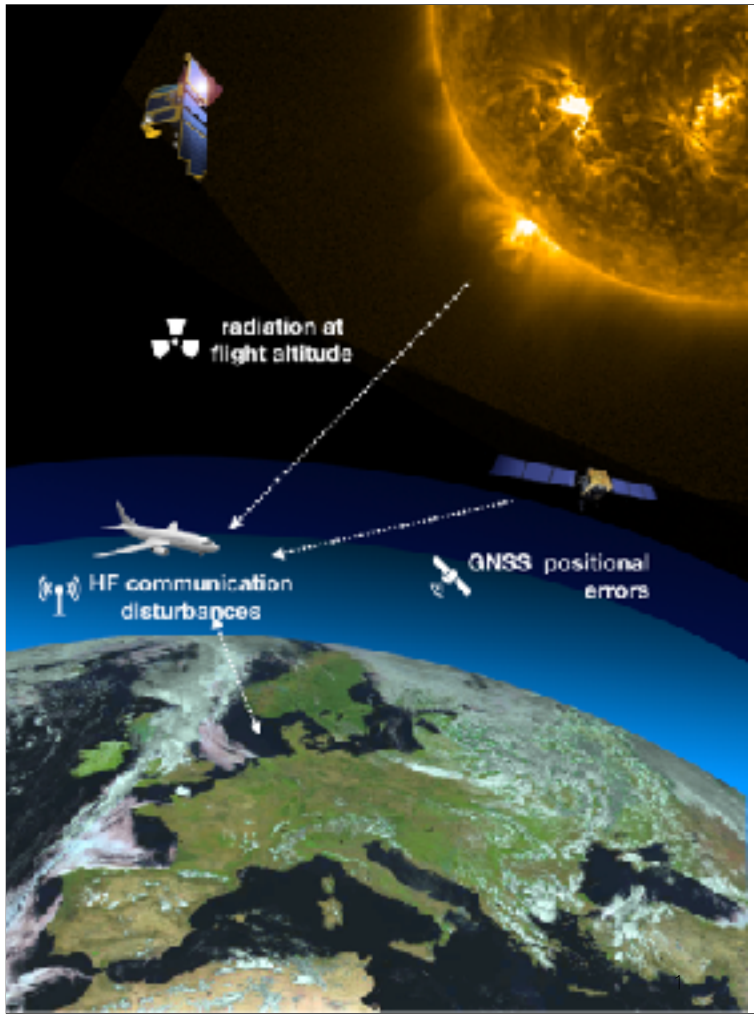
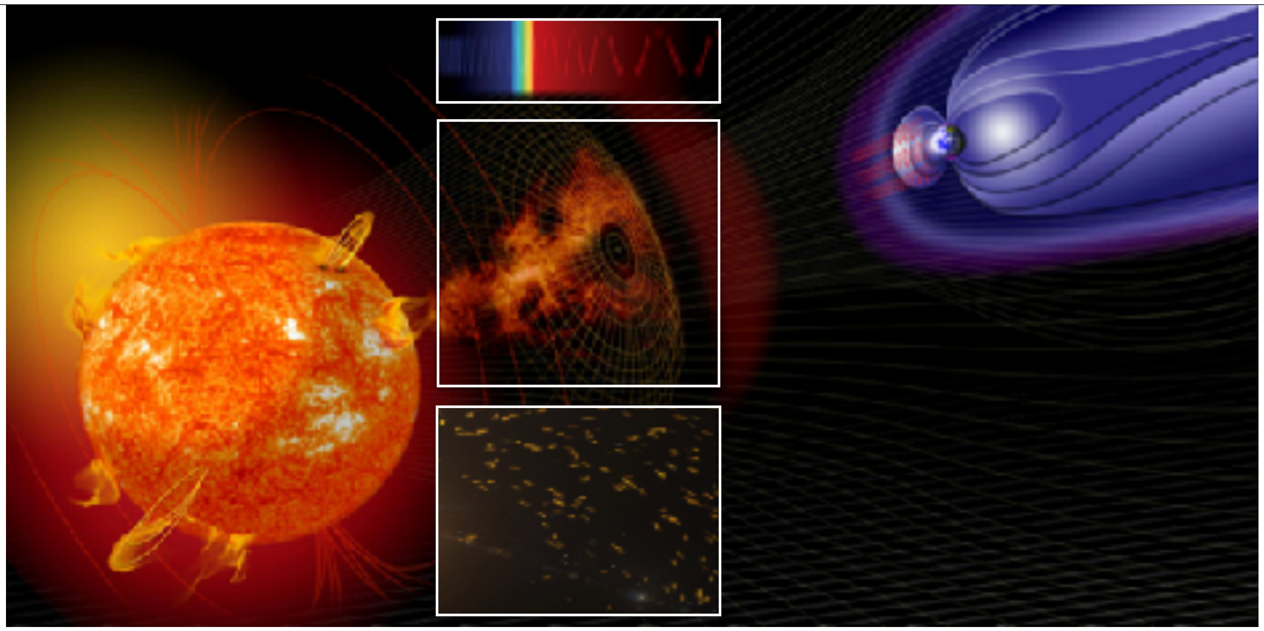


Space Weather impacts on Aviation

PECASUS advisories for ICAO

Course by the
Solar-Terrestrial Centre of Excellence

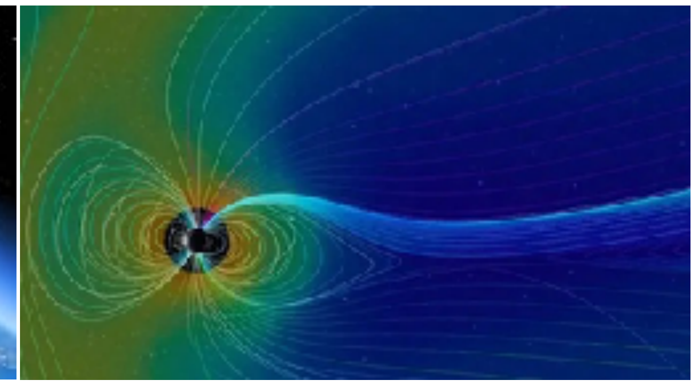
March 2024



SPACE WEATHER

Introduction

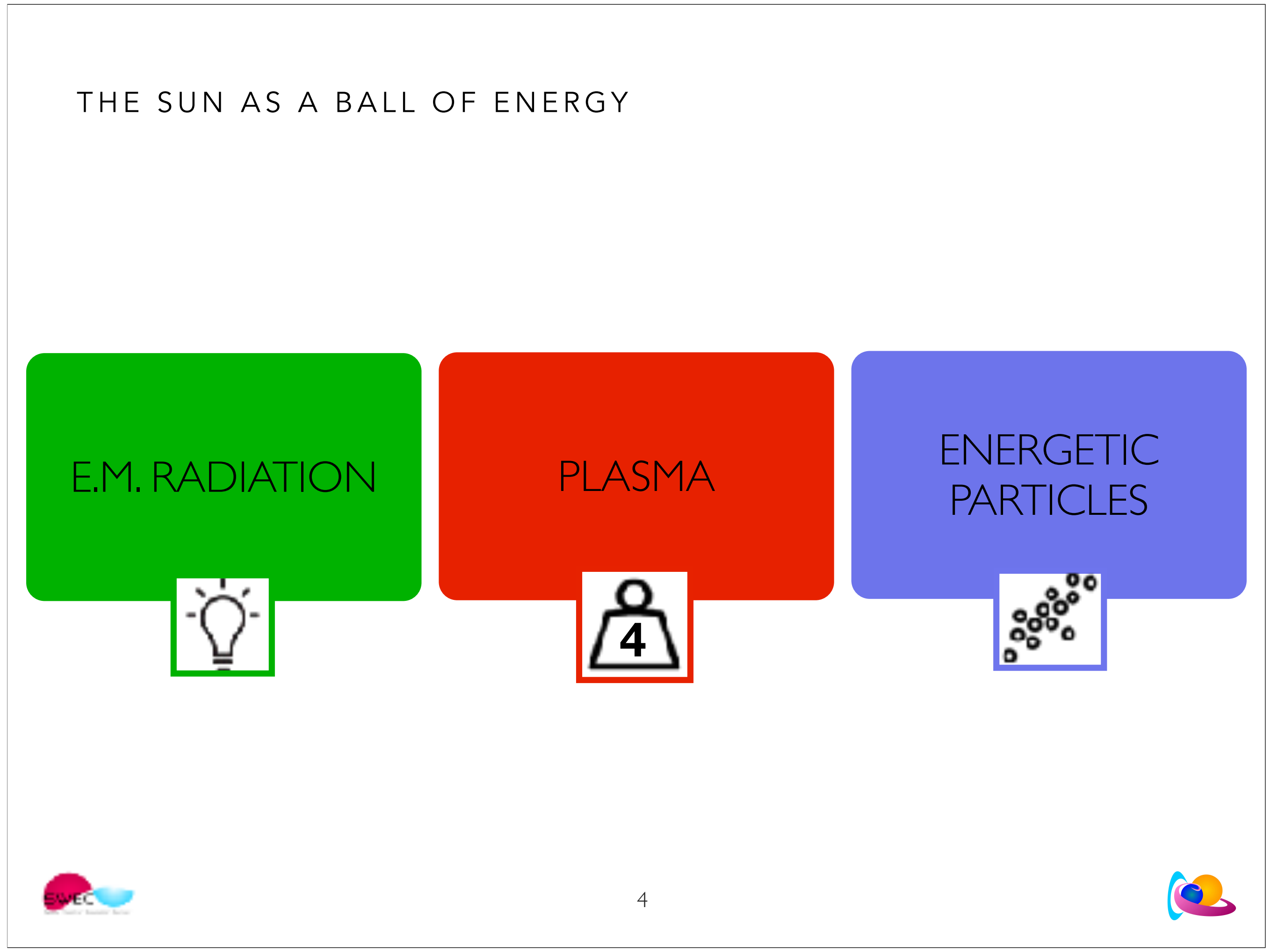
Space Weather
The Sun’s energy impacting earth’s atmosphere and magnetic shield.



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.**

Magnetosphere: area dominated by the magnetic field of Earth



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

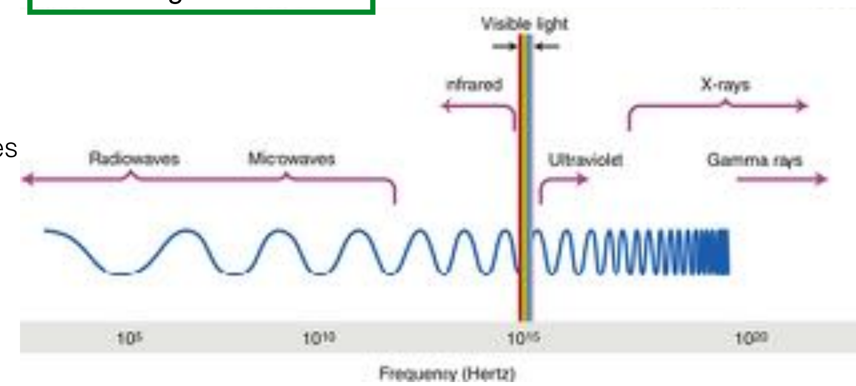
This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

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.

