

# DRIVERS OF SPACE WEATHER

## The source of weather



2



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.

## The main source of space weather

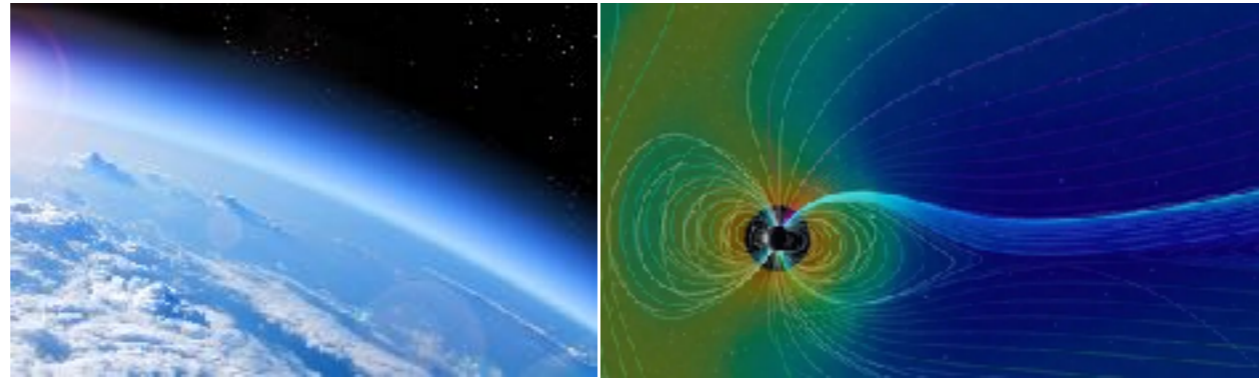


As we go out into space, the atmosphere becomes very thin, until by the time we are in space, it has almost vanished. Almost, but not quite. Even in space there are some atoms which are often moving very quickly. Many forms of energy also move through **space** and it is the **interaction of energy and 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.**

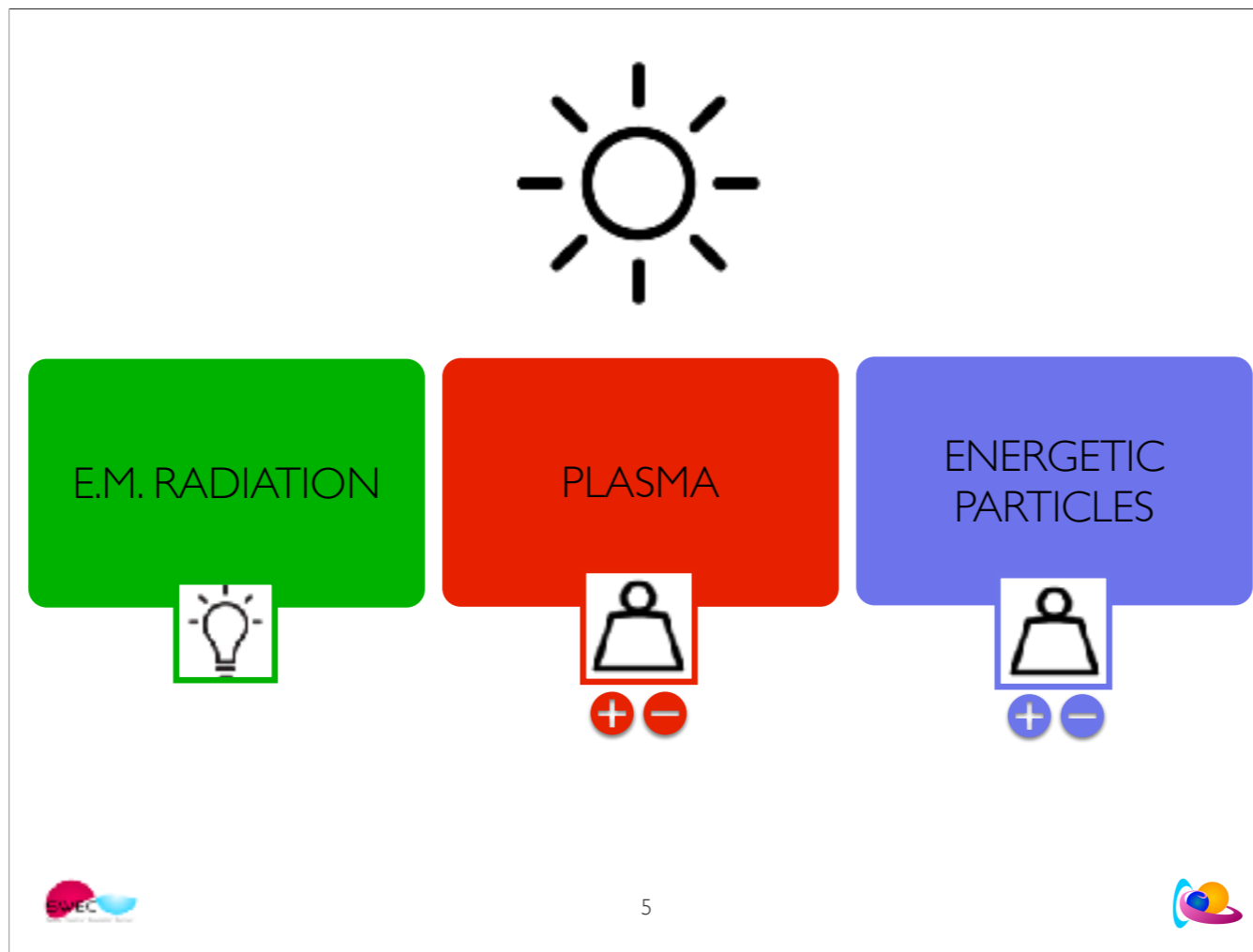
## Space Weather

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



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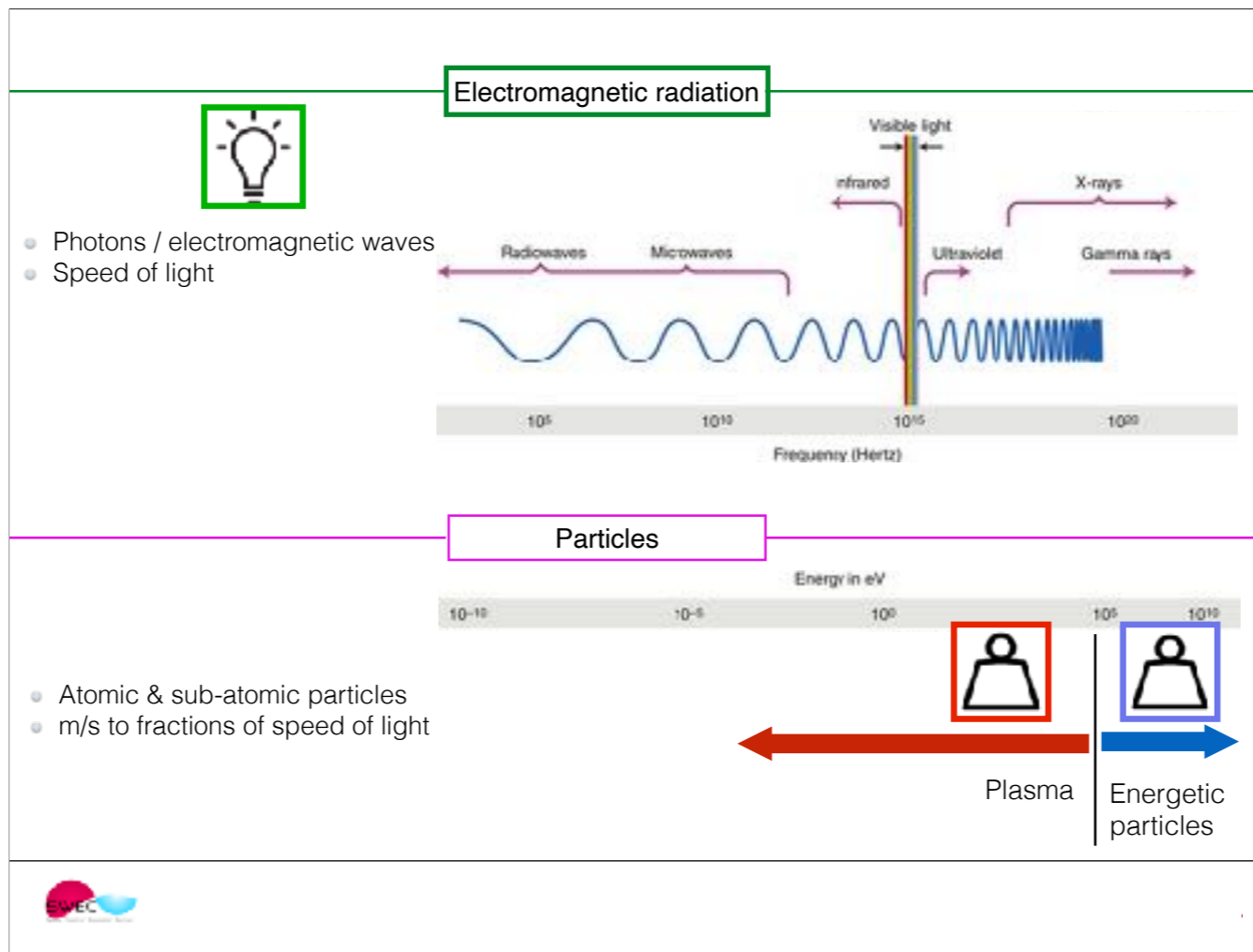
The sun is a gigantic ball of energy: magnetic energy, heat, moving plasma, ...

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

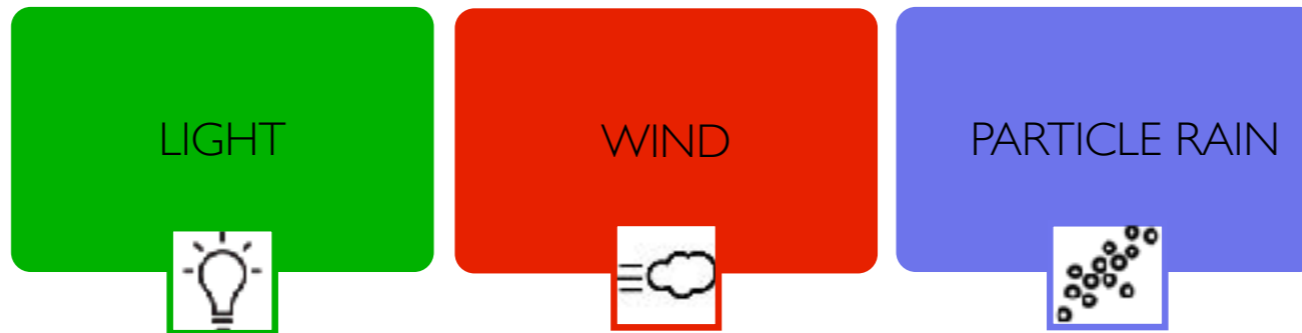
Energetic subatomic particles are individual constituents of atoms, such as electrons, protons, and neutrons, that are moving at high speeds or have high kinetic energy. Plasma, in contrast, is a distinct state of matter consisting of a superheated, ionized gas where these subatomic particles (now called 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.

