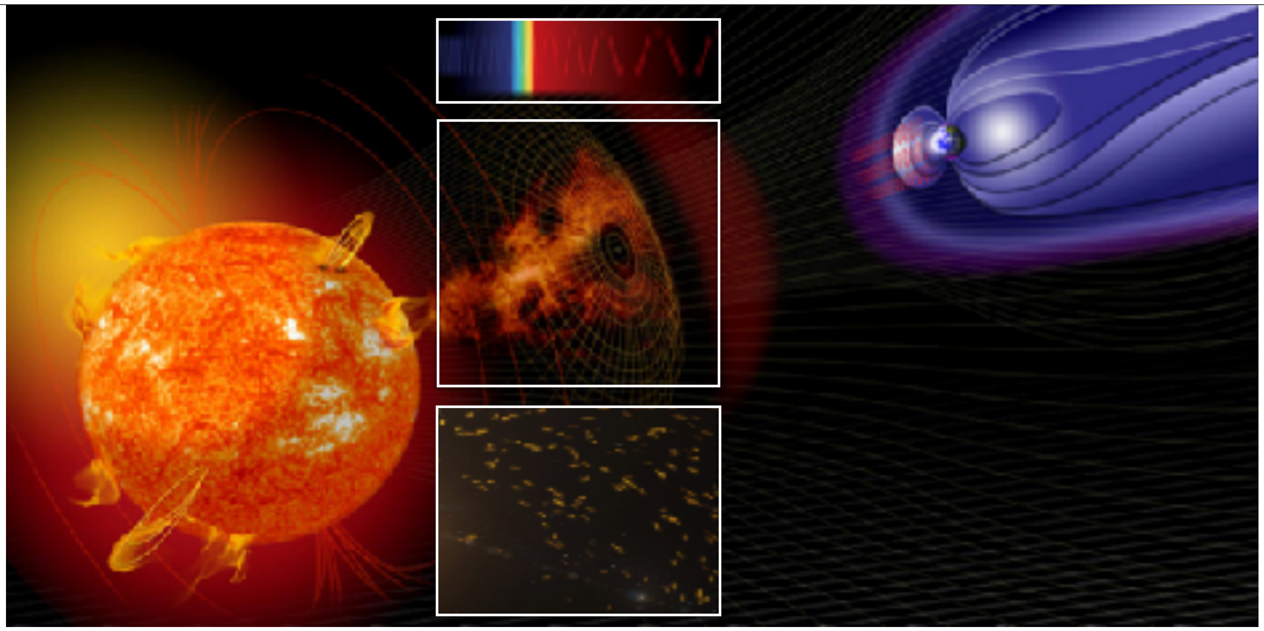


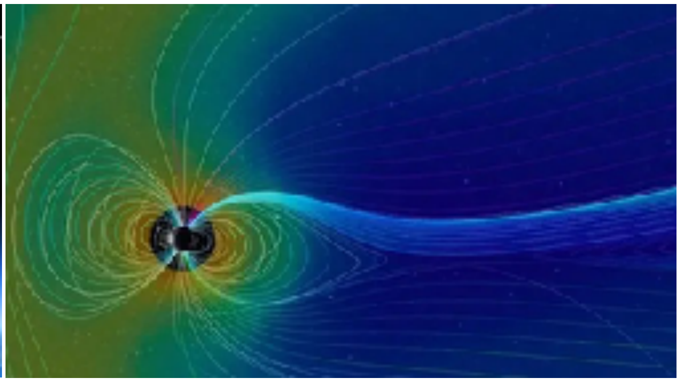
SPACE WEATHER

Introduction

Petra Vanlommel

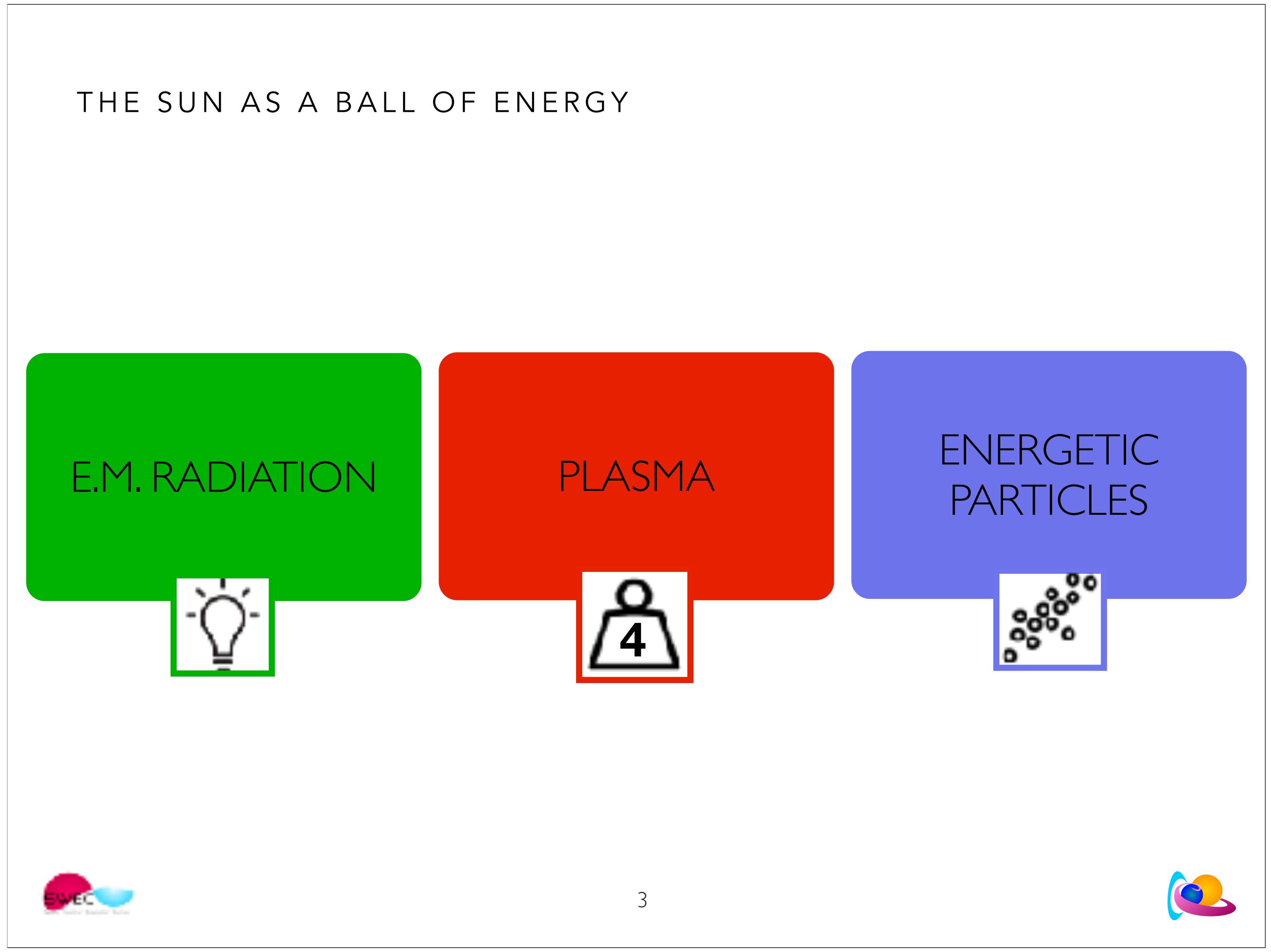
Space Weather

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



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

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



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

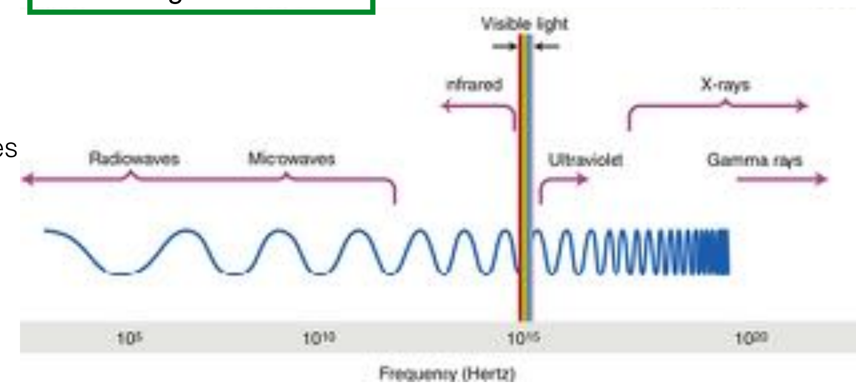
This energy is kept inside the Sun but also on its surface and in its atmosphere in magnetic structures like sunspots and magnetic loops, filaments or prominences ready to be released.

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

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

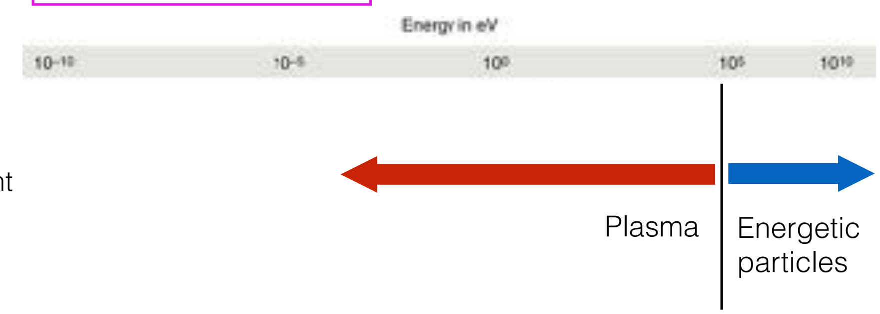
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



Particles

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



100 kEV

3 SPACE WEATHER PHENOMENA

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

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

LIGHT	WIND	PARTICLE RAIN

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.

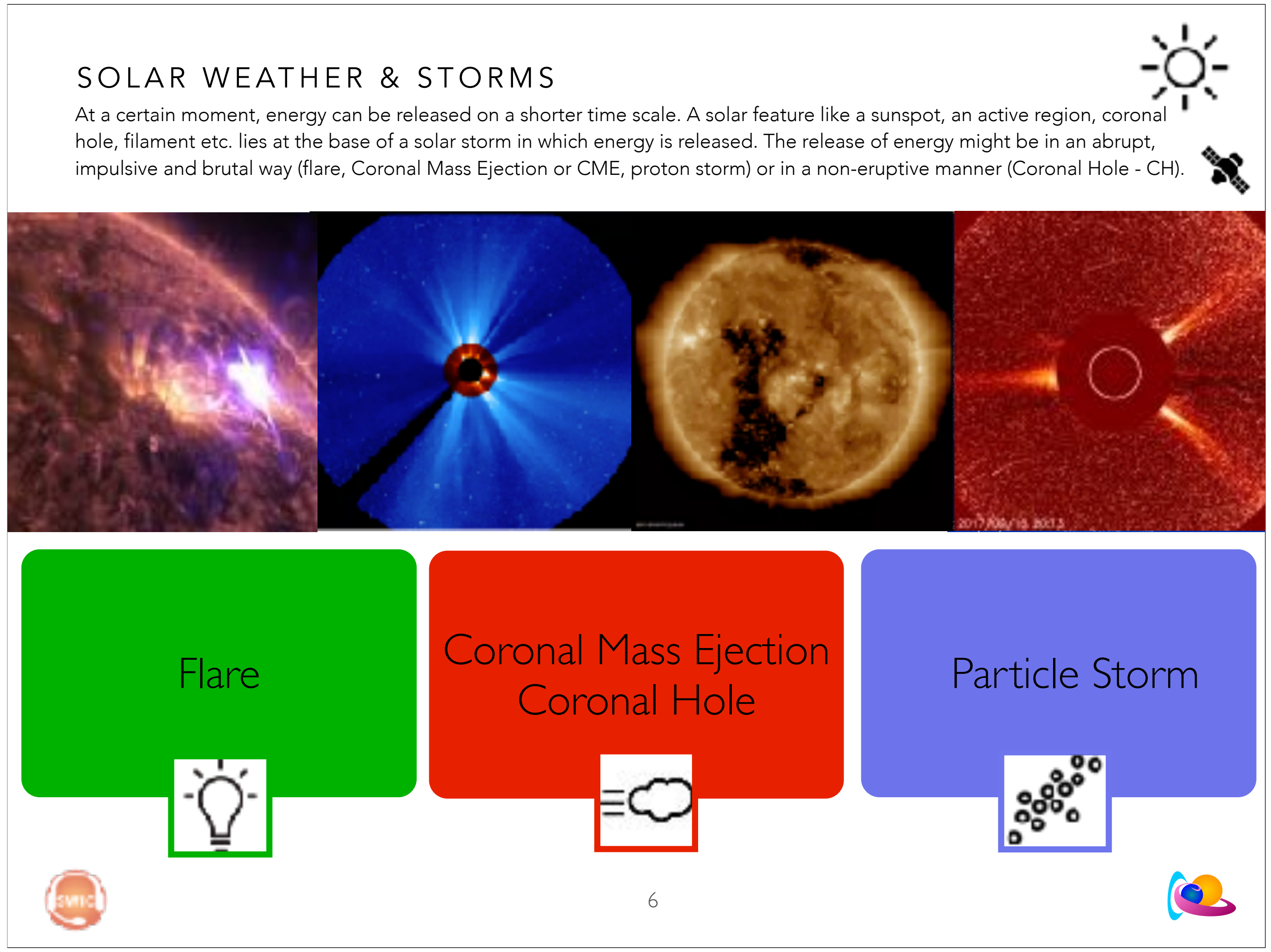
<100 kEV : plasma

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



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

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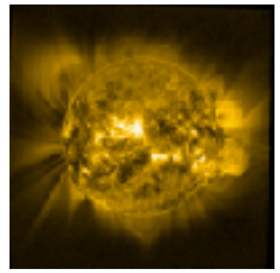
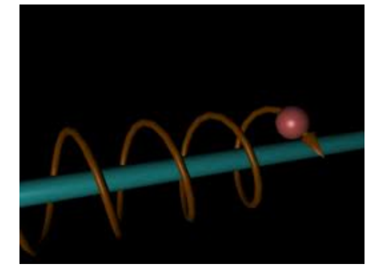
SOLAR SEASONS