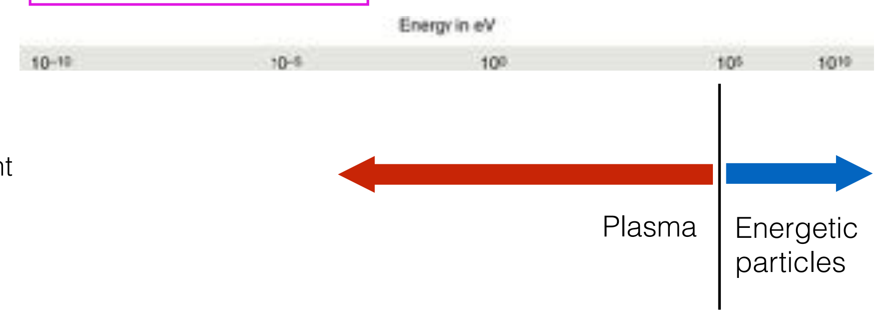
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



Particles

- Atomic & sub-atomic particles
- km/s to fractions of speed of light
- Magnetic Field

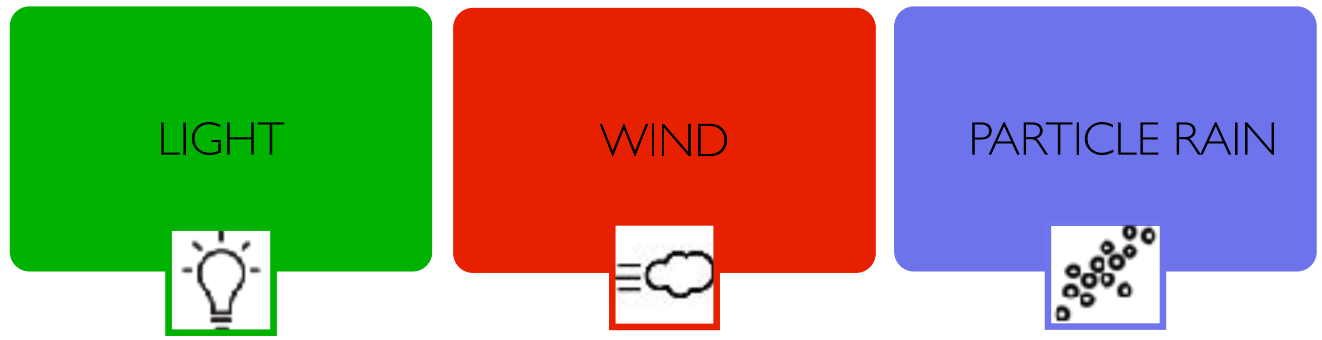


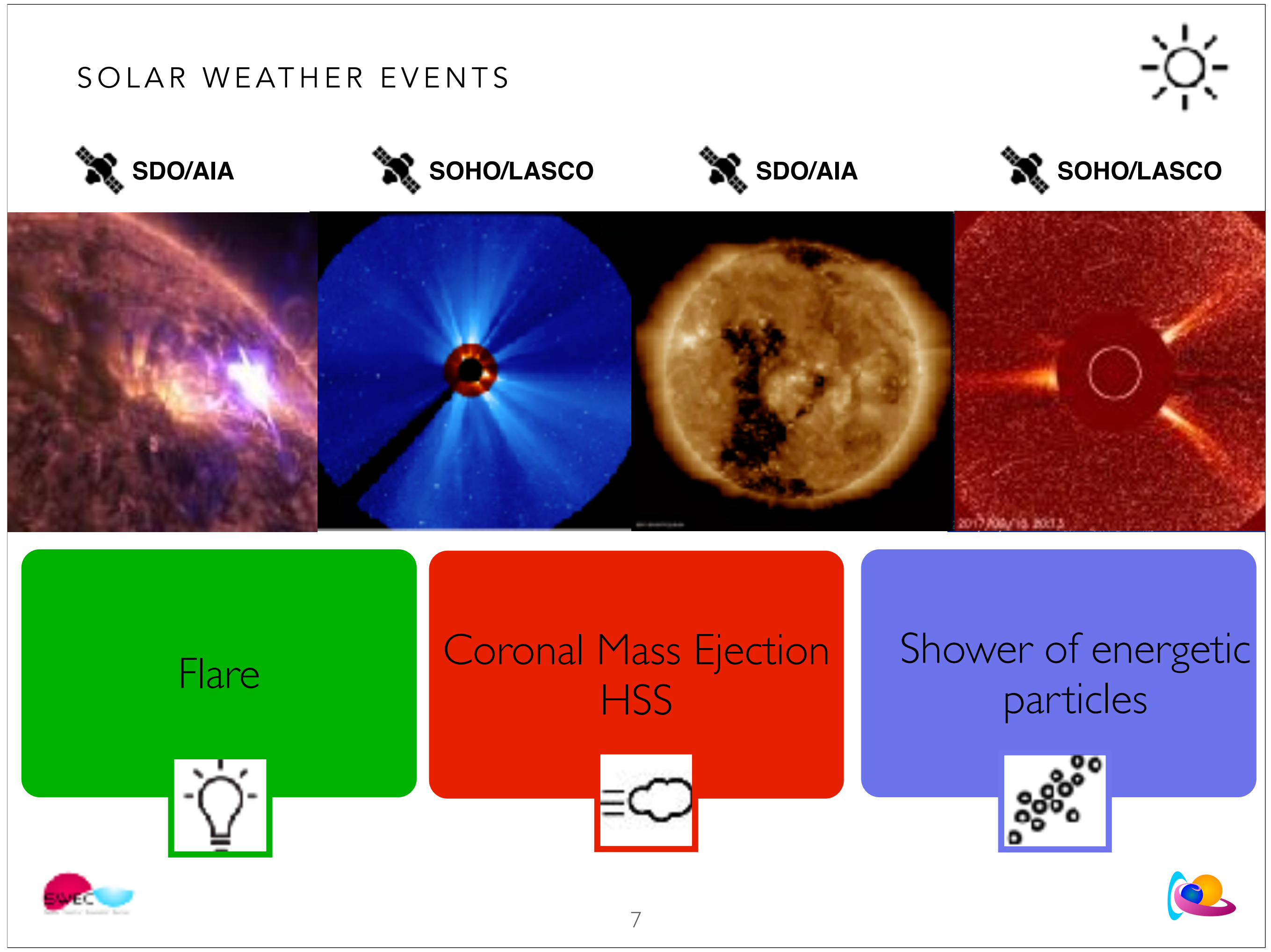
Plasma is the fourth state of matter. Plasma is a gas that is constituted of electrically charged particles.
When the particles have energies above 100 kEV, they don’t behave as a gas but as a (energetic) particle.

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.





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).

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

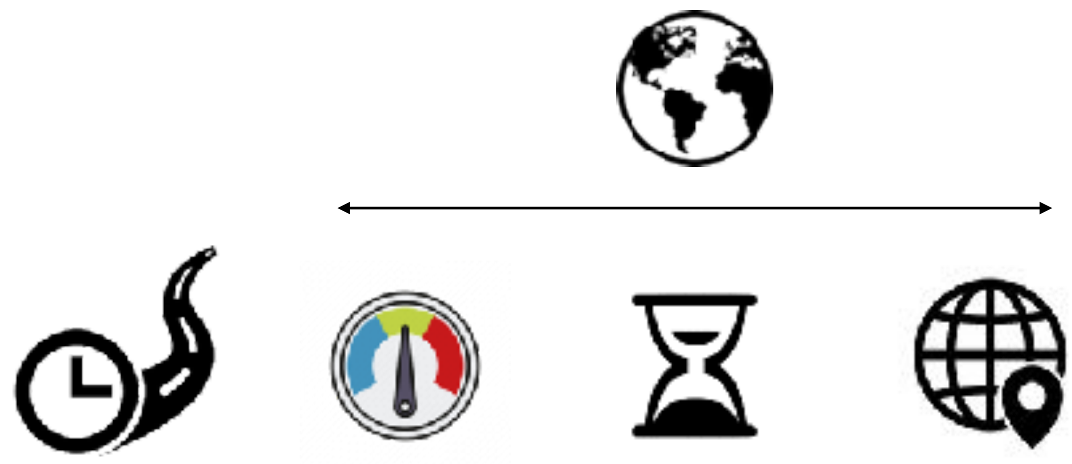
A Coronal Mass Ejection is a plasma cloud that is ejected into space. You consider it as a cloud and not as a bunch of individual particles. It is superimposed on the background solar wind. You can see a CME as a complex magnetic bag with different magnetic layers with plasma in it that travels as a 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.

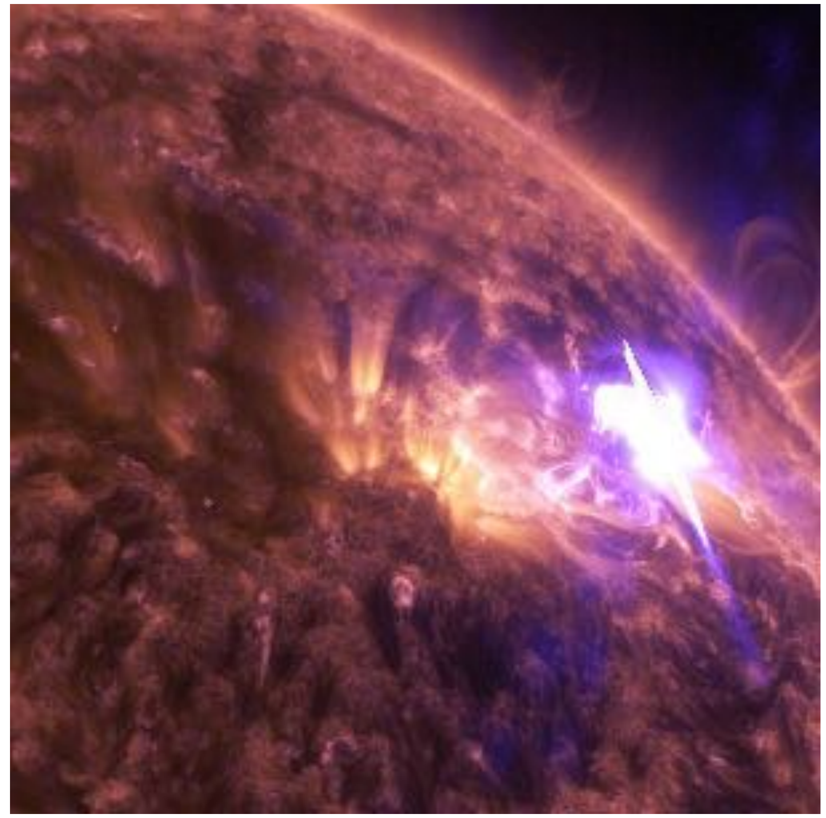
Near Earth, the IMF still controls the solar wind and its movement. If we would go much much further, the CME magnetic bag with solar plasma would be almost empty (all the solar material is spread over an immense volume) and the magnetic bag would have evaporated. But, this doesn’t matter for us. We 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.

