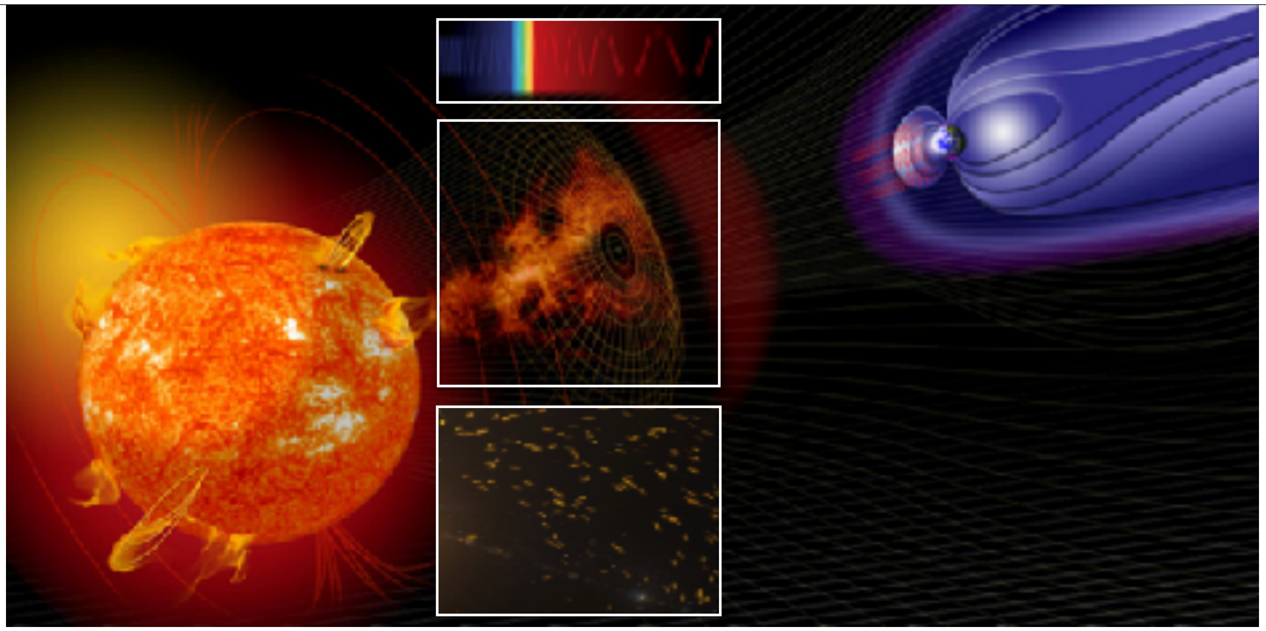
Space Weather impacts on Ionospheric wave propagation
-
Focus on GNSS and HF

SWEC
Solar-Terrestrial Centre of Excellence



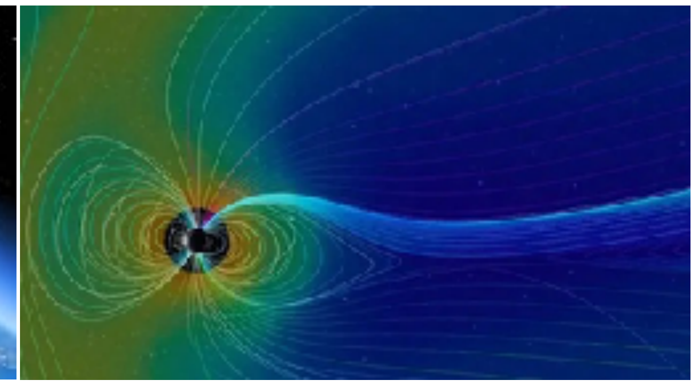
SPACE WEATHER

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 AS A BALL OF ENERGY

The sun emits continuously energy which is expelled to outer space in the form of electromagnetic waves and particles.

E.M. WAVES

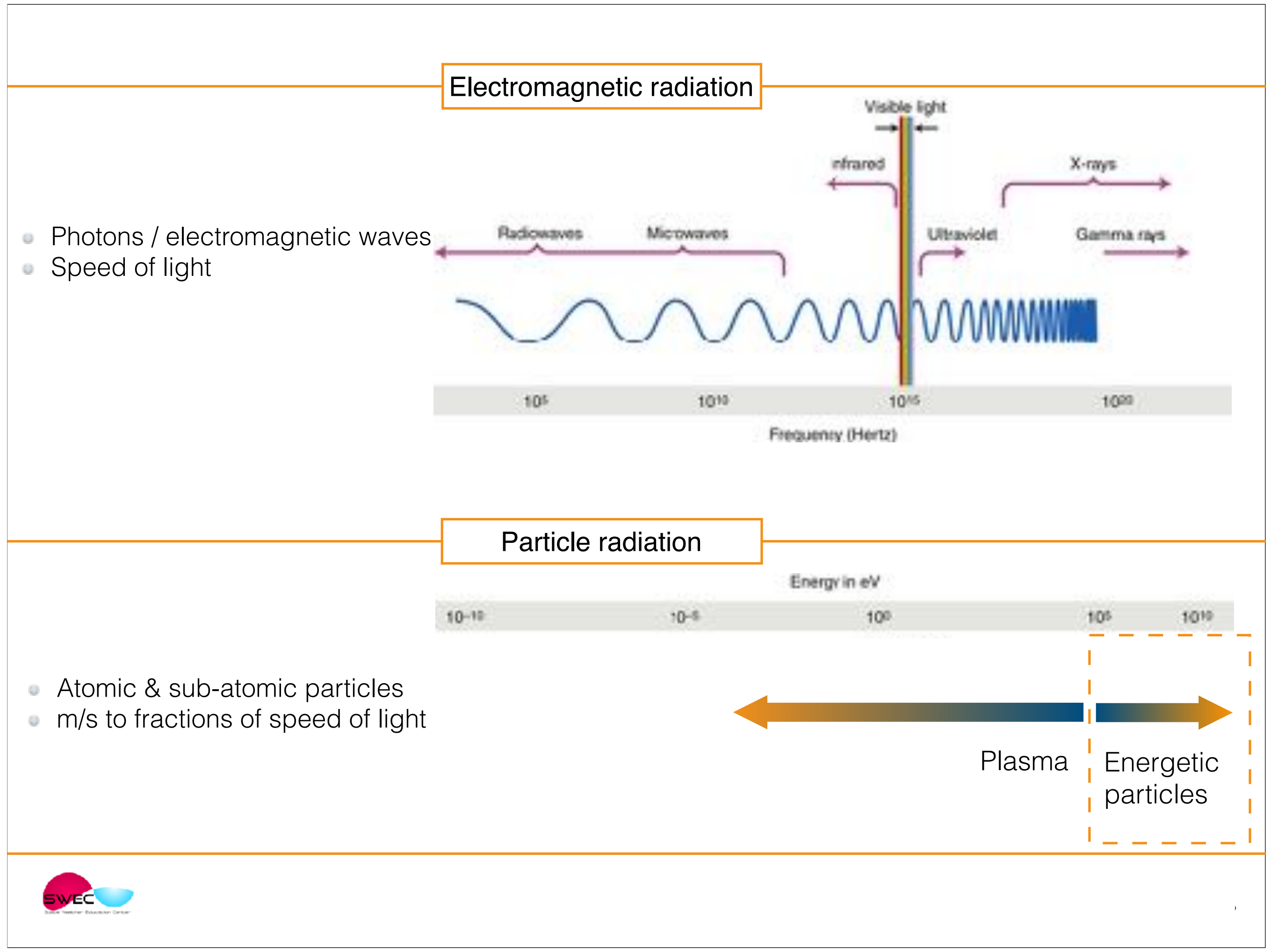
PARTICLES

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 and 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

Wave: wavelength, amplitude

Speed of light in vacuum

Doesn't need a medium to propagate

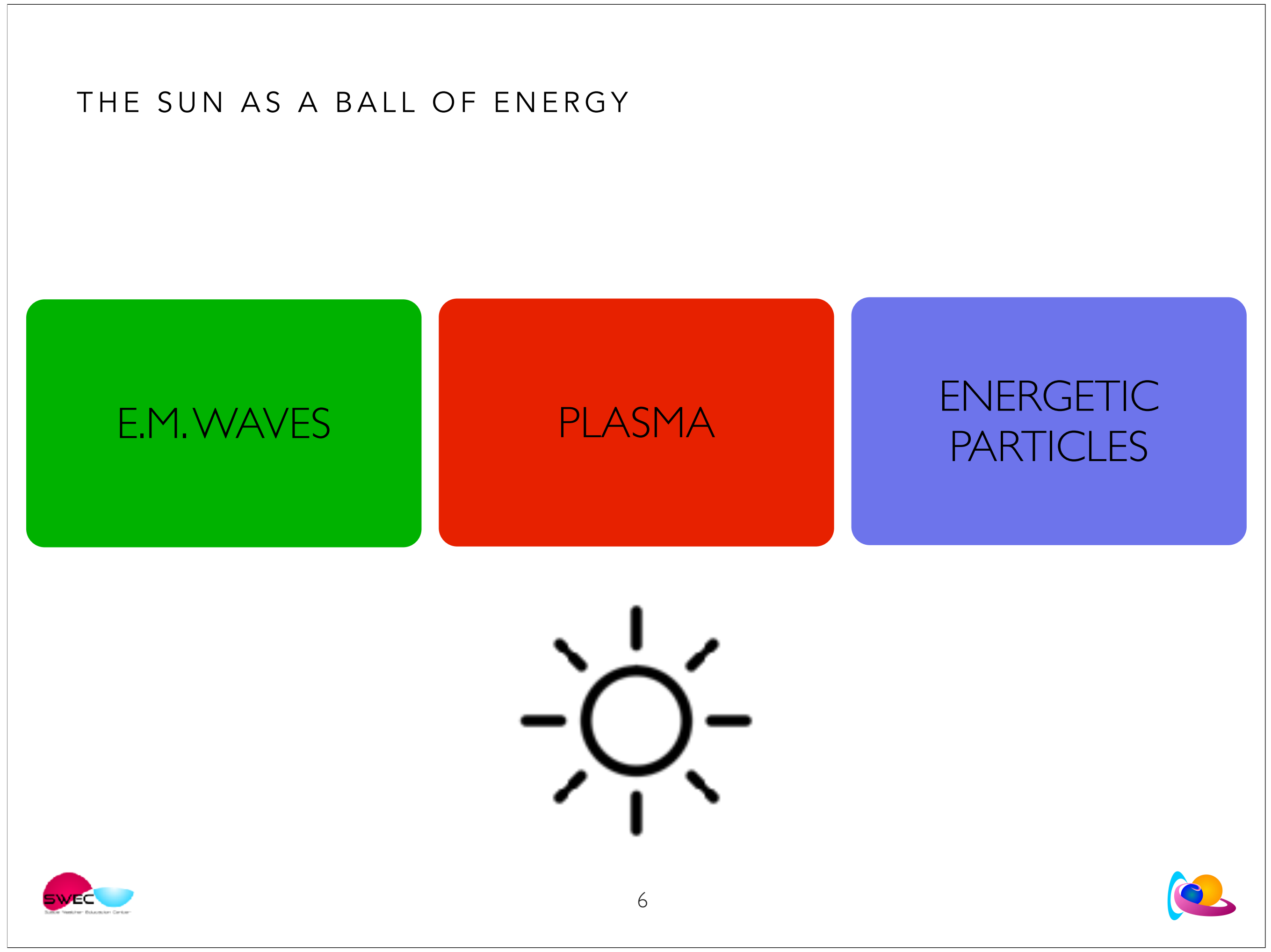
Doesn't need to follow magnetic field

Solar energetic particles

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

Ionizing radiation (or ionising radiation), including nuclear radiation, consists of subatomic particles or electromagnetic waves that have sufficient energy to ionize atoms or molecules by detaching electrons from them.[1] Some particles can travel up to 99% of the speed of light, and the electromagnetic waves are on the high-energy portion of the electromagnetic spectrum.

Gamma rays, X-rays, and the higher energy ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, nearly all types of laser light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and non-ionizing radiation in the ultraviolet area cannot be sharply defined, as different molecules and atoms ionize at different energies. The energy of ionizing radiation starts between 10 electronvolts (eV) and 33 eV.



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

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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	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.

