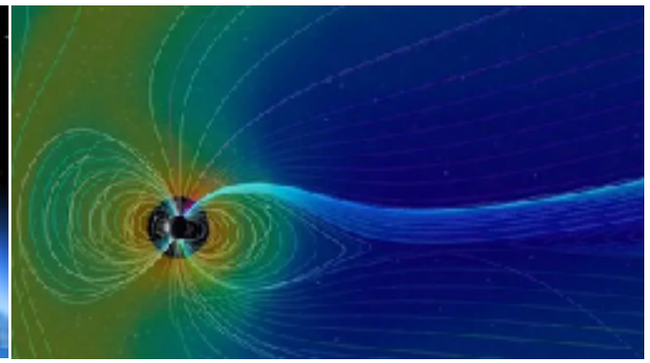
Space Weather

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 AS A BALL OF ENERGY




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

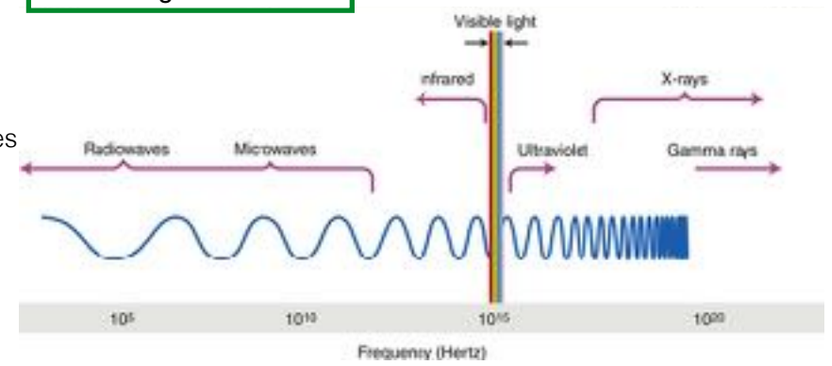
This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

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

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

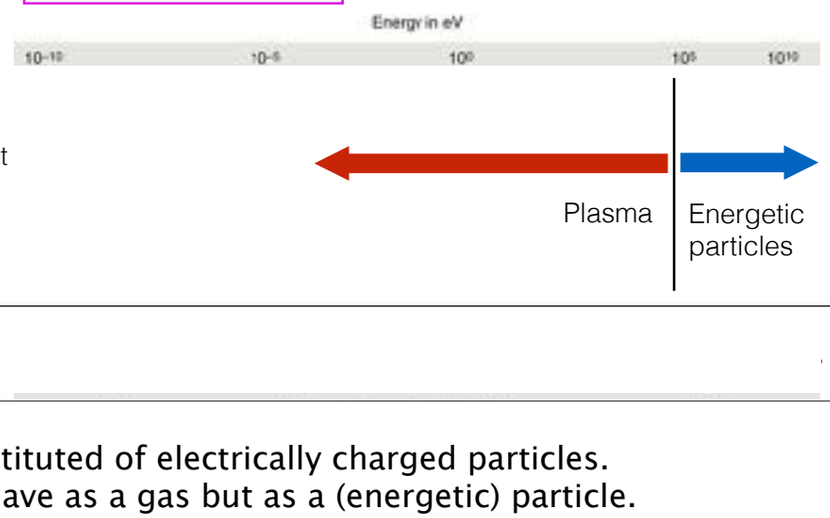
## Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light




## Particles

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

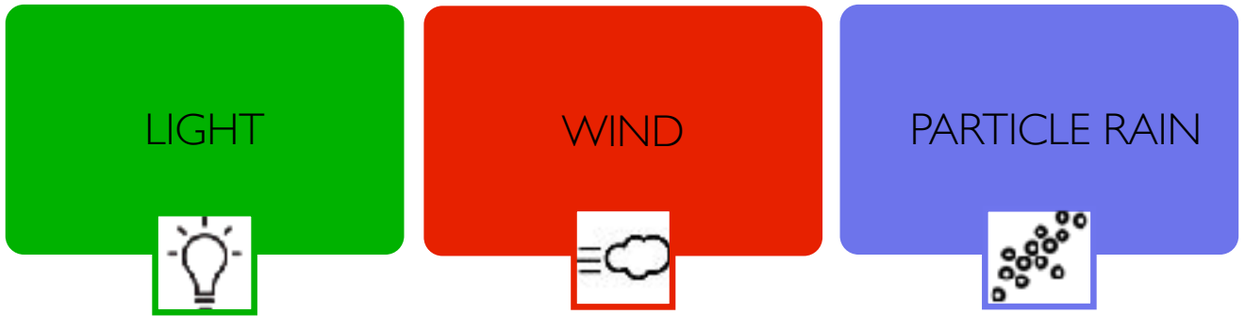



Plasma is the fourth state of matter. Plasma is a gas that is constituted of electrically charged particles.
When the particles have energies above 100 kEV, they don't behave as a gas but as a (energetic) particle.

## 3 SPACE WEATHER PHENOMENA

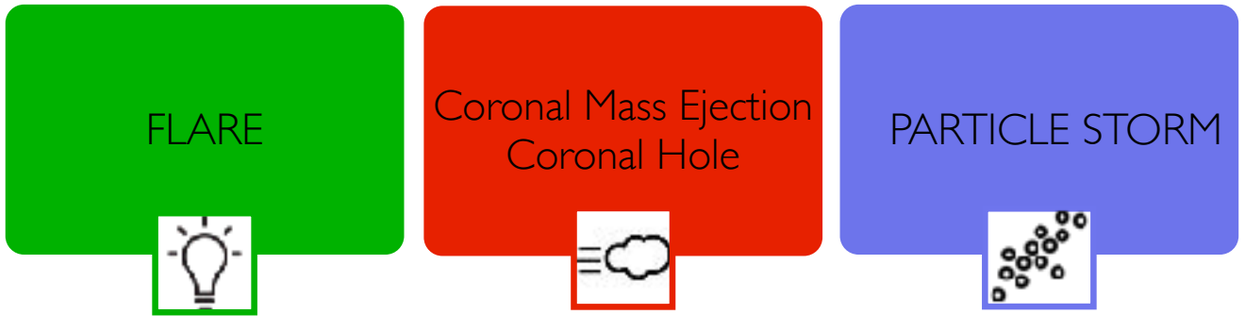
The sun's energy reaches the earth in 3 forms: light, moving gas and particle precipitation. This energy interacts with the magnetosphere and the atmosphere of the earth. This is space weather.

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



## 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).






Change in solar energy output on the scale of minutes, hours, days - this is solar weather.

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

Examples of Solar wind disturbances:
A Coronal Mass Ejection is a plasma cloud that is ejected into space. It is superimposed on the background solar wind. 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.

