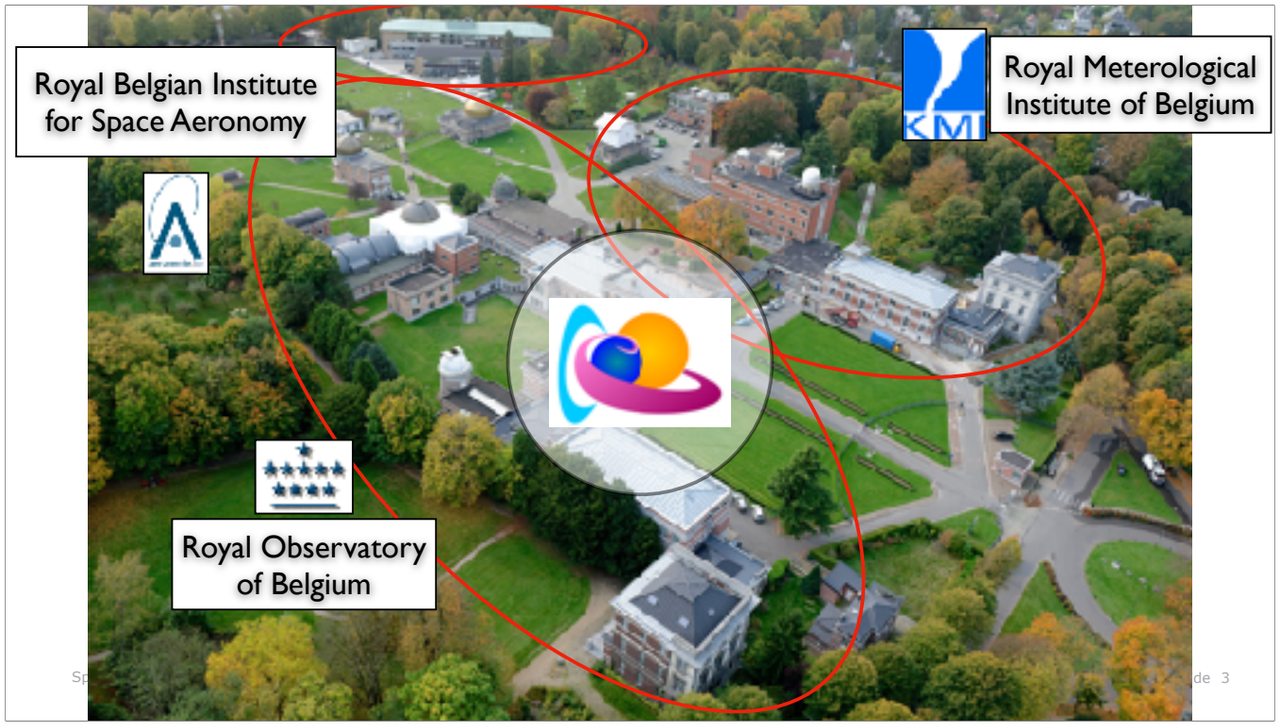
From Physics to Forecasting

PRESENTED BY
PETRA VANLOMMEL
Solar-Terrestrial Centre of Excellence

A collaboration between





Not really interesting
But what is cool and triggers curiosity



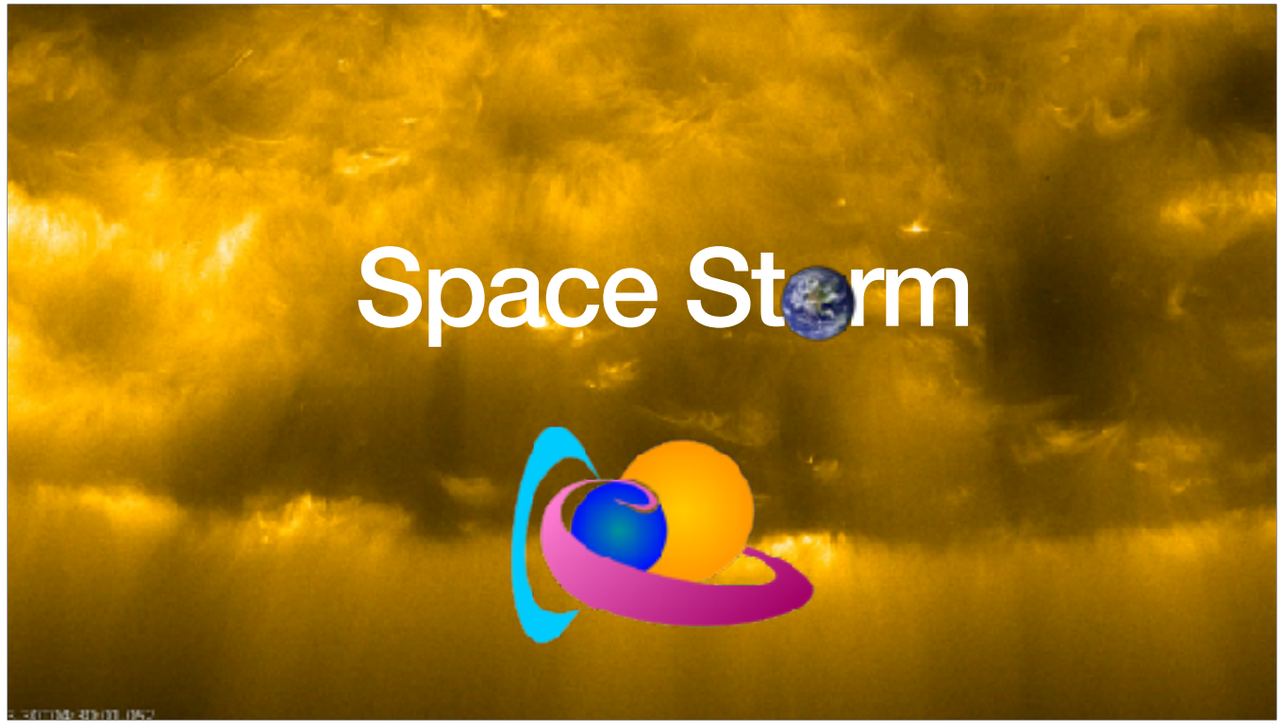
Space
Satellites
Space crafts

Imagine yourself out there in space, onboard of a space craft. Feeling things that only you and your colleagues space travellers feel with 8.1 billion people down under you.



This is how a storm looks like from space - the eye of the storm
It looks terrifying and huge

Space and storms are intriguing and appeal to one’s imagination.
And, we have both


Space Storm



What is this:
A) a part of the green board in the aula or
B) Aurora

January 19 - storm in the sky and a storm on social media
Photo by Jan

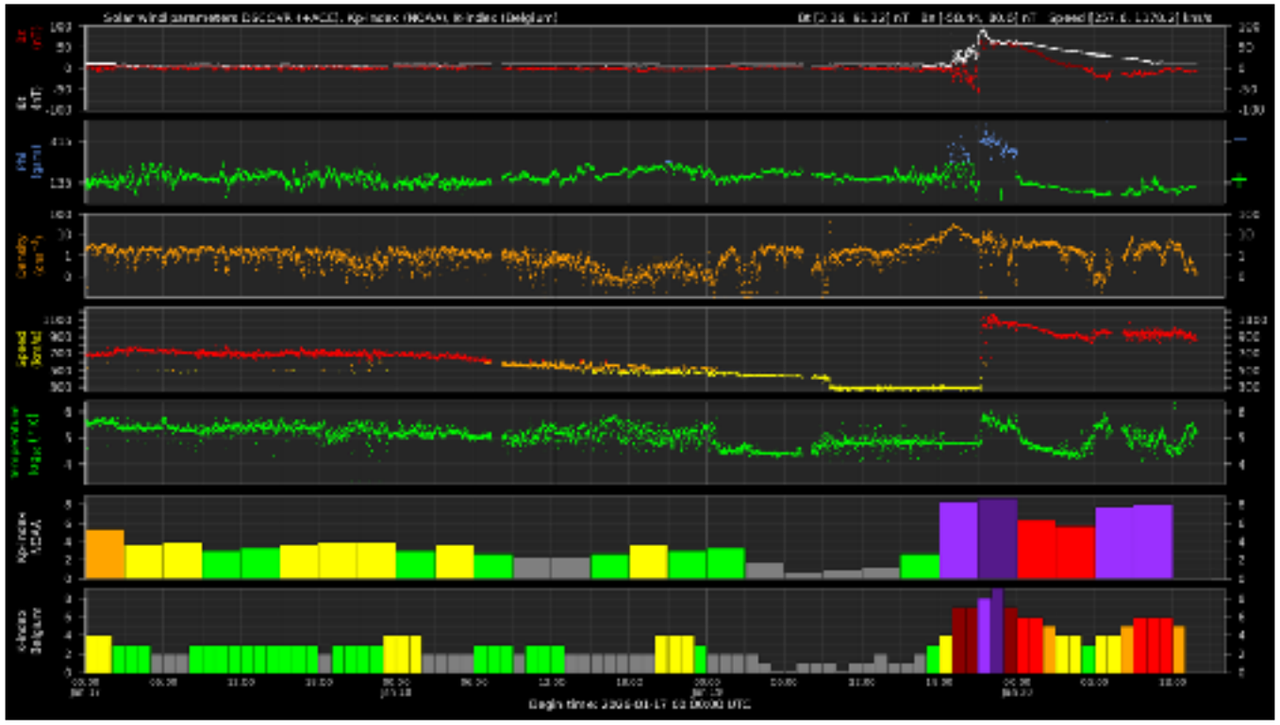


Jenny

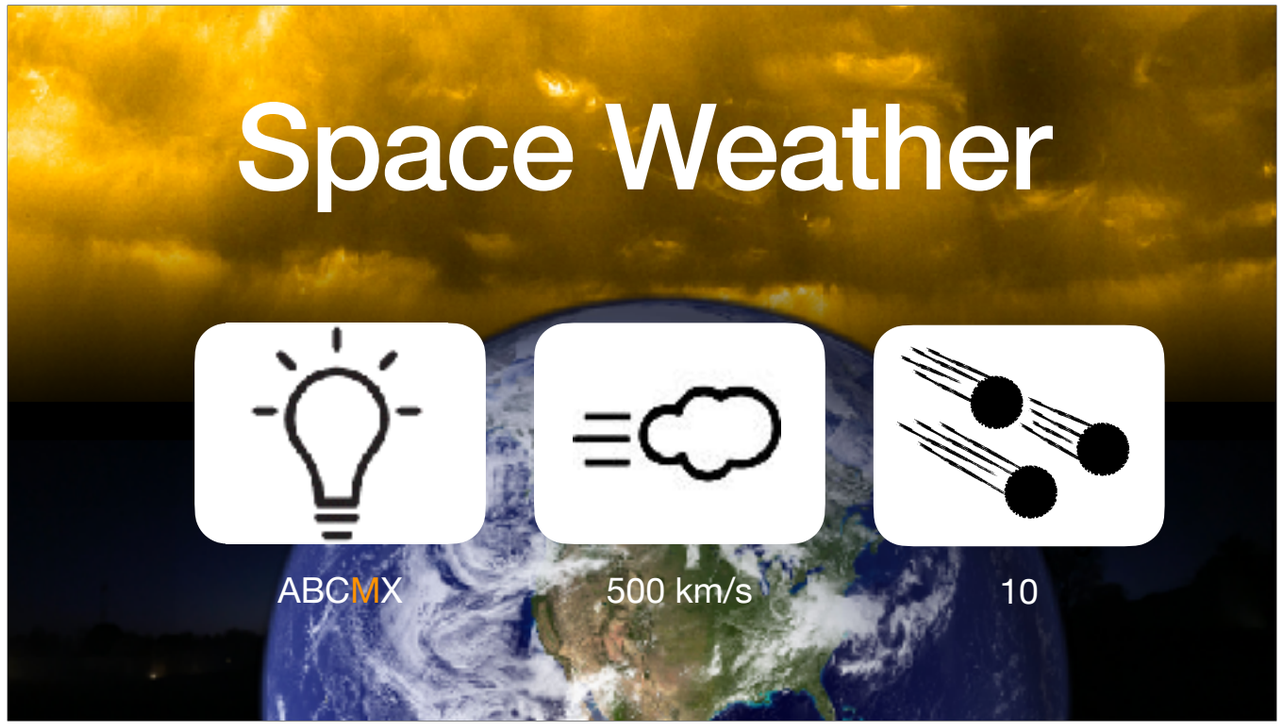


Thomas Lecocq

Exceptional - visible in Brussels
It interests people.



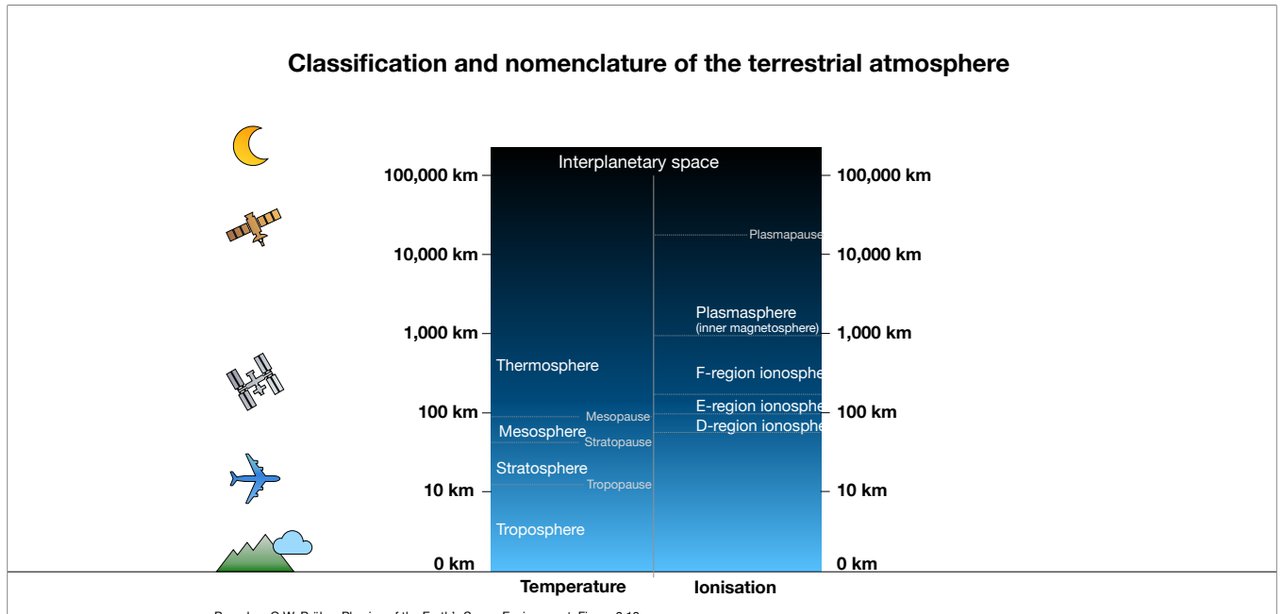
This is what we saw in our space weather data.
Extreme space storm on the planetary level
extreme space storm above Belgium



Bulletin and forecast

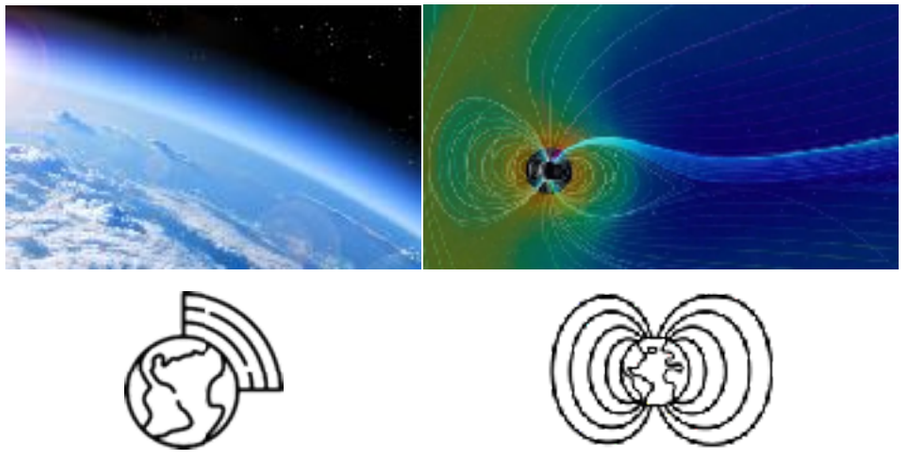
For this you need to understand what space weather is, collect and analyse data which allow you to monitor and forecast space weather.
In case of emergency, alert.

Earth’s spheres



Based on G.W. Prölss, Physics of the Earth's Space Environment, Figure 2.13

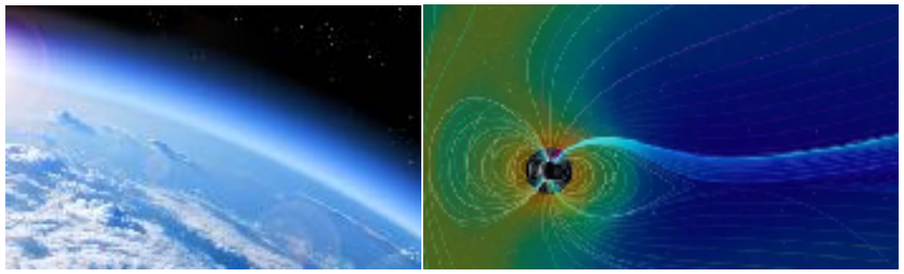
Earth's neutral atmosphere: troposphere, stratosphere, mesosphere and thermosphere
Earth's charged atmosphere: the ionosphere and plasmasphere
Magnetosphere



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's energy impacting earth's atmosphere and magnetosphere





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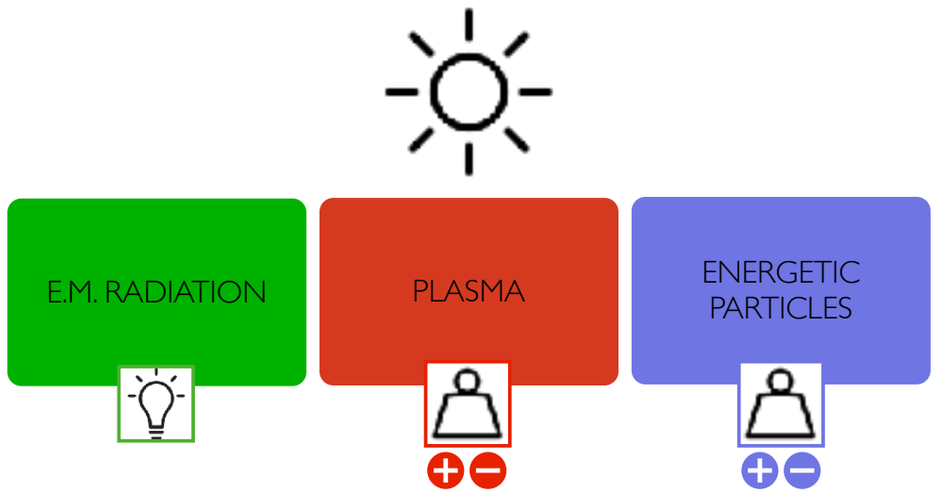
Space Weather

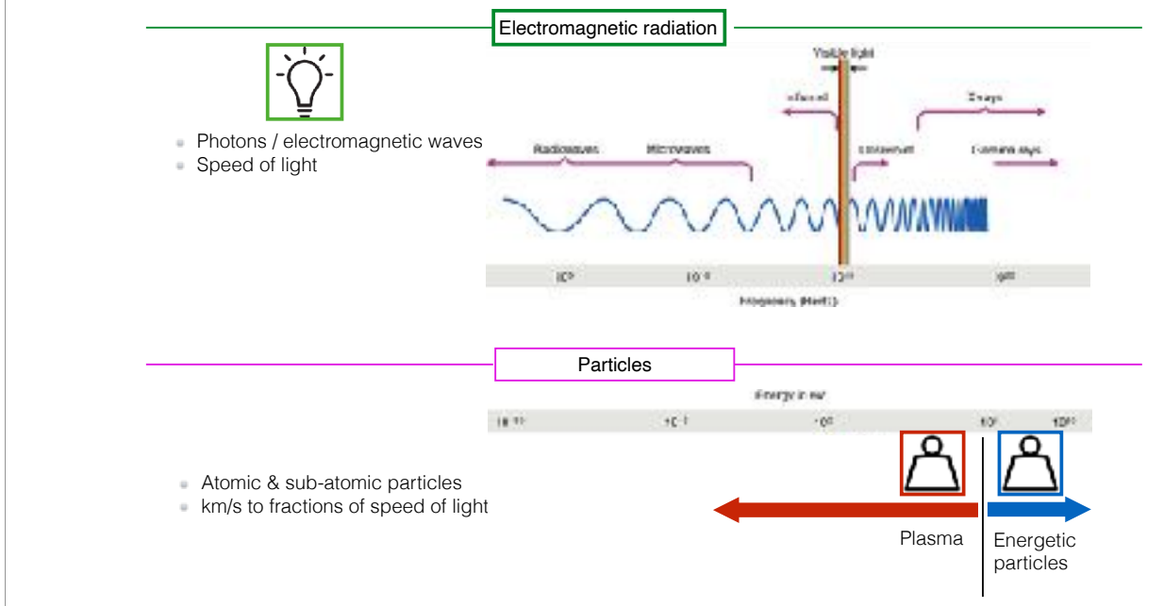


The sun is a gigantic ball of energy: magnetic energy, heat, moving plasma, …

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.



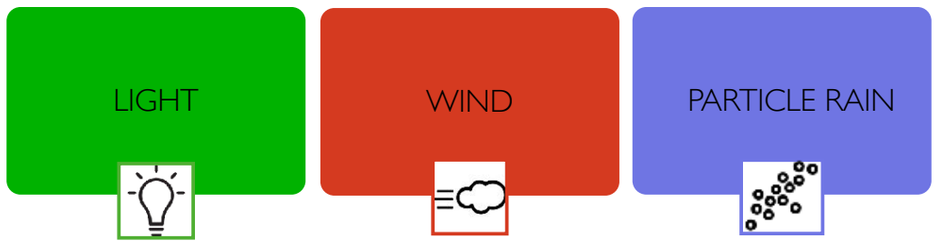
Plasma is the fourth state of matter. Plasma is a gas that is constituted of electrically charged particles.
When the particles have energies above 100 kEV, they don't behave as a gas but as an individual (energetic) particle.

They withdraw from the group, from the gas.

Three 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

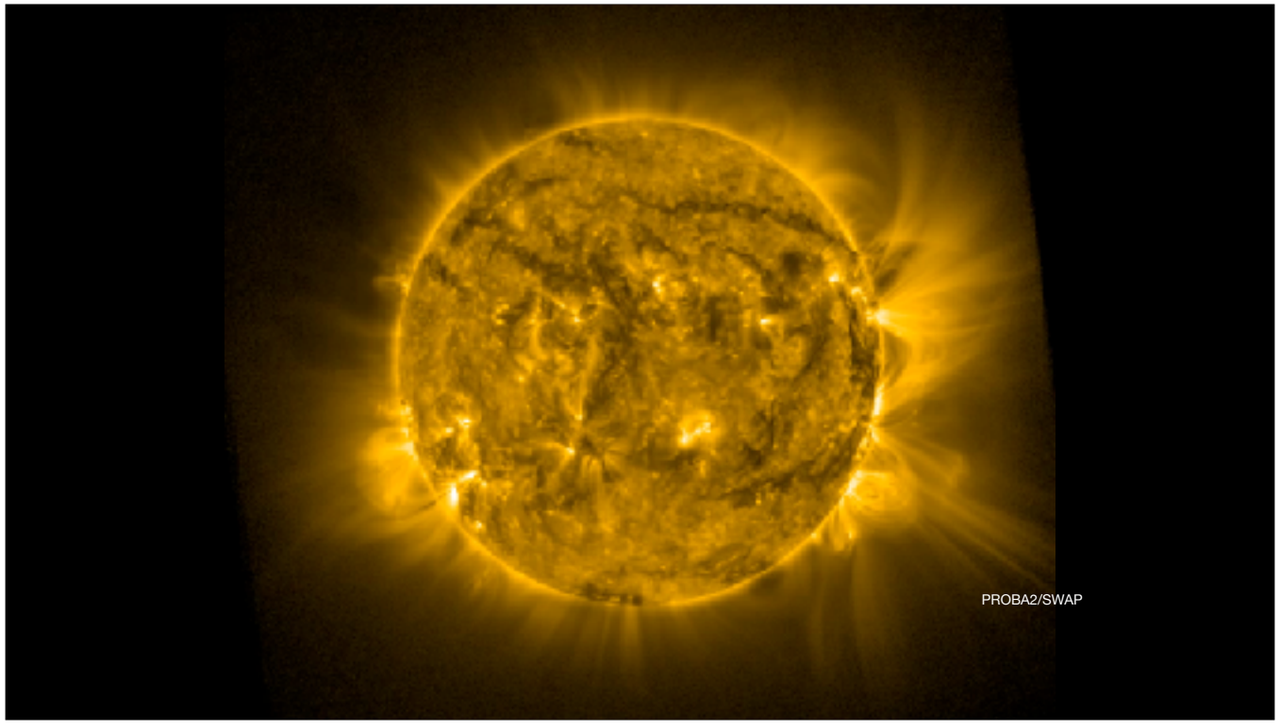
Energy expressed in eV= 1.602 10^-19 J

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

Focus on solar energetic particles

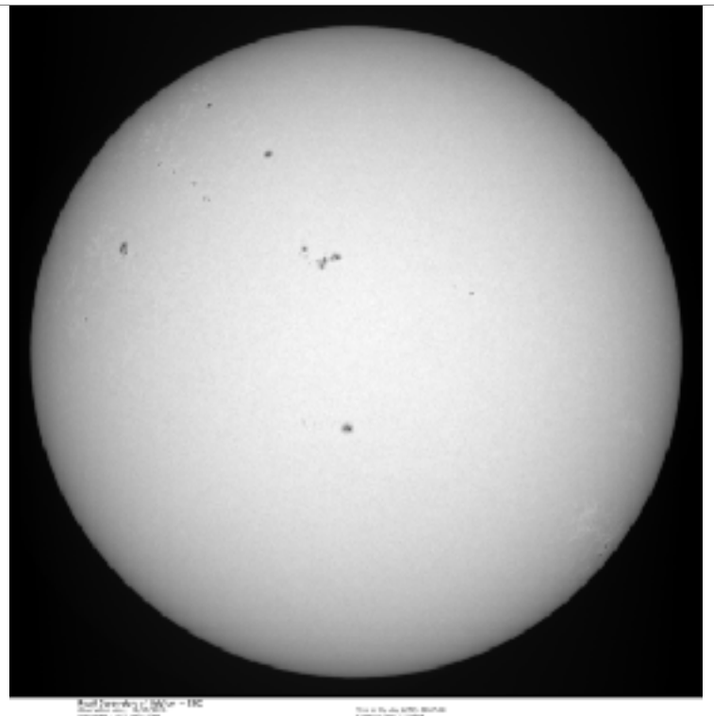


Magnetism drives space weather and the sun’s dynamics.



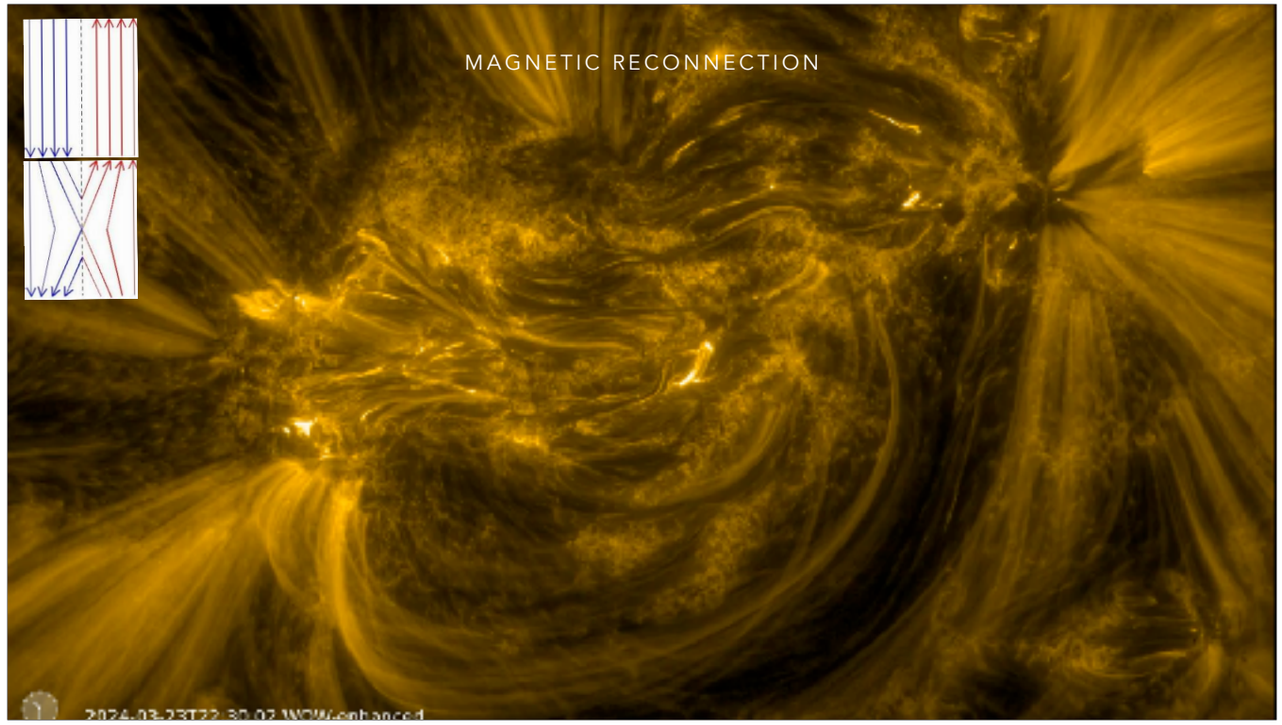
Magnetism drives space weather and the sun’s dynamics.

In the EUV it looks like this!
The sun doesn’t only rotate but it is also tangled with loops which move, shake back and forth, restructure and do all sorts of electric and magnetic magic.
It is a turbulent plasma ball where magnetic fields are moving, shake, connect with other other, ….



Sunspots are bundles of magnetic fields.
This is the photosphere of the Sun, in the visible light.

At the controle room of the solar dome, you saw also H Alpha and Ca II images: they represent the chromosphere, a layer on top of the photosphere.
You saw plages, filaments.
When a filament erupts, it might be watched by LASCO onboard of SOHO as a CME, a coronal mass ejection.



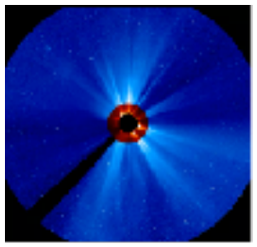
The more sunspots, the higher the chance for magnetic reconnection.

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

Solar Weather & Storms

At a certain moment, energy can be released on a shorter time scale. A solar feature like a sunspot, an active region, filament etc. lies at the base of a solar storm in which energy is released in an eruptive manner.





Flare

Coronal Mass Ejection

• In an abrupt, impulsive and brutal way (flare, Coronal Mass Ejection, proton storm) magnetic reconnection involved
• in a non-eruptive manner (Coronal Hole) — no magnetic reconnection involved

Change in energy output on the scale of minutes, hours, days.

Remote sensing (seeing) - in situ (taste and touch the ambient space)

Space weather is the change of energy that occur in the space environment.

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

A Coronal Mass Ejection is a plasma cloud that is ejected into space. You consider it as a cloud and not as a bunch of individual particles. It is superimposed on the background solar wind. You can see a CME as a complex magnetic bag with different magnetic layers with plasma in it that travels as a tsunami through space. It can go faster/as fast as/slower than the background solar wind. When it is faster, you will see a shock in front of the cloud. This is exactly the same as the shock you see in front of a speed boat.
A CME is visible as a white cloud in corona graphic images like the one on the slide. A coronagraph is a telescope that creates an artificial eclipse and makes pictures in the visible light of the region around the sun.
SOHO/LASCO C2 (red) and LASCO C3 (blue)

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

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.

Solar Weather & Storms

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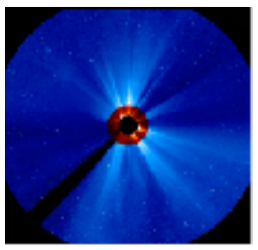

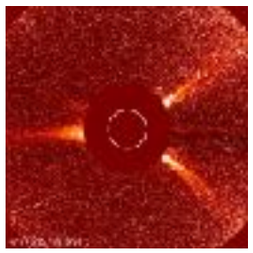

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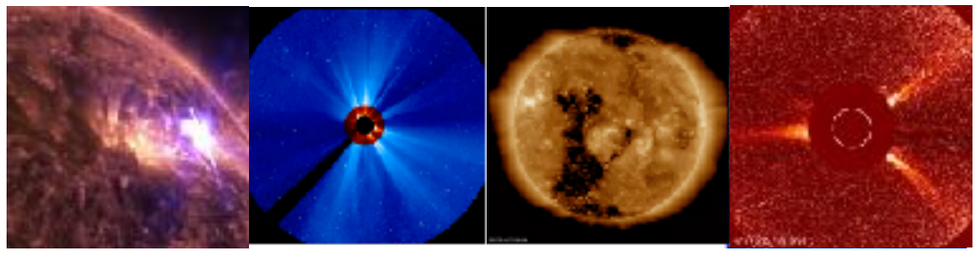
Solar Weather & Storms

At a certain moment, energy can be released on a shorter time scale. A solar feature like a sunspot, an active region, coronal hole, filament etc. lies at the base of a solar storm in which energy is released. The release of energy might be in an abrupt, impulsive and brutal way or in a non-eruptive manner.



Flare

Coronal Mass Ejection
High Speed Stream

Particle Storm

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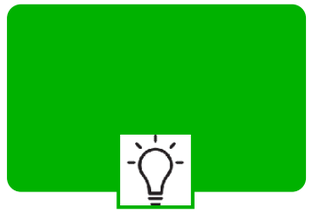
Transit time

On earth
Storm scale - strength
duration
Impact
Area of impact

These facts define the monitoring and forecast of space weather and impacts of space weather.

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



STORM SCALE



A,B,C,M,X



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

DURATION

MINs to HOUR



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.

Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light

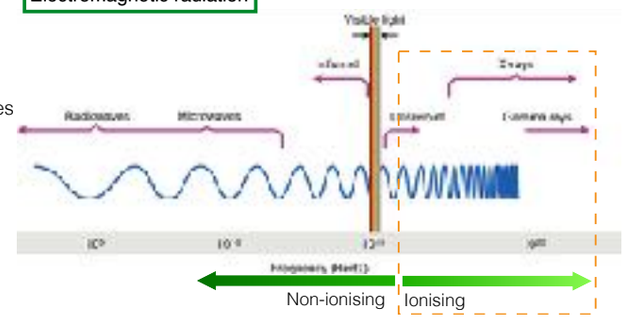


Photo-ionisation — green

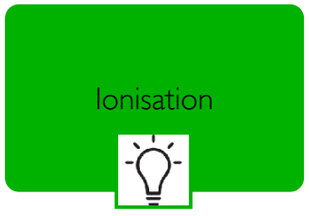
Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

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.

IMPACT







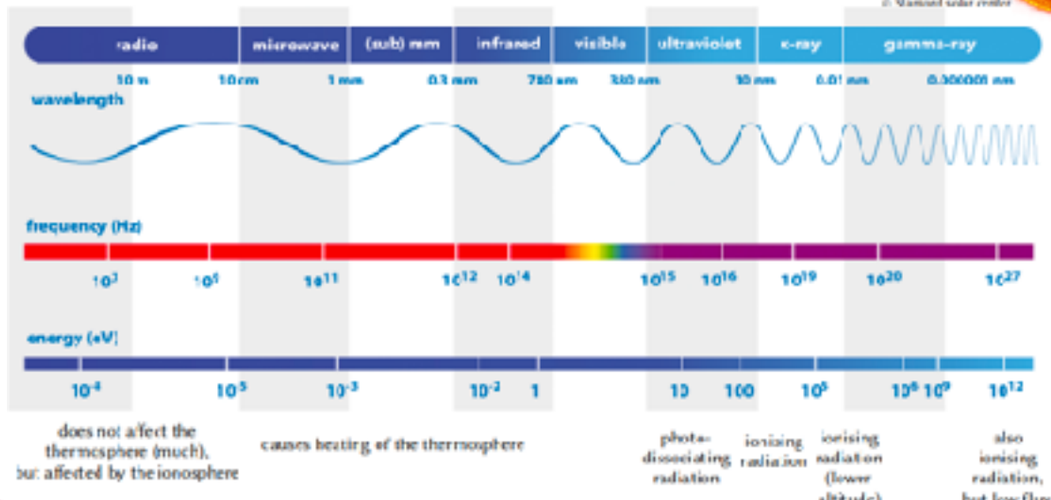


The icon represent the Earth + atmosphere with the ionosphere
Ionisation of atoms and molecules due to photons -

The light smashes atomic particles into pieces. Those pieces are electrically charged.

THE SOLAR ELECTROMAGNETIC SPECTRUM



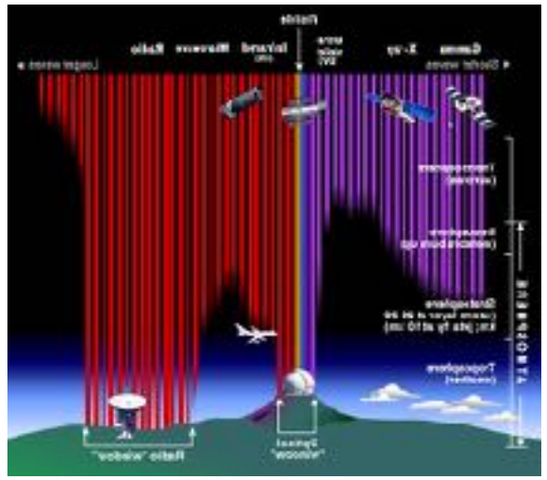


The thermosphere contains mostly atomic gases (produced by photodissociation) rather than molecular ones (O2, N2, CO2,…). Most important are O, H, and He.

Different parts of the EM spectrum are relevant, for different reasons.
Note: besides EM-radiation, ionisation is also produced by high-energy particles (especially in polar region).

