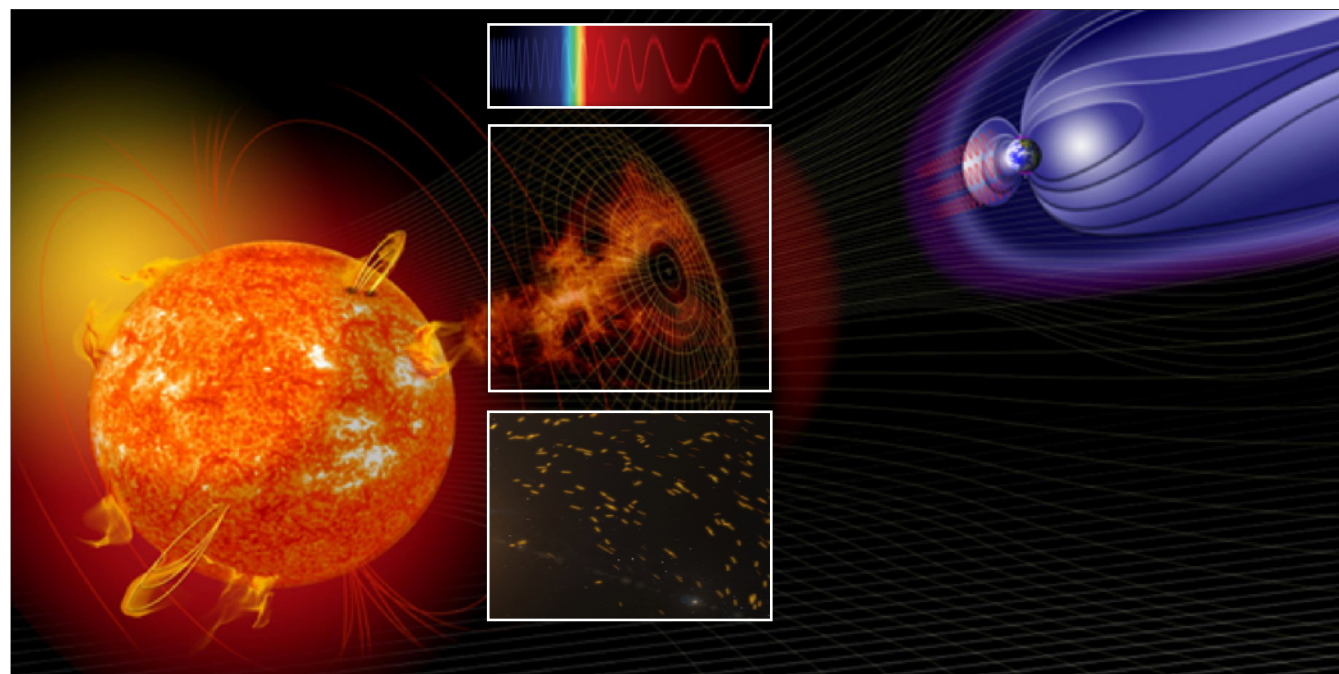


Role of the Ionosphere & SPWx in Military Communications





SOLAR DRIVERS

Petra Vanlommel
Solar-Terrestrial Centre of Excellence (STCE)



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.

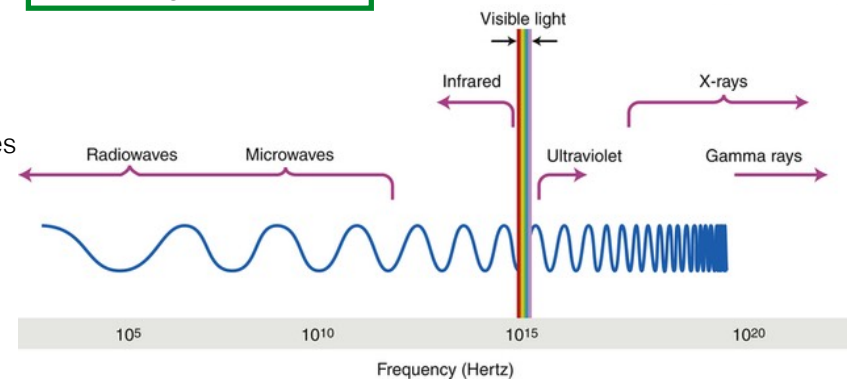
This energy is expelled, leaves the Sun to outer space and is carried away by electromagnetic waves, plasma and energetic particles.

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.

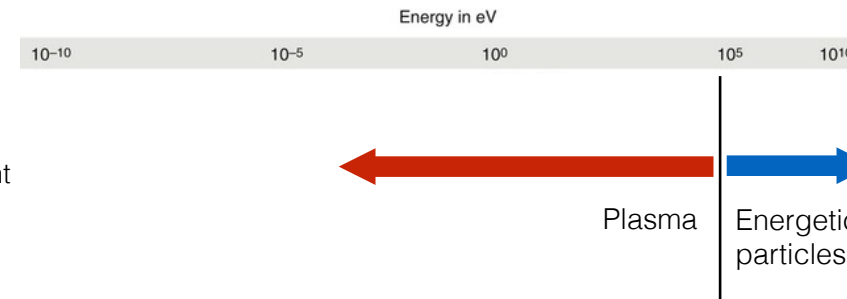
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light



Particles

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

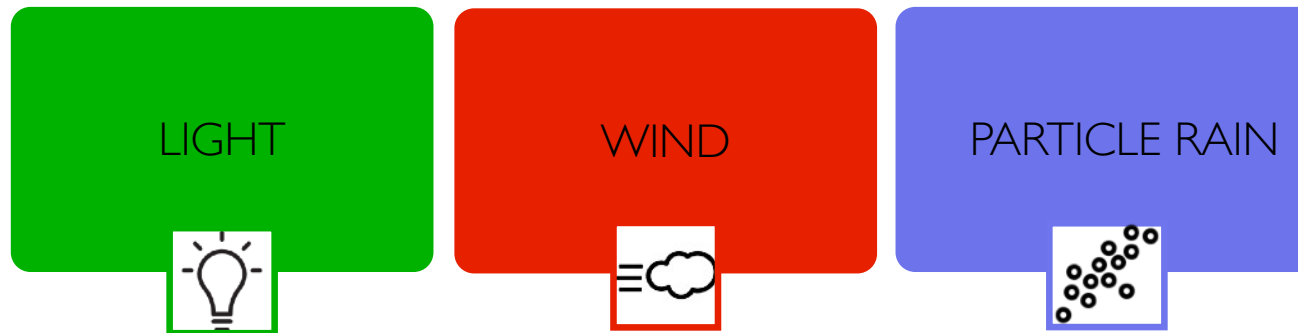


100 kEV

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= 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

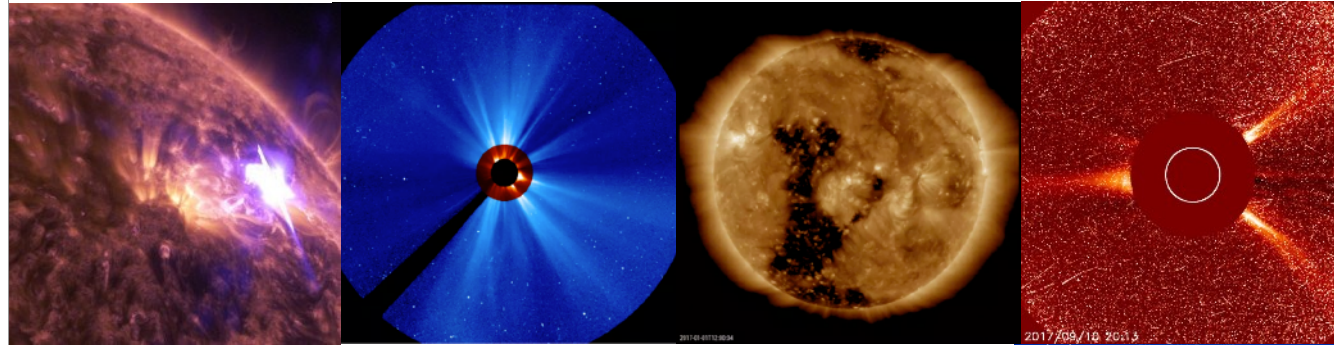
Energy expressed in eV= 1.602×10^{-19} J

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

Focus on solar energetic particles

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
HSS



Particle Storm



6



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.

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SOHO/LASCO C2 (red) and LASCO C3 (blue)

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SDO/AIA

Particle shower

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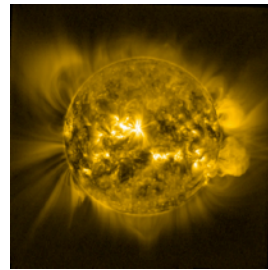
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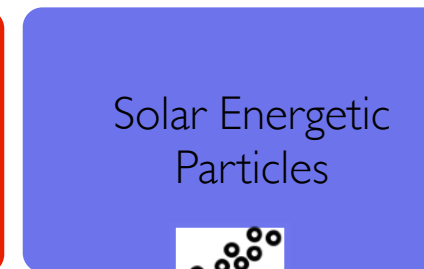
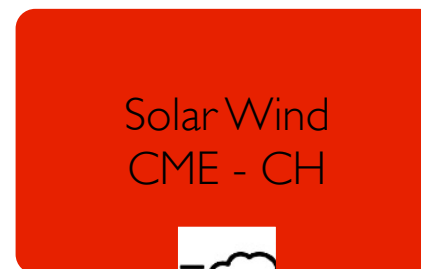
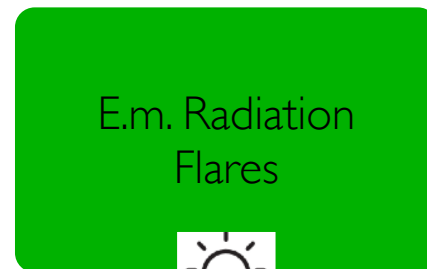
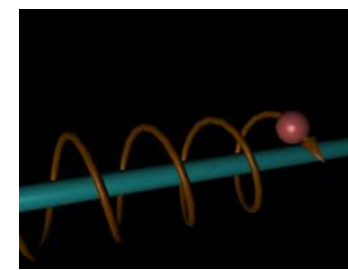
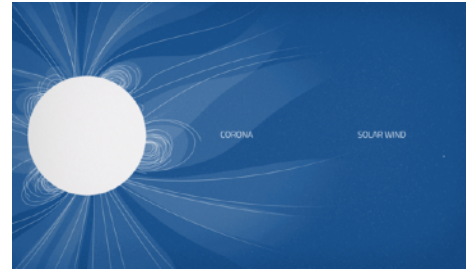
over an immense volume) and the magnetic bag would have evaporated. But, this doesn't matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

SOLAR 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



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 fills 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