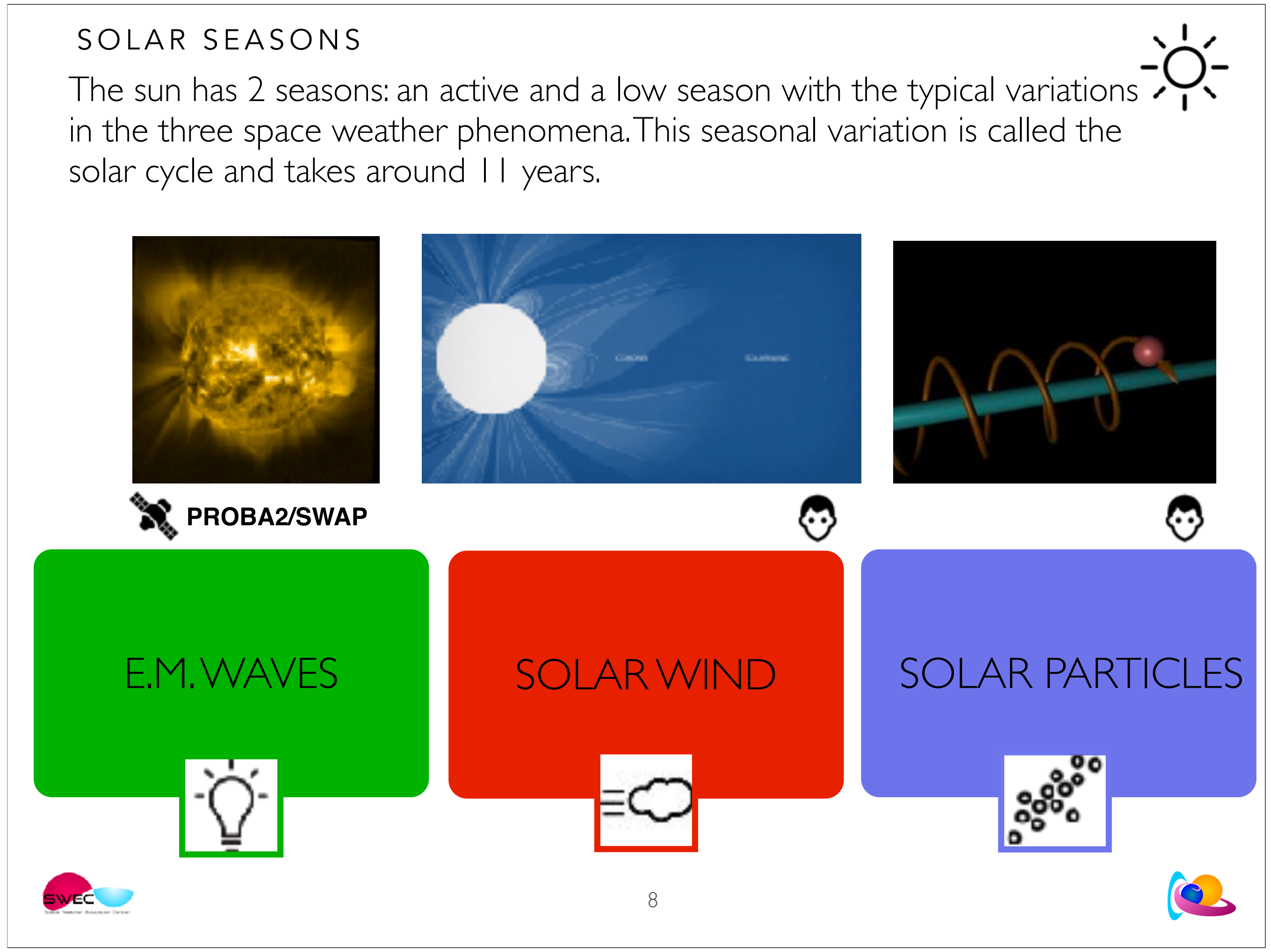
<100 kEV : plasma

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



The energy expelled in the form of solar material 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

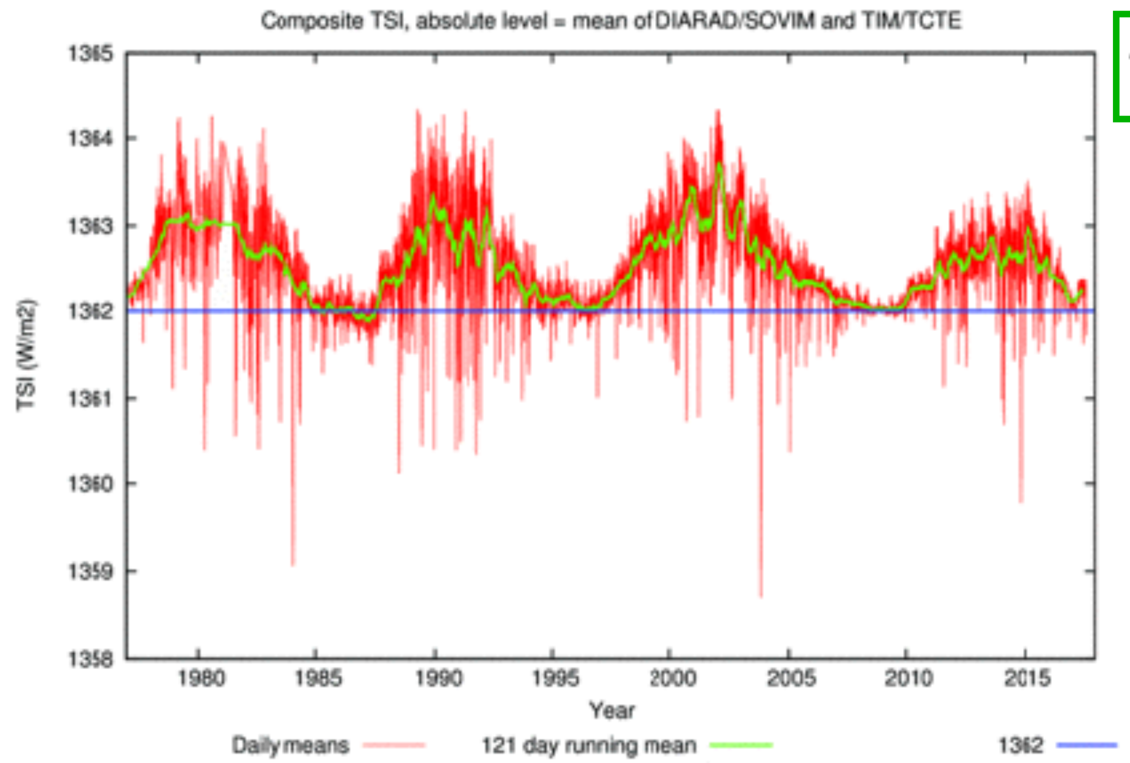
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you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

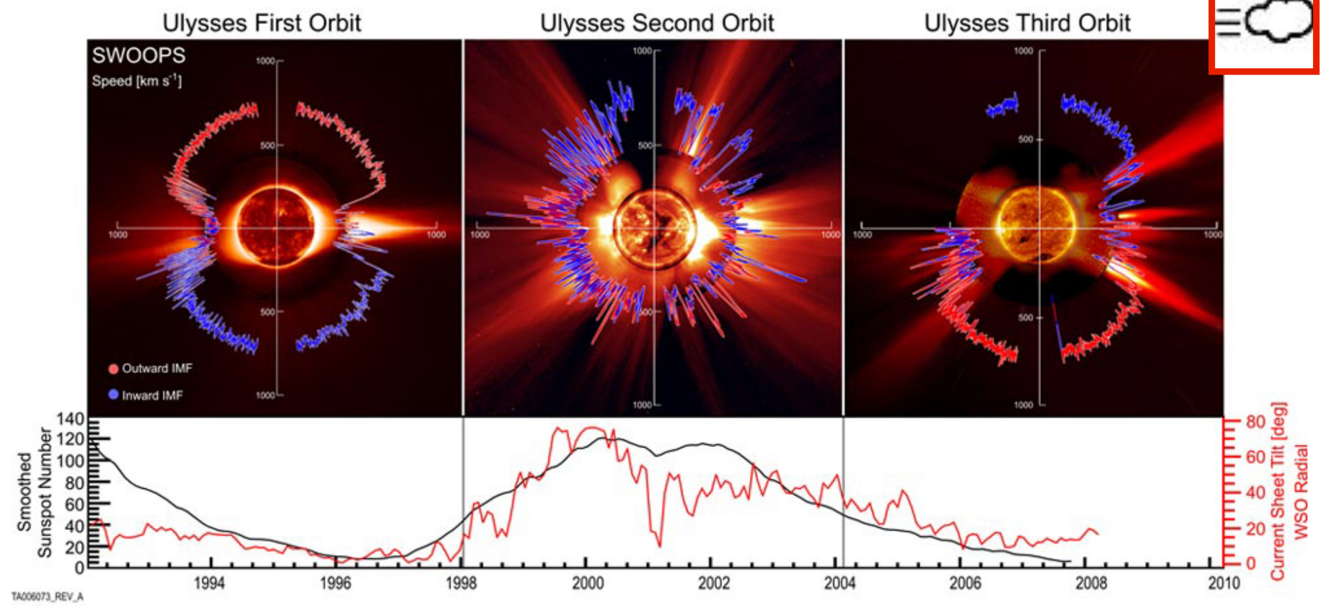
SEASONAL BEHAVIOUR OF LIGHT

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.

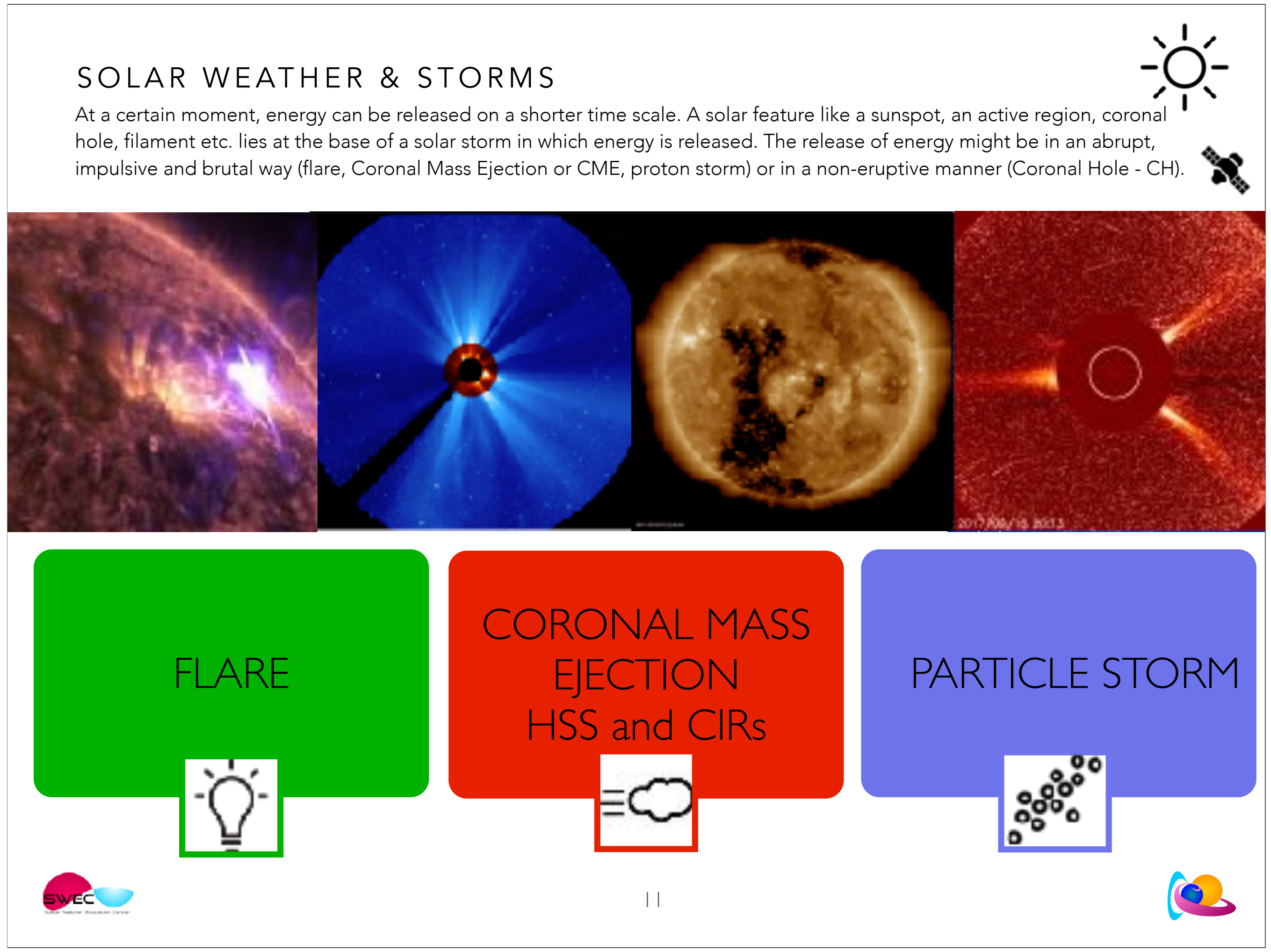
It seems that the solar wind is not the same on all places of the solar disk, it depends on the latitude.

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.



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 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

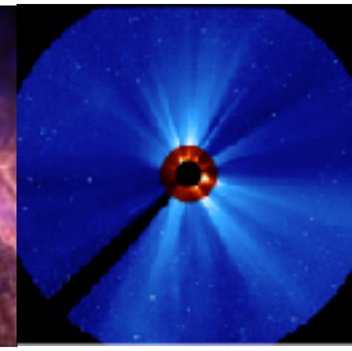
Particle shower
A particle storm is a bunch of electrically charged particles that are accelerated in the solar atmosphere to very high velocities by a large-scale magnetic eruption often causing a CME and/or solar flare.
They follow the IMF
They may impact telescopes. They are seen as white stripes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

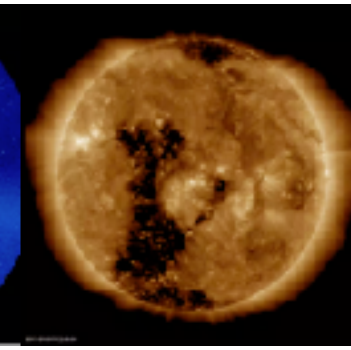
In situ means that you measure a parameter local. Remote sensing means that you look at something from a distance.

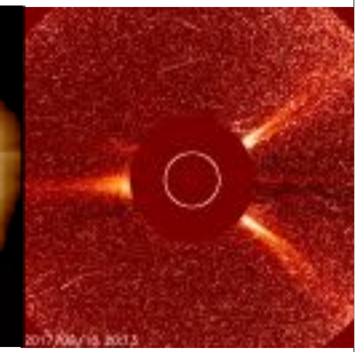
Near Earth, the IMF still controls the solar wind and its movement. If we would go much much further, the CME magnetic bag with solar plasma would be almost empty (all the solar material is spread over an immense volume) and the magnetic bag would have evaporated. But, this doesn’t matter for us. We are at 1AU and at 1AU the IMF and solar plasma make space weather in a normal way, in an extreme way.

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.