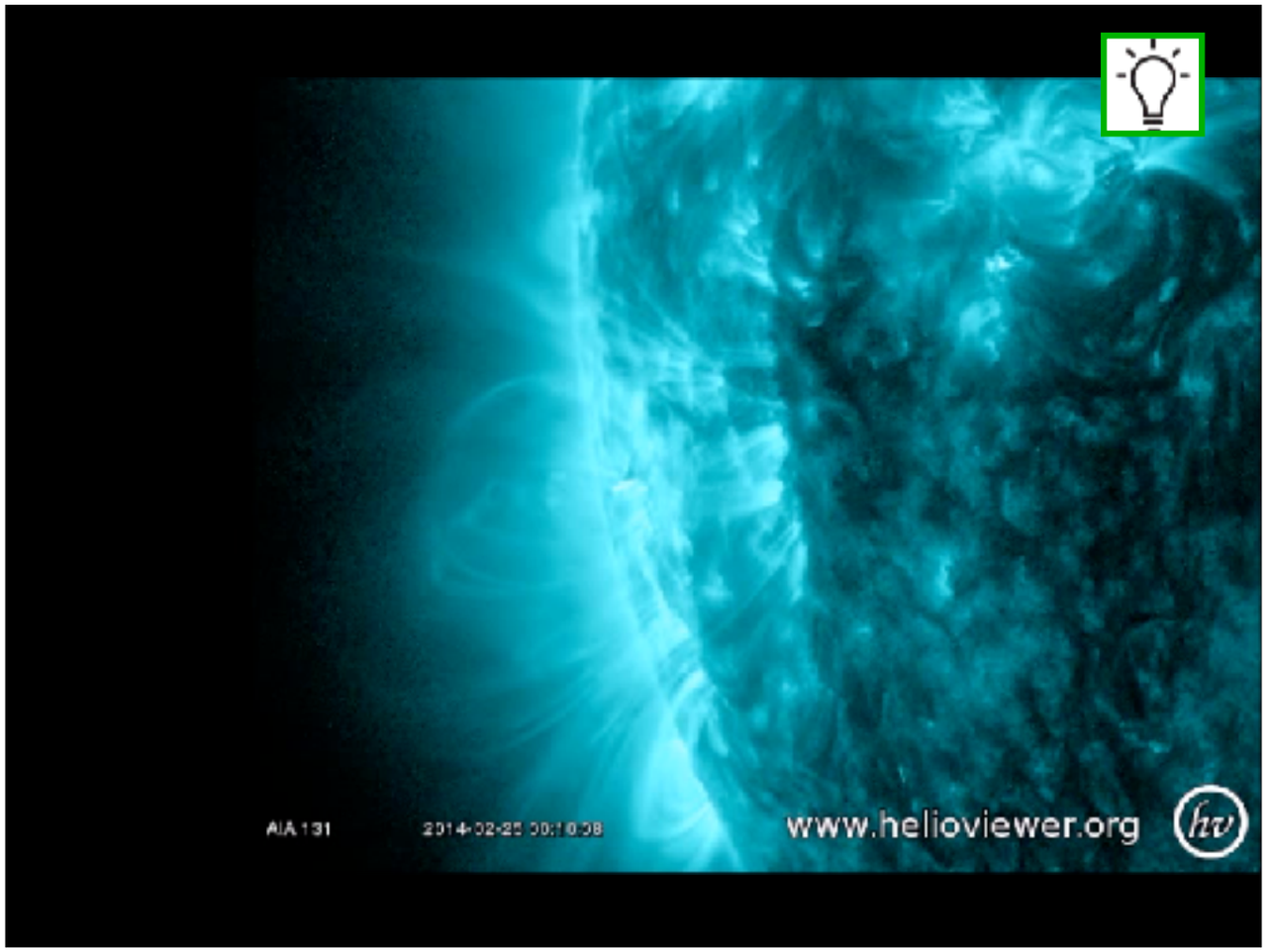
A coronal hole is a structure in the solar corona that you see as a black area in the EUV. It looks black because there is less plasma present that radiates in the EUV. The magnetic field lines are open, i.e. fan out into space. There are no magnetic loops above a coronal hole. The solar wind emanating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

Particle storm
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 gyrate around a magnetic field line.

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
Storm scale
duration
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

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

8 MIN

# STORM SCALE

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

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

# STORM SCALE

A,B,C,M,X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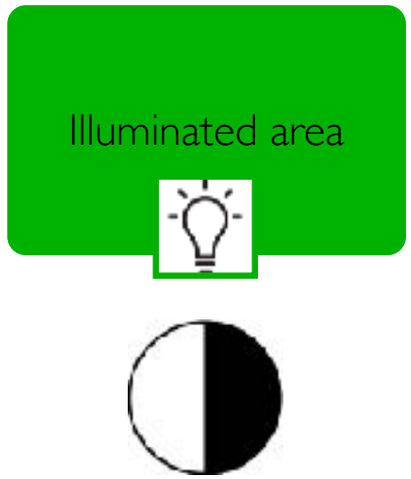
# DURATION