### 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

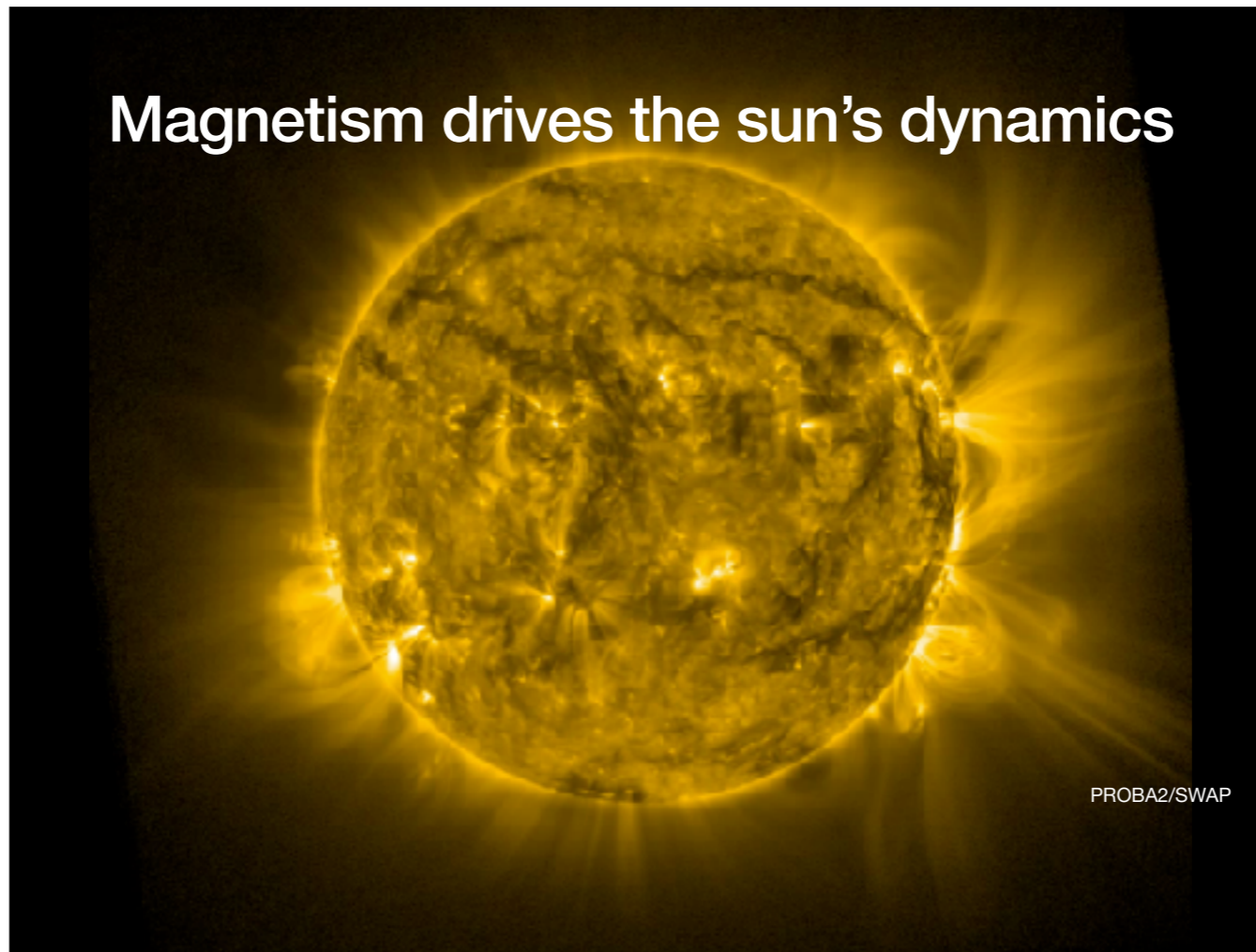
Particle precipitation - energy transmitted in the form of fast-moving atomic or sub-atomic particles → drizzle

Energy expressed in eV=  $1.602 \cdot 10^{-19}$  J

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

Focus on solar energetic particles

# Magnetism drives the sun's dynamics



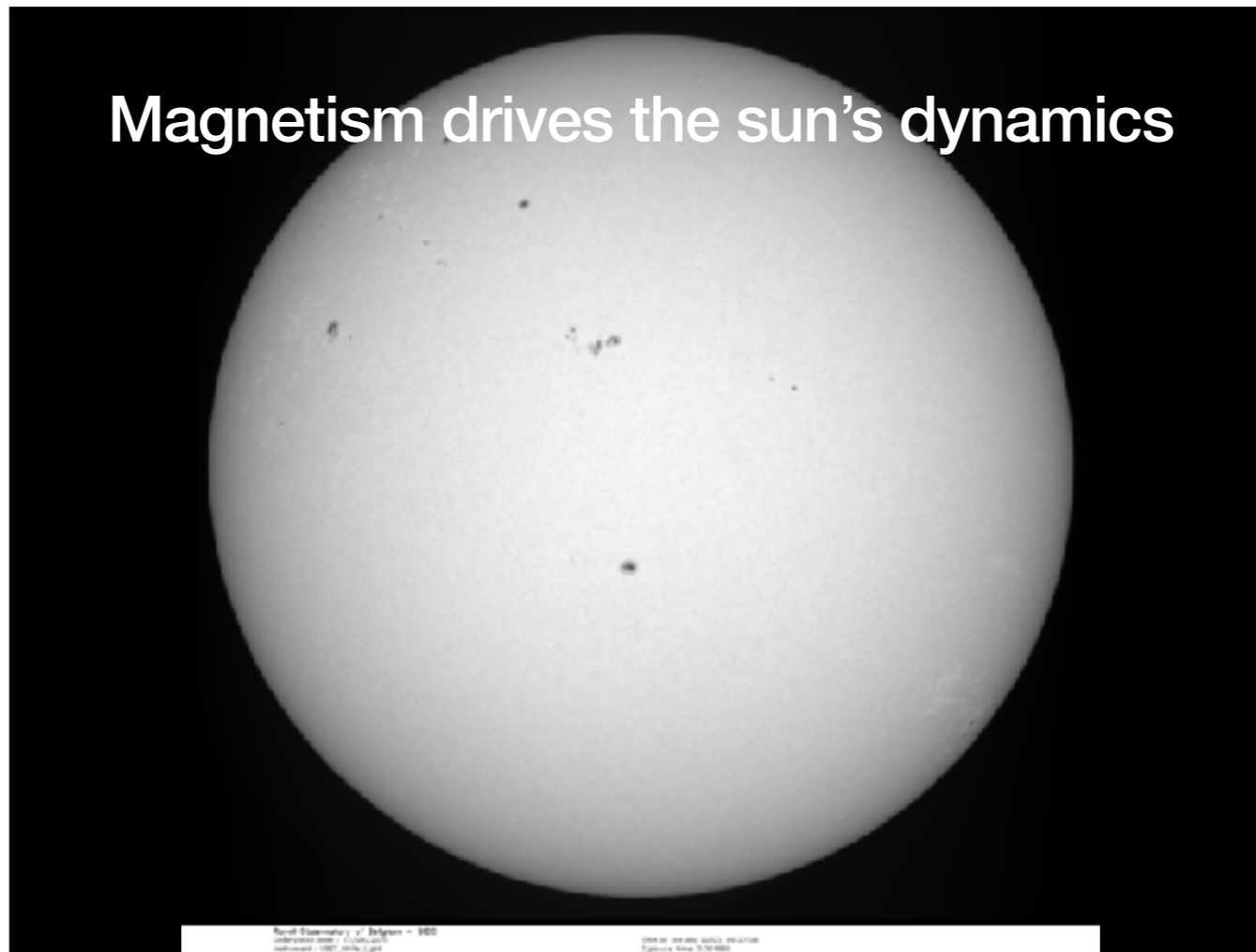
Magnetism drives space weather and the sun's dynamics.

In the EUV it looks like this!

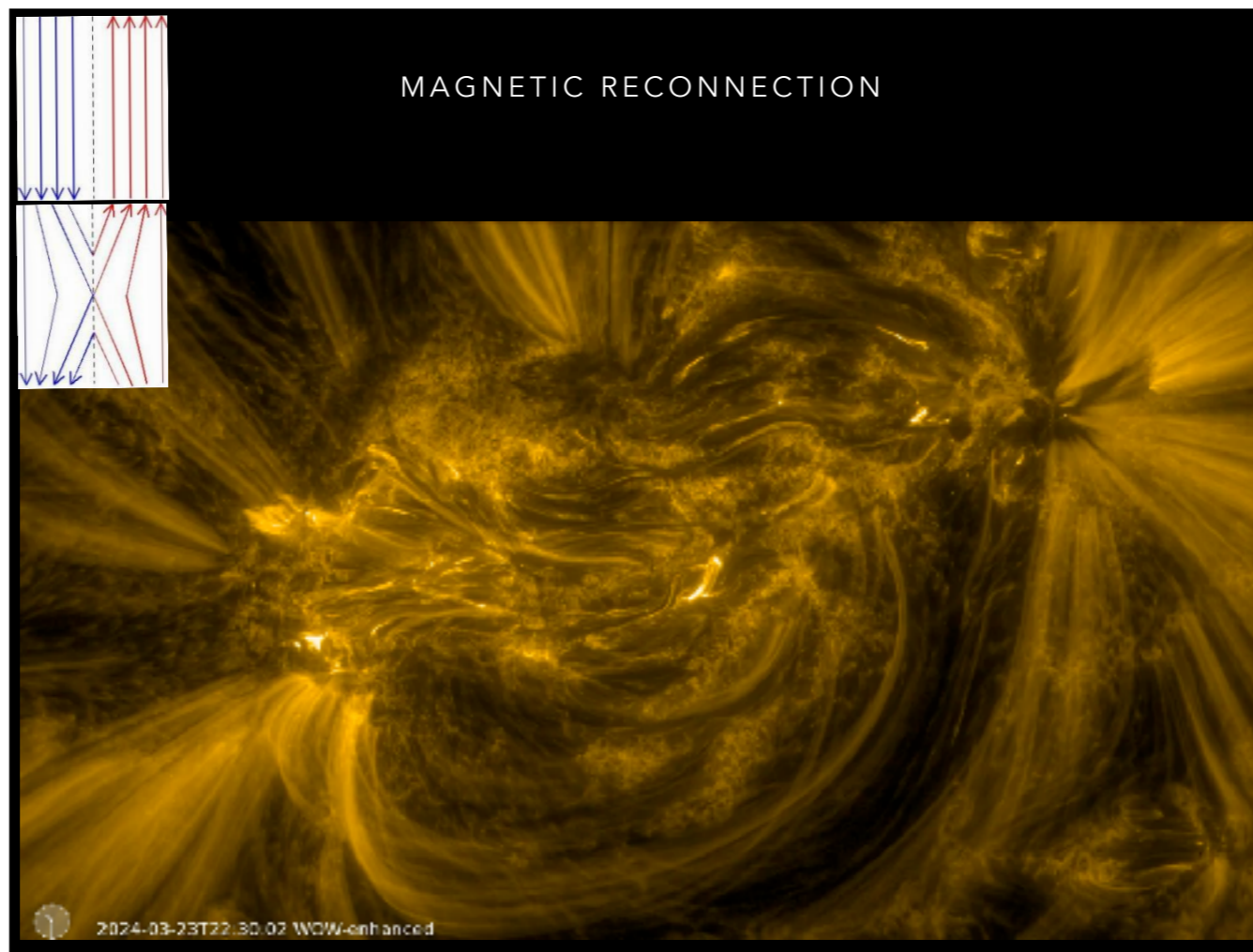
The sun doesn't only rotate but it is also tangled with loops which move, shake back and forth, restructure and do all sorts of electric and magnetic magic.

It is a turbulent plasma ball where magnetic fields are moving, shake, connect with other other, ....

