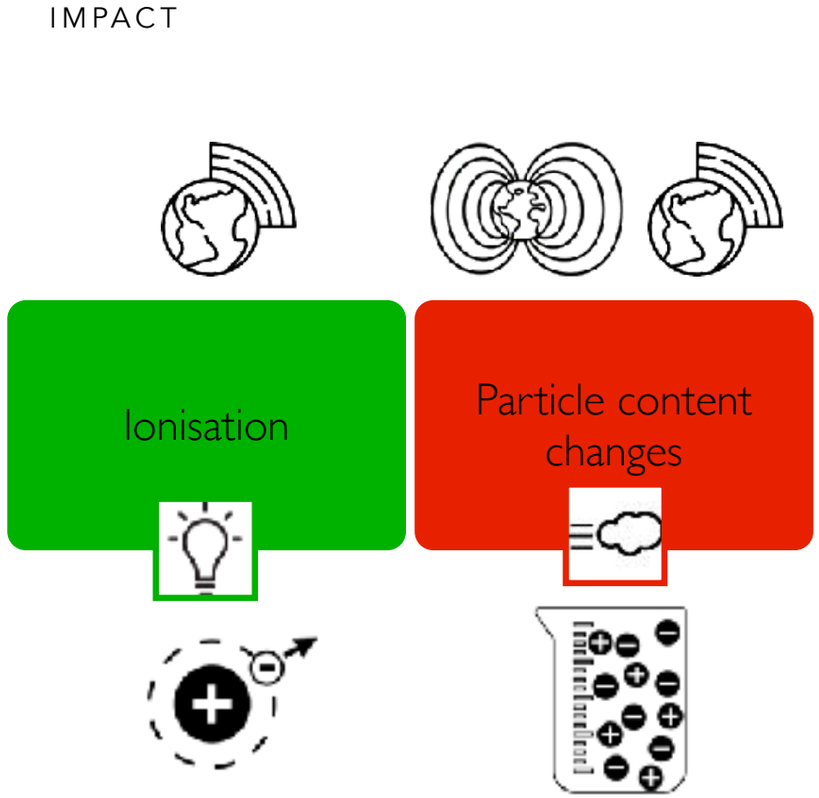
and equatorial regions), and with certain solar-related ionospheric disturbances.

The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases in the sunlit atmosphere and decreases on the shadowed side. Although the Sun is the largest contributor toward the ionization, cosmic rays make a small contribution. Any atmospheric disturbance affects the distribution of the ionization.

The ionosphere is a **dynamic system controlled by** many parameters including **acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field**. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric events.

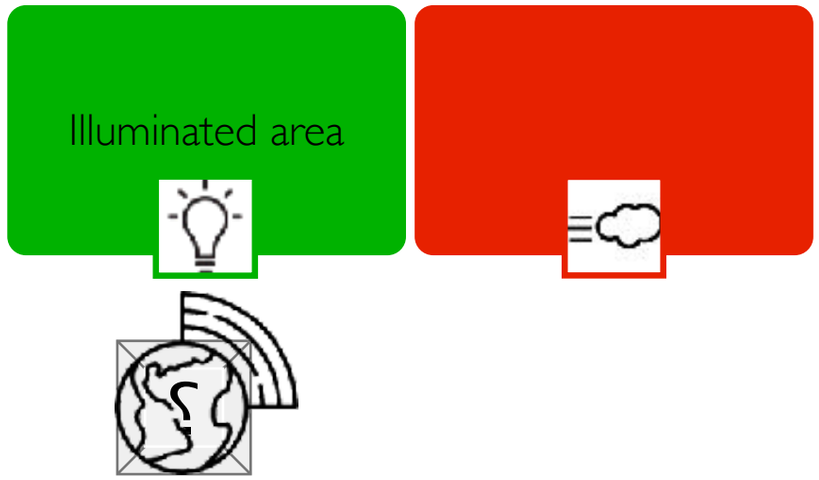
The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.