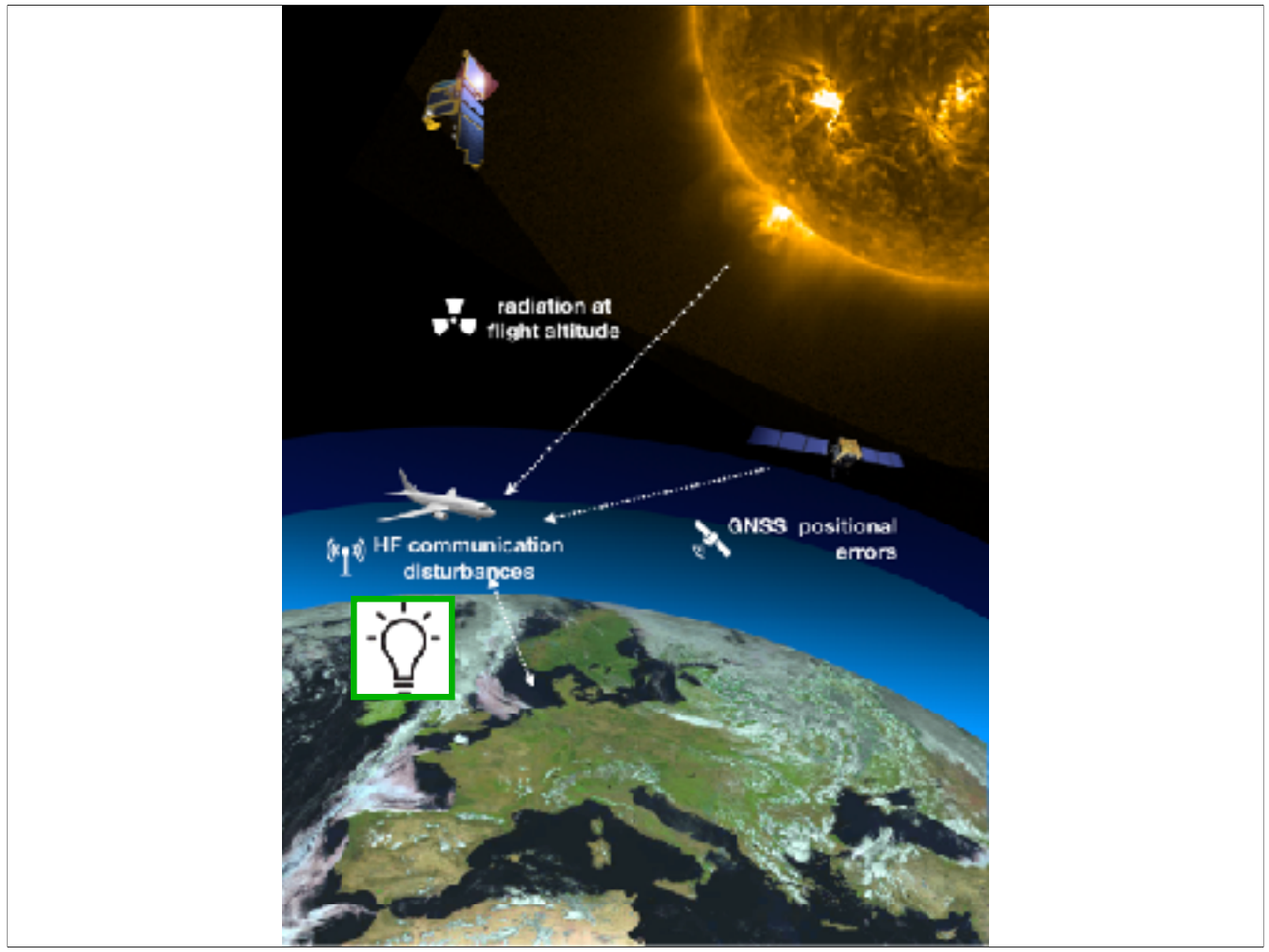
MINs to HOUR

# AREA OF IMPACT

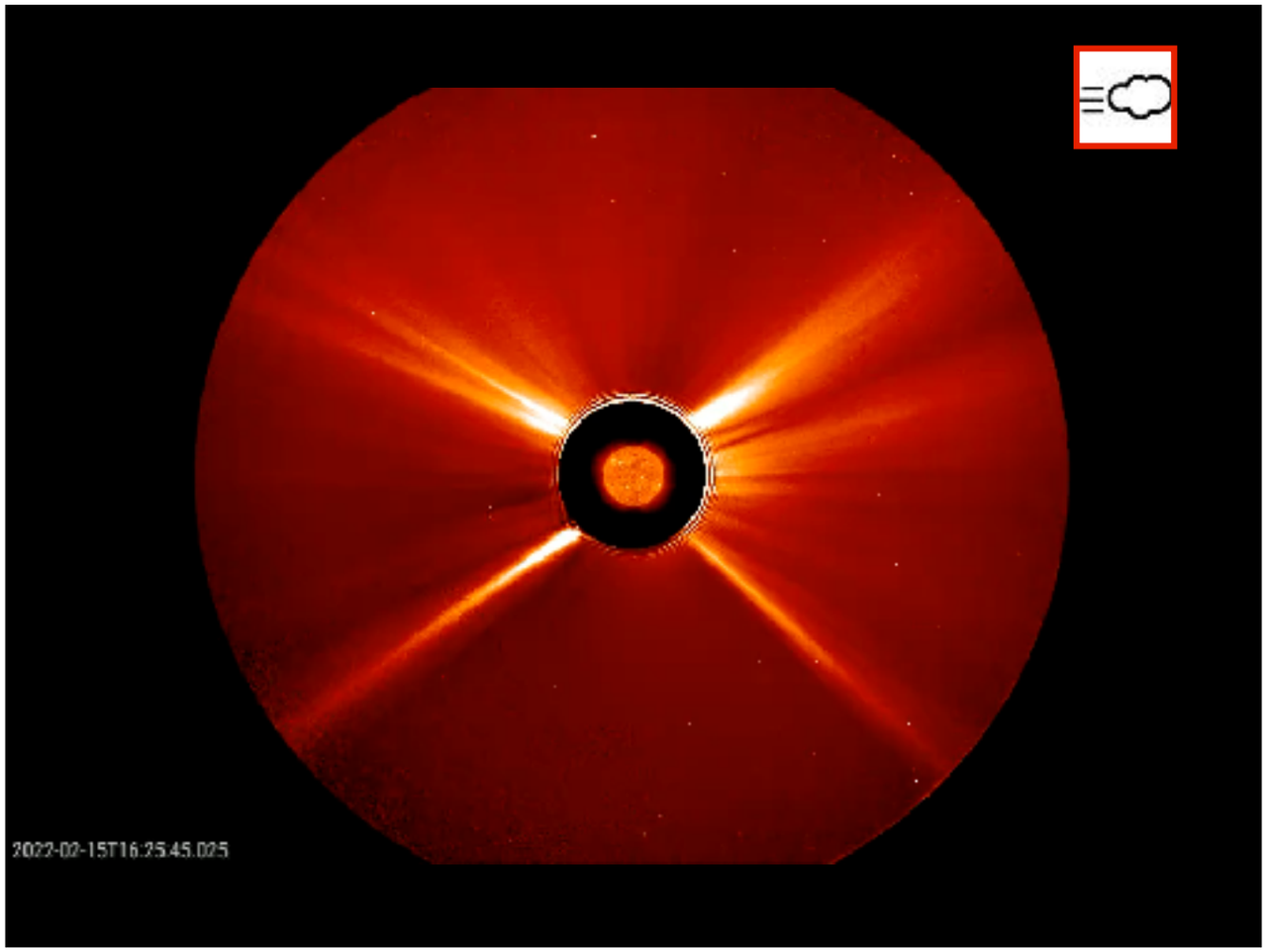
# AREA OF IMPACT




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



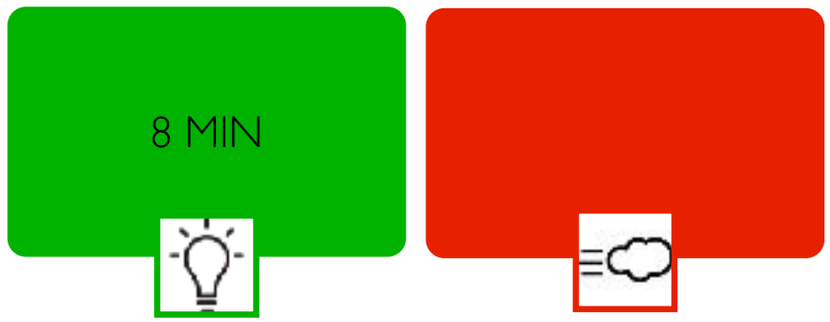

The ionising part of the flare, can cause a Short Wave Fadeout on the dayside of the Earth.
The HF radio signal is being (partially) absorbed while passing through the D-layer of the ionosphere.