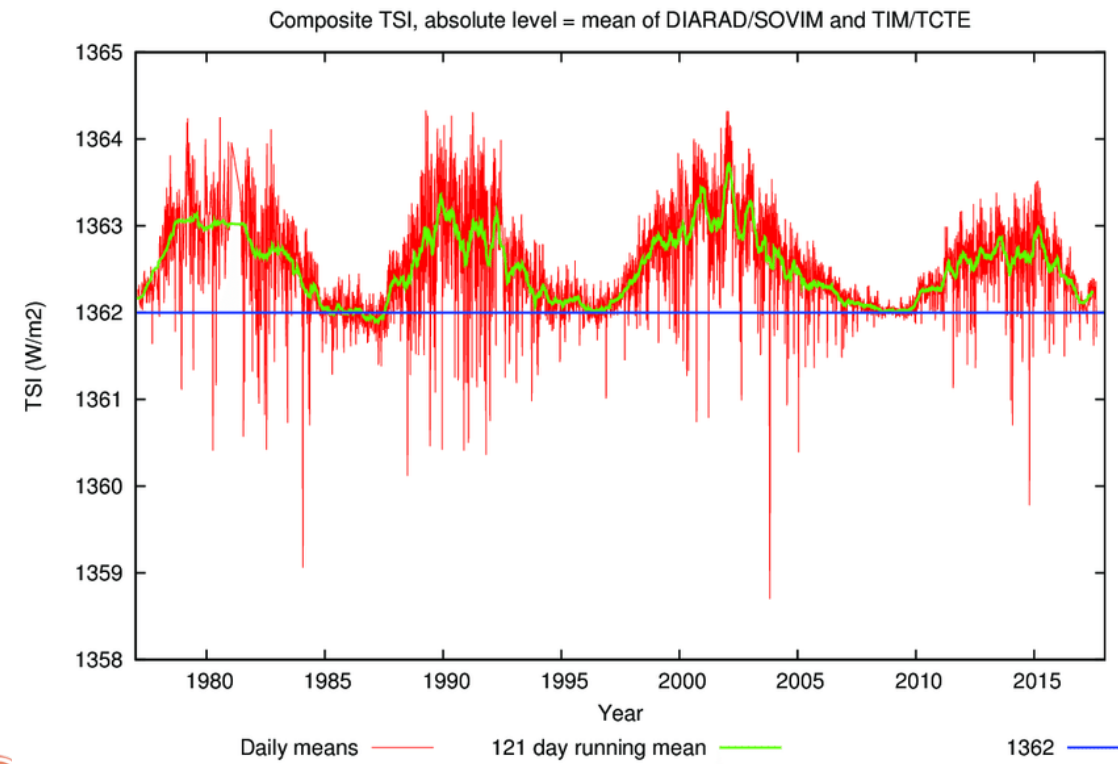
<https://www.nasa.gov/feature/goddard/2016/images-from-sun-s-edge-reveal-origins-of-solar-wind>

https://youtu.be/QYM2_ytkjQo

SEASONAL BEHAVIOUR OF LIGHT

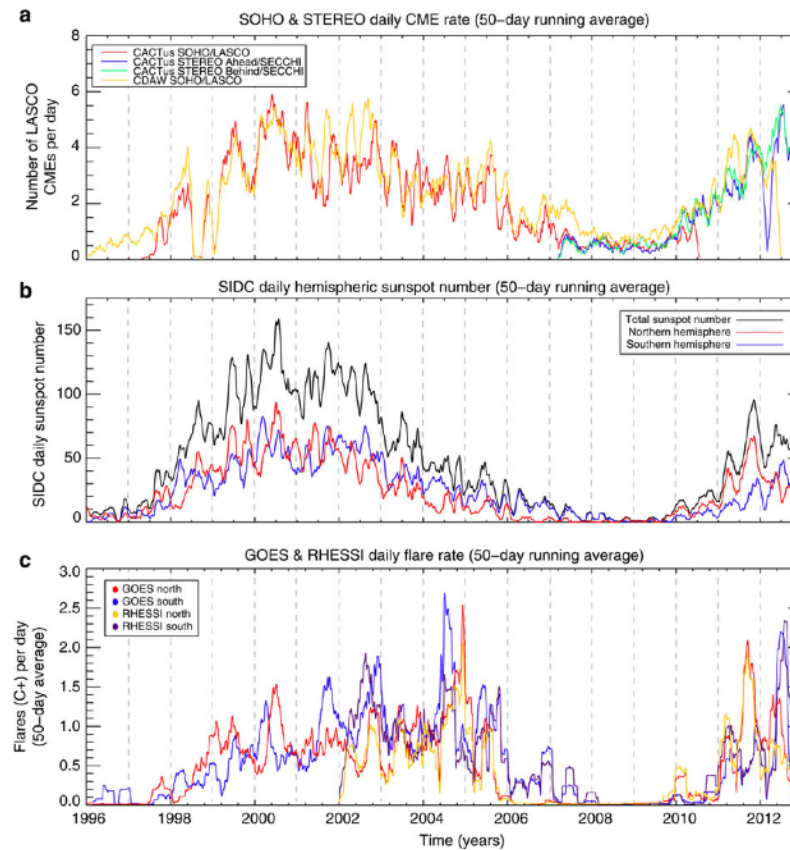
The solar irradiance, i.e. all the solar light, varies over the solar seasons.

The sun radiates stronger in the high season compared to the low season.



SEASONAL BEHAVIOUR OF 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.

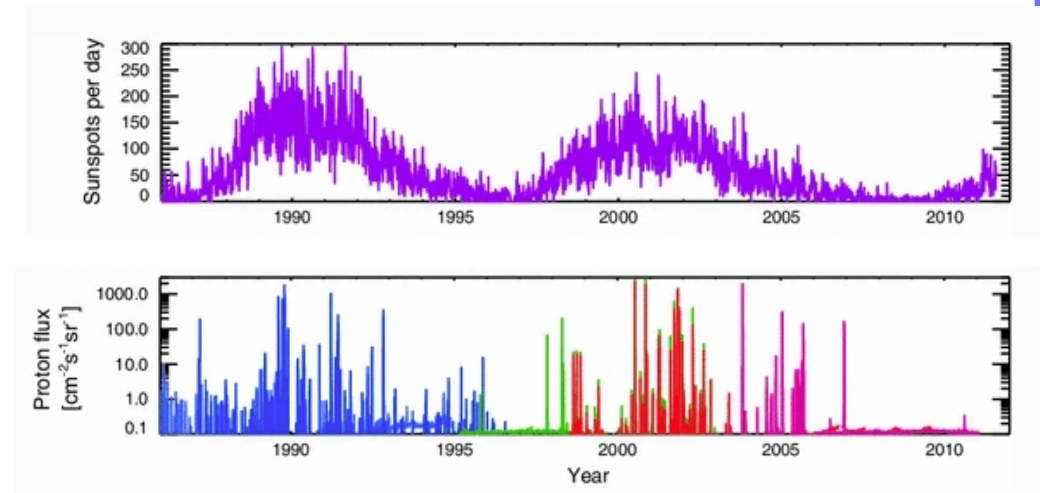
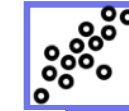


From https://www.researchgate.net/publication/274697133_The_solar_magnetic_activity_band_interaction_and_instabilities_that_shape_quasi-periodic_variability

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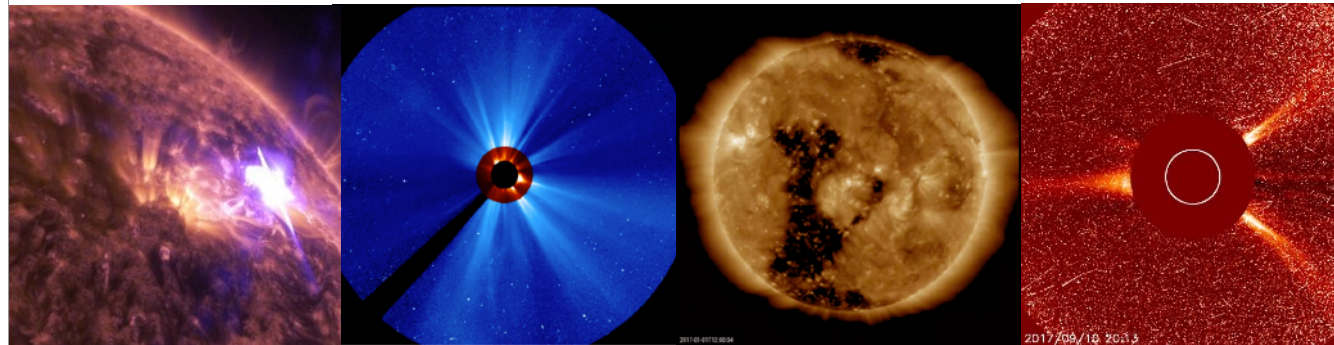
Less/More flares,CME's —> Less/More proton storms

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>)

SOLAR WEATHER & STORMS

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FLARE



CORONAL MASS
EJECTION
CORONAL HOLE



||

PARTICLE STORM



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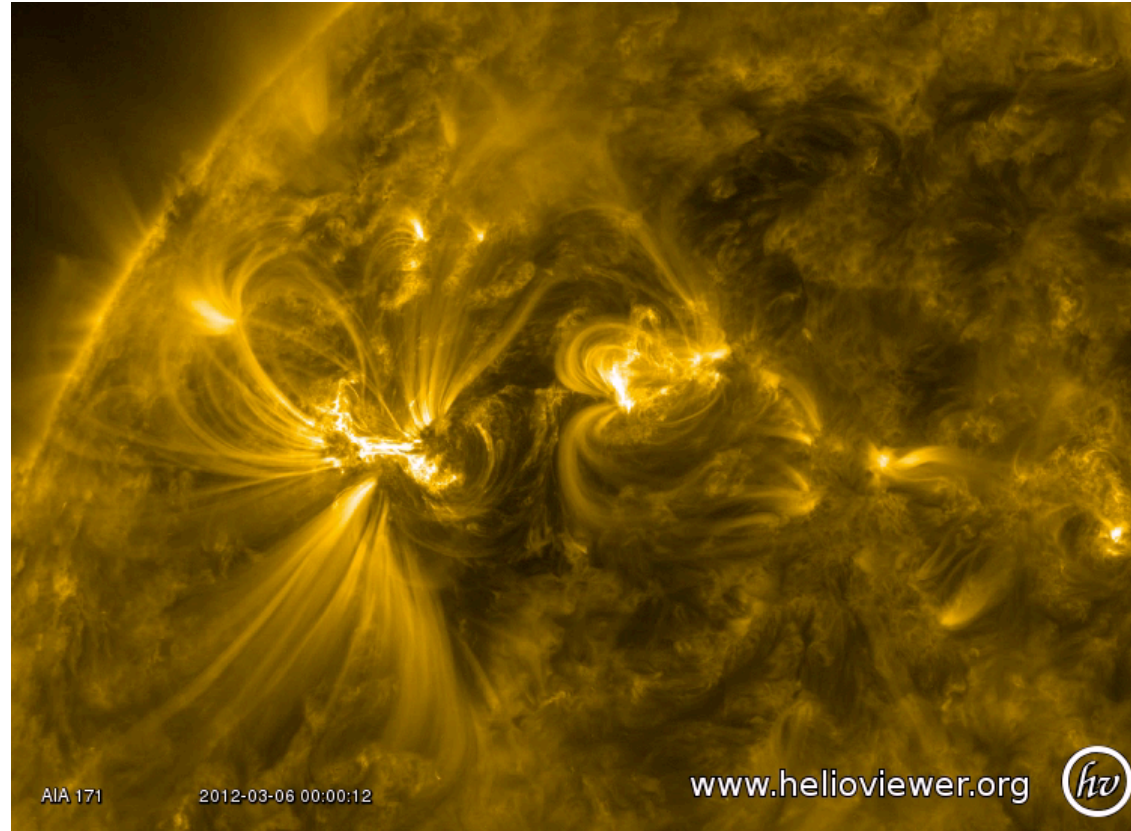
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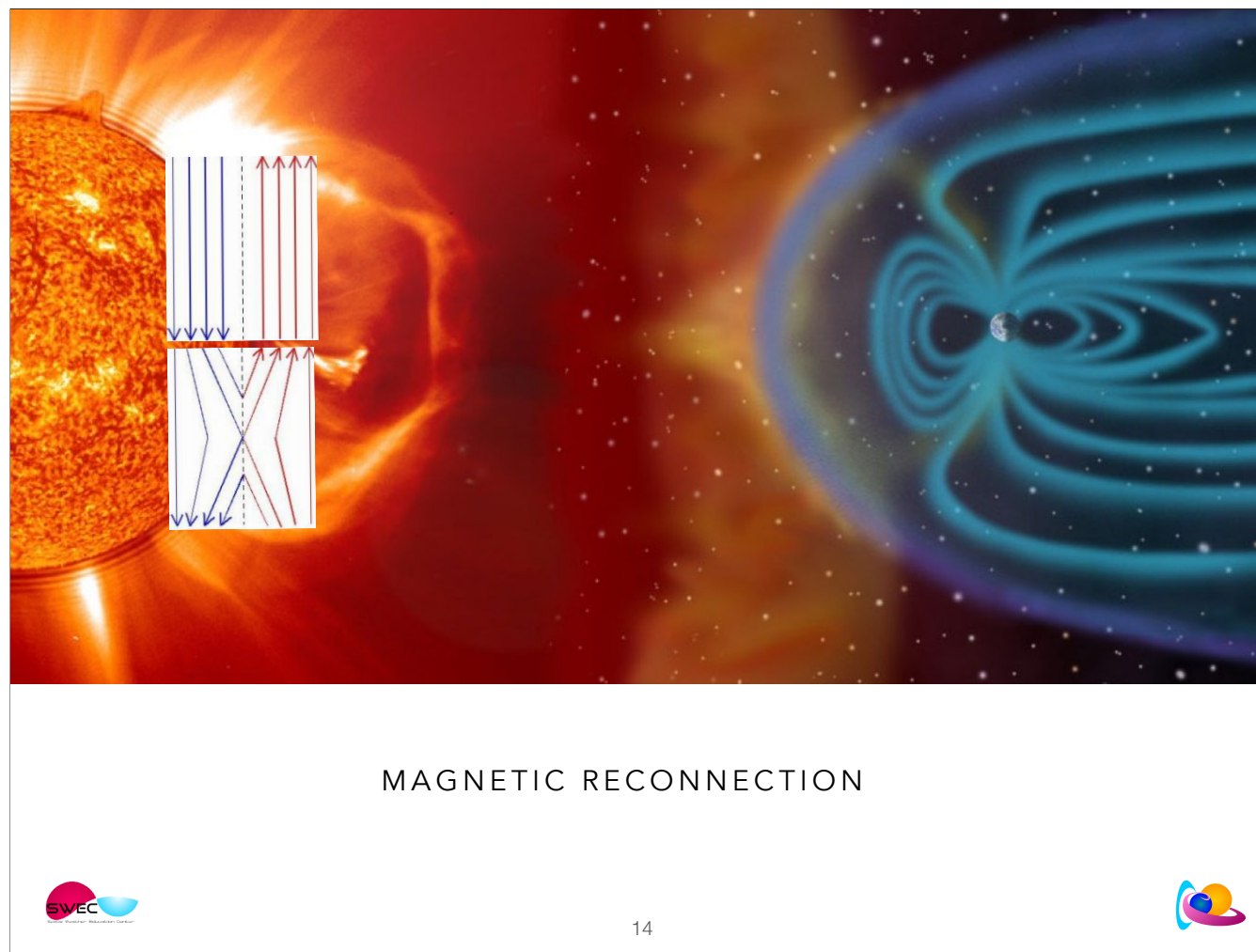
Transit time
Storm scale
duration
Area of impact

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.