IMPACT



Plasmasphere - ionosphere
Moving plasma —> VTEC - irregularities

AREA OF IMPACT



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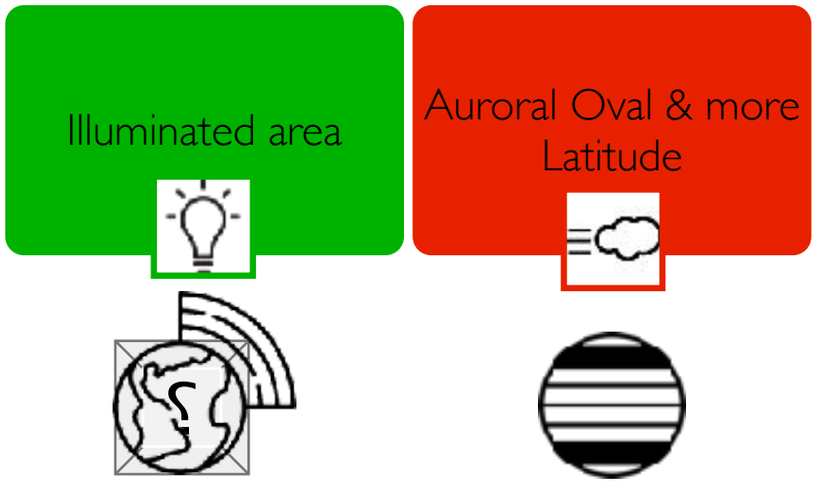
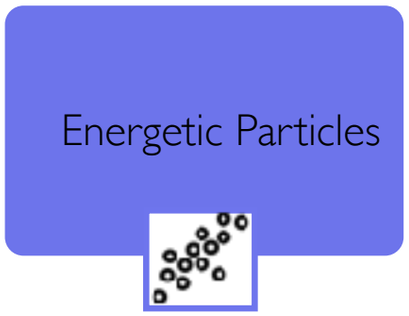


Latitude

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)

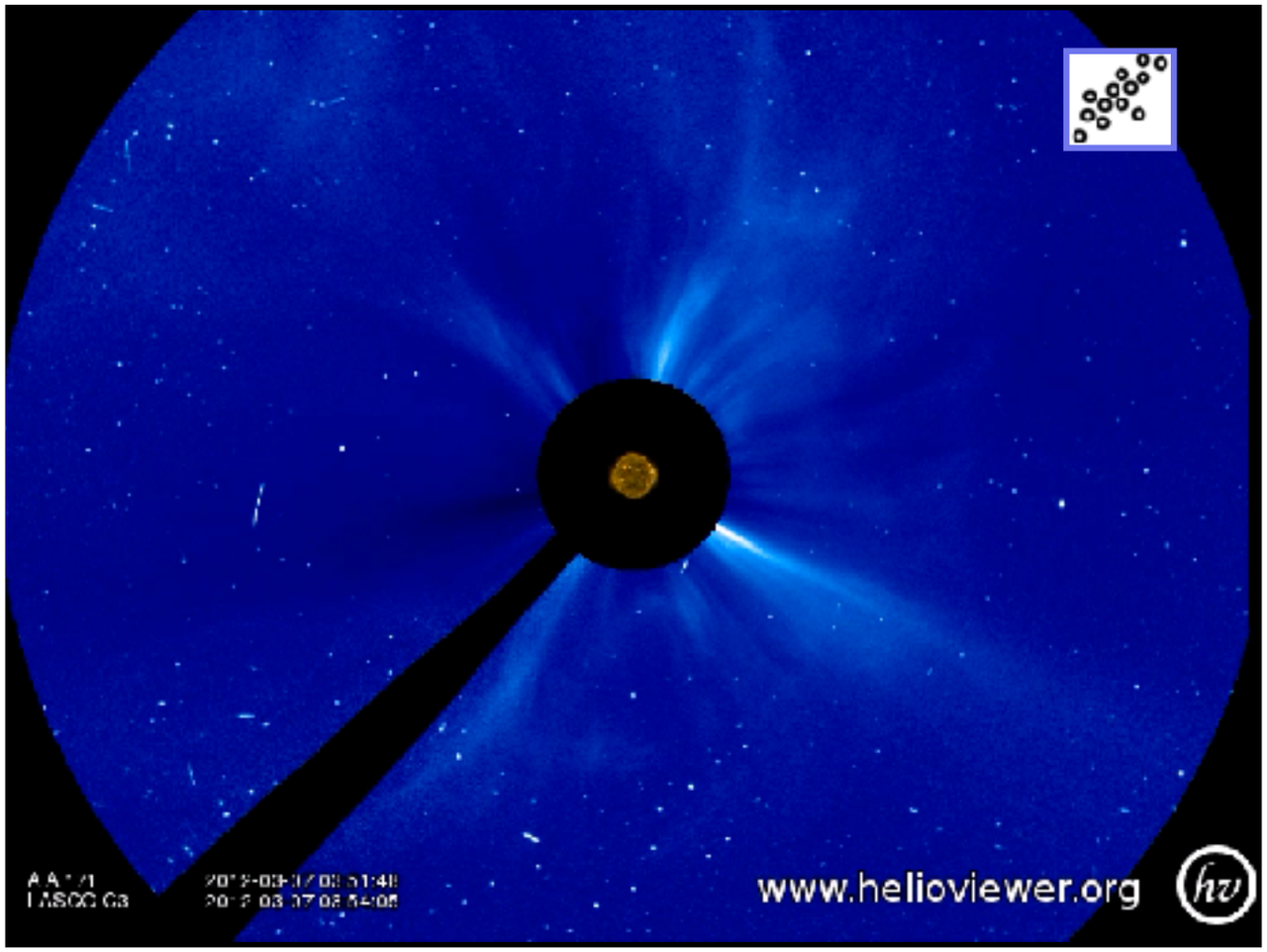
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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