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



PROBA2/SWAP



E.m. Radiation
Flares

Solar Wind
CME - CH

Solar Energetic
Particles

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

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

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

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

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

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

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

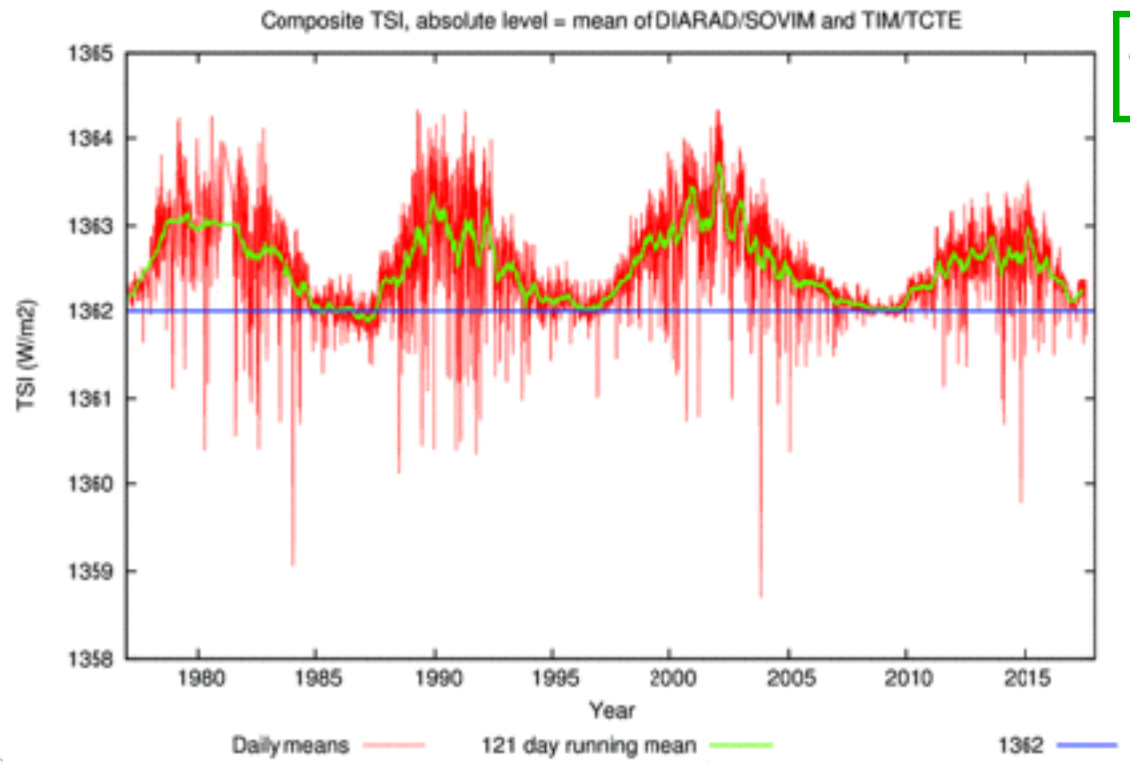
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you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

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

https://youtu.be/QYM2_ytkjQo

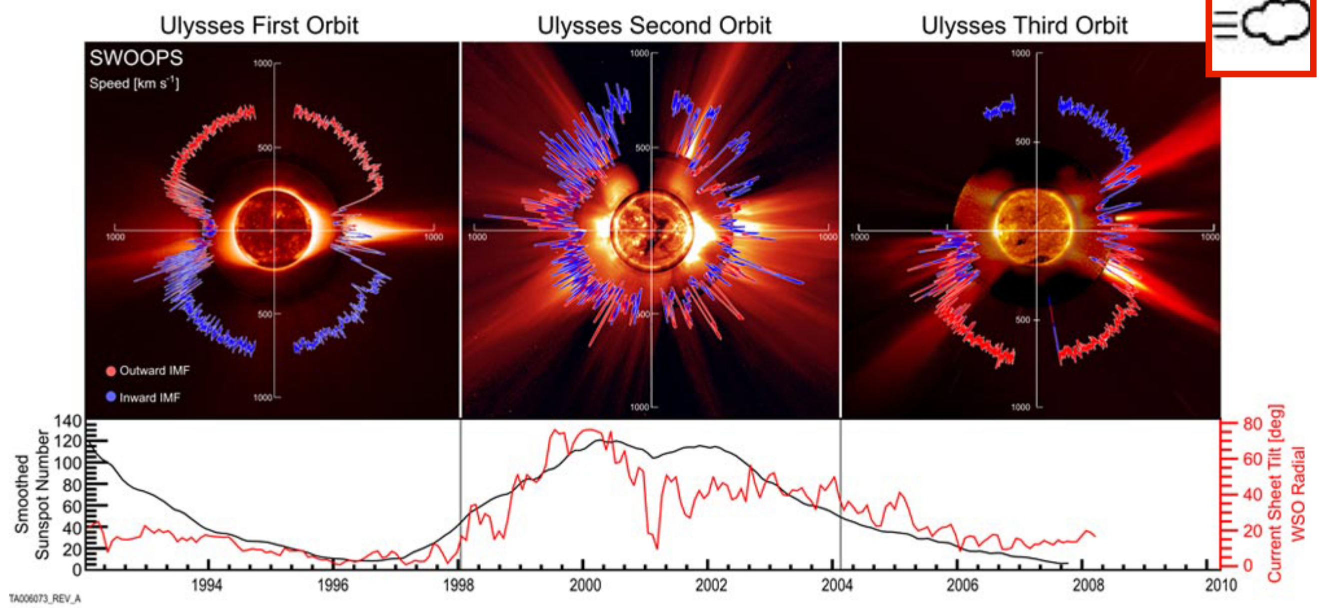
SEASONAL BEHAVIOUR OF LIGHT

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



SEASONAL BEHAVIOUR OF THE SOLAR WIND

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



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

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

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

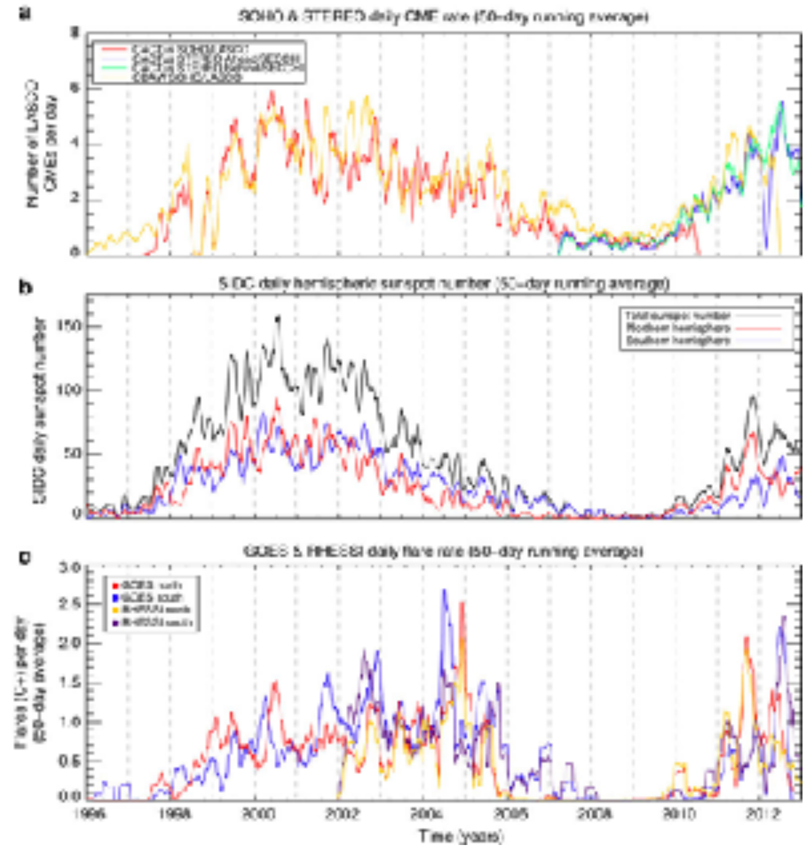
During solar maximum: global and local magnetic field mingle strongly. The solar wind looks more like a mess.

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

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

SEASONAL BEHAVIOUR OF SOLAR LIGHT & WIND STORMS

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



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

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

SEASONAL BEHAVIOUR OF SOLAR PARTICLE STORMS

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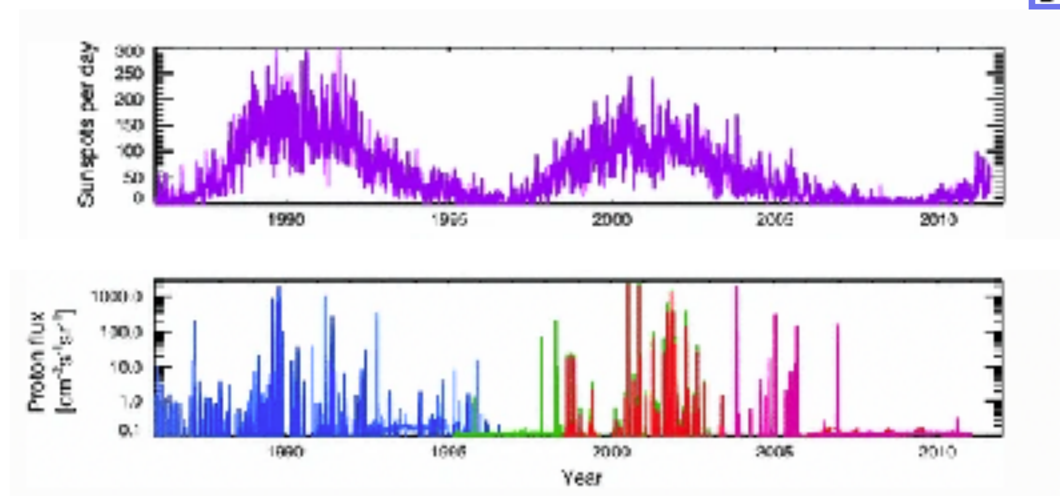
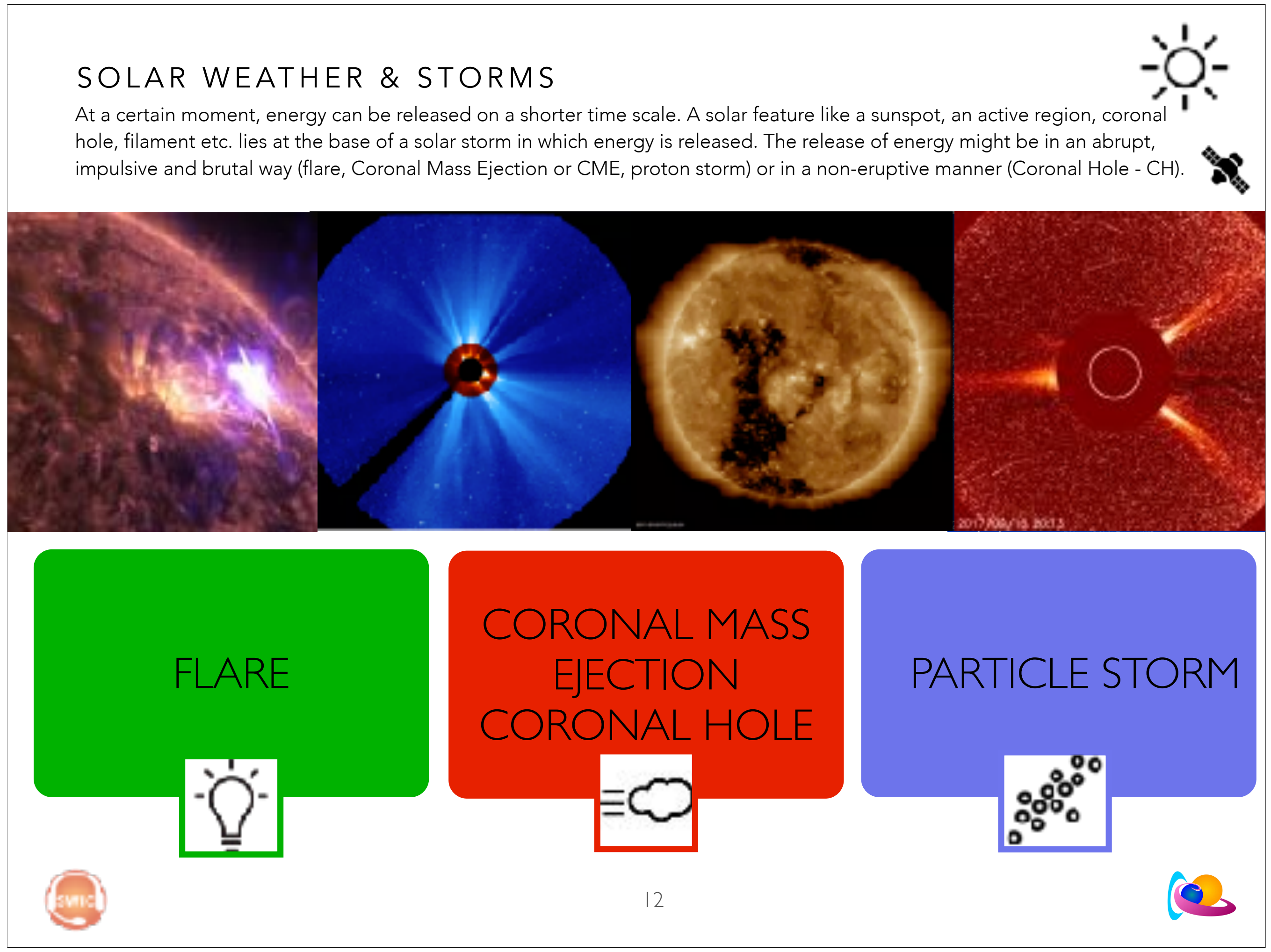