This is the earth's 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 years. The Earth's magnetic poles don't. They are already for ages like this.

The part of the earth's 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 initiates 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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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

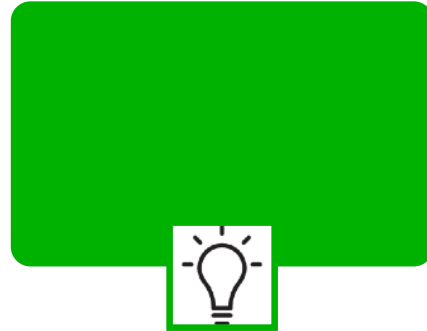
5mT – strength of a typical refrigerator magnet

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

AU TRANSIT TIME

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



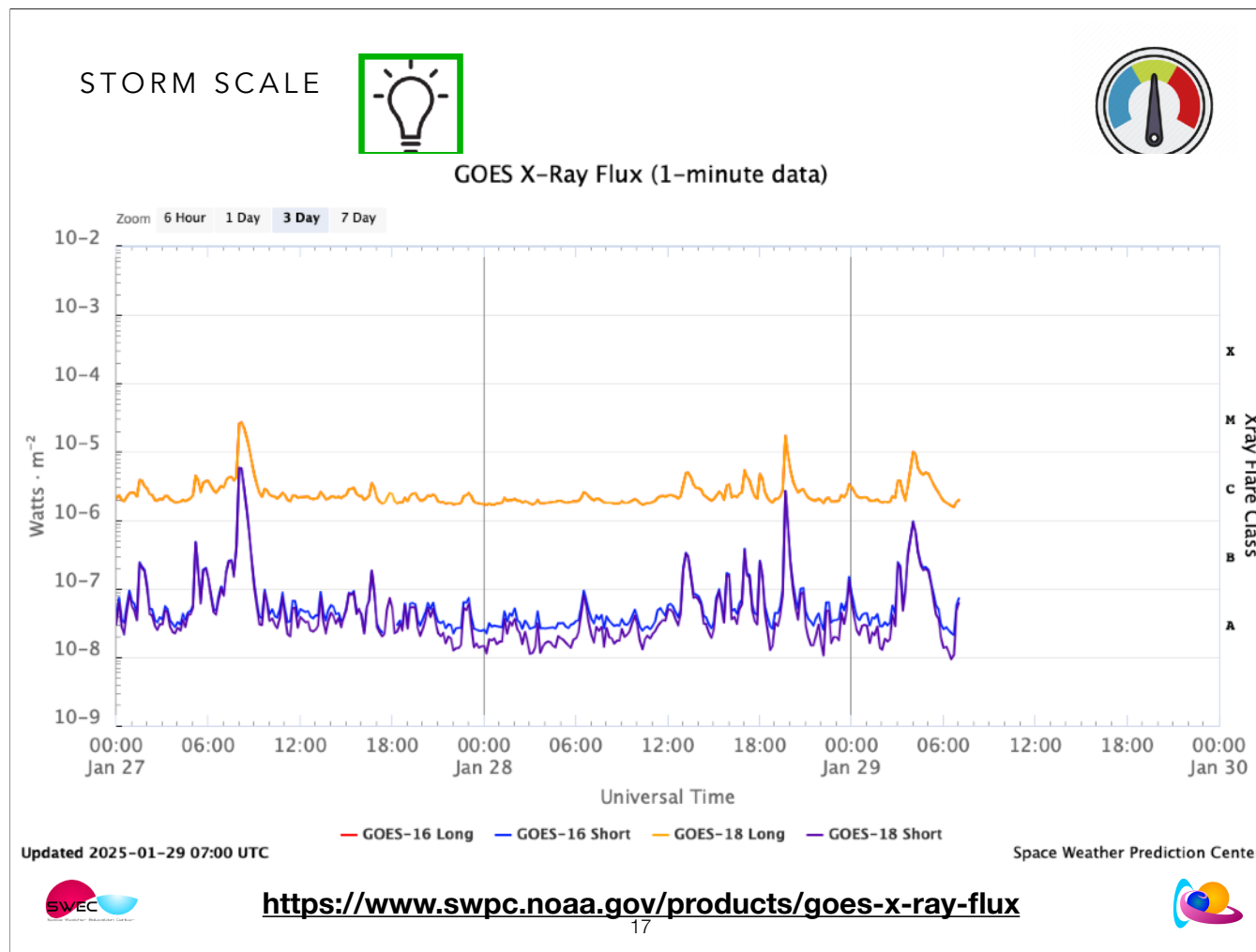
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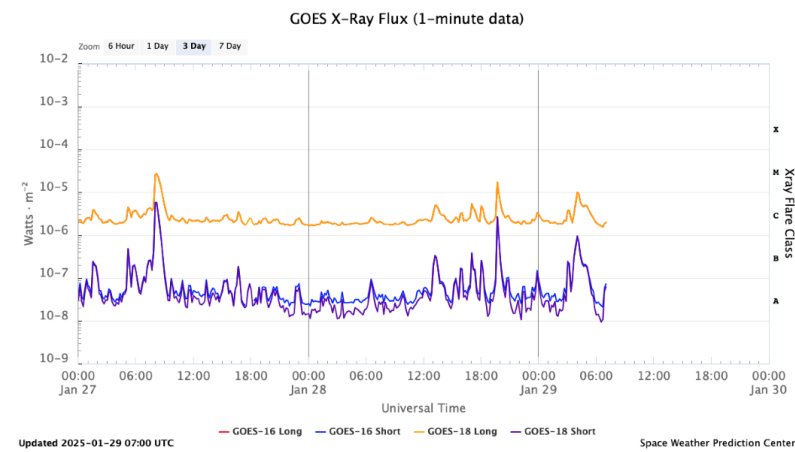
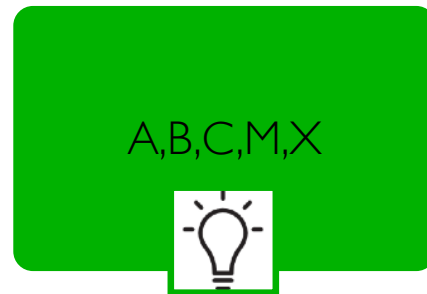
8 MIN





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



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

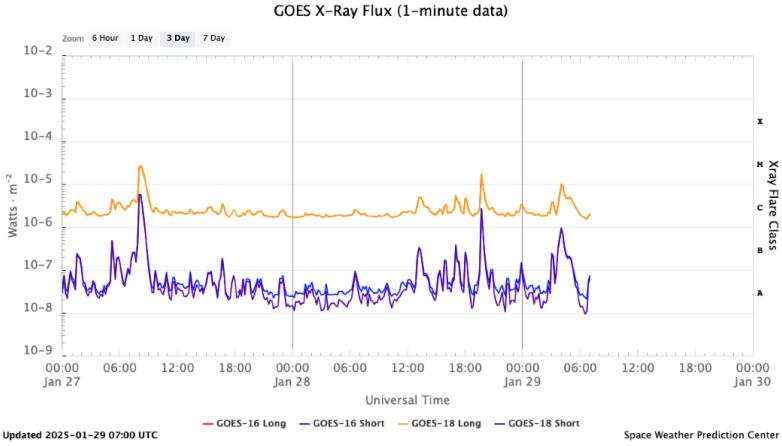


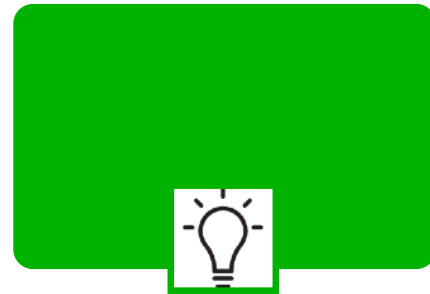
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DURATION

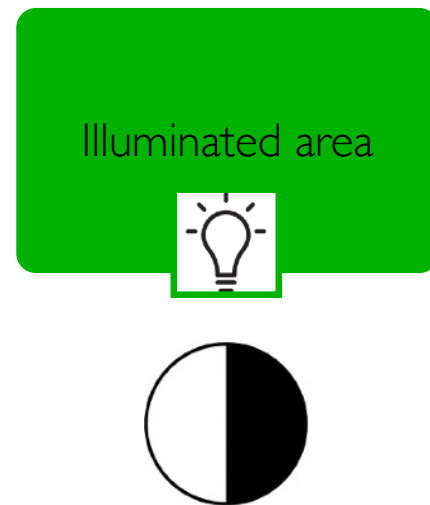


MINs to HOUR

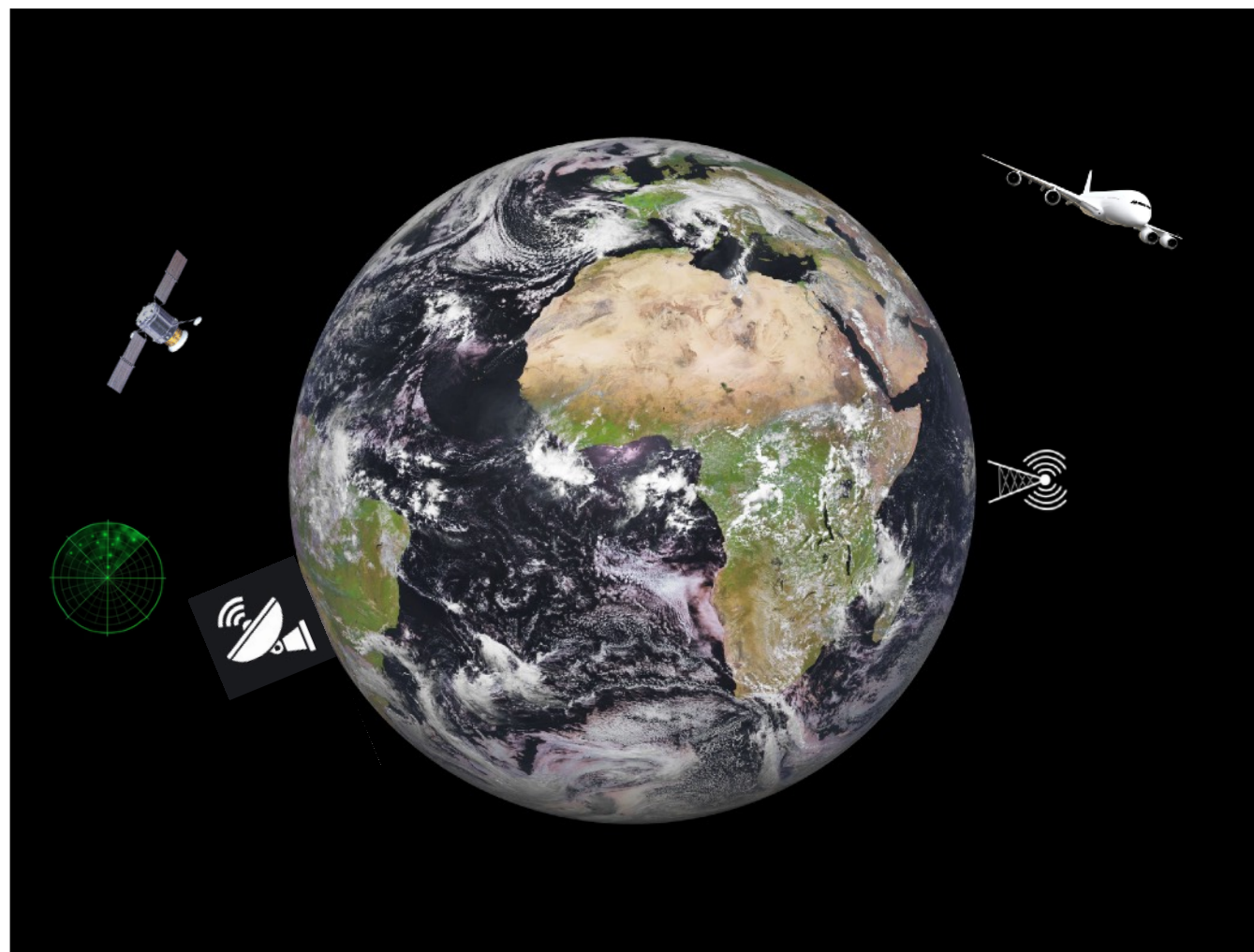




AREA OF IMPACT



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.