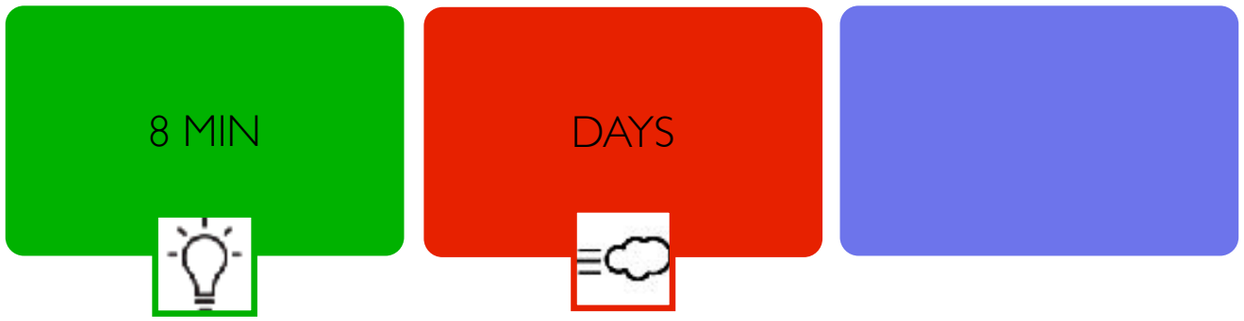
Particle showers

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.)

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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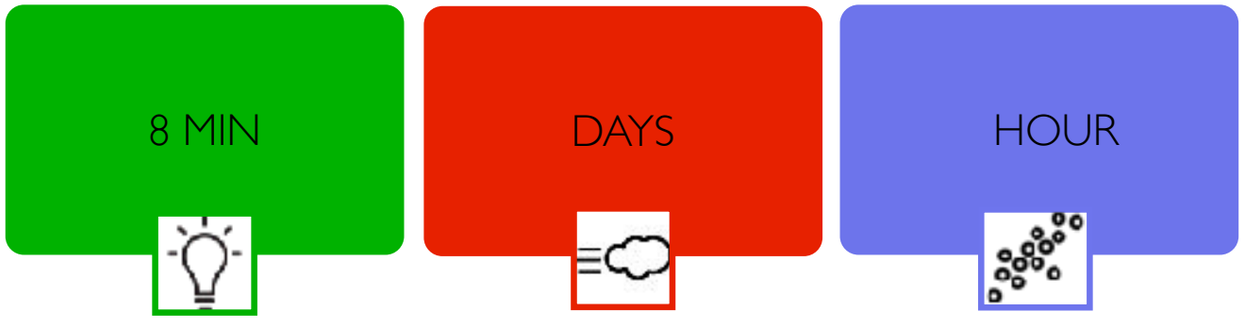
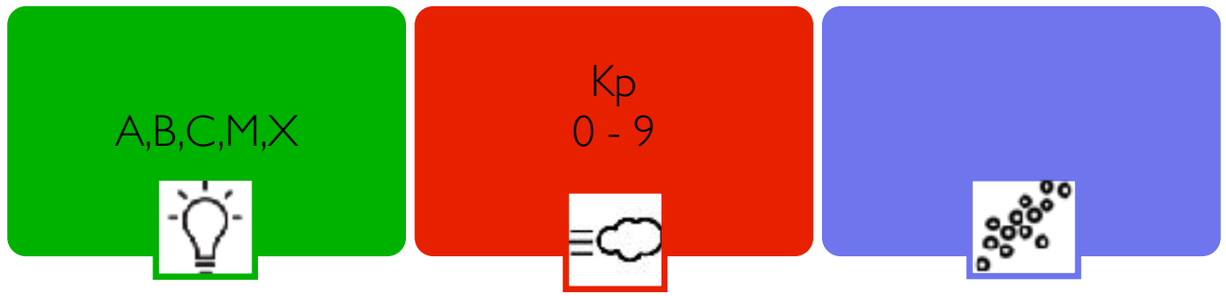