TRANSPARENCY OF EARTH ATMOSPHERE

Our atmosphere protects us against harmful solar light. This ionising solar light can penetrate only until a certain height.



AREA OF IMPACT



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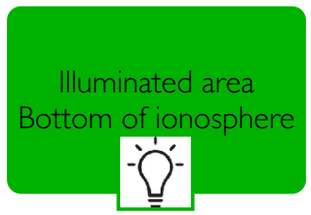



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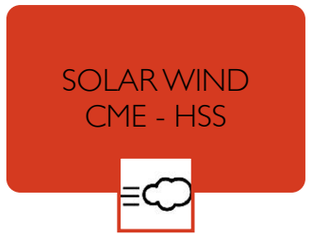
As deep as the lower part of the ionosphere.



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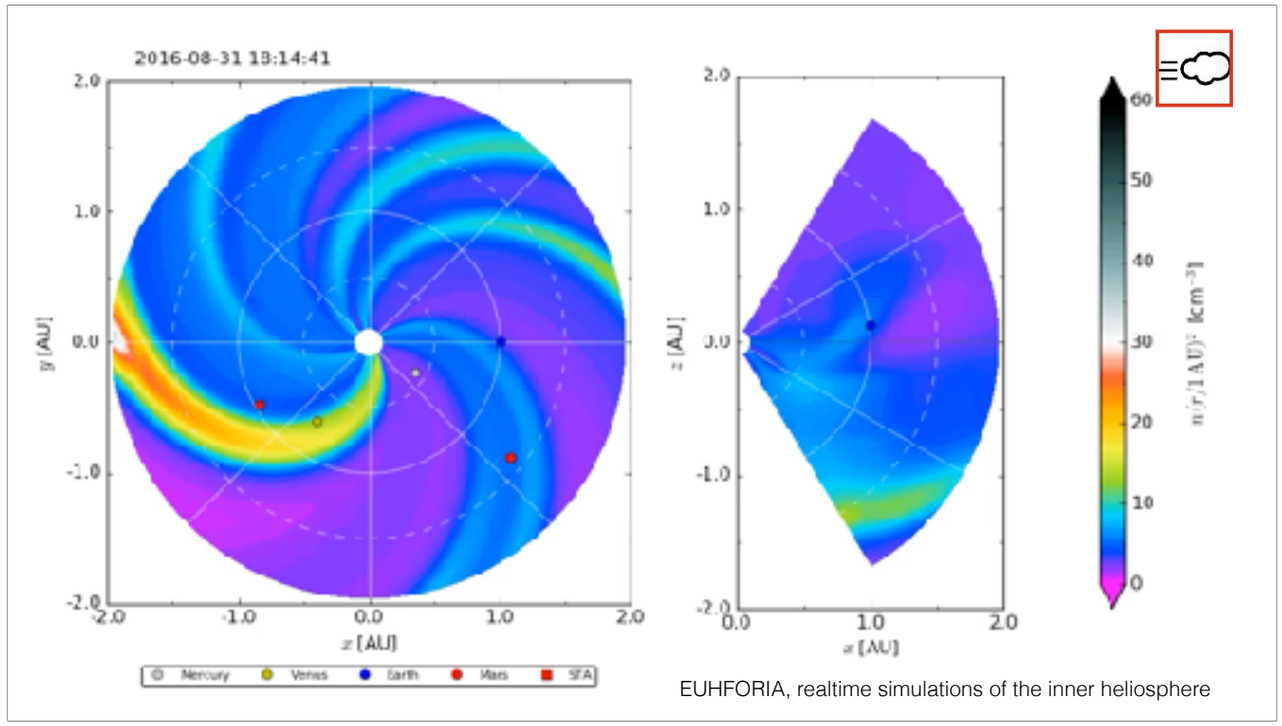
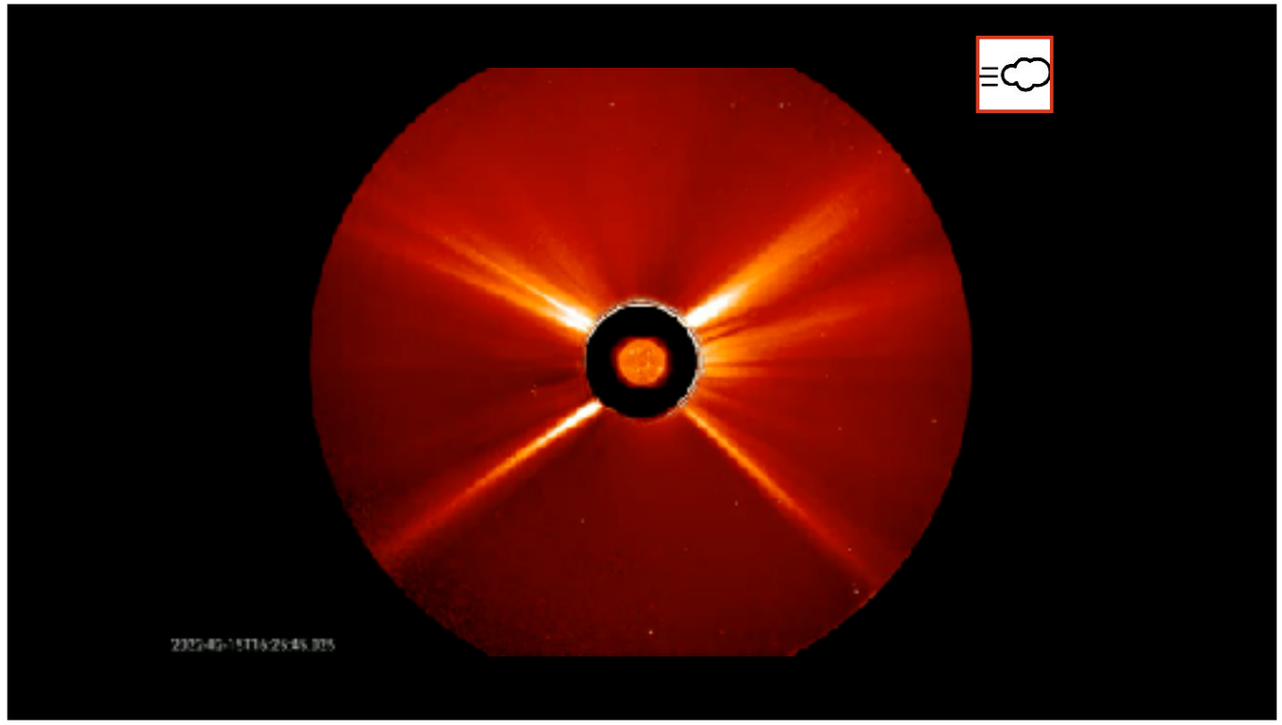


EUHFORIA, realtime simulations of the inner heliosphere

Solar wind model

Like a sprinkler - Radial but looks bent.



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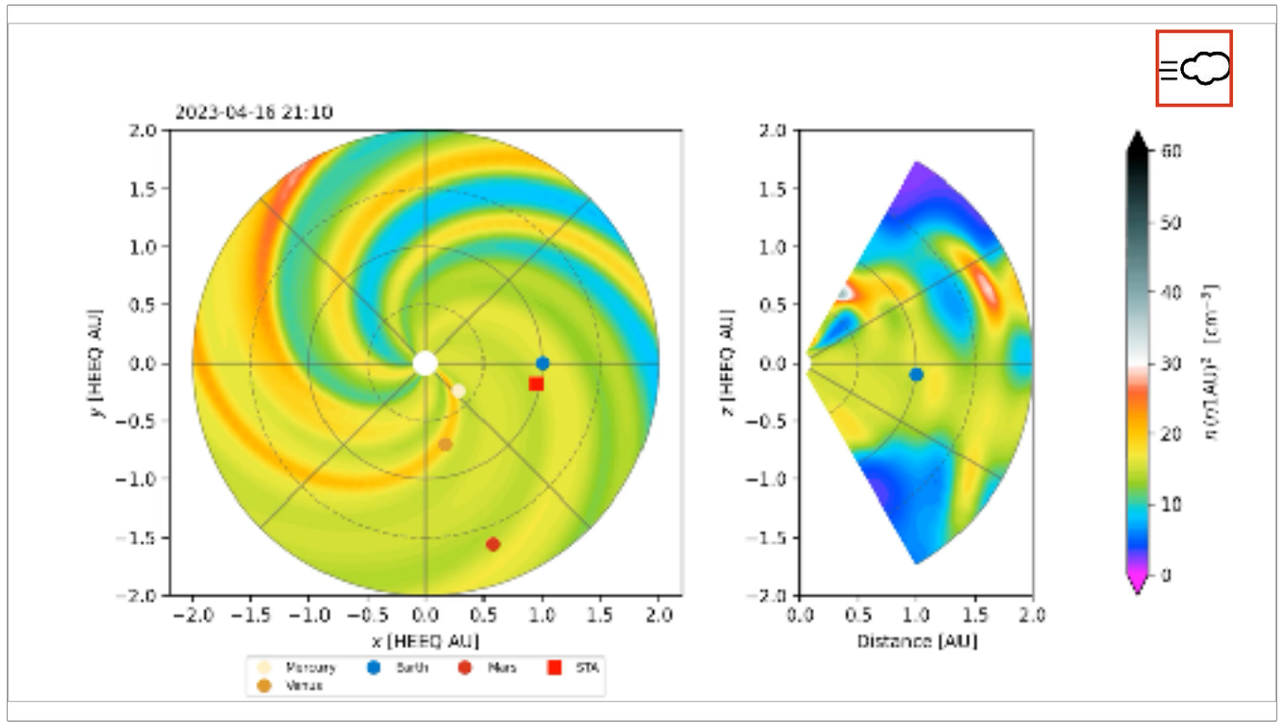
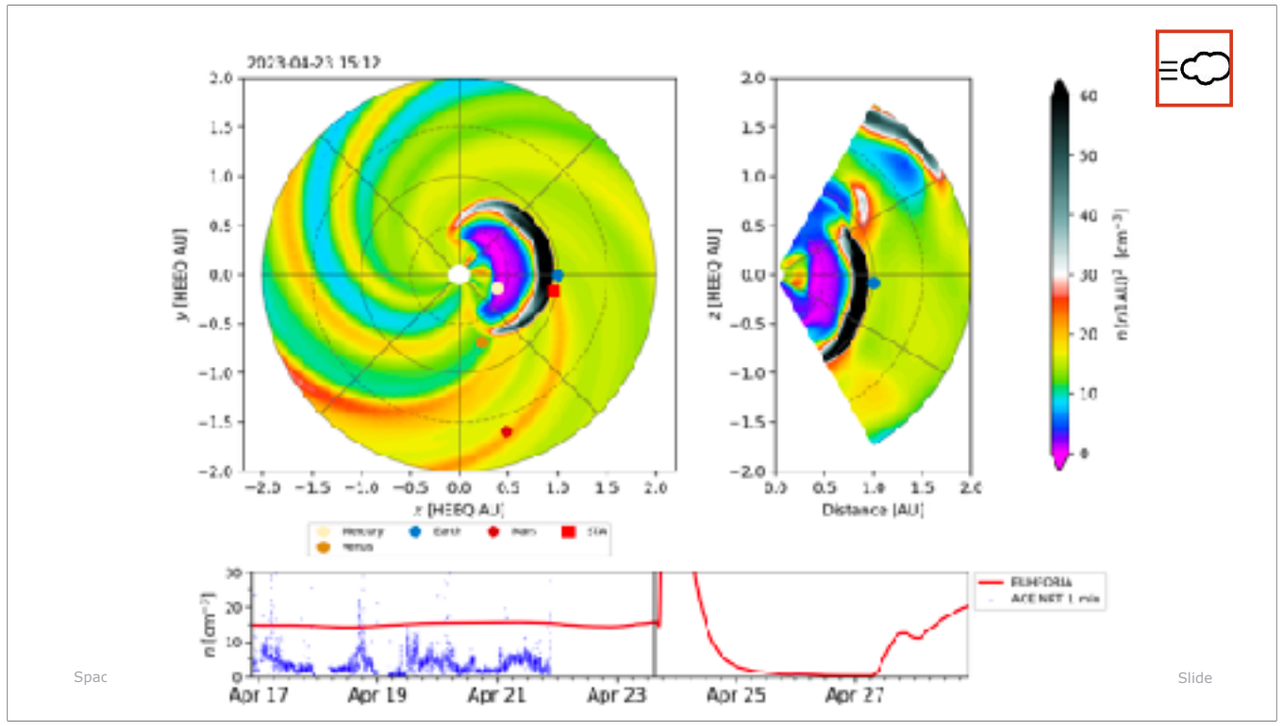
SOHO/LASCO C2



A CME moving through the heliosphere



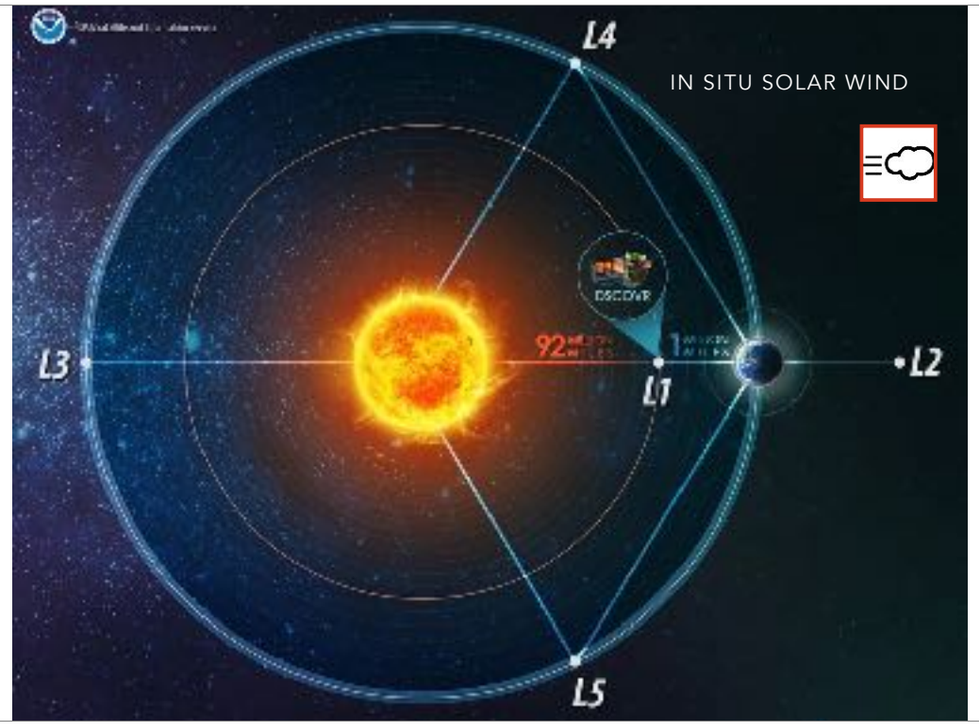
Spac

Slide

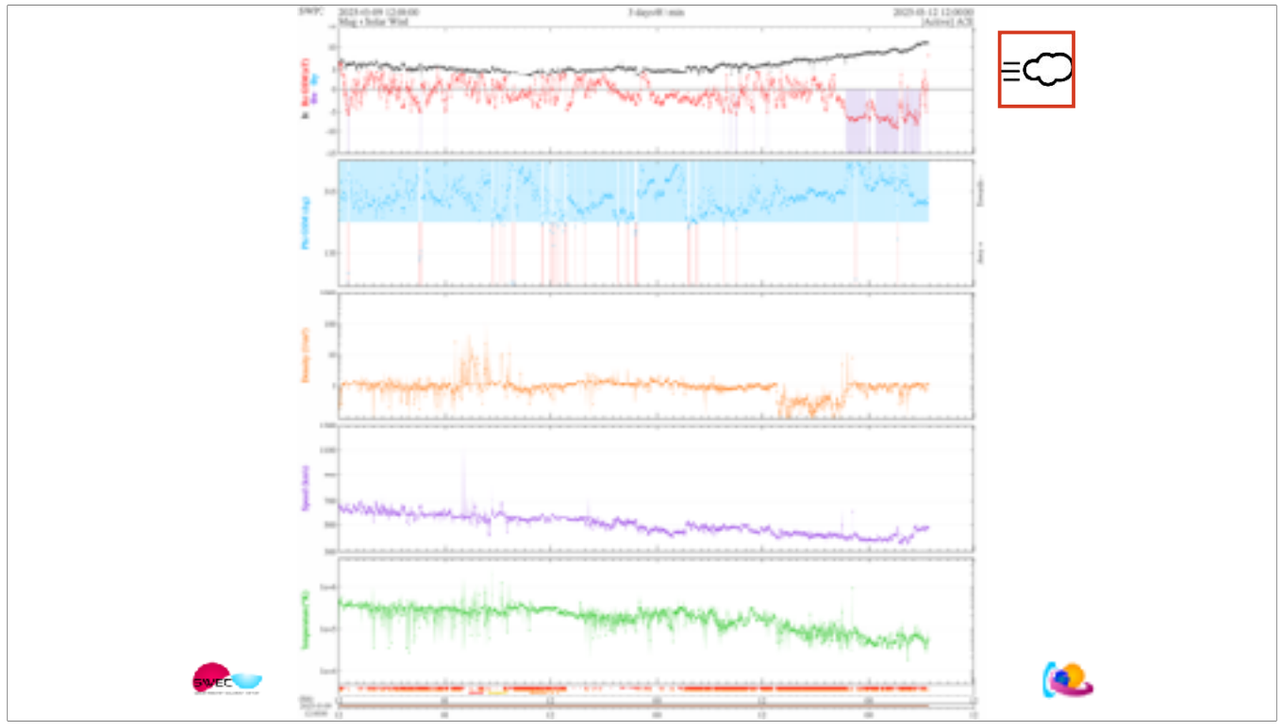
A CME reaches Earth

Next, the forecaster will run a model simulation to have a better estimate of the arrival time. This resulted in an arrival time prediction for late evening on April 23. This is slightly earlier than the first estimation, which was purely based in a projected (and thus underestimated speed).

The picture is the output of a simulation by EUHFORIA of the cloud propagation in the heliosphere. Left is a 'top' view of the sun (white dot) and the earth (blue dot). The black structure is the front of the magnetic cloud (purple) that reaches the earth. On the right is a side view of space. At the bottom, you see that the density curve goes through the roof at the time of arrival.



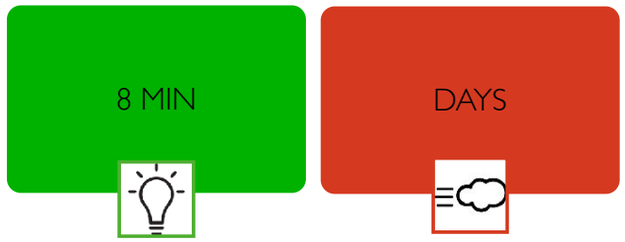
The wind at L1, 1 hour upstream of earth



https://www.swpc.noaa.gov/products/real-time-solar-wind

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 …



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SDO/AIA

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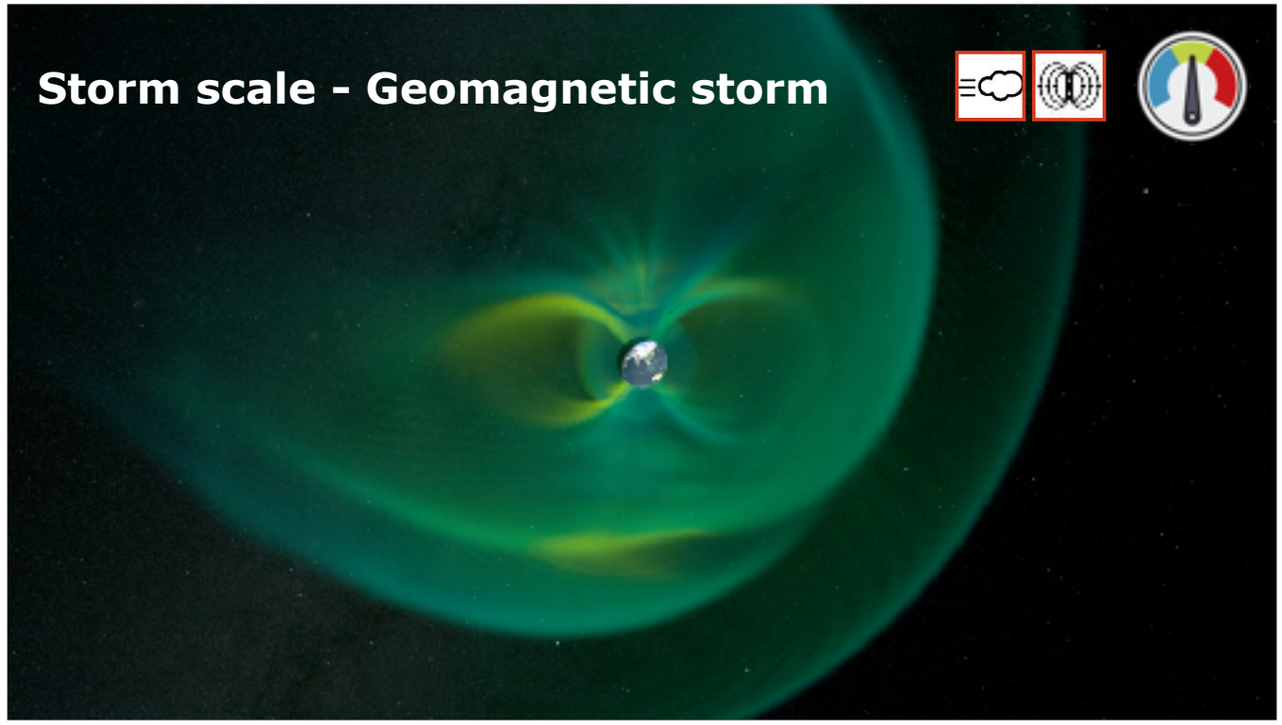
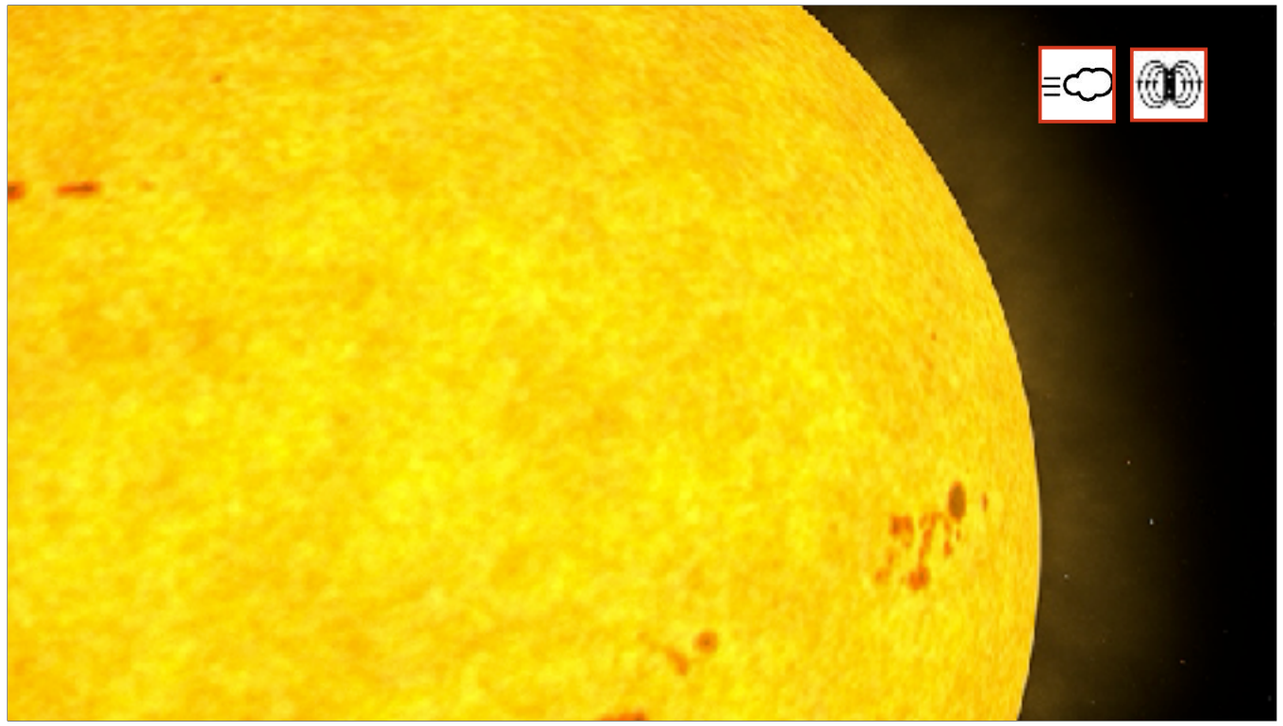


Magnetometers

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.



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.

Storm scale



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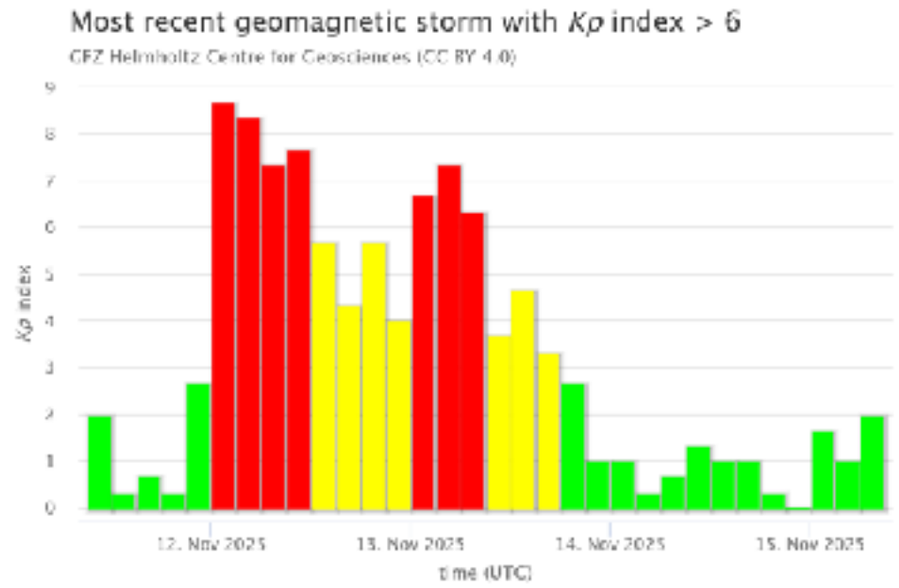
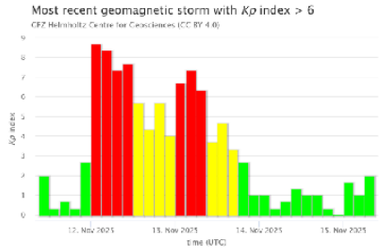
Storm scale


Most recent geomagnetic storm with Kp index > 6
GFZ Helmholtz Centre for Geosciences (CC BY 4.0)
Kp index
12. Nov 2025
13. Nov 2025
14. Nov 2025
15. Nov 2025
Time (UTC)

Storm scale









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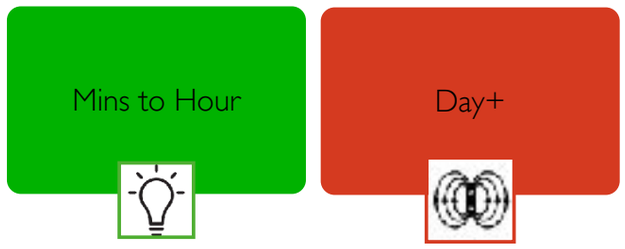
Duration



Magnetometers

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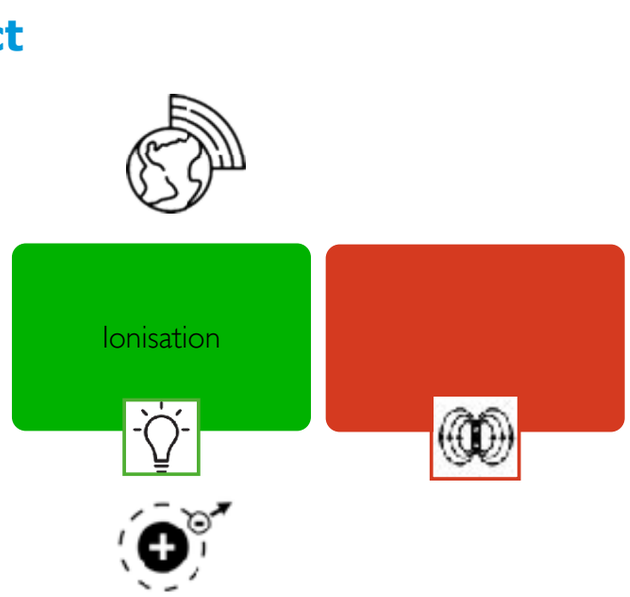
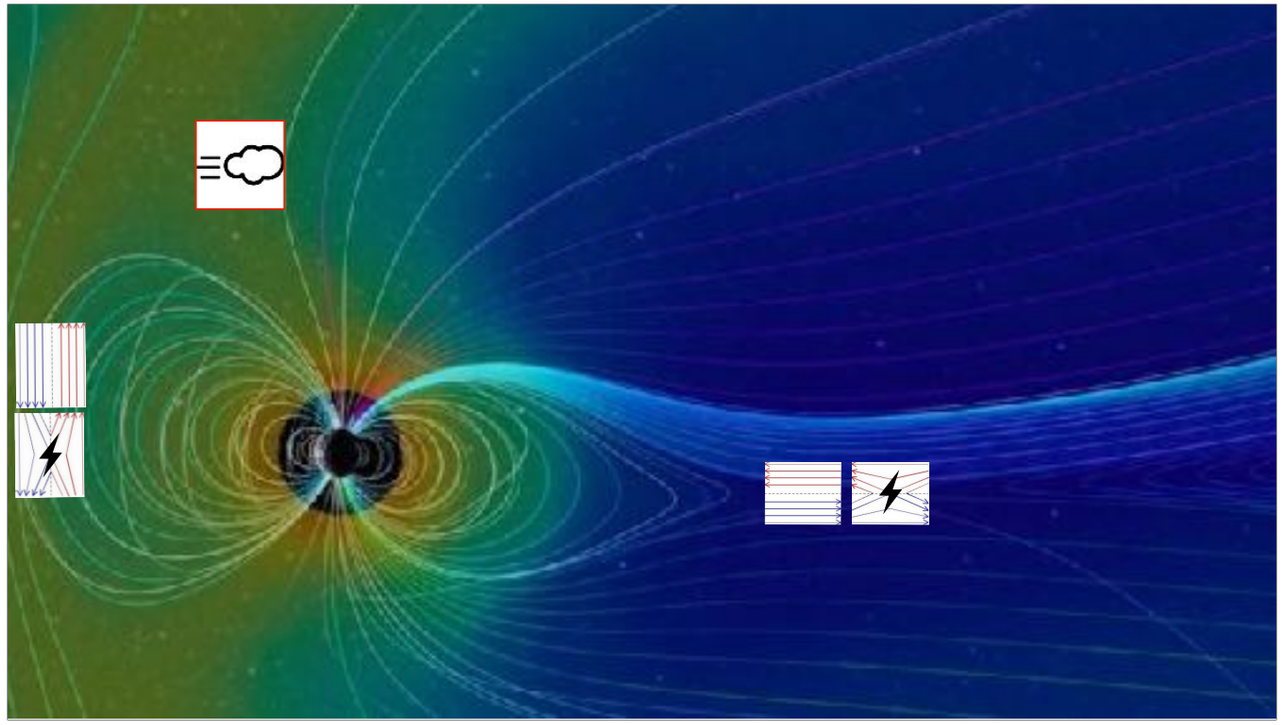
Impact



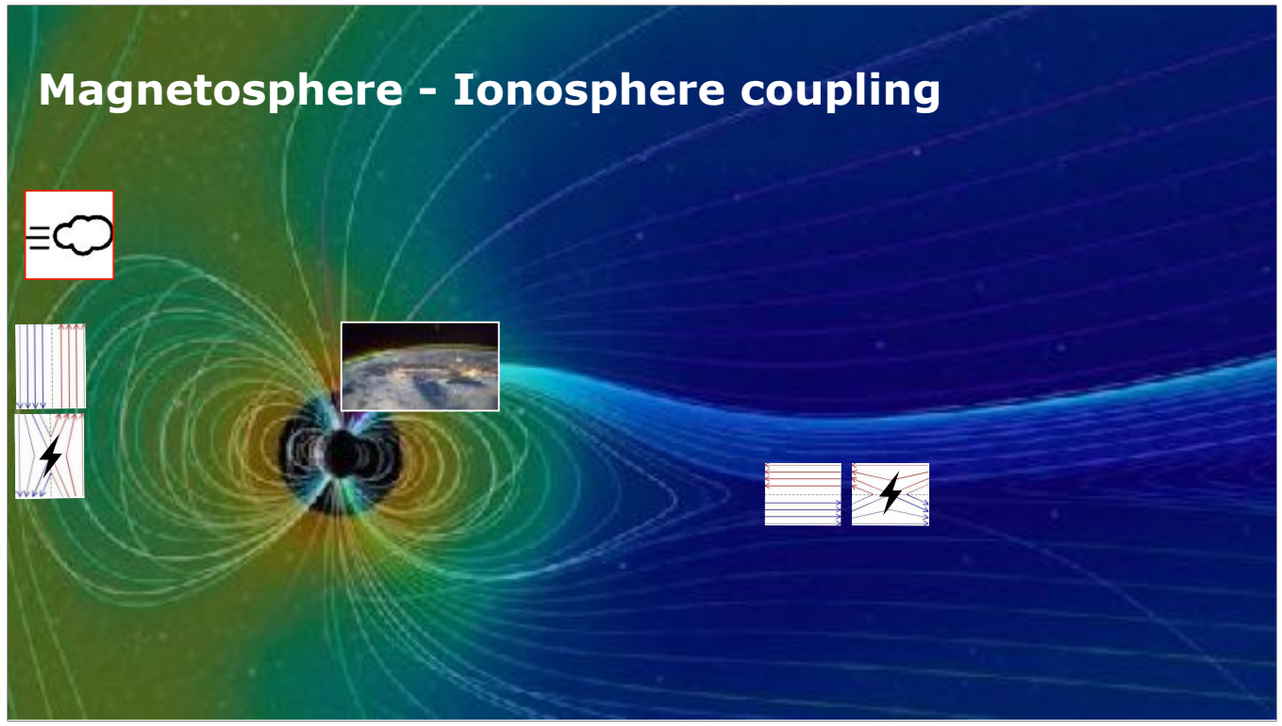


- Ampères law : circulation of magnetic field = enclosed electric current —> sheet current

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 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.

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 connect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.

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



currents

- Ampères law : circulation of magnetic field = enclosed electric current —> sheet current
- Magnetopause current, neutral sheet current, magnetotail current
- can propagate to the ionosphere (field aligned currents)

Ionosphere: a region with free electrons due to ionisation - conductive system

Magnetosphere-ionosphere coupling

The gas-system of the ionosphere is connected with magnetic system of Earth. Both systems intersect and interact with each other.

(Magnetopause current couples to pedderson and hall currents in low ionosphere (E and D-layer))

—> due to the coupling with a magnetic dipolar structure, the ionospheric behaviour is different at low, middle and high latitudes.

Field aligned currents along the magnetic field lines, connect the magnetospheric currents with ionospheric currents. The Pedersen and Hall currents are two main currents in the lower ionosphere. They are localized in the ionospheric D and E regions.

Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an “image” in the ionosphere, and conversely. We identify the following regions:

Magnetopause ↔ footpoints of the cusps
Tail lobes ↔ polar caps
Plasma sheet ↔ auroral oval
Plasmasphere ↔ ionosphere at low latitude

The ionosphere is that part of the upper atmosphere where free electrons occur in sufficient density to have an appreciable influence on the propagation of radio frequency electromagnetic waves. This ionization depends primarily on the Sun and its activity. ionospheric structures and peak densities in the ionosphere vary greatly with time (sunspot cycle, seasonally, and diurnally), with geographical location (polar, auroral zones, mid-latitudes, and equatorial regions), and with certain solar-related ionospheric disturbances.

The major part of the ionization is produced by solar X-ray and ultraviolet radiation and by corpuscular radiation from the Sun. The most noticeable effect is seen as the Earth rotates with respect to the Sun; ionization increases

in the sunlit atmosphere and decreases on the shadowed side. Although the Sun is the largest contributor toward the ionization, cosmic rays make a small contribution. Any atmospheric disturbance affects the distribution of the ionization.

The ionosphere is a **dynamic system controlled by** many parameters including **acoustic motions of the atmosphere, electromagnetic emissions, and variations in the geomagnetic field**. Because of its extreme sensitivity to atmospheric changes, the ionosphere is a very sensitive monitor of atmospheric events.

The most accurate way of measuring the ionosphere is with a ground-based ionosonde, which records data as ionograms.