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

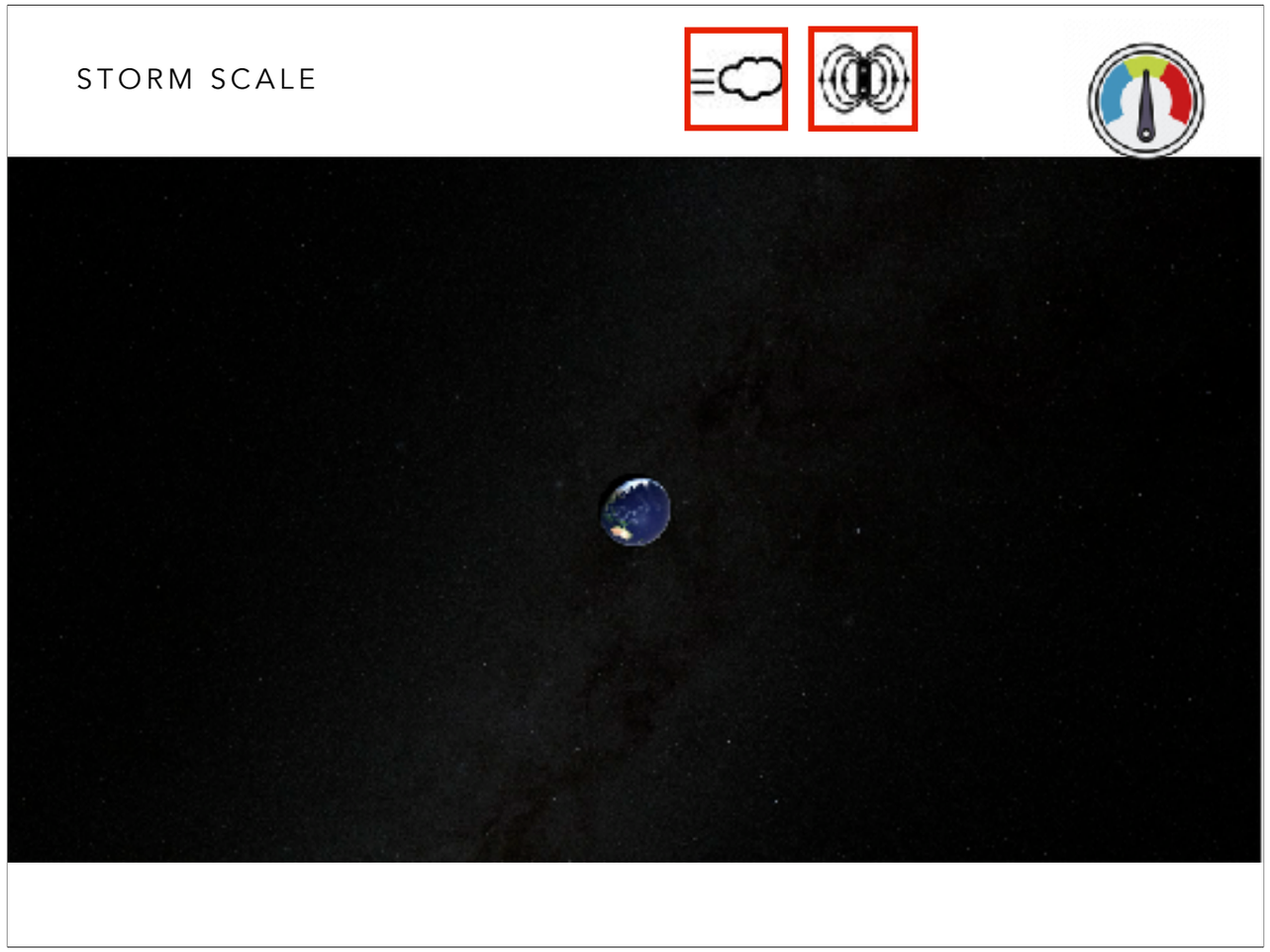
## AU TRANSIT TIME

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,….



## AU TRANSIT TIME

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

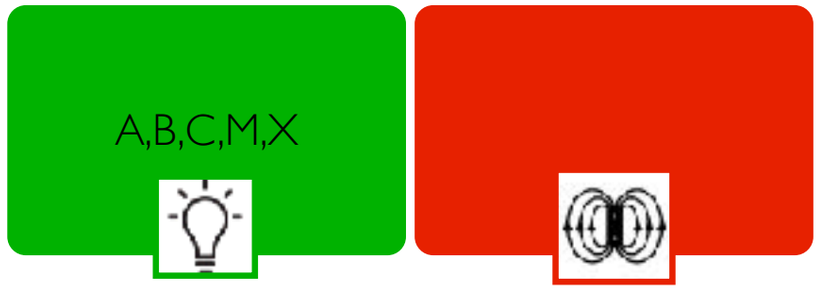



https://svs.gsfc.nasa.gov/5193/
This animation demonstrates the Earth's magnetosphere being hit by a geomagnetic storm on February 3, 2020, simulated by MAGE during the storm that caused the loss of commercial satellites.

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

# STORM SCALE

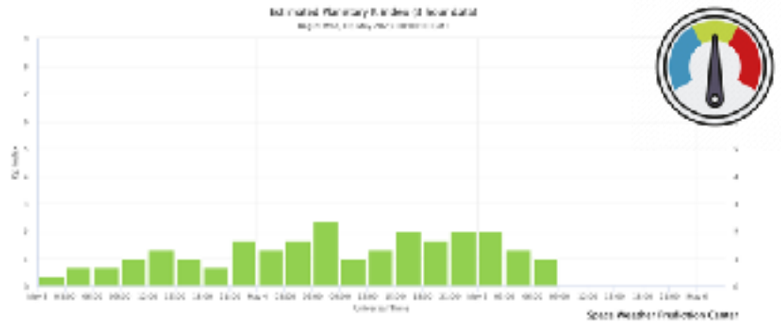
**https://www.swpc.noaa.gov/products/planetary-k-index**