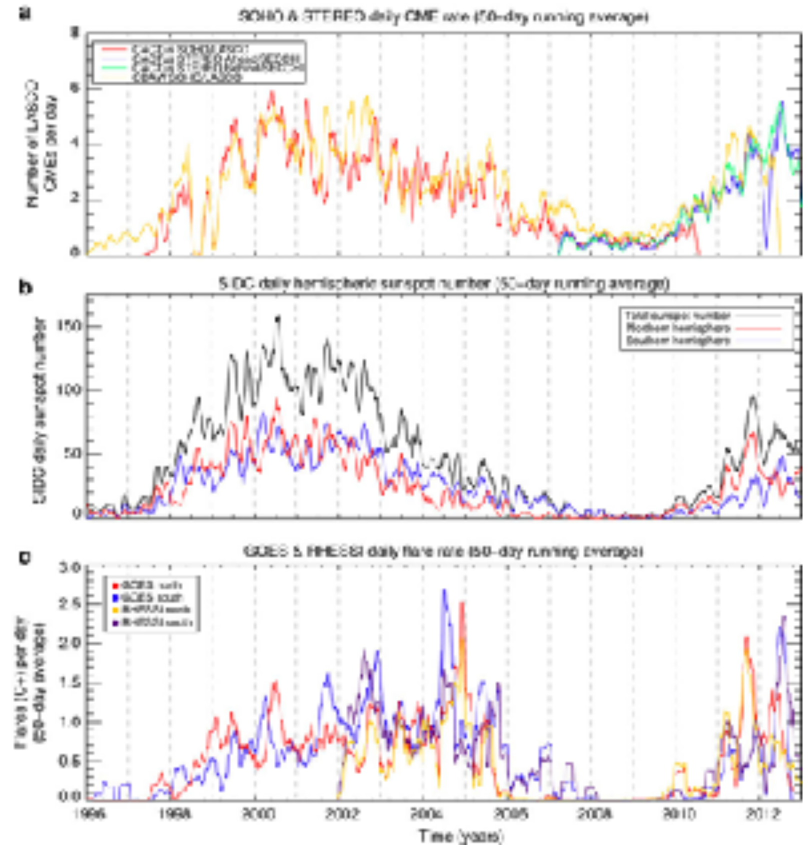
8 MIN

DAYS

HOUR

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.

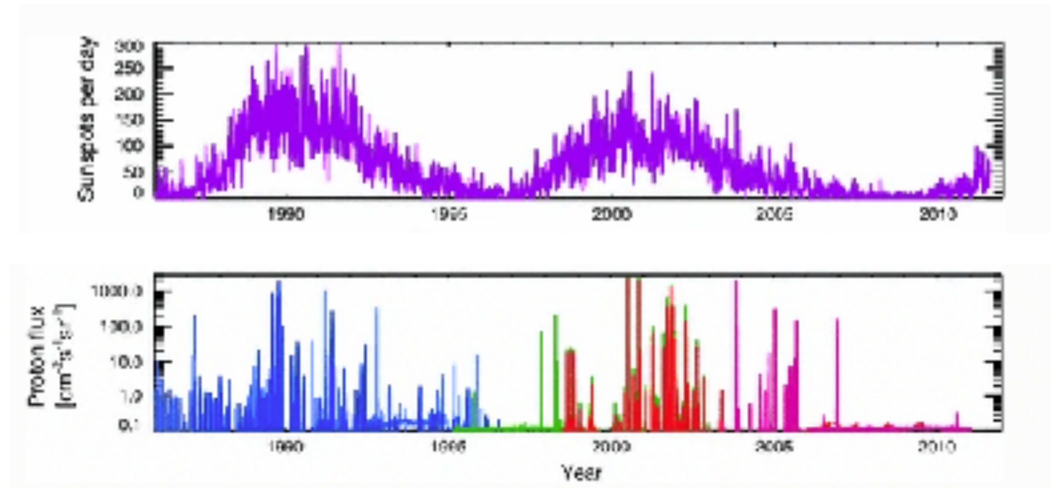


From https://www.researchgate.net/publication/274697133_The_solar_magnetic_activity_band_interaction_and_instabilities_that_shape_quasi-periodic_variability

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

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

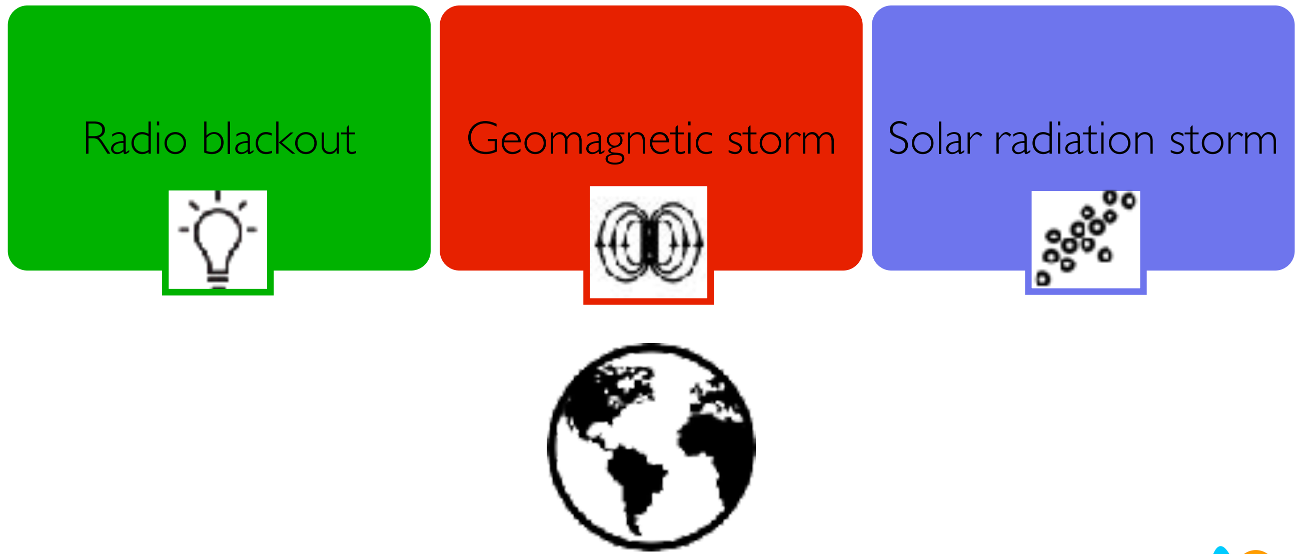


Less/More flares,CME's —> Less/More proton storms

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 <u>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)</u>. Data are from the National Geophysical Data Center (http://www.ngdc.noaa.gov)

SPACE WEATHER

Our atmosphere and magnetosphere can respond in a dramatic way to solar storms. A solar storm can initiate space weather processes in our atmosphere and magnetosphere or directly impact technological systems. Space weather and the strength of a space storm is measured near or on Earth.



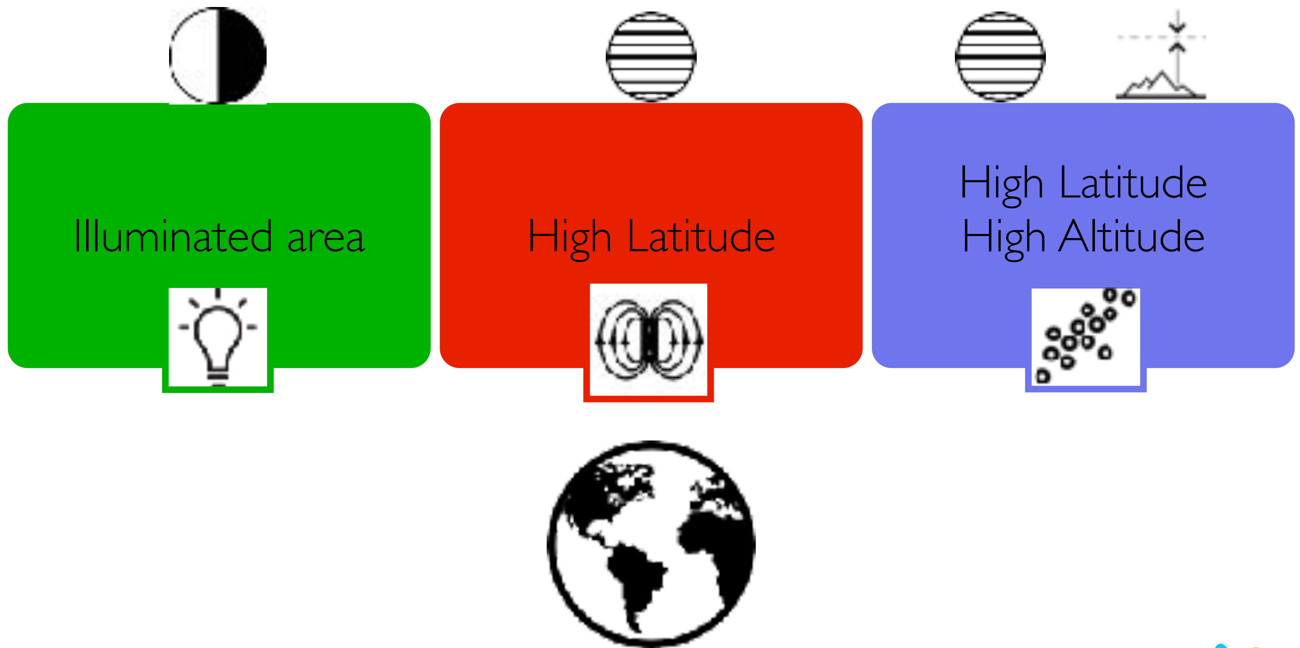
The consequence of a solar flare is a radio black out

The consequence of a troubled solar wind, is a geomagnetic storm.

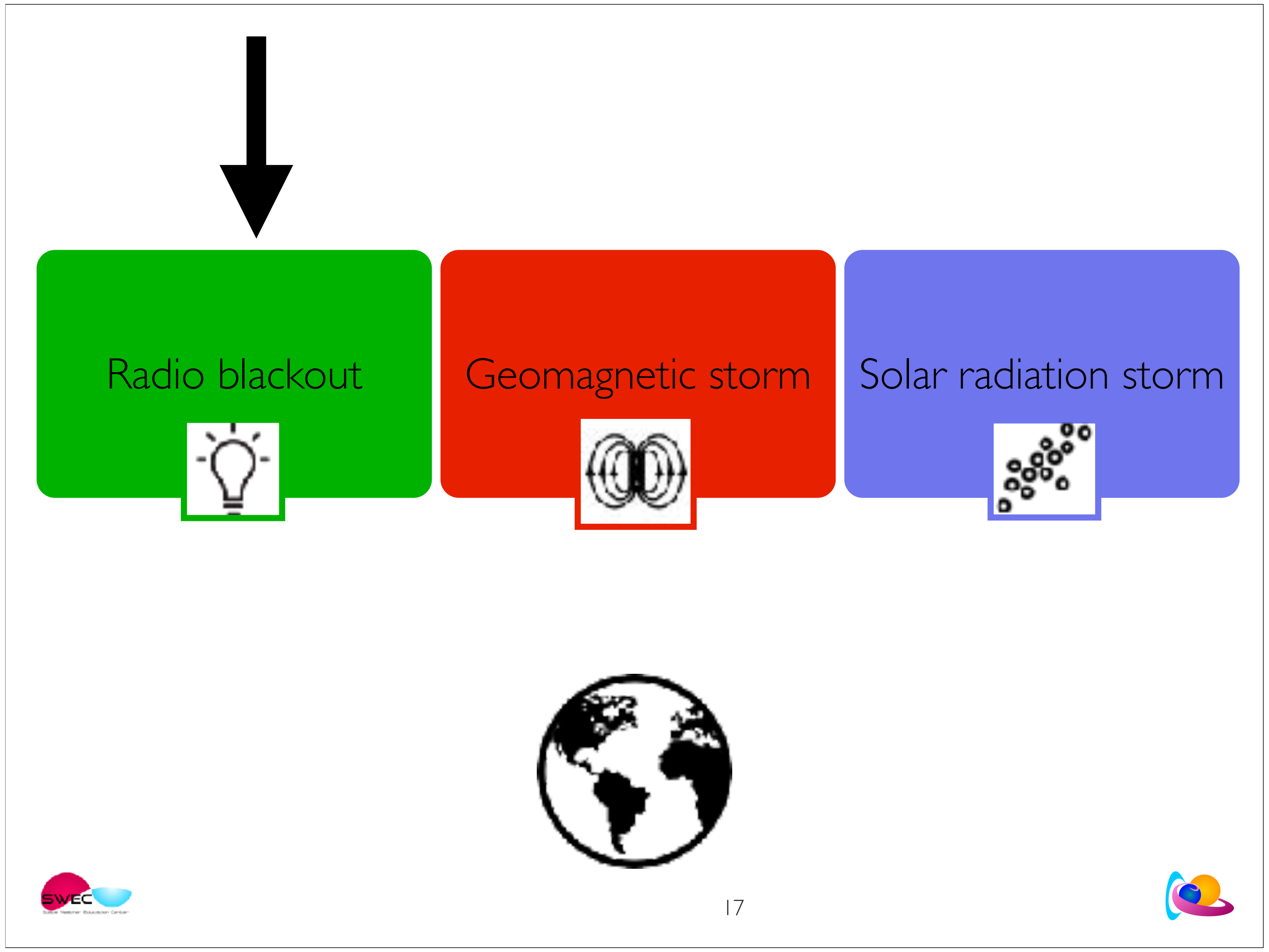
The consequence of a particle storm, is a solar radiation storm.
Not a geomagnetic storm. An individual particle doesn’t carry a magnetic field that can couple or disturb the magnetic field of Earth.

AREA OF IMPACT

Note that the solar wind can change the geomagnetic field by reconnection processes and by adding pressure. Reconnection is possible because the solar wind is magnetised. Charged particles follow simply the magnetic highways.



Solar wind - day and night side because of reconnection processes.
Particles - mainly on the day side.



The impact of a solar flare is a radio black out

The impact of a solar wind disturbance, is a geomagnetic storm.

The solar wind disturbs the earth magnetic field

The impact of a particle storm, is a solar radiation storm.