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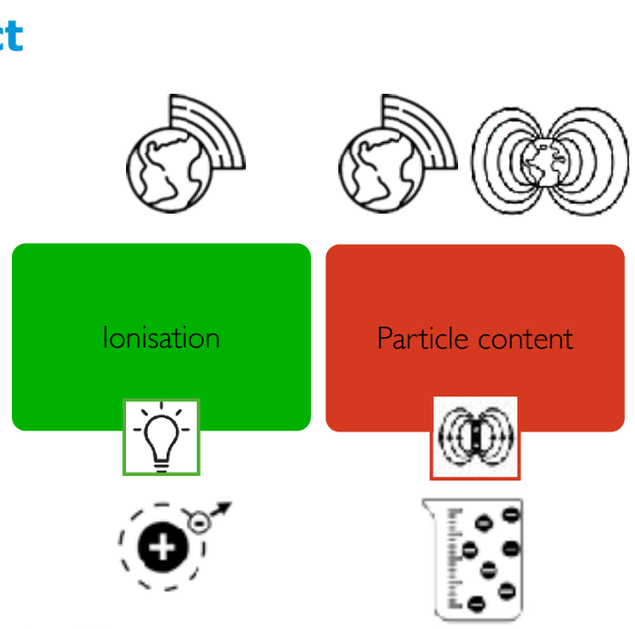
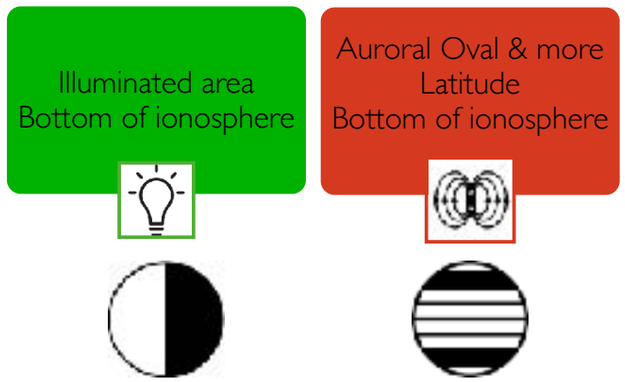
Impact



Area of Impact

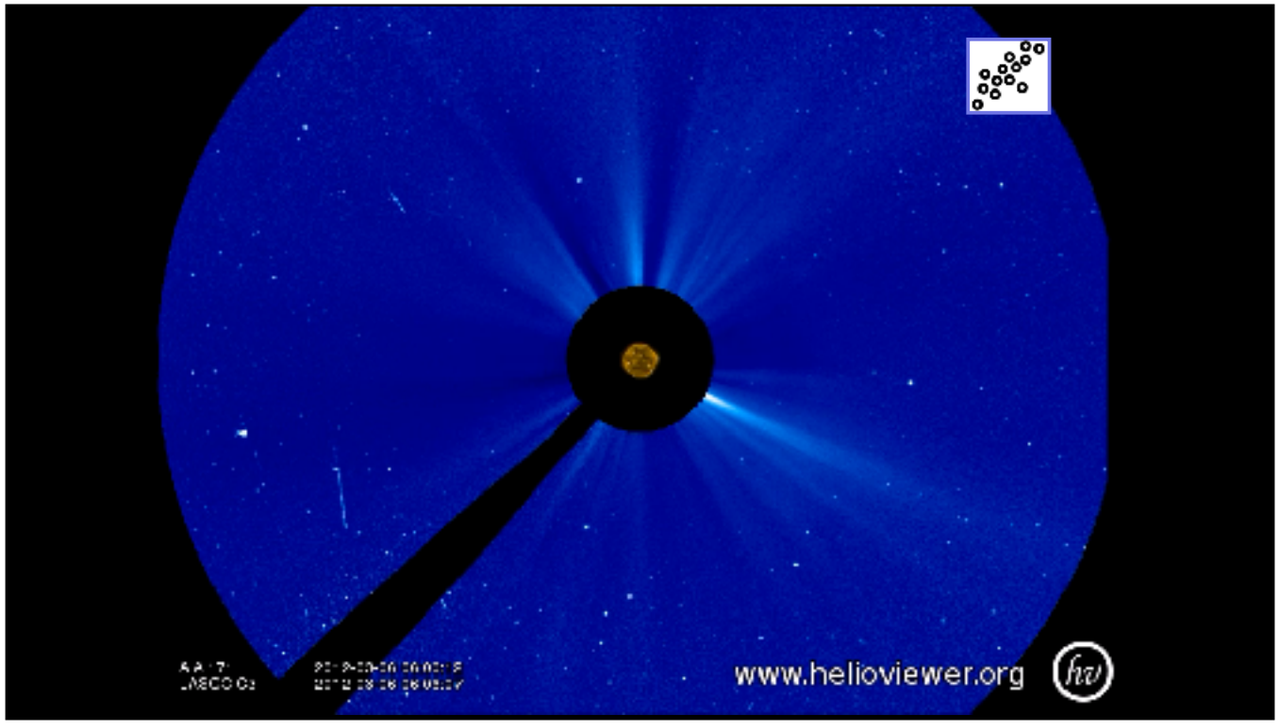




The magnetic field carried by the solar wind can reconnect on the day side with the magnetic field of Earth.
On the night side, magnetic reconnection between opposite magnetic field of the magnetosphere of Earth. (No solar magnetic field involved.)

The icon of the dipole represents the Earth dipolar field.

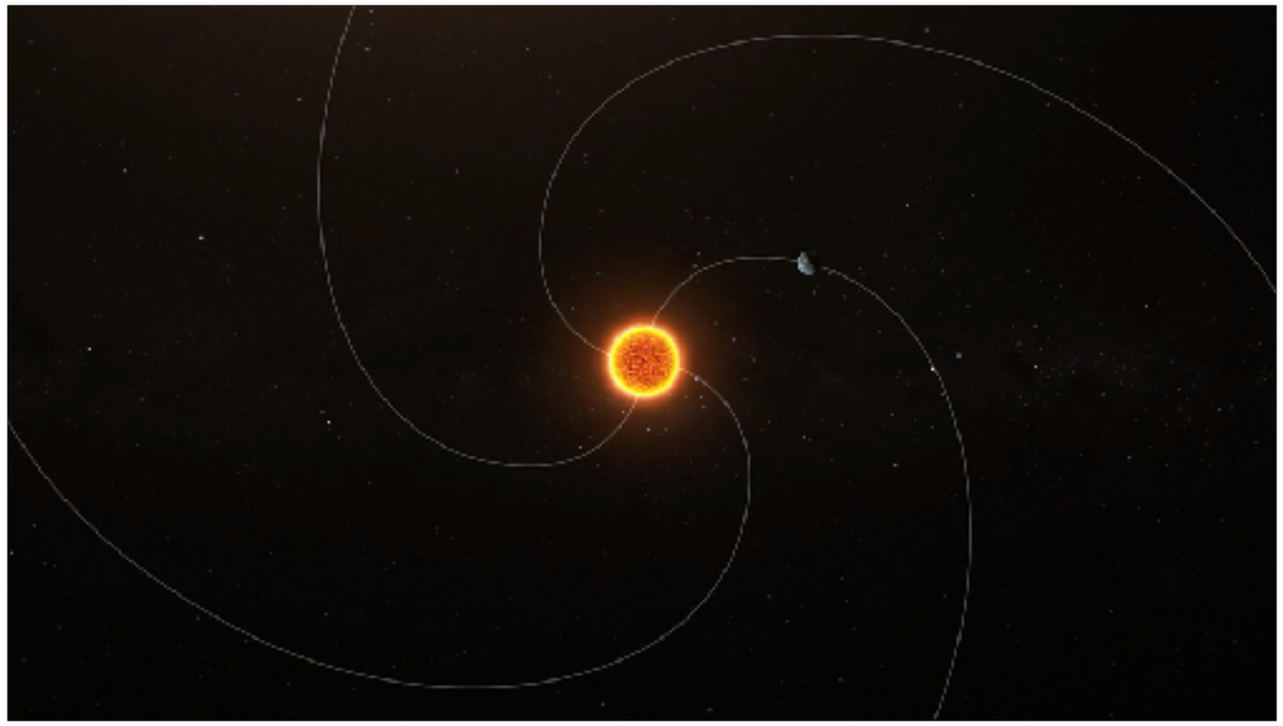
The result is that the Earth’s magnetic field is disturbed and most strong in the polar regions.



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.)



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

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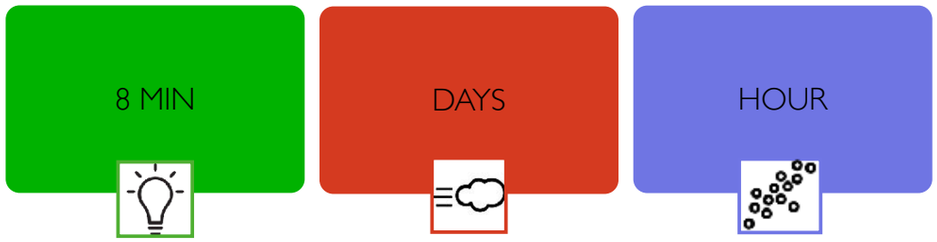

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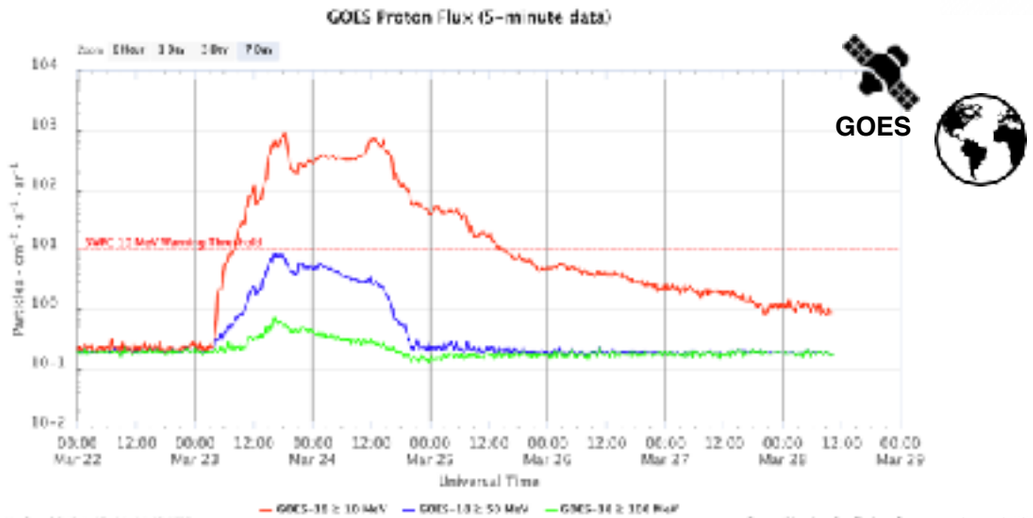
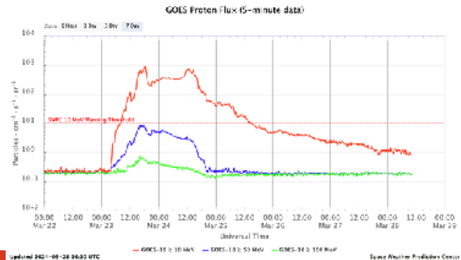
Storm scale



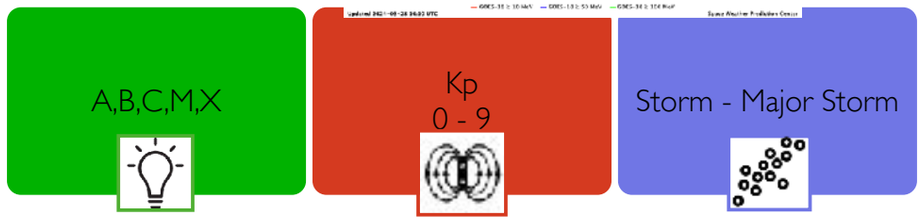
In situ - touch

The satellite GOES measures the proton flux at different energy levels.

Storm scale

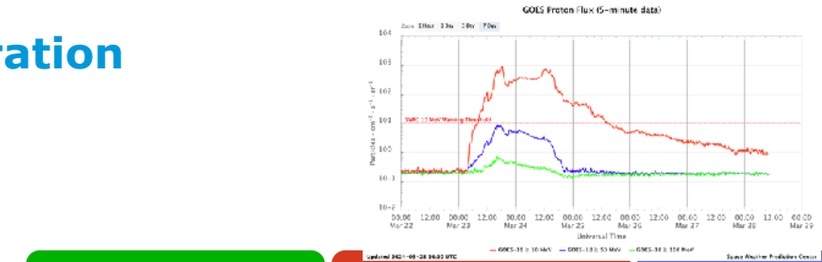




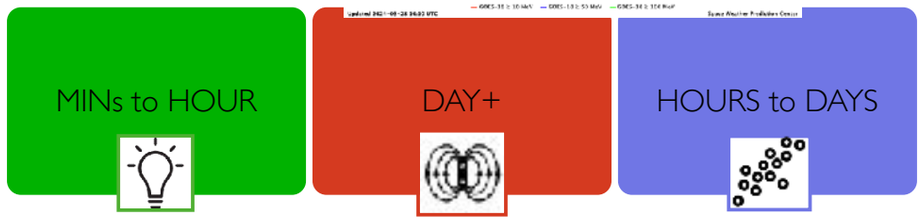


The GOES satellite measures the proton flux.
Storm: 10 pfu (proton flux units) for >10MeV
Major storm: 100 pfu for >100MeV

Duration

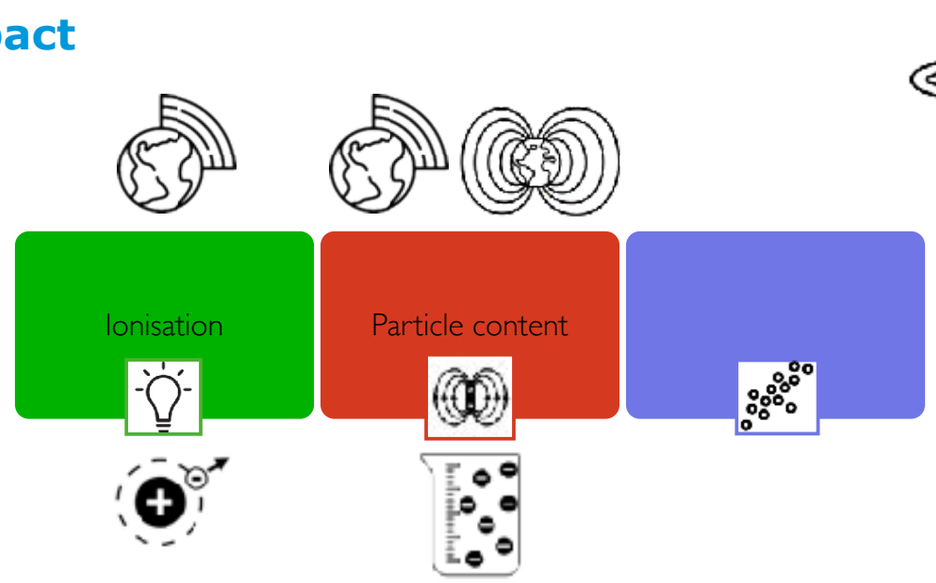






It takes in the order of an hour to reach Earth but the particle shower on Earth can last for days

Impact



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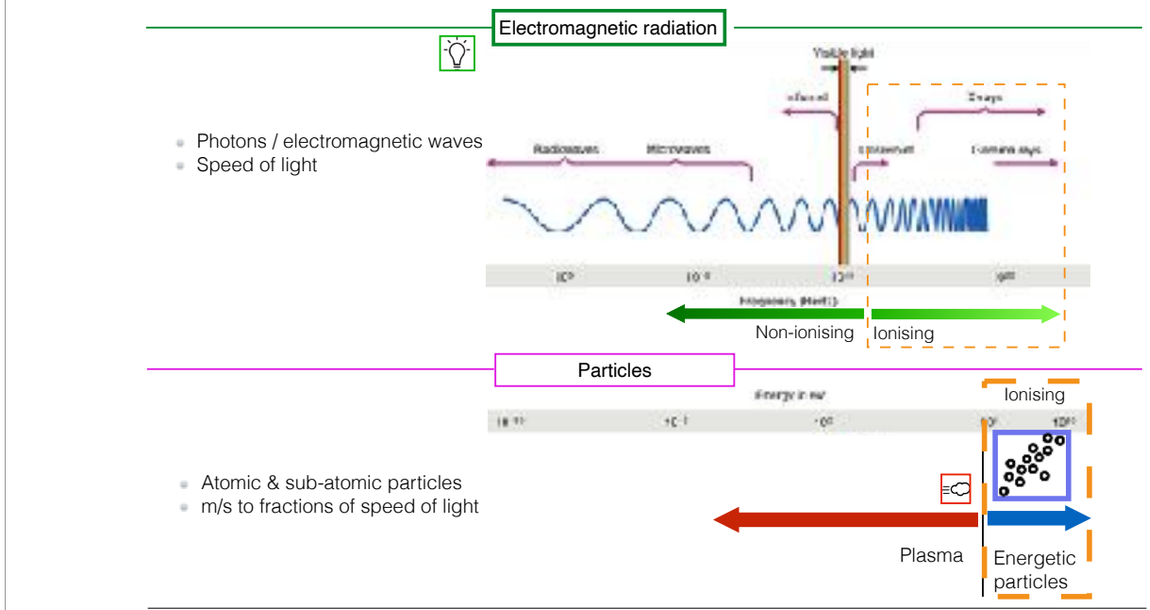


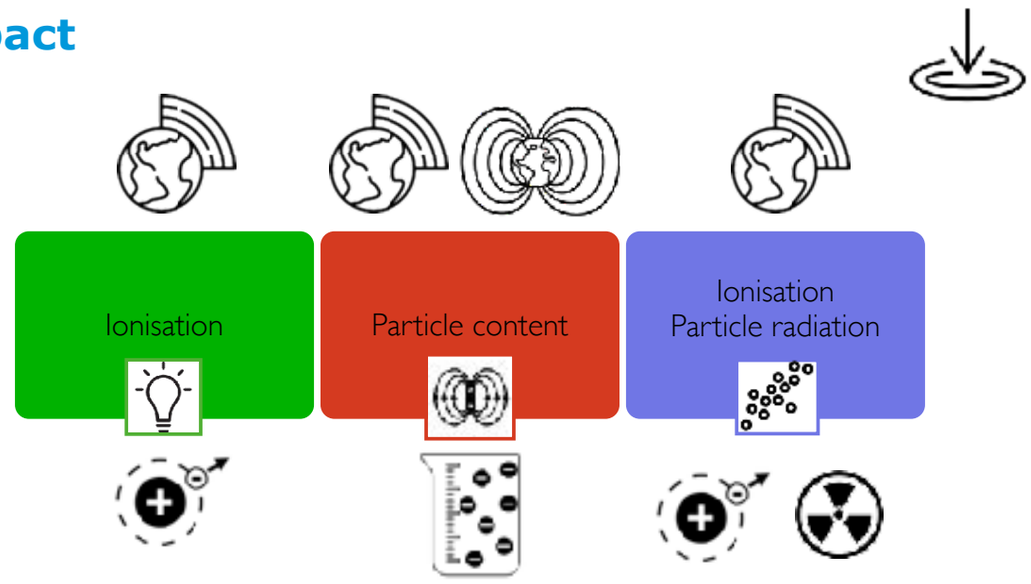
Photo-ionisation — green

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.

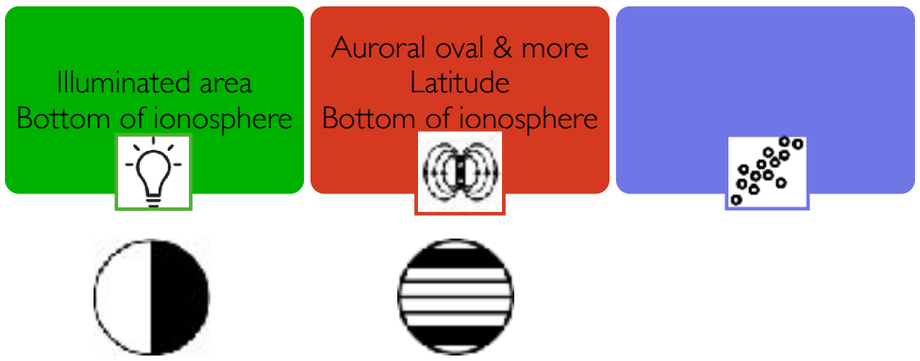
Gamma rays, X-rays, and the higher energy ultraviolet part of the electromagnetic spectrum are ionizing radiation, whereas the lower energy ultraviolet, visible light, nearly all types of laser light, infrared, microwaves, and radio waves are non-ionizing radiation. The boundary between ionizing and 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.

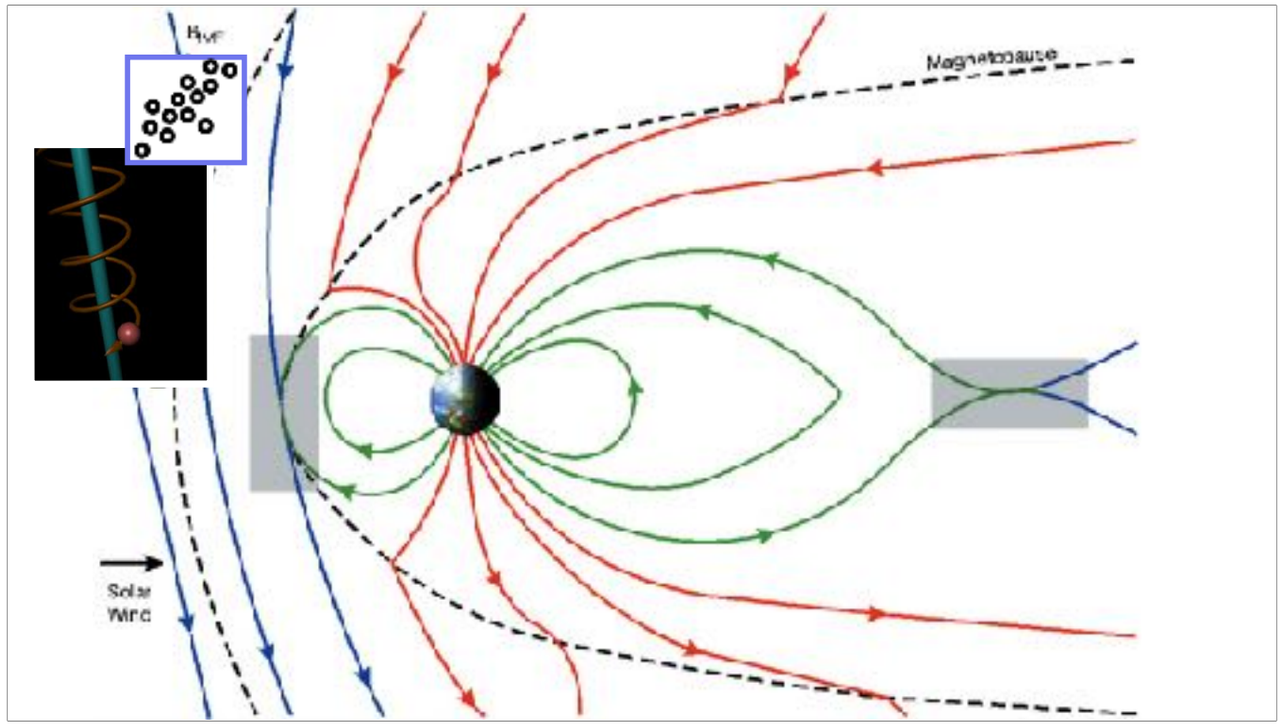
Impact



Radiation at flight altitude

Area of Impact

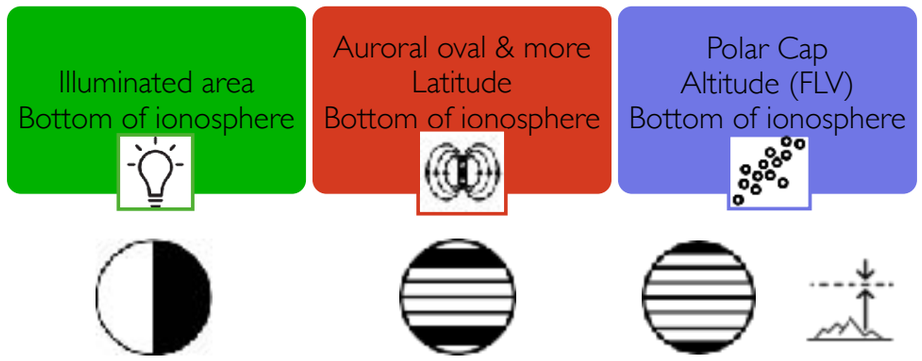


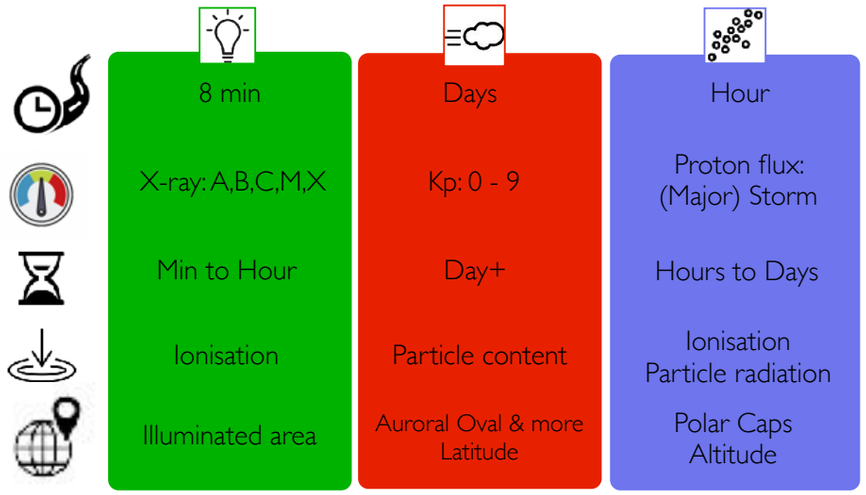


The solar energetic particles catch up with a magnetic field line of the earths magnetosphere and gyrate down towards the polar regions.
They mainly drop in in the area with open magnetic field lines (red).

Area of Impact

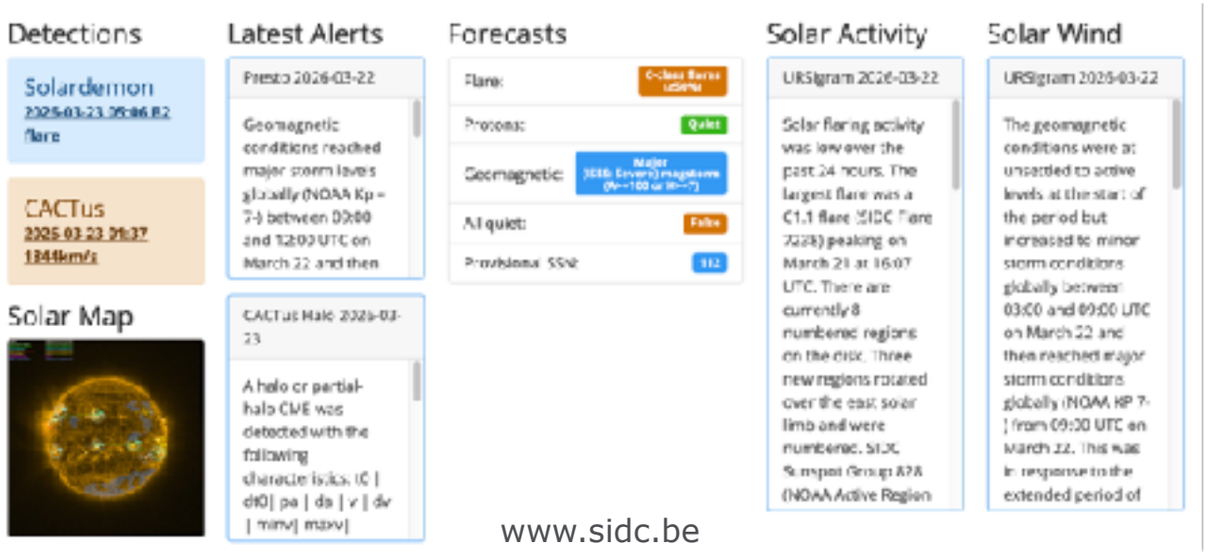





8 min
X-ray: A,B,C,M,X
Min to Hour
Ionisation
Illuminated area
Days
Kp: 0 - 9
Day+
Particle content
Auroral Oval & more Latitude
Hour
Proton flux: (Major) Storm
Hours to Days
Ionisation Particle radiation
Polar Caps Altitude

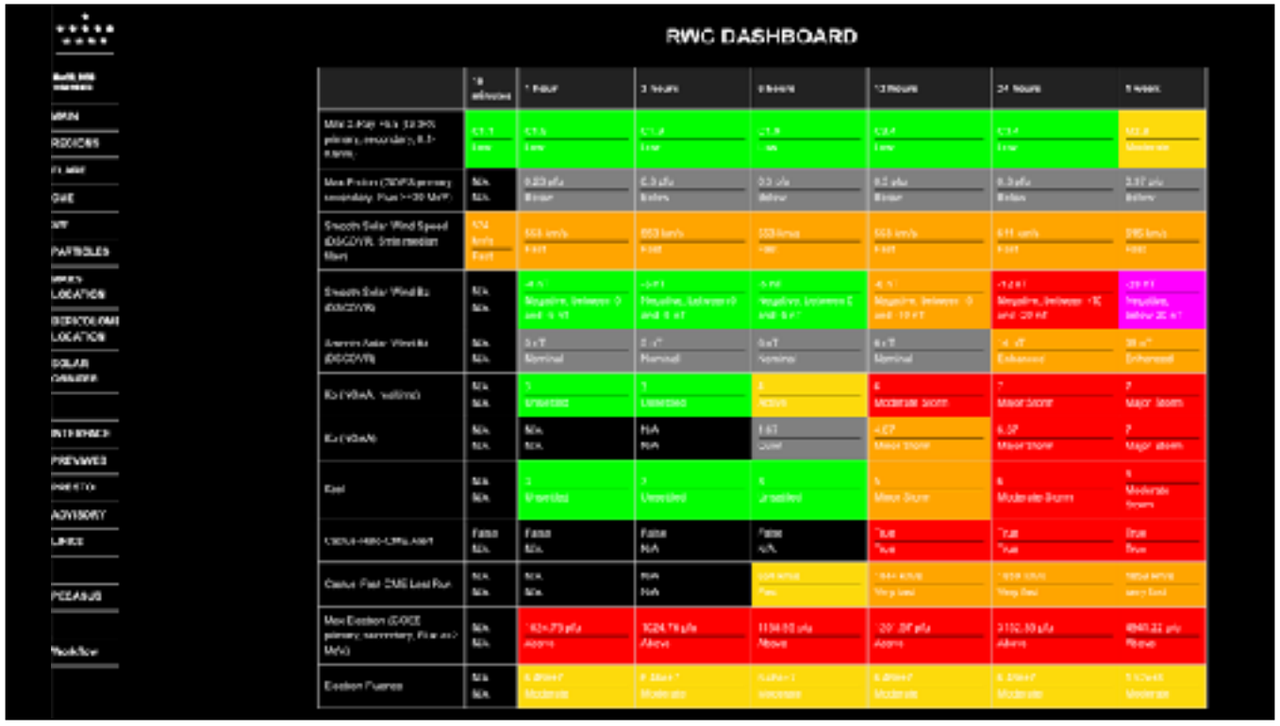
Space Weather Forecasts

STCE Space Weather Services



The STCE's space weather services include a variety of products which are displayed on the front page of our website. We have automated detection tools for flares and CMEs as well as an overview of the solar active regions on the left. On the right there is our daily forecast bulletin, split in the solar activity and geomagnetic parts. In the middle we have a more graphical overview of the current space weather conditions and also the latest fast alert is displayed.
The forecast is made once a day, the detections are continuous and the alerts are sent when needed, eg in case of a strong flare or CME, a proton event or a geomagnetic storm.

A presto alert needs to be sent as soon as one of these events is happening:
- During or just after an X-flare.
- In case of a proton event, i.e., Flux >= 10 pfu (10 MeV particles).
- When Kp > 5 or K > 5.
- When a (frond or back-side) halo CME or a strong Westward directed CME occurred.
- In case you observe a fast forward shock in the solar wind speed.
- In case you observe enhanced solar wind conditions which will likely lead to geomagnetic storm conditions K or Kp > 5.


RWC DASHBOARD

Ursigram



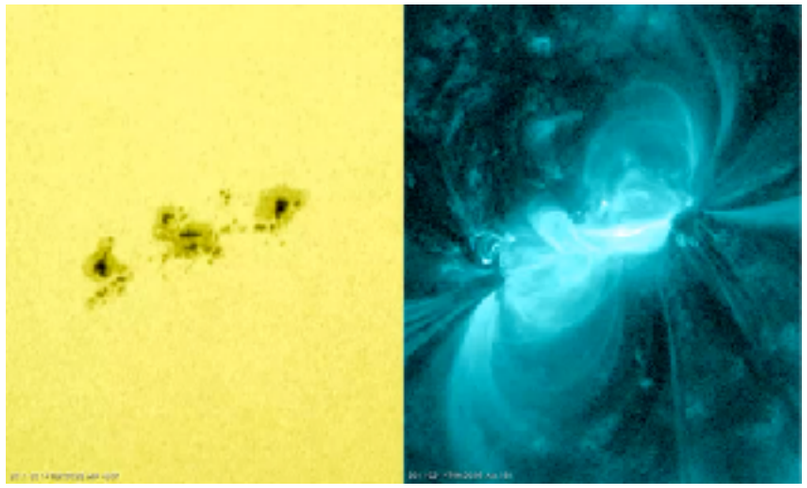
Previweb - Forecaster's page



This is the top of our forecaster prediction page. You can see that besides the preparation of the daily bulletin, the forecaster also makes a weekly overview.

Solar Active Regions and flaring also includes a discussion on CME’s and CHs

Solar Flares - Sunspots



SDO/AIA

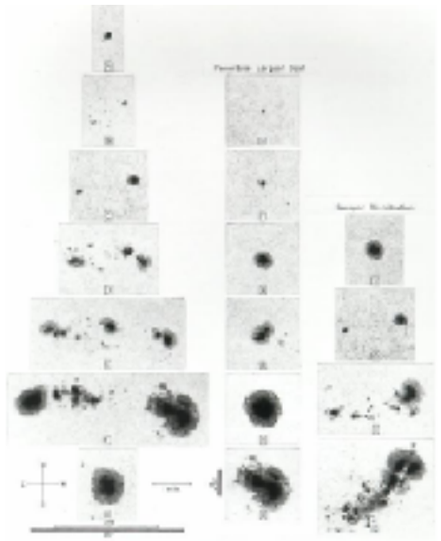
Magnetic restructuring
Magnetic reconnection
Conversion of stored energy

Solar flares are triggered by a restructuring of the magnetic field. When field lines are pushed together and magnetic reconnection occurs, and enormous amount of stored magnetic energy can be converted into radiation (heat, flare) and kinetic energy (CME).
We can spot this in the observations by looking for signs of magnetic restructuring, such as turning and interacting sunspots, growing regions, increasing in complexity. Instability in one region can also cause instability in another nearby region, …

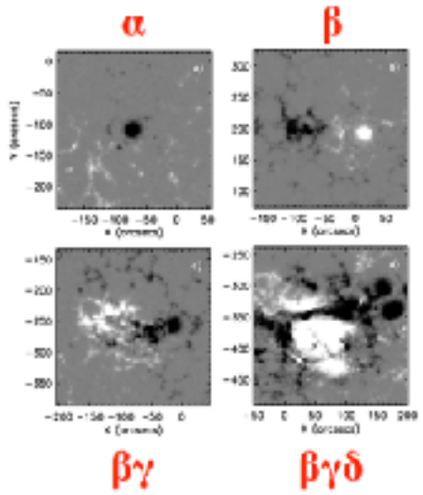
Magnetic restructuring
Magnetic flux emergence
Helical energy storage
Instability in the surrounding field
Interaction with nearby CH
…

Solar Flares - Sunspot Classification

McIntosh



Mount Wilson/Hale



To quantify the complexity of the regions that are at the base of a solar flare, we divide them into different classes which can be linked to their likelihood to produce a flare

a three letter code where the first denotes the original classification, the second gives more information on the largest spot and the third specifies how compact the region is and how the sunspots are distributed between the two major polarities.
We have 60 possible combinations which -through statistical studies- have been linked to flare probabilities, but with rather large uncertainties.

McIntosh classification
goes back to an original classification that was defined at the Zurich observatory.
Zpc (3-letter code)

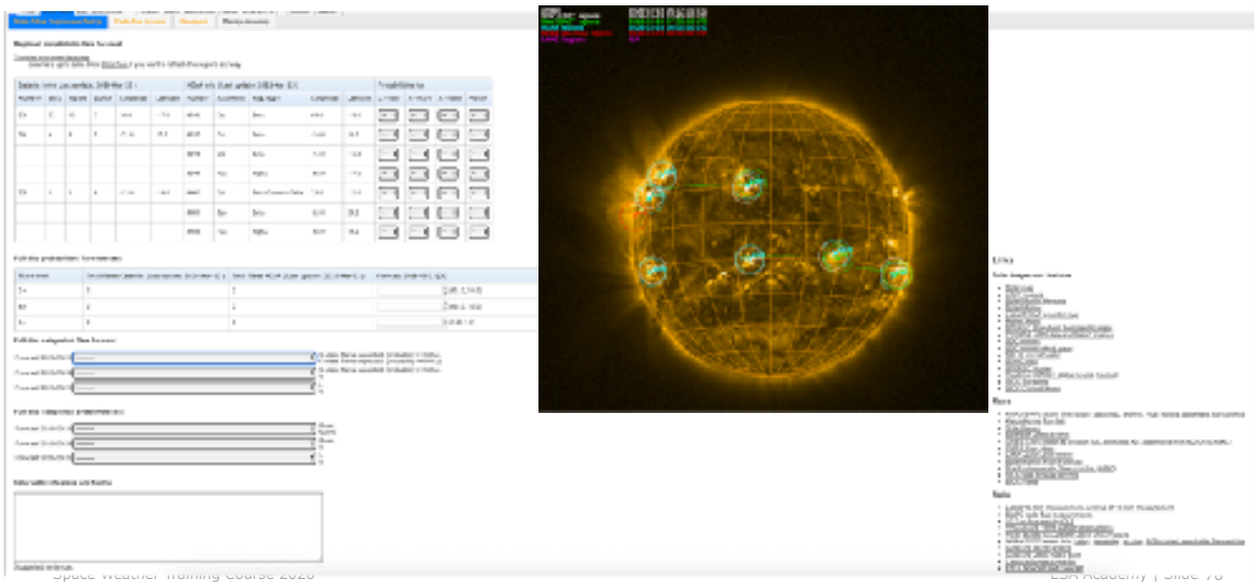
- Z - Modified Zürich classification
- p - Penumbra largest spot
- c - Interior sunspot distribution

60 possible combinations
Linked to flare intensity
Rather large uncertainties
Used worldwide

A second classification scheme for sunspot regions is the Mount Wilson or Hale classification. Here we also take the magnetic properties of the sunspots into account. There are only 7 options with more greek letters indicating a more complex group.
Alpha: unipolar
Beta: bipolar
Gamma: difficult to draw a single line between two polarities
Delta: mixing of the polarities

For space weather forecasting it is important to know how this classification relates to the probability of producing a flare. Intuitively, it is easy to understand that more complex regions, with mixed polarities, will allow for easier interactions of the magnetic field and thus a larger chance of a stronger flare.