Less/More flares,CME's —> Less/More proton storms

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



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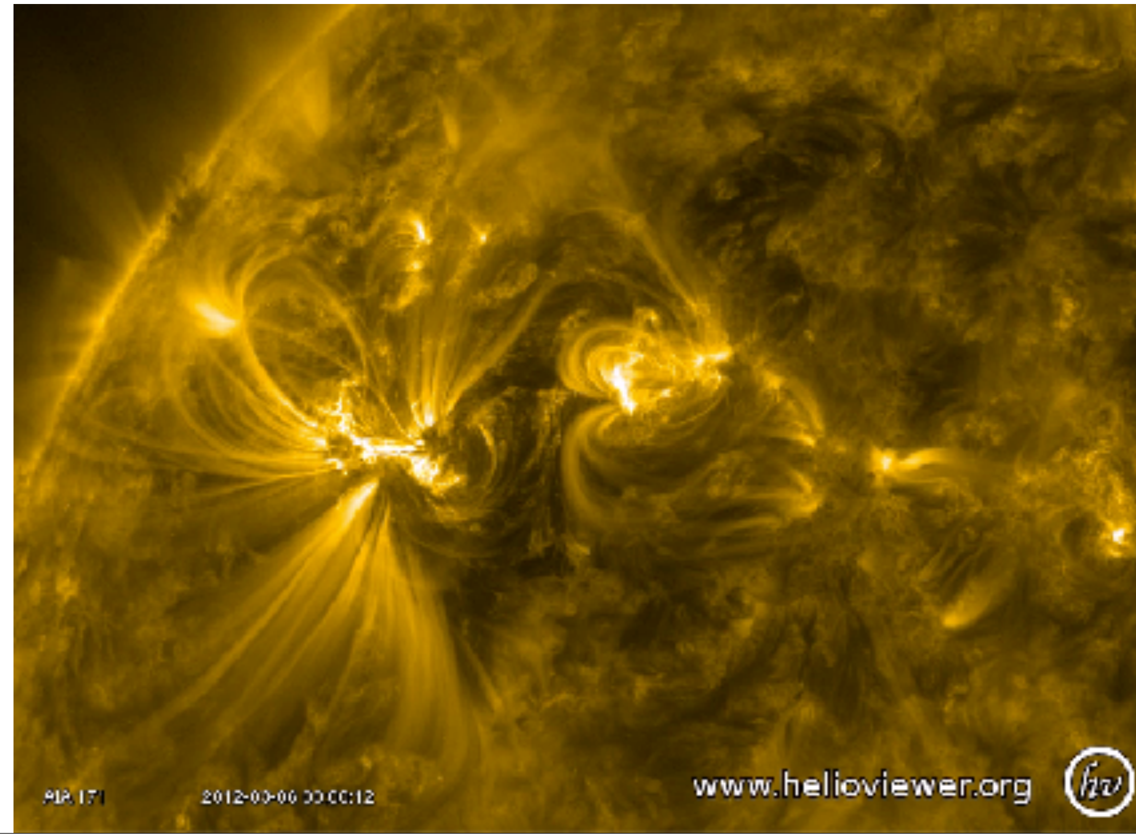
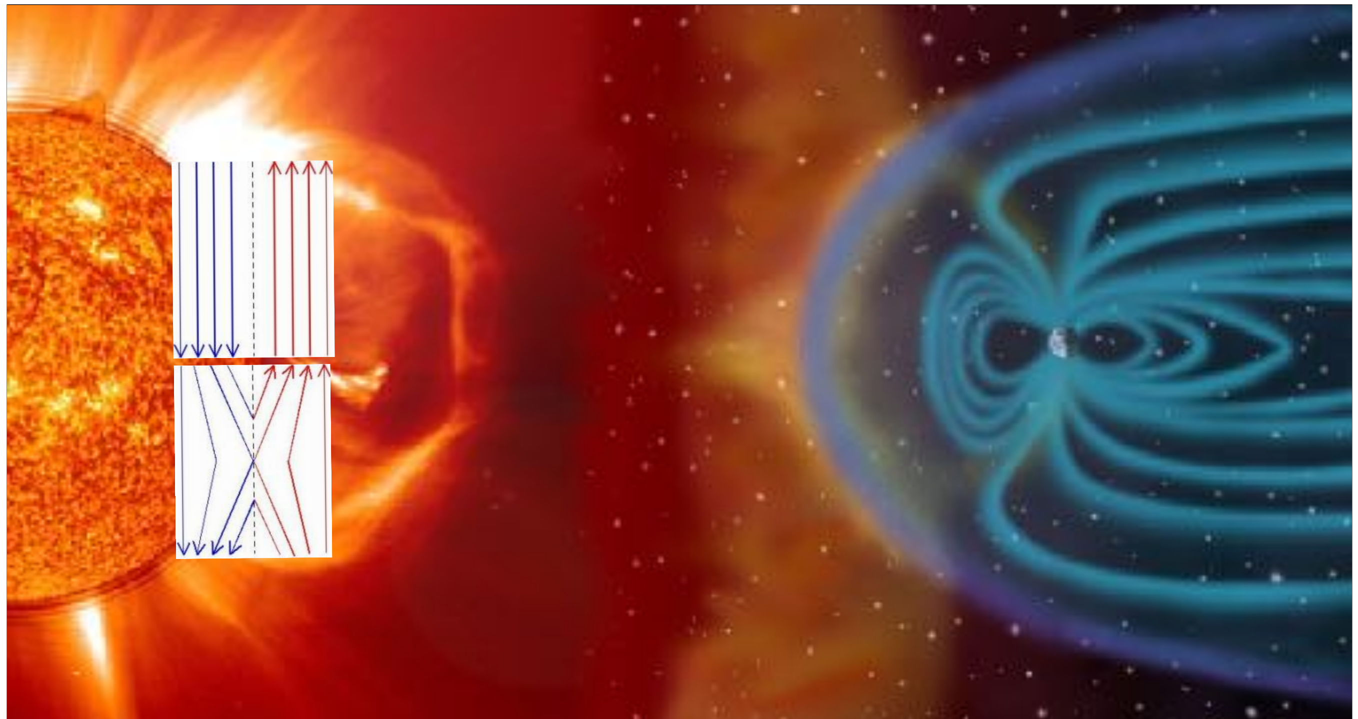
Transit time
Storm scale
duration
Area of impact

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.



MAGNETIC RECONNECTION

15

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.

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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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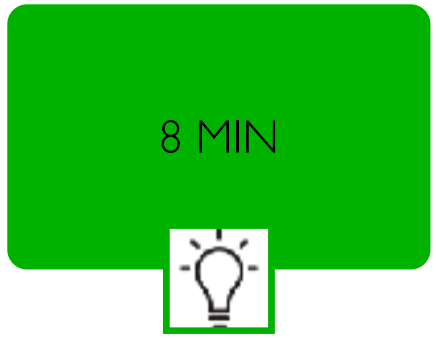

STORM SCALE

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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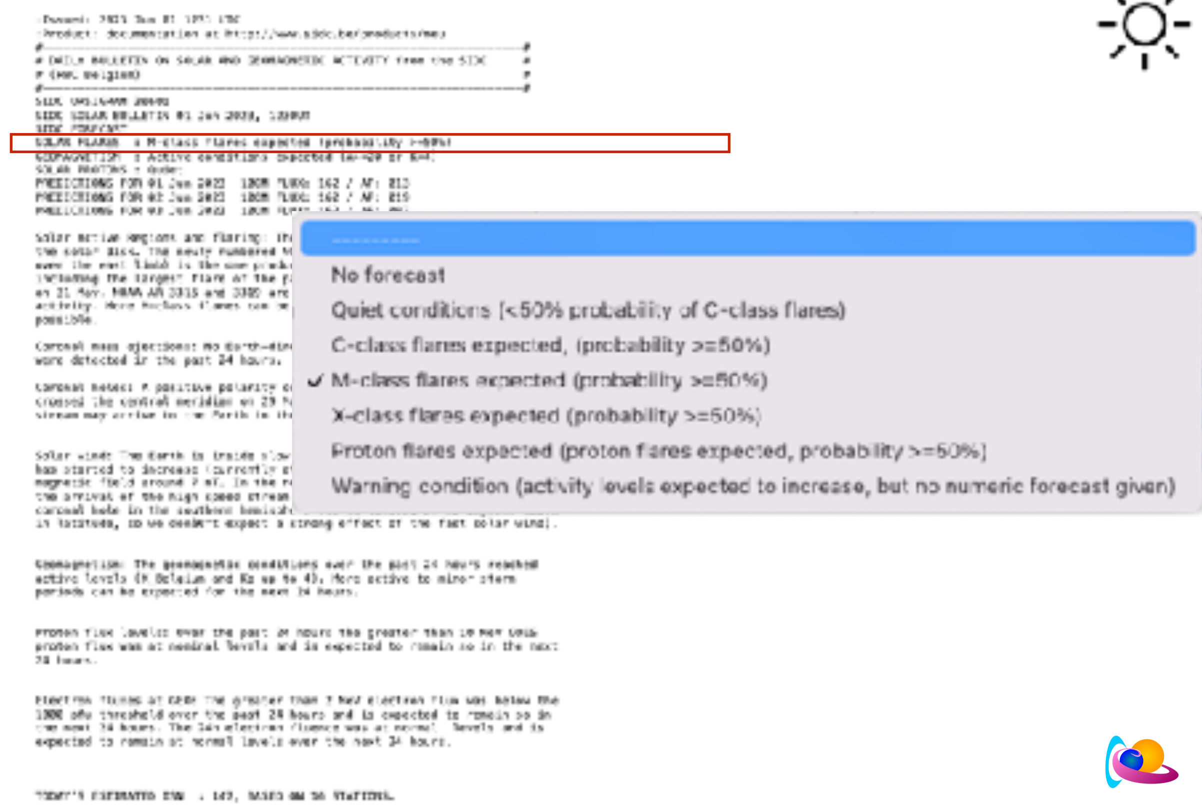
FLARE FORECAST

The sidc/STCE flare predictions refer to the full solar disk.



The Total flare forecast table is automatically computed based on your flare probabilities provided for every active region. Use your judgment to decide and eventually update the full disc probabilities.

Forecasts of categorical variables may be either categorical or probabilistic. The former is definitive – one of the categories is predicted to occur. A probabilistic forecast gives the estimated probability of occurrence of the categories of the variable. -> we do a probabilistic forecast of the flare categories

Flare predictions refer to the full disc but only in the **International Space Environment Service (ISES) categories**: classes according to 50% threshold exceeded for C, M or X flares

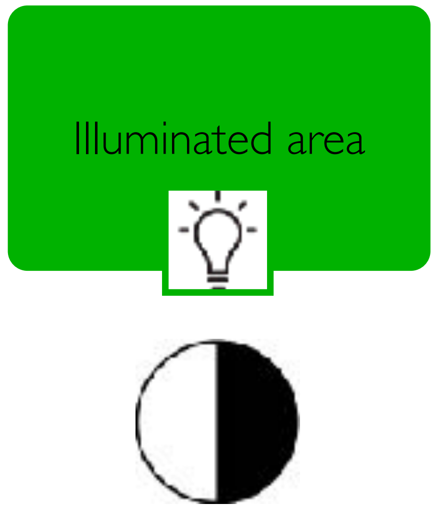
Based on the regional probabilities that are inserted, previweb shows the computed full disc probabilities for C, M, X flares once based on the Catania regions and once based on the NOAA regions. These probabilities are themselves not distributed in the URSIgram. They are intended as a guidance to the forecaster to be consistent with the individual region forecasts, when choosing the full disc prediction. The forecaster must use his/her judgement to decide and enter the full disc probabilities. He/she can take into account additional regions expected to appear from behind the East limb or developing on disc. Based on the full disc probabilities the forecaster chooses the applicable ISES category based on passing the 50 percent threshold for the C/M/X flares.

DURATION

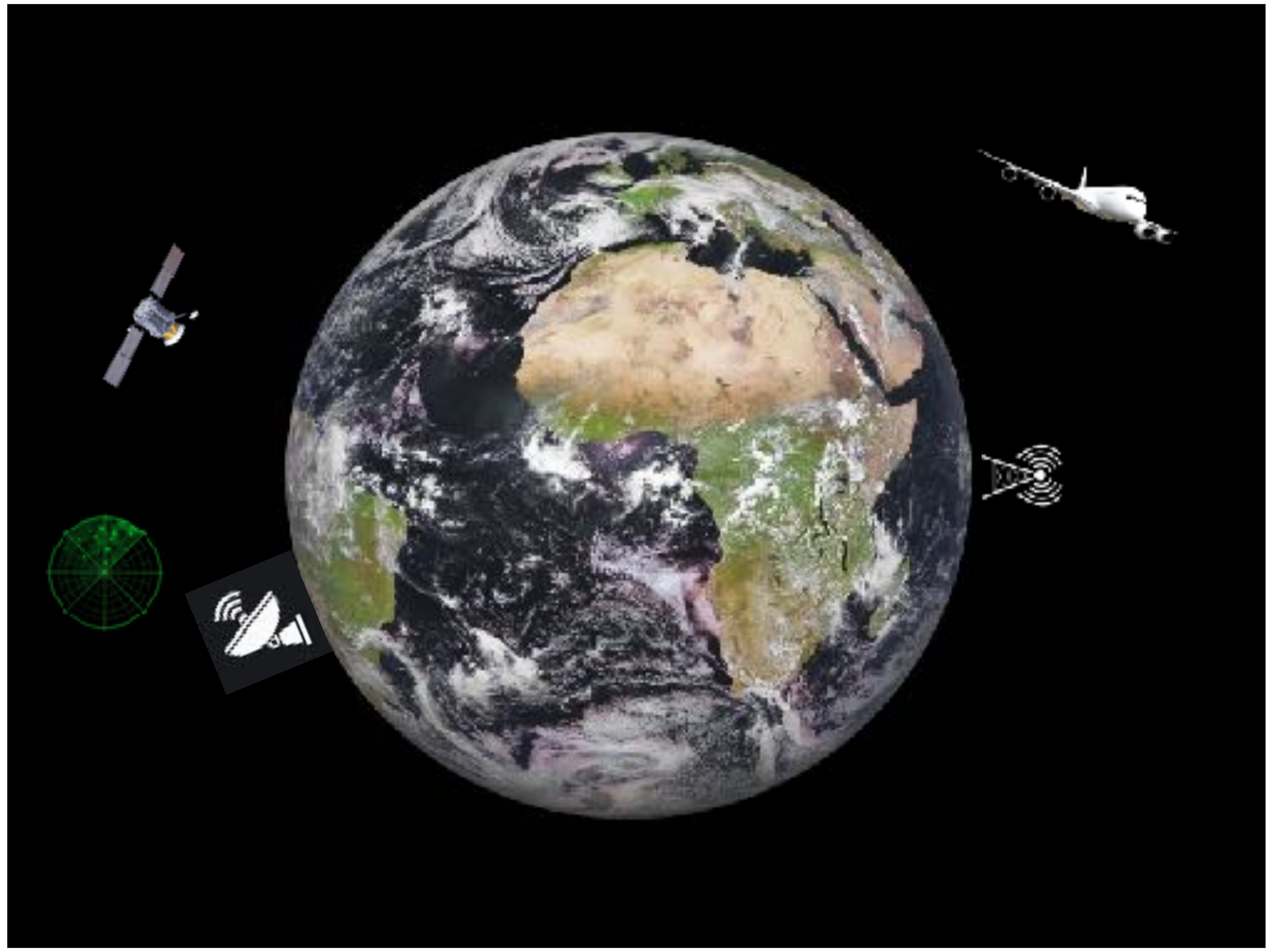
MINs to HOUR

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.