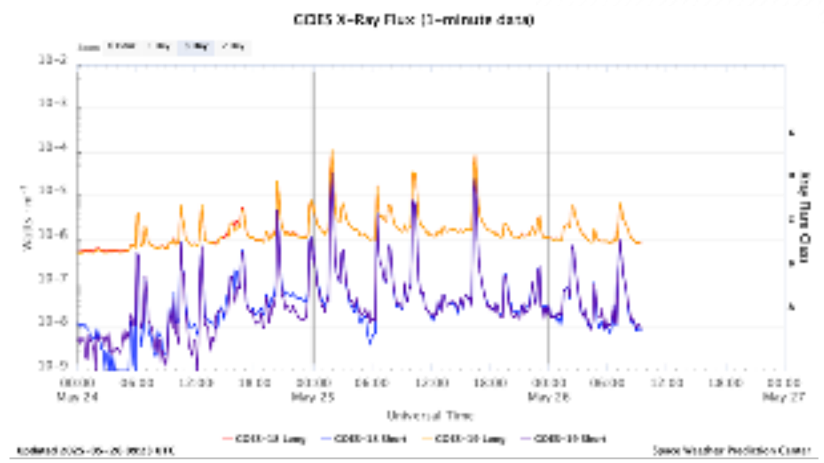
AU TRANSIT TIME

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

8 MIN

SCALE

A,B,C,M,X

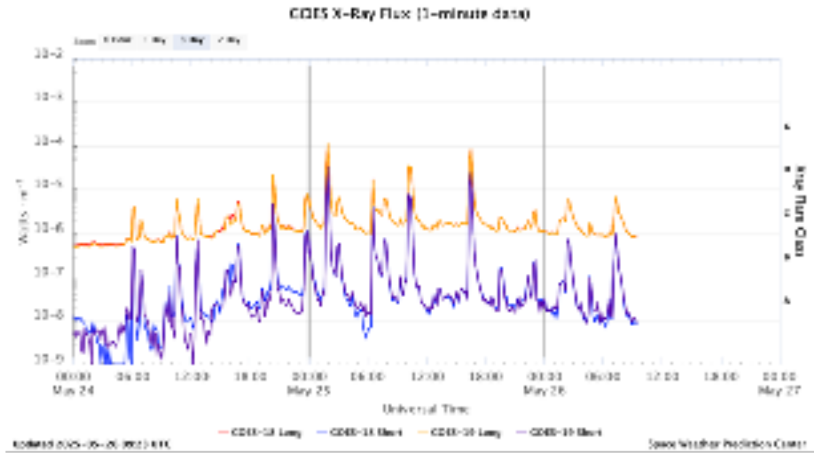


https://www.swpc.noaa.gov/products/goes-x-ray-flux

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

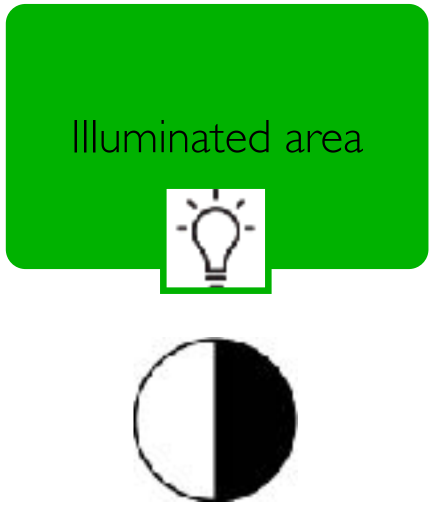
DURATION

MINs to HOUR

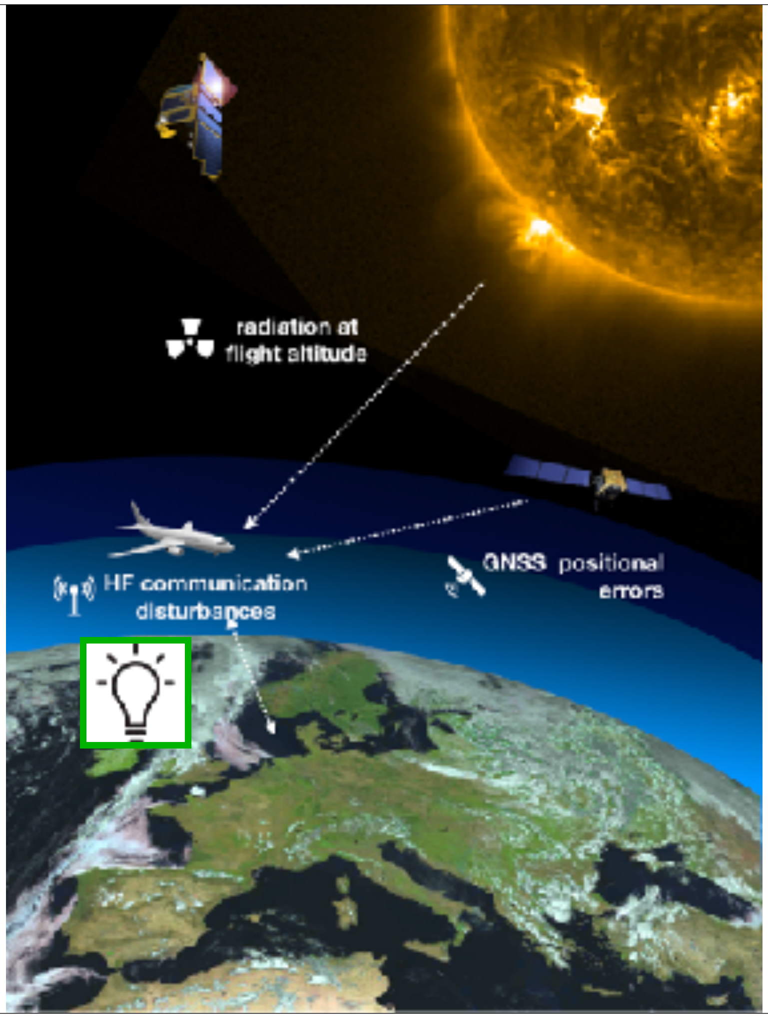


Energy passing in 1 minute per square metre

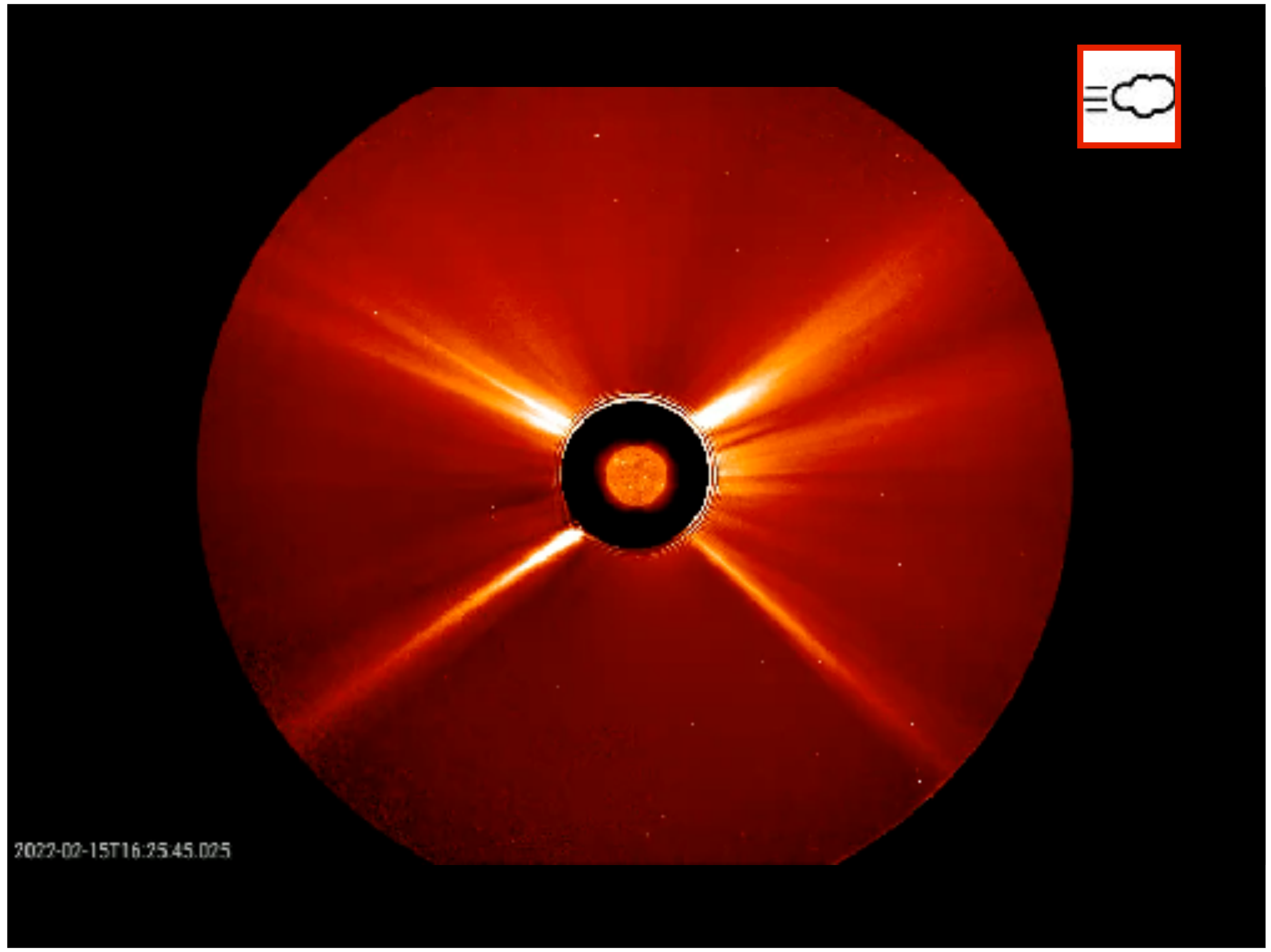
AREA OF IMPACT



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.



The ionising part of the flare, can cause a Short Wave Fadeout on the dayside of the Earth.
The HF radio signal is being (partially) absorbed while passing through the D-layer of the ionosphere.



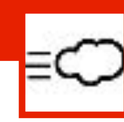
A CME is visible as a white cloud in corona graphic images like the one on the slide. A coronagraph is a telescope that creates an artificial eclipse and makes pictures in the visible light of the region around the sun.
SOHO/LASCO C2

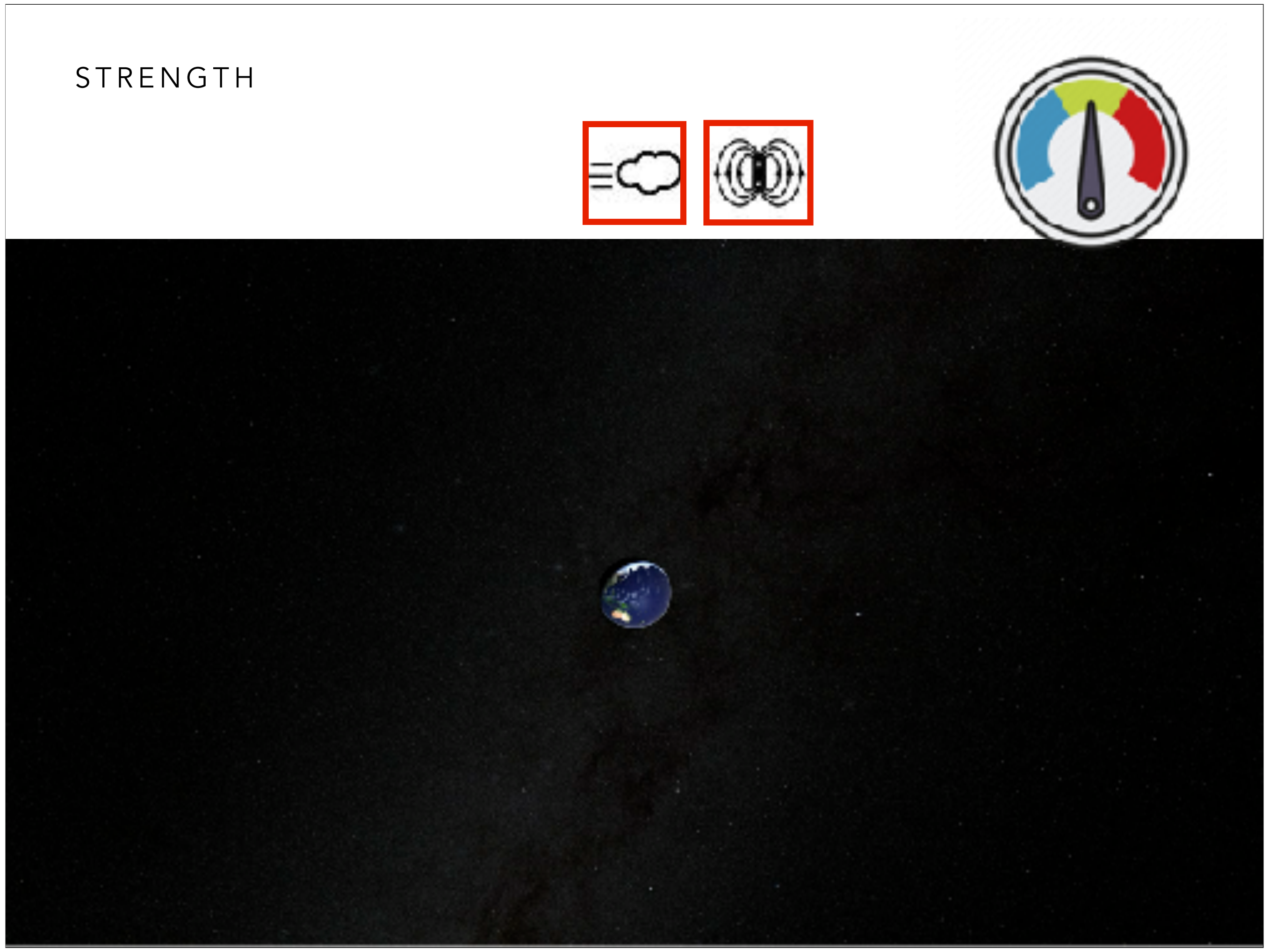
AU TRANSIT TIME

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,….