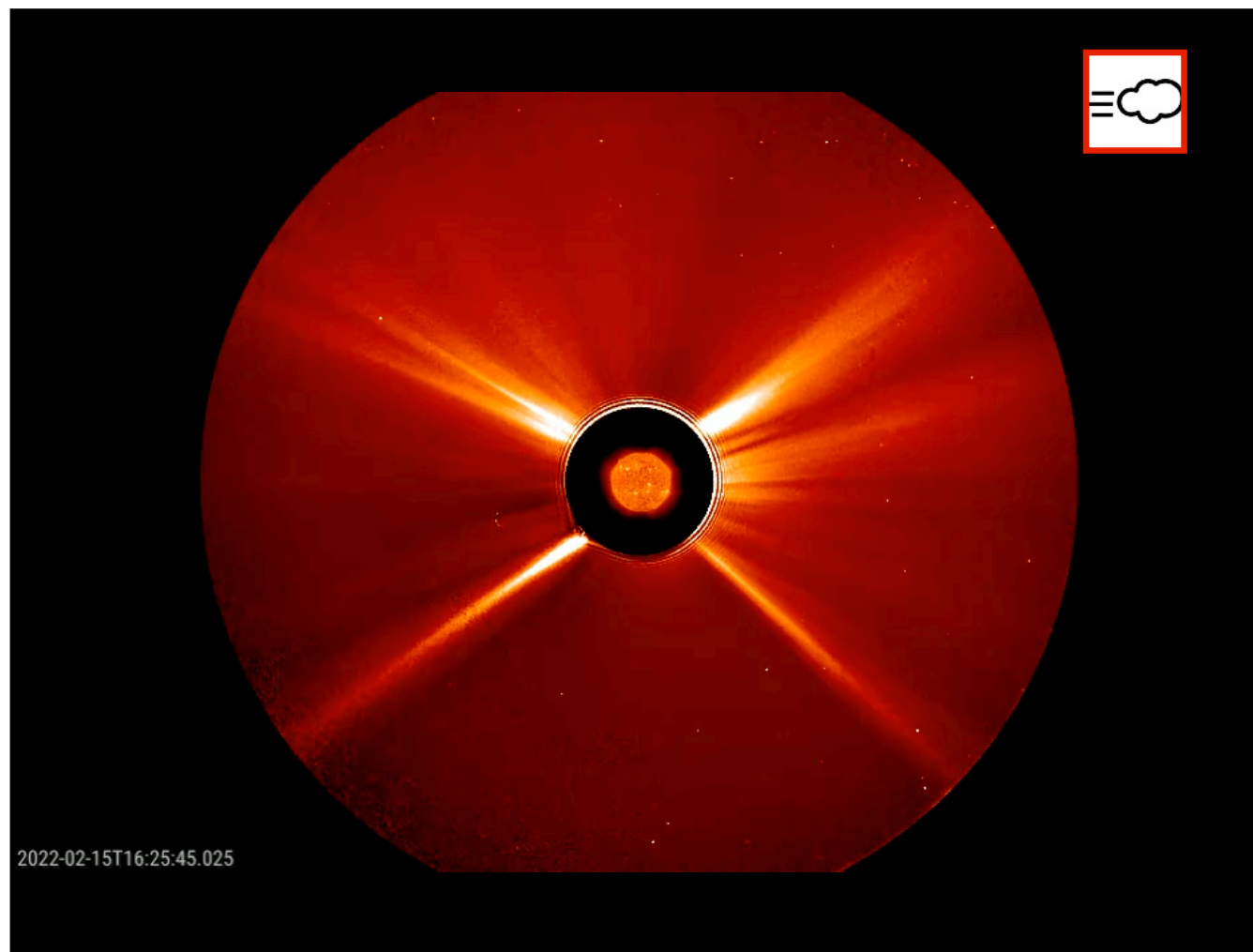
Satellite drag

SWF —> the ionising part of the flare

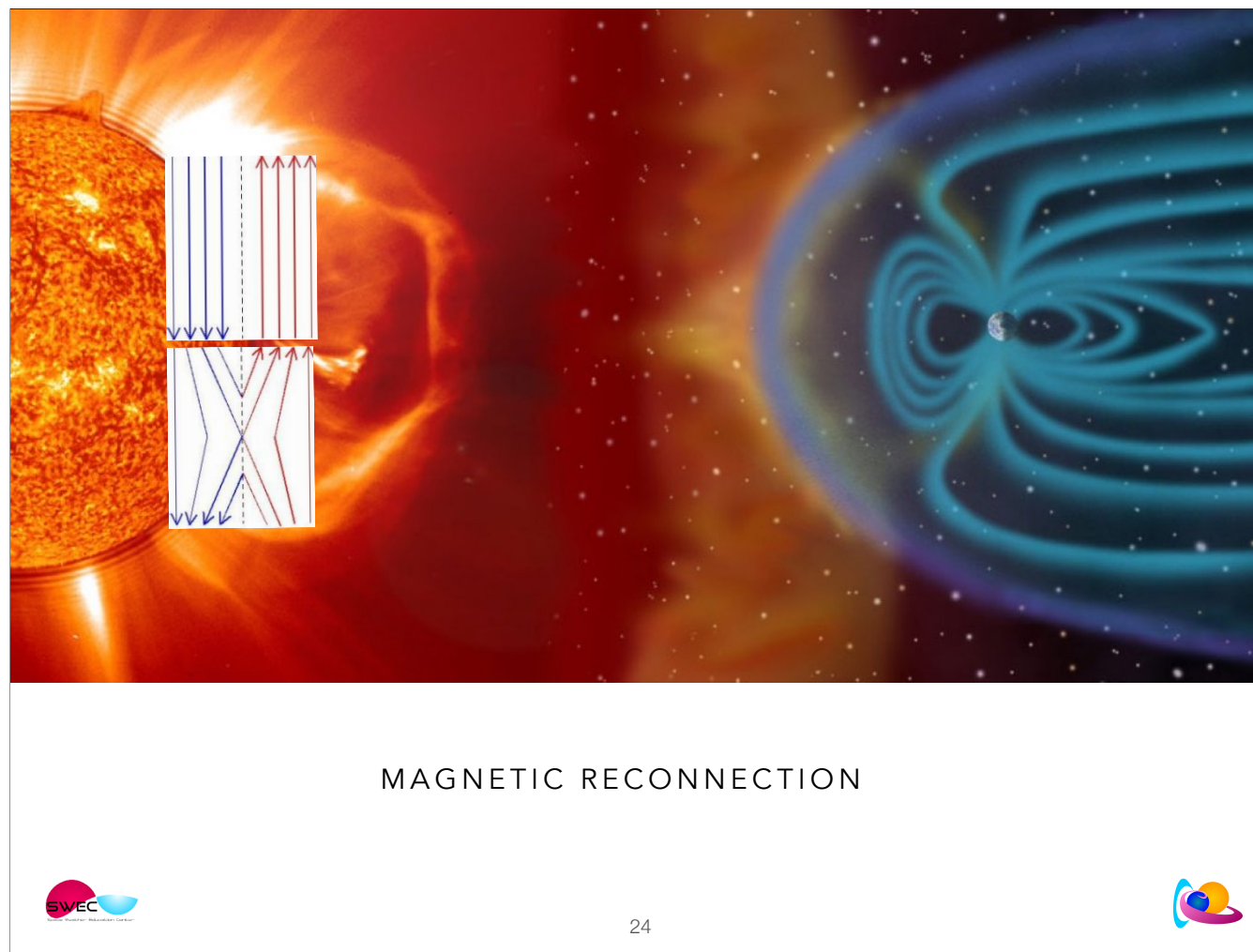
absorption of the HF radio signal in the D-layer of the ionosphere

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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SOHO/LASCO C2



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AU TRANSIT TIME

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8 MIN



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.



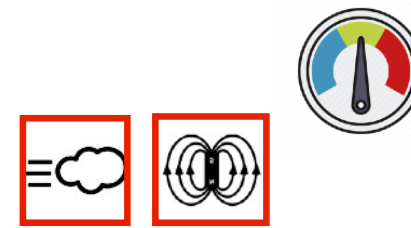
8 MIN



DAYS



STORM SCALE - GEOMAGNETIC STORM



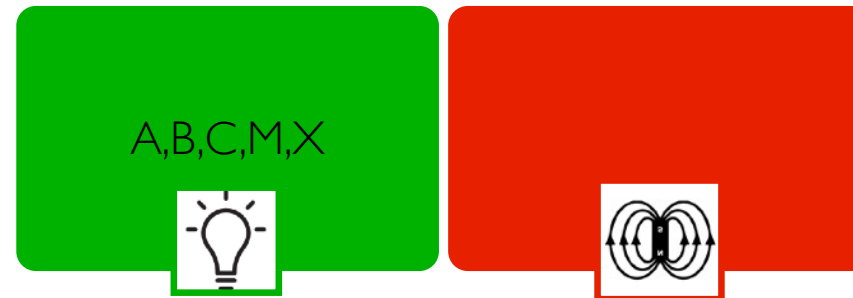
<https://svs.gsfc.nasa.gov/5193/>

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.