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

## STORM SCALE





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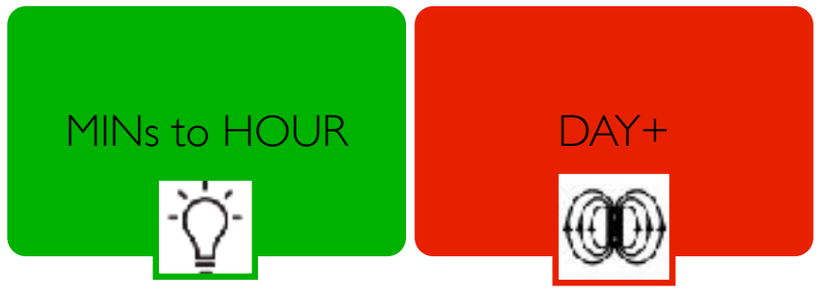
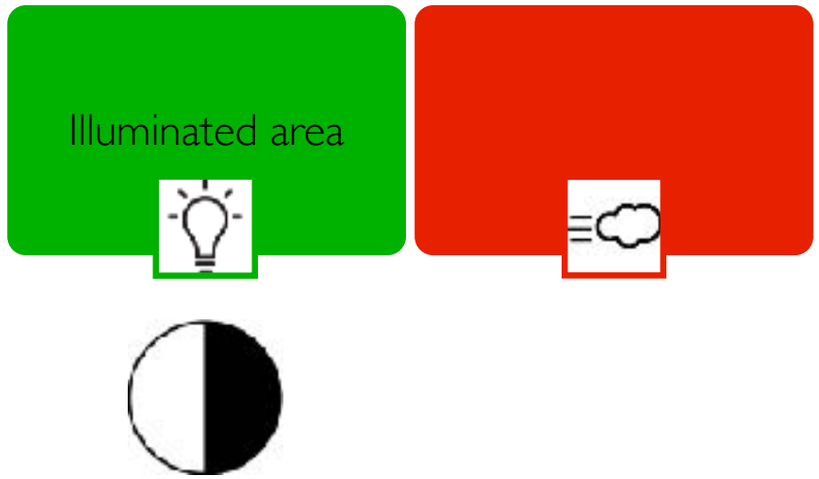
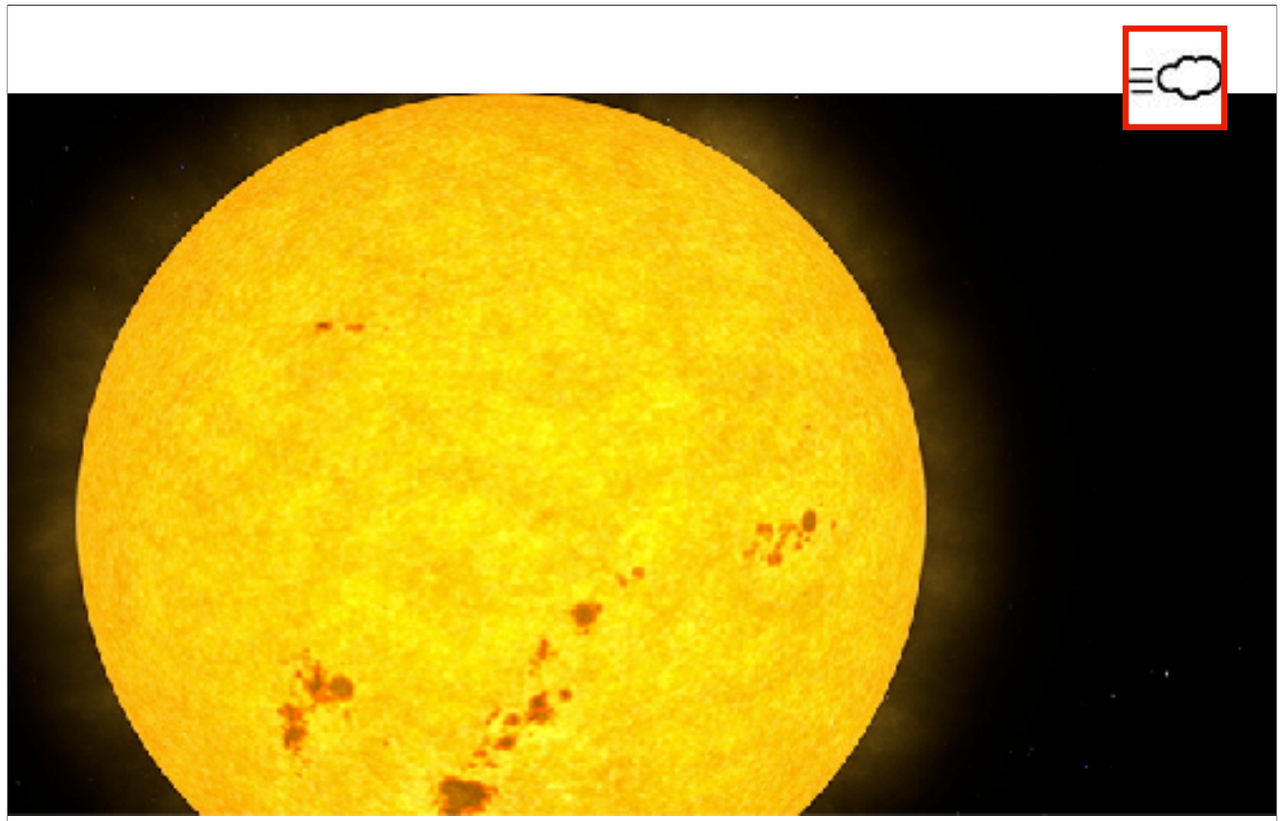
# DURATION




Day or more

# AREA OF IMPACT

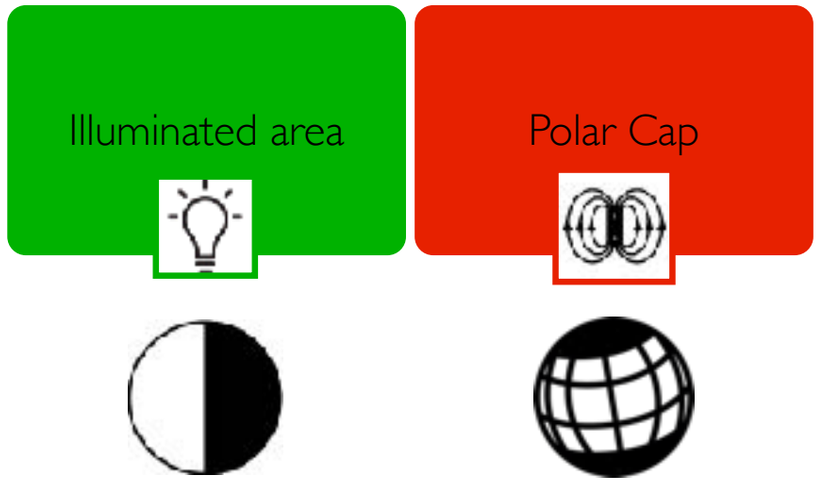




A CME that hits the Earths magnetosphere.
Precipitating electrons coming from the tail of the magnetosphere gyrate along the earths magnetic field and drop into the atmosphere in the auroral oval.