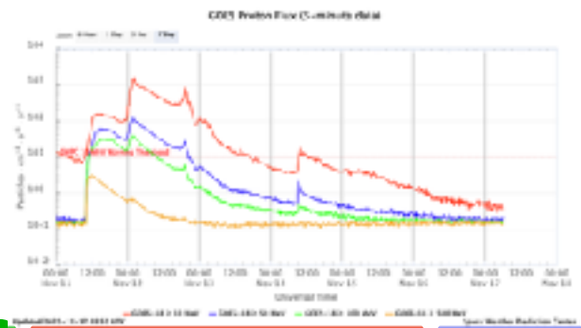
STORM SCALE

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

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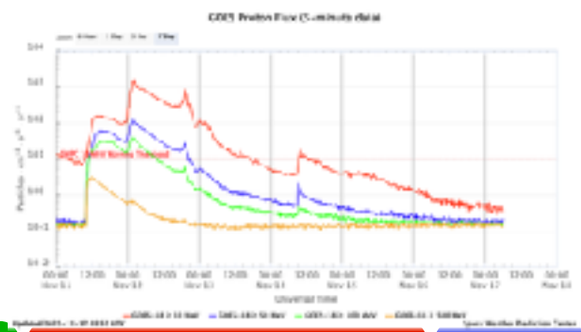
DURATION