8 MIN

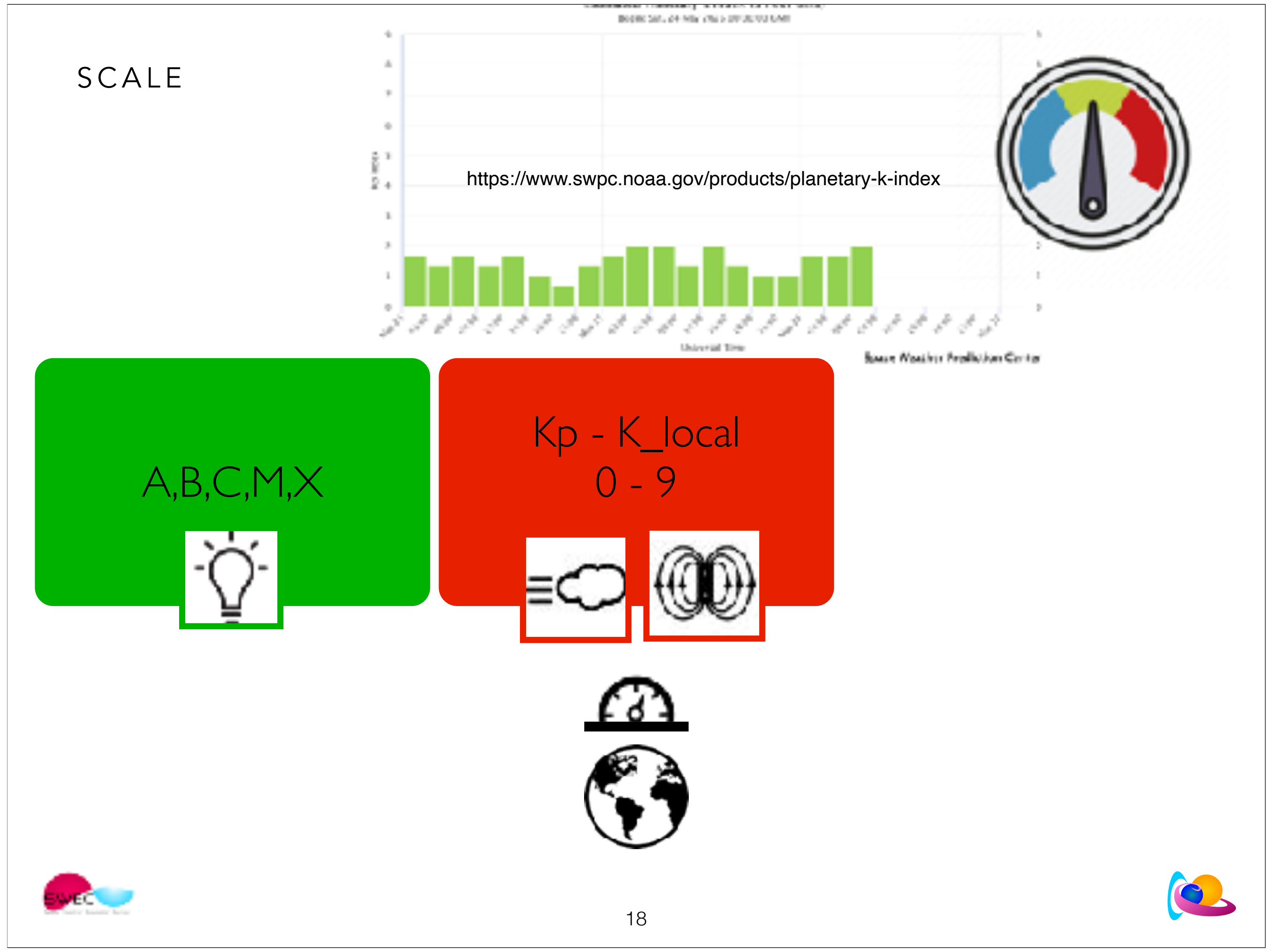
DAYS





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.



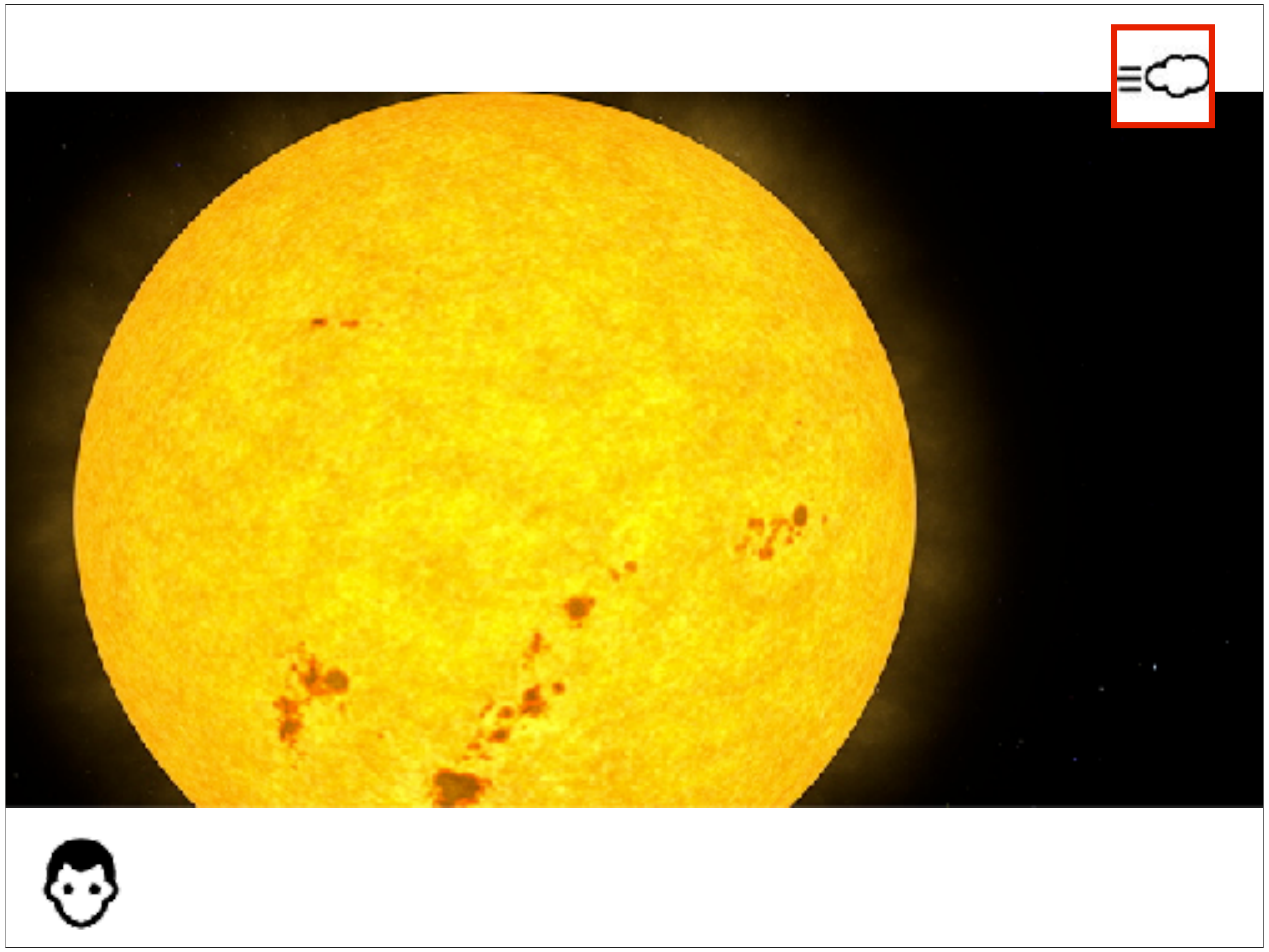
The Kp index is an index that quantifies the disturbance of the magnetic field of Earth. It ranges between 0 and 9, with 0 no disturbance and 9 an extreme disturbance.