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

# AREA OF IMPACT

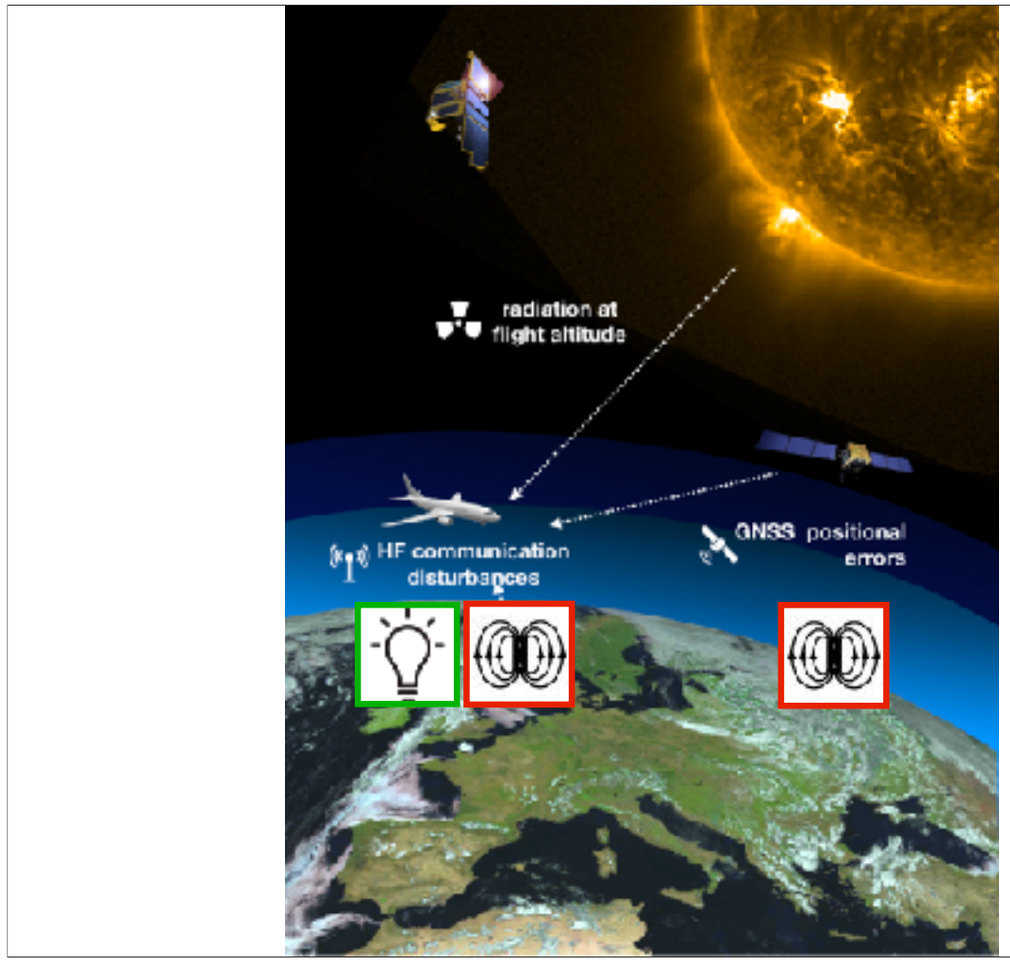





The magnetic field carried by the solar wind can reconnect on the day side with the magnetic field of Earth.
On the night side, magnetic reconnection between opposite magnetic field of the magnetosphere of Earth. (No solar magnetic field involved.)

The icon of the dipole represents the Earth dipolar field.

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

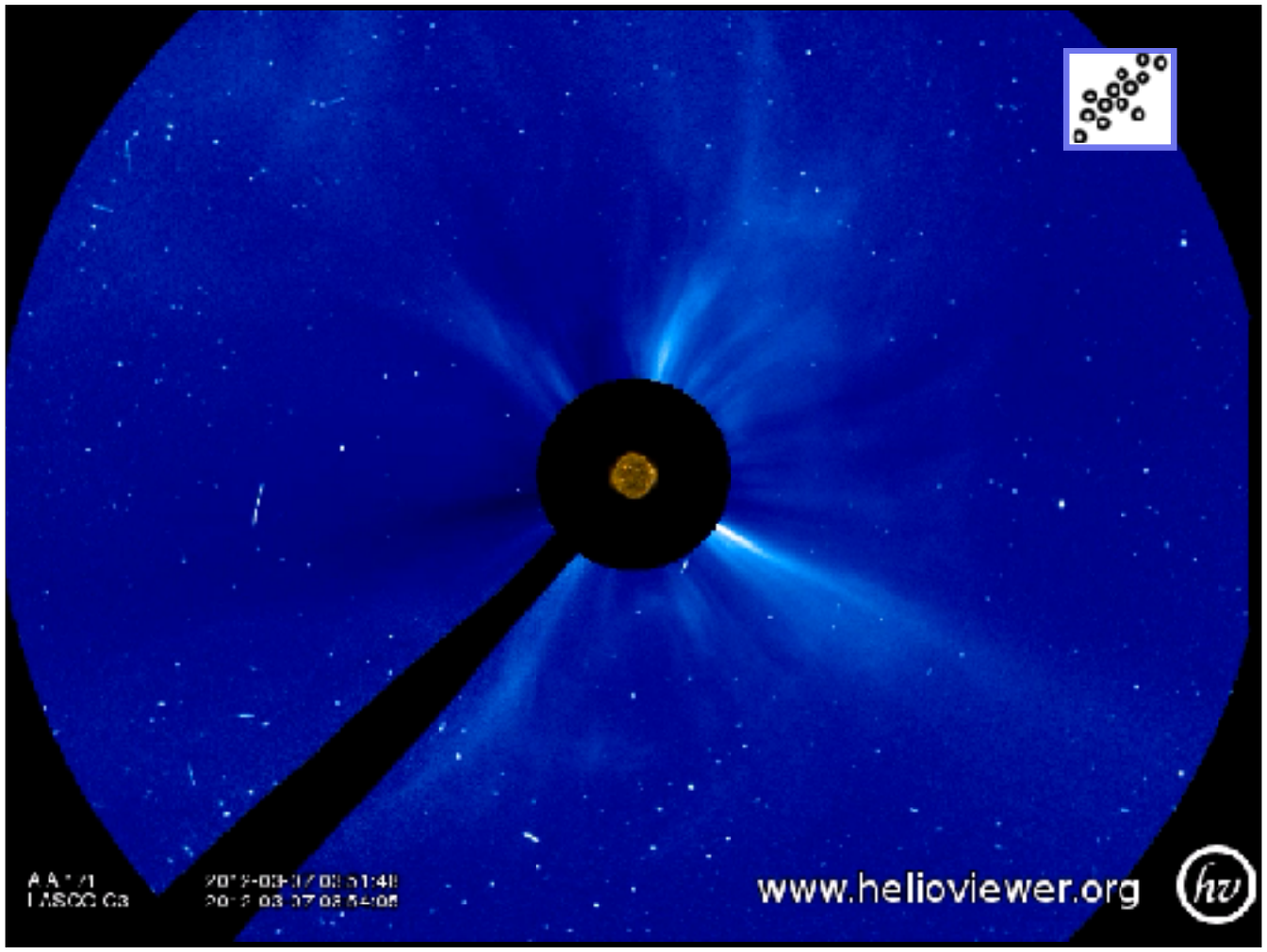



GNSS

- 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.