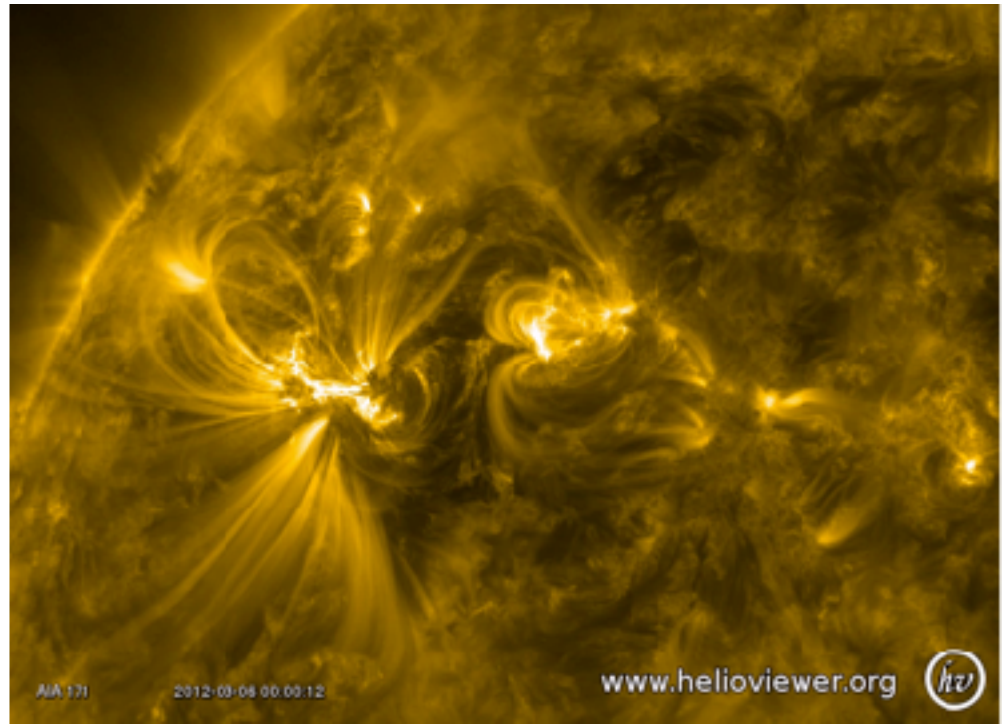
Not a geomagnetic storm. An individual particle doesn’t carry a magnetic field that can couple or disturb the magnetic field of Earth.

Em waves
Flow of gas
Moving particles

Flare

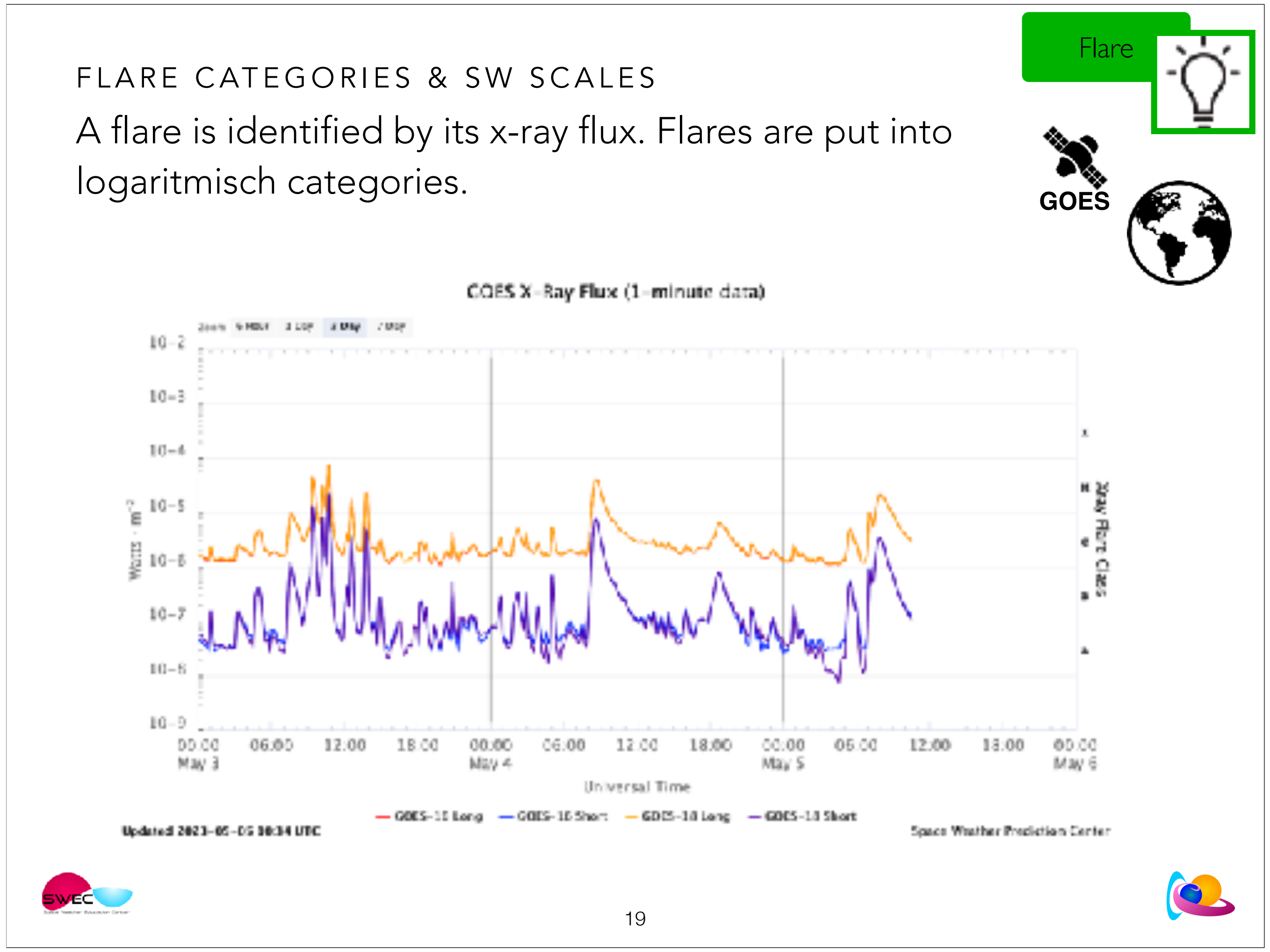
SOLAR FLARES

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



SDO/AIA

During a solar flare a particular plasma volume is heated. This happens in a brutal way and during a limited time. The volume is heated up to 107 K. The heating is a consequence of a fast reconnection and reorganisation of the local magnetic field.



In situ (taste and touch)

C1=1*10-6
C2=2*10-6 or 2*C1
C3=3*10-6 or 3*C1

M1=10-5=1*10*10-6=10*C1=C10 or 10*C1
M2=2*10-5= 2*10*10-6=10*C2=C20 or 20*C1
M3=3*10-5 = 3*10*10-6=10*C3=C30 or 30*C1
...

X1=10-4=1*10*10-5=10*M1=M10 = 1*10*10*10-6=100*10-6=100*C1=C100
X2=2*10-4=2*10*10-5=10*M2=M20 or 200*C1
...
Y1=X10 or 1000*C1
Y2=X20 or 2000*C1
Y8=X80 or 8000*C1
Y9=X90

GOES satellite, geostationary
http://www.swpc.noaa.gov/products/goes-x-ray-flux

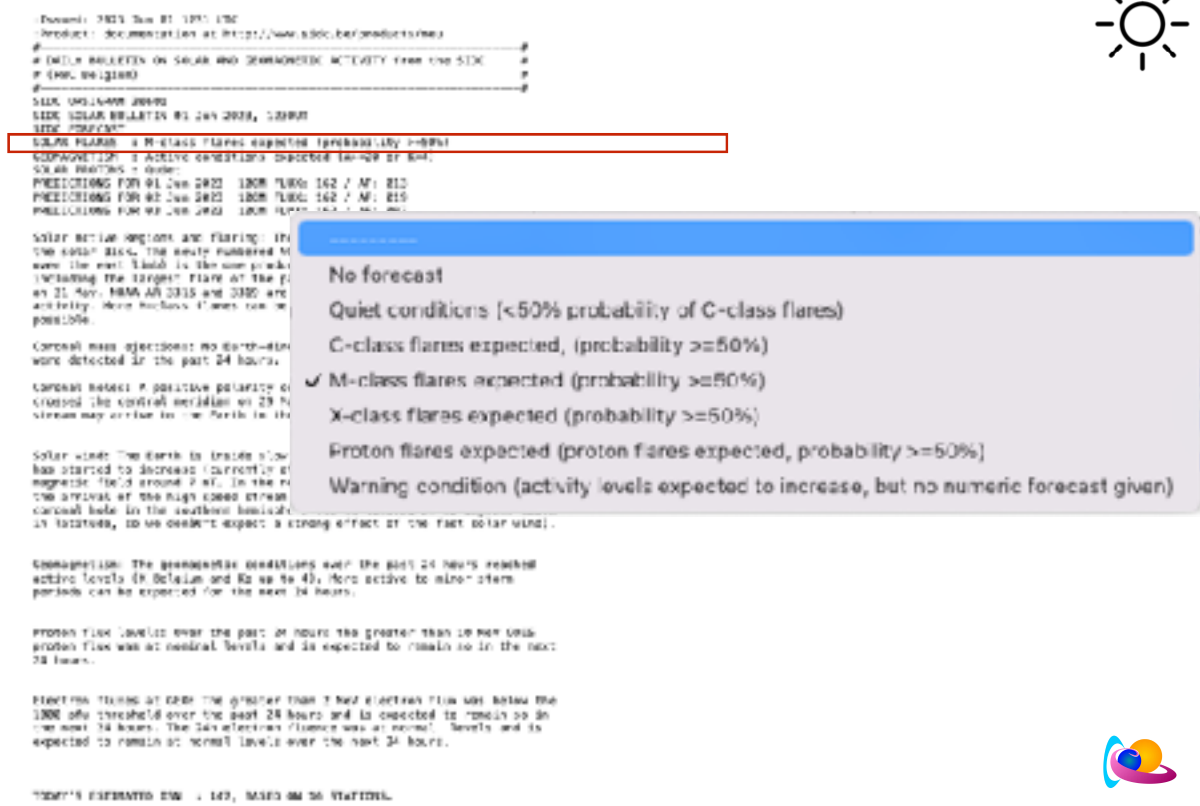
During a flare, magnetic energy is transformed into e.m. waves.

GOES measures the full disk e.m. radiation (Energy per second per square meter) in a particular X-ray wavelength every minute. The more intense, the higher the curve.

Flares are put into X-ray flux categories. The X-ray flux is measured by GOES (meteo-satellites of NOAA). The classes are based on the enlargement factor of the X-flux in the spectral range 1 to 8 Å – logarithmic. This enlargement factor can go up to 10 000, typically between 10 and 100.

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

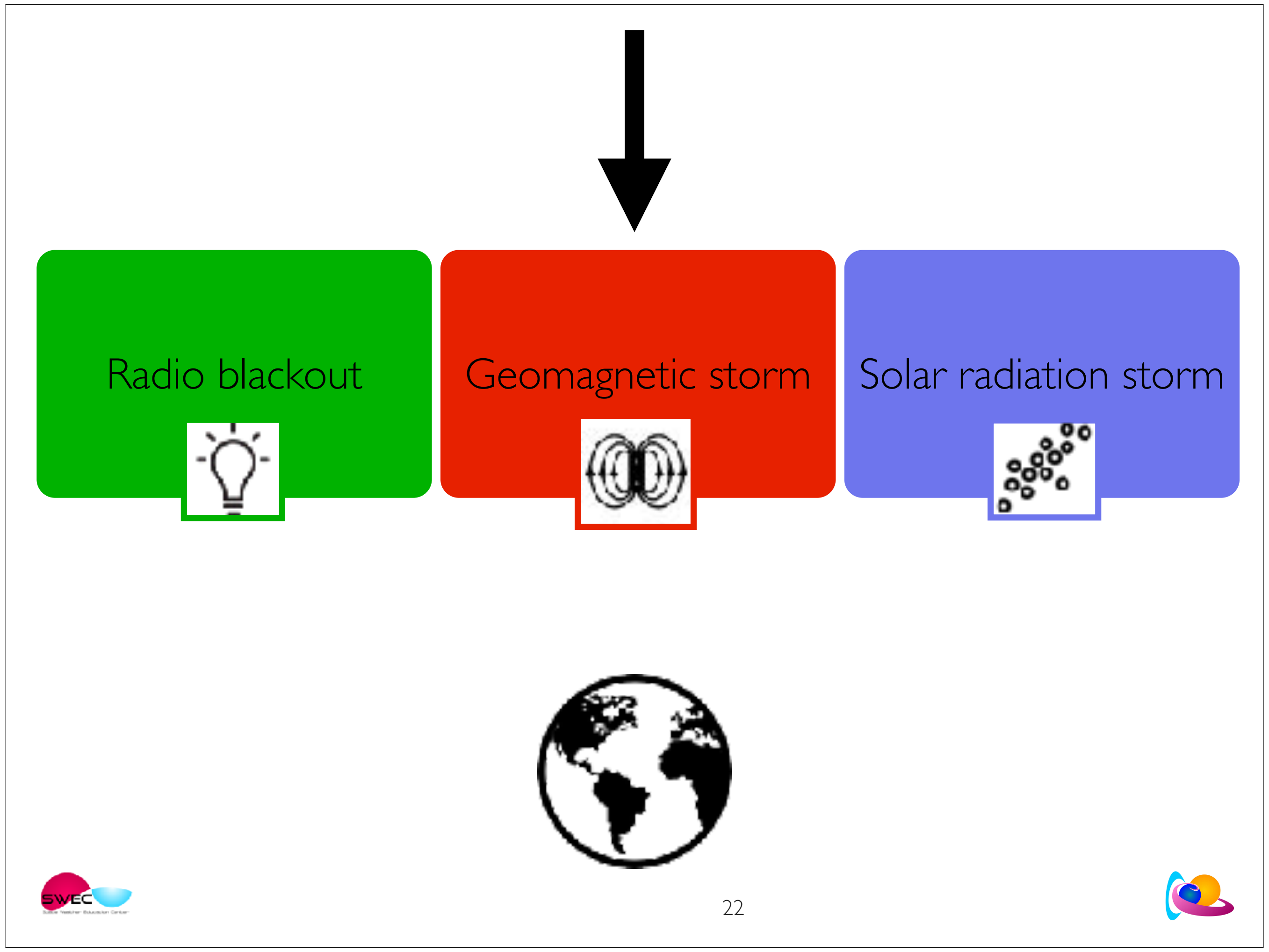
Flare predictions refer to the full disc but only in the **International Space Environment Service (ISES) categories**: classes according to 50% threshold exceeded for C, M or X flares

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.