DURATION

MINs to HOUR

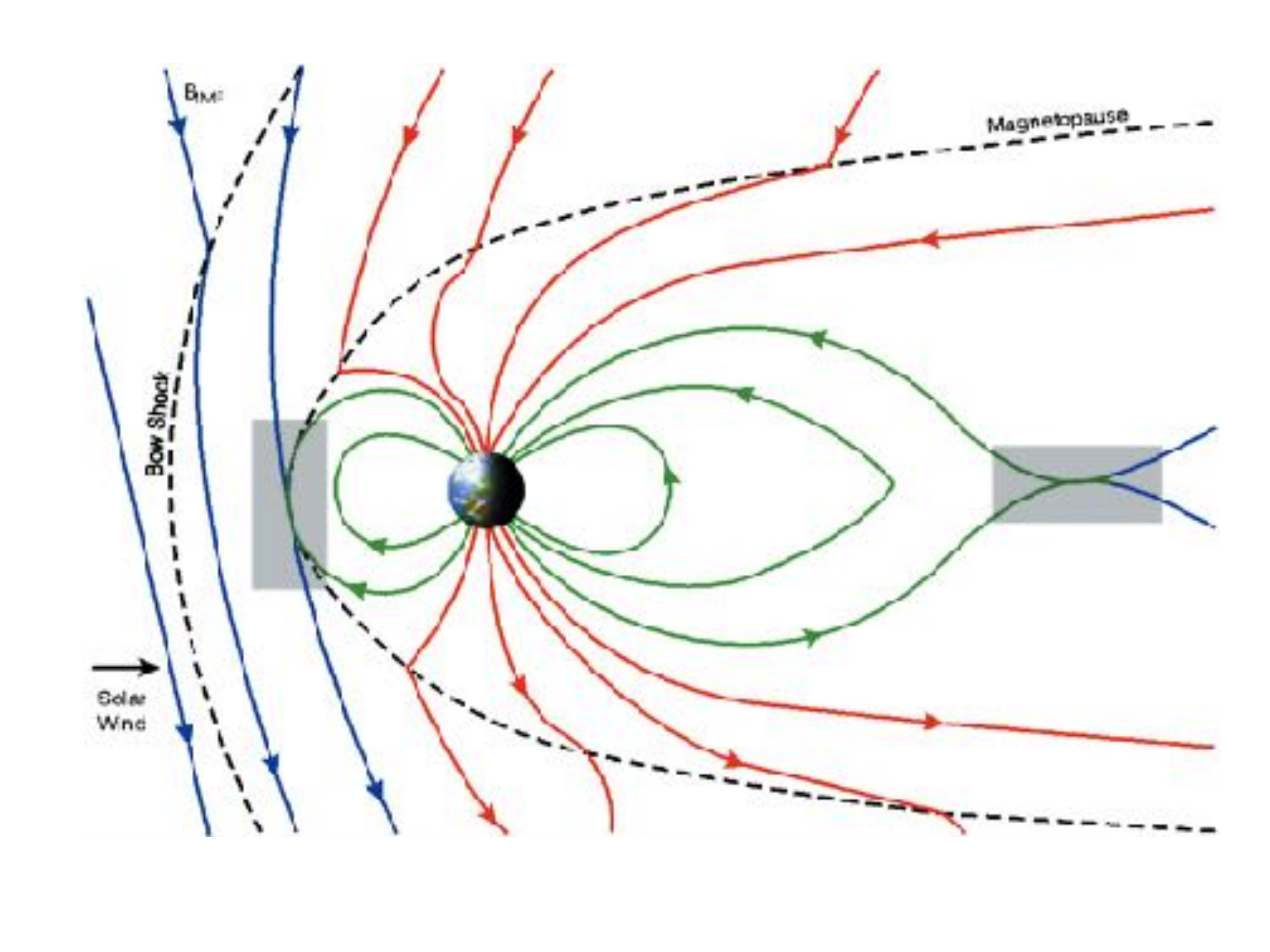
DAY+

Day or more

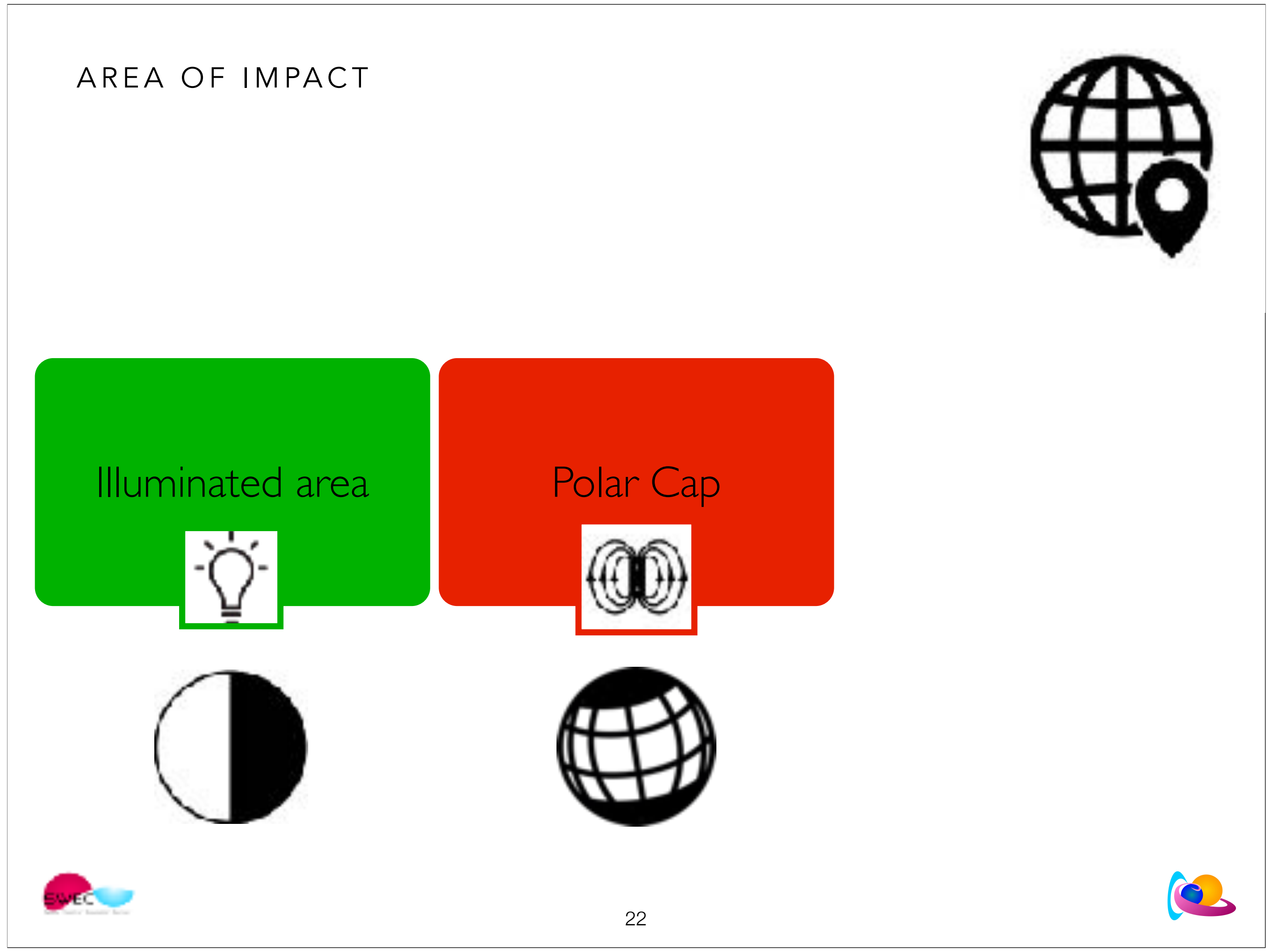


A CME that hits the Earths magnetosphere.
Precipitating electrons coming from the tail of the magnetosphere gyrate along the earths magnetic field and drop into the atmosphere in the auroral oval.

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



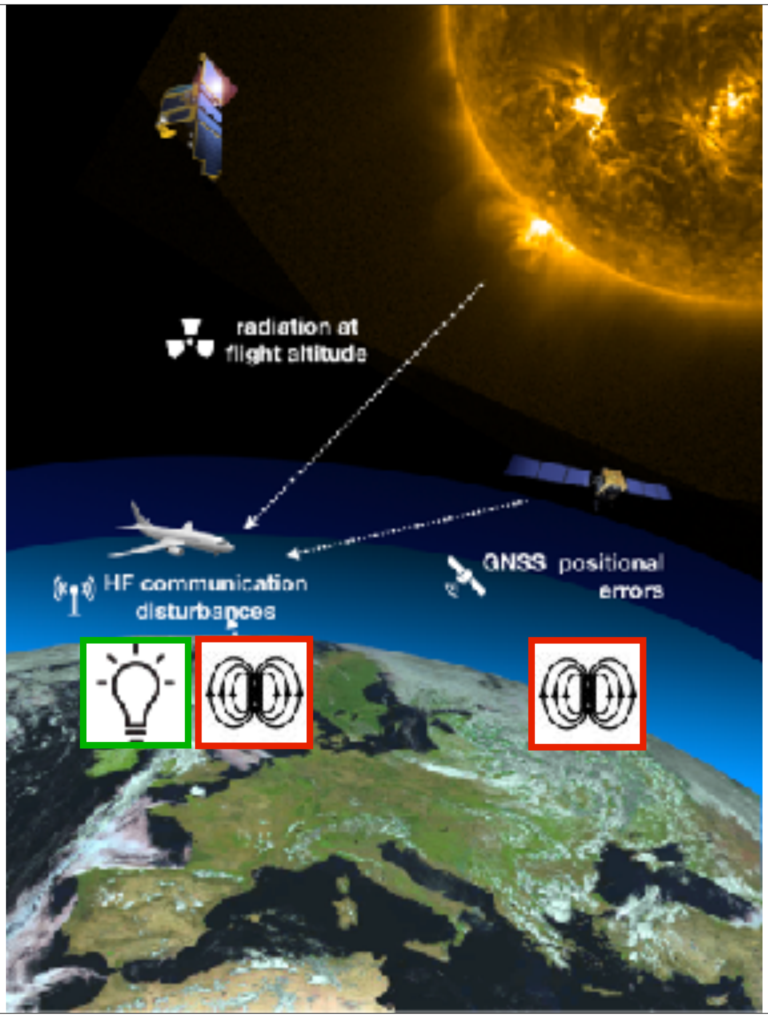
The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).



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.

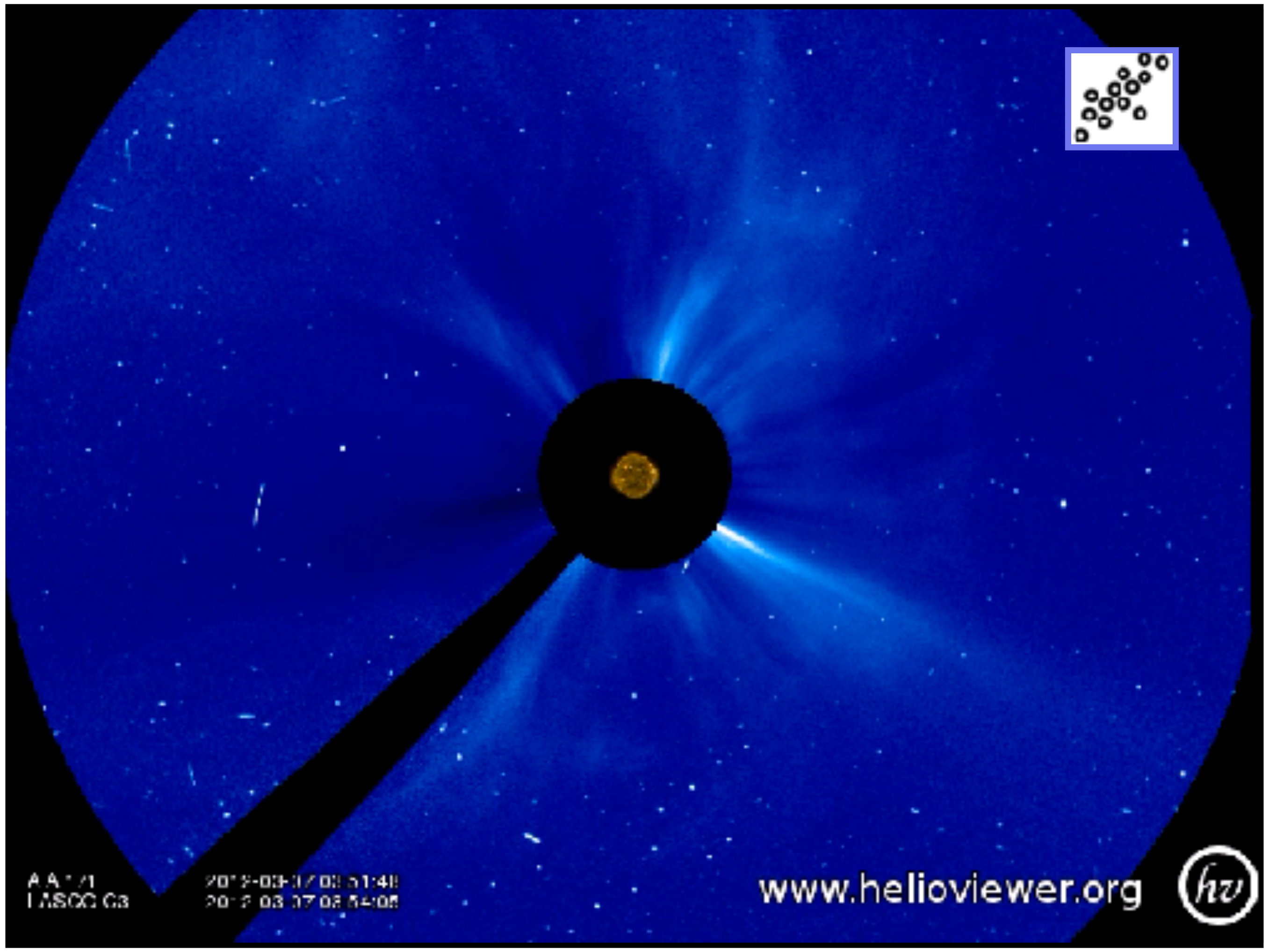


GNSS

- Amplitude or phase scintillation of the radio signal emitted by the GNSS satellites due to small scale irregularities. Scintillation might result in a loss of lock.
- VTEC - Increase the electron density (positive phase of a geomagnetic storm) such that the signal is not following it's regular path and its speed is changed. This results in a delay.