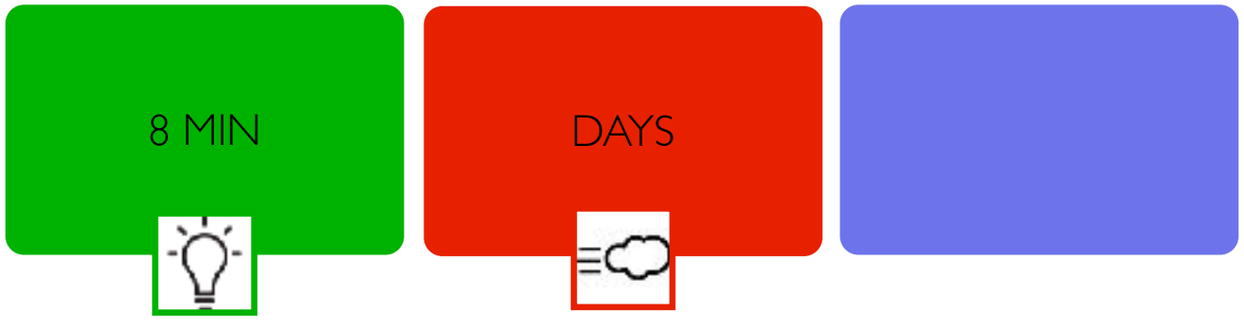

## Particle showers

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.)

## 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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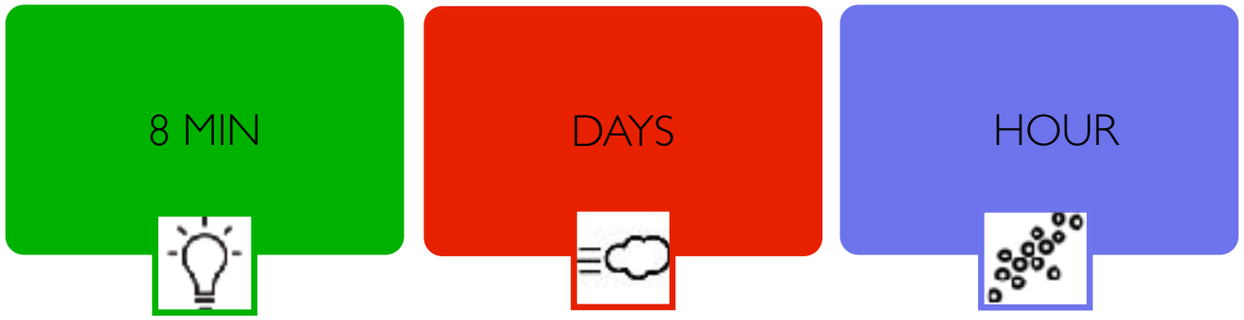
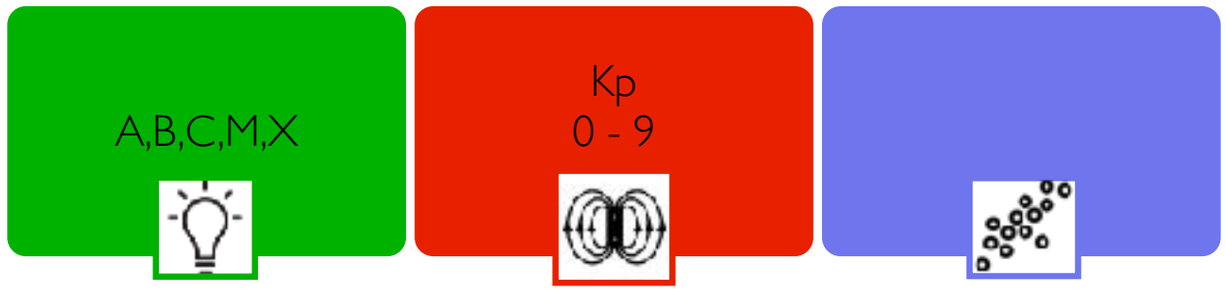