Flare

X-RAY FLUX NOW

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



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https://www.swpc.noaa.gov/phenomena/geomagnetic-storms
A geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very efficient exchange of energy from the solar wind into the space environment surrounding Earth. These storms result from variations in the solar wind that produces major changes in the currents, plasmas, and fields in Earth's magnetosphere. The solar wind conditions that are effective for creating geomagnetic storms are sustained (for several to many hours) periods of high-speed solar wind, and most importantly, a southward directed solar wind magnetic field (opposite the direction of Earth's field) at the dayside of the magnetosphere. This condition is effective for transferring energy from the solar wind into Earth's magnetosphere.

Storms also result in intense currents in the magnetosphere, changes in the radiation belts, and changes in the ionosphere, including heating the ionosphere and upper atmosphere region called the thermosphere. In space, a ring of westward current around Earth produces magnetic disturbances on the ground. A measure of this current, the disturbance storm time (Dst) index, has been used historically to characterize the size of a geomagnetic storm. In addition, there are currents produced in the magnetosphere that follow the magnetic field, called field-aligned currents, and these connect to intense currents in the auroral ionosphere. These auroral currents, called the auroral electrojets, also produce large magnetic disturbances. Together, all of these currents, and the magnetic deviations they produce on the ground, are used to generate a planetary geomagnetic disturbance index called Kp. This index is the basis for one of the three NOAA Space Weather Scales, the Geomagnetic Storm, or G-Scale, that is used to describe space weather that can disrupt systems on Earth.

During storms, the currents in the ionosphere, as well as the energetic particles that precipitate into the ionosphere add energy in the form of heat that can increase the density and distribution of density in the upper atmosphere, causing extra drag on satellites in low-earth orbit. The local heating also creates strong horizontal variations in the ionospheric density that can modify the path of radio signals and create errors in the positioning information provided by GPS. While the storms create beautiful aurora, they also can disrupt navigation systems such as the Global Navigation Satellite System (GNSS) and create harmful geomagnetic induced currents (GICs) in the power grid and pipelines.

SOLAR WIND

Continuous radial outflow of plasma

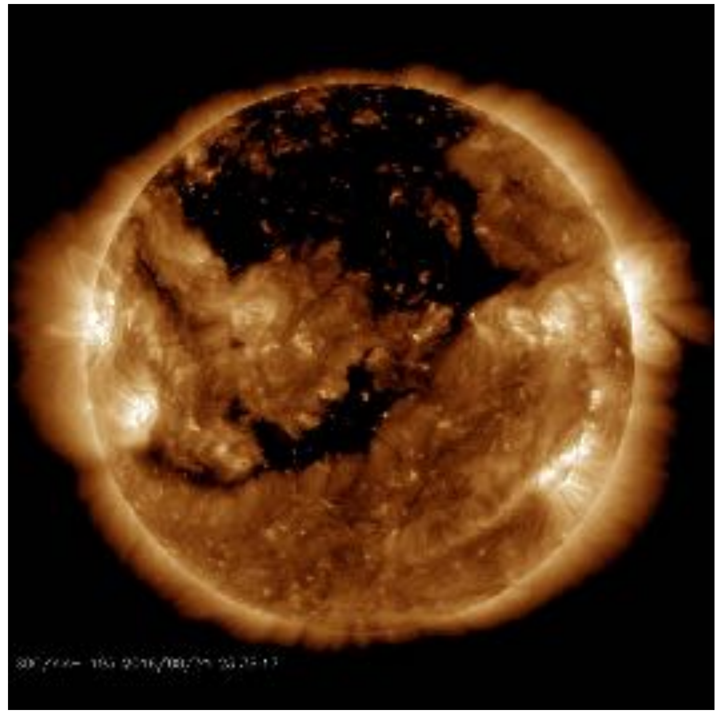
Shapes a magnetic field.

Transients - disturbances

Both constitute the solar wind
The solar wind plasma is glued to the IMF – or the IMF is glued to the plasma.

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.

Transients in the solar wind: lasting for only some time, impermanent



Transients

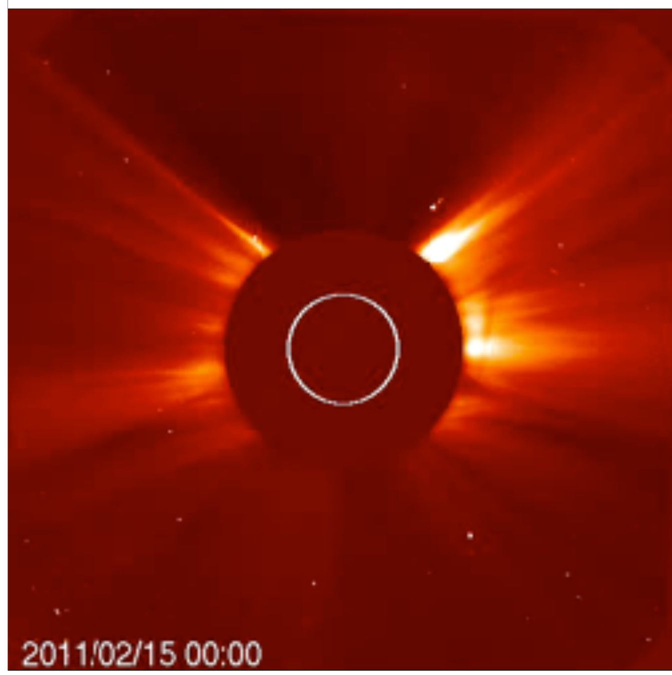
High Speed Streams (HSSs)

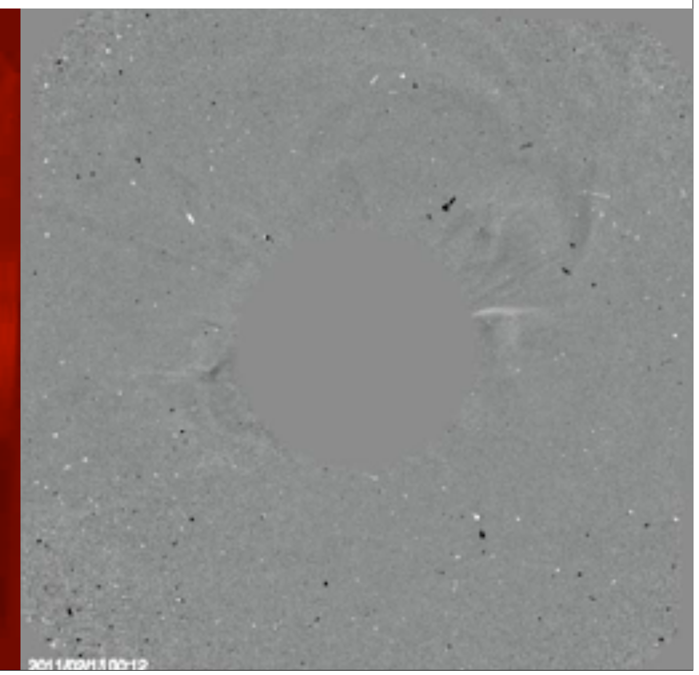
And

Co-rotating Interaction Regions (CIRs)

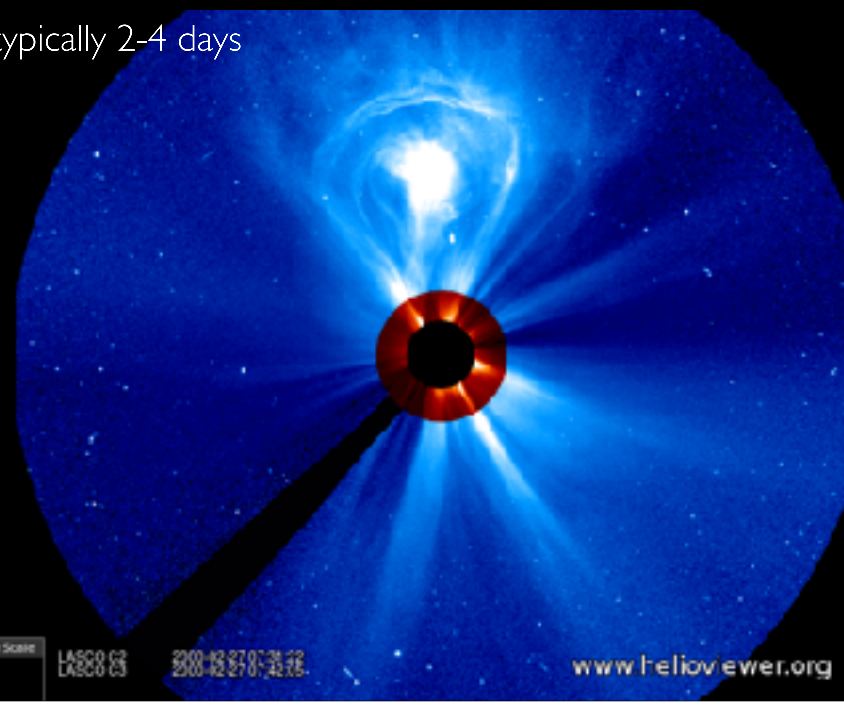
Transients

Coronal Mass Ejections





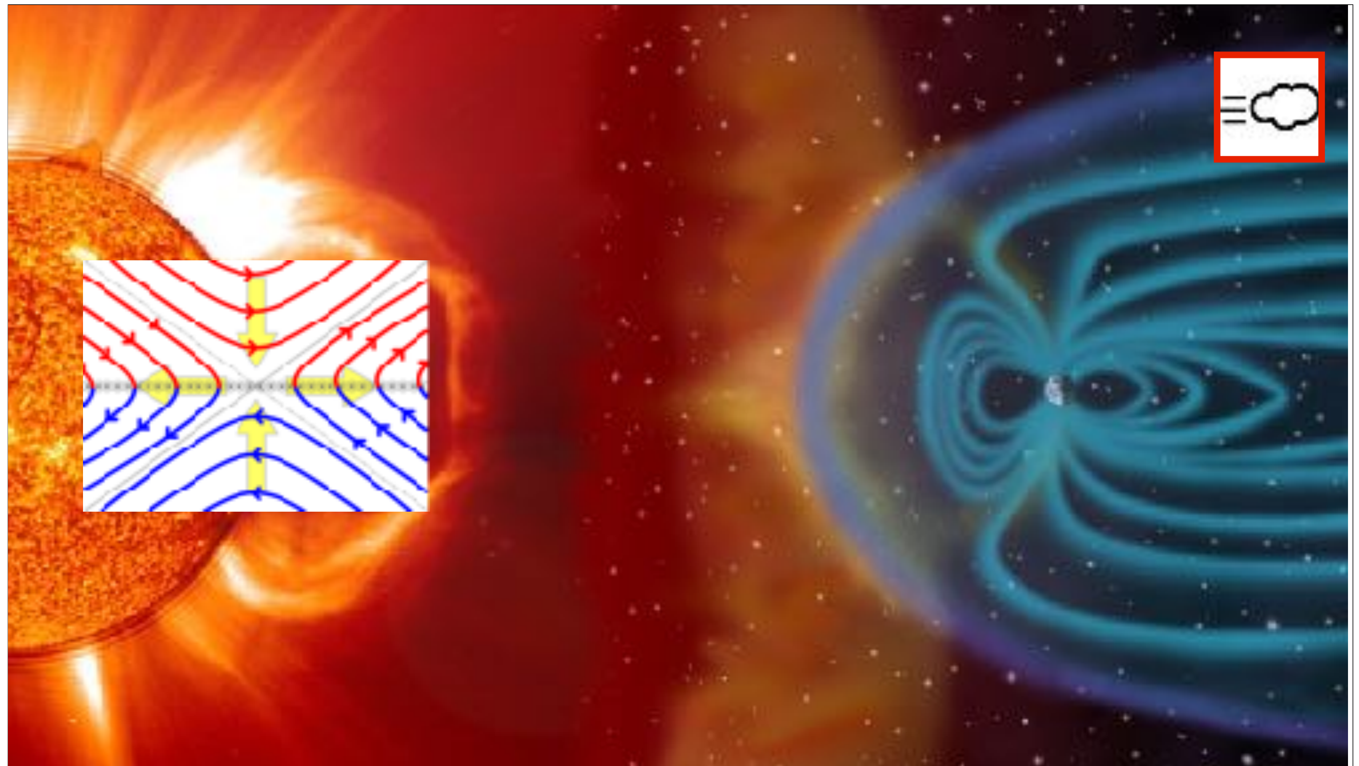
- Trigger the strongest geomagnetic storms
- <1/day during solar min, ~ 3 during solar max
- V between 400 and 2000 km/s
- Travel time typically 2-4 days



Transient: only lasting for a short time

Low density, but enormous and therefore massive.

CME is large: compare its size with the size of the sun.



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.