HF com

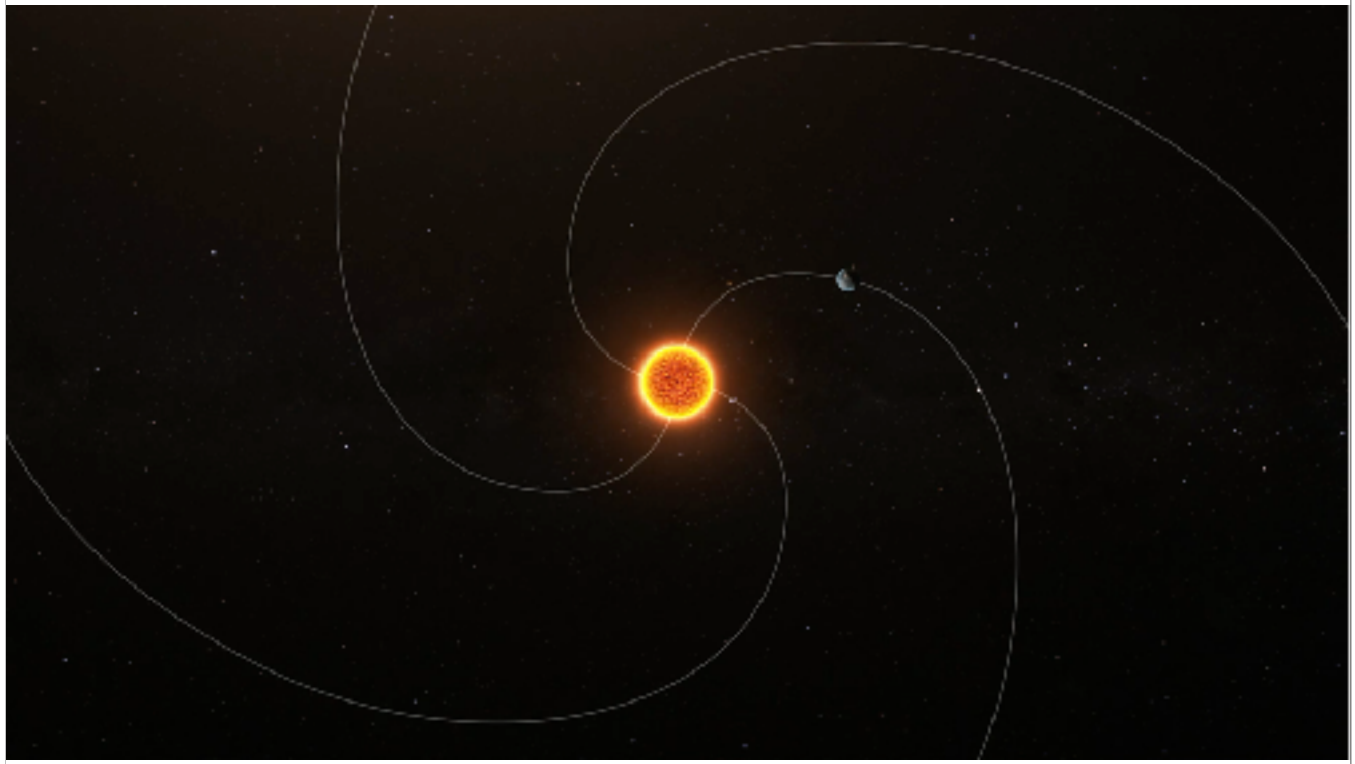
- In the negative phase of a magnetic storm, an electron depletion occurs —> higher frequency radio waves are not reflected anymore by the ionosphere and just pass into space.
- AA: induce extra ionisation in the D-layer of the ionosphere such that radio waves are being absorbed when they pass through the D-layer.



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.)



25

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.

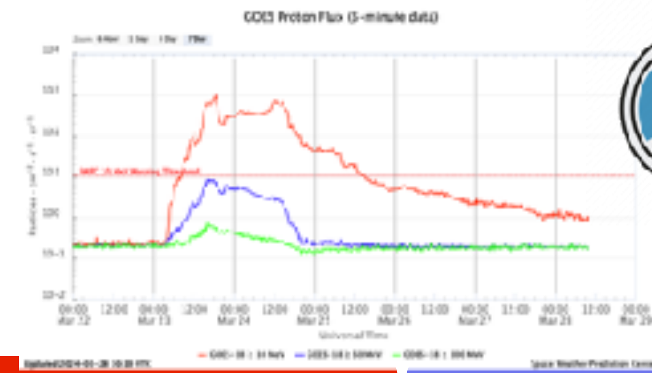
The energy released during a solar storm moves through space, each with its own typical speed: speed of light, order of a few 100 km/s, relativistic speeds.