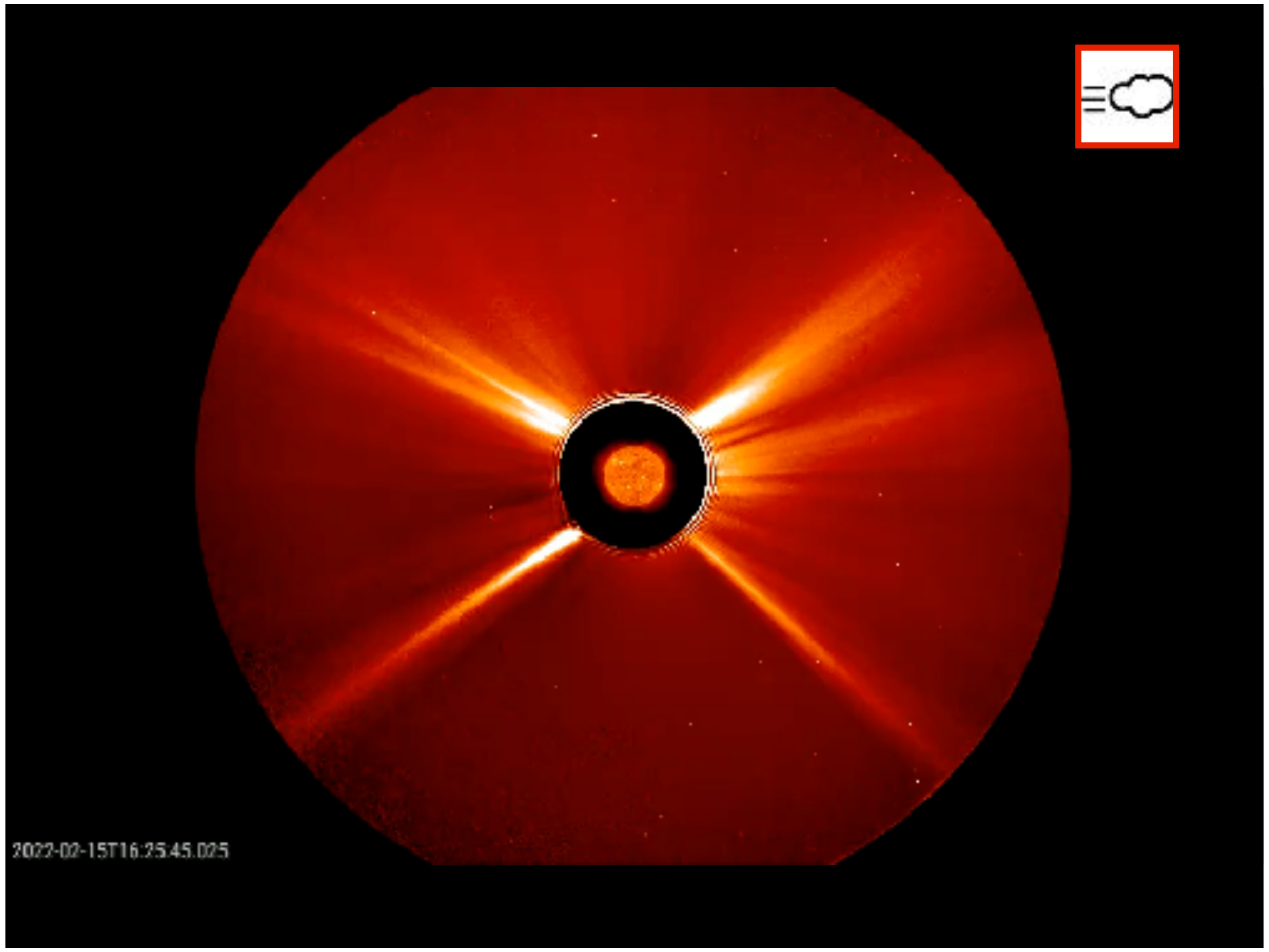
Satellite drag

SWF —> the ionising part of the flare

absorption of the HF radio signal in the D-layer of the ionosphere

Radio part of a flare (or SRB) can

- mislead radar systems —> phantom planes
- GNSS: Shout to a receiver such that the receiver can't hear the satellite signal anymore



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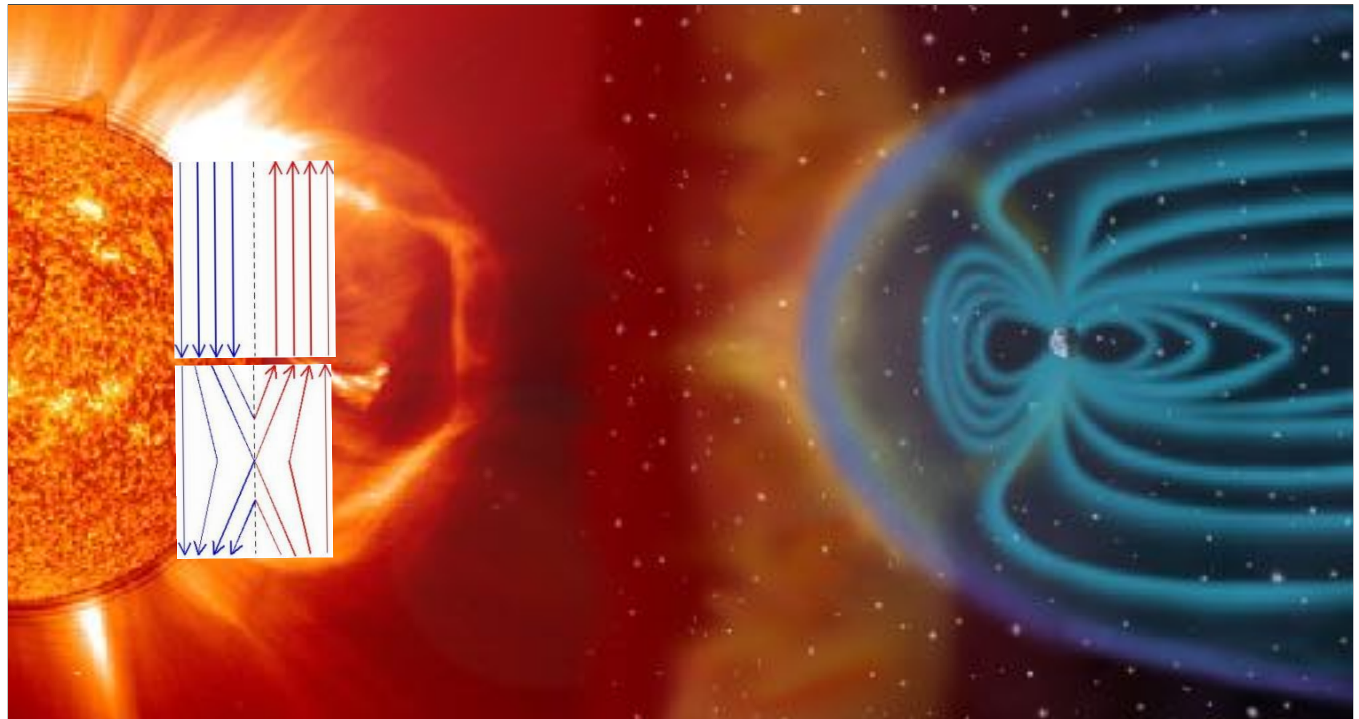

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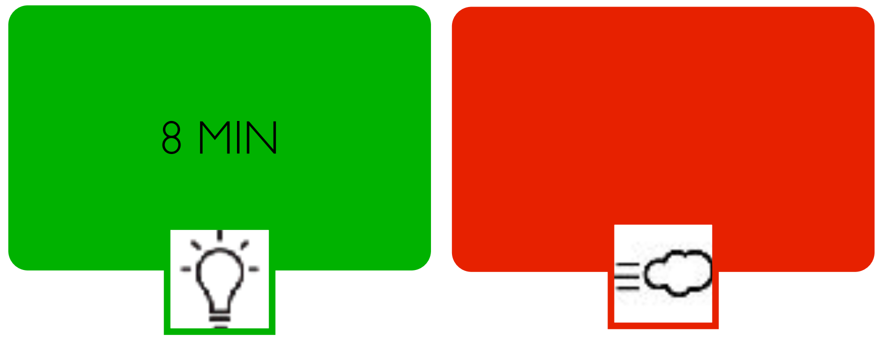
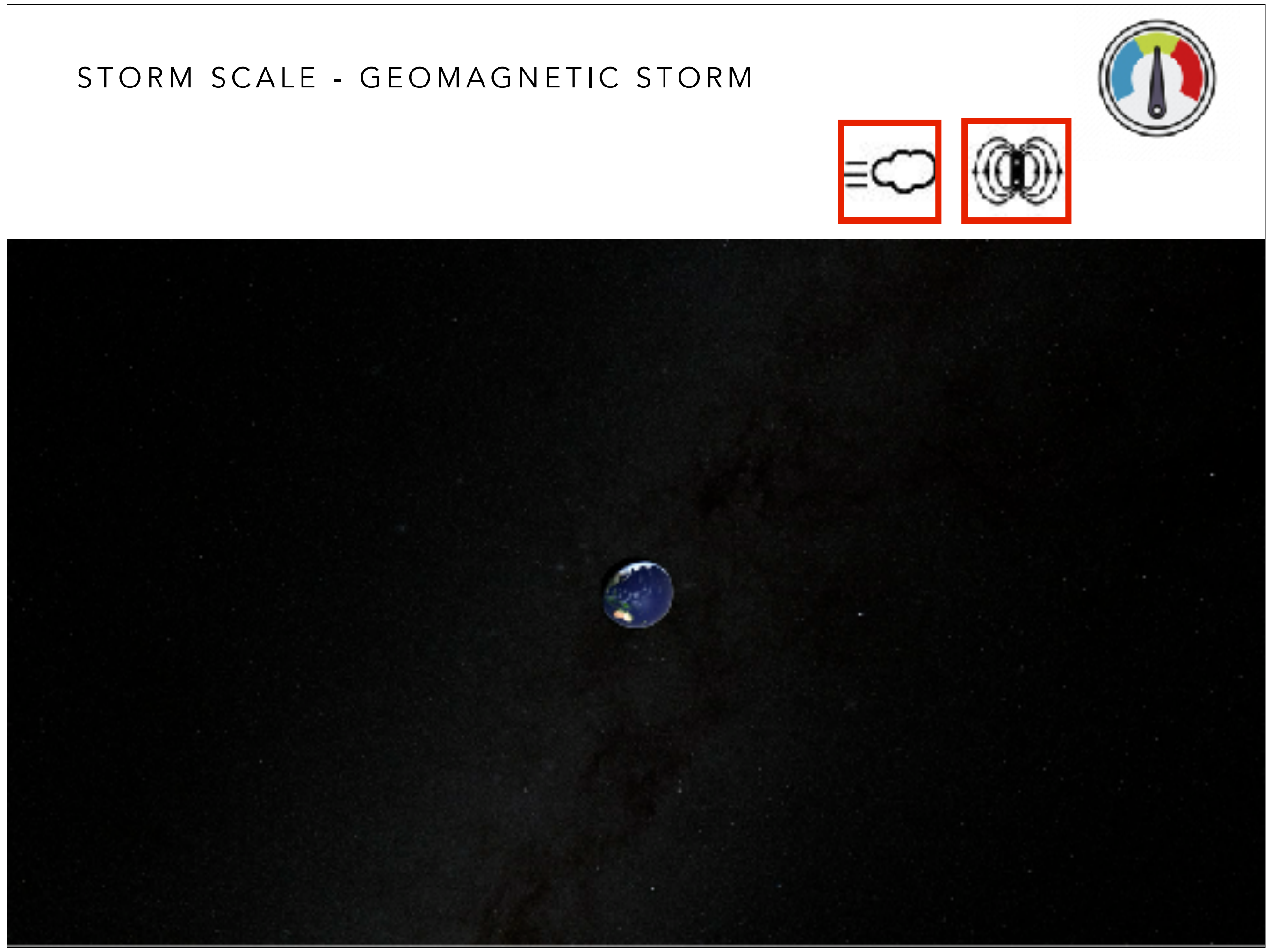


AU TRANSIT TIME

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, relativistic speeds.

8 MIN

DAYS

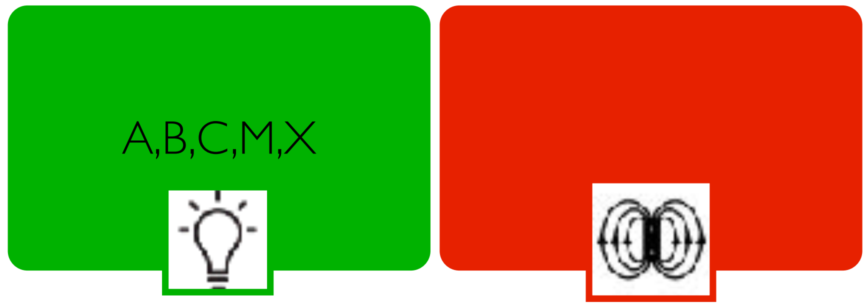


https://svs.gsfc.nasa.gov/5193/
This animation demonstrates the Earth's magnetosphere being hit by a geomagnetic storm on February 3, 2020, simulated by MAGE during the storm that caused the loss of commercial satellites.