# Magnetism drives the sun's dynamics



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

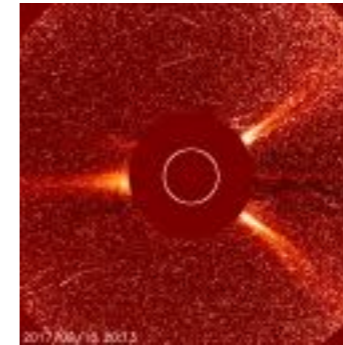
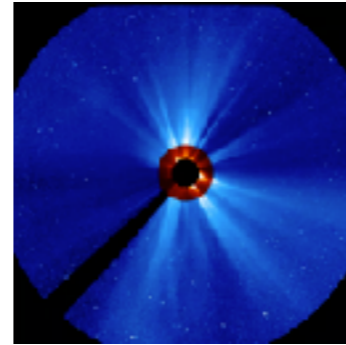
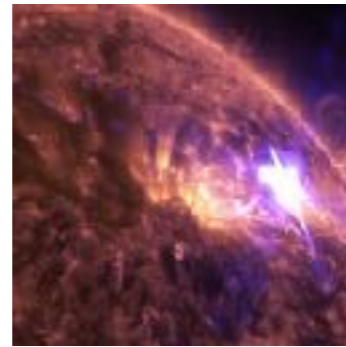
5mT – strength of a typical refrigerator magnet

31.869  $\mu\text{T}$  ( $3.1 \times 10^{-5}$  T) – strength of Earth's magnetic field at  $0^\circ$  latitude (North/South),  $0^\circ$  longitude (west/east)

1 to 5 nT – IMF at L1

## SOLAR WEATHER & STORMS

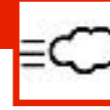
Energy can be released on a shorter time scale. A solar feature like a sunspot, an active region, coronal hole, filament etc. lies at the base of a solar storm in which energy is released. The release of energy might be in an abrupt, impulsive and brutal way (flare, Coronal Mass Ejection or CME, proton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



Flare



Coronal Mass Ejection



Particle Storm



11



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

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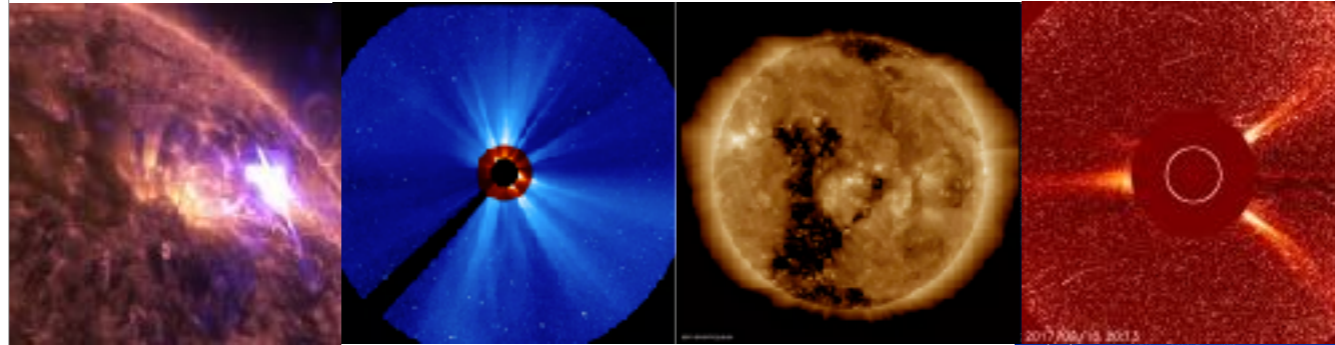
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over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

## SOLAR WEATHER & STORMS

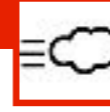
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Flare



Coronal Mass Ejection  
High Speed Stream



Particle Storm



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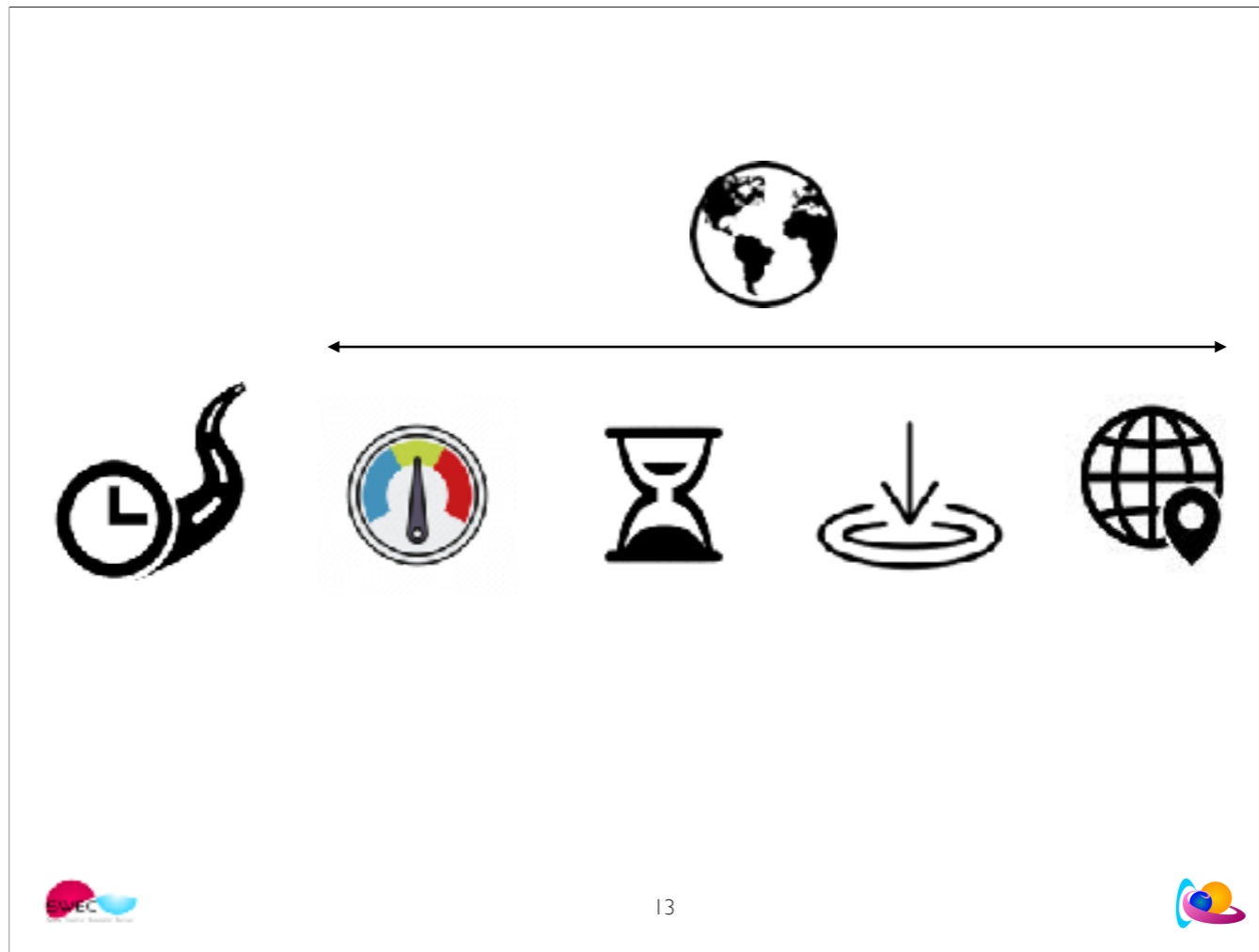
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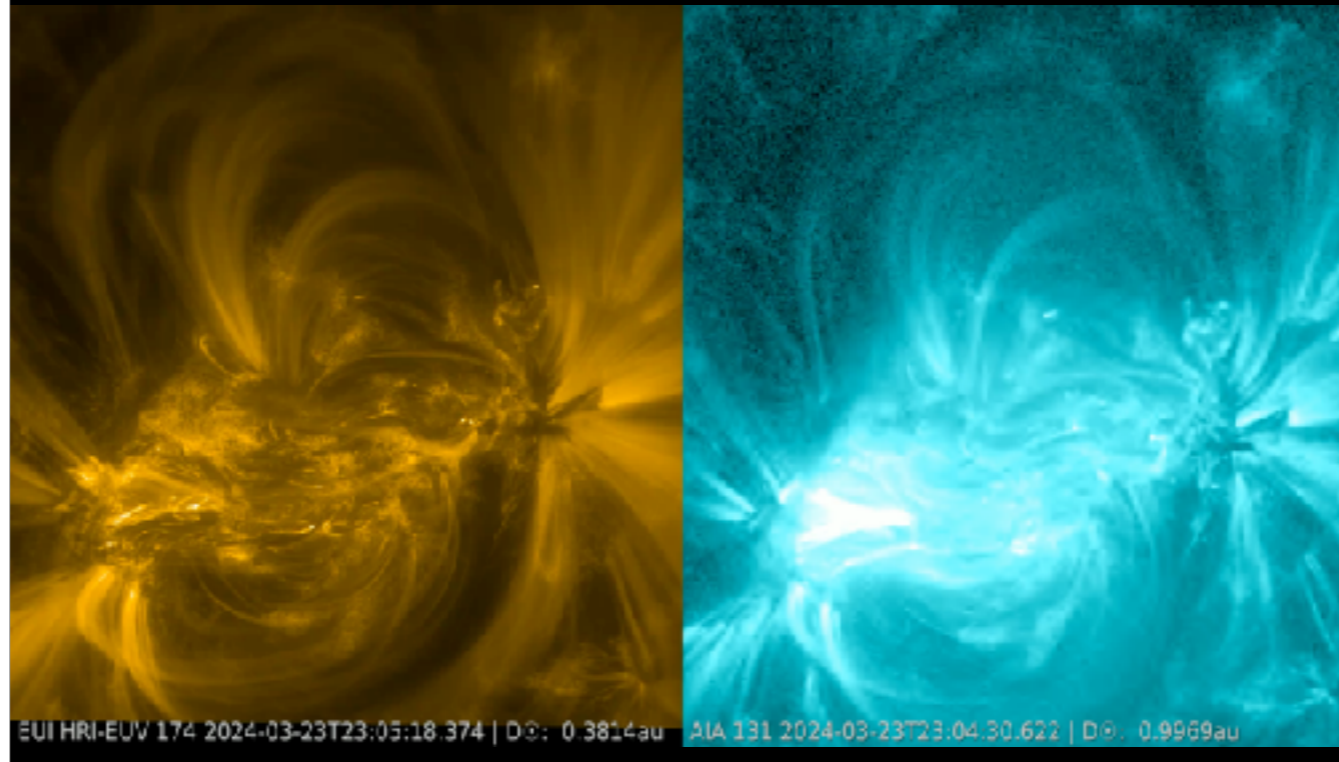
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Transit time

On earth  
Storm scale – strength  
duration  
Impact  
Area of impact

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



EUI HRI-EUV 174 2024-03-23T23:05:18.374 | D☉: 0.3814au AIA 131 2024-03-23T23:04:30.622 | D☉: 0.9969au

## 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, ....



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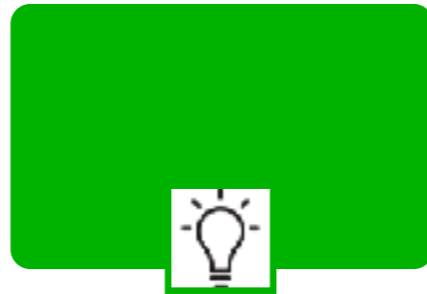


8 MIN



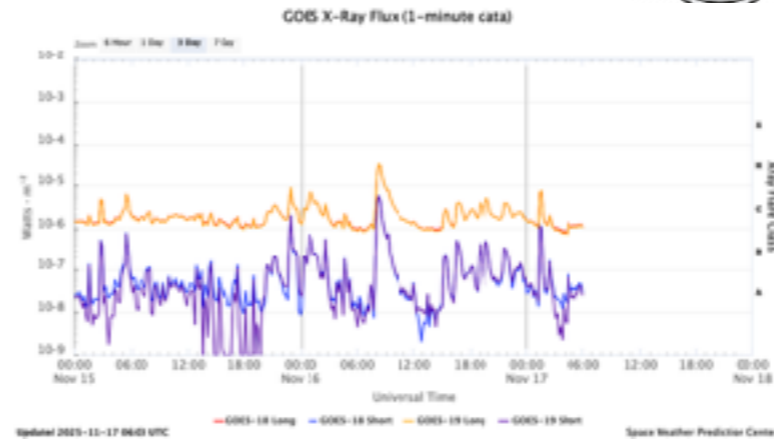


<https://www.swpc.noaa.gov/products/goes-x-ray-flux>



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

# STORM SCALE



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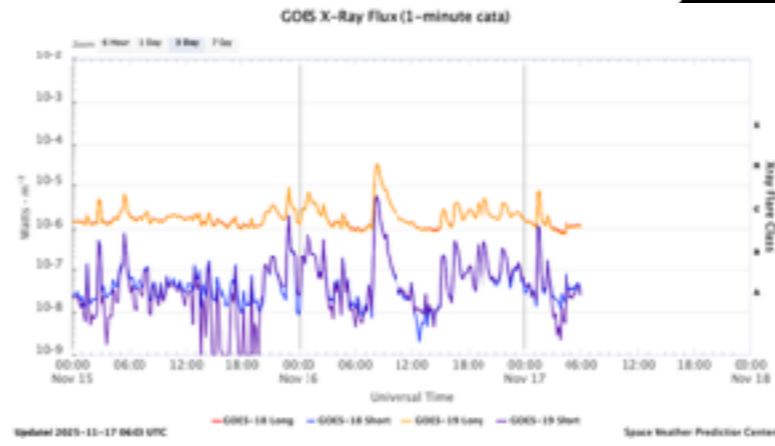


The scale of a flare is defined by it's X-ray flux. The X-ray flux is measured by the geostationary satellite GOES.