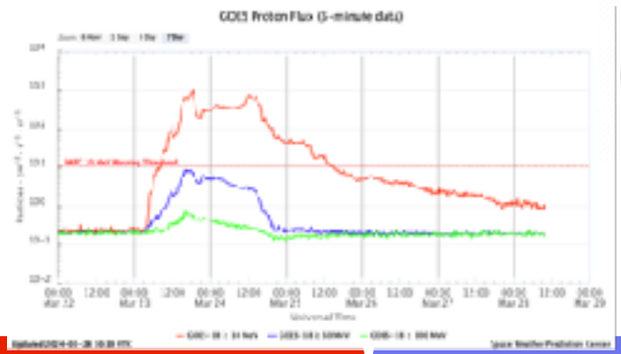
# STORM SCALE

**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



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

# DURATION


MINs to HOUR

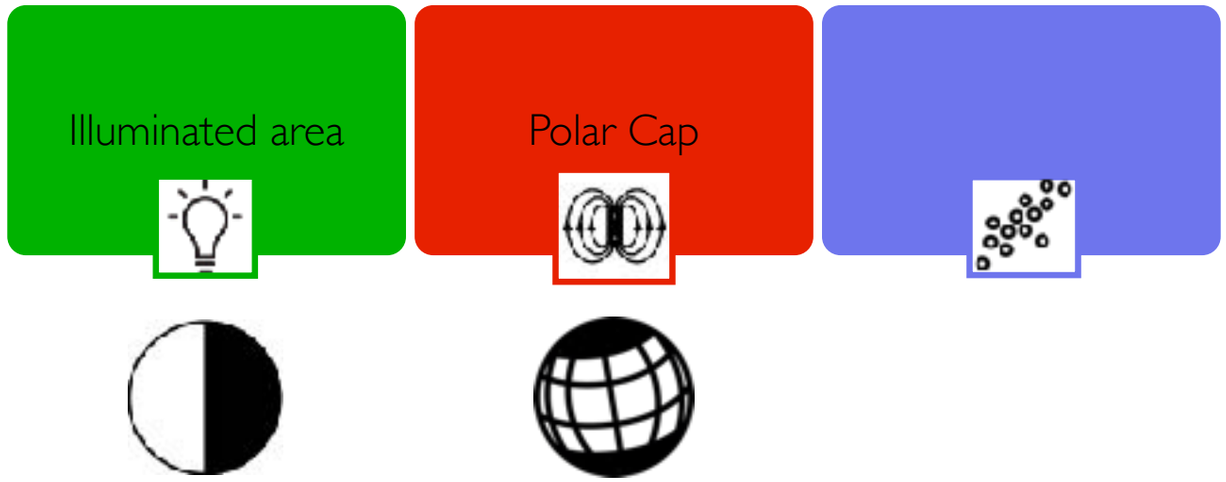
DAY+

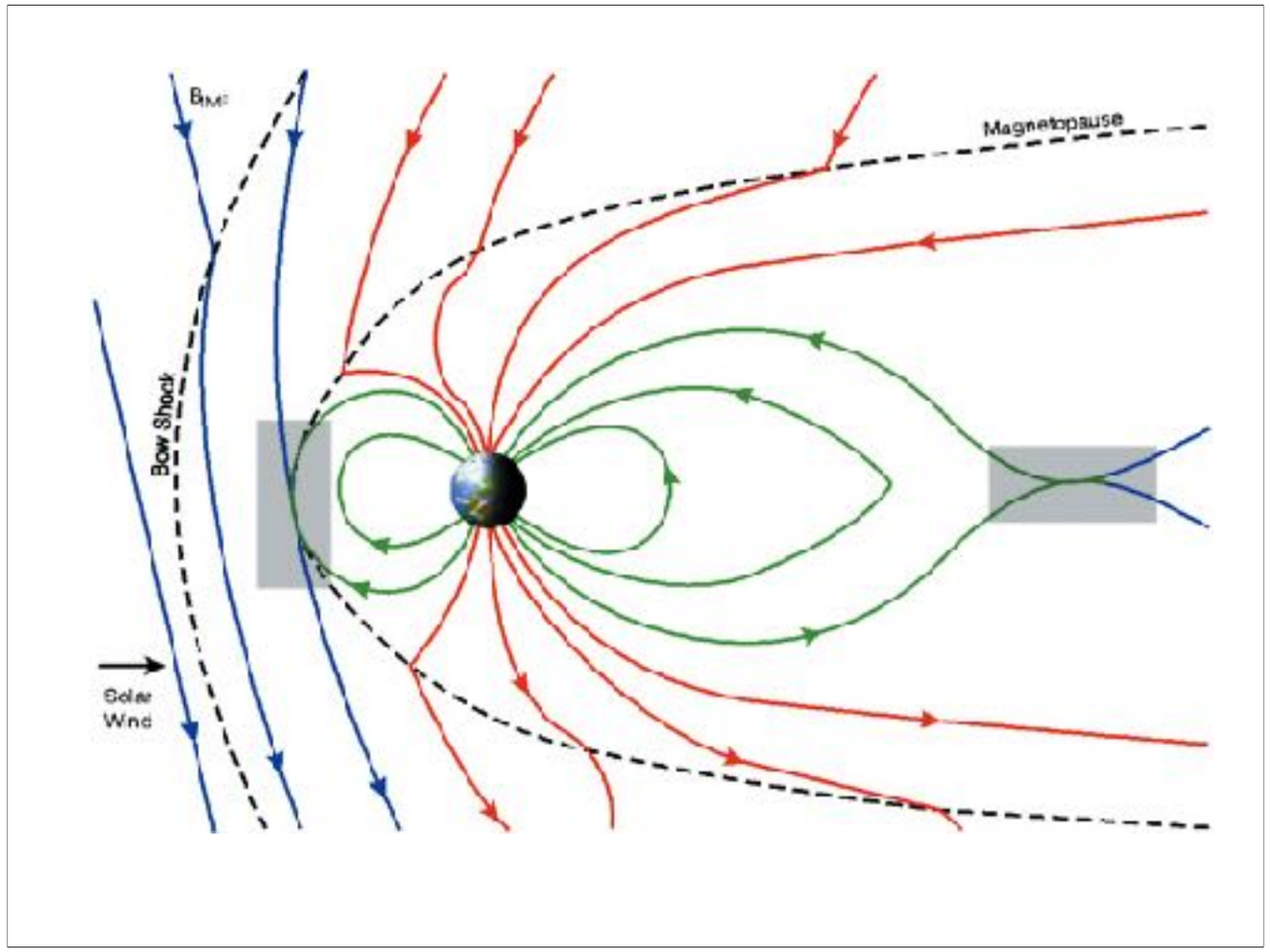
HOURS to DAYS



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

# AREA OF IMPACT



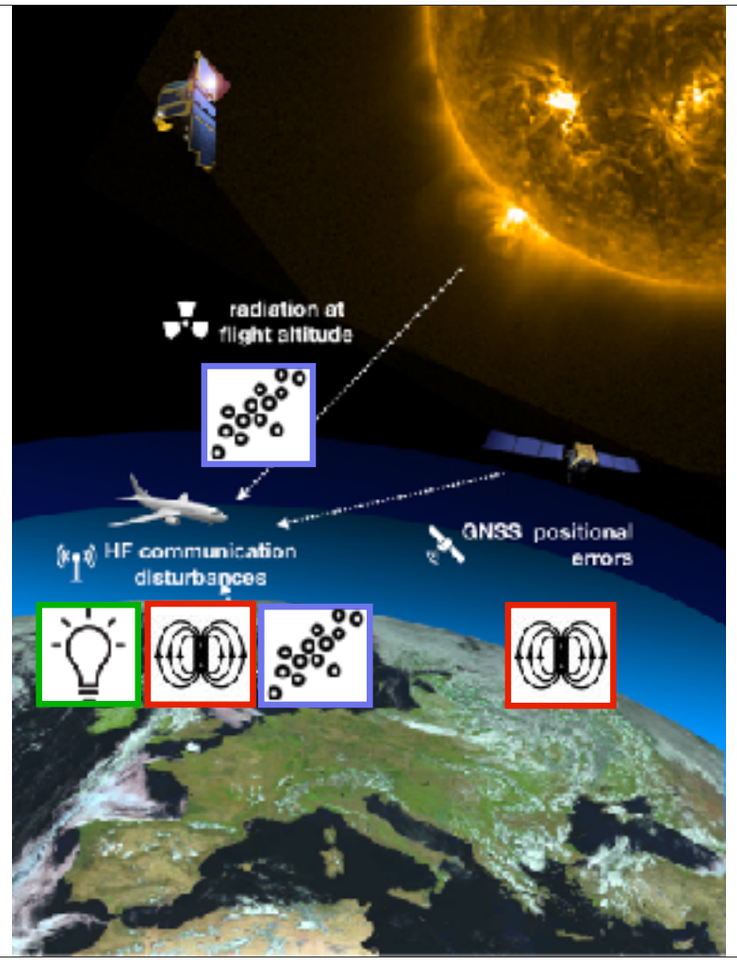



The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).

# AREA OF IMPACT




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




Impact
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.