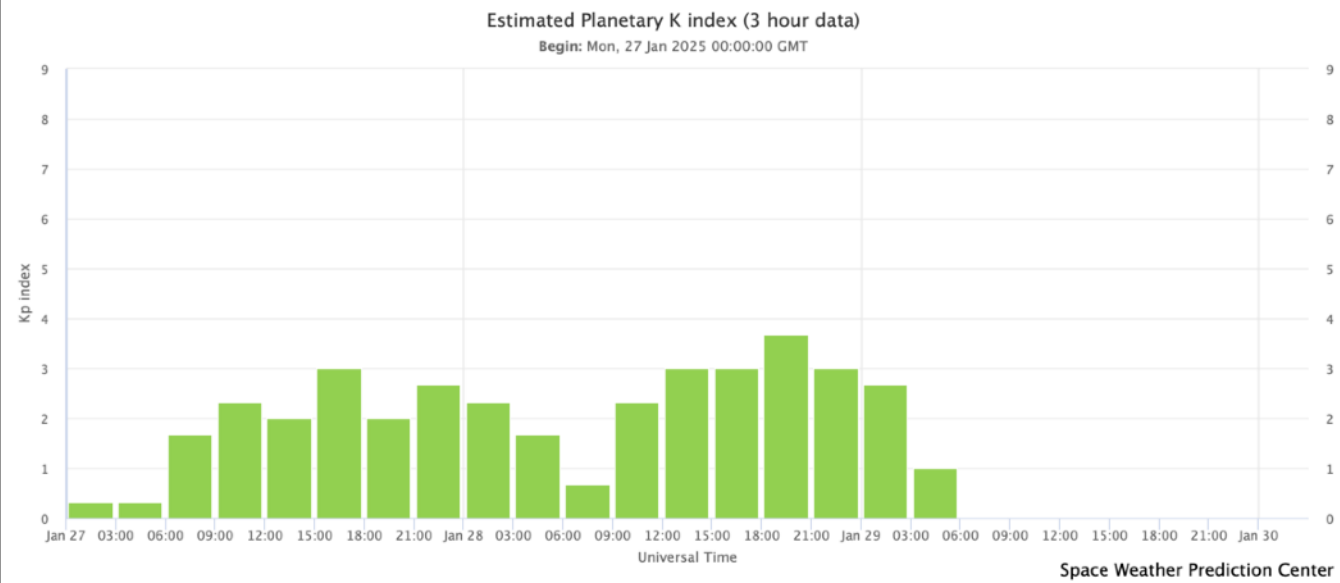


<https://www.swpc.noaa.gov/products/planetary-k-index>



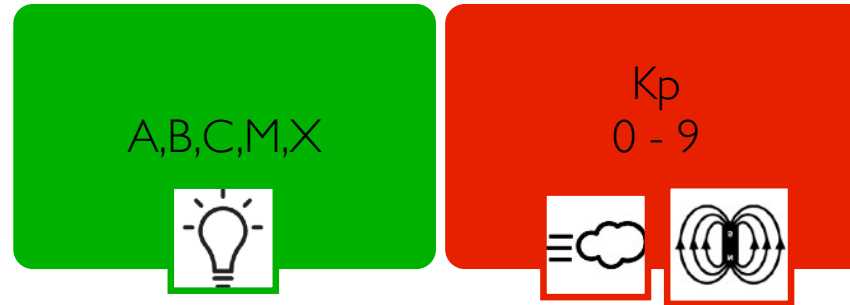
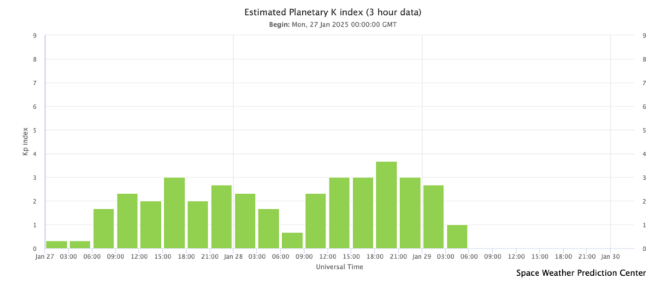
The Kp index is an index that quantifies the disturbance of the magnetic field of Earth. It ranges between 0 and 9, with 0 no disturbance and 9 an extreme disturbance.

STORM SCALE



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DURATION



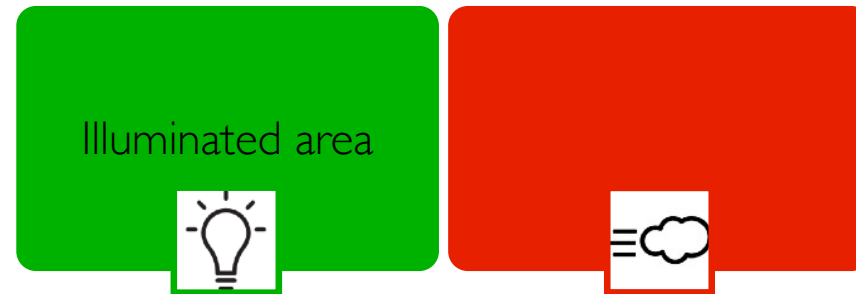
MINs to HOUR

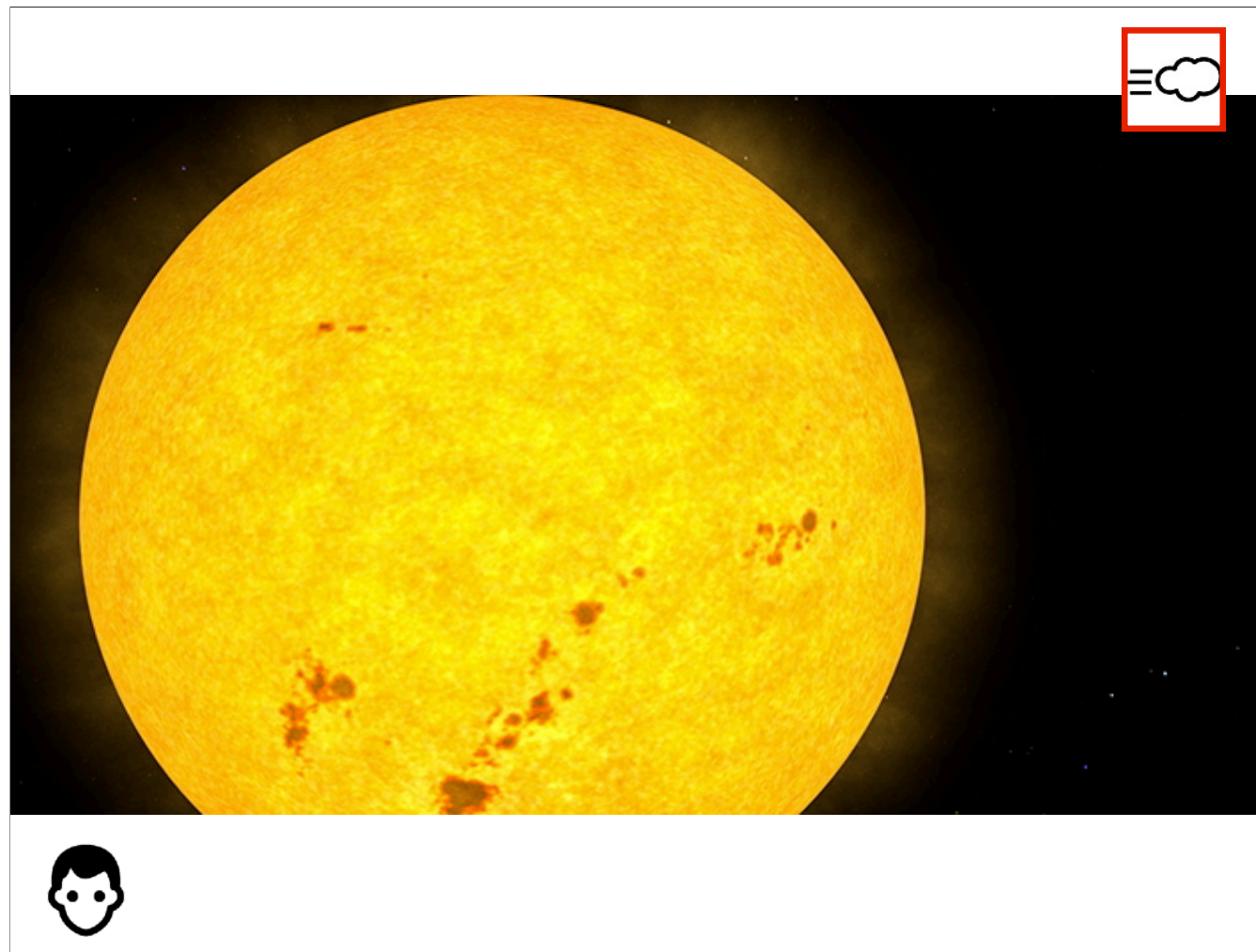


DAY+

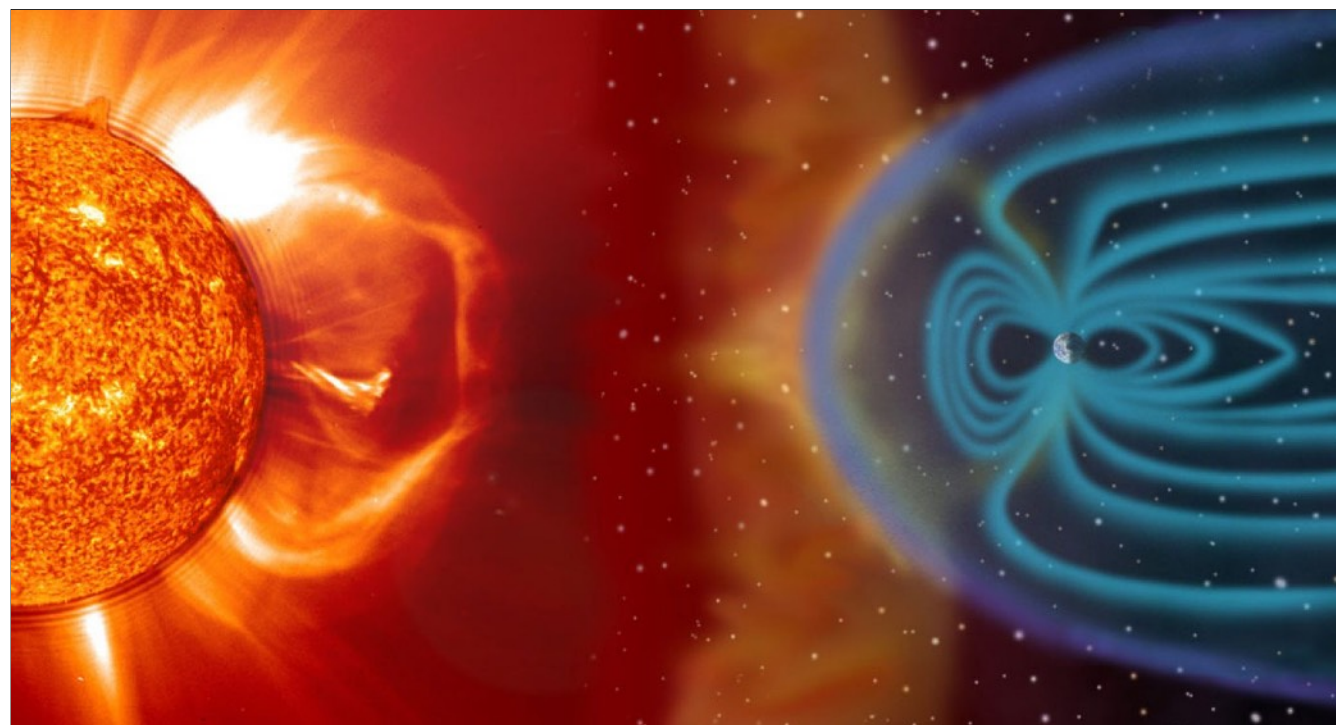


Day or more





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.



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.



34



This is the earth's 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 years. The Earth's magnetic poles don't. They are already for ages like this.

The part of the earth's 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 initiates 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.

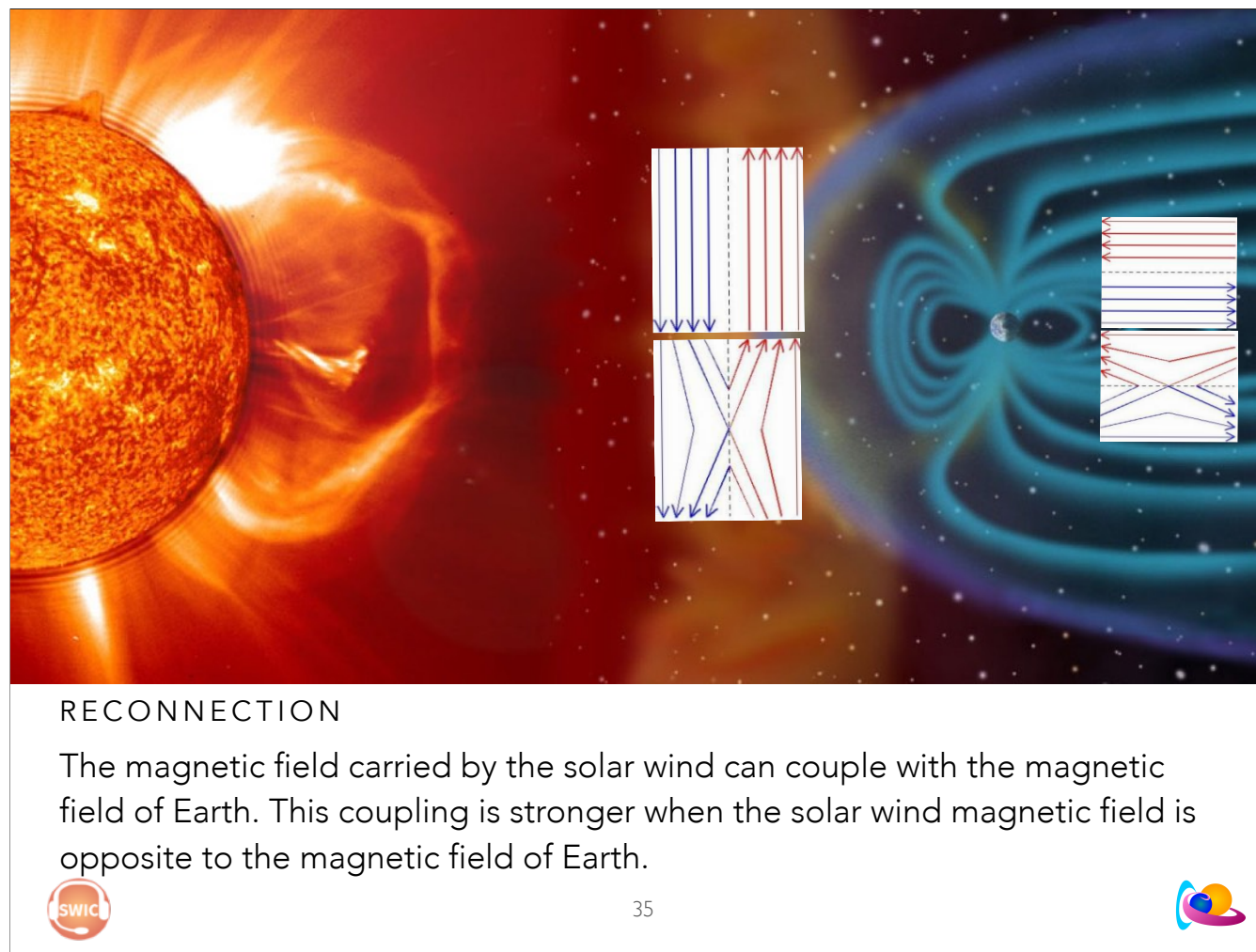
Therefore, it is very important to know how strong the