Solar Flares



Going back to our forecasting tool.
When the forecaster loads this page, it is automatically filled with the regions that are on the solar disk that day.
We use the numbering by the Catania Observatory as a baseline, which is based on the sunspots only (so no magnetic observations), and we thus link it to McIntosh classifications. We have a classification for each Catania group. We also use the NOAA group numbering and as you can see there is not always a one-to-one correspondence between both. For each region, the tool suggest the probability for each type of flare. This is based on a statistical look-up table (that we built internally) linked to the Macintosh classification. The probabilities can be adapted by the forecaster based on their observations, eg. Did the region show increased activity in the past hours, was there flaring observed already, what did this region do during its previous rotation, is the region decaying Etc.
Its position is also important, as for forecasting we are interested in regions that will produce an event that will impact Earth. Therefore, a region on the Eastern side that is approaching Central Meridian should probably be reported

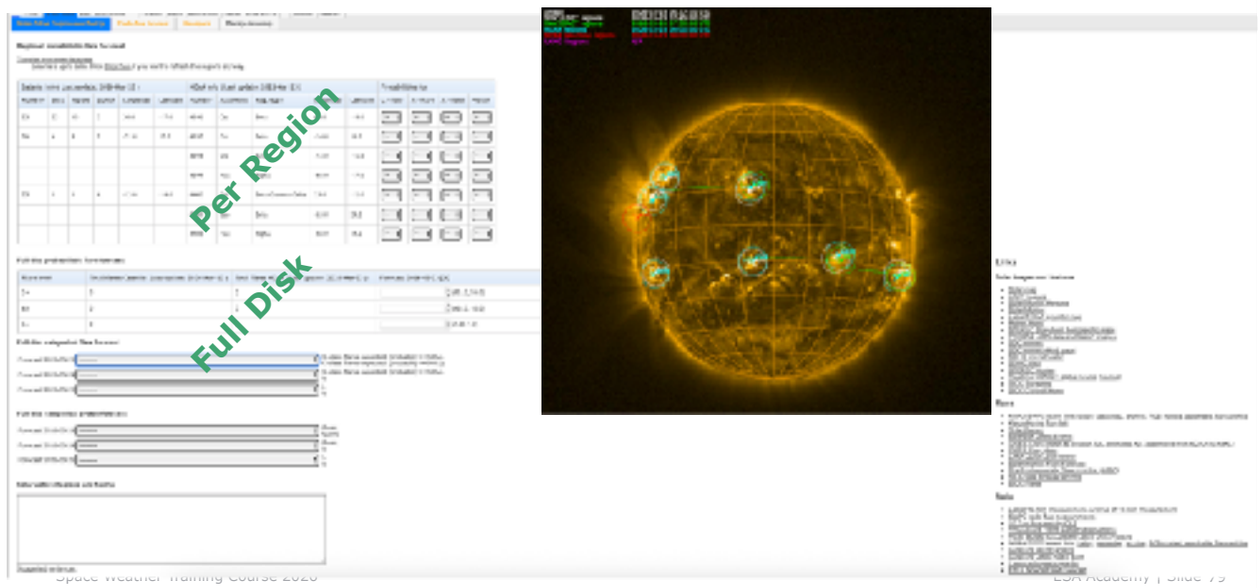
Region data are collected from two sources: Catania Observatory and NOAA.
By convention, we report the regions reported by Catania. SIDC uses NOAA for crossexamination.

A probability here means: “The probability of a flare of a certain magnitude or higher occurring over a certain time period”.
The magnitude bins are interpreted to be unbound at the upper end: e.i. C means C or above, M means M or above, etc.
The time period of prediction covers a period of 24 hours, from 12:30UT of that day until 12:30UT of the next day.

If a region has a complex magnetic configuration it is more likely to flare. Does this region seem to be decaying, or will it develop further the next days? Its position is also important, as for forecasting we are interested in regions that will produce an event that will impact Earth. Therefore, a region on the Eastern side that is approaching Central Meridian should probably be reported. On the other hand, one that has crossed Central Meridian and is moving to the Western limb may be of less significance and therefore not mentioned in the Ursigram.
For each identified region on the visible Earth side of the Sun, fill in your estimated flaring probability for C, M and X Flares from 1 to 99%.

The prediction of the full disc probability corresponds in principle to the sum of all probabilities. However, you might want to increase or decrease your prediction to take into accounted **additional regions expected** to rotate from behind the East solar limb or developing on disc.

Solar Flares



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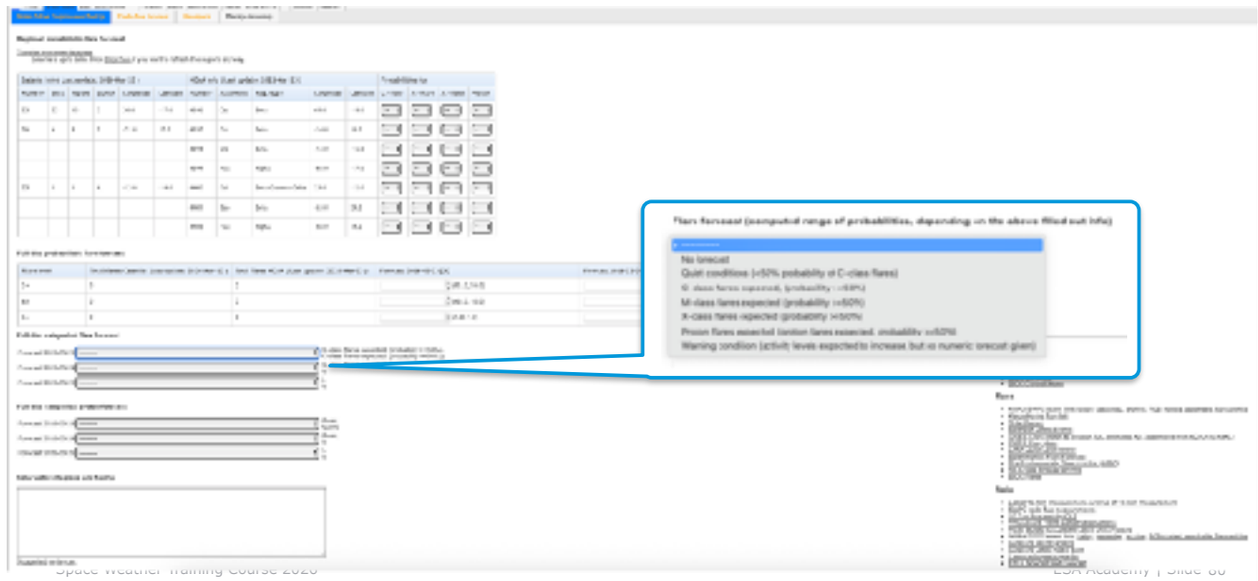
Solar Flares



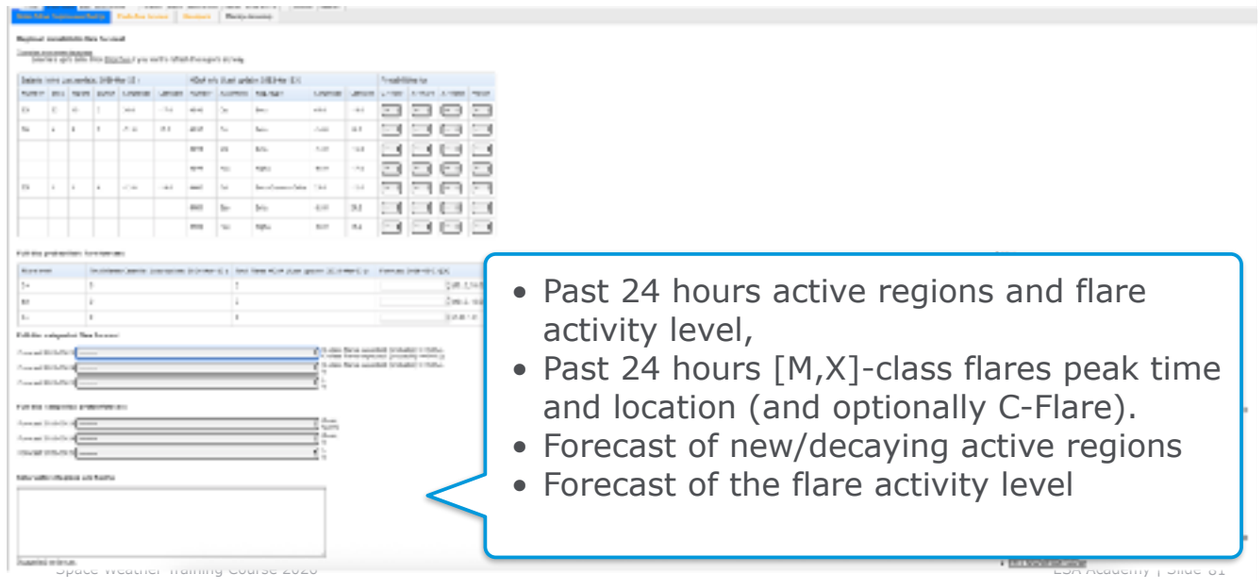
The Total flare forecast table is automatically computed based on your flare probabilities provided for every active region. Use your judgment to decide and eventually update the full disc probabilities.

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.

Solar Flares

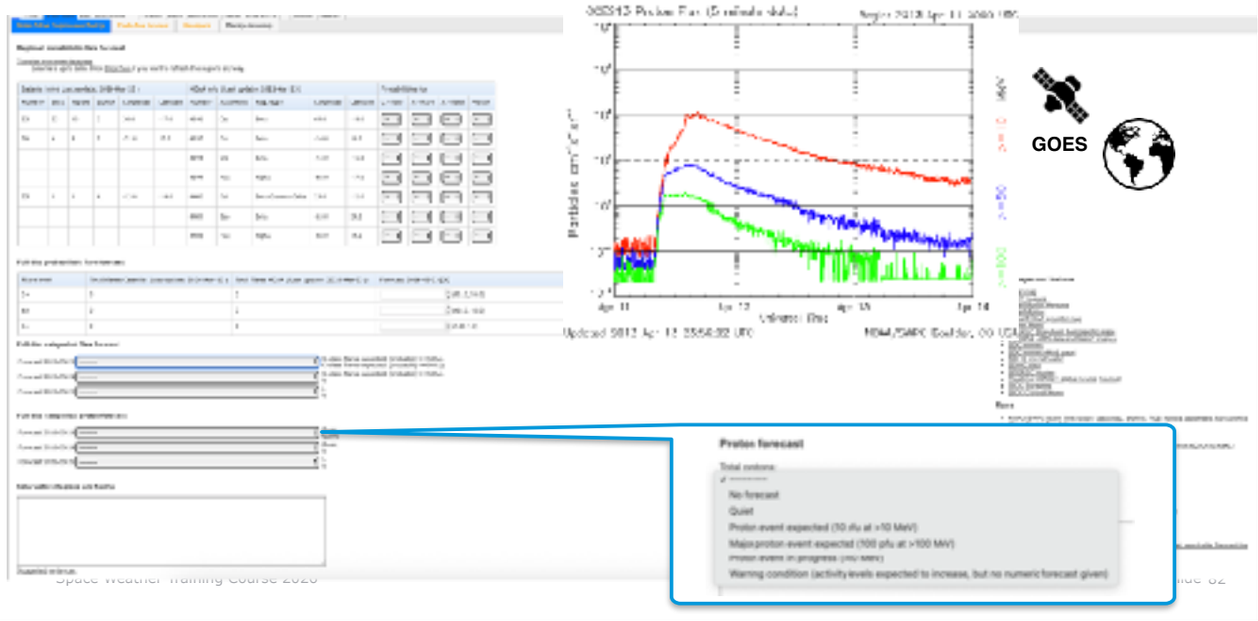


- Past 24 hours active regions and flare activity level,
- Past 24 hours [M,X]-class flares peak time and location (and optionally C-Flare).
- Forecast of new/decaying active regions
- Forecast of the flare activity level

In the info box, the forecaster describes the solar activity that was observed in the past 24h (since the last bulletin). Here also the Hale classifications is used to describe the magnetic complexity of the regions.

When reporting flares, write the biggest flare in the latest 24 hours and those associated with Earth-directed CMEs.

Protons



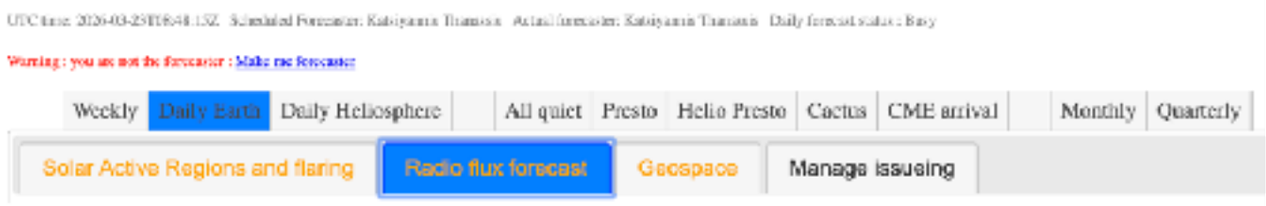
We only see them when they arrive

The forecaster also predicts proton events. These occur when the greater than 10 MeV proton flux exceeds the threshold of 10 particles.
Proton events can be associated with flares (impulsive, particles are accelerated) or CMEs (from shock, gradual event)
There's a higher likelihood for SEP events from the western hemisphere as they travel on magnetic field lines that are connected to the earth's magnetosphere. (Parker spiral)
The stronger gradual events are associated to wider and faster CMEs

Look for active regions & filaments that can:
- Produce strong x-ray flares
- Fast CMEs (~1000 km/s or more)
- Wide CMEs (partial or full halo CMEs)
- Preferably on the western solar hemisphere

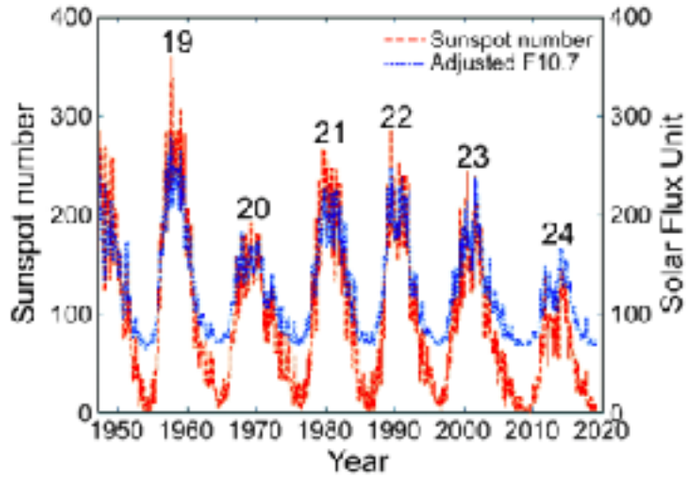
Finetune from history on farside/eastern hemisphere
- Proton flux enhancements,…
- Observations by STEREO spacecraft

Previweb - Forecaster's Page



Radio Flux forecast
This is the top of our forecaster prediction page. You can see that besides the preparation of the daily bulletin, the forecaster also makes a weekly overview.

F10.7 - Observation



The sunspot numbers (red curve) and the 10.7 cm solar flux (F10.7, blue curve) from the middle of the 22th century (1954-71). The F10.7 values are in solar flux units (sfu), 1 sfu is equal to 10−22 W m−2 Hz−1. The observed F10.7 is presented as the right axis.

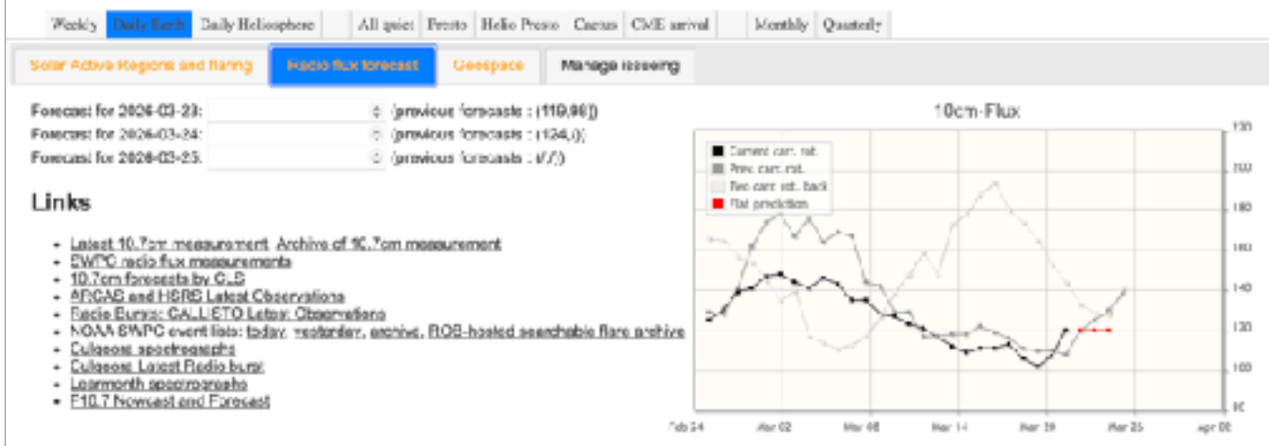
(Grytsai et al., 2020)

A 10.7 cm solar flux measurement is a determination of the strength of solar radio emission in a 100 MHz-wide band centered on 2800 MHz (a wavelength of 10.7 cm), averaged over an hour. It is expressed in solar flux units (sfu), where 1 sfu = 10–22 W m–2 Hz–1.
The F10.7 is well correlated with the sunspot number, and thus a good indicator of the level of solar activity

Note that the baseline F10.7 flux is not at 0, but at ~65 sfu

Three flux determinations are made each day, at 1700, 2000, and 2300 UT, except during the winter months, where the low elevation of the Sun (the Dominion Radio Astrophysical Observatory, DRAO, lies at +50° latitude) and the hilly terrain, forces the times to be changed to 1800, 2000, and 2200 UT. Each flux determination takes 1 h and takes no account of the solar radio emissions recorded outside the intervals covered by the measurements. Since the active region emissions contributing to the slowly varying emission (and F10.7) may vary over hours or less, there may be a significant degree of undersampling. In addition, there could be a contribution by a burst. The undersampling means there is a possible error if one uses a flux value in an application involving a different time from that at which the flux measurement is made.

F10.7 - Forecast



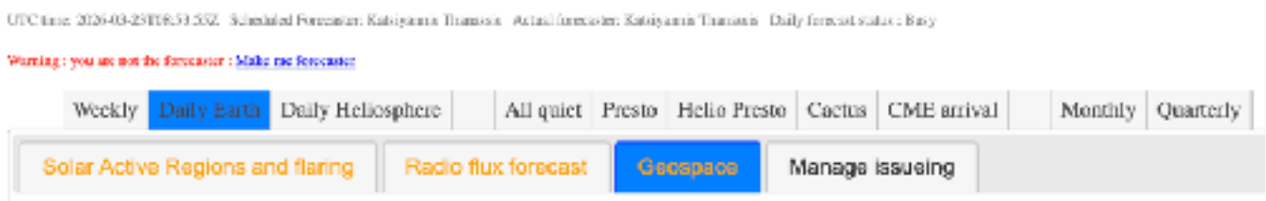
The 10.7cm radio flux has **contributions from three sources**. Firstly, it can be impacted by **radio bursts** (associated with eruptive phenomena), causing a changes to its values ranging from minutes to hours. Secondly, the **presence of active regions, dimmings or bright loops** will lead to an increase of its values, lasting from days to years. Finally, there is always present the contribution from the **background emission** of the Sun. As a result, **the bottom threshold for the 10.7cm flux is about 65 sfu.**

F10.7 is a continuous variable to forecast

Recurrence is a very good predictor for the background emission. What was the value during the previous rotation? Take that again and adjust for bursts or brighter regions.
We predict the F10.7 cm flux for the coming 3 days.

For the time already passed, we report the 10.7cm flux measurements reported by Natural Resources Canada recorded on 20:00:00UT. For any other time, we estimate how much the flux could be.
There are a number of models available to for 10.7cm flux prediction. One available on the links is by CLS, which you can use to have an idea of the future values. There is also the model created and used by Jan. In any case, the conditions on the Sun should also be taken into account:
• eruptive phenomena, bright loops, rising sunspots on solar surface? Increase the prediction by 1 or 2
• decaying sunspots on solar surfaces? Increase the prediction by 1 wing-periods

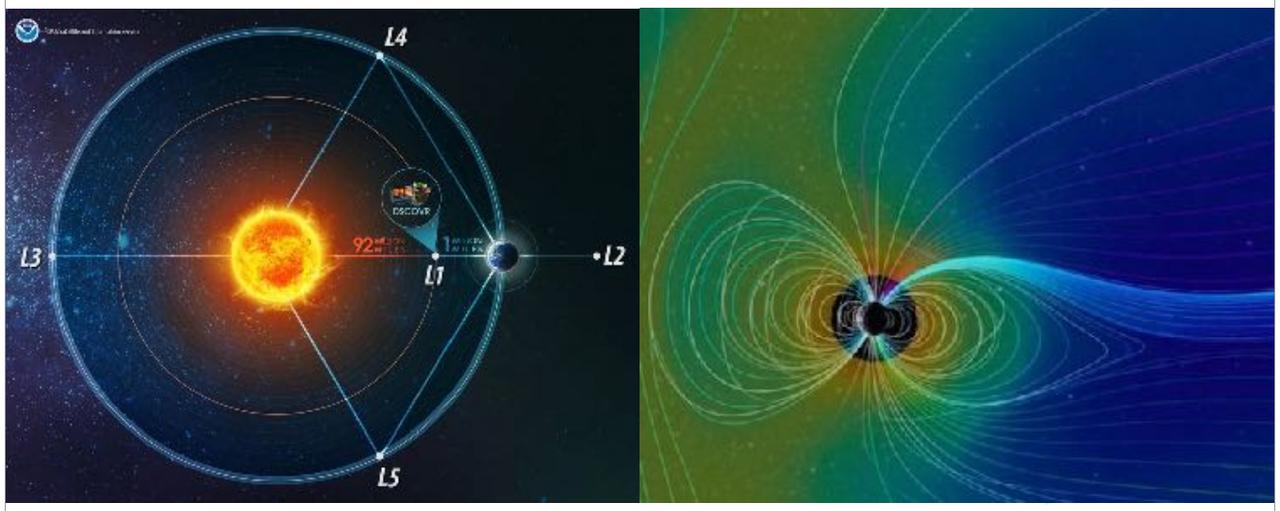
Previweb - Forecaster's Page



L1 and magnetosphere
This is the top of our forecaster prediction page. You can see that besides the preparation of the daily bulletin, the forecaster also makes a weekly overview.

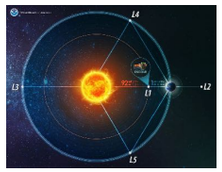
L1 and Magnetosphere

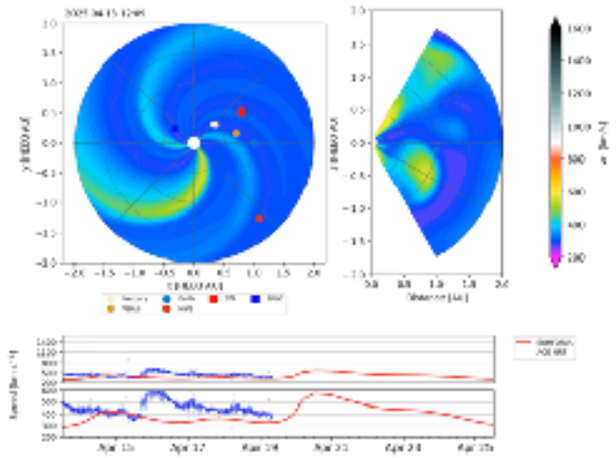




The wind at L1, 1 hour upstream of earth

3 Solar Wind Transients: HSS

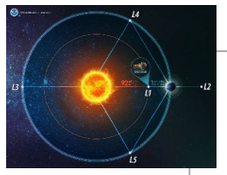


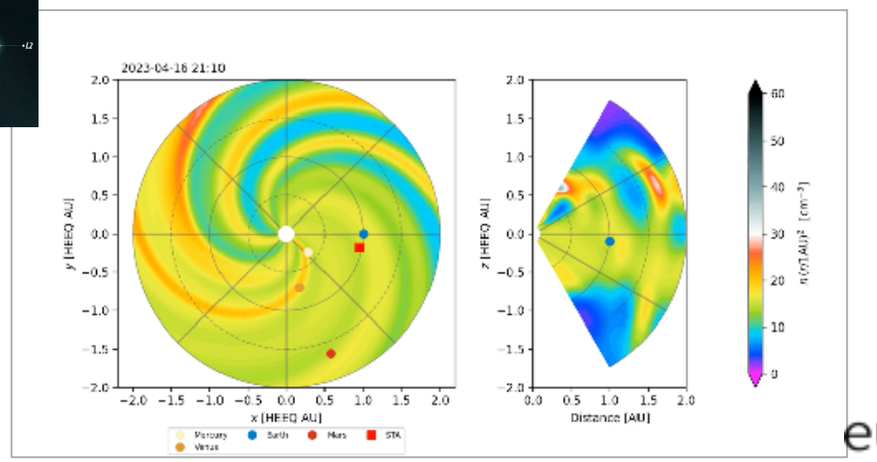


lasting only for a short time; impermanent.

Look at the sun for coronal hole, RECURRENCE is important here

3 Solar Wind Transients: CME





lasting only for a short time; impermanent.

CME arrival prediction

Look at the sun, corona graphic images, CACTUS
Euphoria
Drag based models

CME - coronagraph - front or back - low coronal signatures - geomagnetic storm

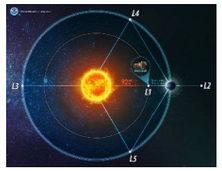
Solar wind disturbances that provoke strong geomagnetic storms are usually linked to either a CME (eruptive) or a coronal hole (non-eruptive)
Eruptive events (CMEs) typically have a stronger impact compared with CH because CME is a magnetic structure with a Bz component

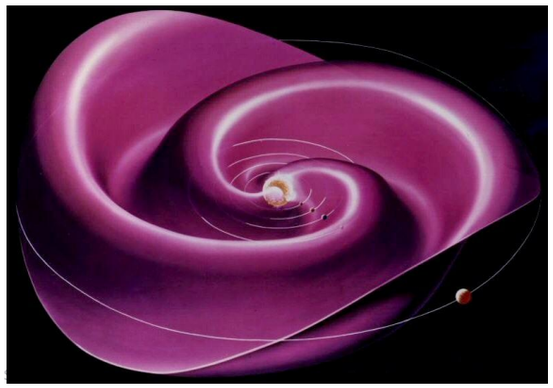
CMEs originate from active regions with a complex (sheared and twisted) magnetic field structure or high/old filaments. A filament that in imaging data (SDO/AIA) seems to develop and suddenly disappear indicates a CME eruption. Another feature associated with CMEs are coronal dimmings. If you track one at the AIA data, search for a possible associated CME that took place about time of its appearance.

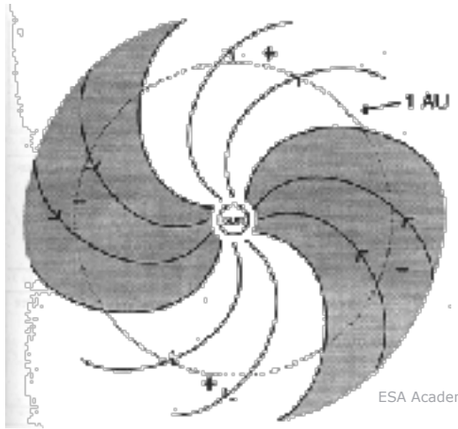
Check the position of STEREO on that date to understand the orientation of the CME. LASCO provides coronagraphic images of the CMEs, giving information on its structure, but not of its origin. It is therefore not possible to identify whether the eruption was **front or back-sided**. For forecasting purposes, we are interested in reporting either front-sided or Halo-CMES only, as those can have an impact on Earth.

As coronagraphic observations cannot distinguish between front side and backside halos, a forecaster thus has to look for low-coronal CME signatures like coronal dimming, EITwaves, post-eruption arcades and eruptive prominences. In order to understand whether the CME is front or back-side, use SDO/AIA or STEREO/EUVI 195A data. If a CME was seen by STEREO, you can additionally use the SIDC tool cor2speed to get a crude estimate of the CME speed. You will still need to calculate the inclination angle.

3 Solar Wind Transients: SBC







lasting only for a short time; impermanent.
Cravens 1997

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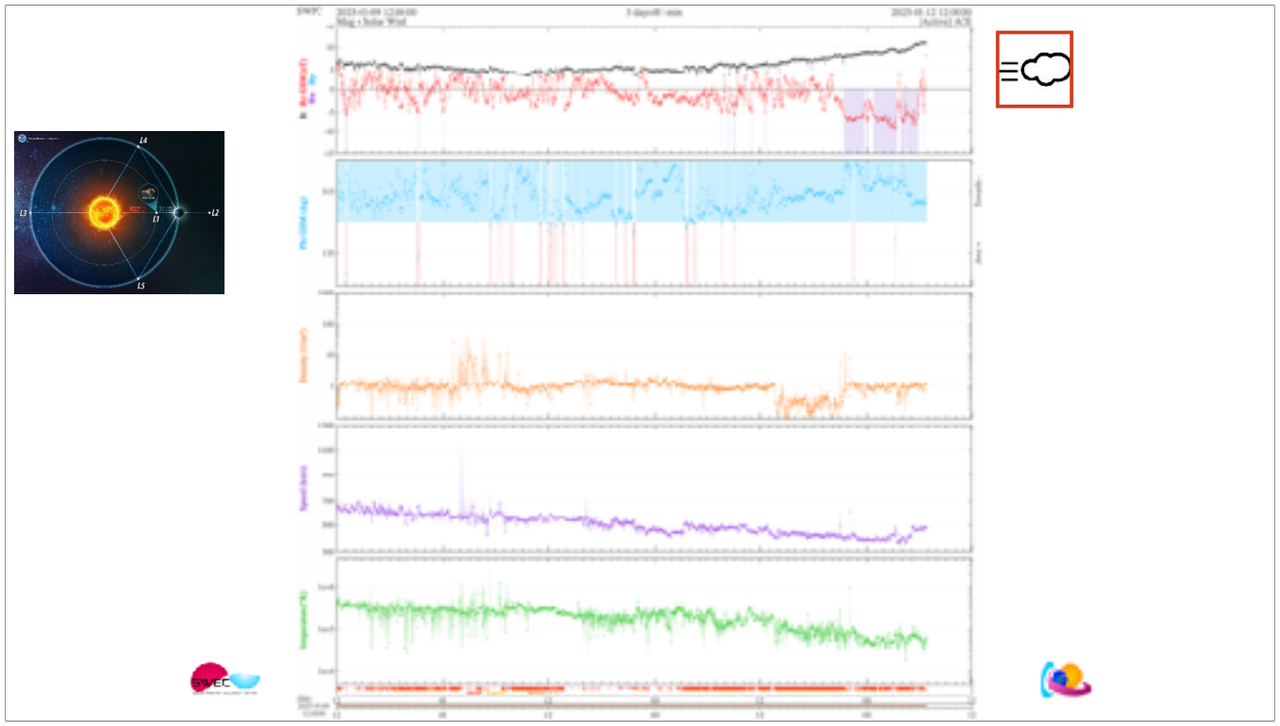
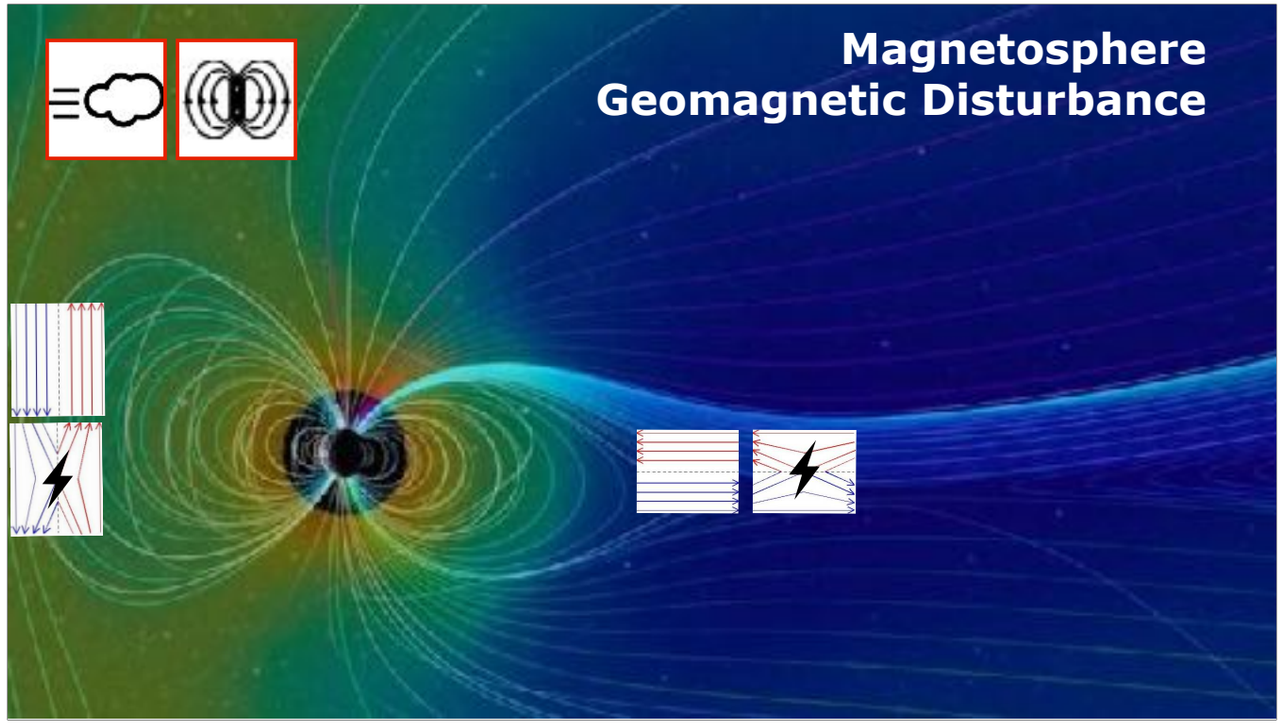


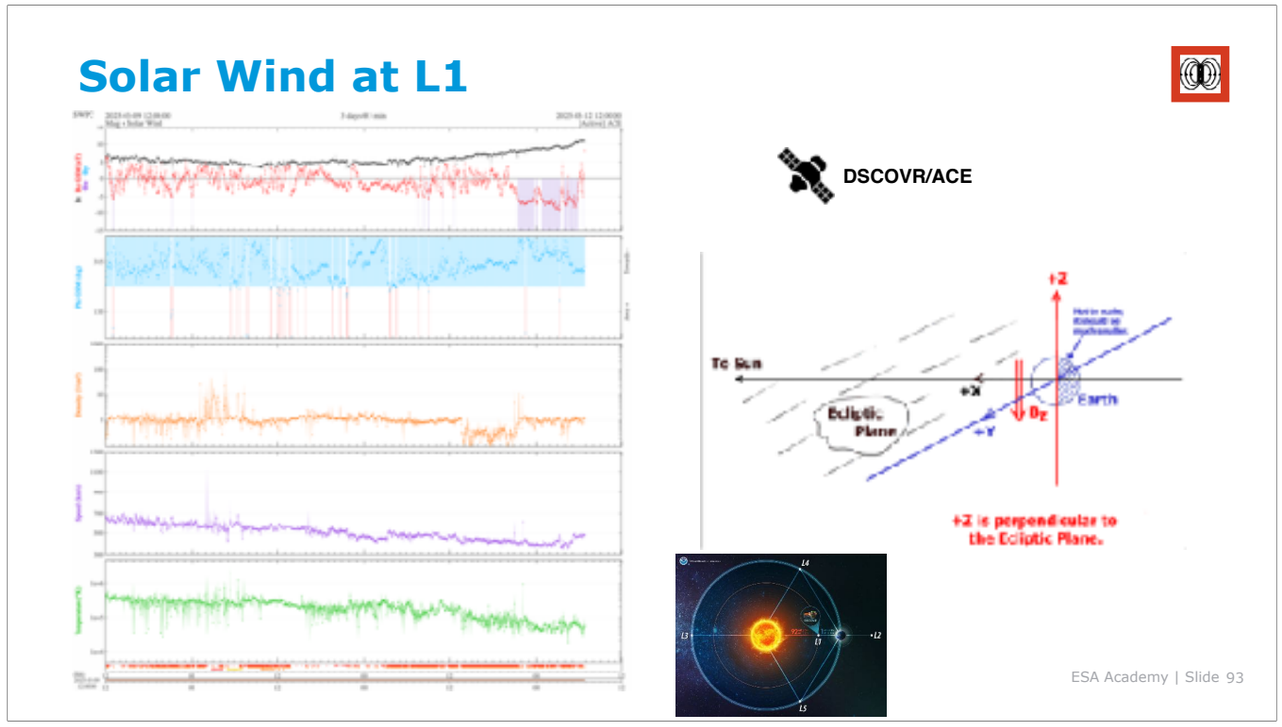
https://www.swpc.noaa.gov/products/real-time-solar-wind



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 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.

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 connect easily and 'open'. This causes geomagnetic storms. Magnetic field lines in the same direction interact less.