8 MIN

DAYS

HOUR

SCALE

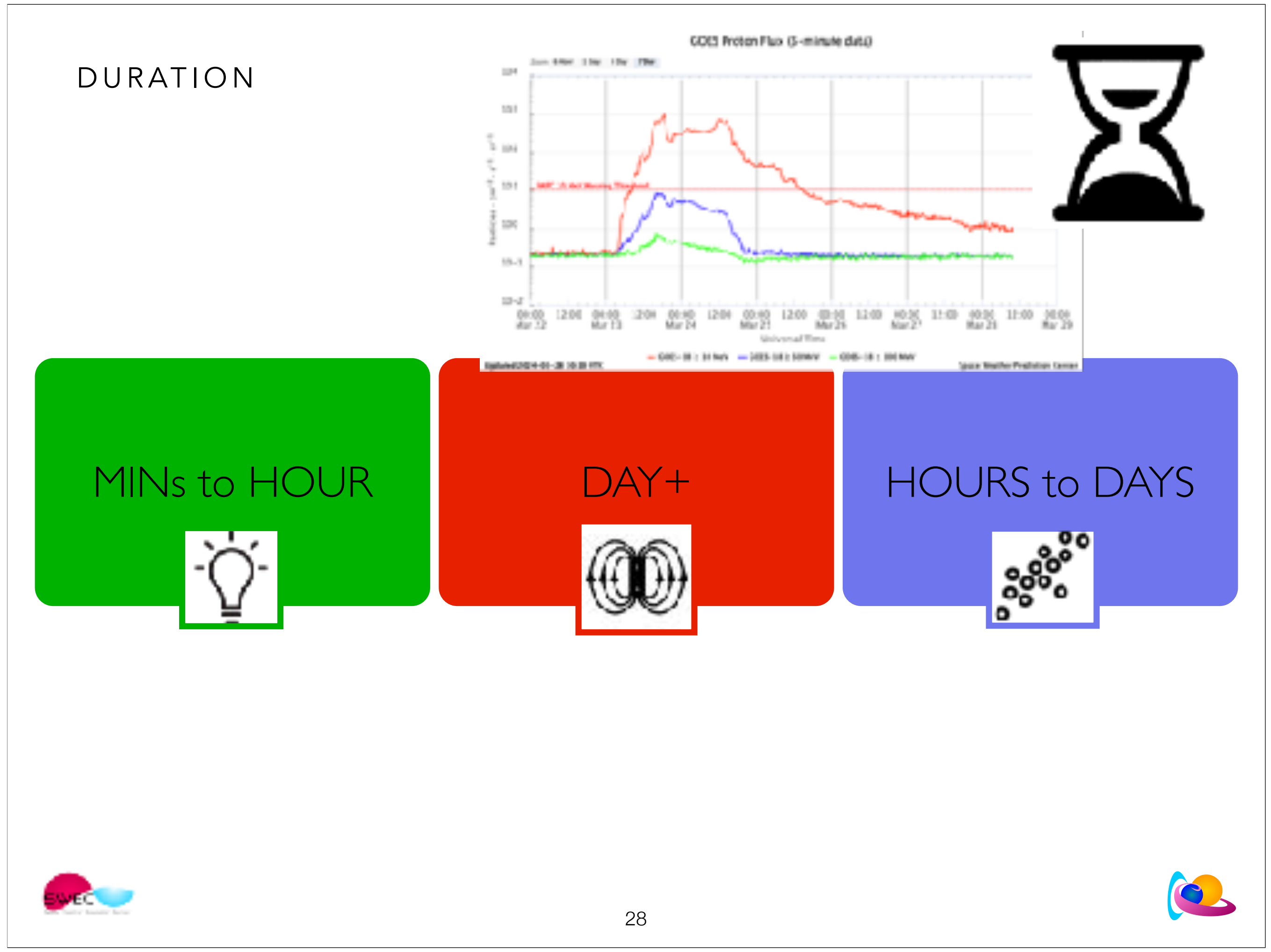


A,B,C,M,X

Kp
0 - 9

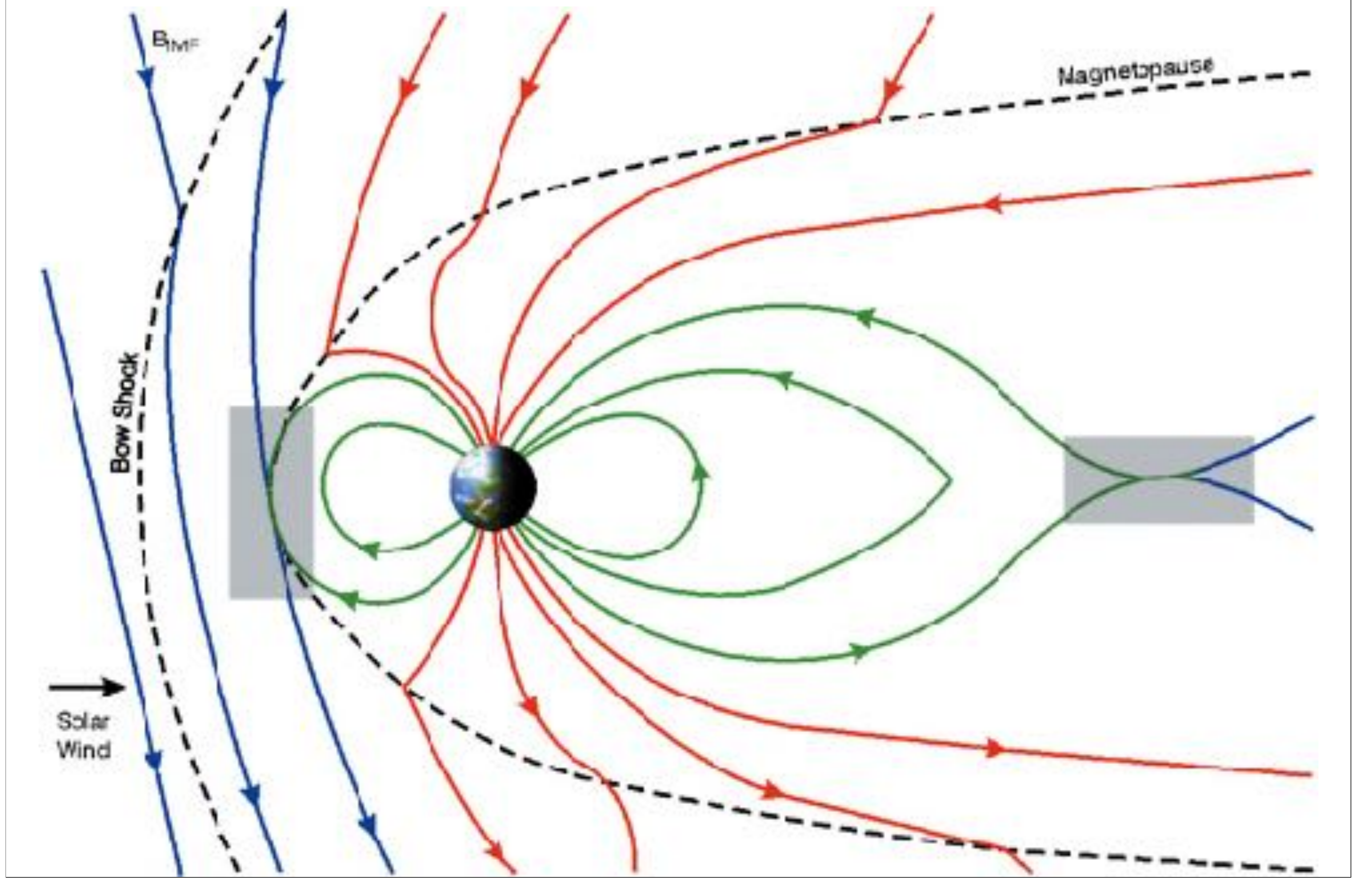
Storm - major storm

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



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

AREA OF IMPACT



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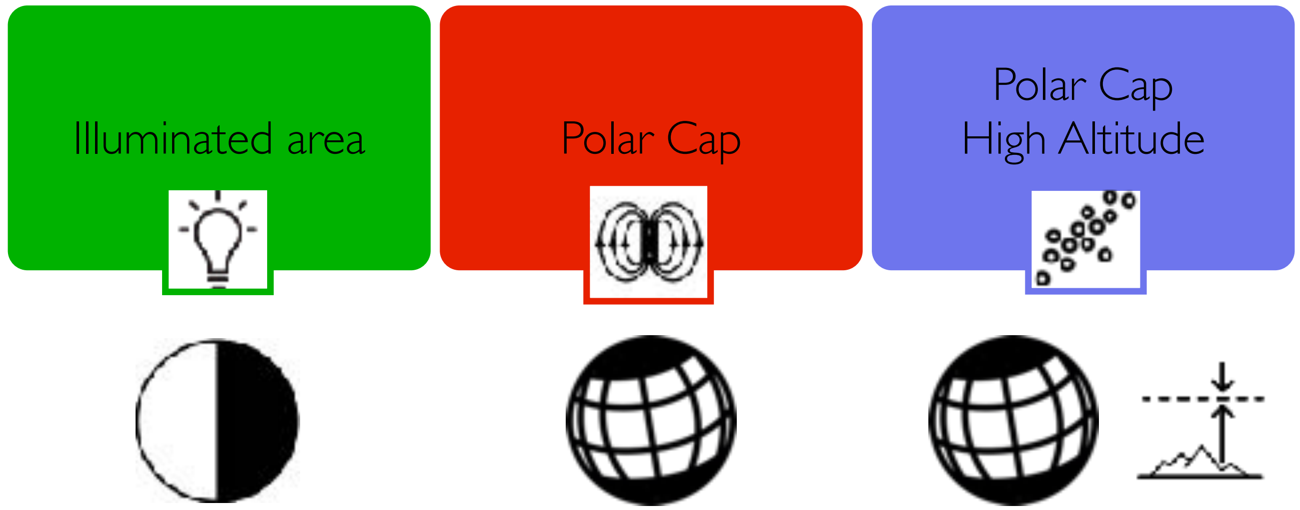
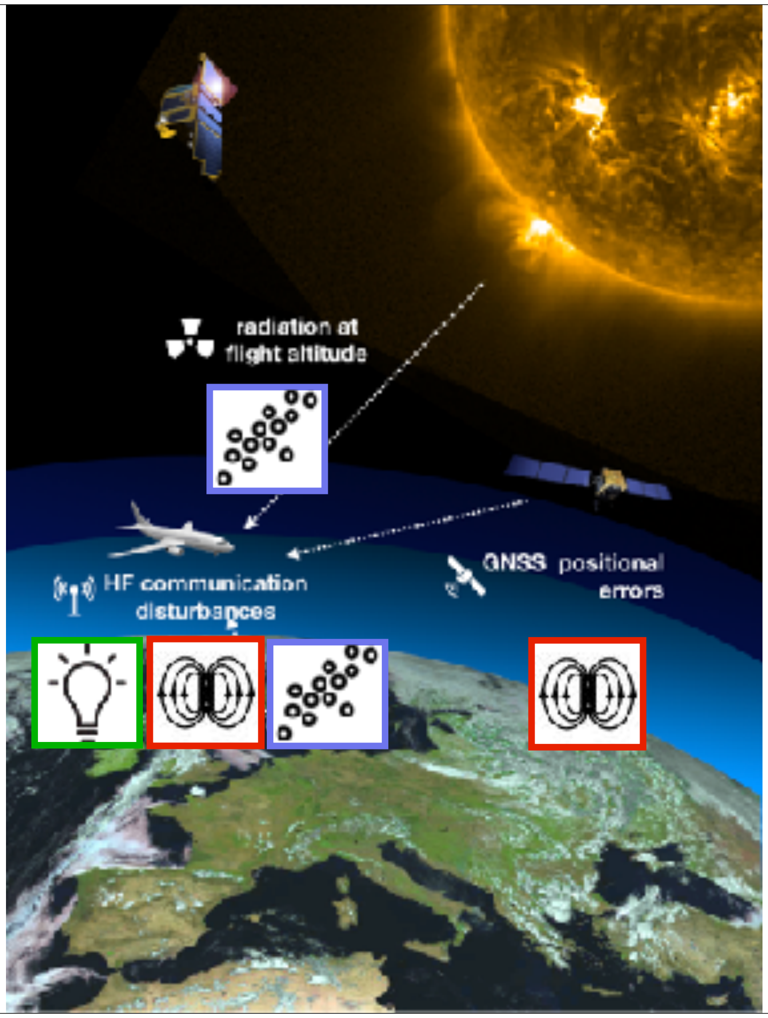
AREA OF IMPACT



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



Impact
Radiation at flight altitude

HF com

- Polar Cap Absorption. The incoming energetic particles induce extra ionisation in the D-layer resulting in possible absorption of the HF radio waves that pass through.

OVERVIEW

8 min	Days	Hour
X-ray: A,B,C,M,X	Kp: 0 - 9	Protons: Storm - Major Storm
Min to Hour	Day+	Hours to Days
Illuminated area	Polar Caps	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. The peak of the red/orange curve defines the flare class.

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.

Estimated

by NOAA, US

Data location

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

Definitive

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

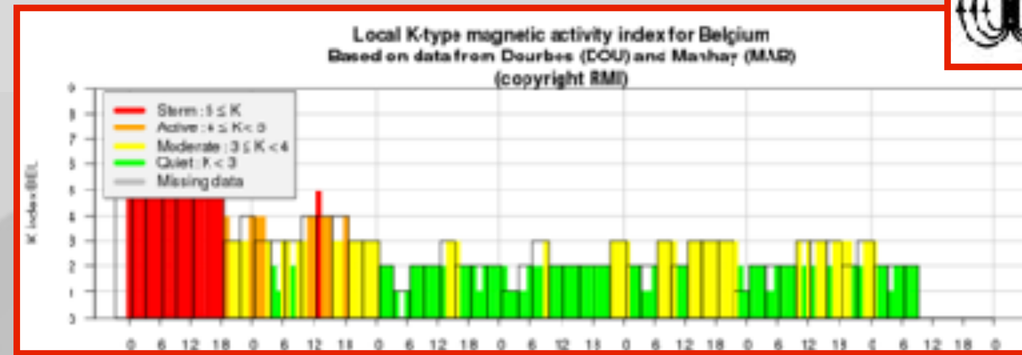
Magnetometers

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.

K Belgium Passport



What

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

Sensors

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

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 .

Provider

Royal Meteorological Institute of Belgium

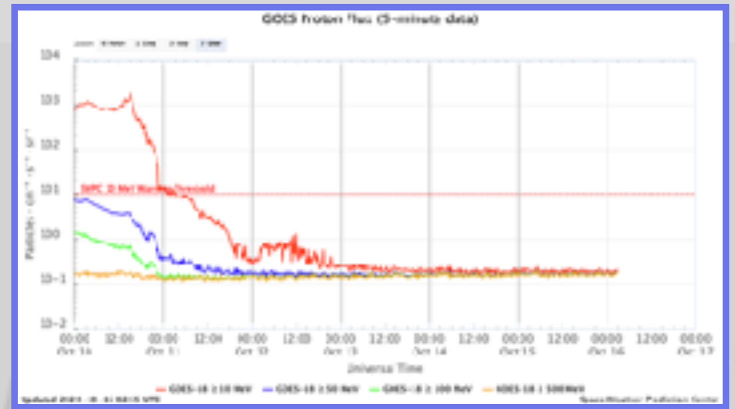
Plot

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

Data location

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

Proton Flux Passport



Type

Graph, flux of solar protons versus time.

Sensor

GOES-18 satellite

Use

To quantify proton events impacting Earth.