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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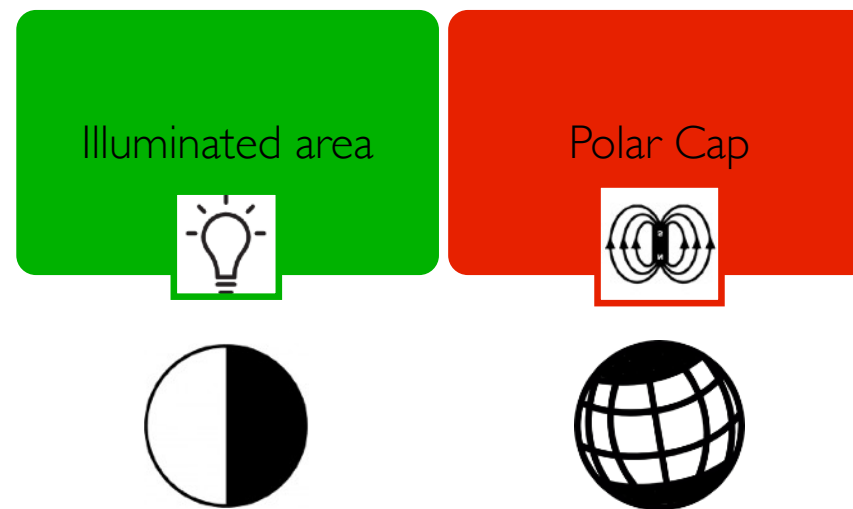
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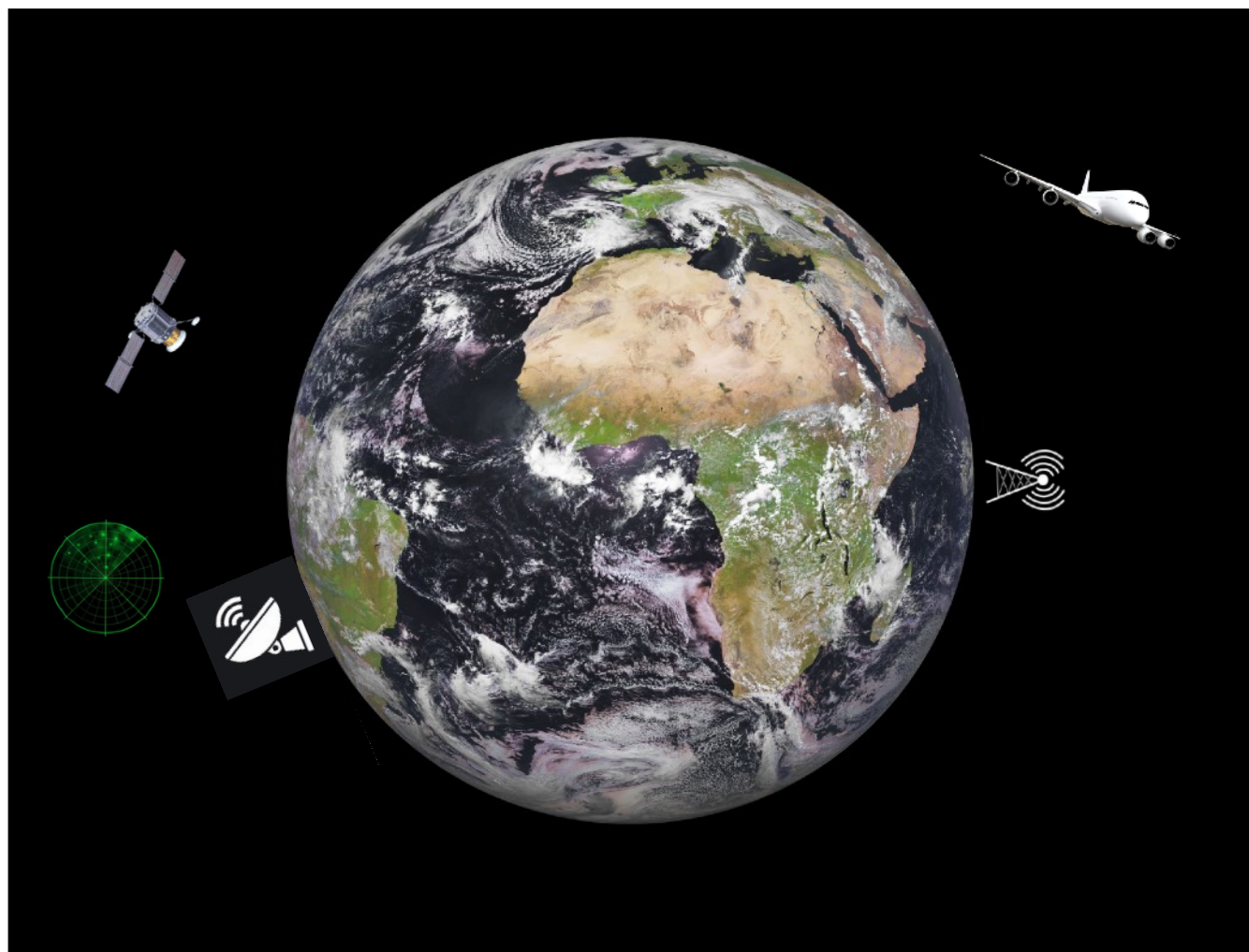
AREA OF IMPACT



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.



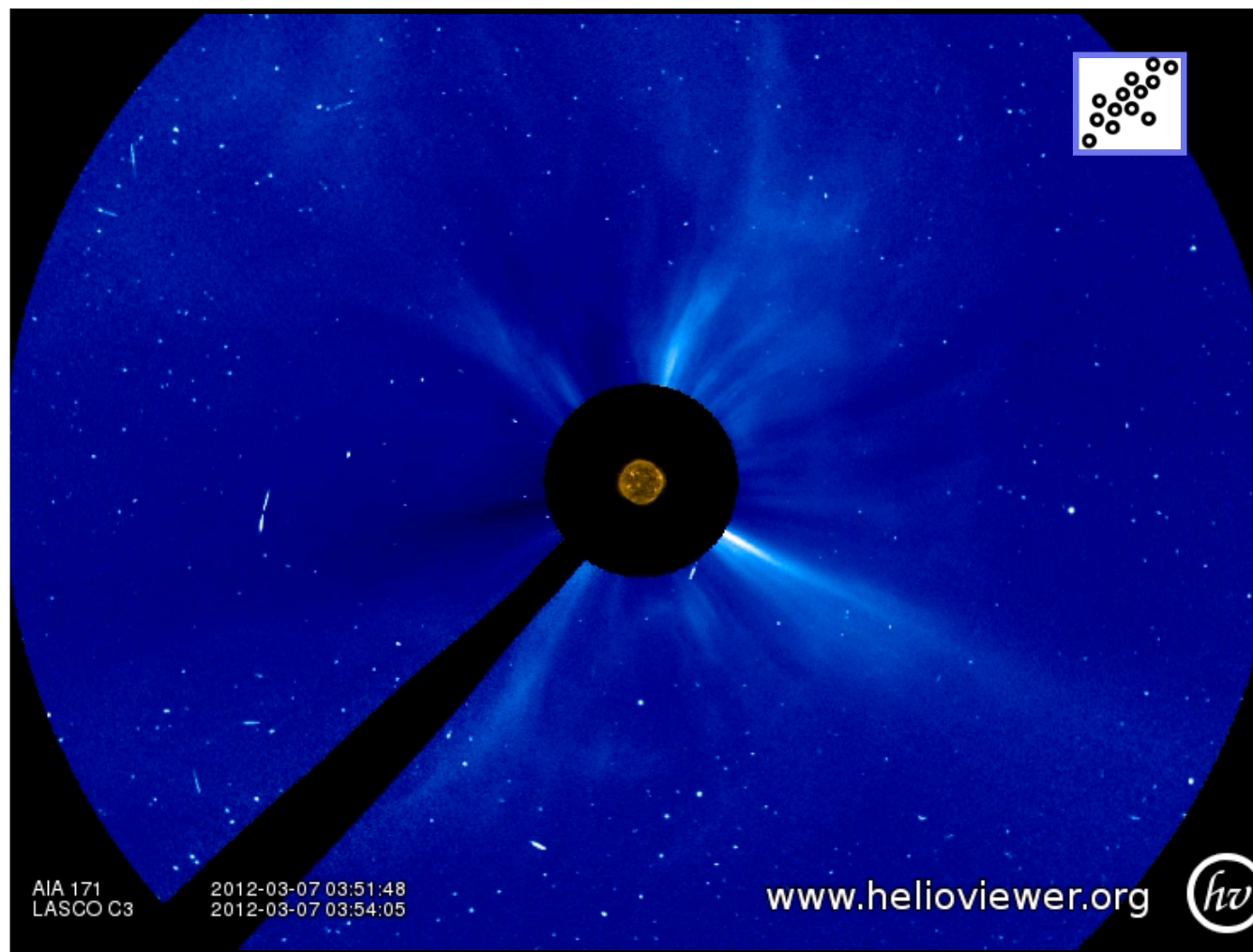
Satellite drag

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 its 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.

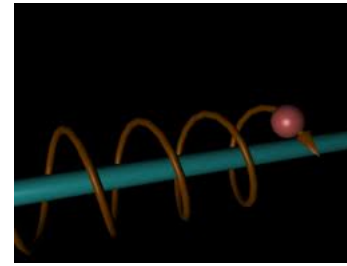


Particle showers

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 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.)