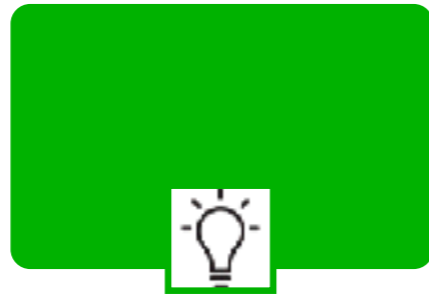
# DURATION



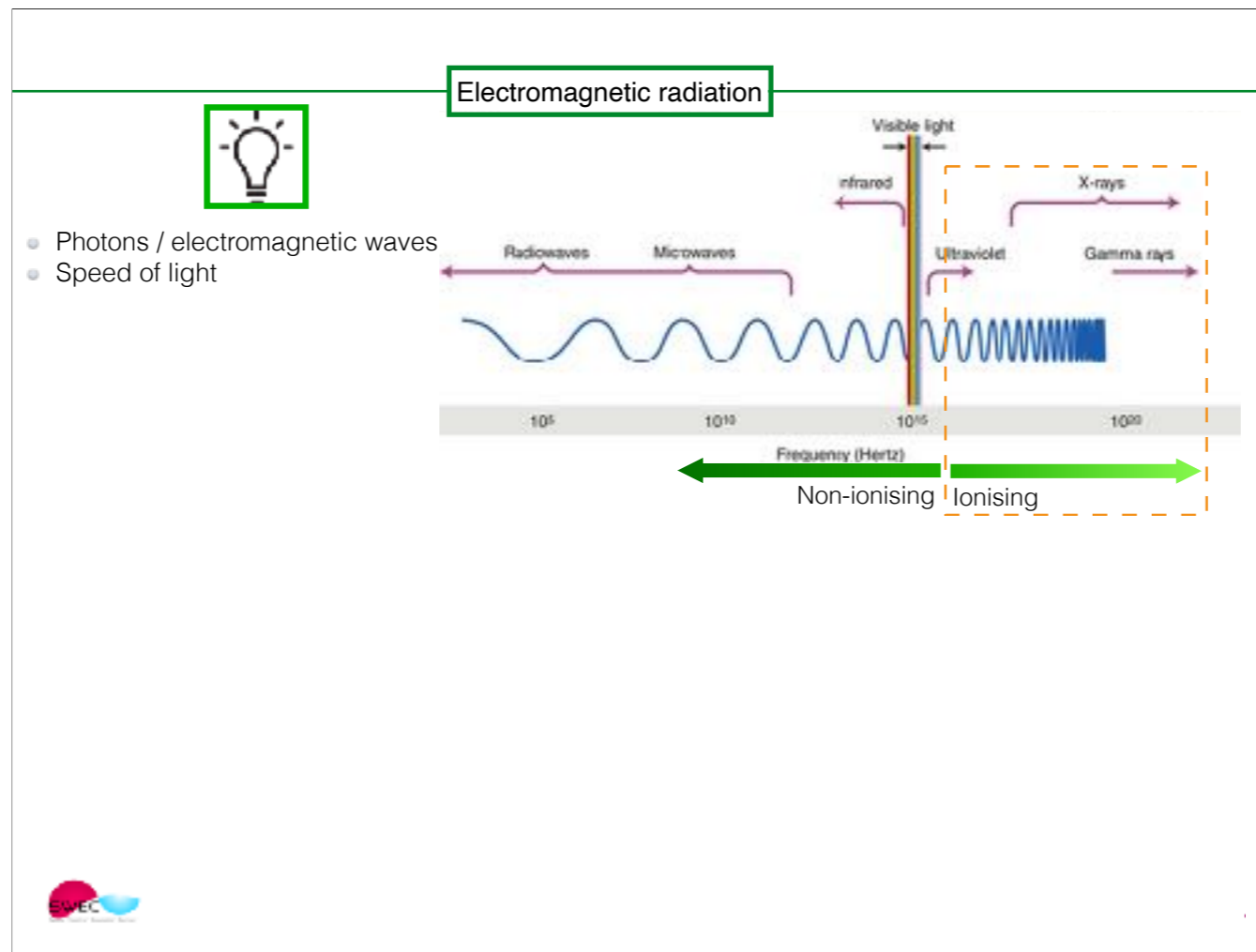
MINs to HOUR



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.



### 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

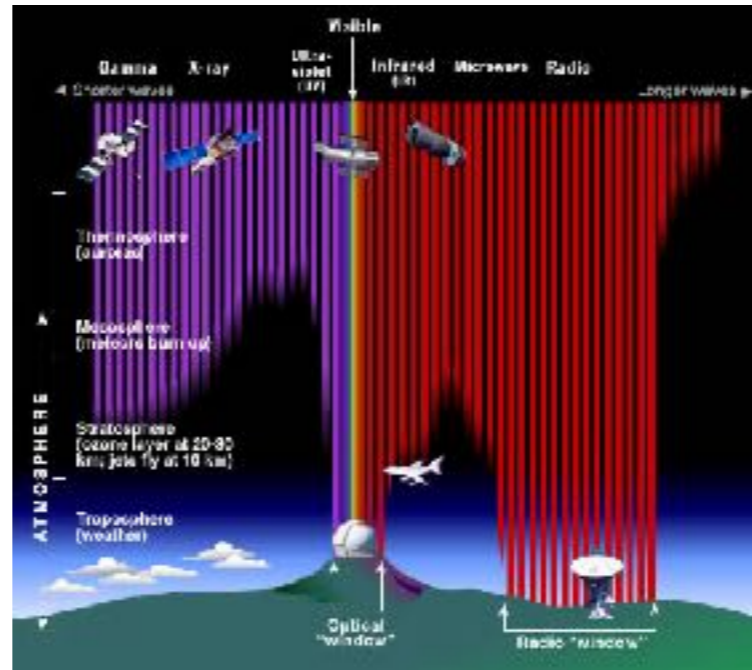


The icon represent the Earth + atmosphere with the ionosphere  
Ionisation of atoms and molecules due to photons -

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

## TRANSPARENCY OF EARTH ATMOSPHERE

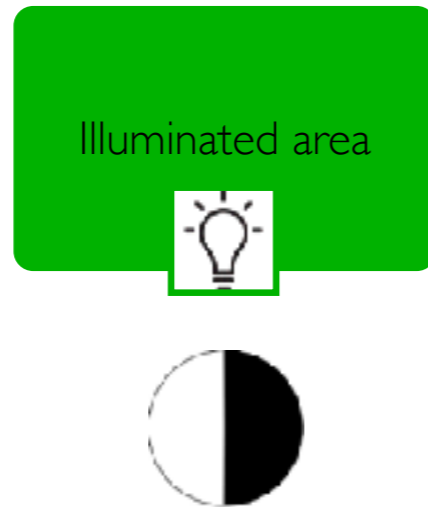
Our atmosphere protects us against harmful solar light. This ionising solar light can penetrate only until a certain height.



AREA OF IMPACT



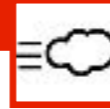
# AREA OF IMPACT



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Solar wind  
CME - HSS



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Particle shower

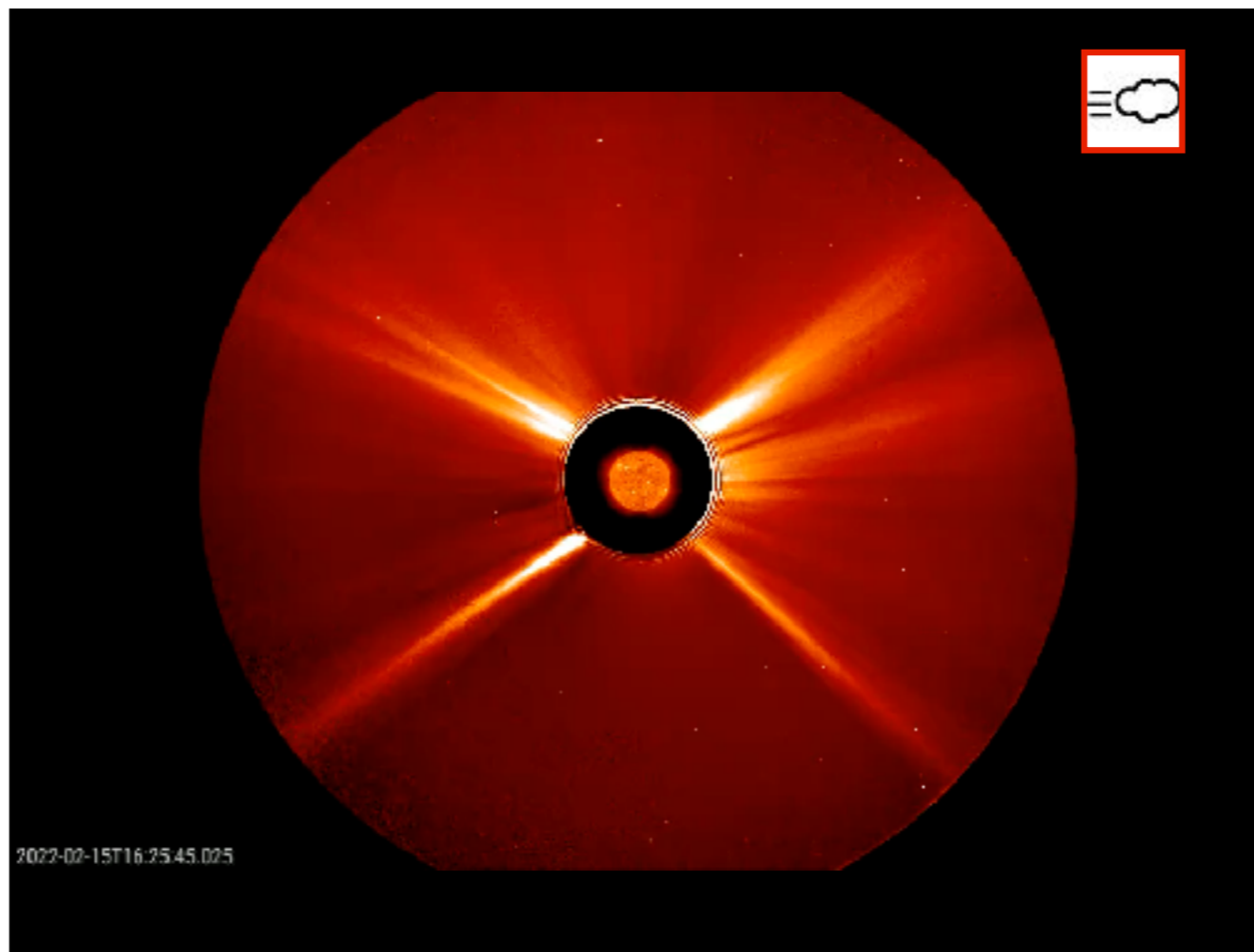
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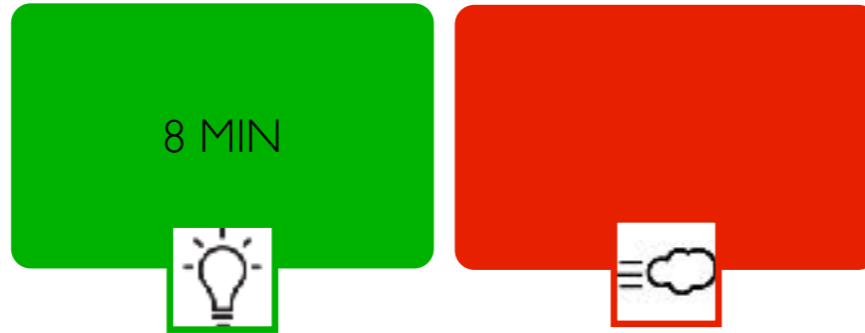
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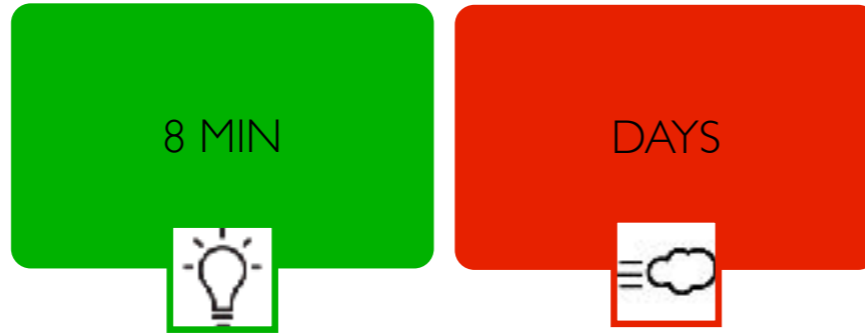
## AU TRANSIT TIME