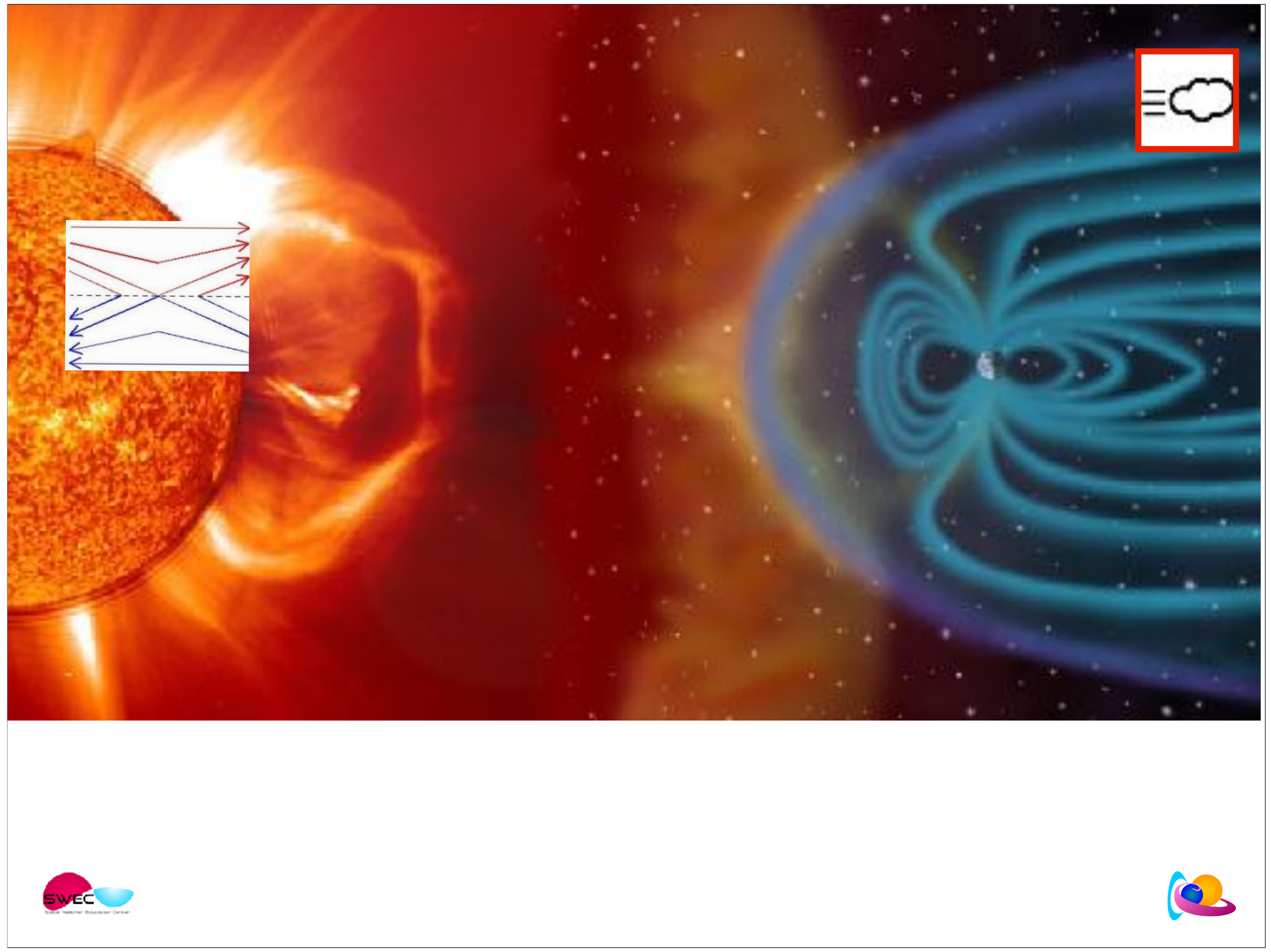
This is a structure similar like a shock in front of a speed boat that moves very fast over water: the water waves that the moving boat initiate are slower compared to the speed of the boat. The boat is super-water wave.
When a plane is super-sonic, there is also a shock in front of it. The pressure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



This is the earths magnetosphere. The sun is somewhere far away in the right top corner.
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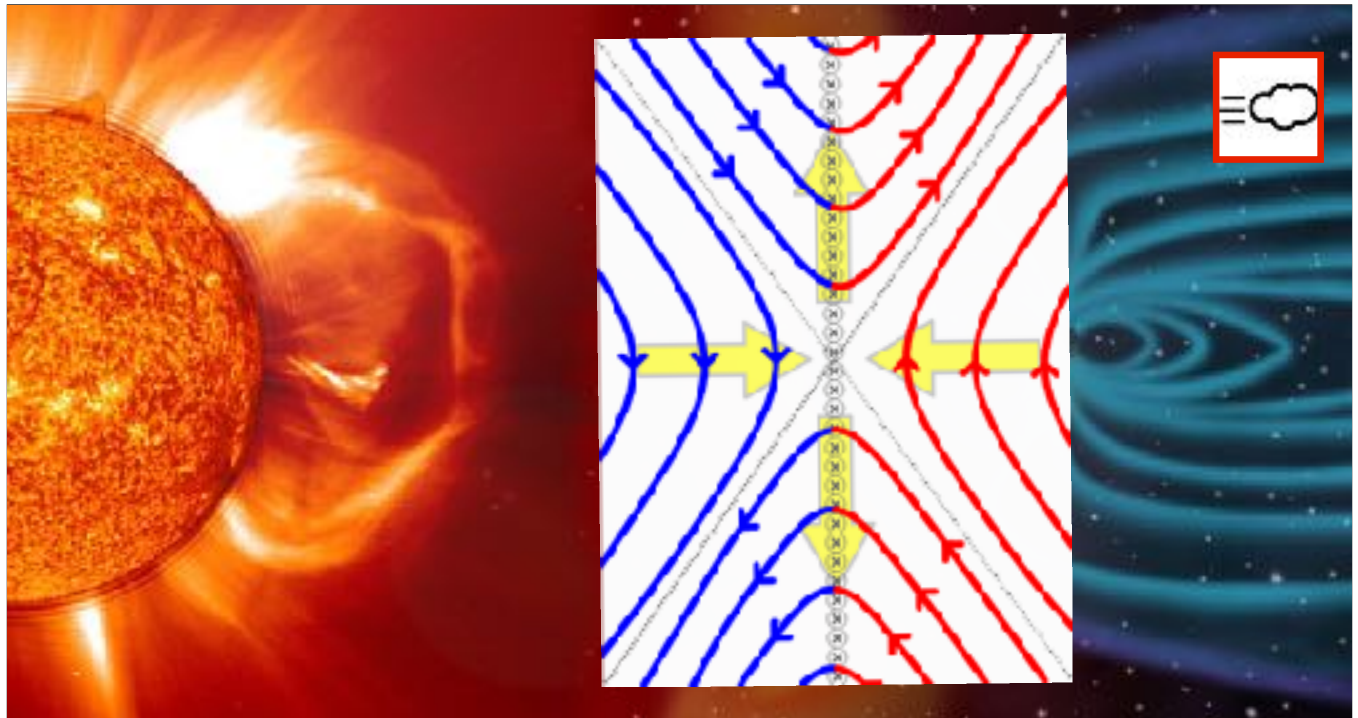
Solar wind meets Earth
Geoeffectivity



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.

Magnetic reconnection at the magnetosphere of Earth.
Doesn't matter if the wind is linked with a CH or CME.

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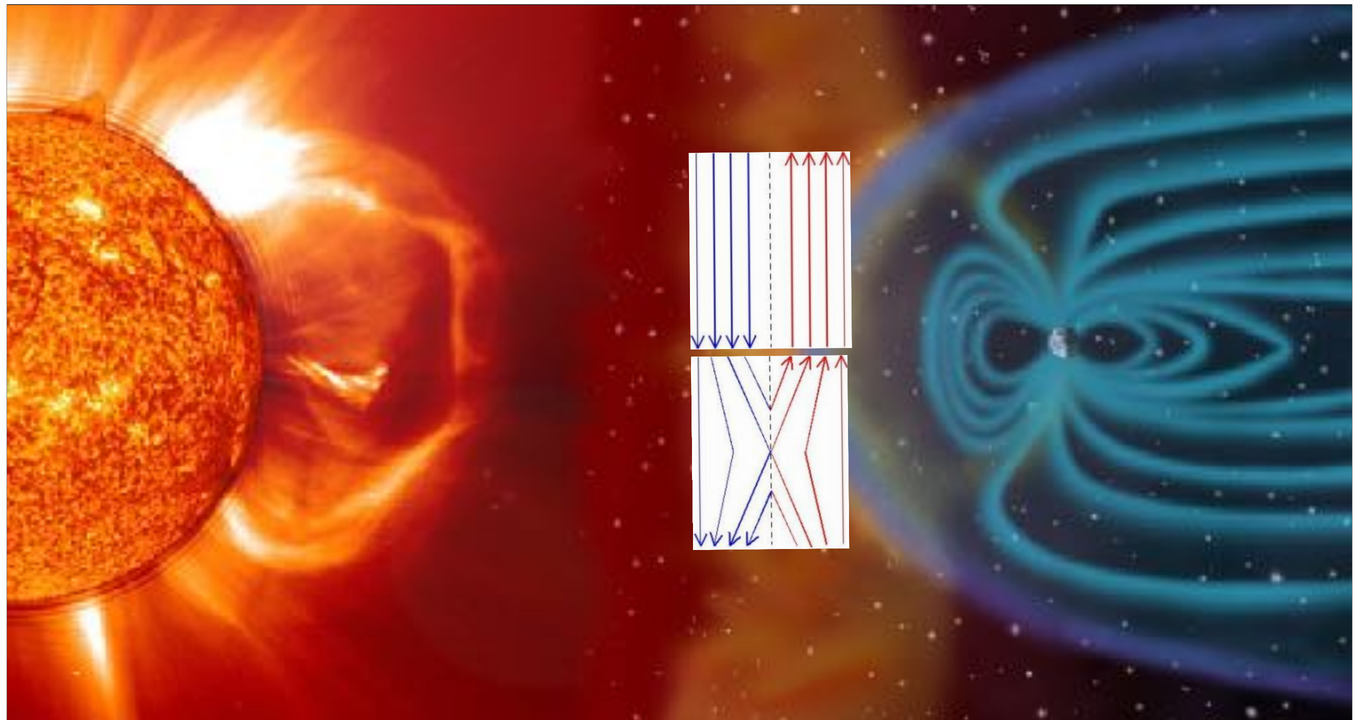

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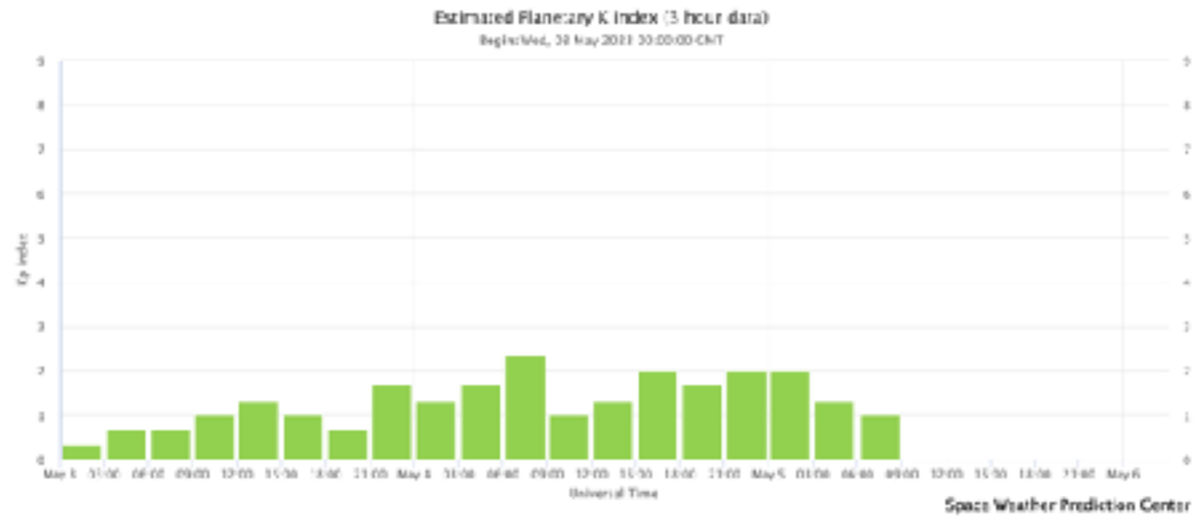
GEOMAGNETIC STORM

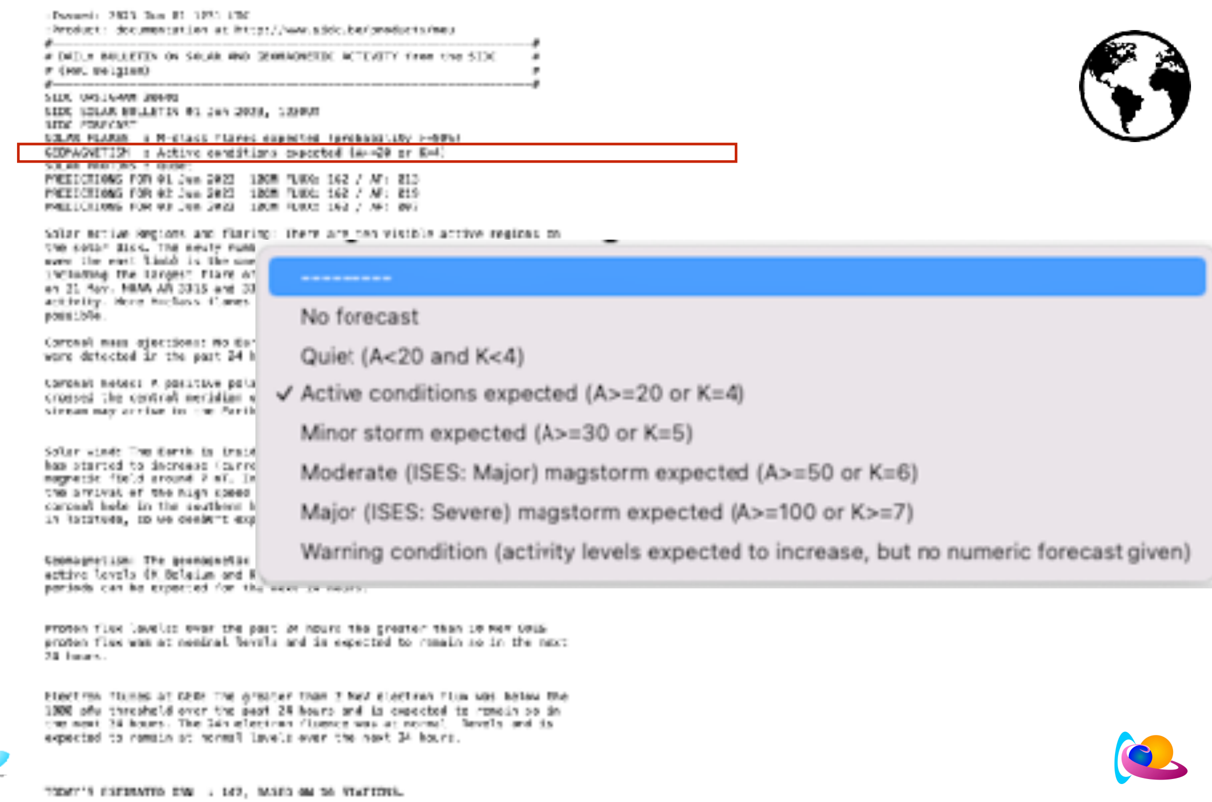
The effect of a geomagnetic storm depends on how strong the geomagnetic field is disturbed. This is described by an index Kp. This is an index that describes the conditions of the geomagnetic field at planetary level.