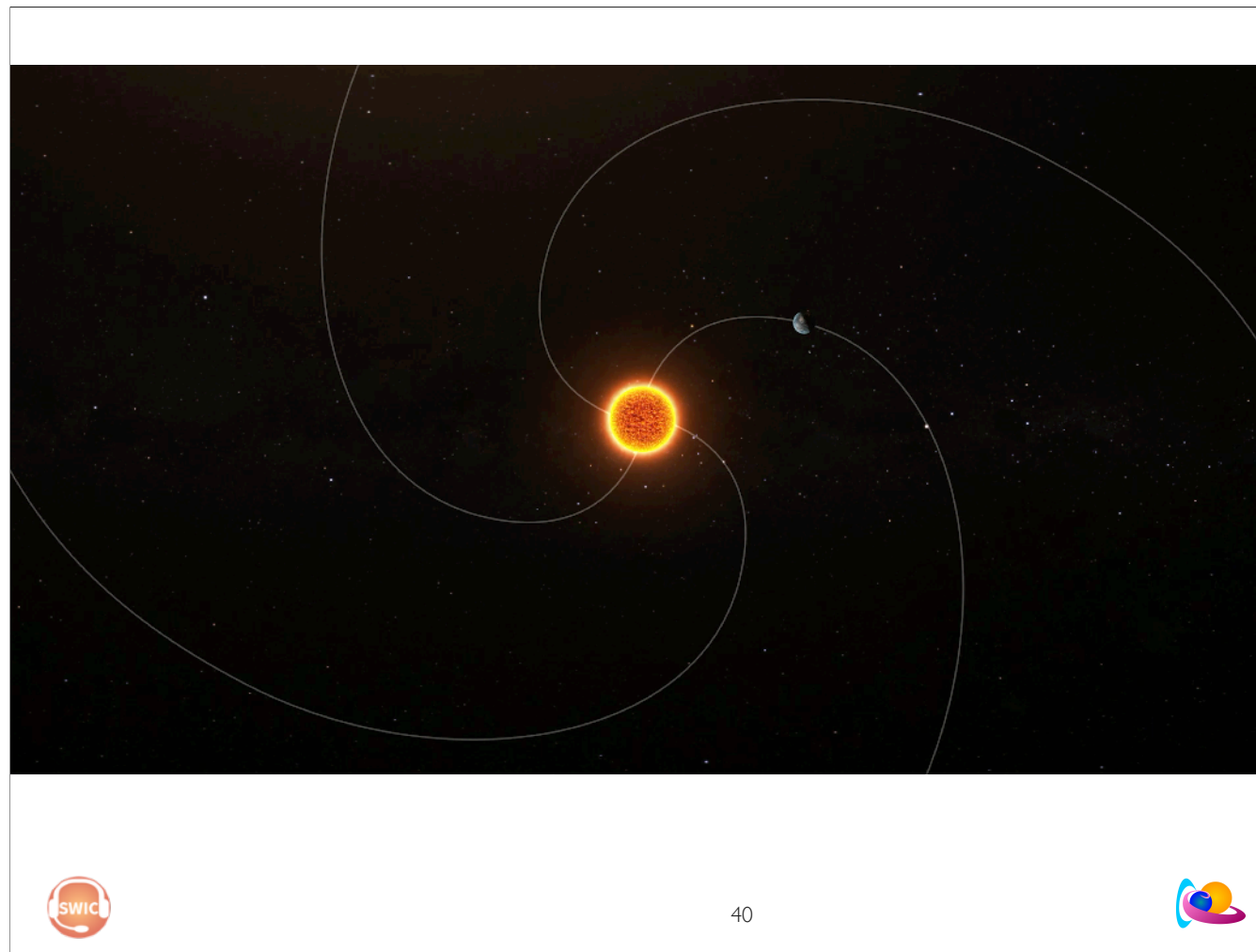
SOLAR PARTICLES



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



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



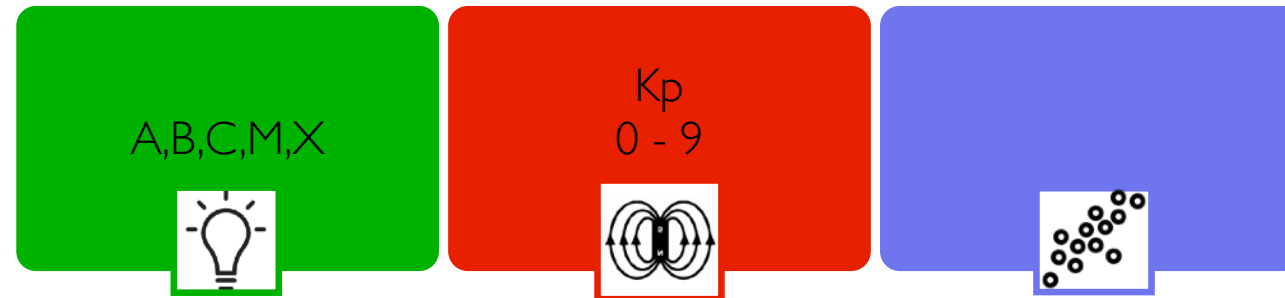
HOUR



STORM SCALE

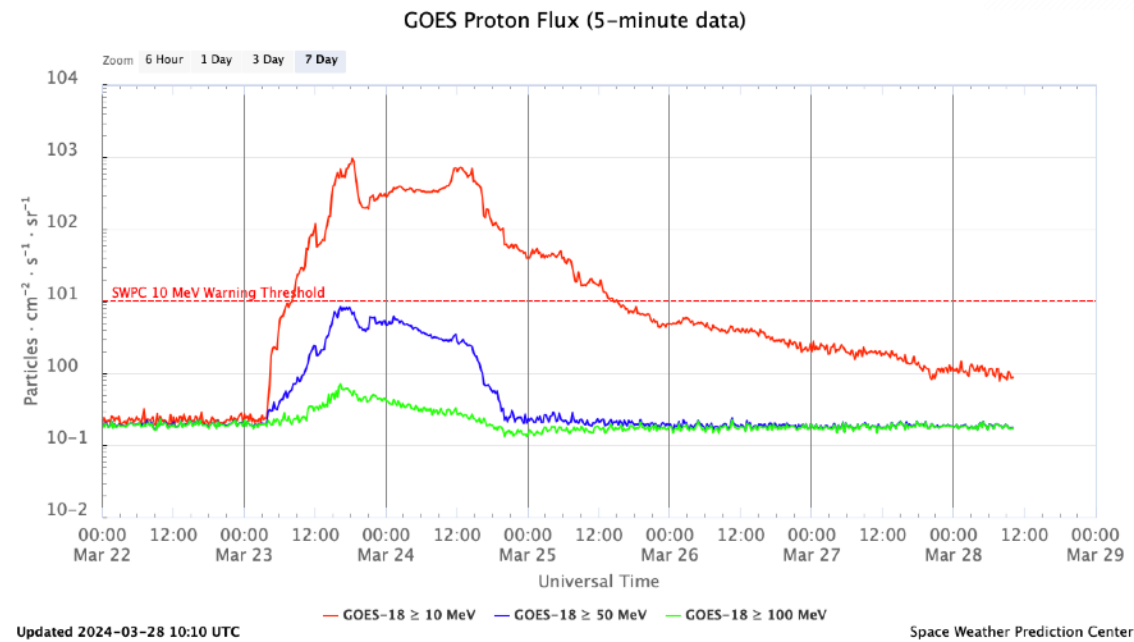


<https://www.swpc.noaa.gov/products/goes-proton-flux>



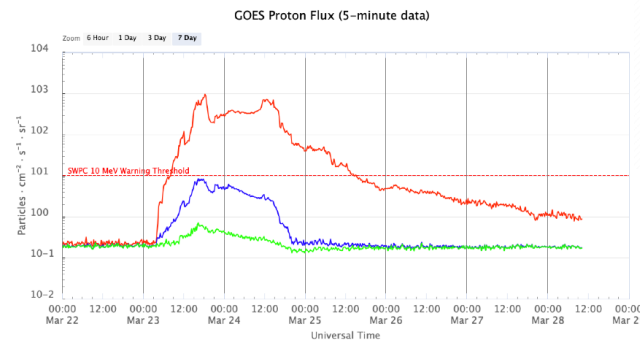
The GOES satellite measures the proton flux.
Storm: 10 pfu (proton flux units) for >10MeV
Major storm: 100 pfu for >100MeV