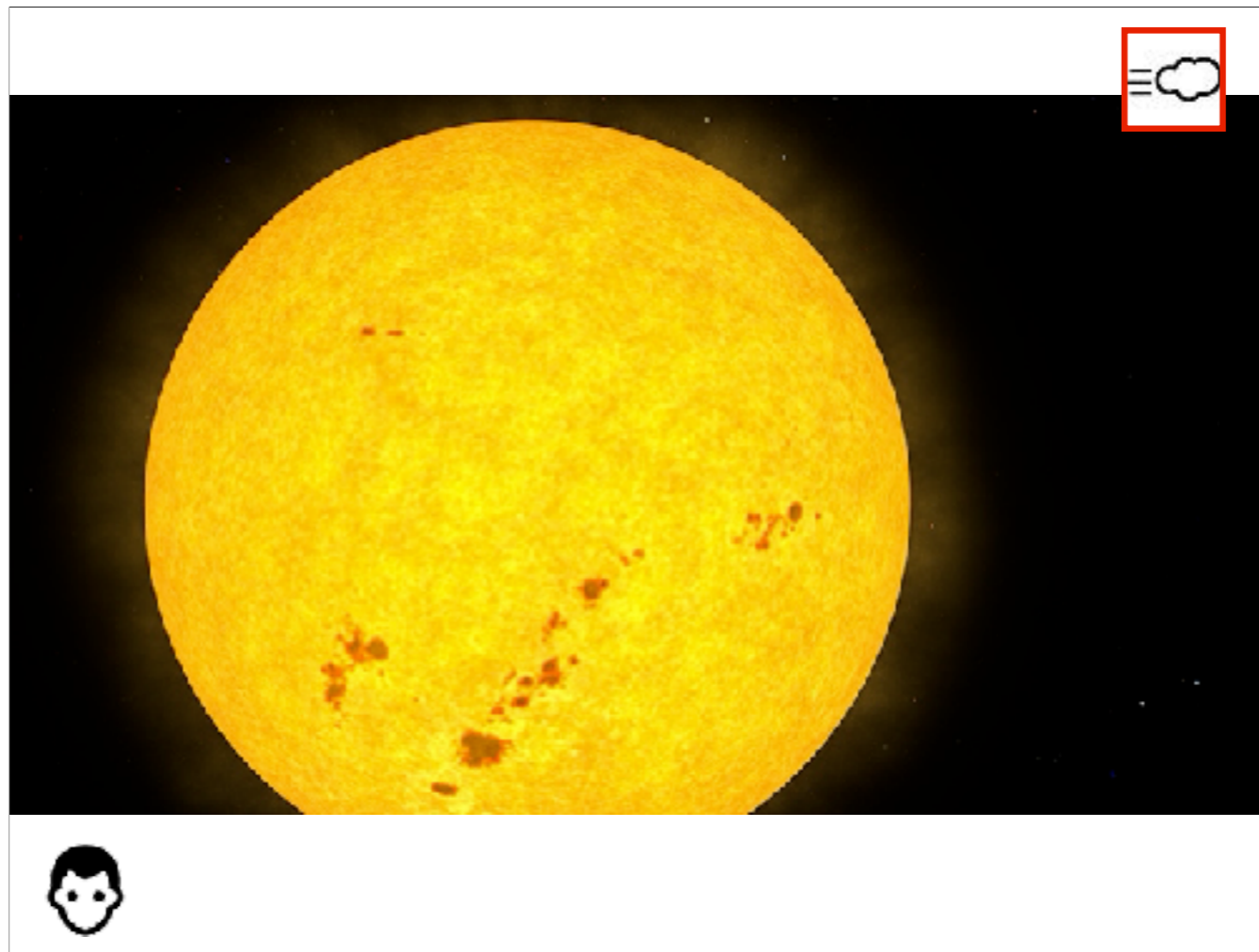
The energy released during a solar storm moves through space, each with its own typical speed: speed of light, order of a few 100 km/s,....



## 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.





A CME that hits the Earth's magnetosphere.  
Precipitating electrons coming from the tail of the magnetosphere gyrate along the Earth's 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.

# STORM SCALE

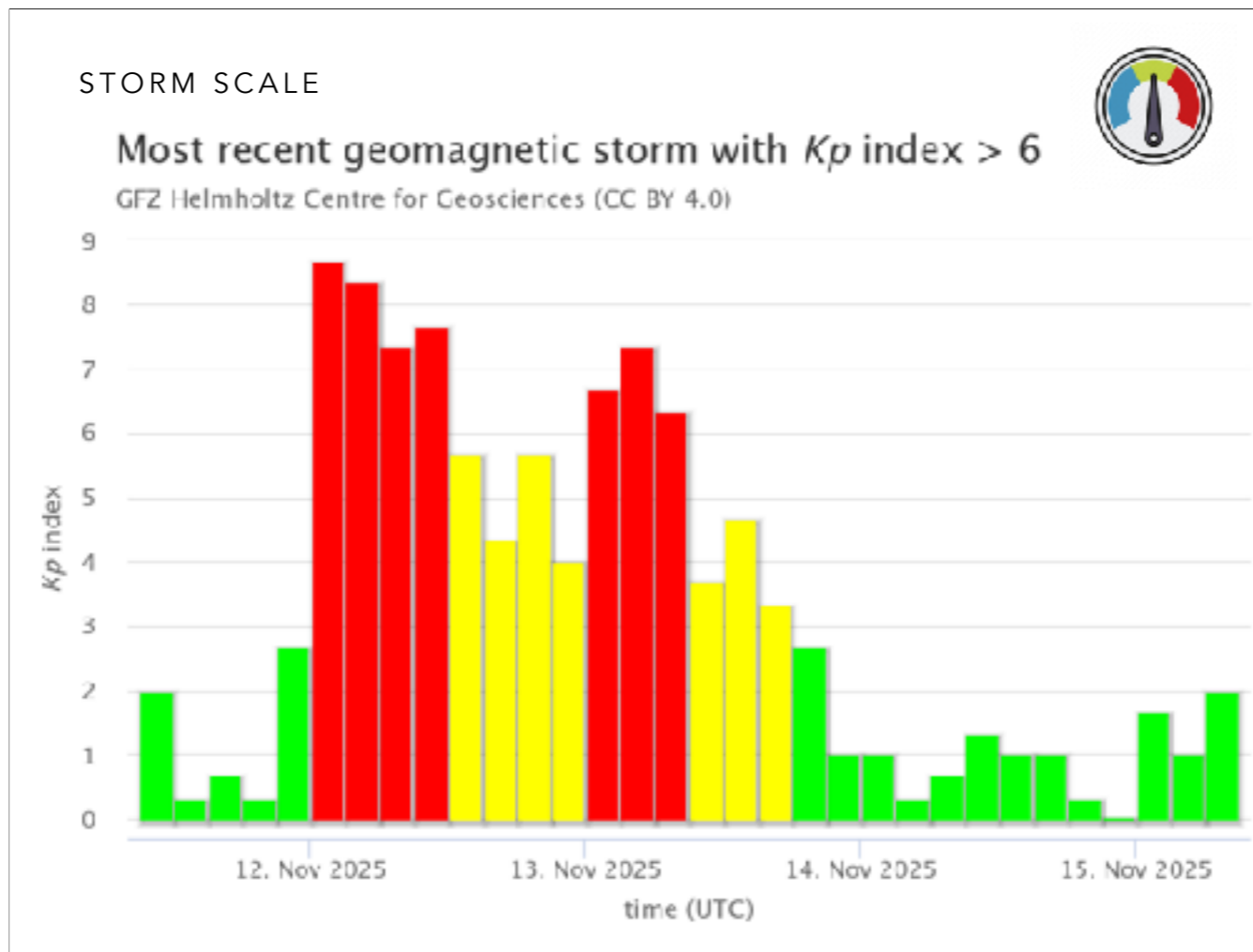


<https://kp.gfz.de/en/>

A, B, C, M, X

A green rounded rectangle containing the text "A, B, C, M, X" and a lightbulb icon. To its right is a red rounded rectangle containing a cloud icon and a radio wave icon.

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.

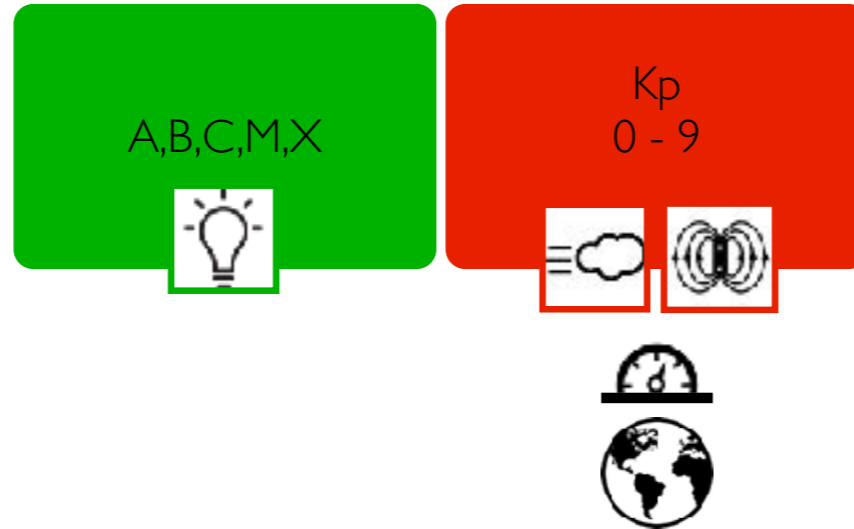
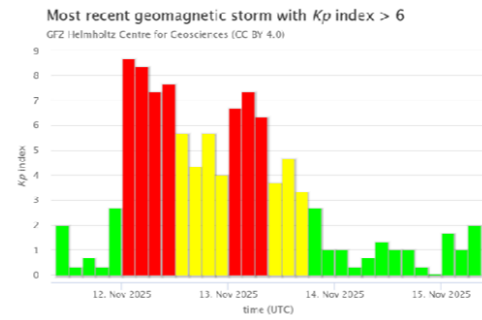


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measure for the energy input from the solar wind to Earth and it is used by space weather services in near real-time. Kp goes back to 1932 and is an important parameter to investigate long-term climate change in the upper atmosphere, in geospace, in the solar wind and on the sun. Kp is based on the data of 13 geomagnetic observatories around the globe.