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



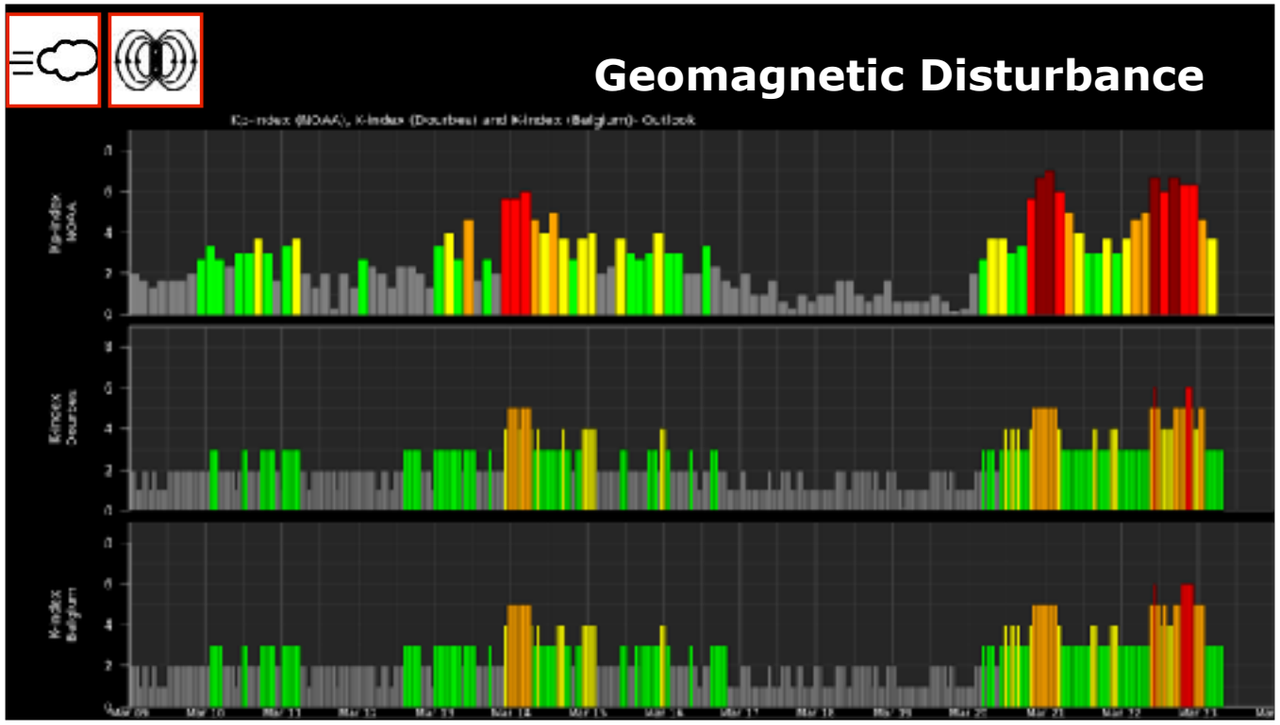
To forecast the geomagnetic index K, we need to look at disturbances of the solar wind which will provoke disturbances in the Earth's magnetic field.

Solar wind disturbances that provoke strong geomagnetic storms are usually linked to either a CME (eruptive) or a coronal hole (non-eruptive)
Eruptive events (CMEs) typically have a stronger impact compared with CH because CME is a magnetic structure with a Bz component

When we monitor the magnetic field, we look at these parameters. These measurements are made by the DSCOVR satellite. They characterise the solar wind. From top to bottom there are measurements of: the magnetic field, the phi angle, the density, the speed, and the temperature.

These measurements show the impact of two coronal mass ejections on the solar wind parameters: we see e.g. a clear rise in the speed of the solar wind, and a strong southward component of the magnetic field for the second coronal mass ejection.

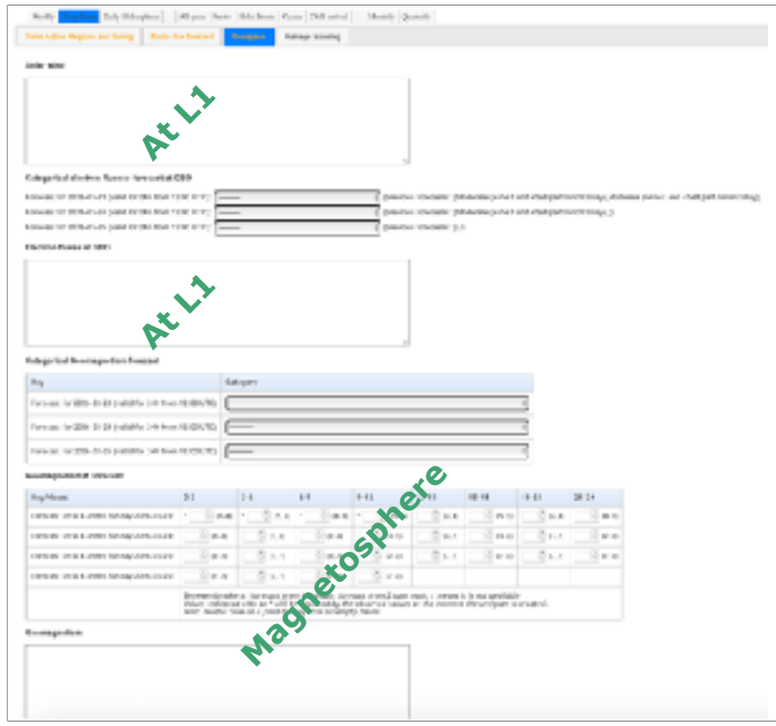
Why is the southward component of the magnetic field so important: because a strongly southward oriented magnetic field allows reconnection with the magnetic field of the earth. (See coordinate frame used for the solar wind).



The main purpose of geomagnetic indices is to objectively **quantify the level of perturbations of the earth's magnetosphere**. They are simple measures of magnetic activity that occurs, typically, over periods of time of less than a few hours and which is recorded by magnetometers at ground-based observatories.

K index - The K index (K stands for "Kennziffer") is a 3-hourly quasi-logarithmic local index of geomagnetic activity relative to an assumed quiet-day curve for the recording site. The observations measure the deviation (minimum-to-maximum amplitude) of the most disturbed horizontal component, and are corrected for diurnal and seasonal changes. A scaling is done such that the historical number of disturbances at a certain K-level are about the same at all stations, thereby also removing the latitudinal effect. **The K index ranges from 0 to 9** (dimensionless integer). It was introduced by Bartels in 1938 and Bartels et al. in 1939. Note the K index is a **local index**, and as such often the subscript "k" is used to indicate the individual station, e.g. pending the context, KD, KDO, KDOUR, ... may all refer to the Dourbes K index. Underneath a graph showing the evolution of the K index at Dourbes during one of the strongest geomagnetic storms of solar cycle 24, on 22-23 June 2015. The colored bars in the K_BEL and K Dourbes indices are hourly updated K values, calculated from data over the previous 3 hours, e.g. The value declared at 10:00UT is based on data over the timerange 7:00-10:00UT. The transparent bars are the 3-hourly values at the typical intervals, i.e. at 03:00UT for the interval 00:00-03:00UT, at 06:00UT for the interval 03:00-06:00UT, and so on.

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. Also here, the subscript "k" used in ak refers to the individual station “k".



Solar Wind



K index - Forecast



Recurrence!
But also CME arrival, HSS arrival from CH and orientation of the magnetic field
We predict local K, not Kp!
The K index is a categorical variable to forecast

Recurrence (27 day rotation) + Coronal hole evolution (from EUV) + STEREO in situ measurements
Competitive with physics based models like ENLIL and EUHFORIA
Verification of these forecasts is an ongoing activity

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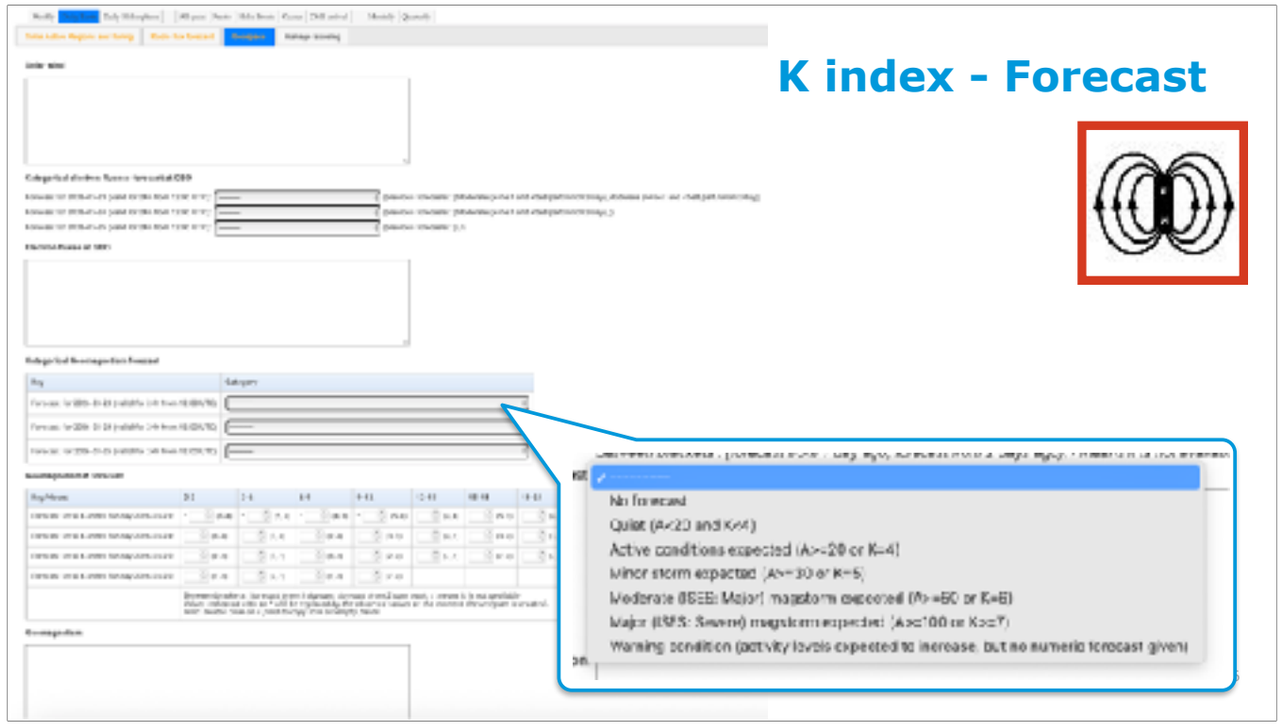

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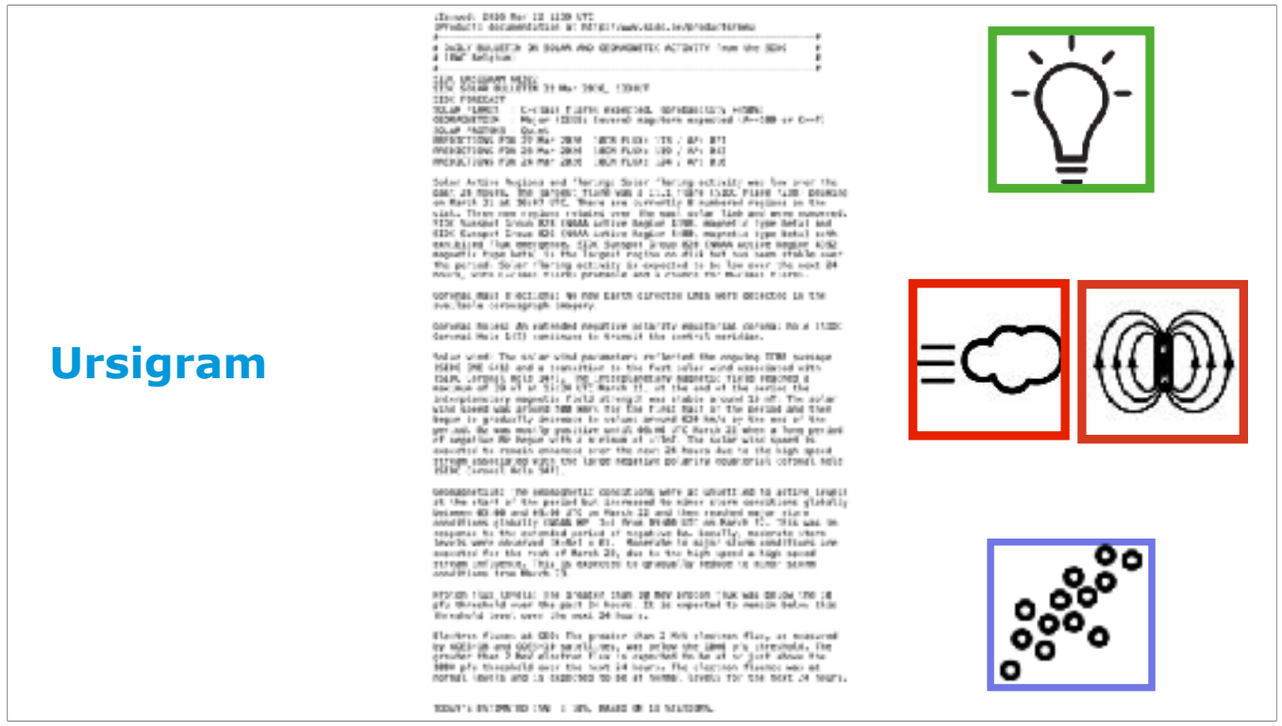
Ursigram



2000 - very first ursigram - space weather bulletin - we were the first to broadcast space weather bulletins on a daily basis.

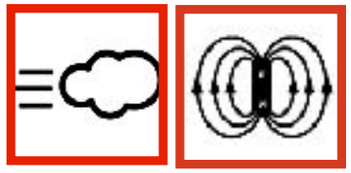
Ursigram - Union radio-scientifique Internationale
French for the International Union of Radio Science. Founded in 1919, it is a non-profit, international scientific organization dedicated to coordinating studies, research, and applications in radio science, electromagnetics, and telecommunications.

Alerts







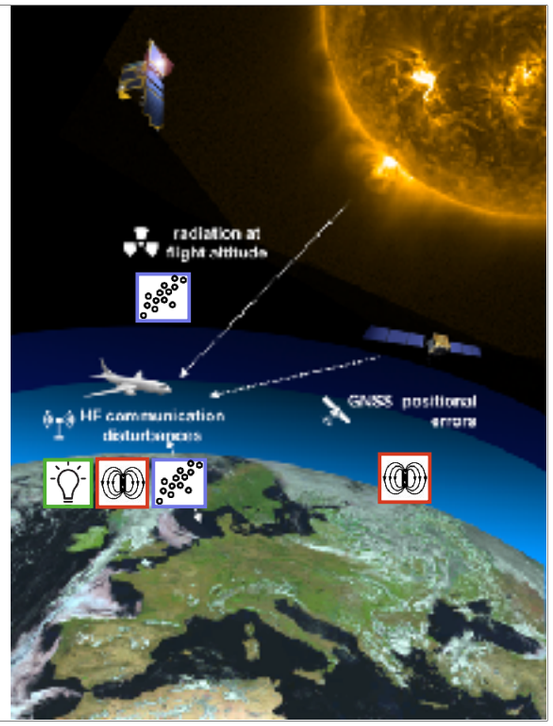




IMPACTS

SWx IMPACT on aviation

Space weather impact our navigation and radio communication systems and can cause an increase of radiation levels at flight altitude.



A solar storm initiates space weather processes which impact our navigation and radio communication systems and can cause an increase of radiation levels at flight altitude.

GNSS	Moderate	Severe	Time UTC	Value	Status	Alert	3h-Value	3h-Status
GNSS amplitude HNH	0.6	0.8	2026-02-10 10:05	0.00	QUIET		0.00	QUIET
GNSS phase HNH	0.4	0.7	2026-02-10 10:05	0.00	QUIET		0.00	QUIET
GNSS amplitude HSH	0.6	0.8	2026-02-10 09:48	0.00	QUIET		0.00	QUIET
GNSS phase HSH	0.4	0.7	2026-02-10 09:45	0.00	QUIET		0.00	QUIET
GNSS amplitude EQMH	0.6	0.8	2026-02-10 10:10	0.00	QUIET		0.00	QUIET
GNSS phase EQMH	0.4	0.7	2026-02-10 10:10	0.00	QUIET		0.00	QUIET
Vertical TEC	125	175	2026-02-10 10:10	71	QUIET		79	QUIET

RADIATION	Moderate	Severe	Time UTC	Value	Status	Alert	3h-Value	3h-Status
Effective Dose FL ≤ 460	30	80	2026-02-10 10:10	0	QUIET		0	QUIET
Effective Dose FL > 460	1	80	2026-02-10 10:10	0	QUIET		0	QUIET

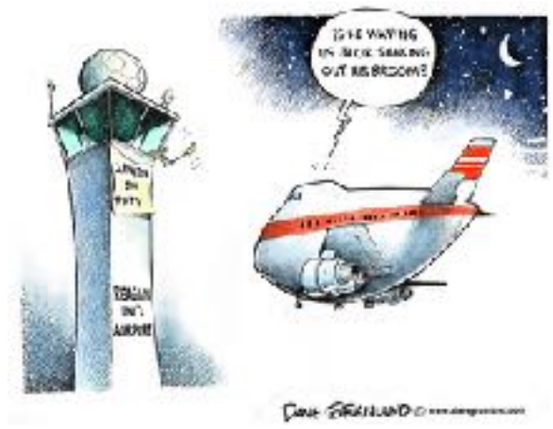
HF	Moderate	Severe	Time UTC	Value	Status	Alert	3h-Value	3h-Status
Auroral Absorption (AA)	7.66	8.66	2026-02-10 10:00	2	QUIET		2	QUIET
Polar Cap Absorption (PCA)	2	5	2026-02-10 10:05	0.15	QUIET		0.31	QUIET
Shortwave Fadeout (SWF)	X1.0	X10.0	2026-02-10 10:10	C1.5	QUIET		C3.2	QUIET
Post-Storm Depression (PSD)	0.3	0.5	2026-02-10 10:00	0	QUIET		0	QUIET

HF Advisory:

0000057501
FNXX02 EFKL 020814
SWX ADVISORY
DTG: 20260202/0814Z
SWXC: PECASUS
SWX EFFECT: HF COM
ADVISORY NR: 2026/63
OBS SWX: 02/0808Z MOD DAYSIDE
FCST SWX +6 HR: 02/1500Z NOT AVBL
FCST SWX +12 HR: 02/2100Z NOT AVBL
FCST SWX +18 HR: 03/0300Z NOT AVBL
FCST SWX +24 HR: 03/0900Z NOT AVBL
RMK: SPACE WEATHER EVENT (SOLAR FLARE) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY BANDS EXPECTED
ON THE DAYLIGHT SIDE. HIGHER FREQUENCY BANDS MAY BE LESS
IMPACTED.
NXT ADVISORY: WILL BE ISSUED BY 20260202/1408Z=

SWXC: PECASUS/SWPC/ACFJ/CRC
Type of advisory - MOD/SEV
Sequence - per domain, across centres - no combined domains
Forecast up to 24hr
Time +impacted area/NO SWX EXP/Not AVBL
Textual explanation: observed or expected impacts on technology, no details on physics, no mitigation actions

Radio Frequencies used in aviation



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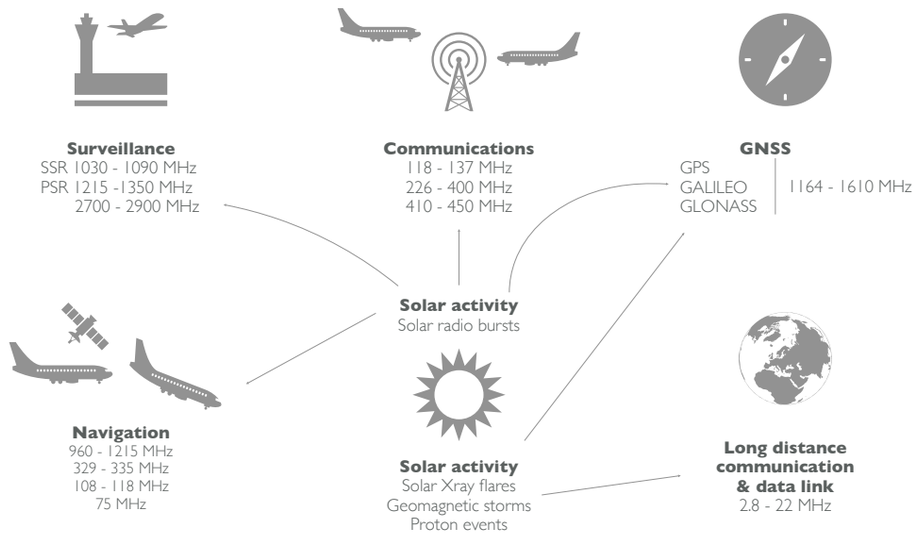


Long Distance Communication & data link
In aviation, **HF communication** systems are required for all trans-oceanic flights. These systems incorporate frequencies down to 2 MHz to include the 2182 kHz international distress and calling channel.

Navigation
https://en.wikipedia.org/wiki/Air_navigation
The basic principles of air navigation are identical to general navigation, which includes the process of planning, recording, and controlling the movement of a craft from one place to another.

https://en.wikipedia.org/wiki/Communication,_navigation_and_surveillance
Communication
Communication, i.e. aviation communication, refers to radio communication between two or more aircraft, or the exchange of data or verbal information between aircraft and air traffic control.[2] For continental airspace, VHF (civil) and UHF (military) systems are used whereas for oceanic areas, high frequency systems and SATCOMs are used.[3]

Navigation
Navigation, i.e. air navigation, refers to the process of planning, recording, and controlling the movement of an aircraft from one place to another by providing accurate, reliable and seamless position determination capability.[2][4]

Surveillance

Surveillance systems are used by air traffic control to determine the position of aircraft. There are two types of surveillance systems:

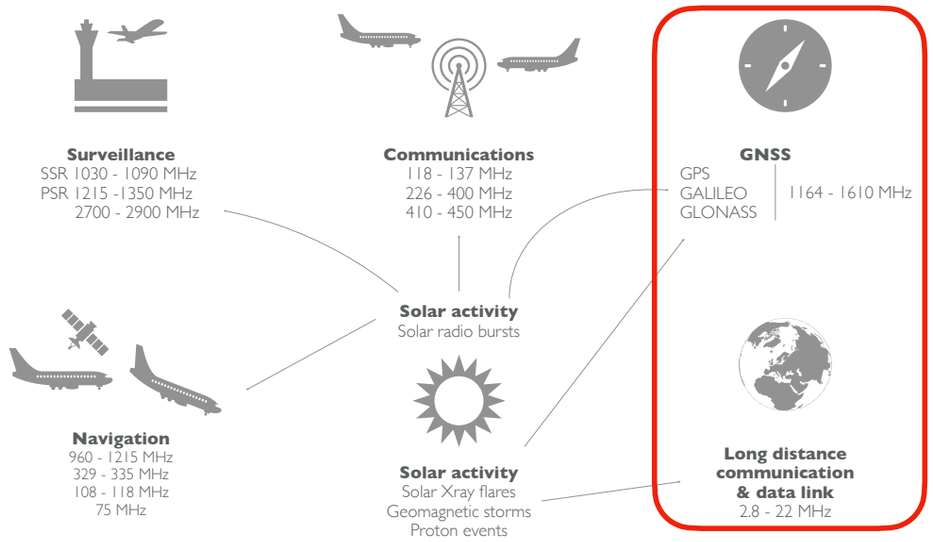
Cooperative systems[edit]
Cooperative systems (a.k.a. dependent surveillance): Under this form of surveillance, systems on the ground (such as SSR) communicate with equipment (such as transponders) on board the aircraft to determine the position and other details of the aircraft. Aircraft information, which may include position from GNSS or other means is determined on board and then transmitted to ATC in response to interrogation.[2][3] Other cooperative systems such as ADS-B rely on aircraft transmitting their position and other information without interrogation from the ground.

Non-cooperative systems[edit]
Non-cooperative systems (a.k.a. independent surveillance): Under this form of surveillance, systems on the ground (such as PSR) are able to locate the aircraft and measure its position from the ground by transmitting pulses of radio waves which reflect off the aircraft's hull.[2][3]

——

https://www.swpc.noaa.gov/impacts/hf-radio-communications
Space weather impacts radio communication in a number of ways. At frequencies in the 1 to 30 mega Hertz range (known as “High Frequency” or HF radio), the changes in ionospheric density and structure modify the transmission path and even block transmission of HF radio signals completely. These frequencies are used by amateur (ham) radio operators and many industries such as commercial airlines. They are also used by a number of government agencies such as the Federal Emergency Management Agency and the Department of Defense.

Radio Frequencies used in aviation



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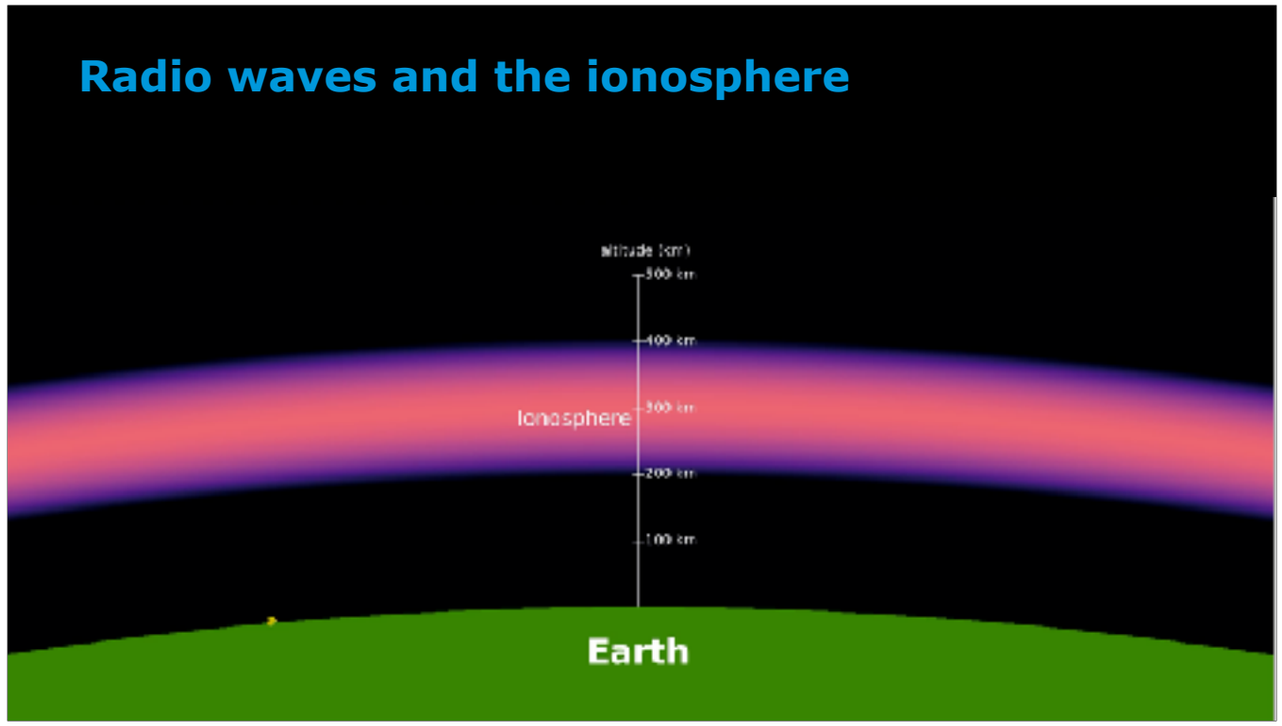


The plasma frequency is the resonant frequency of the electrons in an ionized medium.
There is a direct relation between the electron density and the plasma frequency, which can be approximated as f ≈ 8.9 Ne^1/2.

Reflection is binary: or wave is reflected or wave is not reflected
Absorption comes in gradation

Both GNSS and HF com use radio waves —> how do radio waves behave in an ionised medium

n0, electron content —> critical frequency f0F2 or fp or characteristic frequency—> refractive index
n=c/v
v=c —> n=1
V<c —> n>1

A qualitative understanding of how an electromagnetic wave propagates through the ionosphere can be obtained by recalling geometric optics. **Since the ionosphere is a plasma, it can be shown that the refractive index is less than unity.** Hence, the electromagnetic "ray" is bent away from the normal rather than toward the normal as would be indicated when the refractive index is greater than unity. It can also be shown that the refractive index of a plasma, and hence the ionosphere, is frequency-dependent, see Dispersion (optics).[24]

In physics, refraction is the change in direction of a wave passing from one medium to another or from a gradual change in the medium.

f>fp—> passes through ionosphere
f< fp —> reflected by ionosphere

The ionosphere is the key-layer for HF communication and GNSS performance: or radio waves are reflected at, or pass through the ionosphere. The reflection is used for long distance communications.

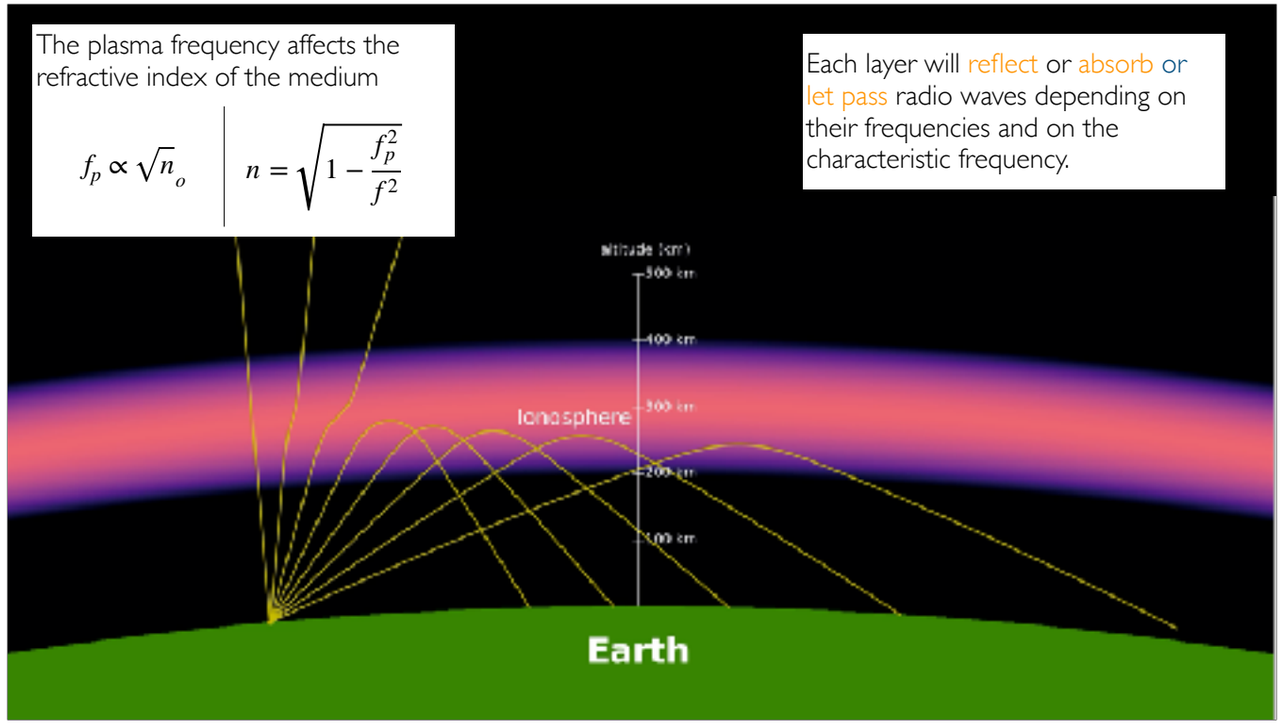
The ionosphere has the ability to reflect radio waves. If the degree of ionisation would be zero, no radio waves would be reflected and all would pass.

Reflection - binary: or it is being reflected or not
Transmission —> refraction (In physics, refraction is the redirection of a wave as it passes from one medium to another. The redirection can be caused by the wave's change in speed.) For light, refraction follows Snell's law.

Absorption

Ionisation can change over time.
Ionisation is not the same everywhere.

During the night, the ionisation decreases - the skill to reflect drops.
—> also LF goes through —> Maximum Usable Frequency, MUF decreases.



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What can ionise and define the electron density?

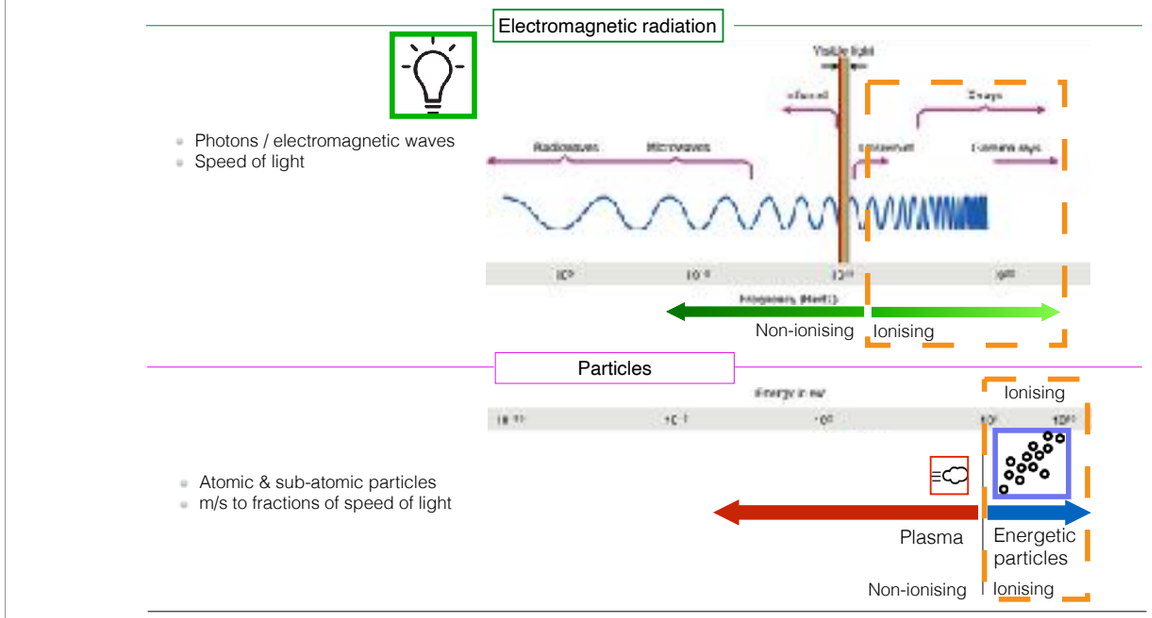


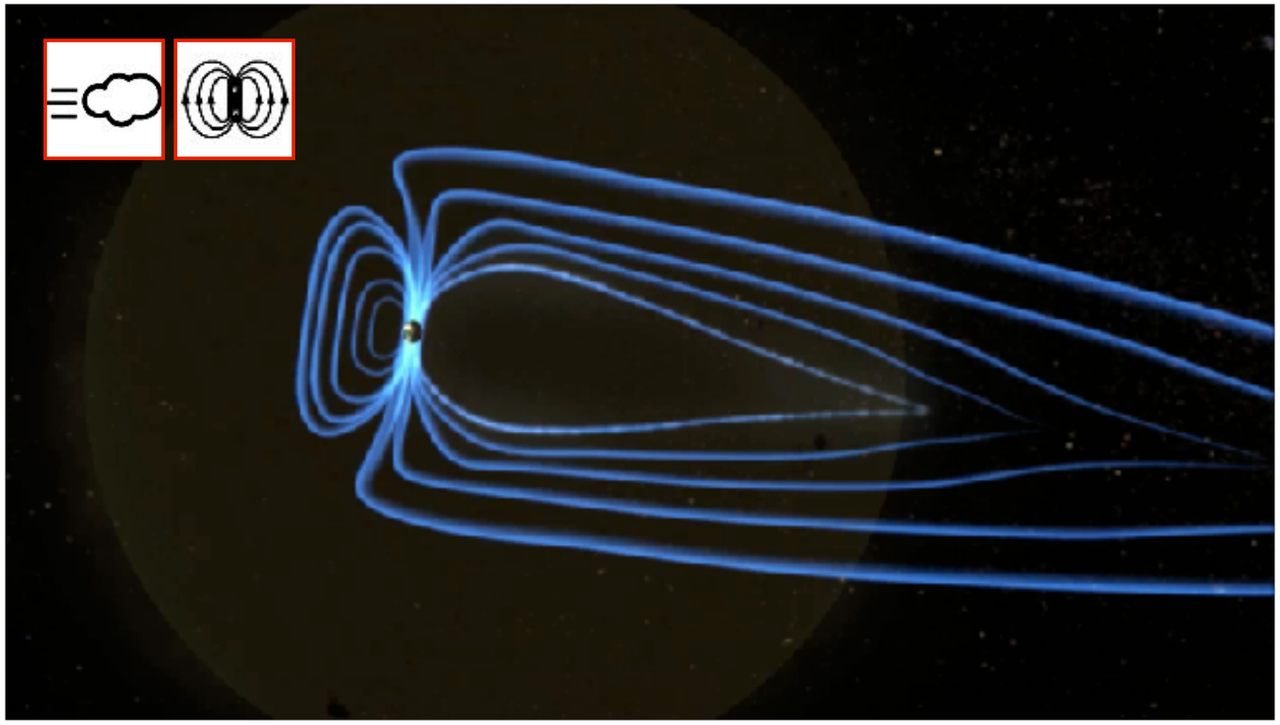
Photo-ionisation — green
Particle ionisation - blue

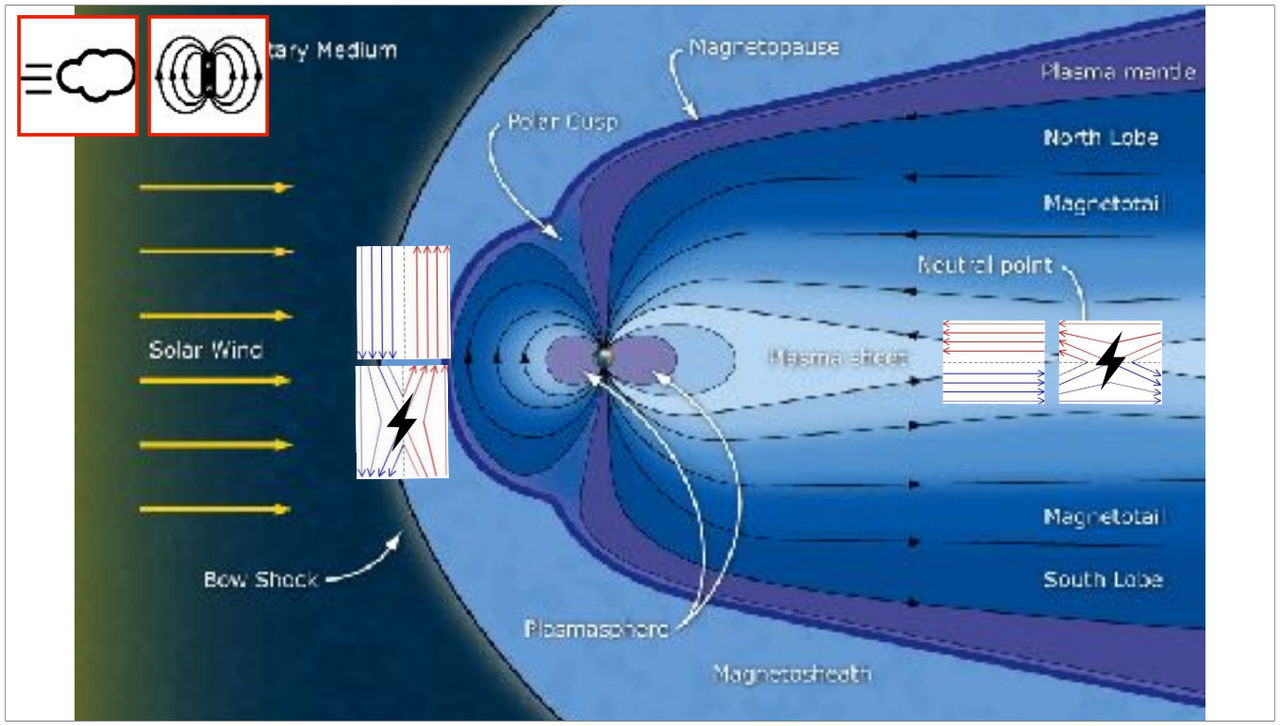
Ionizing radiation is a type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). The spontaneous disintegration of atoms is called radioactivity, and the excess energy emitted is a form of ionizing radiation.