STORM SCALE



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

STORM SCALE



A,B,C,M,X



Kp
0 - 9

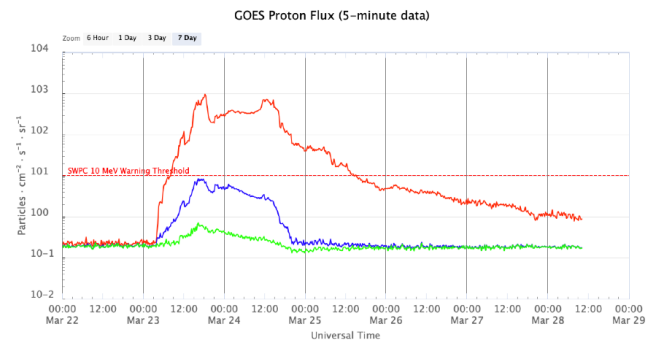


Storm - major storm



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

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

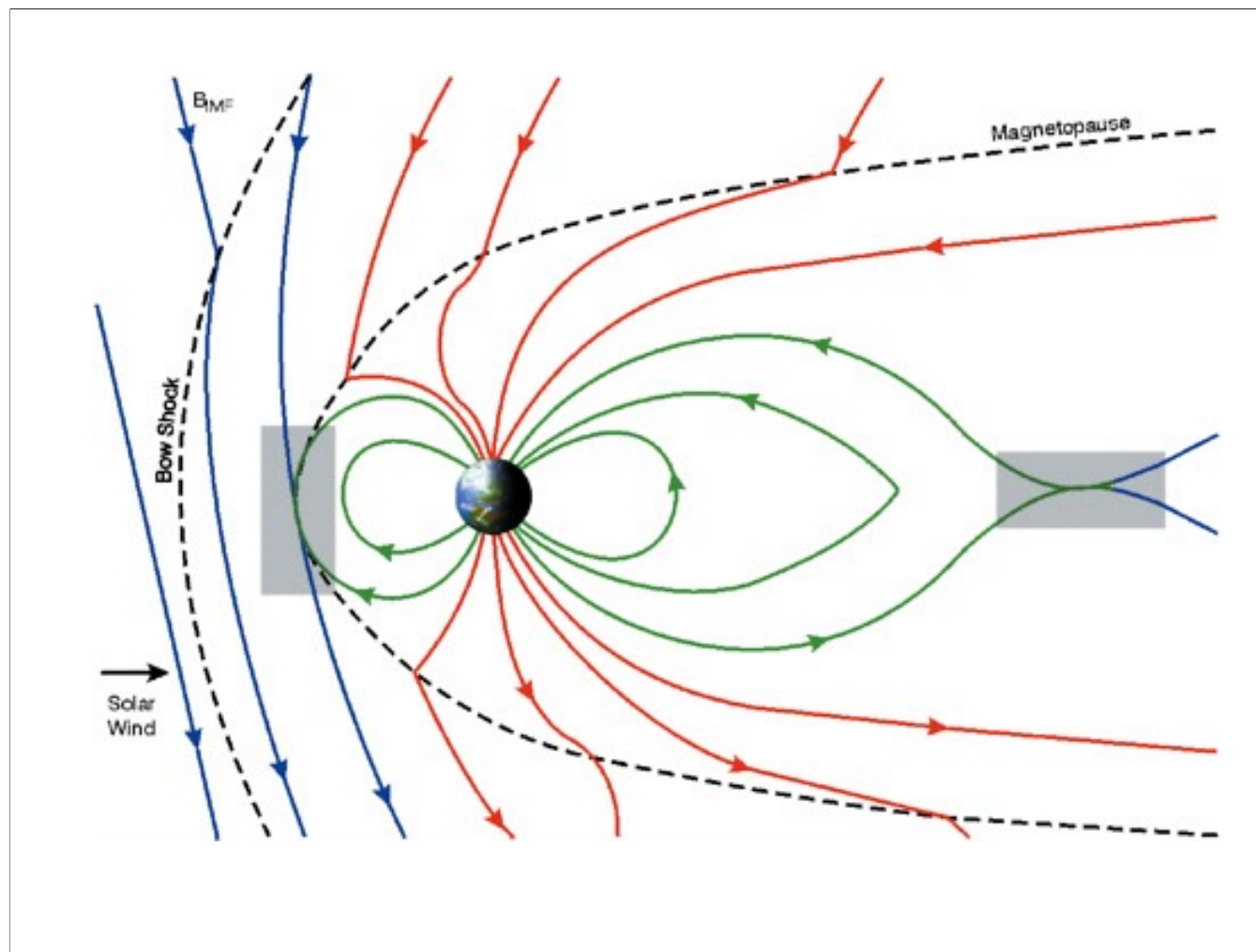


Illuminated area



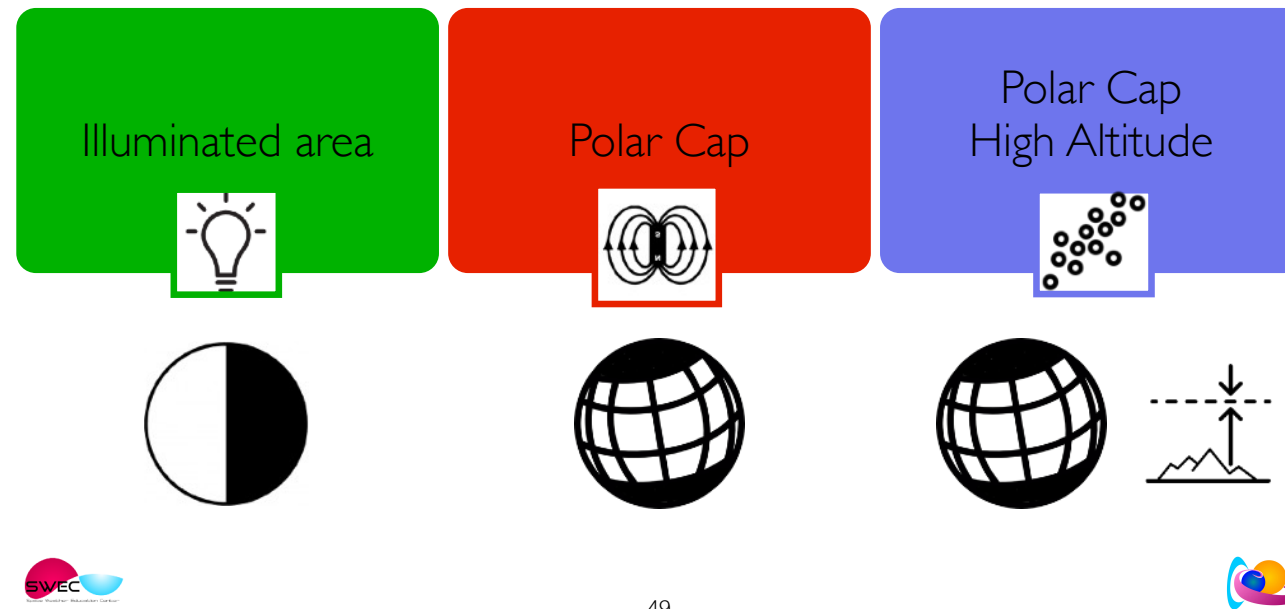
Polar Cap



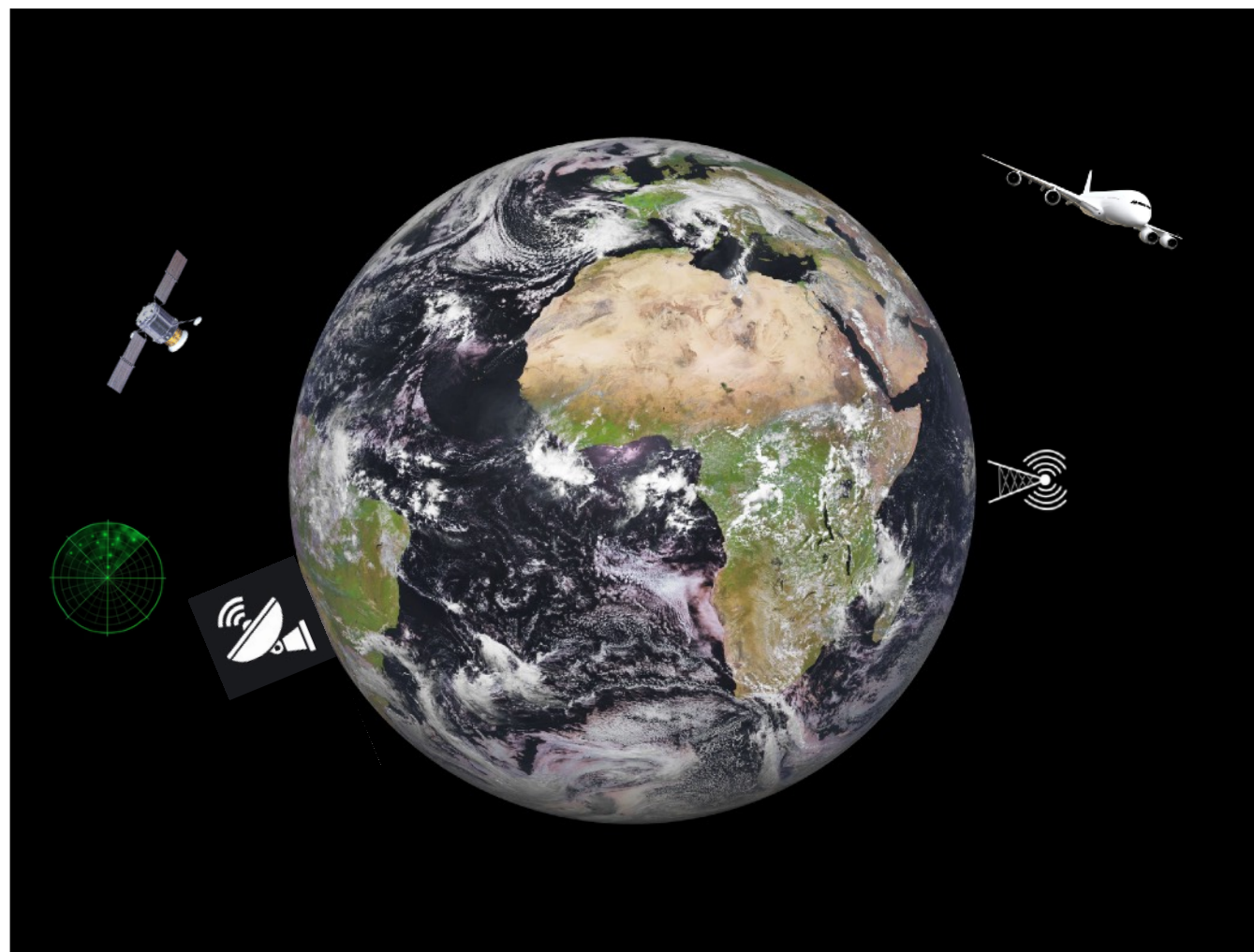


The solar energetic particles catch up with a magnetic field line of the earth's magnetosphere and gyrate down towards the polar regions. They mainly drop in in the area with open magnetic field lines (red).

AREA OF IMPACT



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

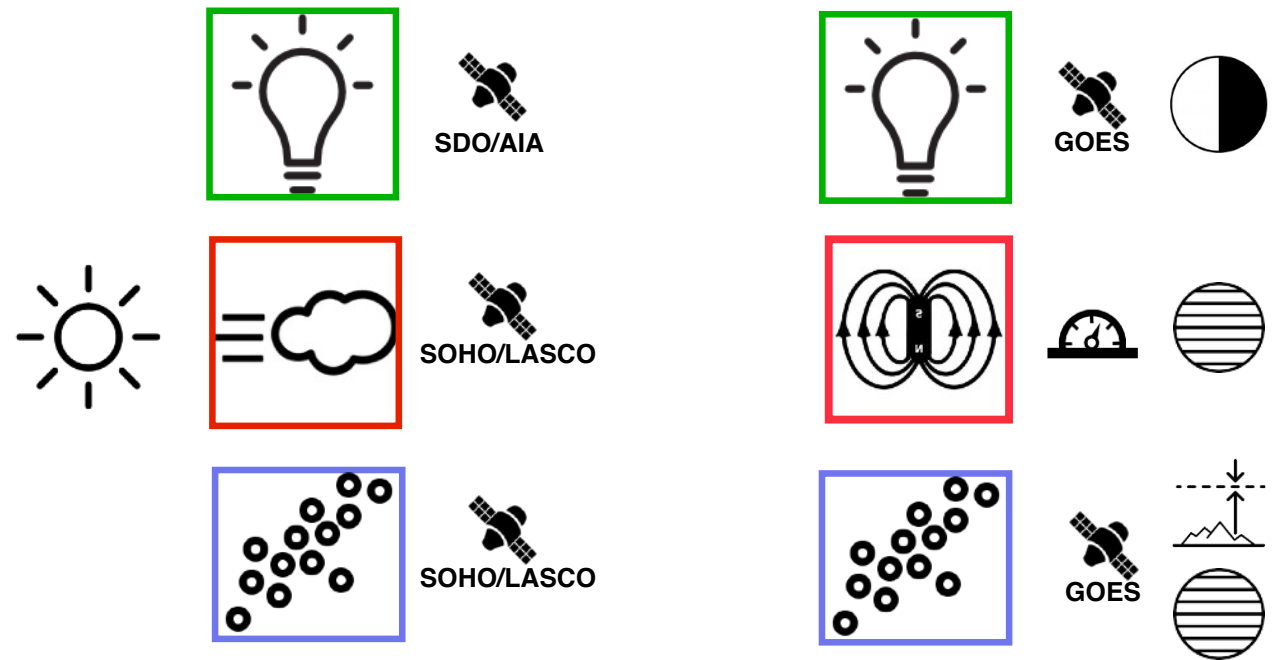


Radiation at flight altitude

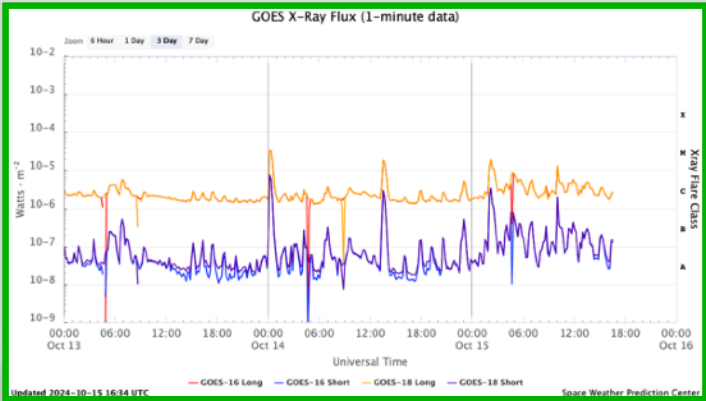
HF com

- PCA - extra ionisation that absorbs HF radio waves when they pass.

OVERVIEW



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.

Use

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

Units

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

Data location

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

Sensor

GOES-16 satellite
GOES-18 satellite

Sensor location

Geostationary orbit

Cadence

Integrated over 1 min

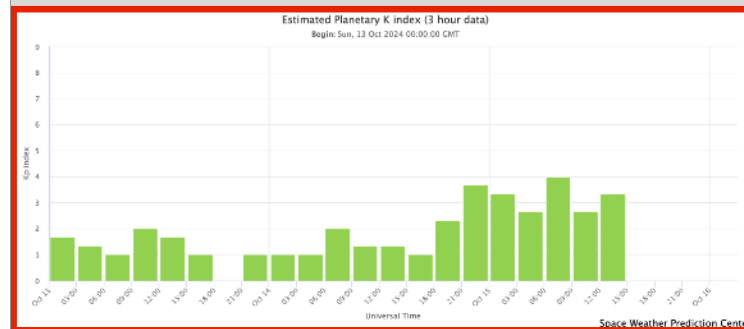
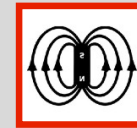
Plot

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



Definitive

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

Observatories

Thirteen (13) Geomagnetic Observatories between 44 degrees and 60 degrees northern or southern geomagnetic latitude.

Magnetometers

The calculation is based upon the measurements done by magnetometers.

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.

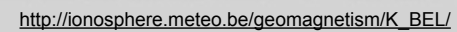
Estimated

by NOAA, US

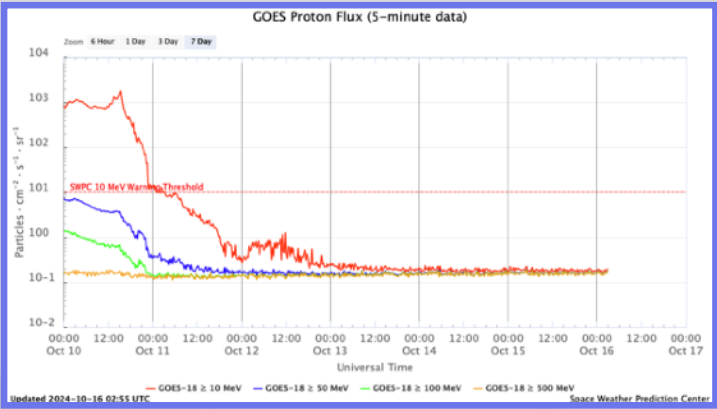
Data location

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

Space Weather Education Center



Proton Flux Passport



Plot

X-axis: time in UTC
Y-axis: Particles/(cm²*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.

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/(cm²*s*sr) with s=second and sr=steradian

Cadence

Integrated over 5 min

Data location

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

Space Weather Education Center