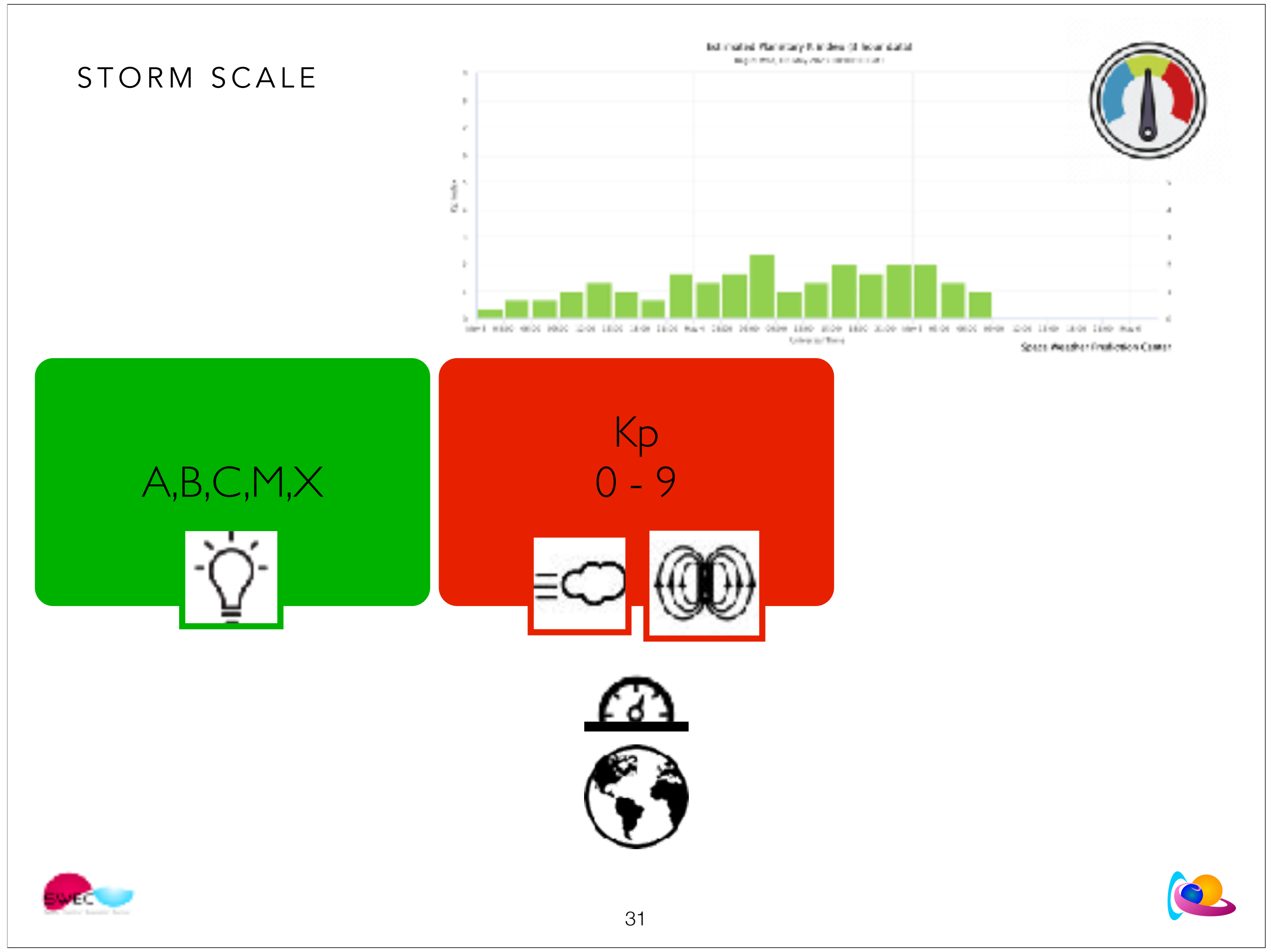
The green current density shows where magnetic current is strong. Lines tracing out the magnetic field are purple in regions of weaker magnetism, and orange-yellow where the magnetic field is strongest. Blue tracers in the velocity field represent the solar wind, and they have been calibrated to appear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

STORM SCALE

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



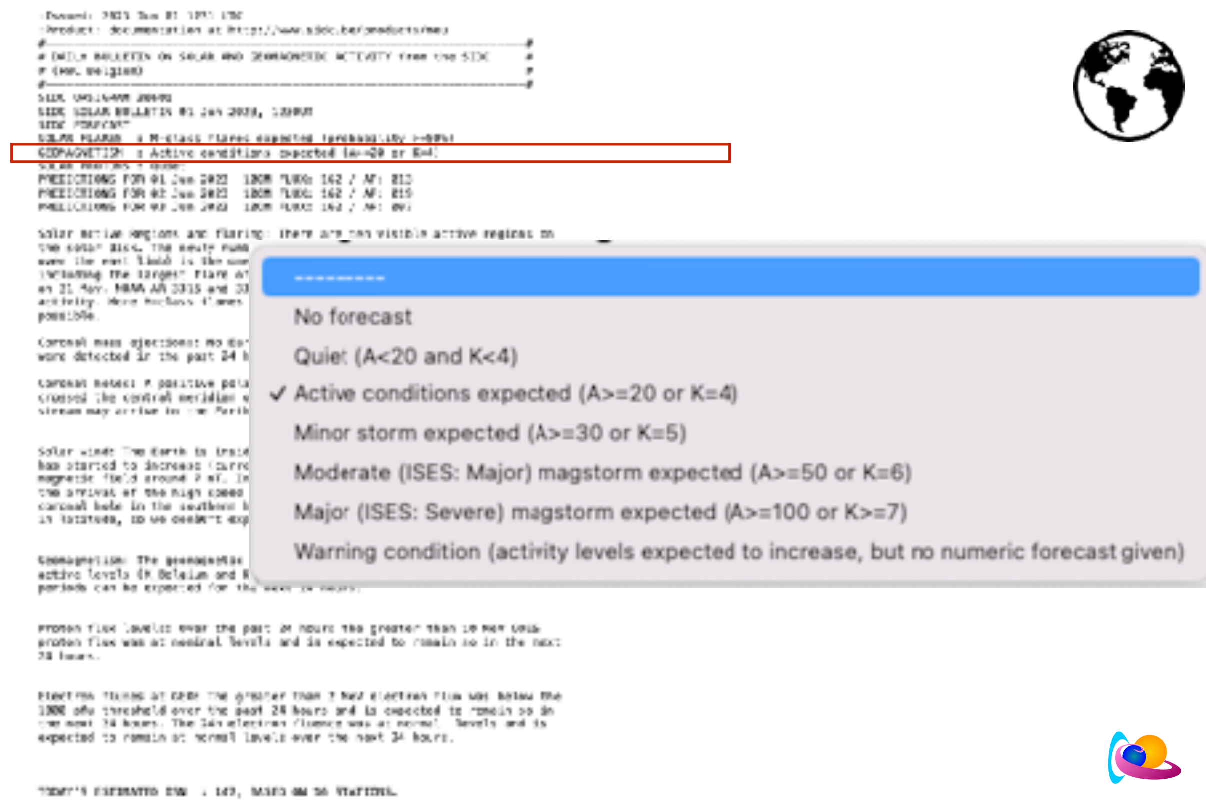
The Kp index is an index that quantifies the disturbance of the magnetic field of Earth. It ranges between 0 and 9, with 0 no disturbance and 9 an extreme disturbance.



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.

GEOMAGNETISM

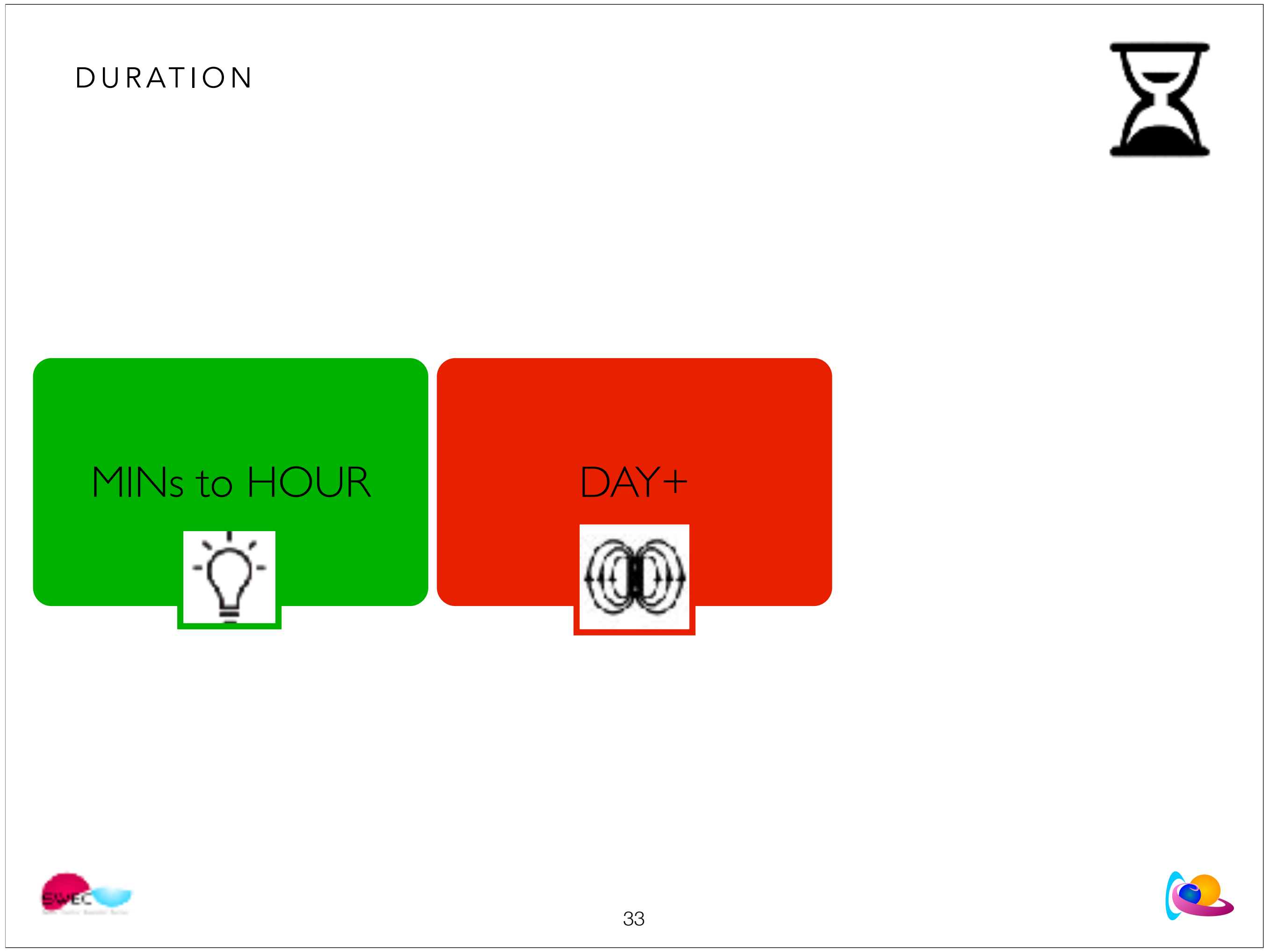
A K-index can be translated in an equivalent a-index value. The average of the a-indices over a day is called the A-index. Since K-index values are interpreted locally, the computed A-index is also local.



Careful!: The ISES scales are based on thresholds both in A-index and K-index values while one is a daily value and the other a 3 hourly value. This is ambiguous.

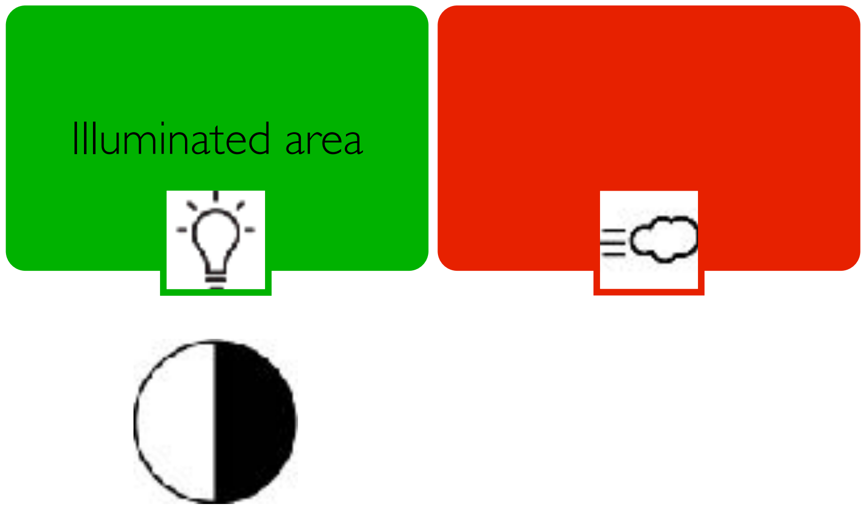
ak index - The local K index is a quasi-logaritmic index, and as such averages cannot be taken. This poses a problem when one wants to express geomagnetic activity over e.g. a day or a month. To this aim, a 3-hourly "equivalent amplitude" index of local geomagnetic activity was established, with "ak" related to the 3-hourly K index according to the scale underneath