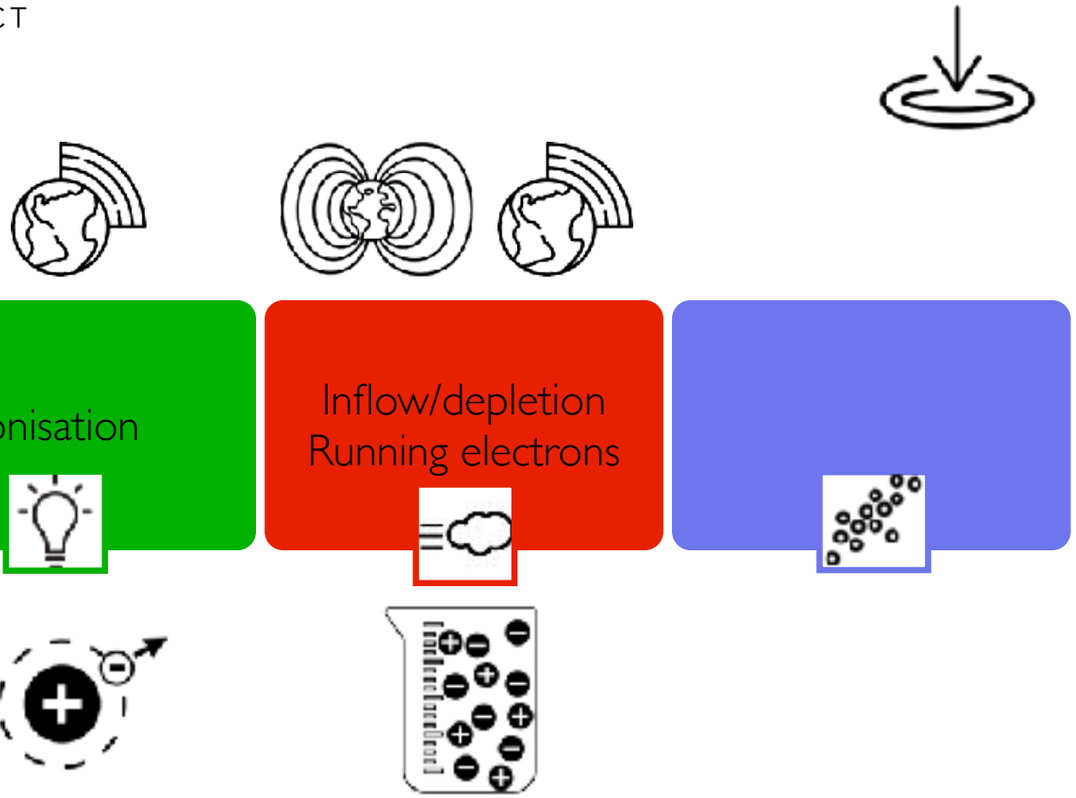
MINs to HOUR

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

IMPACT



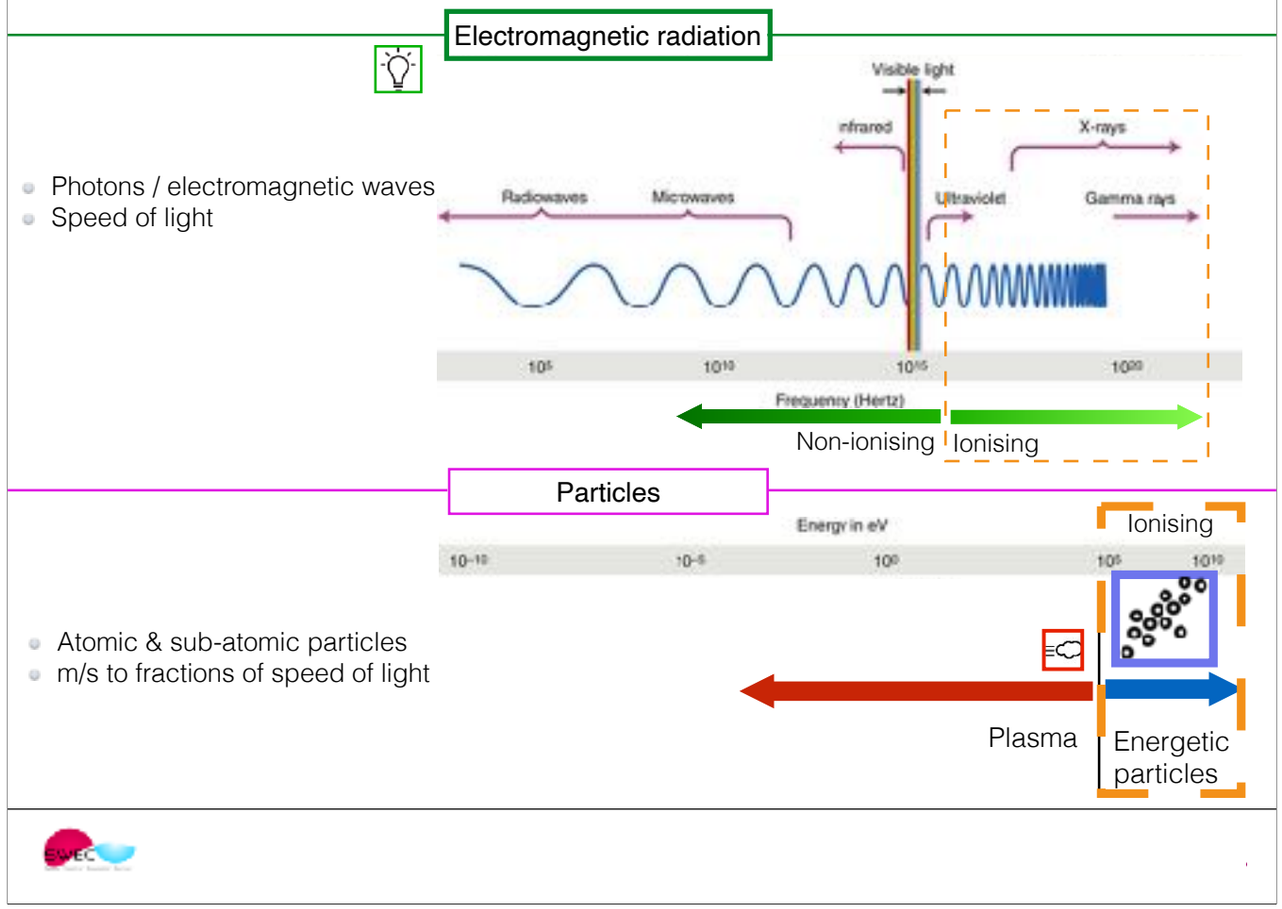


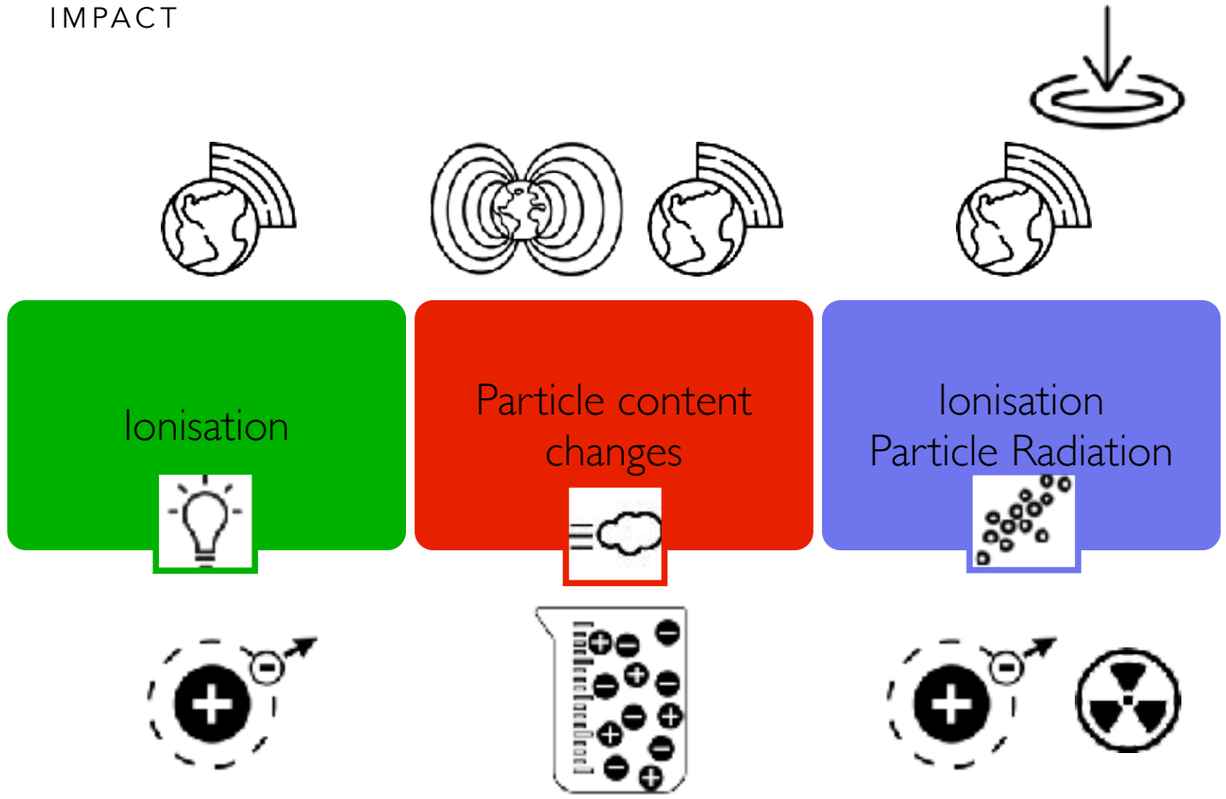
Photo-ionisation — green

Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

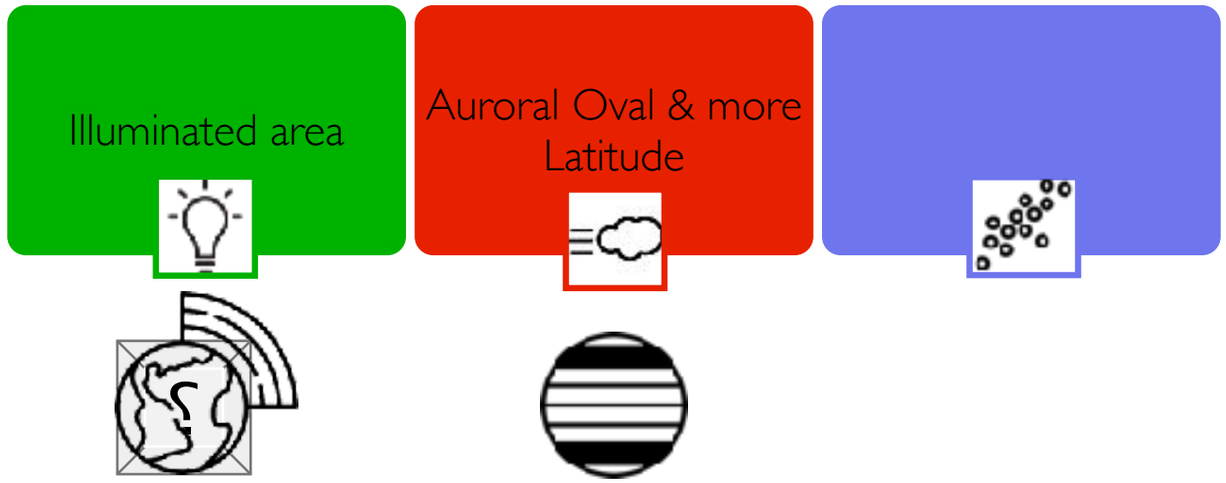
Ionizing radiation (or ionising radiation), including nuclear radiation, consists of subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules by detaching electrons from them.[1] Some particles can travel up to 99% of the speed of light, and the electromagnetic waves are on the high-energy portion of the electromagnetic spectrum.

Gamma rays, X-rays, and the higher energy ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, nearly all types of laser light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and non-ionizing radiation in the ultraviolet area cannot be sharply defined, as different molecules and atoms ionize at different energies. The energy of ionizing radiation starts between 10 electronvolts (eV) and 33 eV.