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.

Can the solar wind impact the ionosphere and change the electron density?





Magnetosphere - ionosphere coupling

The solar wind is a magnetized plasma. It encounters the environment of the Earth, which also turns out to be a magnetized plasma. Indeed, the Earth has an internal magnetic field. That field is produced in the Earth's interior. It is changing slowly. (The magnetic poles move with a speed of about 10 km/year.)

The magnetosphere is the region around Earth that is dominated by the geomagnetic field. The magnetospheric plasma originates in part in the ionosphere; the rest is captured solar wind material.

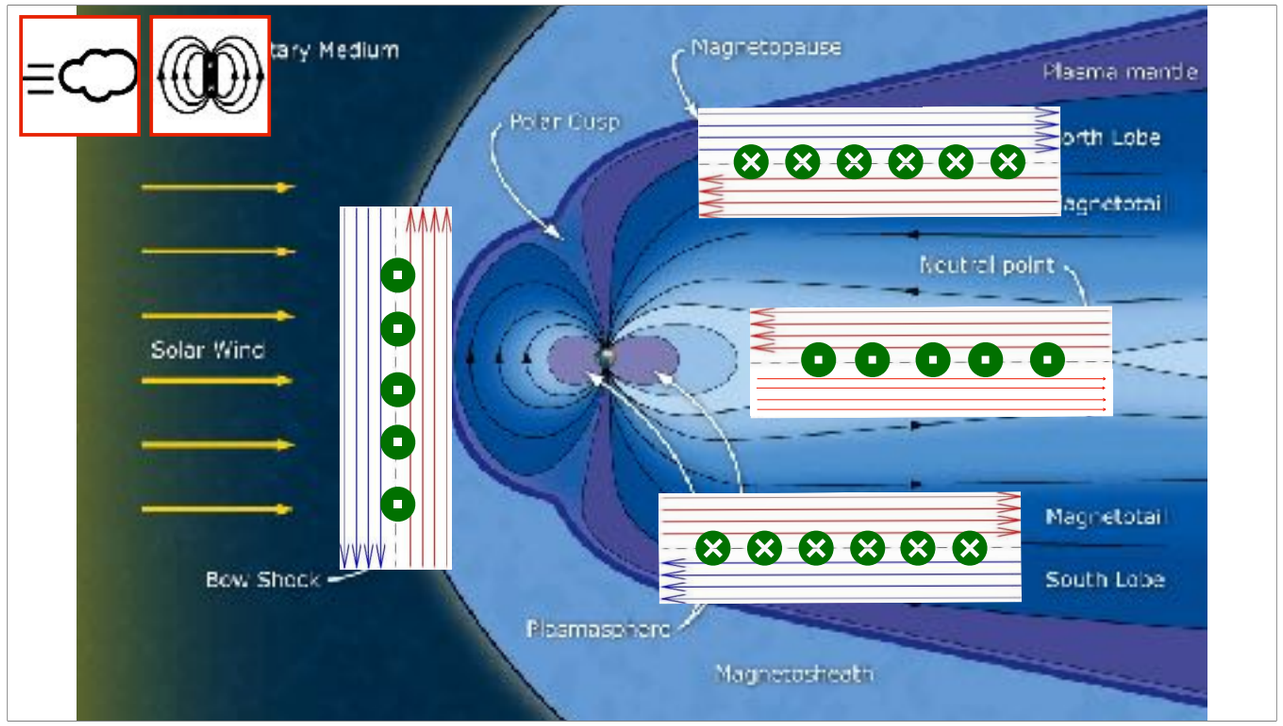
Magnetosphere is a highly dynamical system
https://www.researchgate.net/figure/Structure-of-Earth-magnetosphere-with-magnetopotentials-in-blue-inner-radiation-belt-in_fig3_351130787
Structure of Earth magnetosphere with magnetopotentials in blue, inner radiation belt in green, and outer radiation belt in red.

The magnetosphere consists of a (1) bow shock, where the solar wind (the stream of protons from the Sun) is slowed; (2) the magnetosheath behind the bow shock that contains thermalized solar plasma; (3) t**he magnetopause, where the thermalized solar plasma pressure is balanced by the plasma pressure generated by the magnetosphere**; (4) the magnetotail, where the magnetic field is stretched out by the solar wind behind the dipole; and (5) the plasmasphere, where plasma is trapped by the magnetic field. The radiation belts are formed in the plasmasphere of the Earth's magnetosphere.

When the plasma up above is caused to move, magnetic field lines communicate this motion down to the ionosphere as if they were pieces of string tying the different plasma regions together.

Charged particles can move rather freely along field lines and therefore are good electric conductors. Electric currents flow along the field lines and connect magnetosphere and ionosphere. Therefore every electric feature in the magnetosphere has an "image" in the ionosphere, and conversely. We identify the following regions:

- Magnetopause ↔ footpoints of the cusps
- Tail lobes ↔ polar caps
- Plasma sheet ↔ auroral oval
- Plasmasphere ↔ ionosphere at low latitude



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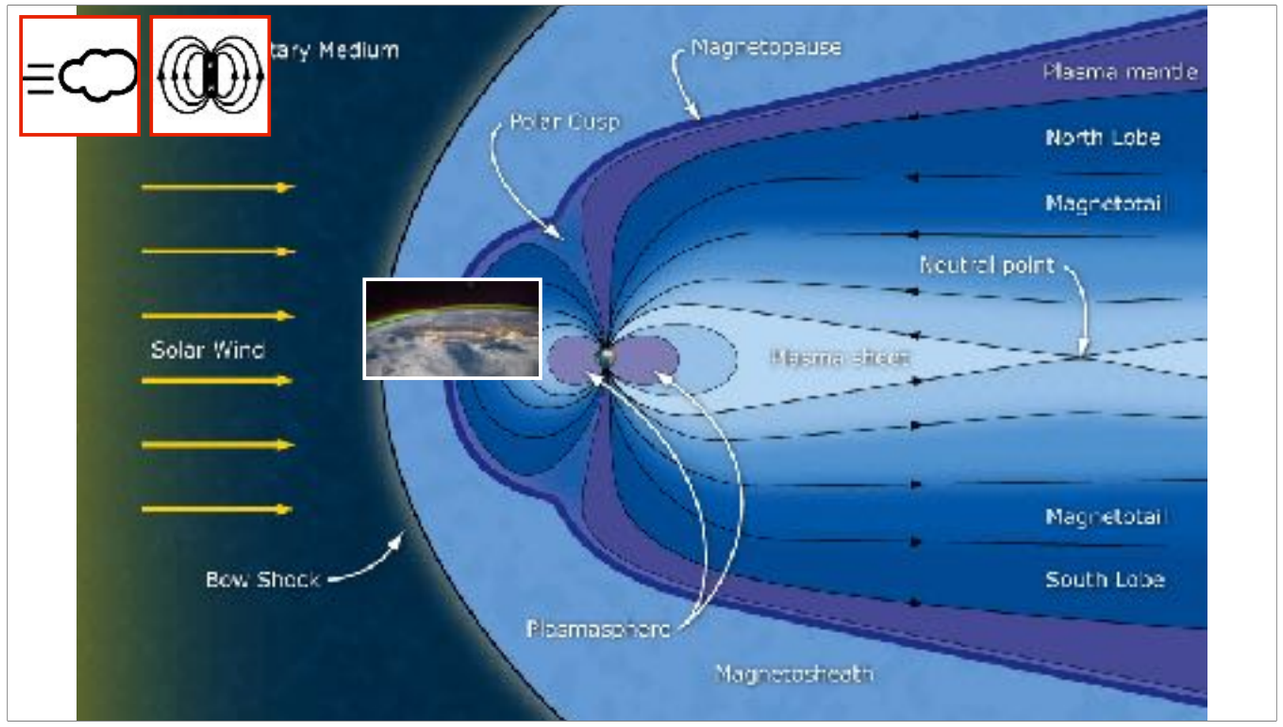

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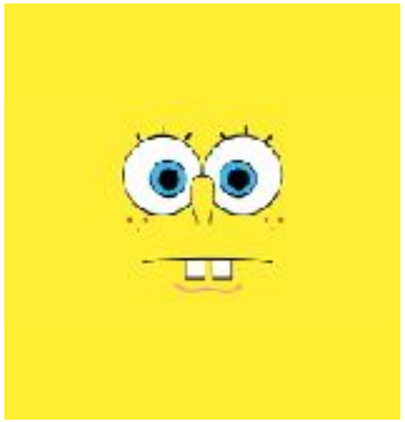
Impact of space storms on Radio Waves

Absorption



Decrease of MUF



Scintillation



Radio waves can be

- absorbed,
- transmitted instead of being reflected when frequency is higher than the MUF= Maximal Usable Frequency
- scintillate (twinkle)

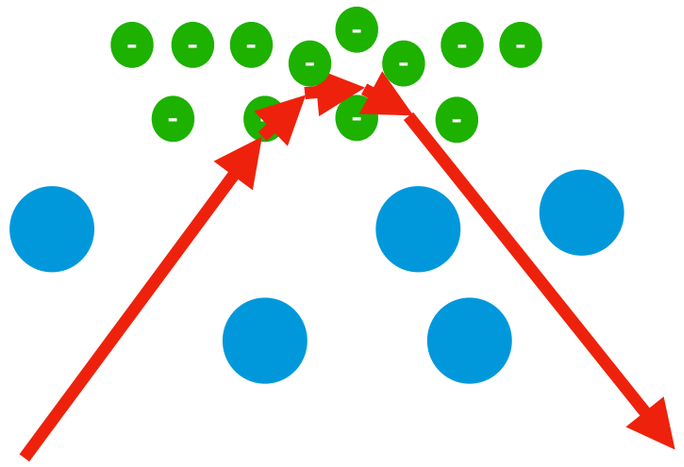
Impact: Absorption of waves



Reflection - binary: or it is being reflected or not
Transmission —> refraction (In physics, refraction is the redirection of a wave as it passes from one medium to another. The redirection can be caused by the wave's change in speed.)

Absorption

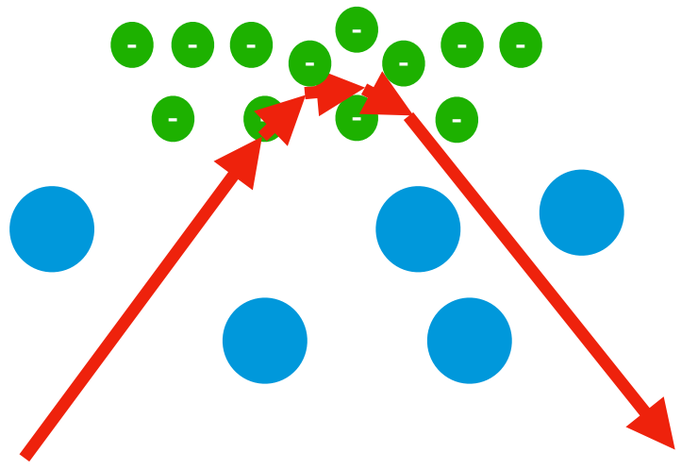
Reflection of waves



Radio wave makes the electrons move. Those moving electrons reproduce on their turn the radio signal and re-emitting it.

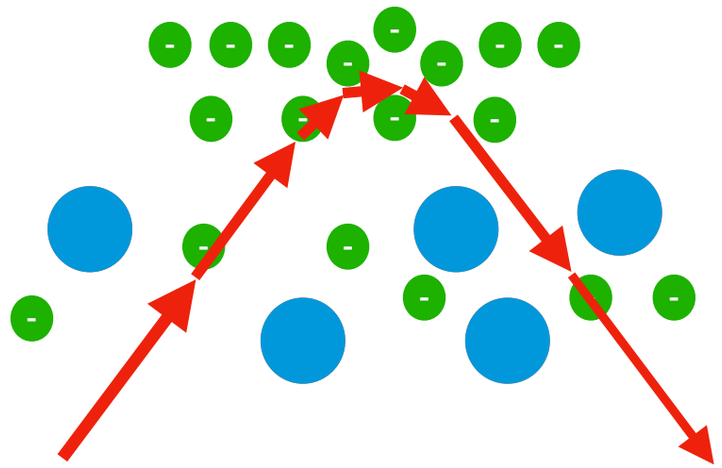
The ionosphere refracts radio waves
More refraction when higher the electron density or lower the frequency
When there are more electrons, the wave is more bent and again bent and again … until it is going down.
This is how reflection works in the ionosphere. It is a region full of magic (with a negative number under the square root of the refractive index).

D-layer during the night



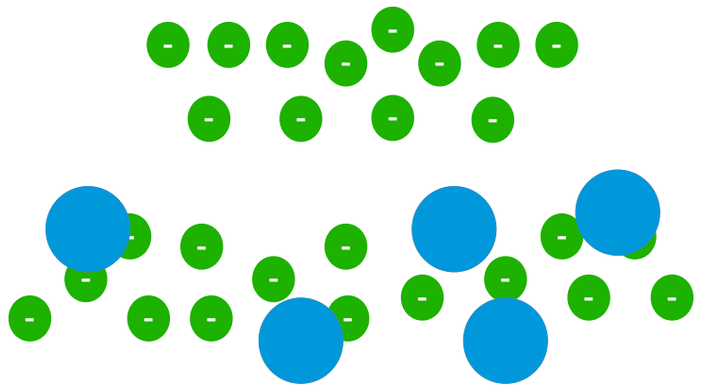
This is the D-layer during the night.
Neutrals are being present in the D-layer.

D-layer during the day



This is the D-layer during the day.
The radio wave also meets electrons in the D-layer. These electrons can’t move as much due to the neutral —> absorption.
Luckily, there are not many electrons and the absorption is minimal.

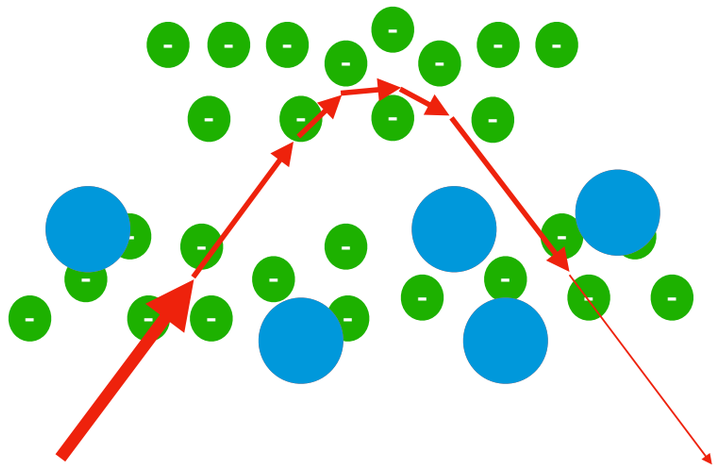
D-layer with extra ionisation



The incoming solar energetic particles ionise the D-layer.

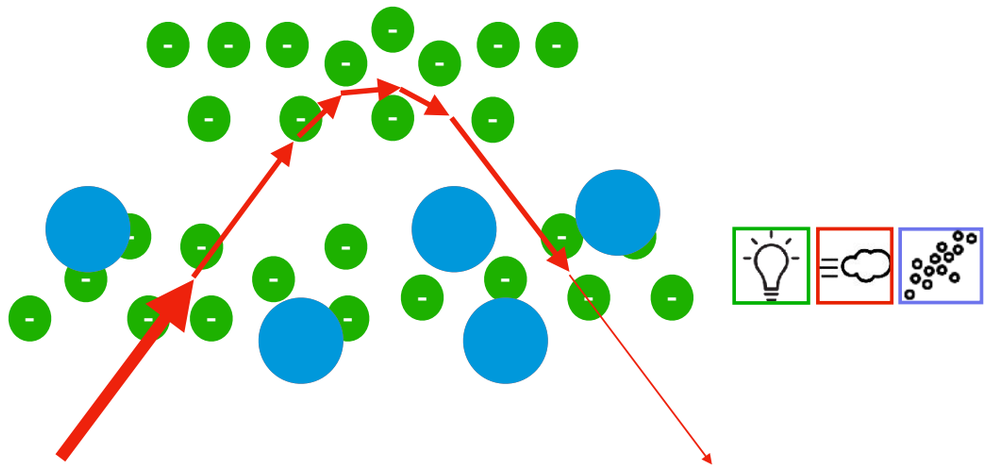
The radio wave meets more electrons in the D-layer. During each encounter, the wave is being absorbed.

D-layer absorbs radio waves



The radio wave meets more electrons in the D-layer. During each encounter, the wave is being absorbed.

D-layer with extra ionisation due to a solar event

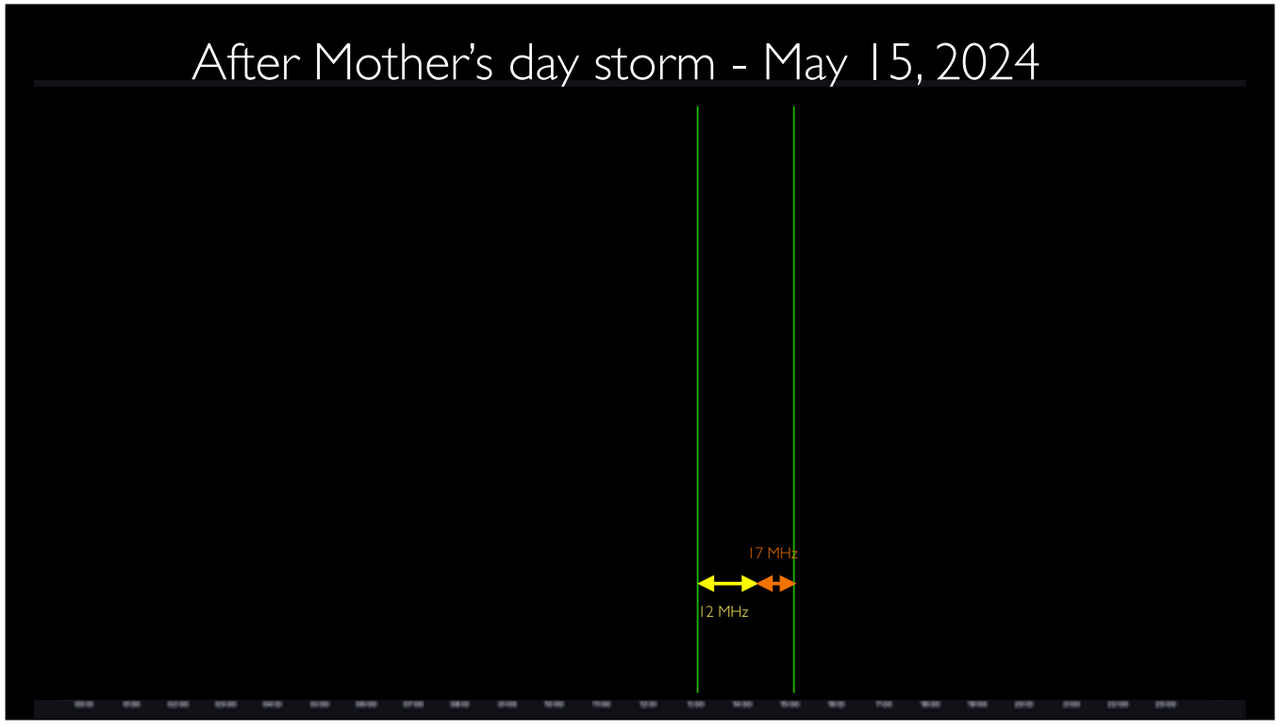


Short Wave Fadeout, auroral absorption, PCA

After Mother's day storm - May 15, 2024



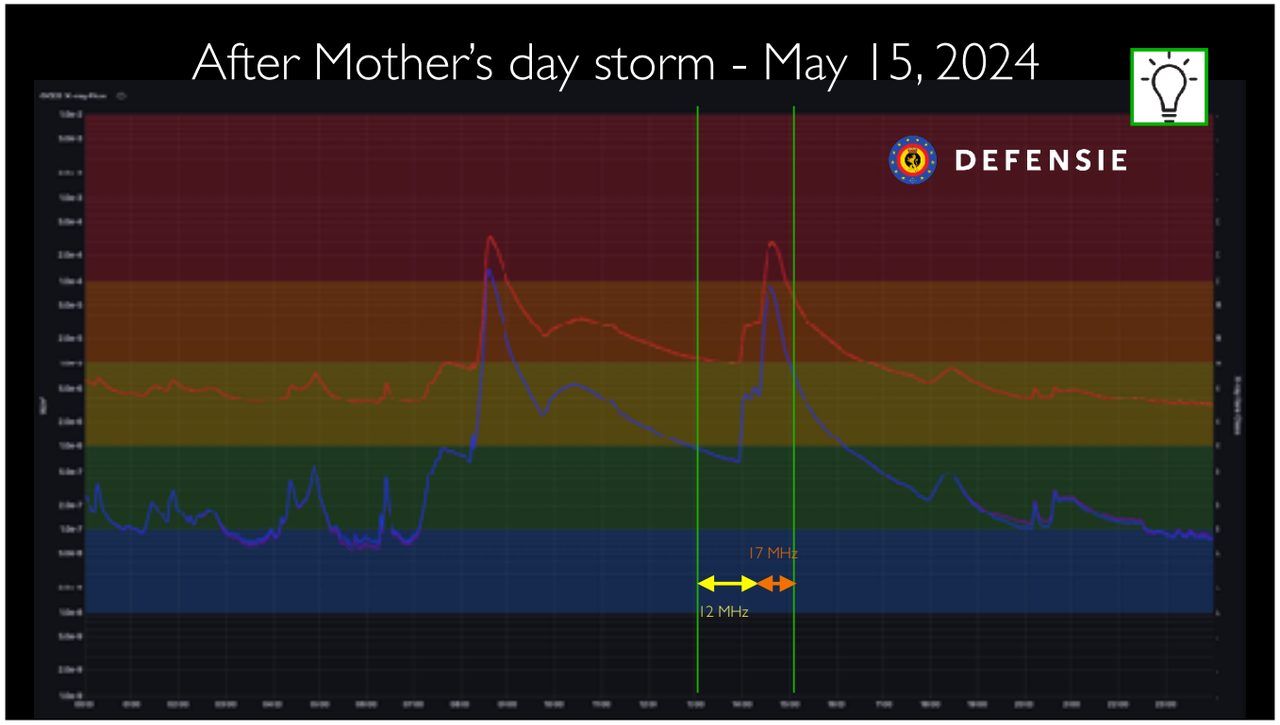
DEFENSIE



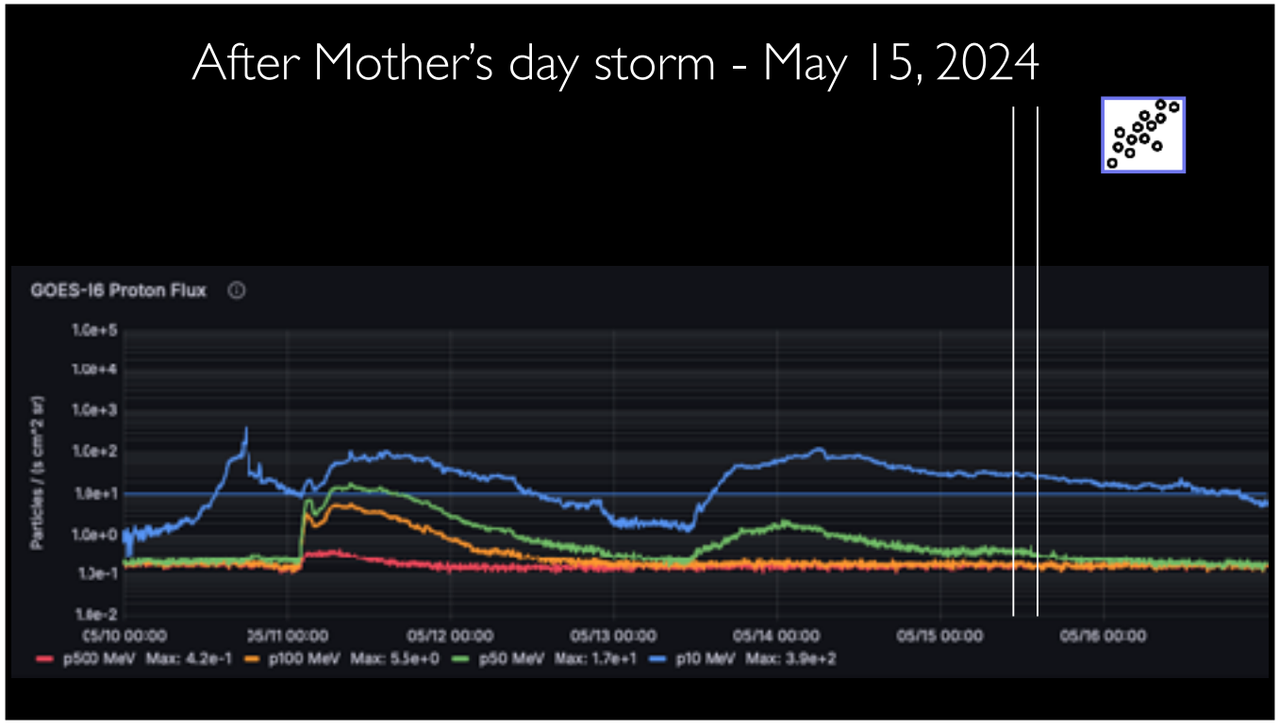
15 mei was een test tussen België en Canada.

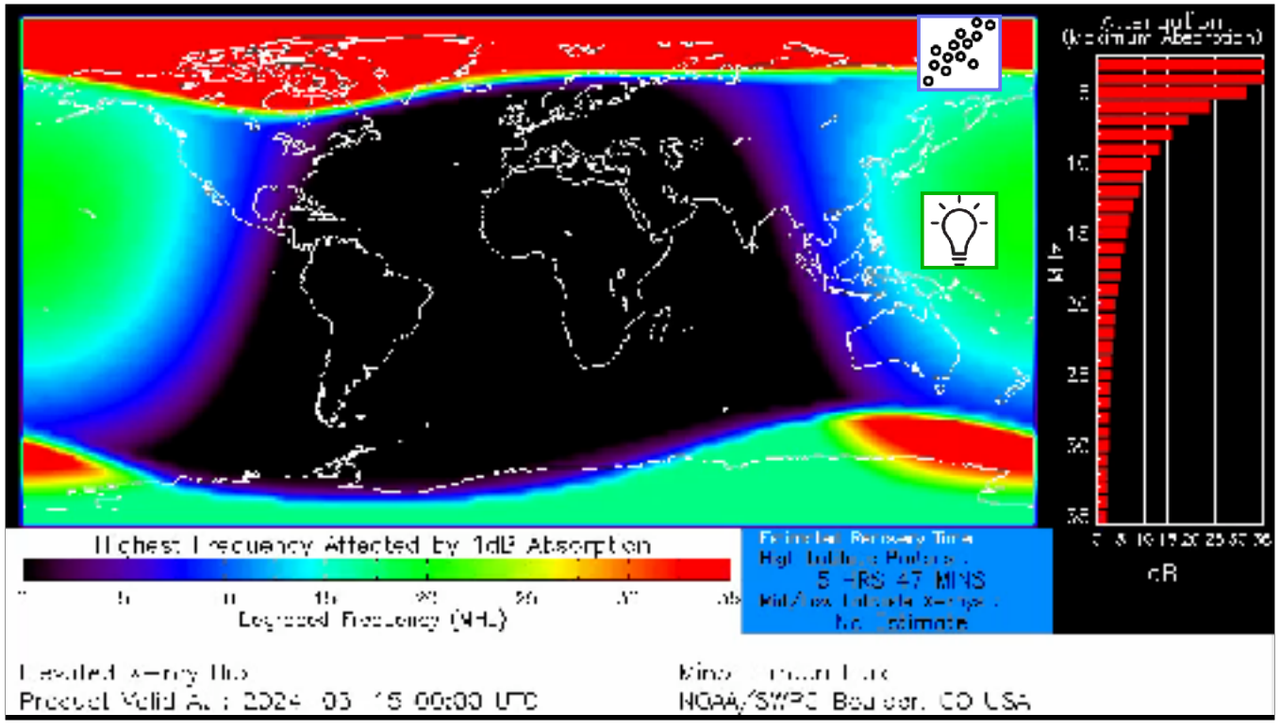
We hebben toen getest van 13u tot laat in de avond en niets heeft gewerkt. Dat heeft een aantal redenen, maar ik ben ervan overtuigd dat SWx er een belangrijke rol in heeft gespeeld.
13u-14u: Gestart op 12 MHz, mogelijks niet een ideale frequentie, maar ik denk het eigenlijk wel. Ik denk dat er hier niets gelukt was wegens andere verkeerde instellingen. Rond 14u zijn ze dan overgeschakeld naar 17 MHz, maar het is net op dat moment dat er een M class flare begon, gevolgd door een X class flare! Spreekt voor zich dat er met die ionosfeer niet te veel meer aan te vangen viel.
Men is dan blijven testen op 17 MHz, maar dat is waarschijnlijk al te hoogfrequent, en zeker naar de avond toe.

De volgende dag heeft men de testen hervat in de namiddag, toen was er een Kp van 4, ook toen kwam er niets door.


After Mother's day storm - May 15, 2024
DEFENSIE
17 MHz
12 MHz

After Mother's day storm - May 15, 2024





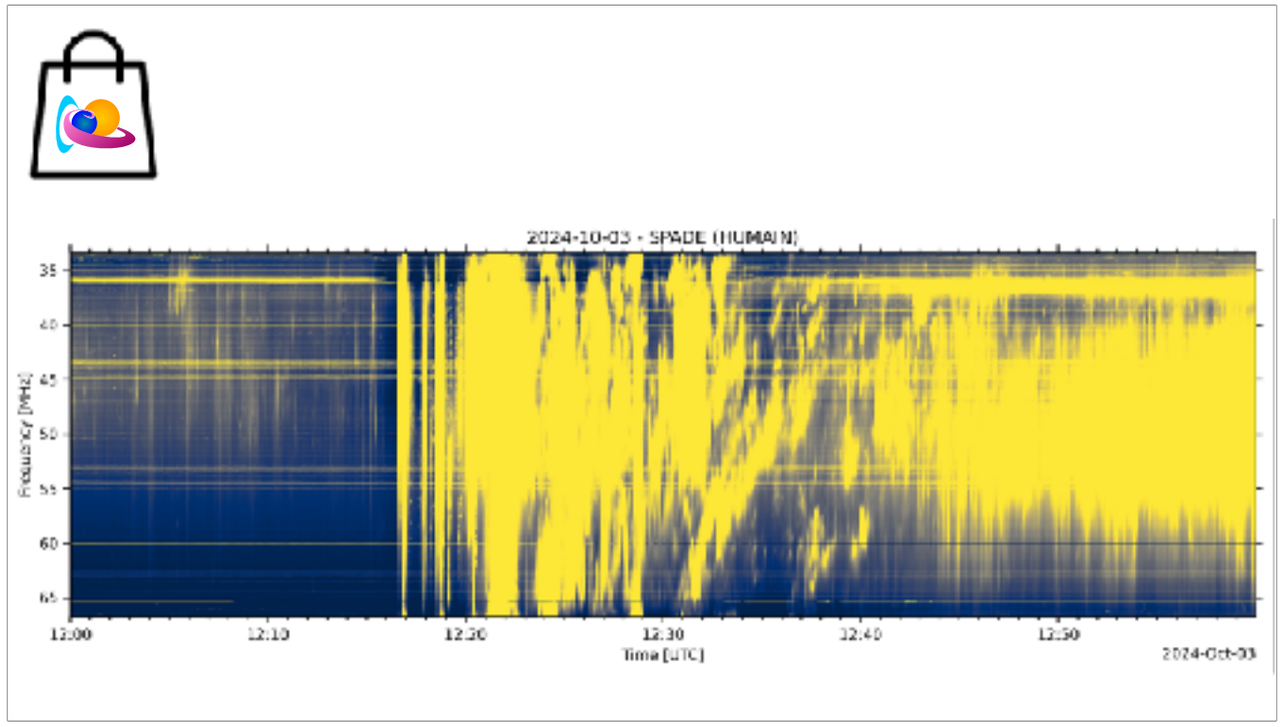
Flare
Solar energetic particles
Causing absorption of radio waves
DRAP model - D region absorption predictions

SPADE

- 25 - 75 MHz
- 8 antennas - phased array
- 20 x 20 m square grid
- Solar spectrograph



Solar Radio Station in Humain



X9.9 flare - 12:08 - 12:18 - 12:27
—> absorption in HF due to X-rays + SRB (adds noise)

Horizontal lines: selfmade interference at 40, 50, 60 MHz
36 MHz - terrestrial beacon - is being absorbed —> background is little bit darker

SRB: At the right type IV

Zoom
36 MHz line - stops when it is being absorbed.

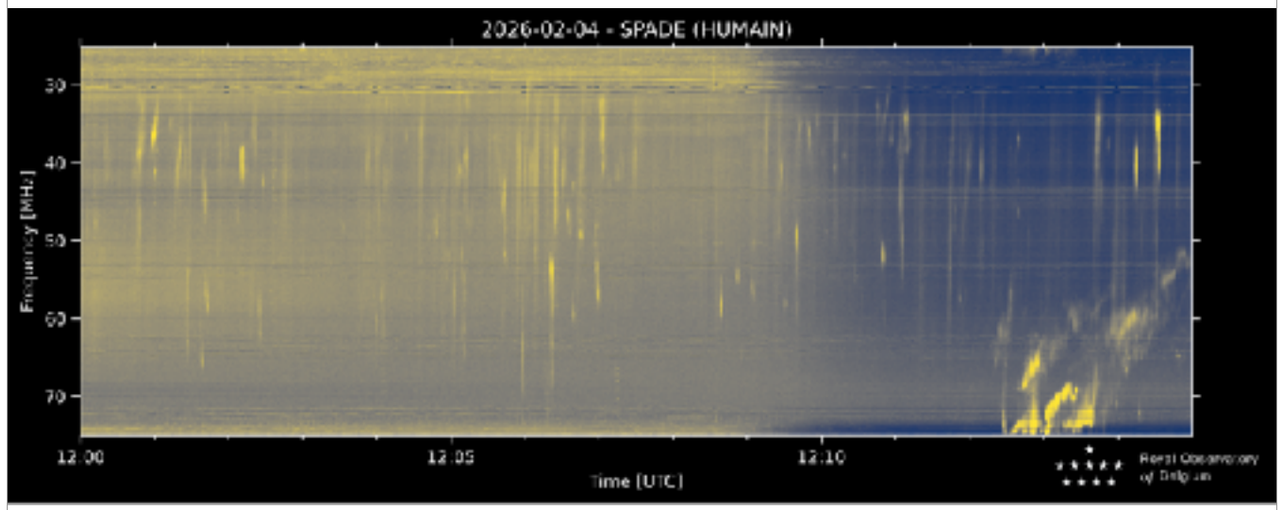
SRB
type III (three lines)
Type II

Data is also a product

During the night we don’t measure:
—> not possible

—> This is not a problem, because there is no absorption

Riometer (looks at zenith): same principle as the solar radio telescope (looks at the sun) of Antonio/Christophe



the yellowish background is the normal background noise which turns blueish at the time of the flare around 12:10. The bright yellow patches are solar radio bursts (before and during the flare time), including a small type II burst at 12:13 UT from 75 down to ~ 50 MHz

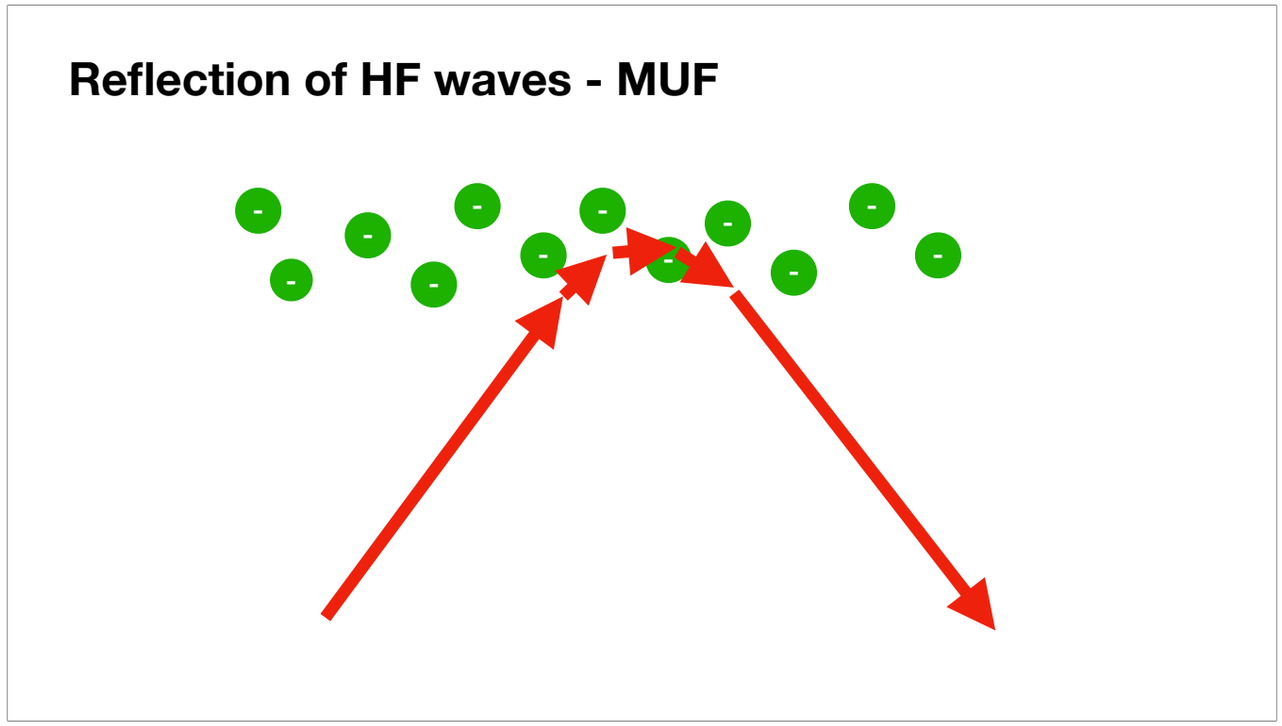
Impact: decrease of MUF



"Before I answer that, may I remind you that it's seven years of bad luck to break a mirror?"