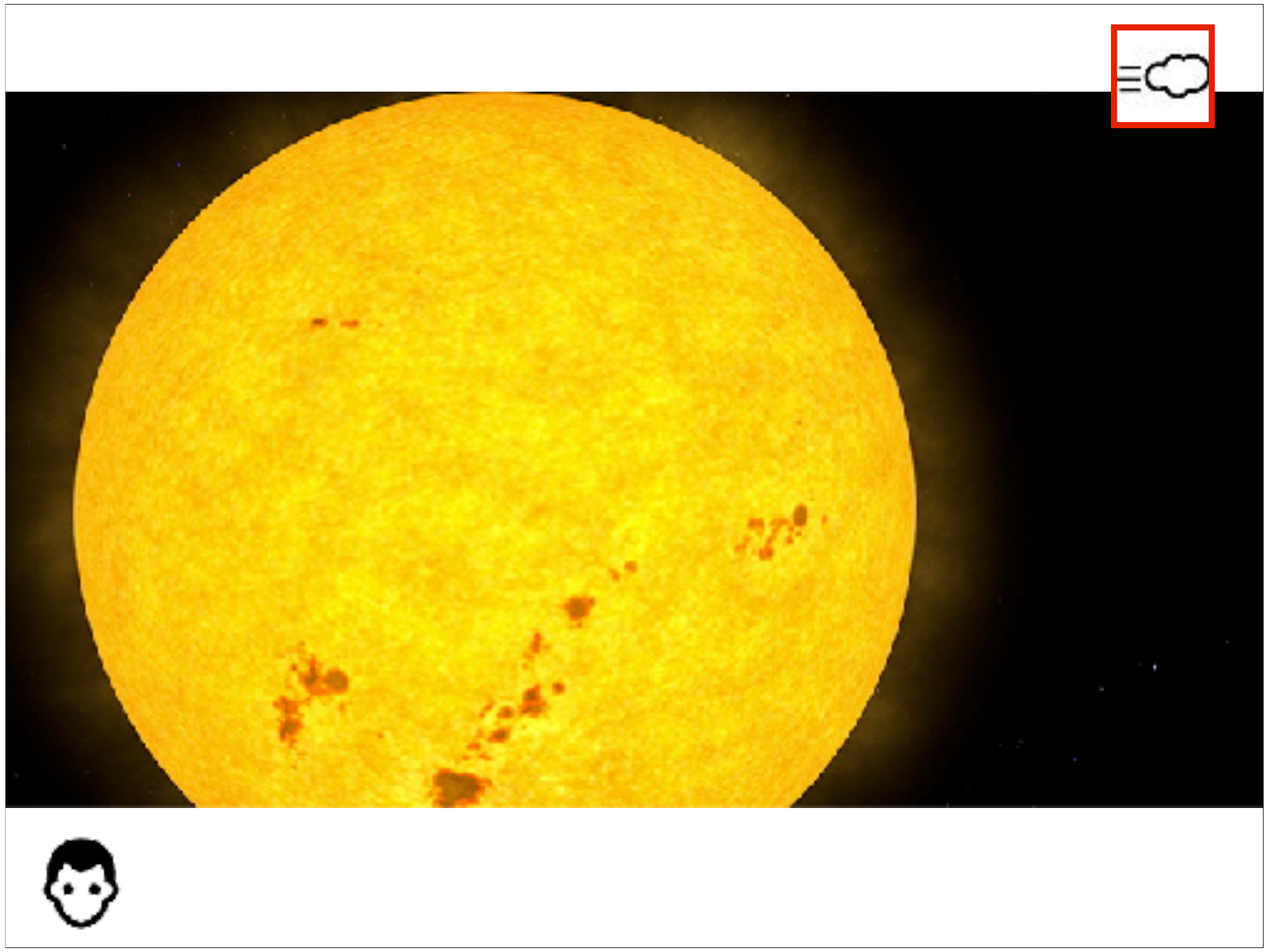
Ak index - The Ak index for a station "k" is simply the average of the eight ak indices for that station for the UT day. The subscript "k" used on the Ak refers to the individual station, e.g. pending the context, AD, ADO, ADOUR, ... may all refer to the Dourbes A-index.



Day or more

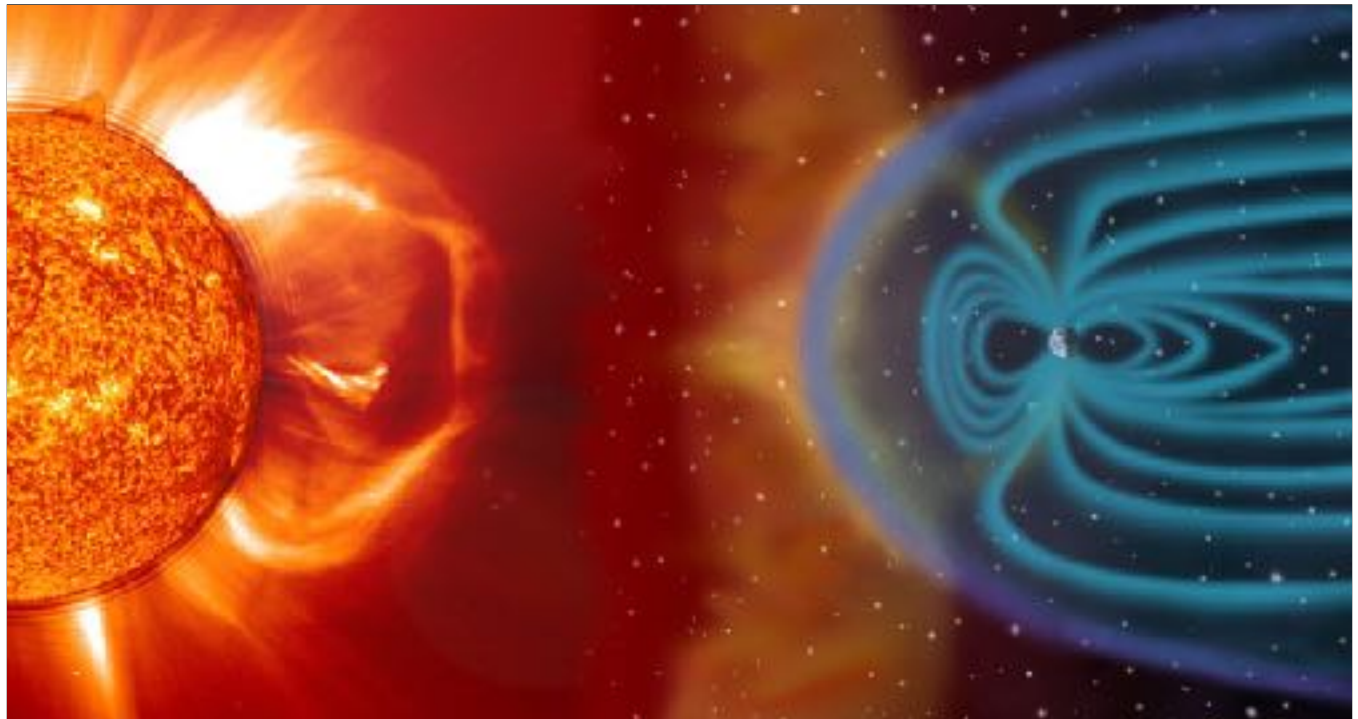
AREA OF IMPACT





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.



RECONNECTION

The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.

This is the earths magnetosphere. The sun is somewhere far away in the right top corner.
The earth is a giant dipole - similar as the sun. Except, the solar magnetic dipole field reverses every 11 year. The Earths magnetic poles don't. They are already for ages like this.
The part of the earths dipole facing the sun/solar wind is pushed more together, while the part behind the earth is stretched and forms a tail. In front of the magnetic structure, you have a shock.

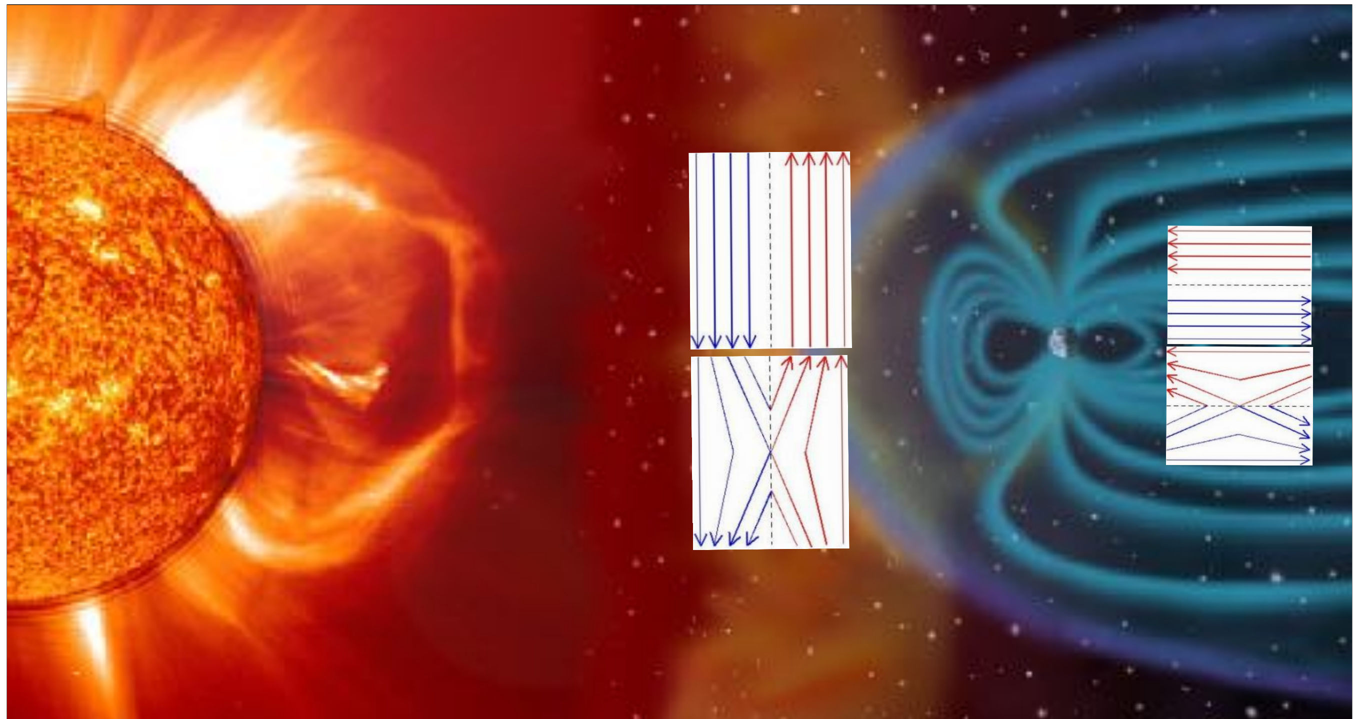
This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiate are slower compared to the speed of the boat. The boat is super-water wave.
When a plane is super-sonic, there is also a shock in front of it. The pressure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