Magnetometers

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.

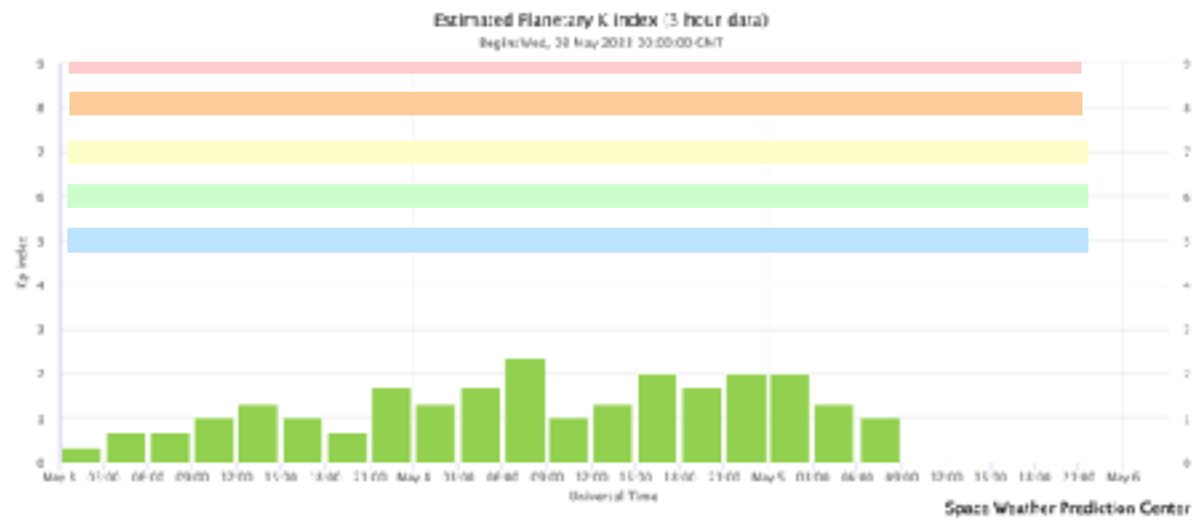


Careful!: The ISES scales are based on thresholds both in A-index and K-index values while one is a daily value and the other a 3 hourly value. This is ambiguous.

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.

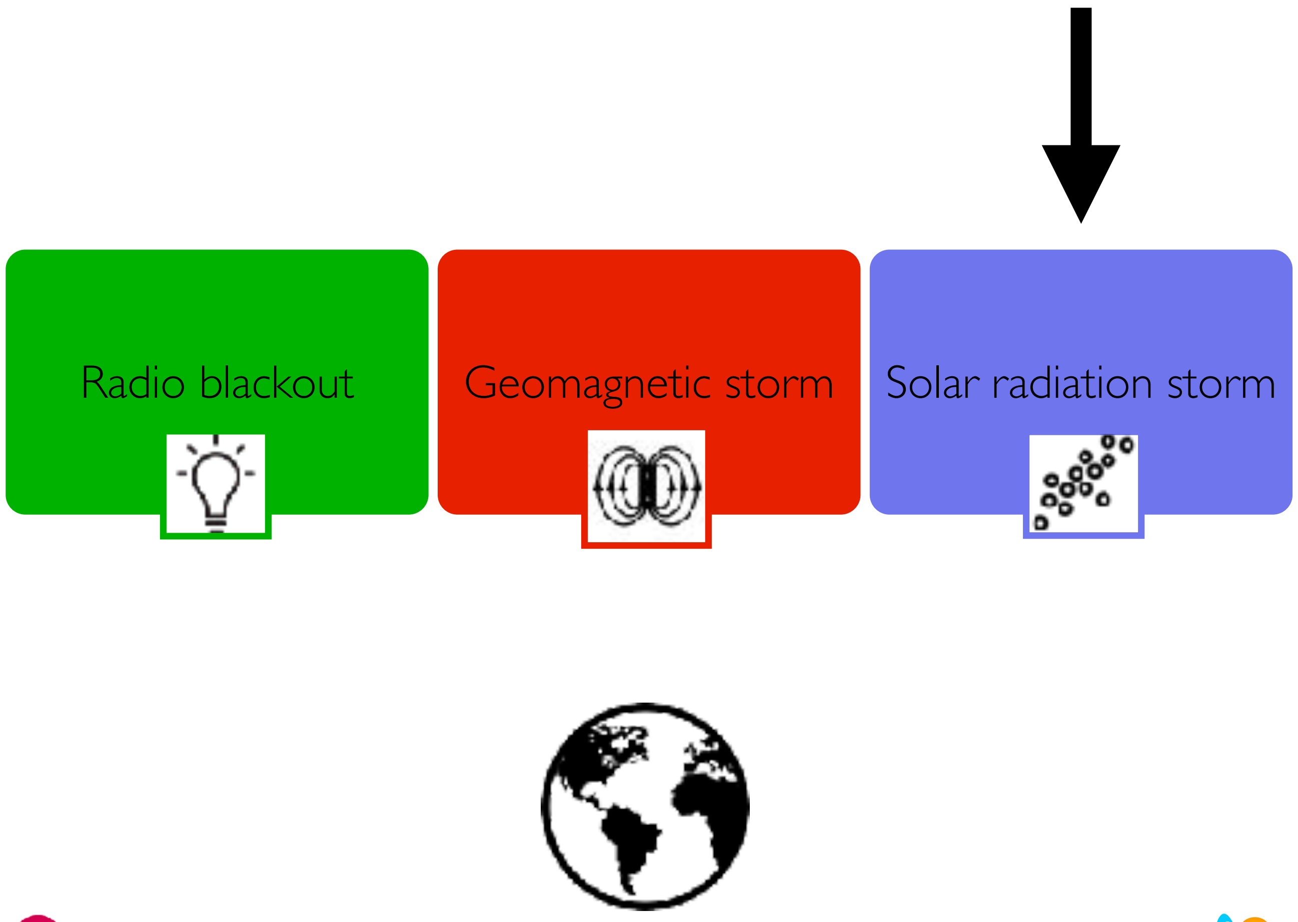
GEOMAGNETIC STORM DESCRIBED BY KP



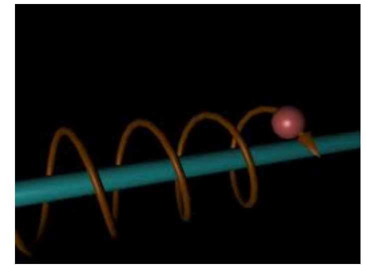
7.66<= 8- < 8
8= 8o
8 < 8+<=8.33

GEOMAGNETIC STORM - KP INDEX NOW

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


Radio blackout
Geomagnetic storm
Solar radiation storm

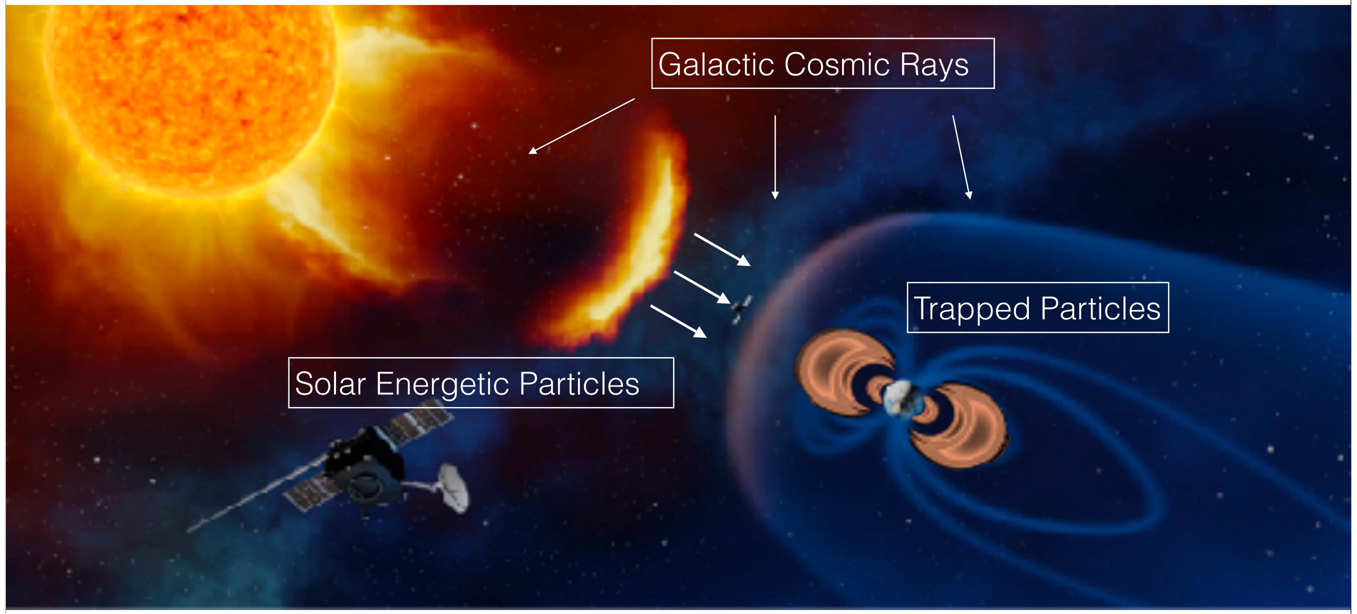
SOLAR PARTICLES



Solar energetic particles follow magnetic field lines.

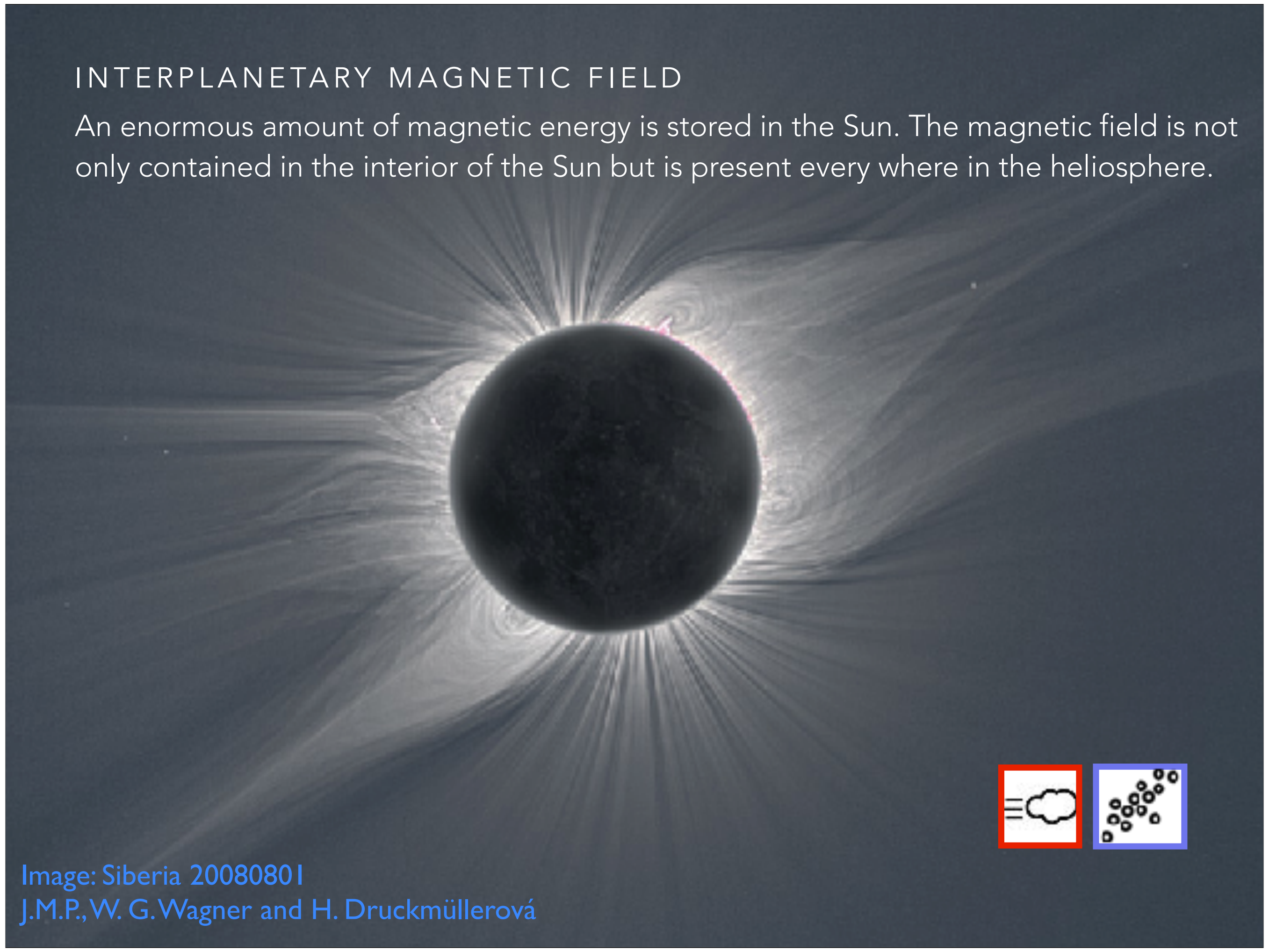
They have to go where the magnetic field takes them.