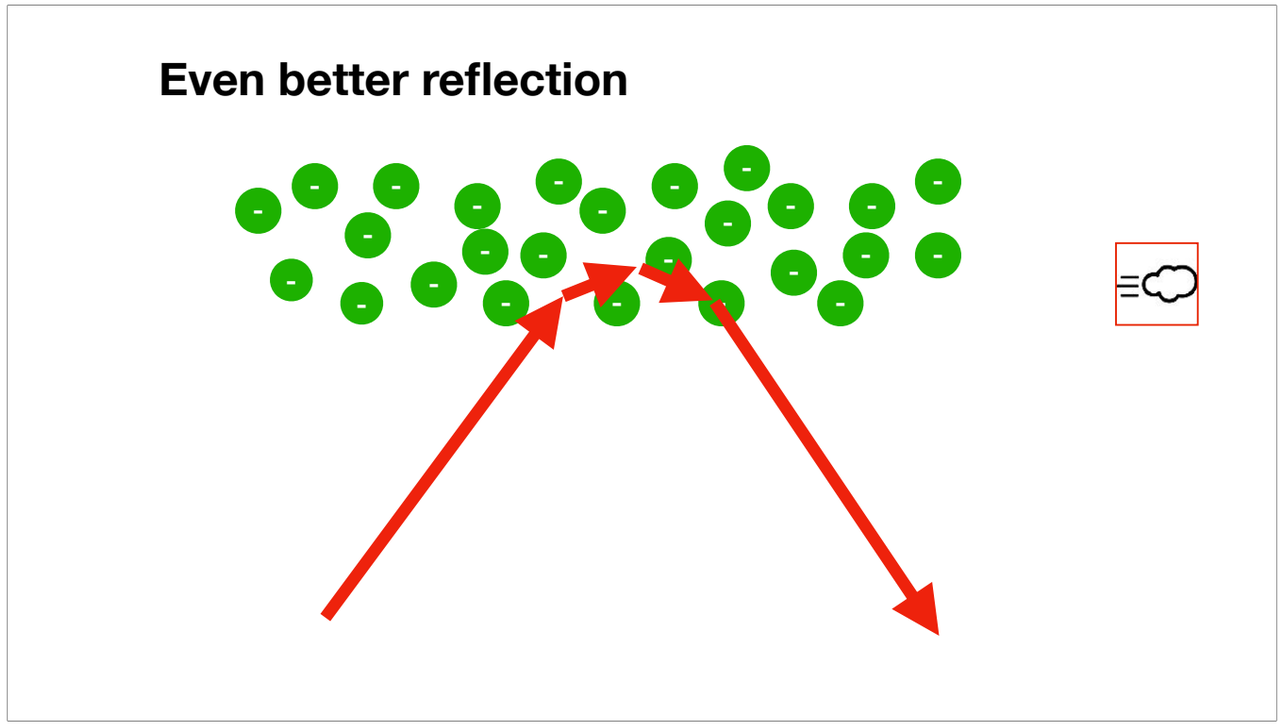
Post storm depression

What is the MUF?



The ionosphere can reflect waves

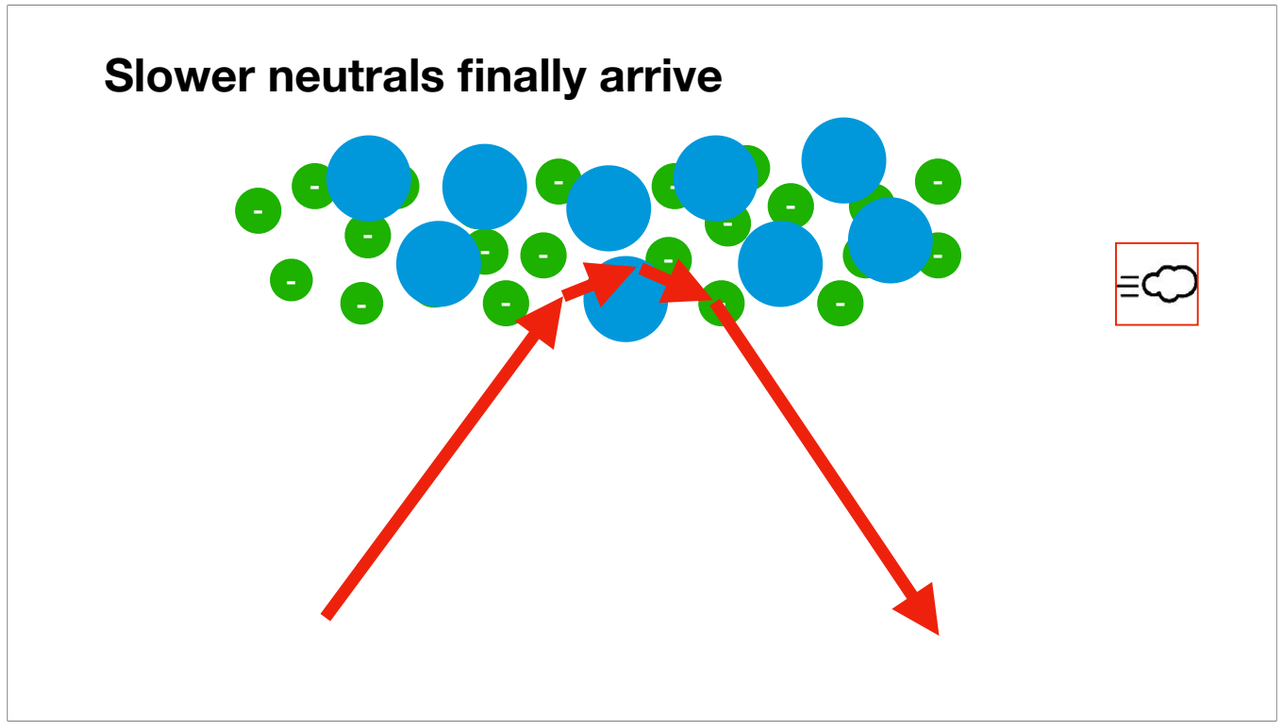
When the ionosphere is not ionised, which waves are being reflected?
As soon as the ionisation increases, waves under the MUF are being reflected.
The higher the ionisation, the higher the MUF.



Increase of electrons - positive phase of the storm - VTEC increases
increase is due to Drift of plasma across B = upward flow
Better HF communication because more waves are being reflected.
Also waves with a higher freq are being reflected. MUF increases

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the auroral oval expands in height and width
3 The plasma moves together with the expanding air. This causes a large scale movement of plasma towards the equator.
4 Drift along the magnetic field lines cause the ionosphere to move up,
which can increase electron density (“positive storm phase”).
5 Finally, upwelling of N2 causes increased recombination, leading to a depletion of ionisation (“negative storm phase”).



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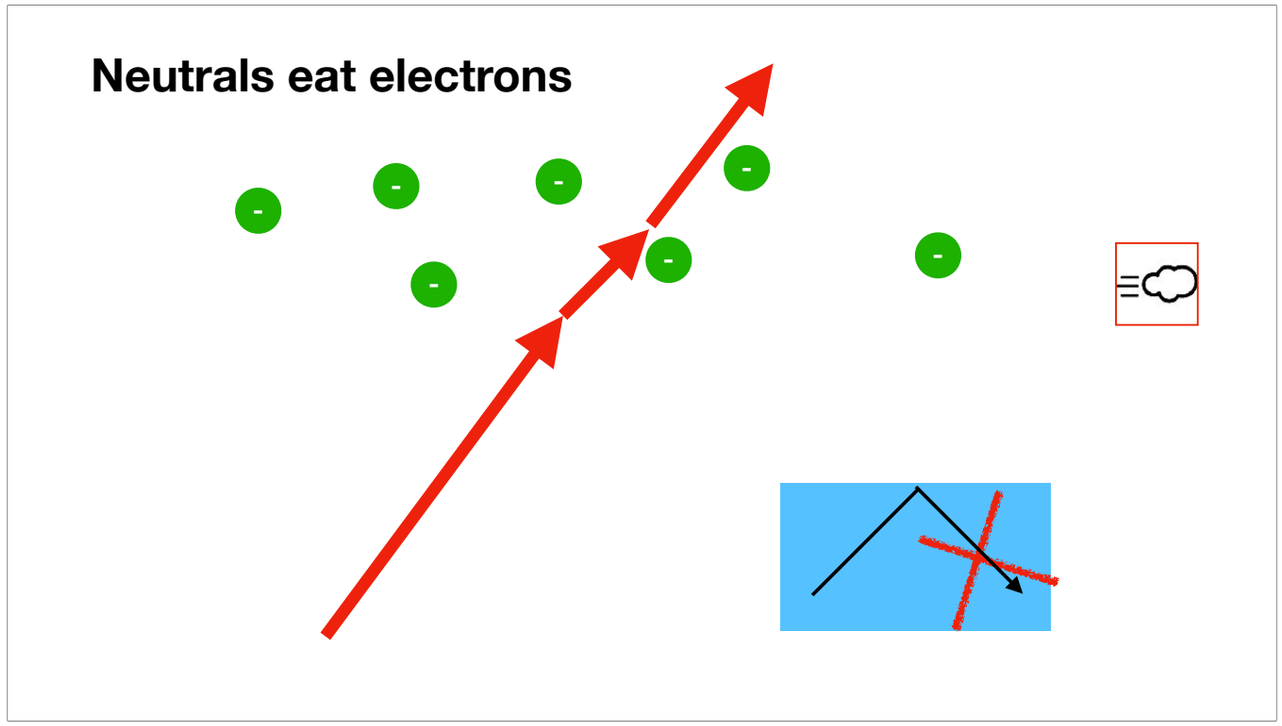

Neutrals are being transported to the F2 layer. This is the second, negative phase of the storm - more electron are being eaten by neutrals.
Less electrons, the MUF decreases —> less frequencies available for HF com
Higher freq radio waves pass through
—> mid-latitude

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

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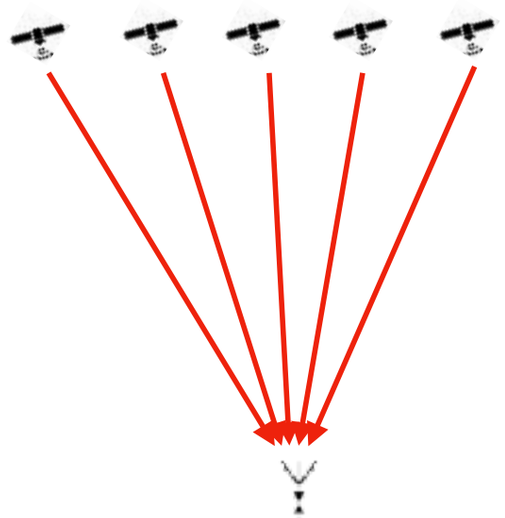
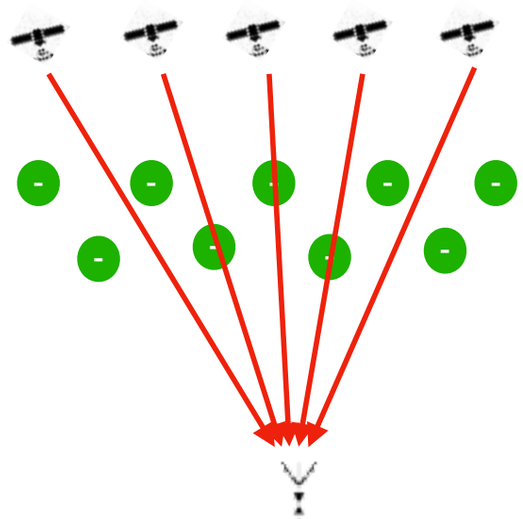
Impact: Scintillation





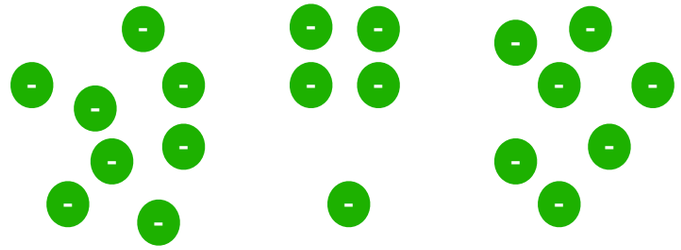
no ionosphere - or an ionosphere that behaves as expected

No refraction
No diffraction: bend around an obstacle or pass through an opening
The waves nicely reach the receiver without meeting another wave.

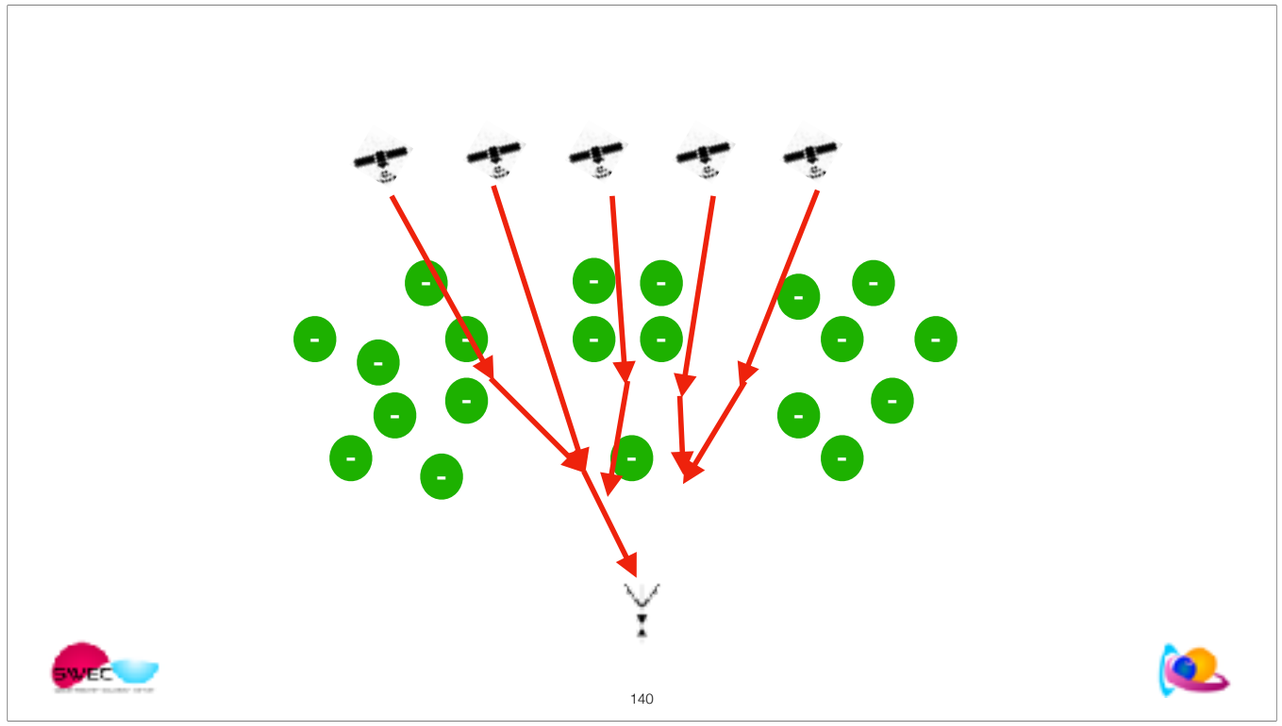


Even with an ionosphere that behaves, it is OK.
Their wavelength is small, so, the electrons don’t need much space

Strong gradients



Strong gradients
Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised



Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised
REFRACTION
When a wave enters another medium, its speed is different. The wave is redirected as it passes from one medium to another —> delay
DIFFRACTION
A wave bends around the corner of an obstacle.
—> refracted and diffracted waves interfere —> As a result, the receiver sees a twinkling signal, i.e. the signal with rapid variations superimposed on it.

Regions of scintillation:
- Polar caps — solar energetic particles
- Auroral oval - trapped particles from the plasma sheet
- Equatorial region - equatorial ionisation anomaly - plasma bubbles - Rayleigh Taylor instability

The result is the same, the cause of the density irregularity is different.

SCINTILLATION MECHANISMS

1. Post-sunset Plasma Bubbles (decreased ionisation) at lower latitudes (Equatorial ionisation anomaly)
2. Structures (increased ionisation) in the auroral oval
3. Patches (increased ionisation) in the polar caps
4. Travelling ionospheric disturbances

Scintillation is caused by small-scale (tens of meters to tens of km) structures in the ionospheric electron density

Equatorial induced anomaly allows the plasma bubbels to rise

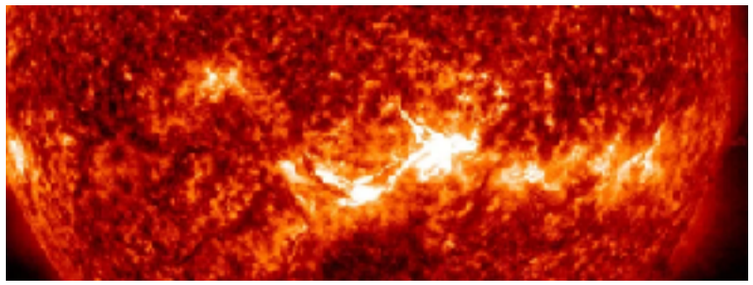
The four mechanisms that give rise to scintillation are
- Post-sunset Plasma bubbles (in the lower latitudes) -
- Precipitating particles (auroral oval) - backscatter
- Patches in the polar caps
- Travelling ionospheric disturbances

All three happen more or less depending on the circumstances, but plasma bubbles happen most of the days.

Precipitating particles
—> come towards Earth from the reconnection areas in the plasmasheet
—> follow the magnetic field form sheets
—> typical form of auroras.
—> small scale irregularities
—> induces scintillation
—> example auroral clutter: aurora acts as a echo

Solar and heliospheric storms impacting aviation

CASE STUDY - April 23, 2023



GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET		0.14	QUIET
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL≤460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	1	80	2020-10-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	6	9	2020-10-12 14:15	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

Ionosphere is needed for long distance HF communication which makes use of the reflective capability of the ionosphere. The ionosphere acts as a mirror.

AA, PCA, SWF are absorption events - low frequencies
PSD reduces the range of frequencies available - high frequencies are not available.

HF Com
If you have a strong radio burst in HF, your MUF might be full of solar noise and in practice not usable. But SRB are not taken into account by ICAO

Similar, Solar Radio Bursts can impact also GNSS by adding noise.

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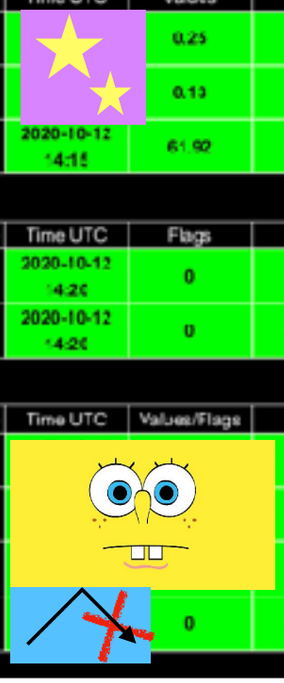

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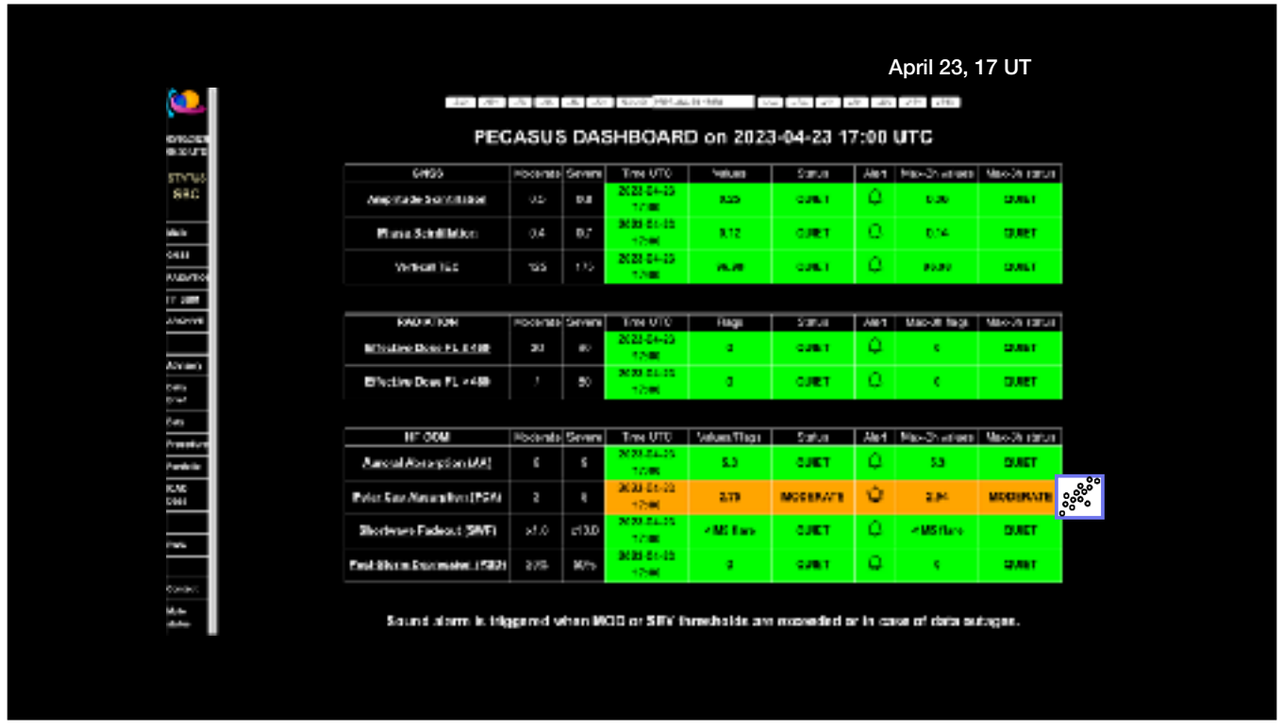
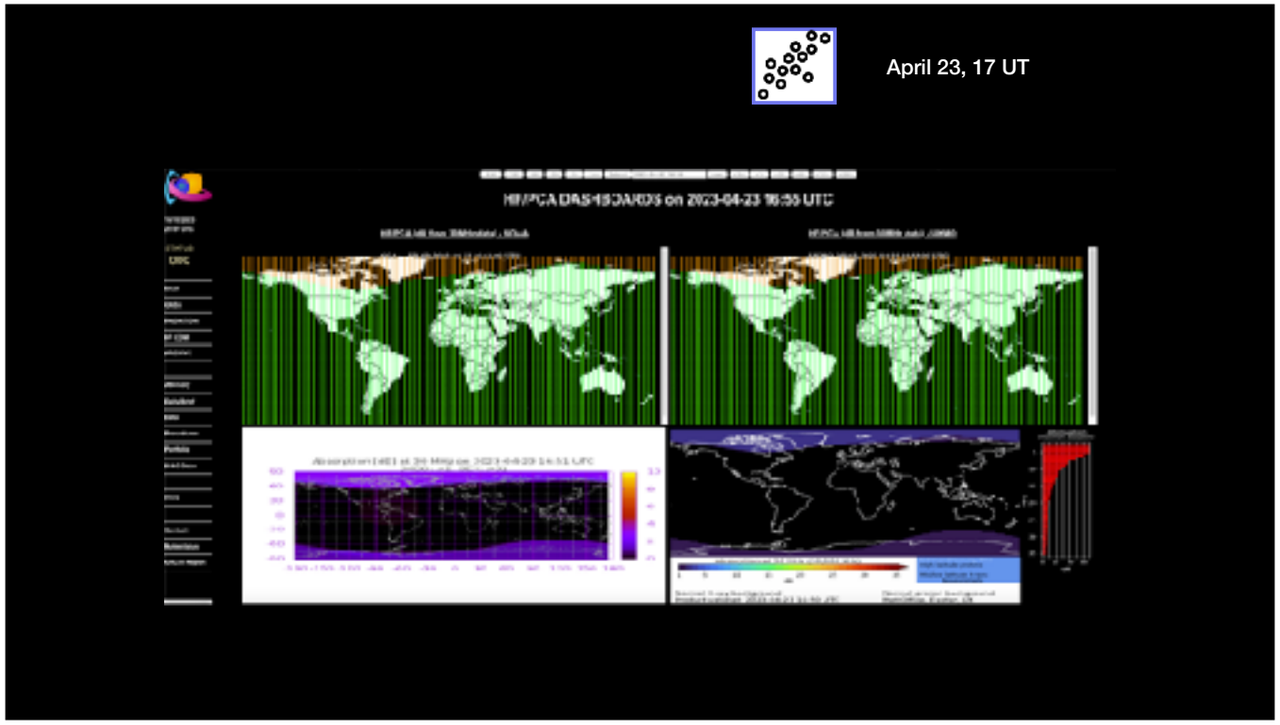
April 23, 17 UT



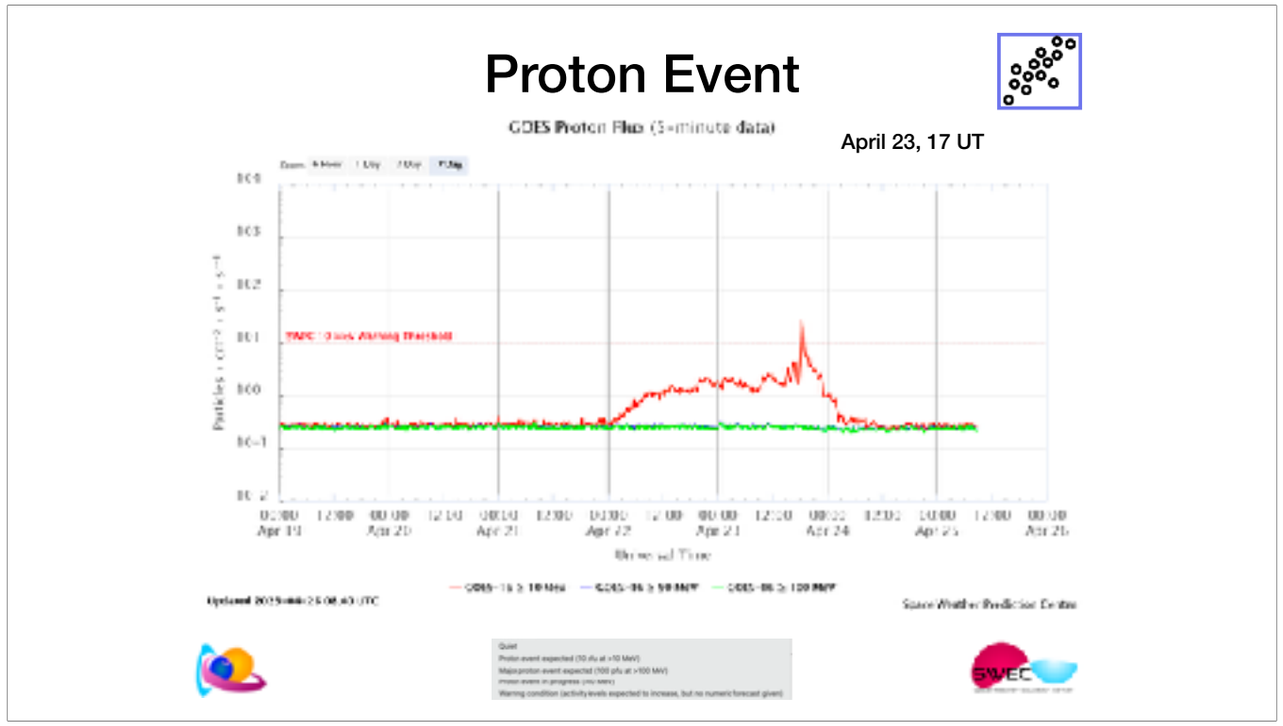
19LT —> 17 UTC



DRAP model

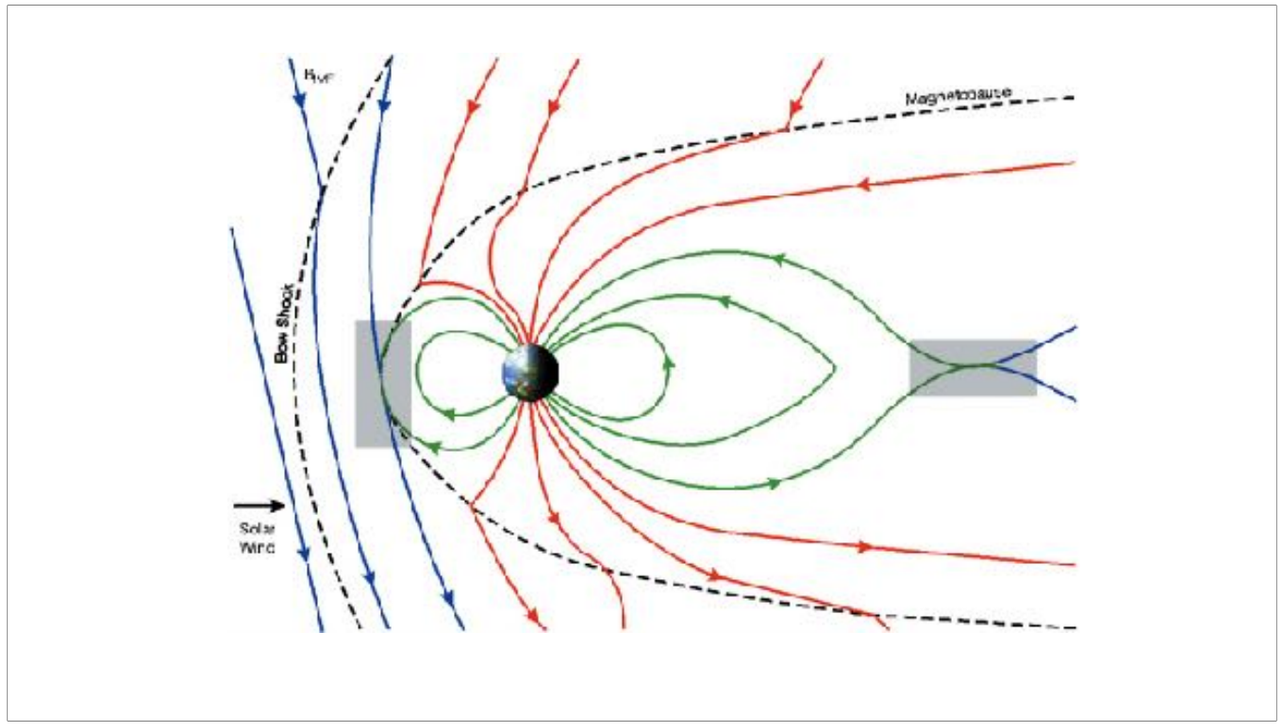
D-Region Absorption Predictions
Map giving info on spatial extend and which frequencies are impacted

PCA - scherpe overgang van open naar gesloten magnetische veldlijnen.
De deeltjes moeten een open route (open veldlijn) hebben om af te dalen naar de D-laag



A shock was recorded in the solar wind parameters on 23 April at 17:00UTC (DSCOVR ; graph). It marked the **somewhat (a few hours) earlier-than-expected arrival of the interplanetary coronal mass ejection (ICME**). **The passage of the shock briefly drove the already enhanced greater than 10 MeV proton flux finally above the proton event threshold (10 pfu)**, with a maximum of 26 pfu recorded at 18:20UTC (graph underneath). This is called an Energetic Storm Particles event (ESP), and originates from the acceleration of charged particles by a fast, usually ICME-driven shock in interplanetary space (e.g. Ameri et al. 2023). The proton flux drops sharply after the **shock** passage, as was the case here.

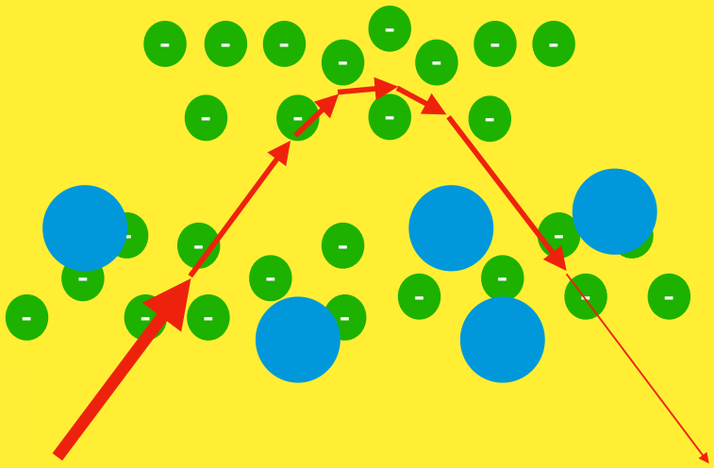
Shock pushes



This is why the transition between the impacted area and the undisturbed area is abrupt: a ‘sharp’ transition area (plasmasheet - see next slide)
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).

Plasma sheet: area between open and closed magnetic fields

Polar Cap Absorption





Extra ionisation in the D-layer where big fat neutrals are present limiting the movement of the electrons.

April 23, 17:06 UT





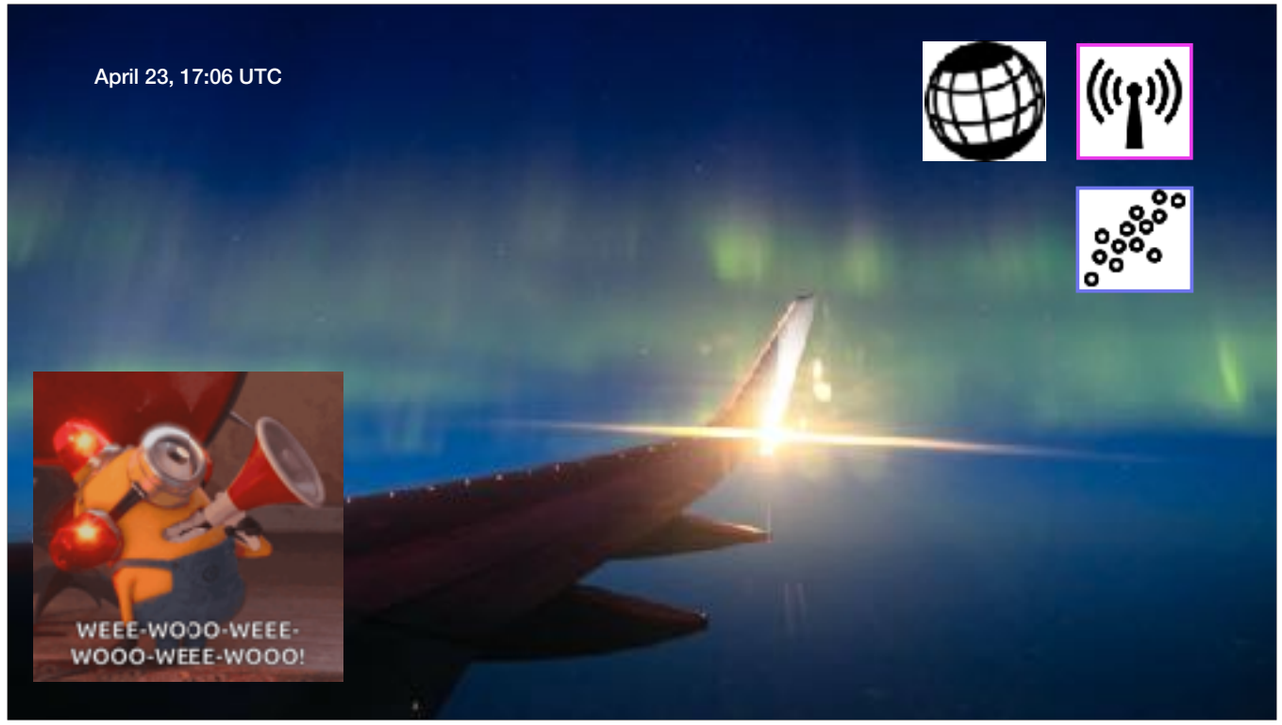


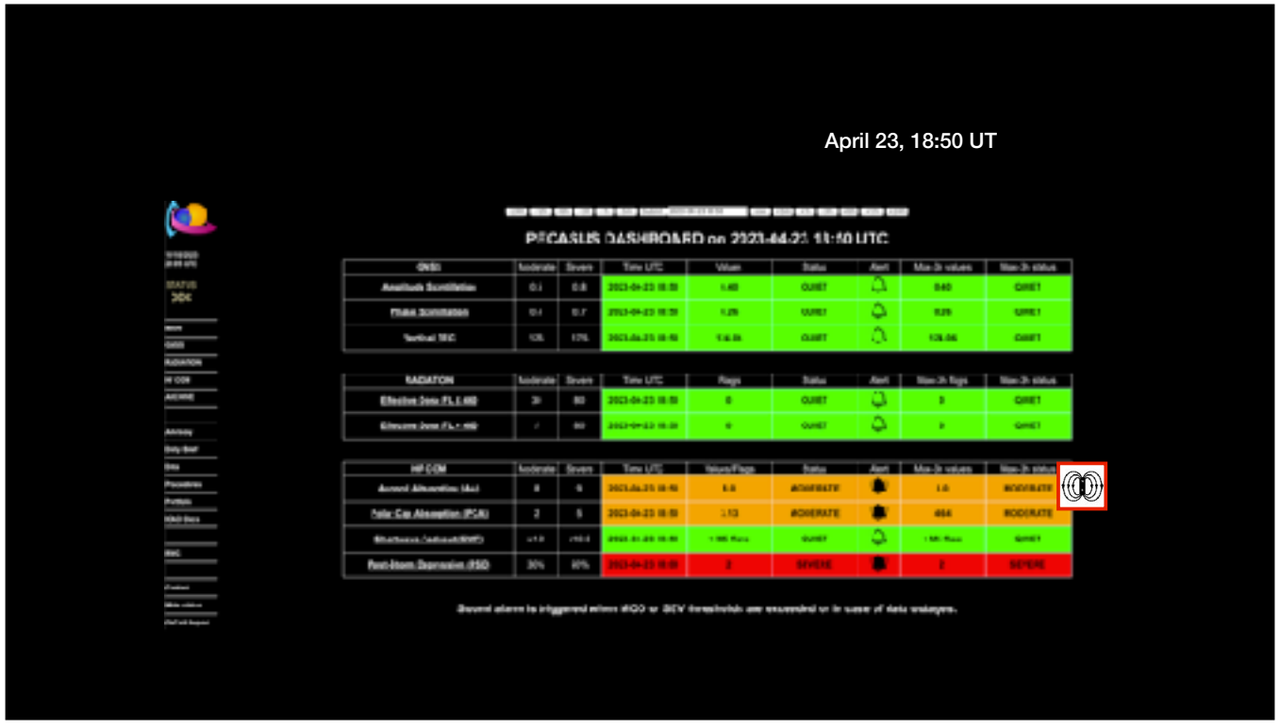
```
SWX ADVISORY
DTG:              20230423/1706Z
SWXC:             PECASUS
ADVISORY NR:      2023/59
SWX EFFECT:       HF COM MOD
OBS SWX:          23/1655Z HNH W150 - E000
FCST SWX +6 HR:   23/2300Z NOT AVBL
FCST SWX +12 HR:  24/0500Z NOT AVBL
FCST SWX +18 HR:  24/1100Z NOT AVBL
FCST SWX +24 HR:  24/1700Z NOT AVBL
RMK:              SPACE WEATHER EVENT (HF COM POLAR CAP
ABSORPTION) IN PROGRESS. IMPACT ON LOWER HF COM FREQUENCY
BANDS EXPECTED AT HIGH LATITUDES.
NXT ADVISORY:     WILL BE ISSUED BY 20230424/2256Z=
```





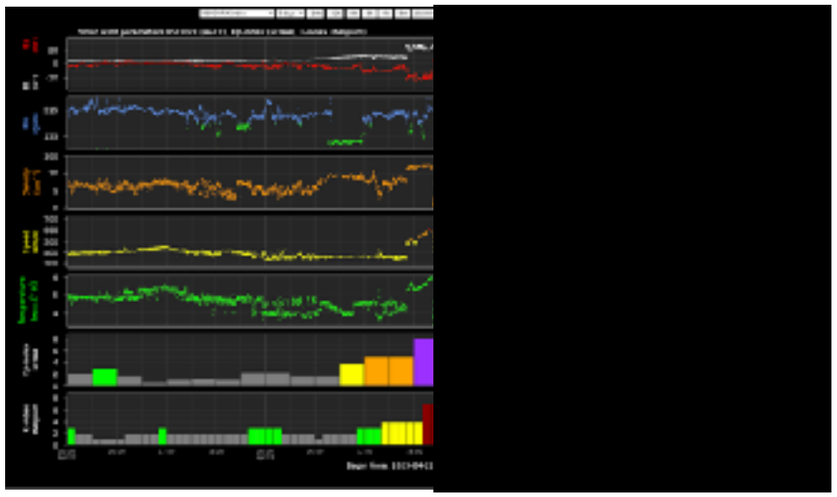
Should have been: HNH + HSH W180-E180


April 23, 17:06 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!