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

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

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

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



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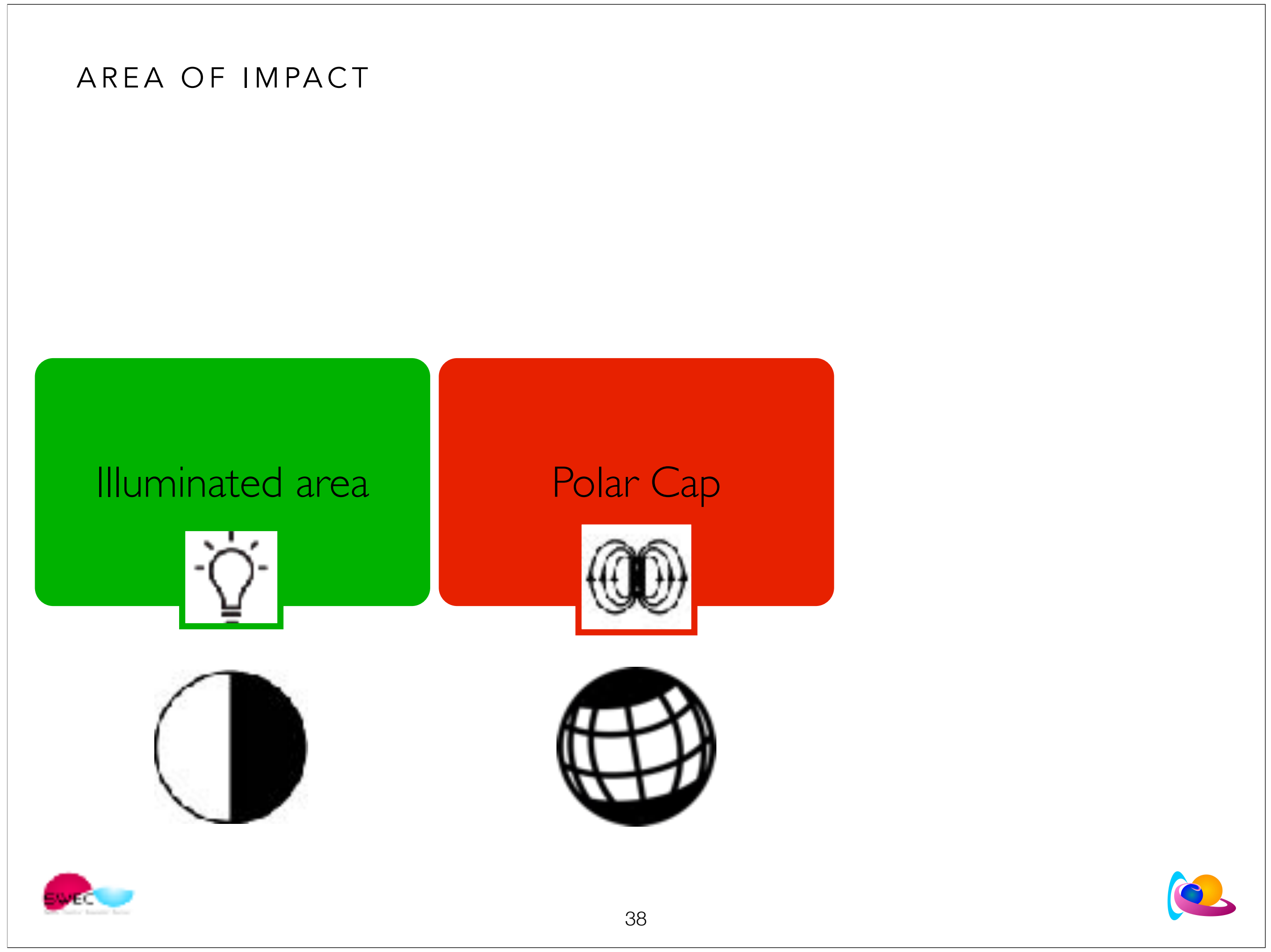
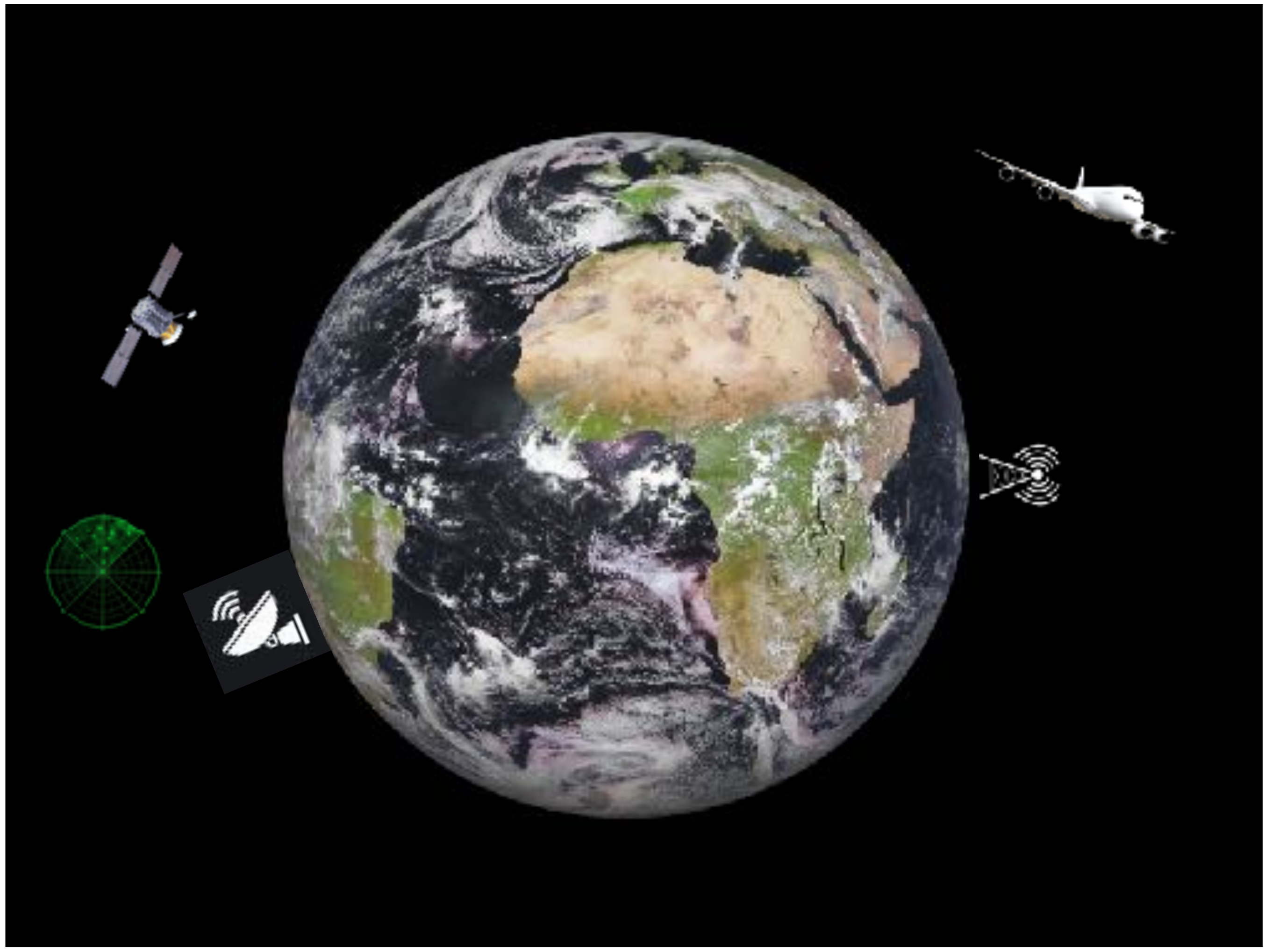


The magnetic field carried by the solar wind can reconnect on the day side with the magnetic field of Earth.
On the night side, magnetic reconnection between opposite magnetic field of the magnetosphere of Earth. (No solar magnetic field involved.)

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.

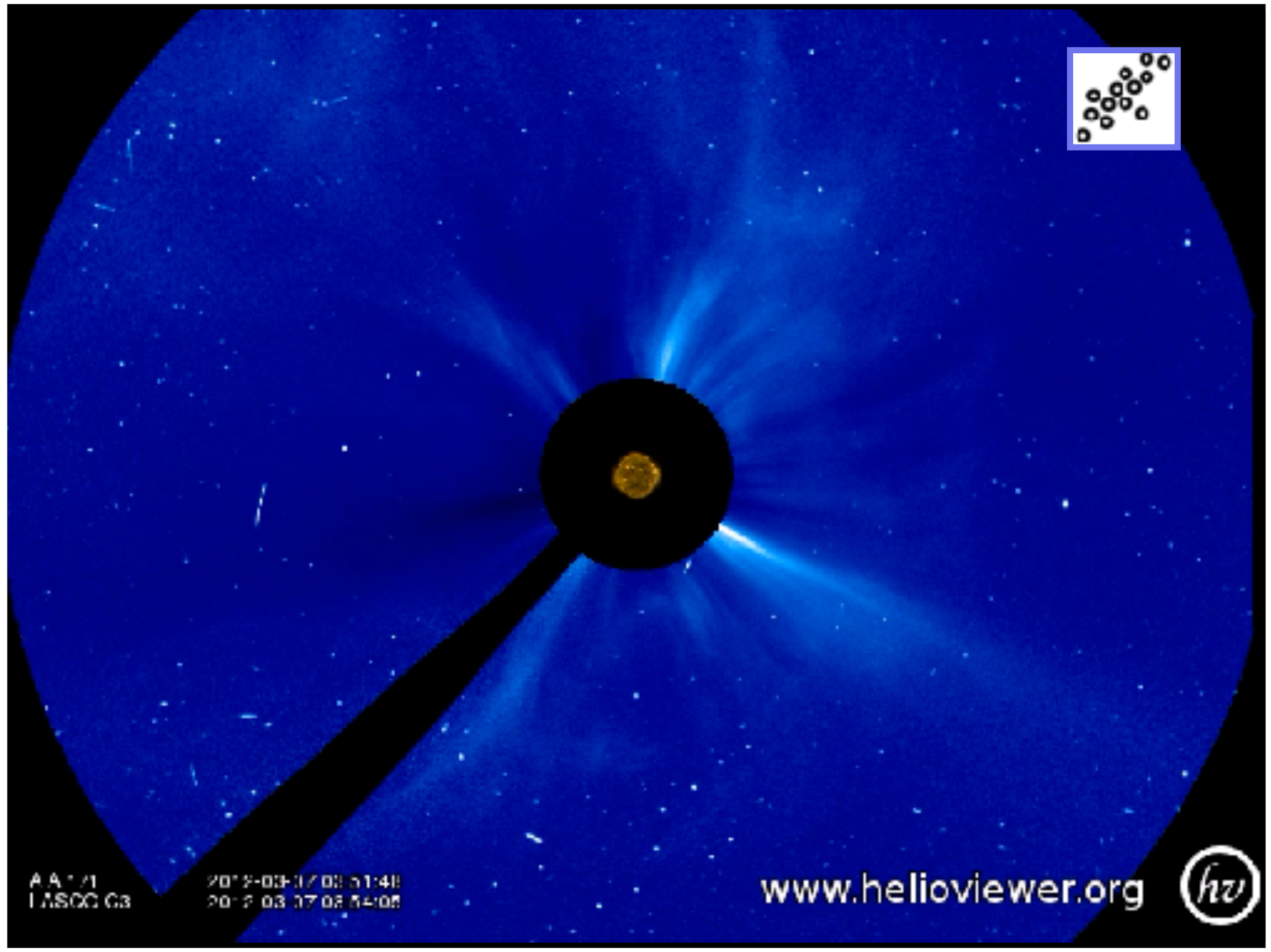


Satellite drag
GNSS

- scintillation of the signal such that the receiver doesn't recognise the signal anymore
- 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

HF com

- In the negative phase of a magnetic storm, an electron depletion occurs —> higher Freq radio waves are not reflected anymore and just pass into space.
- AA: induce extra ionisation such that radio waves are absorbed.

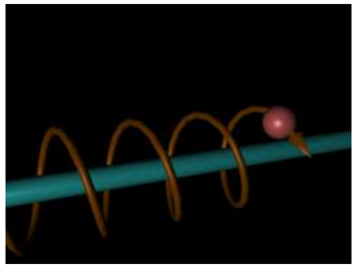


Particle showers

You see energetic particles that impact the telescope LASCO/C3 onboard of SOHO. They are seen as white stripes and dots: these are particles that fall into the lens, hit a pixel or more pixels. The impacted pixel in blinded. The dots and stripes represent an in situ measurement.

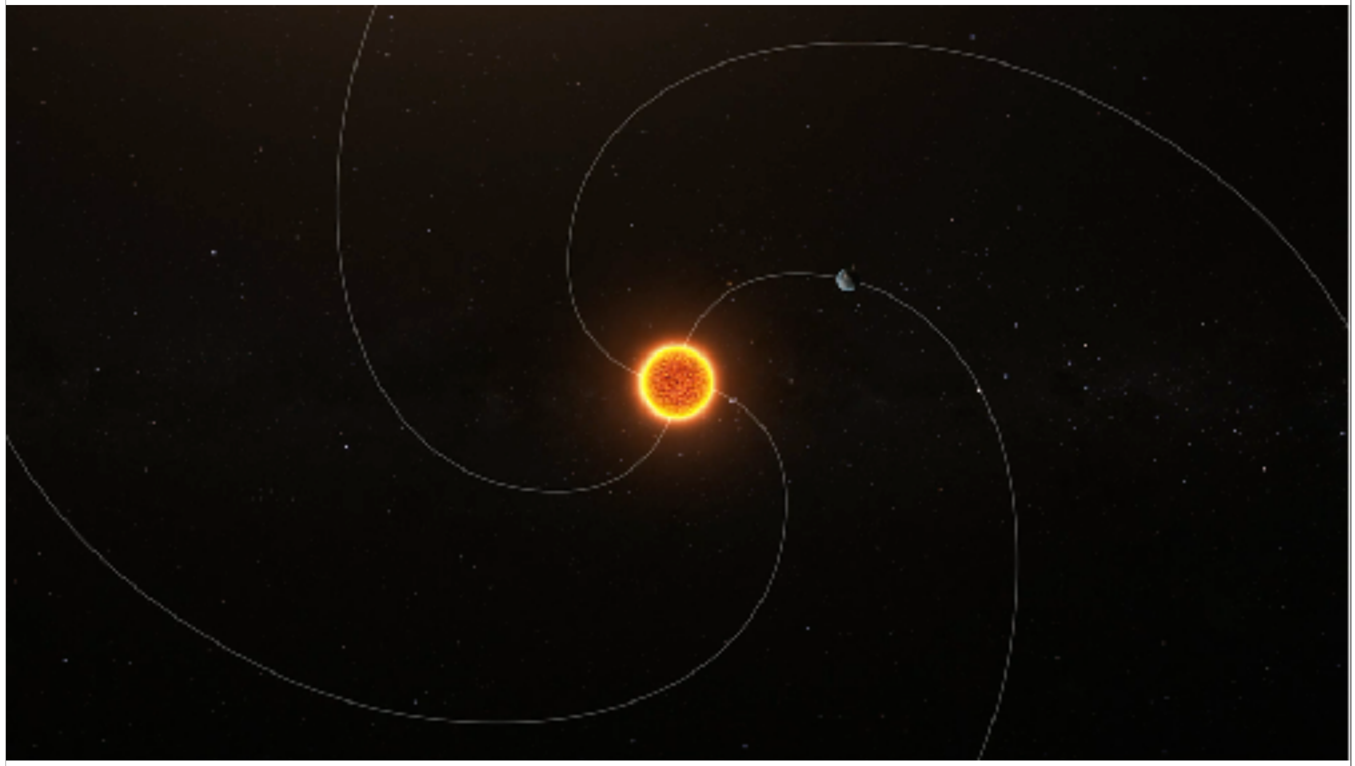
(The image in the middle of the occulter is an EUV image from the instrument AIA onboard of SDO.)

SOLAR PARTICLES



Solar energetic particles follow magnetic field lines.

They have to go where the magnetic field takes them.



https://svs.gsfc.nasa.gov/20320
An intense solar eruptive event has many parts. This animation starts with a solar flare, which sends light and energy in straight paths, traveling at the speed of light. A coronal mass ejection, or CME, appears next – this is a giant cloud of solar particles that also expands in a straight direction with speeds up to two thousand miles an hour. The eruption also generates solar energetic particles, with speeds nearly reaching the speed of light, following the spiral shape of the solar wind’s magnetic fields into interplanetary space.