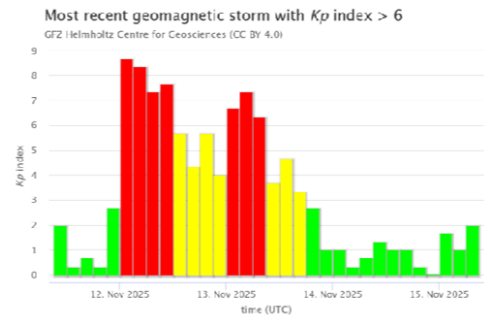
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# DURATION



MINs to HOUR

DAY+

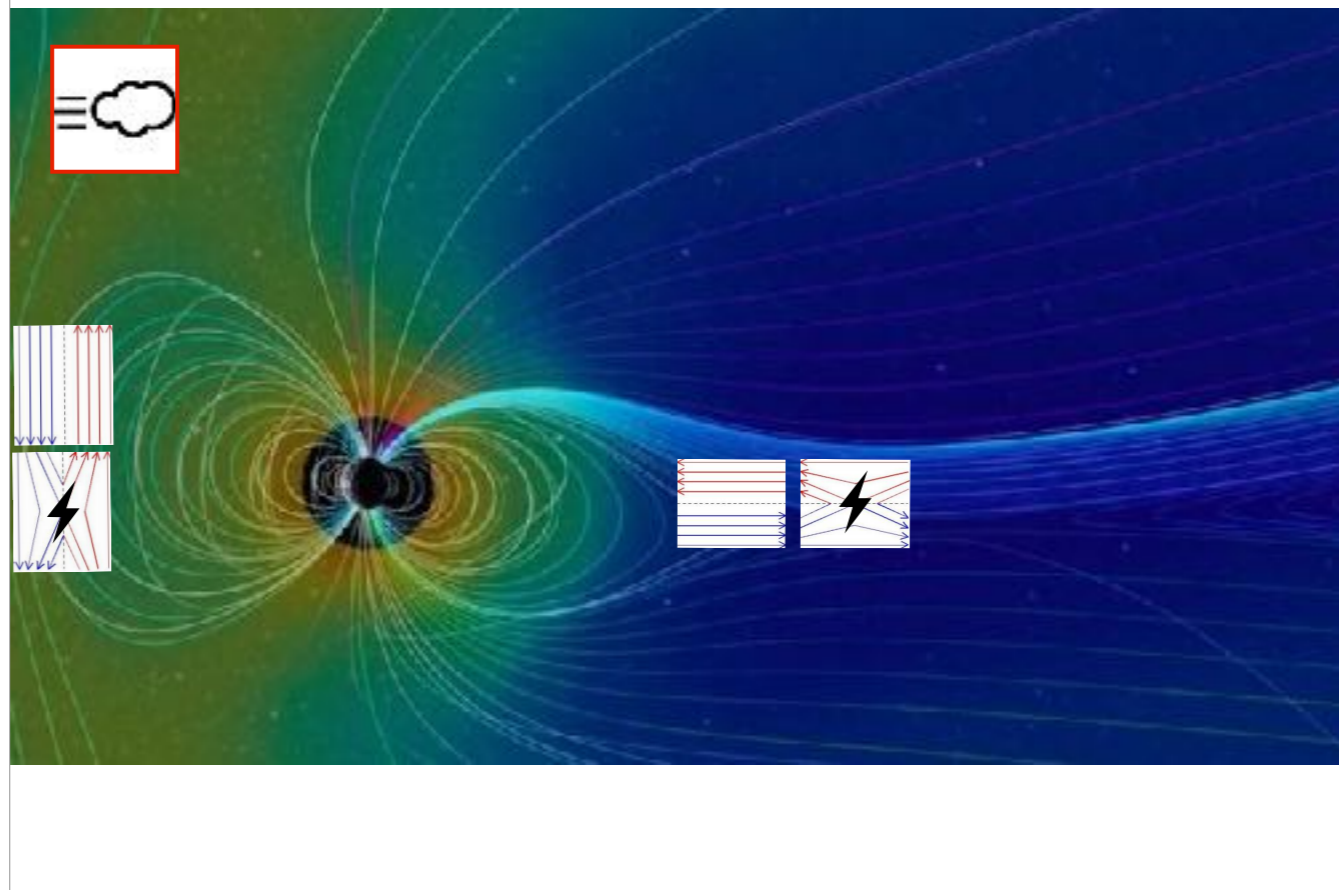


Day or more

IMPACT



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- Ampère's 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.

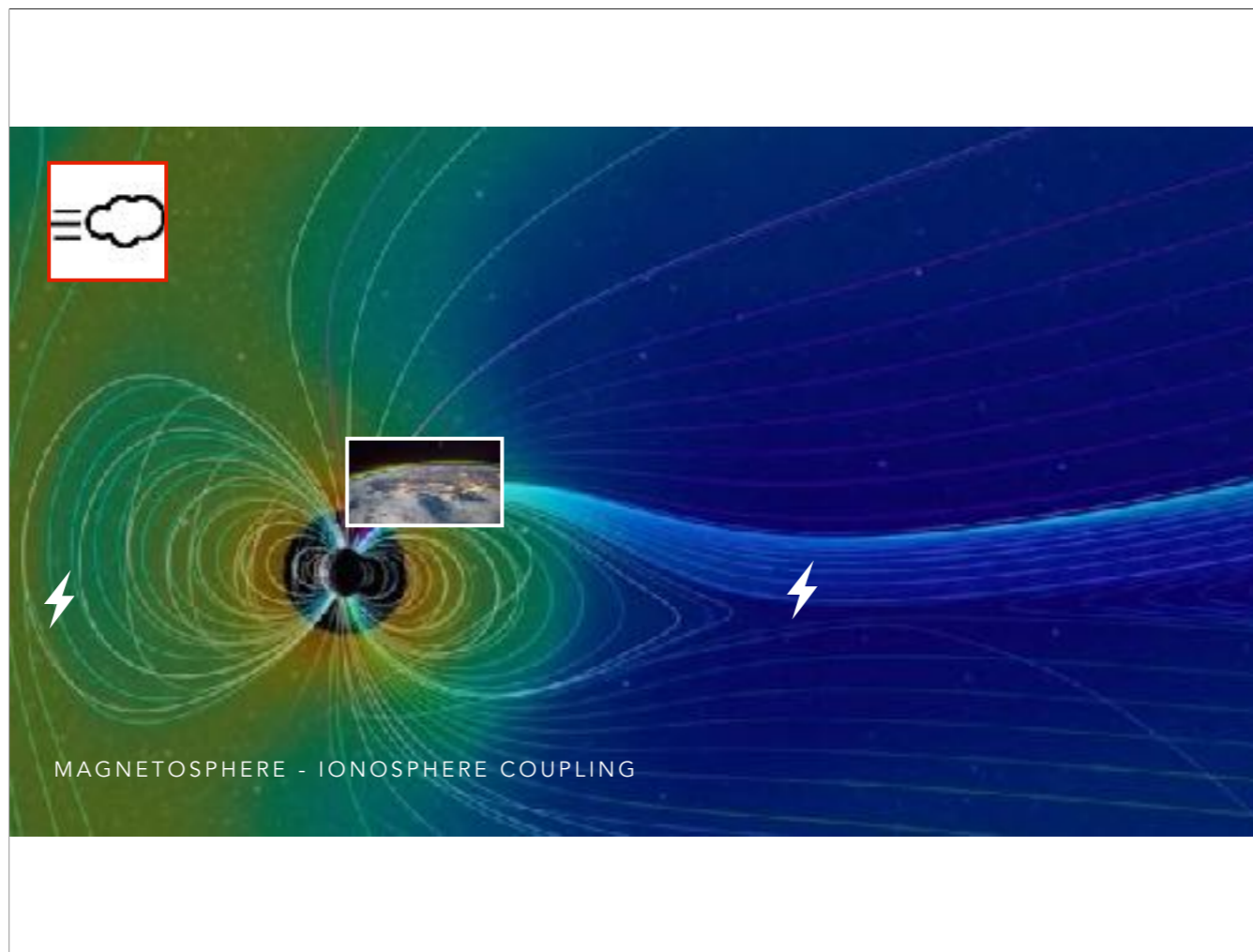
The blue magnetic field lines are imbedded in the solar wind.  
 The red magnetic field lines represent the earth magnetosphere.  
 The blue and the red magnetic region have to face each other. Opposite magnetic field lines can connect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.

0.3 T - solar sunspot

5mT - strength of a typical refrigerator magnet

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1 to 5 nT - IMF at L1



currents

- Ampère's 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 Pedersen 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 ↔ footprints of the cusps
- Tail lobes ↔ polar caps
- Plasma sheet ↔ auroral oval
- Plasmasphere ↔ ionosphere at low latitude

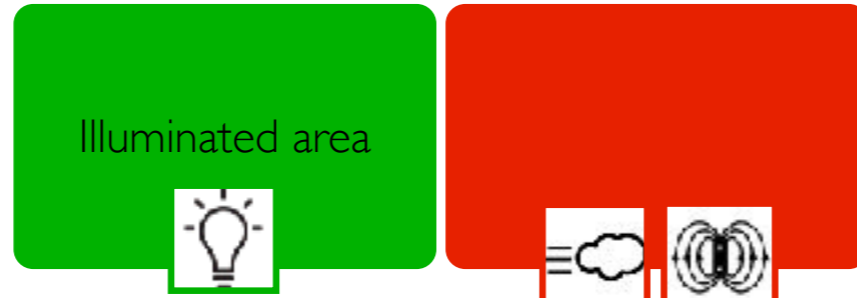
The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. Ionospheric structures and peak densities in 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.





Illuminated area



Auroral Oval & more Latitude



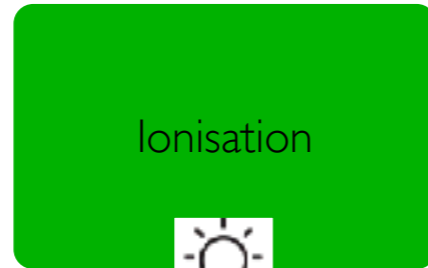
## Latitude

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.

IMPACT



Plasmasphere - ionosphere  
Moving plasma → VTEC - irregularities



Energetic Particles



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

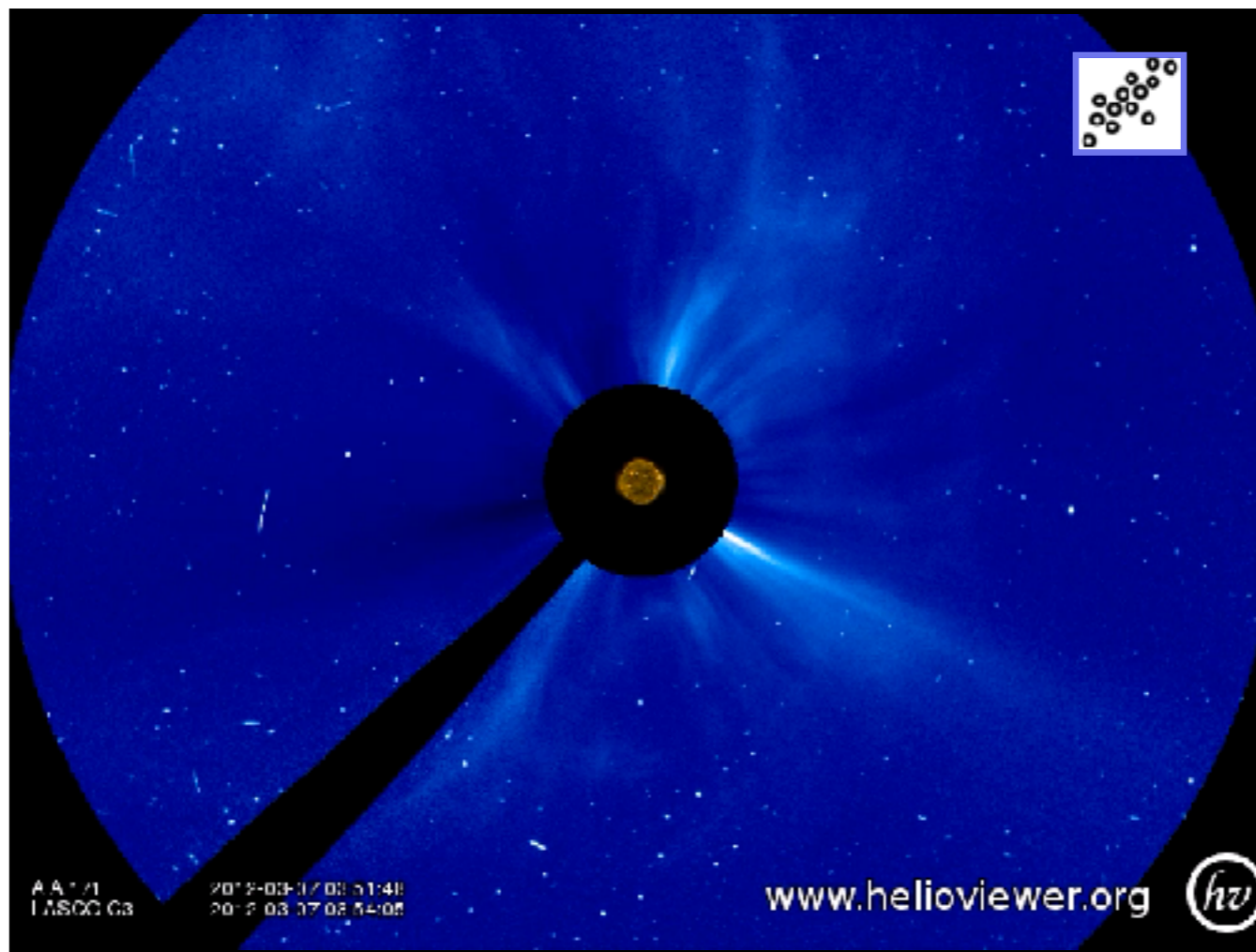
A particle storm is a bunch of electrically charged particles that are accelerated in the solar atmosphere to very high velocities by a large-scale magnetic eruption often causing a CME and/or solar flare. They follow the IMF

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.