IMPACT


Ionisation
Particle content changes
Ionisation
Particle Radiation

AREA OF IMPACT



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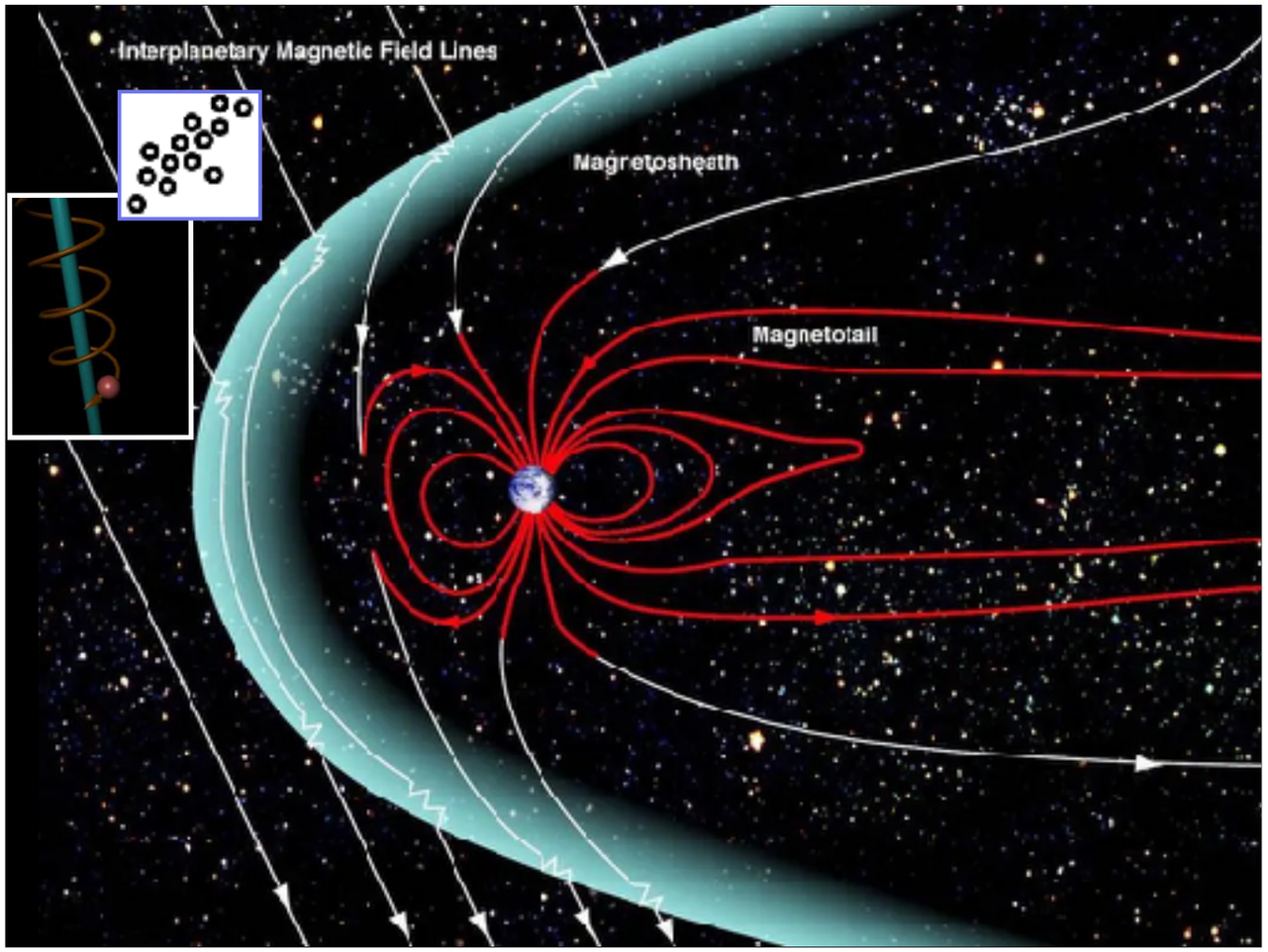
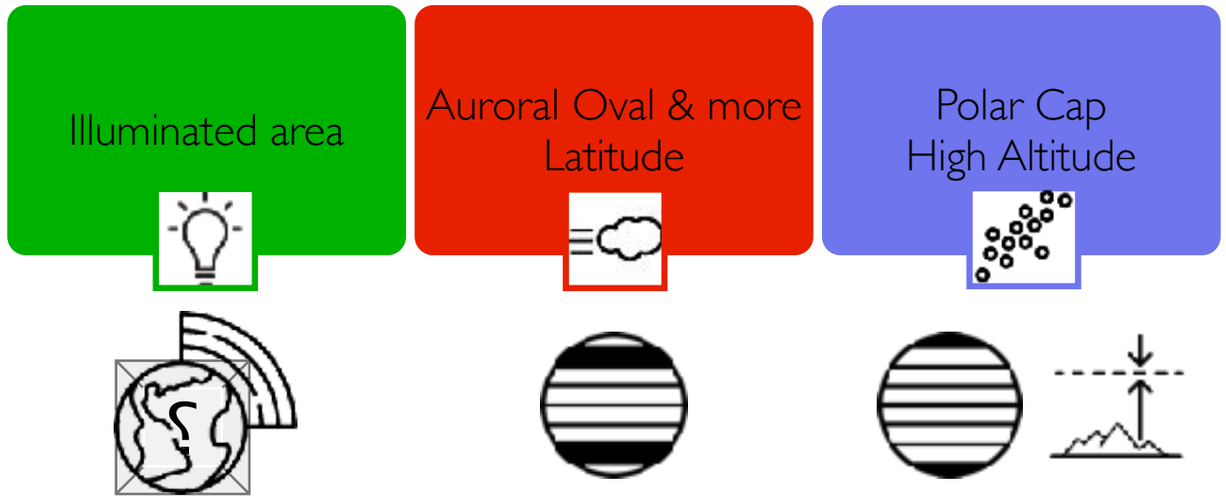
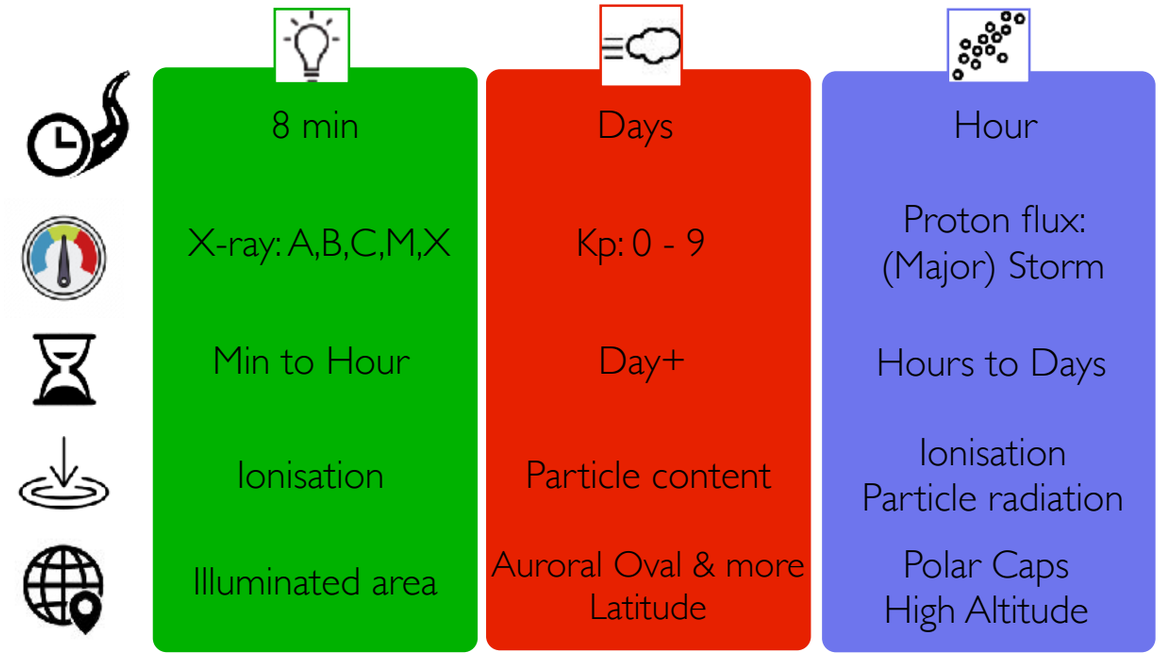


The particles grab the open magnetic field lines and enter in this way the magnetosphere and finally the atmosphere of earth.

AREA OF IMPACT



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


8 min
X-ray: A,B,C,M,X
Min to Hour
Ionisation
Illuminated area
Days
Kp: 0 - 9
Day+
Particle content
Auroral Oval & more
Latitude
Hour
Proton flux:
(Major) Storm
Hours to Days
Ionisation
Particle radiation
Polar Caps
High Altitude