AU TRANSIT TIME

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

8 MIN

DAYS

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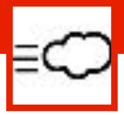

HOUR

STORM SCALE

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

A,B,C,M,X

Kp
0 - 9

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

GOES

The GOES satellite measures the proton flux.
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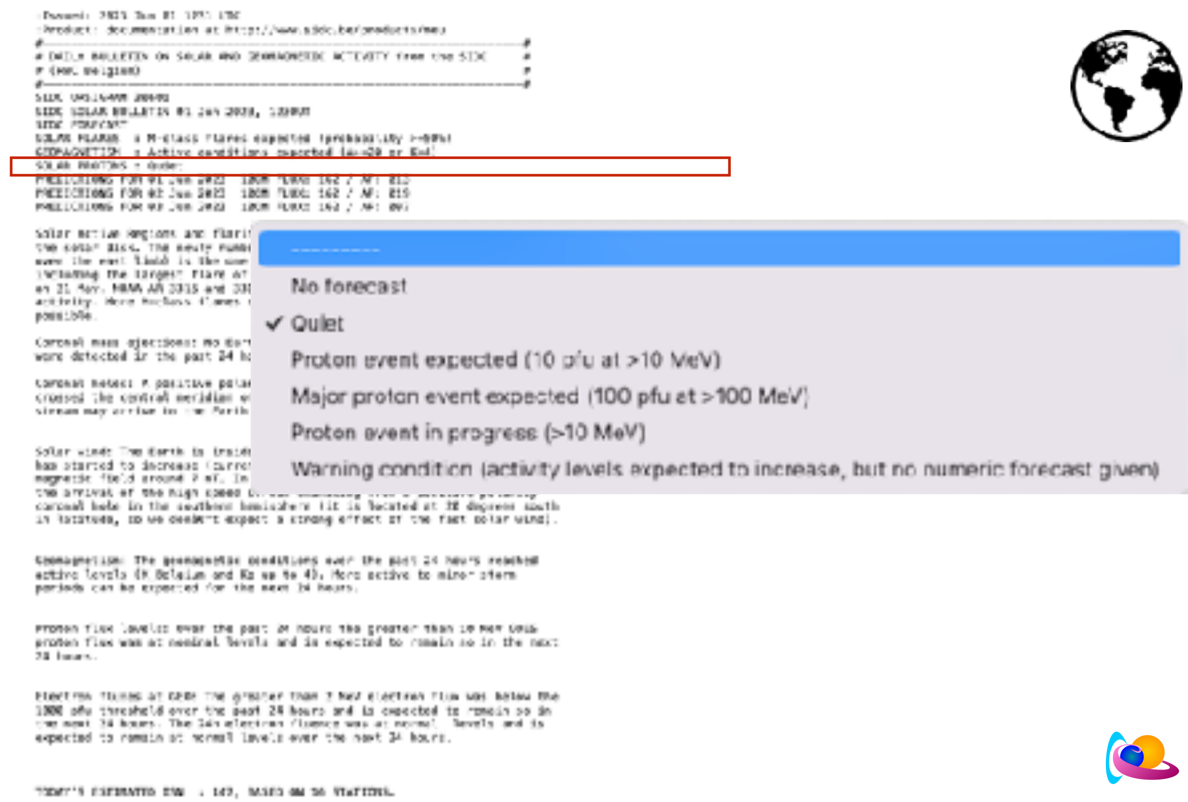
SOLAR PROTON FLUX BY GOES



DURATION

MINs to HOUR

DAY+

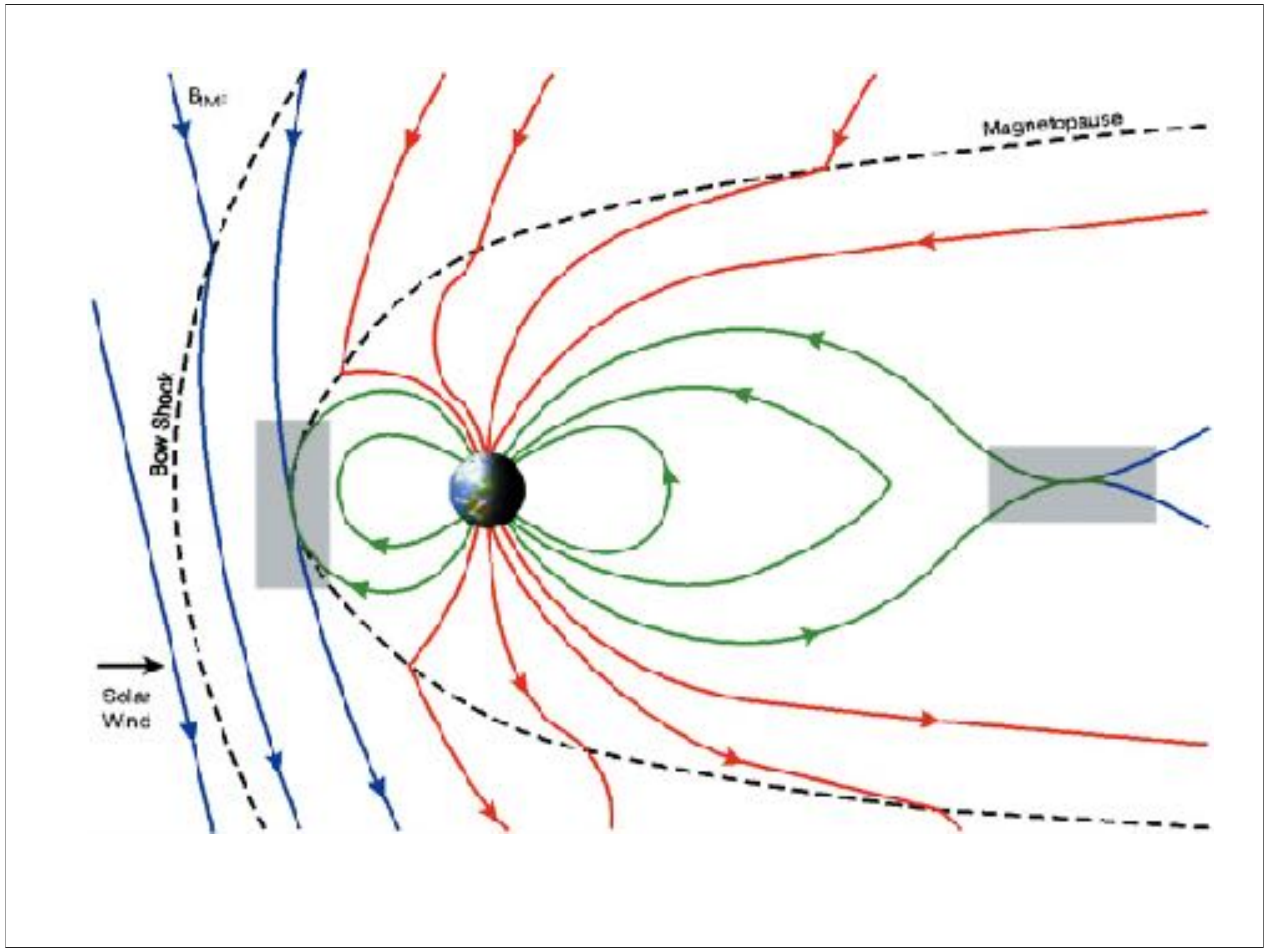
HOURS to DAYS

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

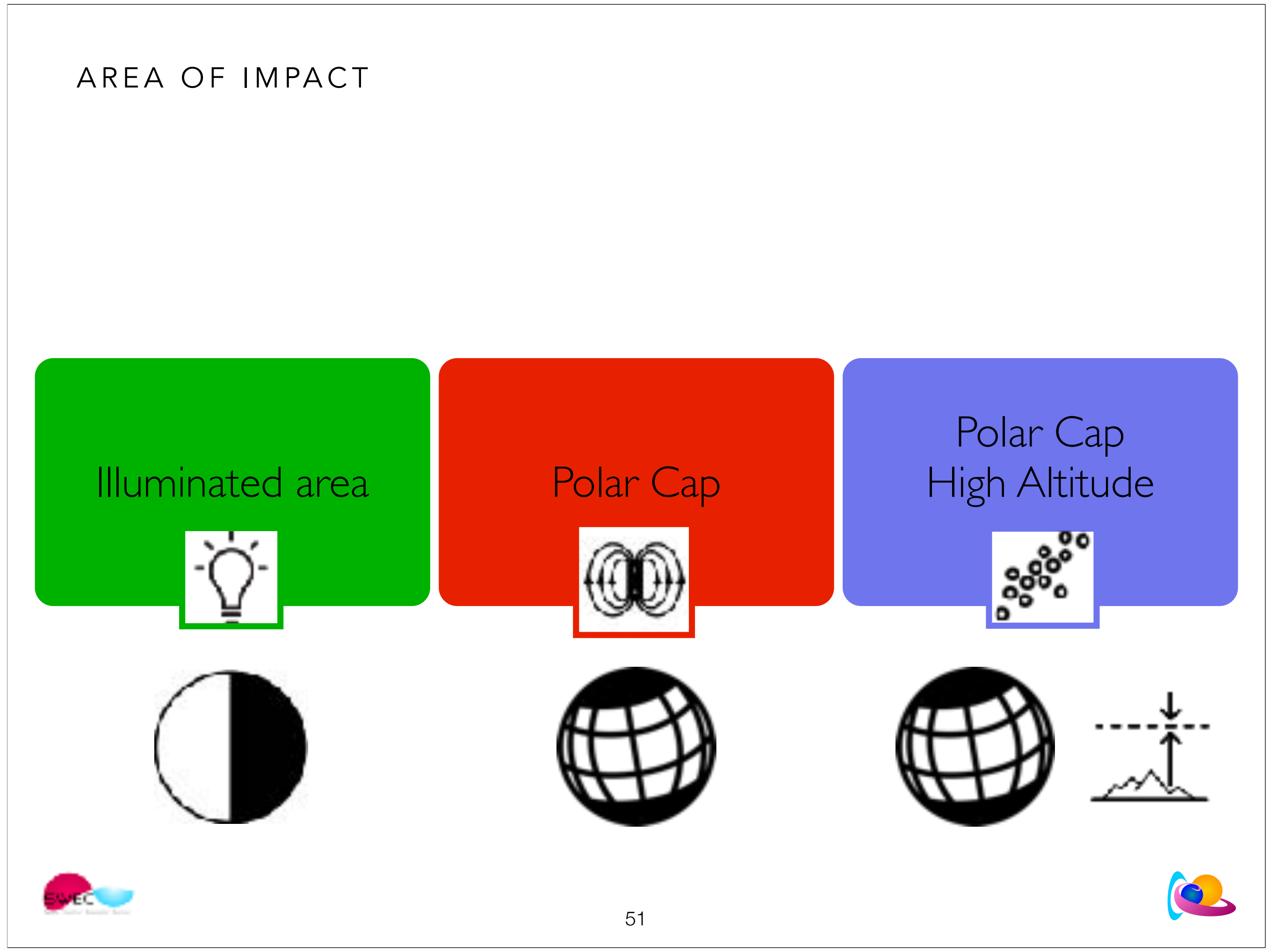
AREA OF IMPACT

Illuminated area

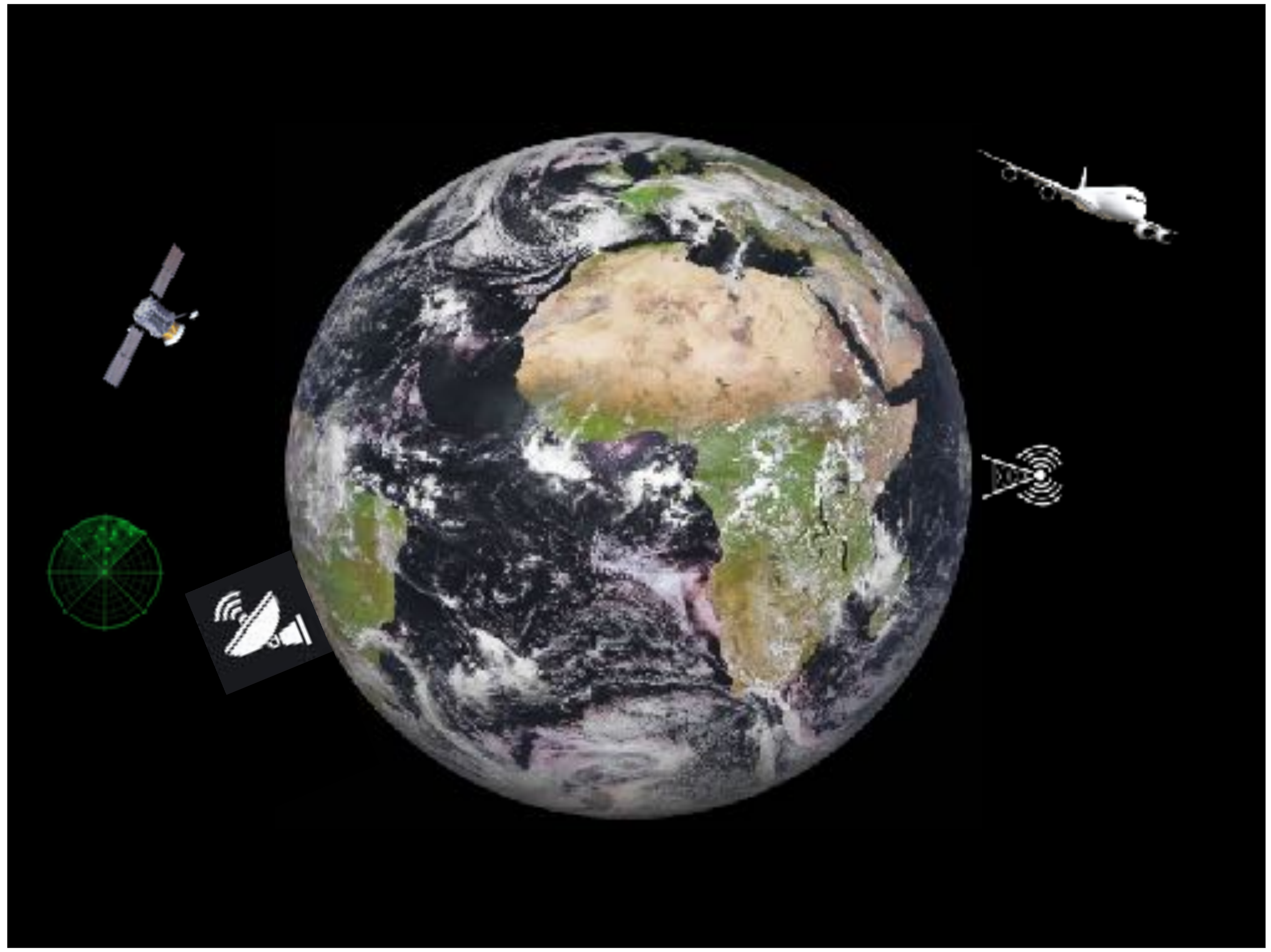
Polar Cap



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



Radiation at flight altitude
HF com
- PCA - extra ionisation that absorbs HF radio waves when they pass.

OVERVIEW