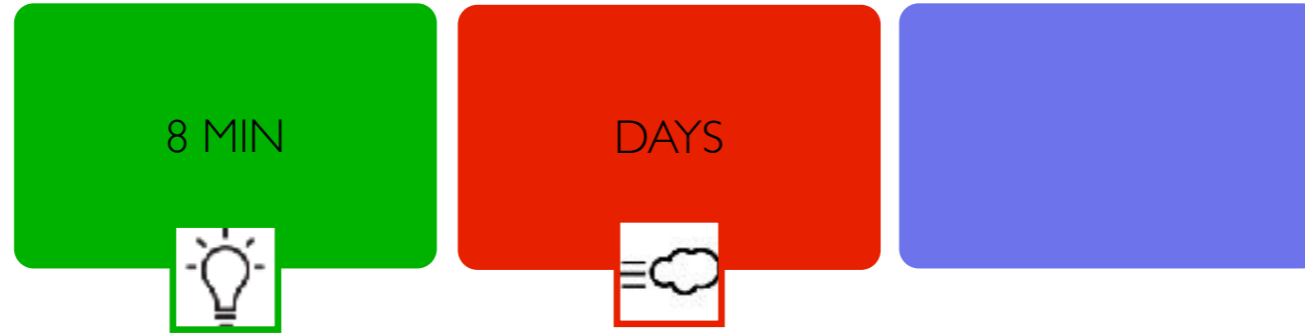
## Particle showers

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 is 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.)

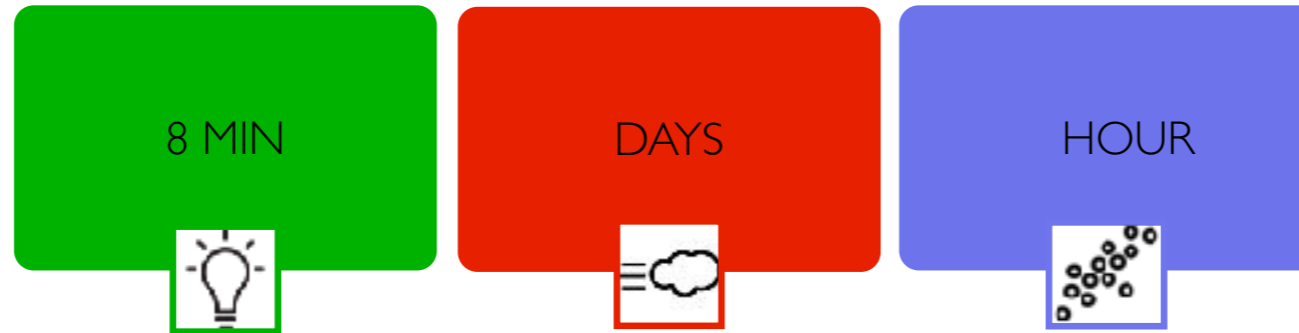
## AU TRANSIT TIME

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.



## AU TRANSIT TIME

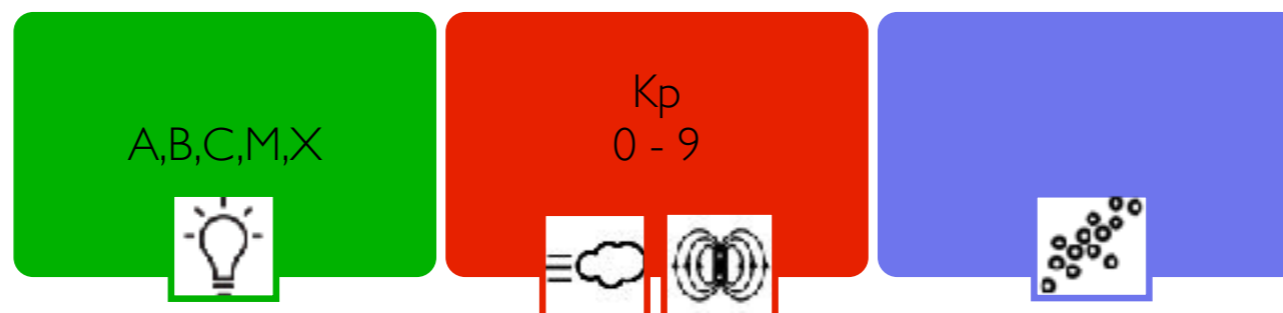
The energy released during a solar storm moves through space, each with its own typical speed: speed of light, order of a few 100 km/s, relativistic speeds.



# STORM SCALE

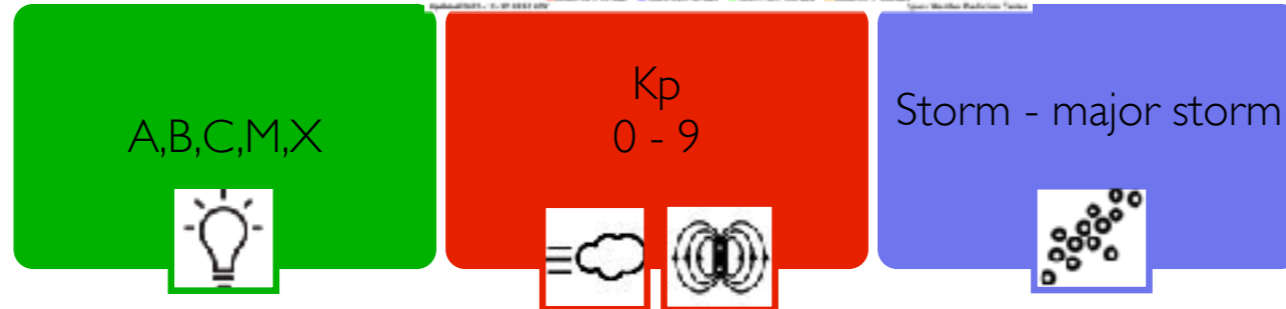


<https://www.swpc.noaa.gov/products/goes-proton-flux>



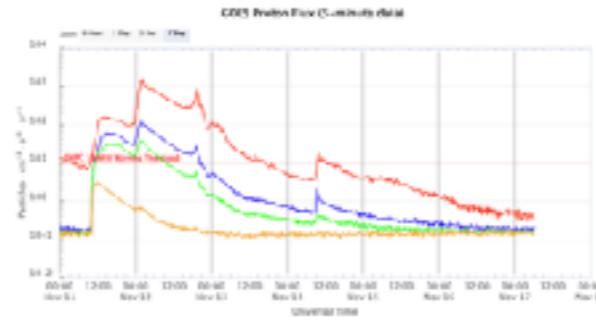
The GOES satellite measures the proton flux.  
Storm: 10 pfu (proton flux units) for >10MeV  
Major storm: 100 pfu for >100MeV

# STORM SCALE



The GOES satellite measures the proton flux.  
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Major storm: 100 pfu for >100MeV