ENERGETIC PARTICLES IN THE NEAR-EARTH ENVIRONMENT



GCR
High energy charged particles produced outside the solar system
• ~ 83% protons, ~ 13% 4 He ions (alphas), ~3% electrons and ~1 % heavier nuclei
• E ~ MeV GeV and > TeV (extra galactic)
Omnidirectional flux modulated by solar activity
• Solar cycle: GCR max (min) @ solar min (max)
• Coronal Mass Ejection (CME) [?] Forbush decrease (see later)

Solar energetic particles
>90% protons, electrons, heavy ions
E: keV–GeV

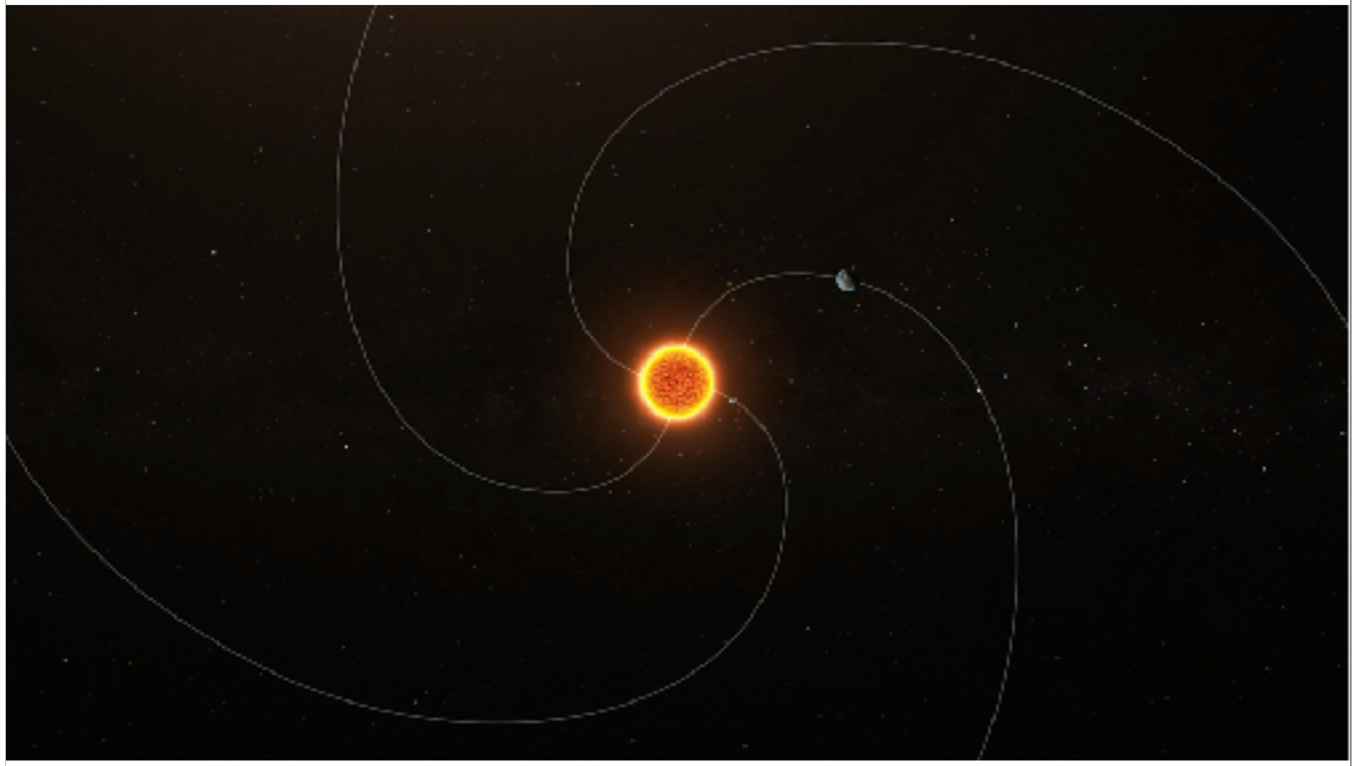


The interplanetary magnetic field plays a key role for the energy transport in the form of plasma.

Plasma is a charged gas. They have to listen to the magnetic field, which expels a force on moving electric particles.

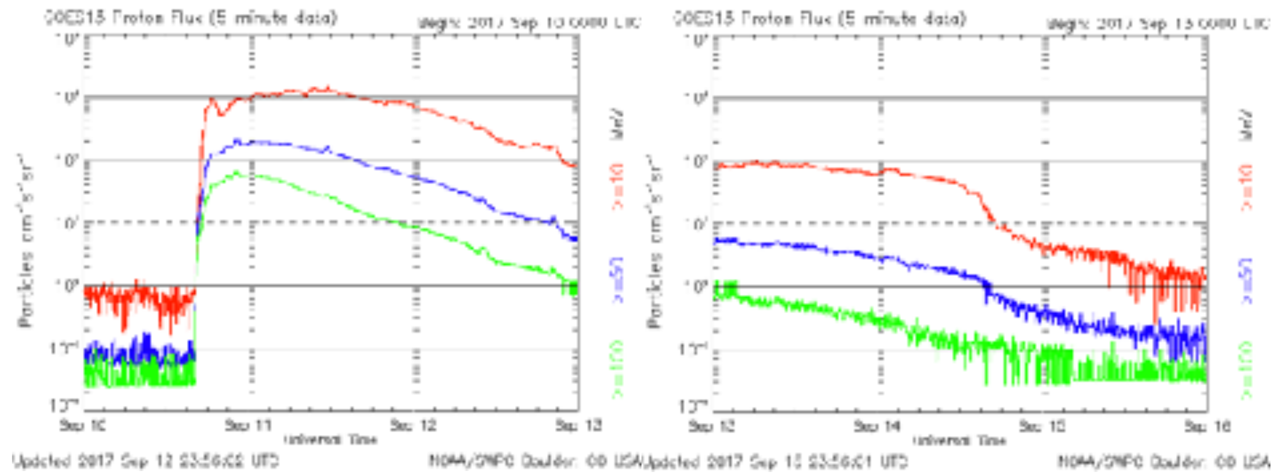
Magnetic signature visible here is at a large length scales.

Large spatial and time scale: Solar dipole – visible during a solar eclipse, near the solar surface, it is more pronounced at solar minimum. The dipole 'flips' every 11 years.

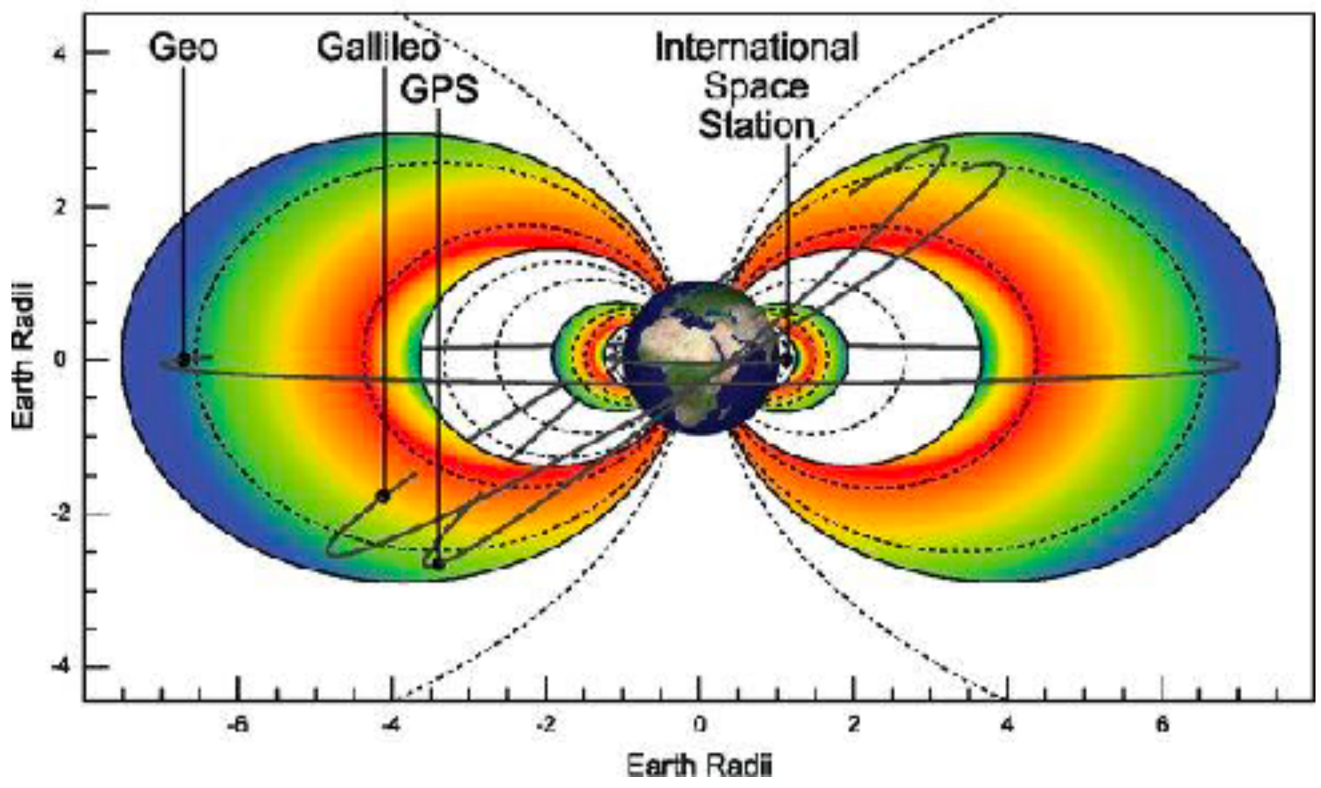


https://svs.gsfc.nasa.gov/20320
An intense solar eruptive event has many parts. This animation starts with a solar flare, which sends light and energy in straight paths, traveling at the speed of light. A coronal mass ejection, or CME, appears next – this is a giant cloud of solar particles that also 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.

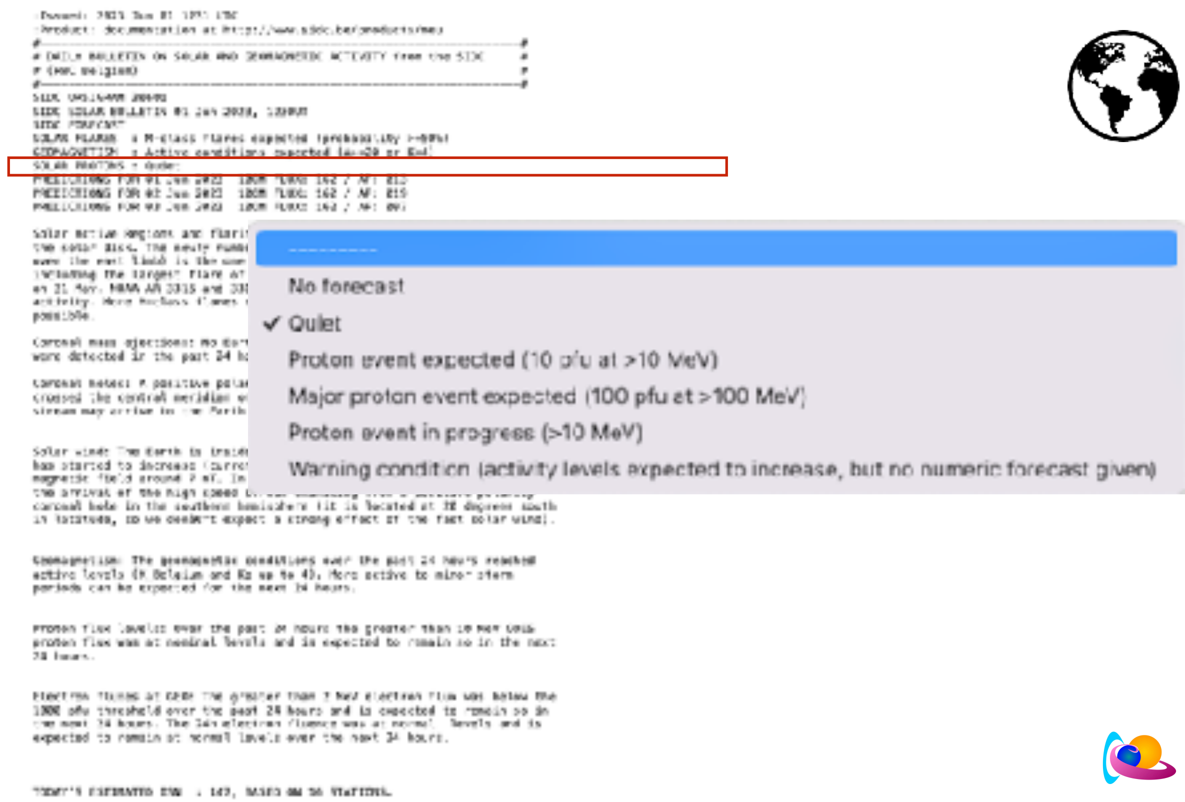
PROTON FLUX BY GOES



In situ (taste and touch)


Geo
Gallileo
GPS
International Space Station
Earth Radii
Earth Radii
4
2
0
-2
-4
-6
-4
-2
0
2
4
6

SOLAR PROTON FLUX BY GOES



PROTON FLUX NOW

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

https://en.wikipedia.org/wiki/Steradian

Steradian is a dimensionless unit, the 3D version of the 2D radian.
Radian is the unit for a solid angle and links the angle to a length on a circumference.

For a circle
Circumference length = angle * radius
SI unit of length is m.
With angle in radian, dimensionless
The angle of a complete circle is 2*pi, the circumference of a circle with radius R is 2*pi*r

For a sphere
Sphere surface = area subtended * radius^2
SI unit of a surface is m^2
With area subtended in steradian, dimensionless
Area subtended of a complete sphere is 4*pi, the surface of a sphere with radius r is 4*pi*r^2

Flux is 'something' through a surface - everything in SI units.
E.g. magnetic flux: the number of magnetic field lines through a surface.
When 'something' moves, you speak about that something per second through a surface, a flow rate.
E.g. flow rate of a river: the volume water that flows per second through a m^2-surface.

Proton-flux has a direction. This is expressed by using the word steradian. You count all the protons that are present in the cone defined by the area subtended. The apex of the cone is the Sun.

You take only the perpendicular flow through the surface: so only the protons from the cone.

For a flux, you need a vector-field: magnetic flux, flow (velocity field)
It is the component perpendicular to the surface that contributes to the flux. The component parallel to the surface doesn't contribute to the flux.
In our case, it is the cone with apex located at the Sun (which is a simple point at such a distance).