Sensor location

Geostationary orbit

Units

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

Cadence

Integrated over 5 min

Data location

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

Plot

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

After Mother's day storm - May 15, 2024

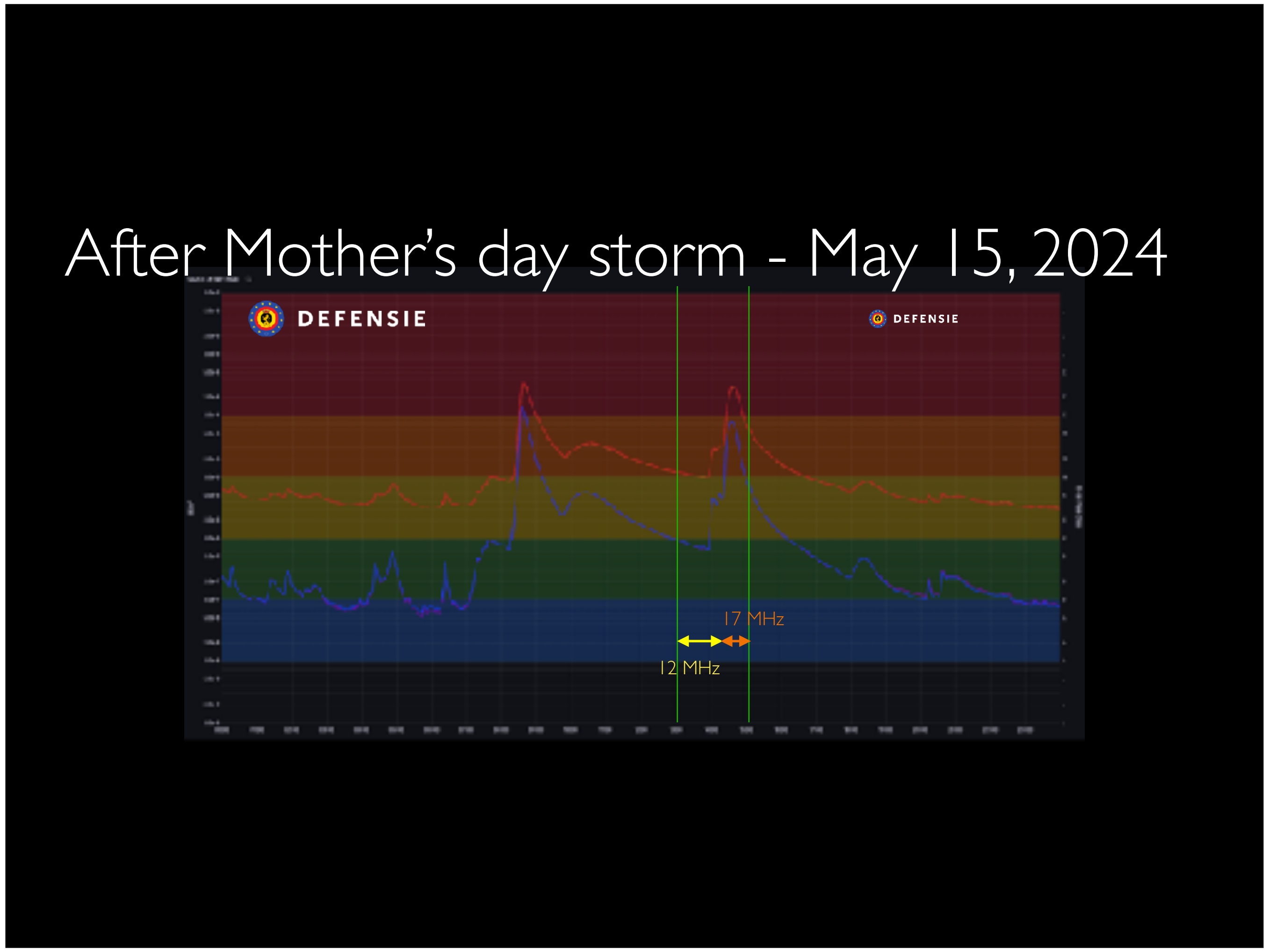
DEFENSIE

HF COM test between Canada and Belgium on May 15, 2024

HF COM - uses the F-layer as a reflector.

After Mother's day storm - May 15, 2024

Test from 13h until late in the evening.
Nothing worked.
13h-14h at 12 MHz
From 14h at 17 MHz.

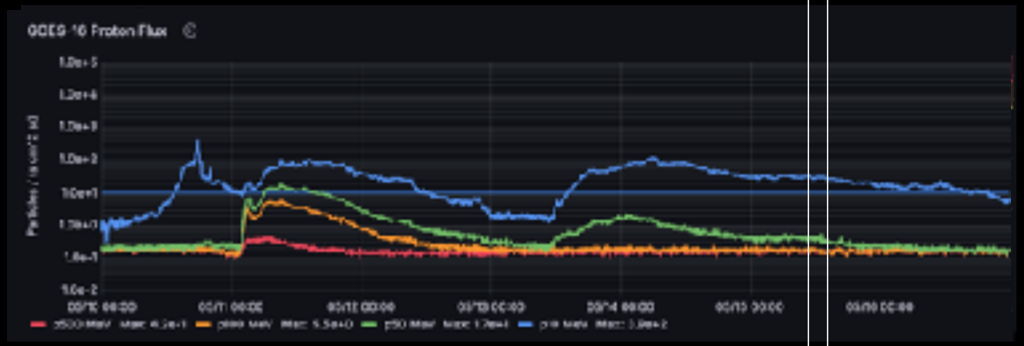


Background in the M-level
At 14h, an X-flare

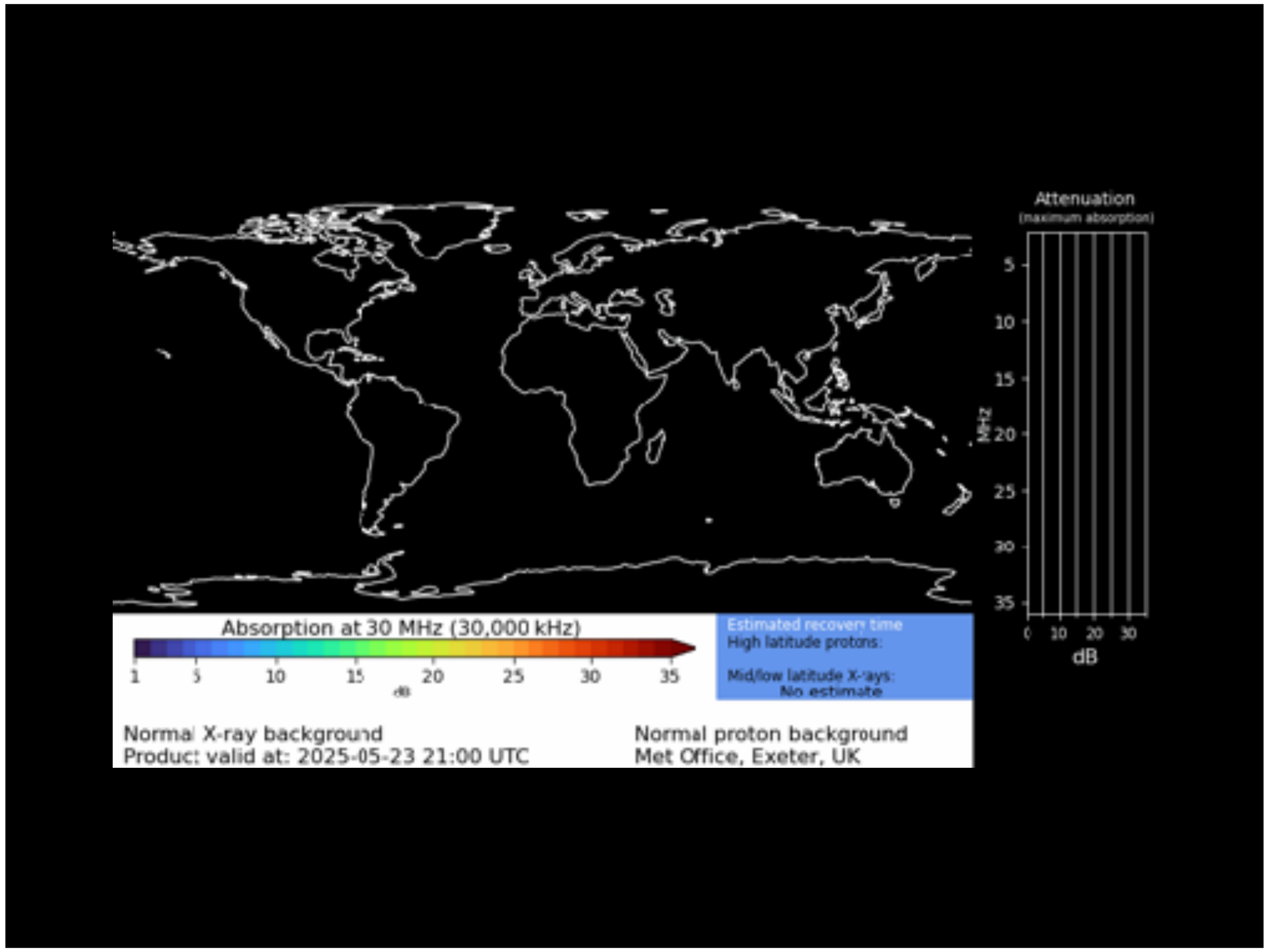
After Mother's day storm - May 15, 2024

OK

After Mother's day storm - May 15, 2024

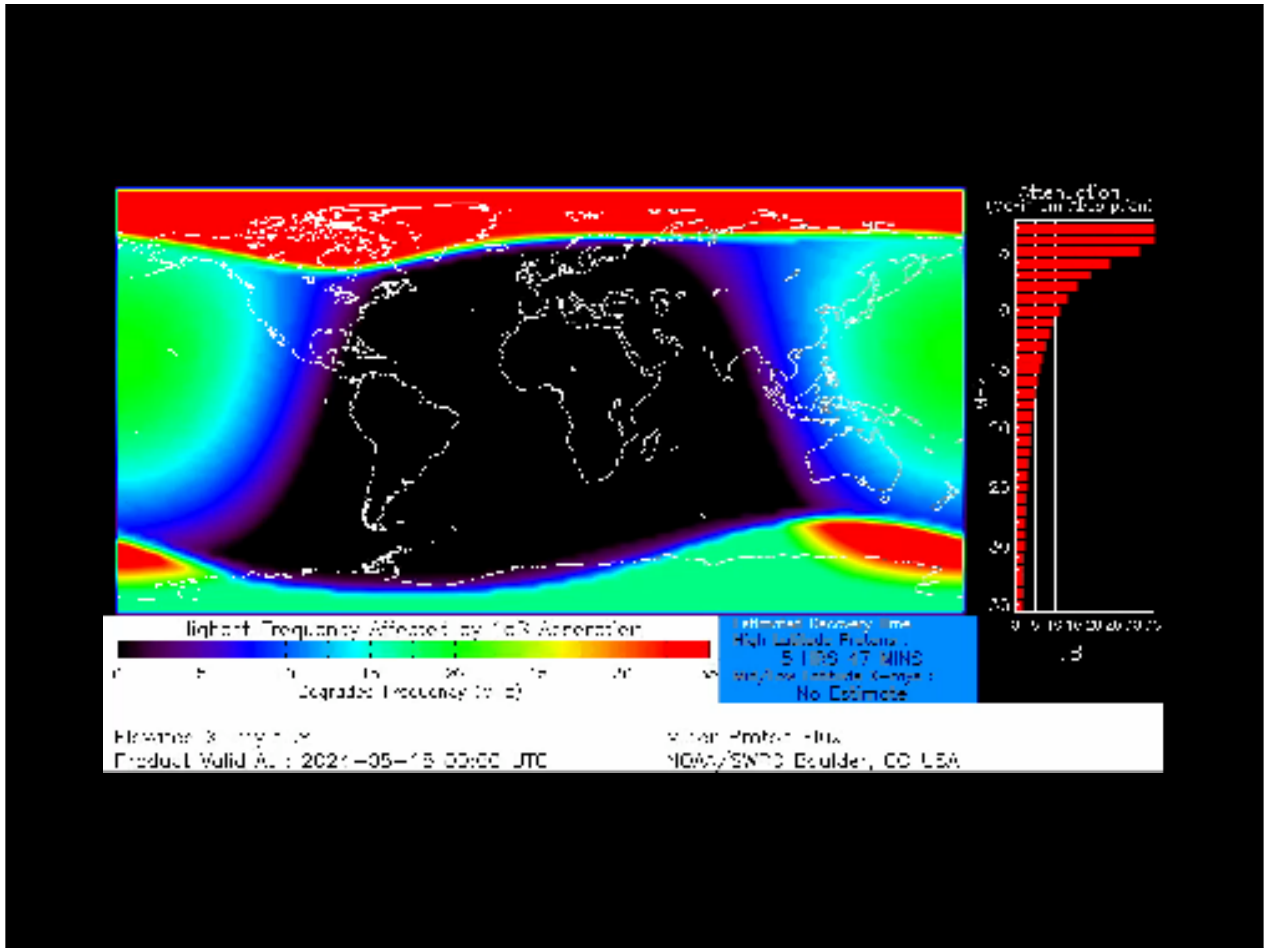


Ongoing proton storm.



HF waves pass through the D-layer, reach the F-layer where they are being reflected, pass again through the D-layer to reach the receiver.

D-Region Absorption Prediction model



D-region was impacted - due to the solar storms, extra ionisation in this ionospheric layer was induced.