# DURATION



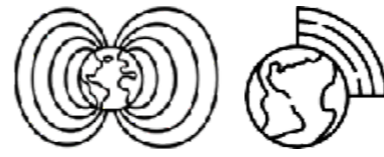
MINs to HOUR

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

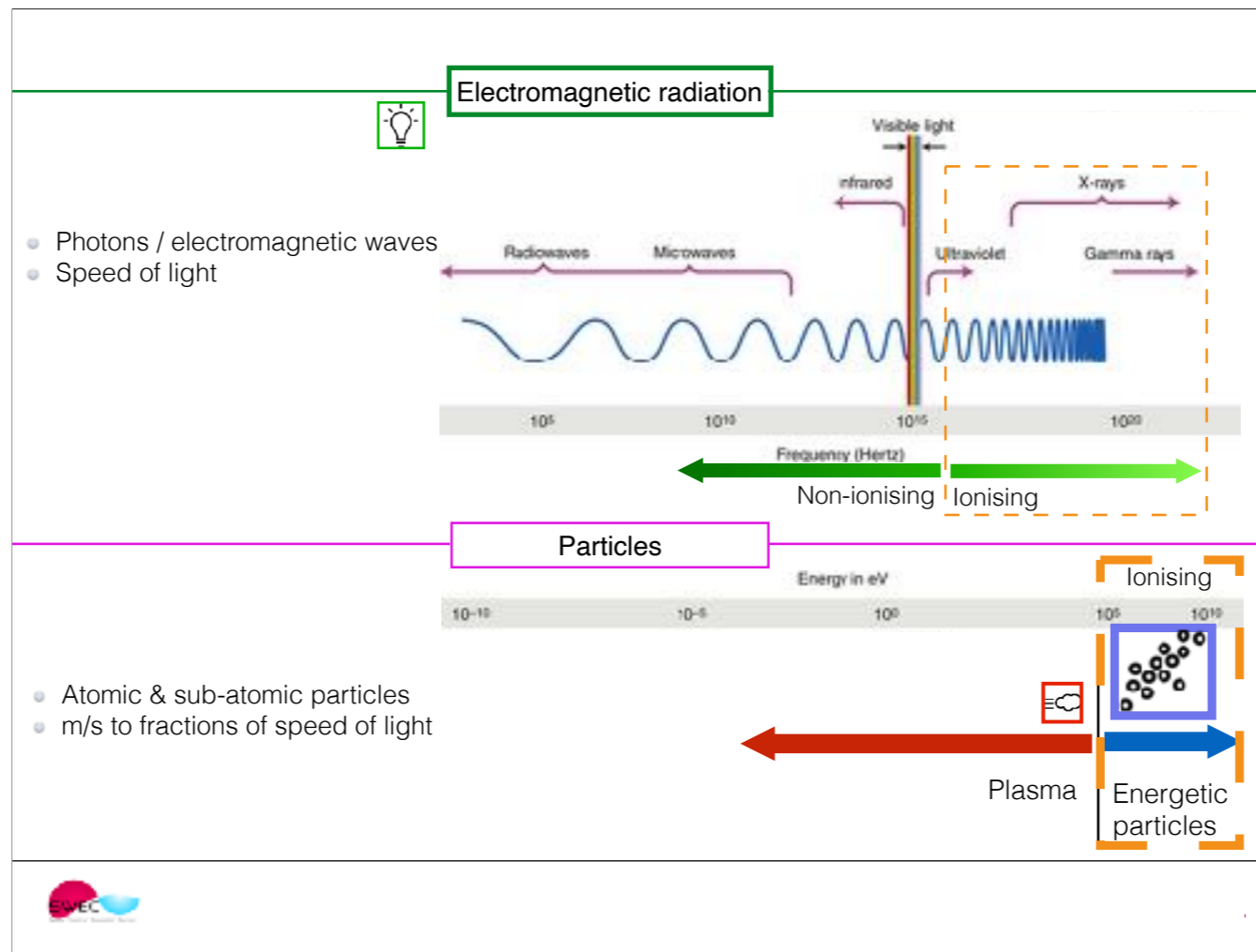


Ionisation



Particle content





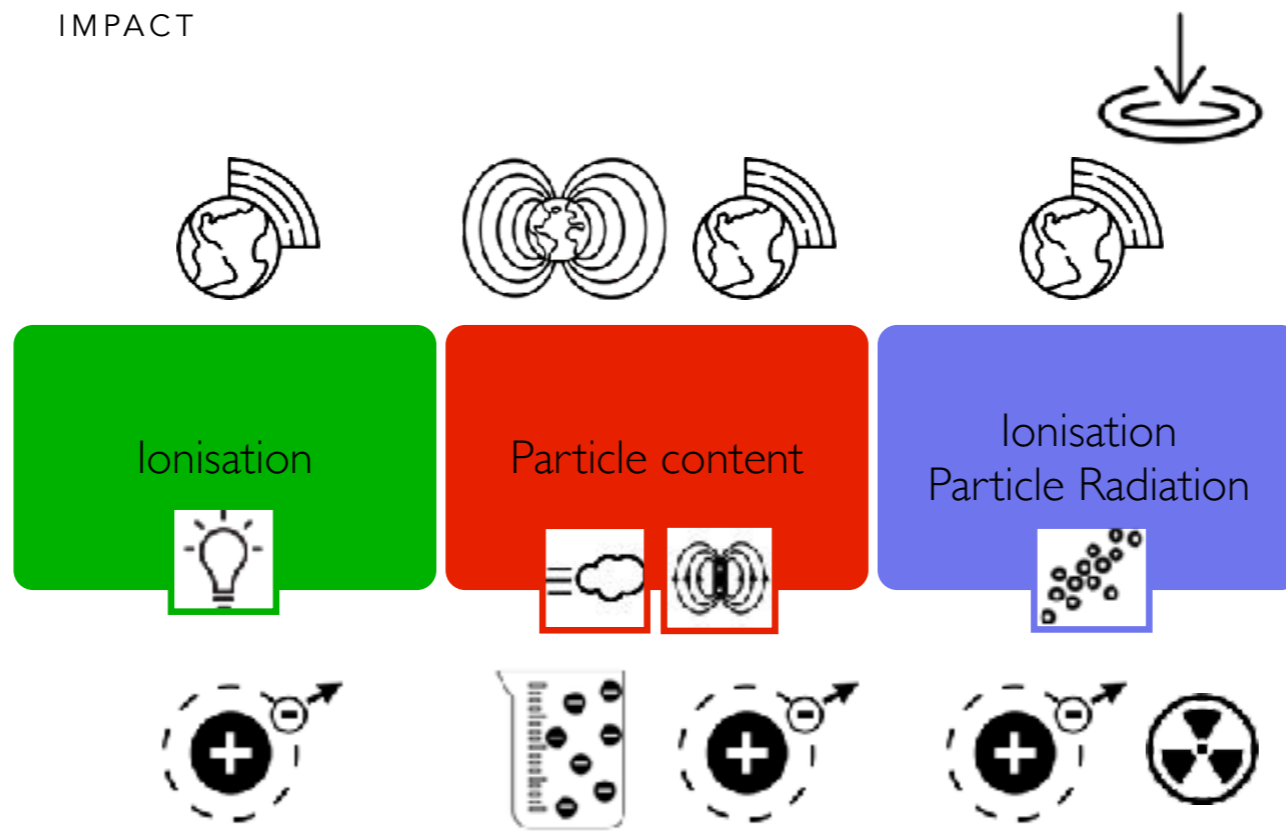
### Photo-ionisation — green

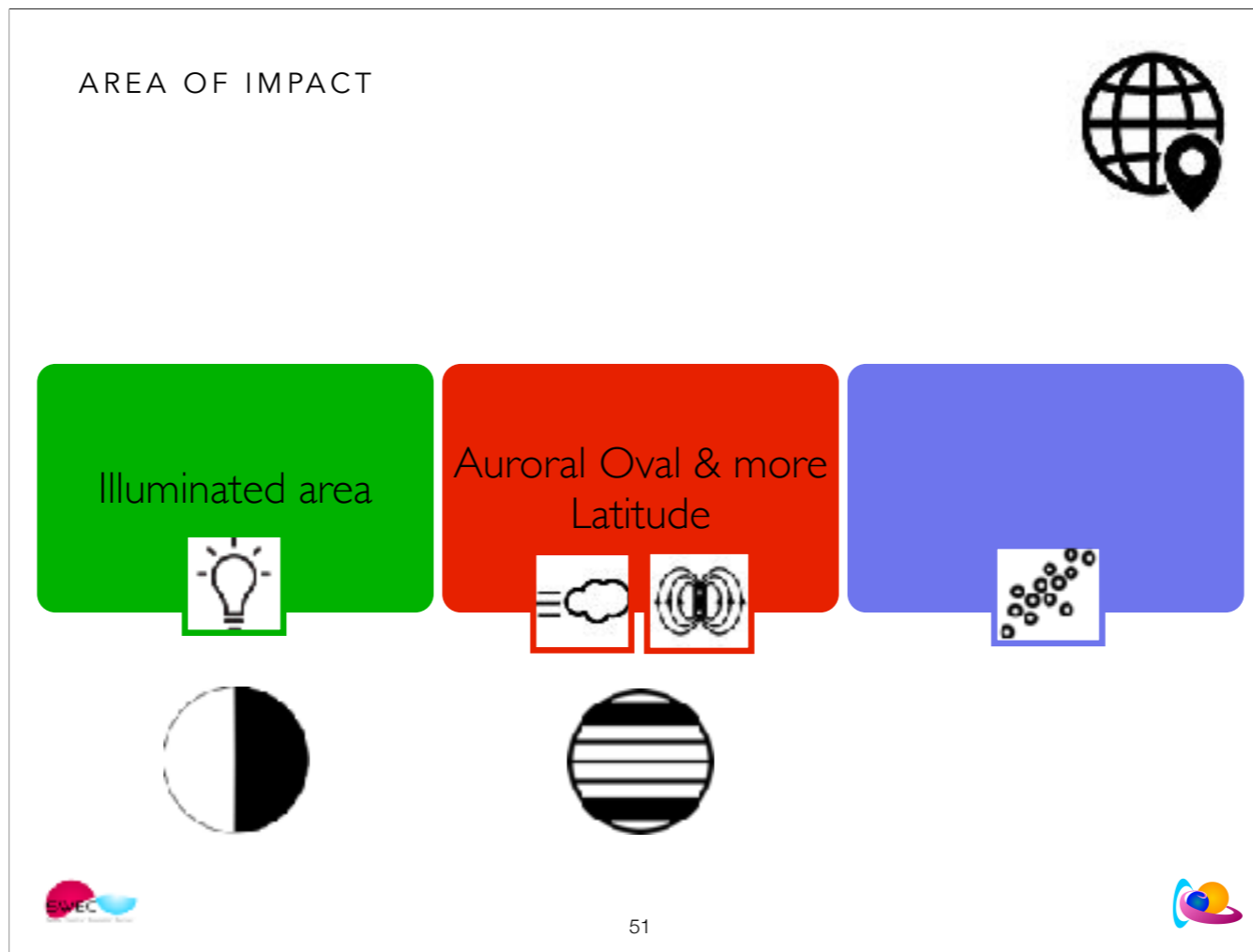
Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

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



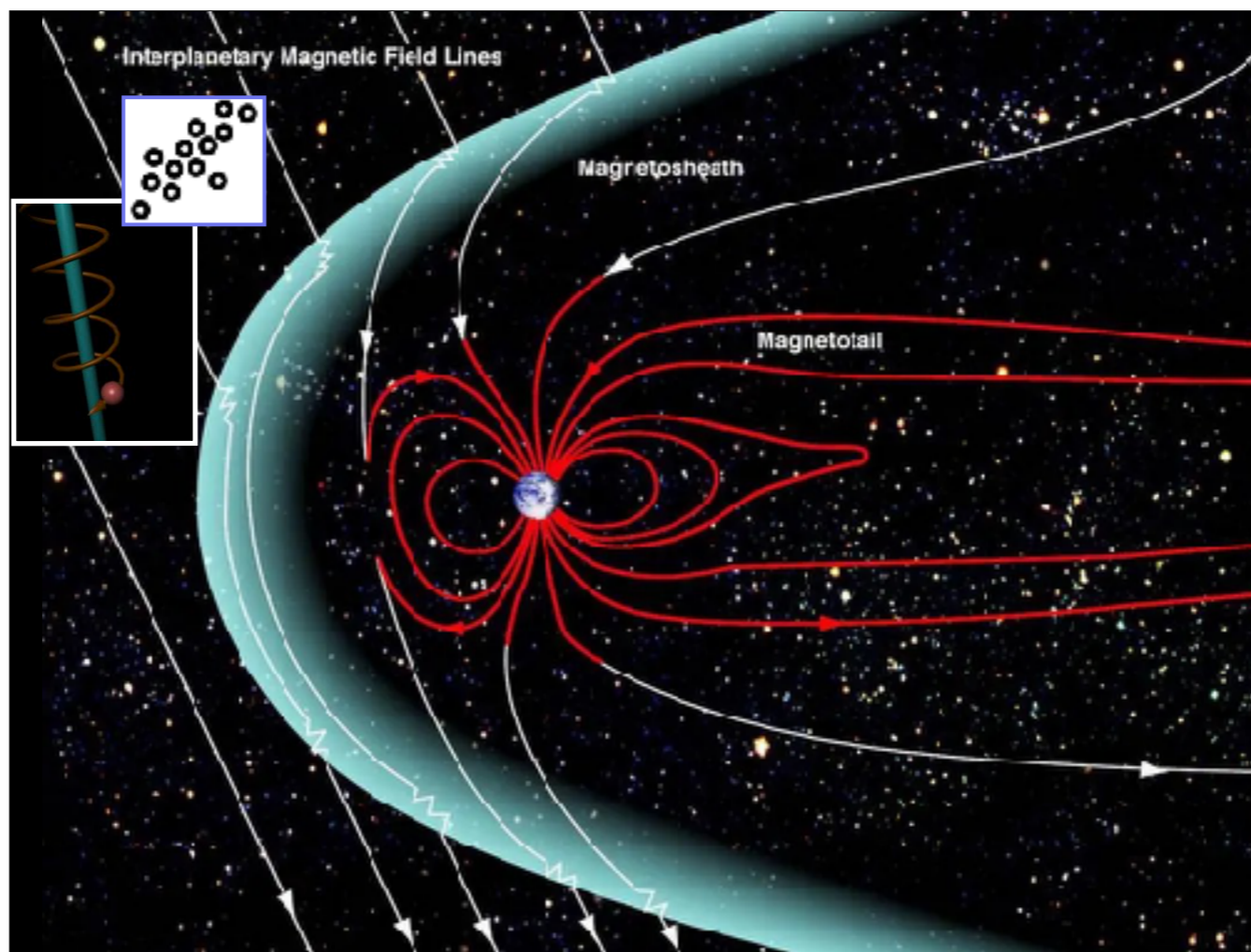


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The icon of the dipole represents the Earth dipolar field.

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



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

AREA OF IMPACT



Illuminated area



Auroral Oval & more Latitude



Polar Cap  
High Altitude



The higher the energy, the deeper they can penetrate into the Earth's atmosphere.



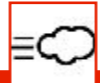
8 min

X-ray: A,B,C,M,X

Min to Hour

Ionisation

Illuminated area



Days

Kp: 0 - 9

Day+

Ionisation  
Particle content

Auroral Oval & more  
Latitude



Hour

Proton flux:  
(Major) Storm

Hours to Days

Ionisation  
Particle radiation

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.

## Sensor

GOES-16 satellite  
GOES-18 satellite

## Use

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

## Sensor location

Geostationary orbit

## Units

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

## 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>



# 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<sup>2</sup>\*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<sup>2</sup>\*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.

Space Weather Education Center