>1 hour later, it began
Passed Kp 6, leading to PSD but first focus on AA

CME arrival

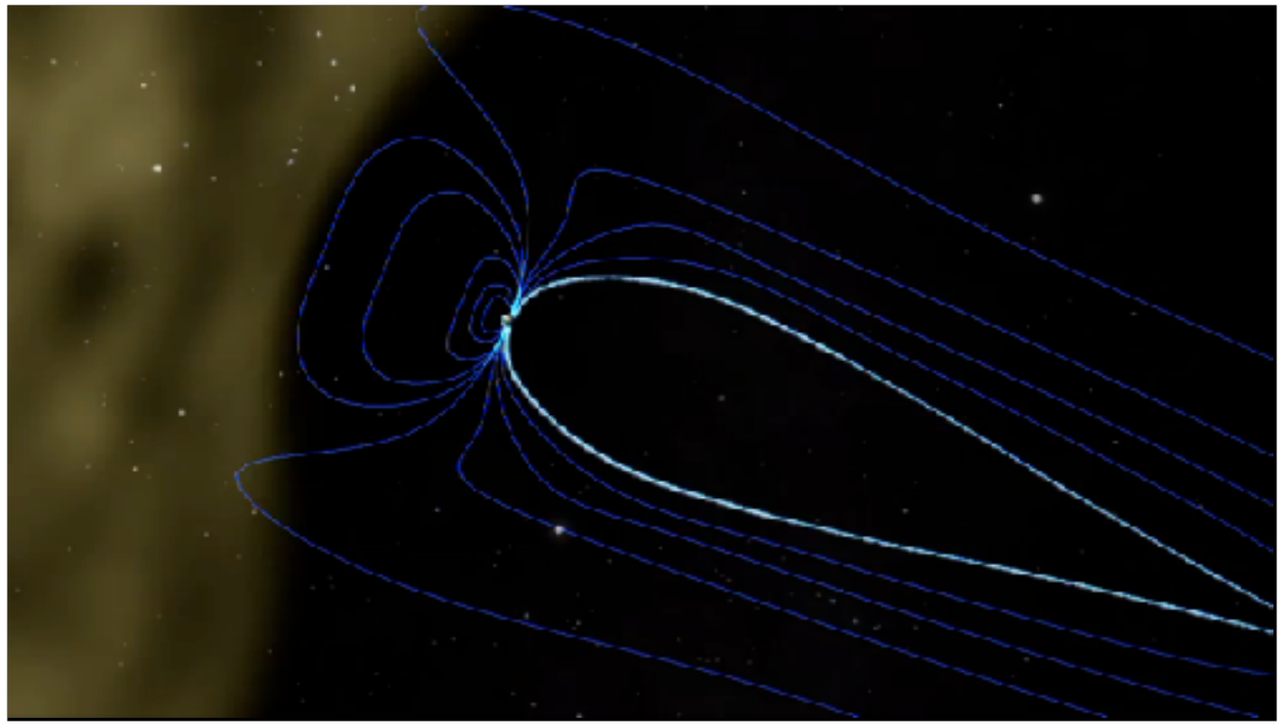


Geomagnetic Storm because of a CME arrival!

The cloud induced a **severe geomagnetic storm on the planetary level** (purple rectangles in the 6th panel)) and a **moderate geomagnetic storm locally** in Belgium (dark red rectangles in the 7th panel).

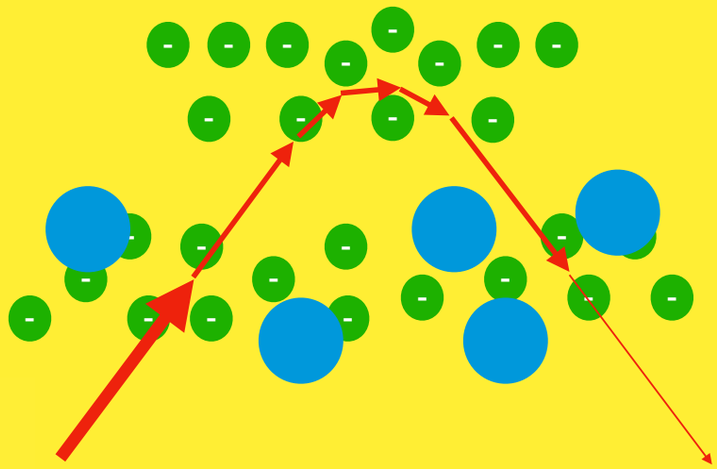
These graphs show (from top to bottom): the outward component of the magnetic field, the total magnetic field, the direction of the magnetic field, the density of the solar wind, the velocity of the solar wind, the temperature of the solar wind, The planetary K-index and the Local K-index for Belgium.

Solar wind speed jumped from 360 to 475 km/s, then gradually further increased to values near 700 km/s by 21:00UTC. Bz, the north-south component of the interplanetary magnetic field, showed 2 prolonged periods of negative values: during the 17-20UTC interval, when its value was at a fairly stable -24 nT, and again on 24 April during the 01-09UTC interval when Bz evolved from -33 nT to -9 nT. The Bz value of -33 nT was the lowest since the 7 September 2017 storm (also -33 nT). For even more negative Bz, we have to go back all the way to the Solstice storm of 22 June 2015 when it reached values of -39 nT.



Precipitating electrons coming from the tail

Auroral Absorption











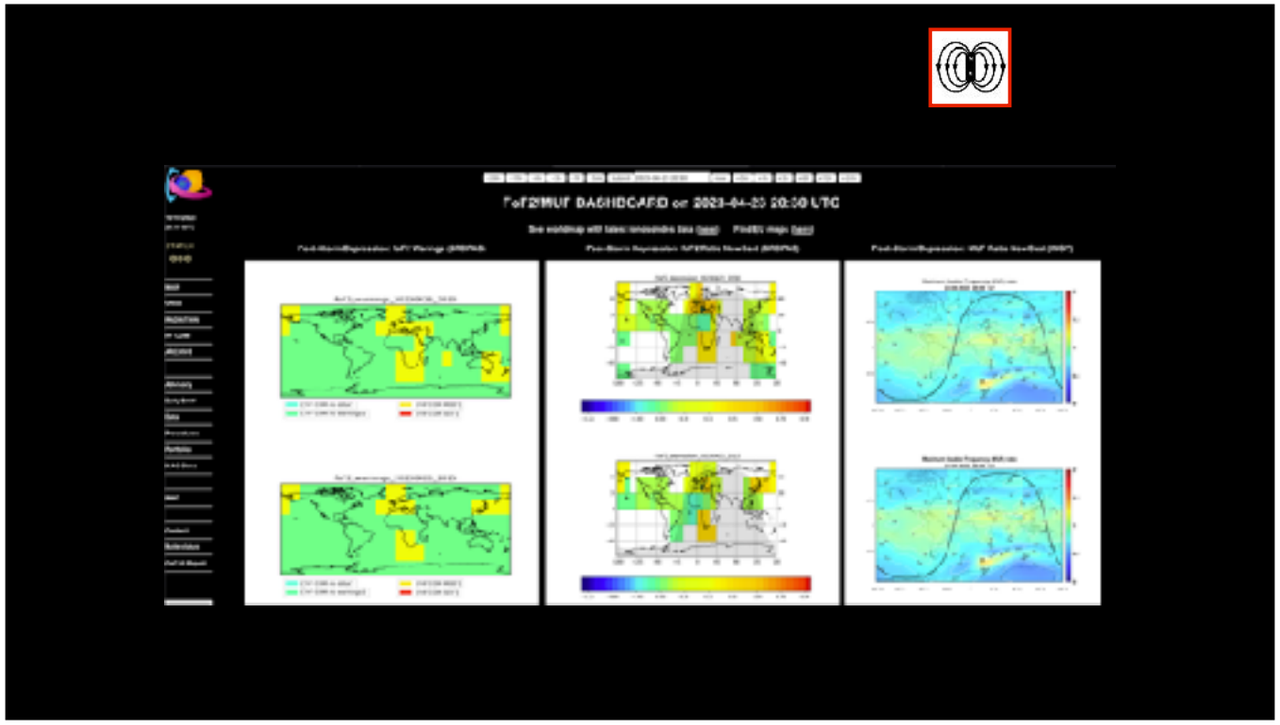


Extra ionisation in the D-layer where big fat neutrals are present limiting the movement of the electrons.

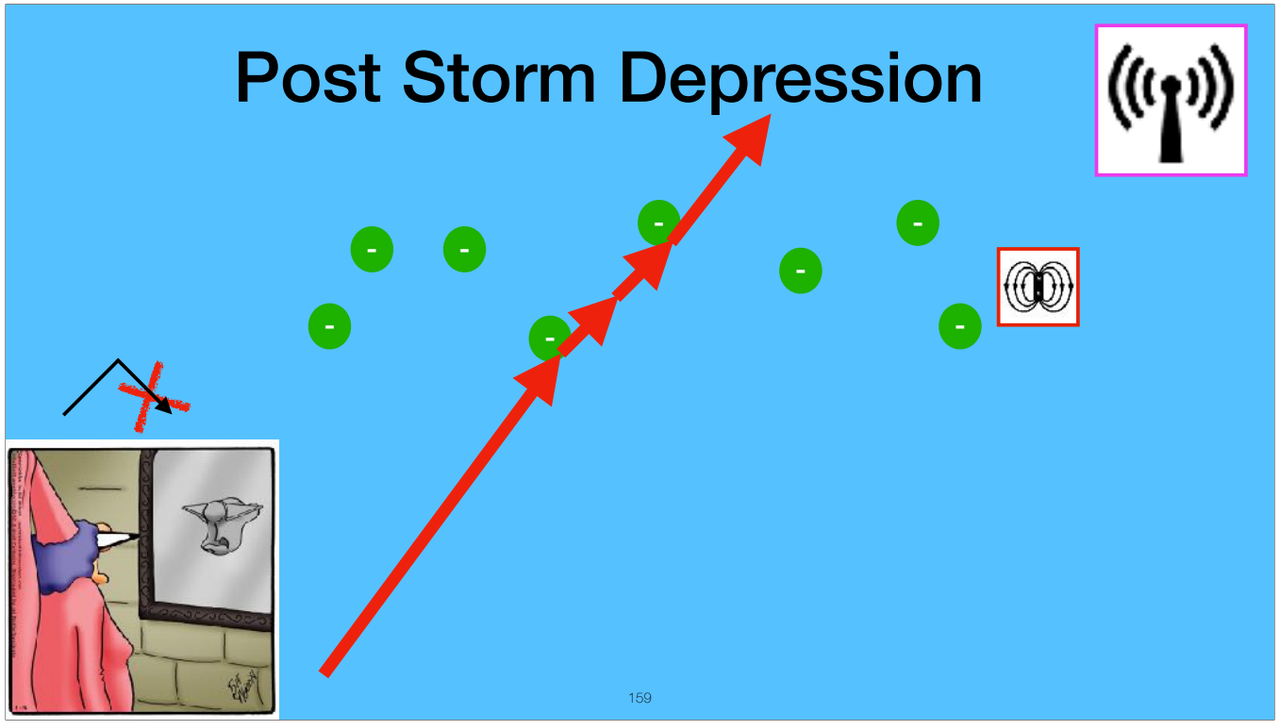

April 23, 20:29 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!



Focus on Post Storm Depression



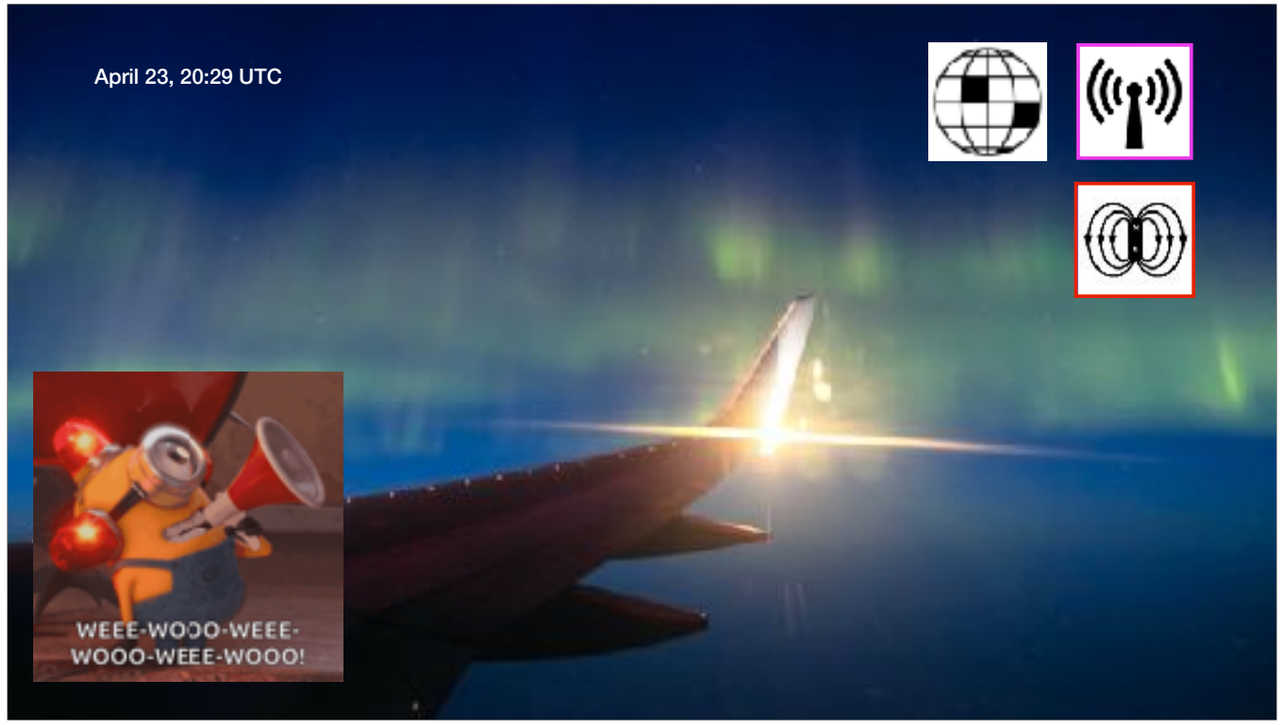
Areas of PSD —> where there are stations.



Neutrals are being transported to the F2 layer. This is the second, negative phase of the storm - more electron are being eaten by neutrals.
Less electrons, the MUF decreases —> less frequencies available for HF com
Higher freq radio waves pass through
—> mid-latitude

The most significant disturbances to the ionosphere result from solar events (CMEs, CIRs), propagating through the solar wind and interacting with the magnetosphere.

1 Energy injected into the ionosphere, mainly at high latitude.
2 As a result, the auroral oval expands.
3 This causes large scale movement of plasma towards the equator.
4 Drift along the magnetic field lines cause the ionosphere to move up, which can increase electron density (“positive storm phase”).
5 Finally, upwelling of N2 causes increased recombination, leading to a depletion of ionisation (“negative storm phase”).


April 23, 20:29 UTC
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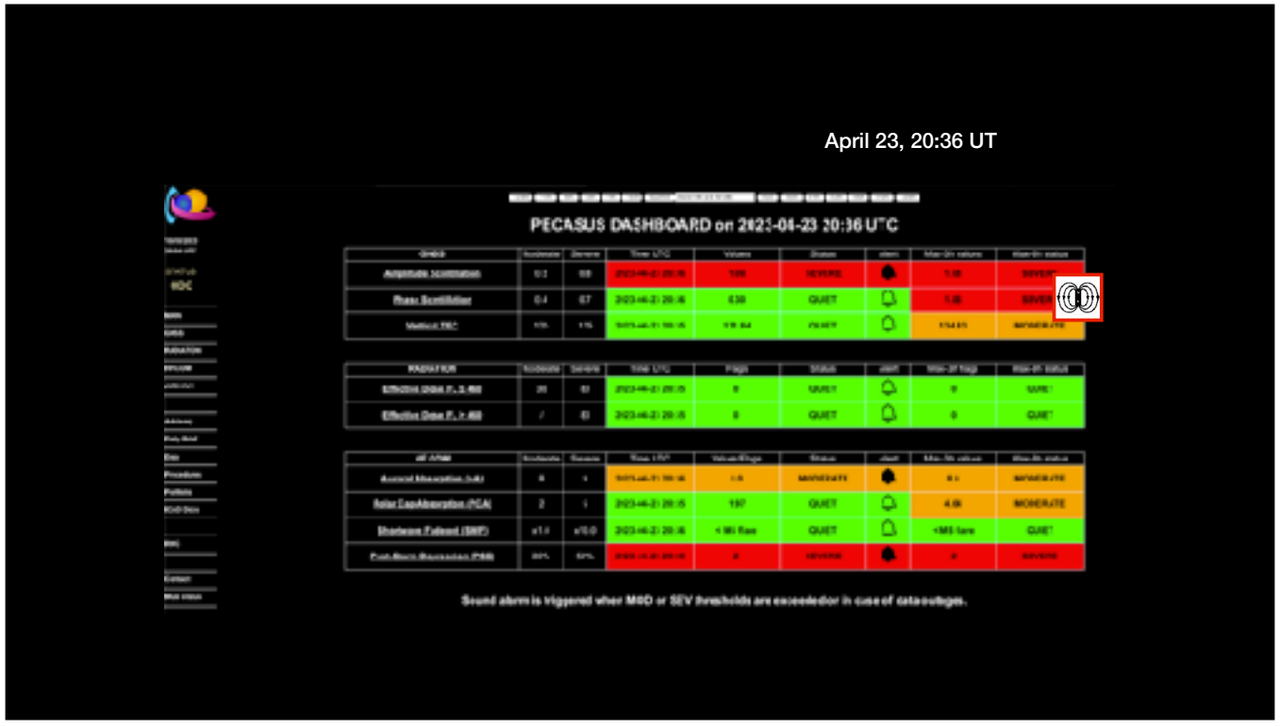
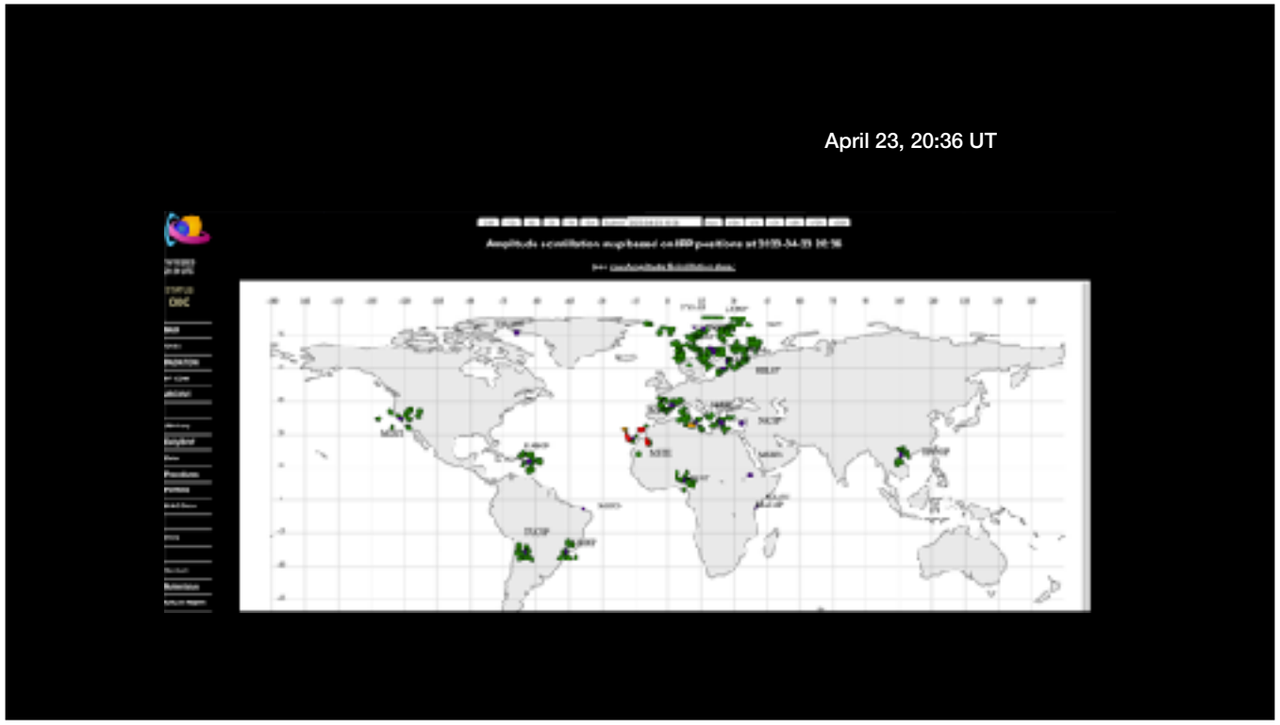
WOOO-WEEE-WOOO!



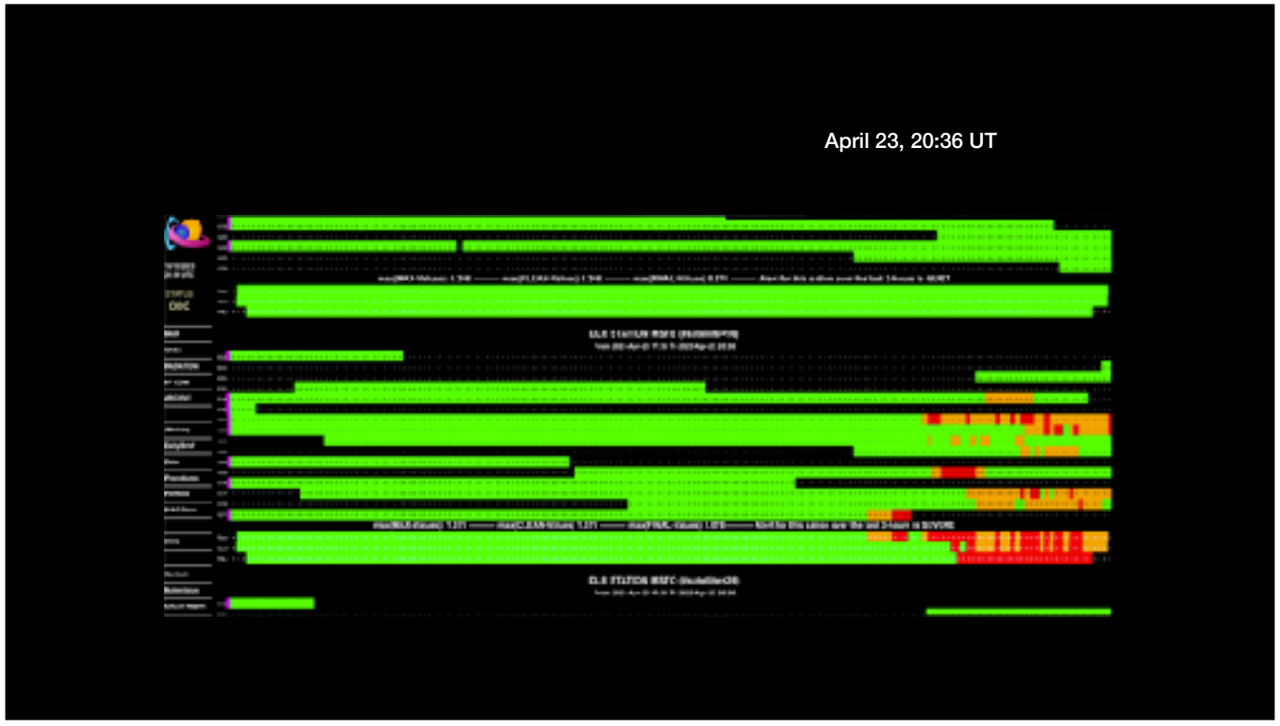
New telephone call
focus on AS



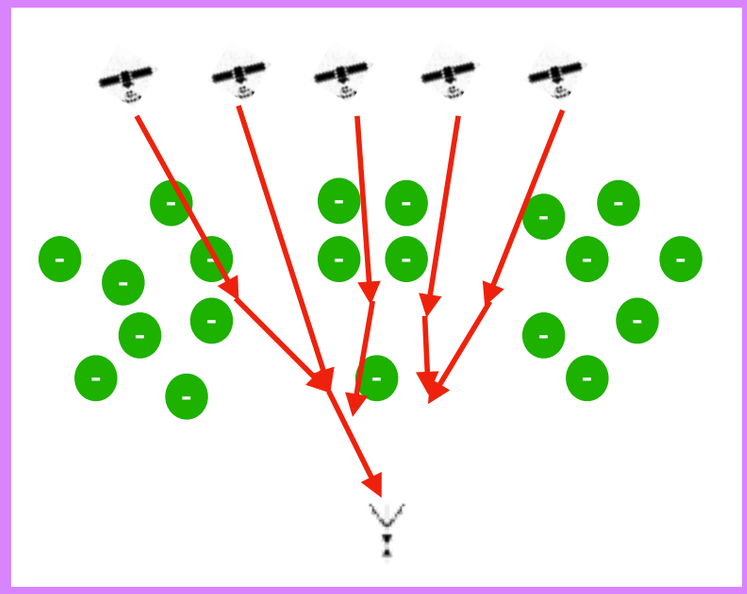
The four mechanisms that give rise to scintillation are

- Plasma bubbles (in the lower latitudes)
- Precipitating particles (auroral oval)
- Patches in the polar caps
- Travelling ionospheric disturbances

All three happen more or less depending on the circumstances, but plasma bubbles happen most of the days.



Link between a station and satellites
A cross is one minute.

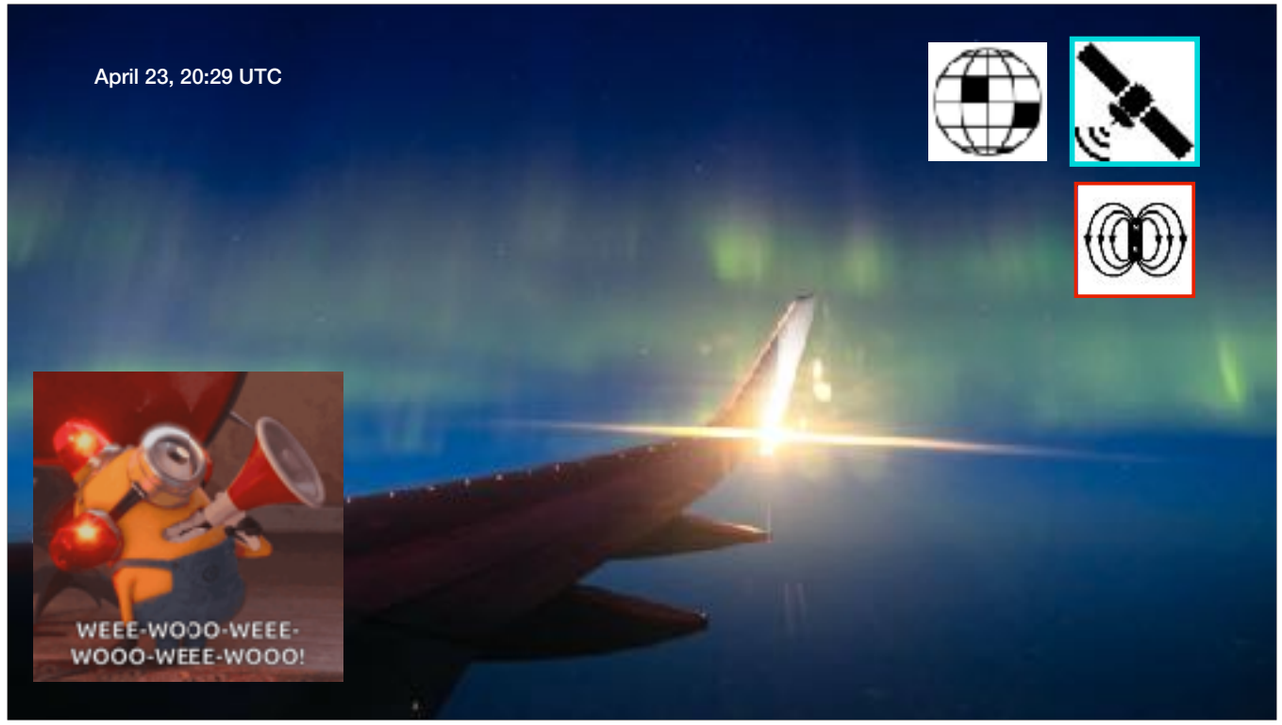




Due to space weather, small scale irregularities exist in the ionosphere.
Landscape of electrons - dense regions and less dense regions
Localised
REFRACTION
When a wave enters another medium, its speed is different. The wave is redirected as it passes from one medium to another —> delay
DIFFRACTION
A wave bends around the corner of an obstacle.
—> refracted and diffracted waves interfere —> As a result, the receiver sees a twinkling signal, i.e. the signal with rapid variations superimposed on it.

Regions of scintillation:
- Polar caps — solar energetic particles
- Auroral oval - trapped particles from the plasma sheet
- Equatorial region - equatorial ionisation anomaly - plasma bubbles - Rayleigh Taylor instability

The result is the same, the cause of the density irregularity is different.


April 23, 20:29 UTC
WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

You made it until the end of this presentation!
Well done.

The PECASUS operator on duty at that time was not done yet. Trouble in the ionosphere continues until 4 days after Kp=6

BIS slides

GNSS	Moderate	Severe	Time UTC	Values	Status	Alert	Max-3h values	Max-3h status
Amplitude Scintillation	0.5	0.8	2020-10-12 14:15	0.25	QUIET		0.35	QUIET
Phase Scintillation	0.4	0.7	2020-10-12 14:15	0.13	QUIET		0.14	QUIET
Vertical TEC	125	175	2020-10-12 14:15	61.92	QUIET		61.93	QUIET

RADIATION	Moderate	Severe	Time UTC	Flags	Status	Alert	Max-3h flags	Max-3h status
Effective Dose FL<460	30	80	2020-10-12 14:20	0	QUIET		0	QUIET
Effective Dose FL > 460	1	80	2020-10-12 14:20	0	QUIET		0	QUIET

HF COM	Moderate	Severe	Time UTC	Values/Flags	Status	Alert	Max-3h values	Max-3h status
Auroral Absorption (AA)	6	9	2020-10-12 14:15	3.0	QUIET		3.0	QUIET
Polar Cap Absorption (PCA)	2	5	2020-10-12 14:20	0.00	QUIET		0.00	QUIET
Shortwave Fadeout (SWF)	x1.0	x10.0	2020-10-12 14:17	< M.5-flare	QUIET		< M.5-flare	QUIET
Post-Storm Depression (PSD)	30%	50%	2020-10-12 14:15	0	QUIET		0	QUIET

Micro = 10^-6
Sieverts = J/kg
Effective dose = Micro Sievert / hour

Whole body cancer risk -

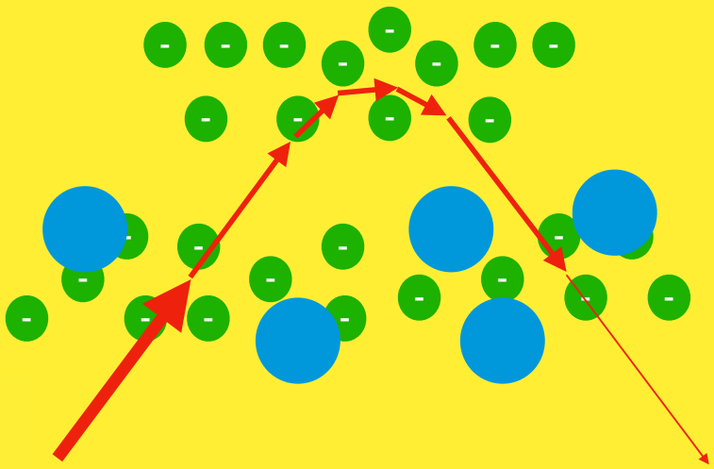
Ionosphere is needed for long distance HF communication which makes use of the reflective capability of the ionosphere. The ionosphere acts as a mirror.

AA, PCA, SWF are absorption events - low frequencies
PSD reduces the range of frequencies available - high frequencies are not available.

HF Com
If you have a strong radio burst in HF, your MUF might be full of solar noise and in practice not usable. But SRB are not taken into account by ICAO

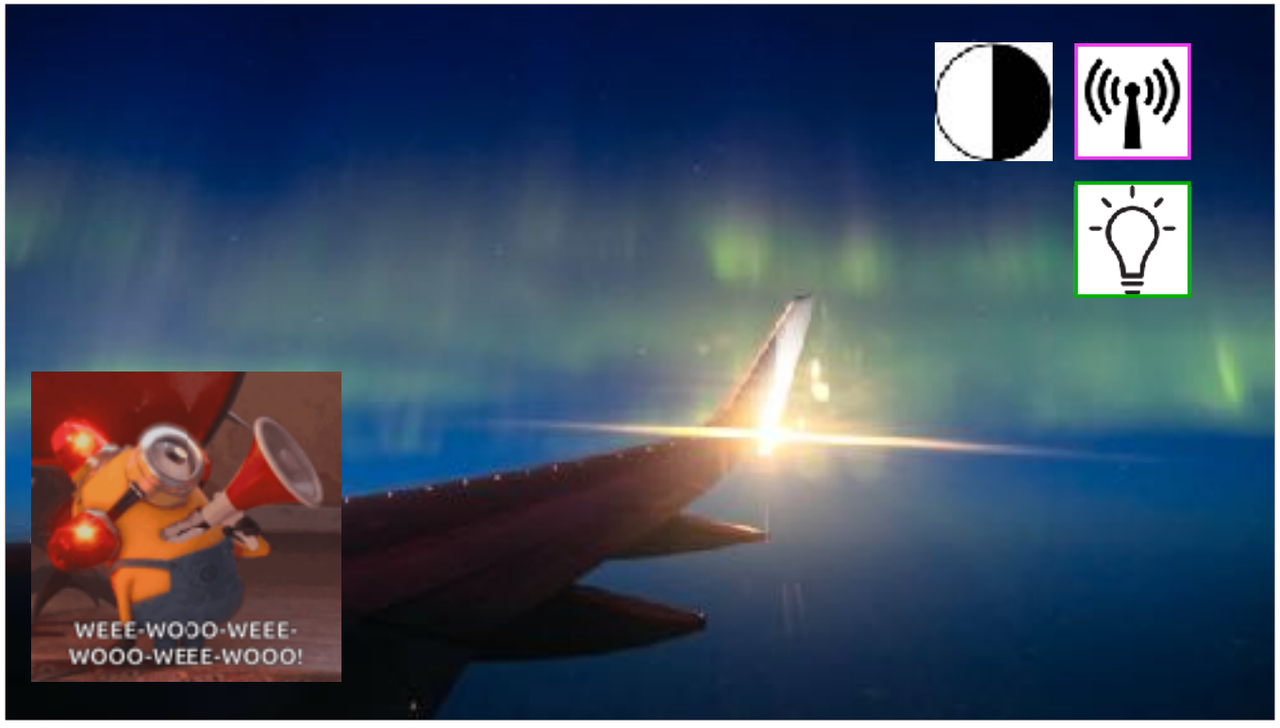
Similar, Solar Radio Bursts can impact also GNSS by adding noise.

Short Wave Fadeout



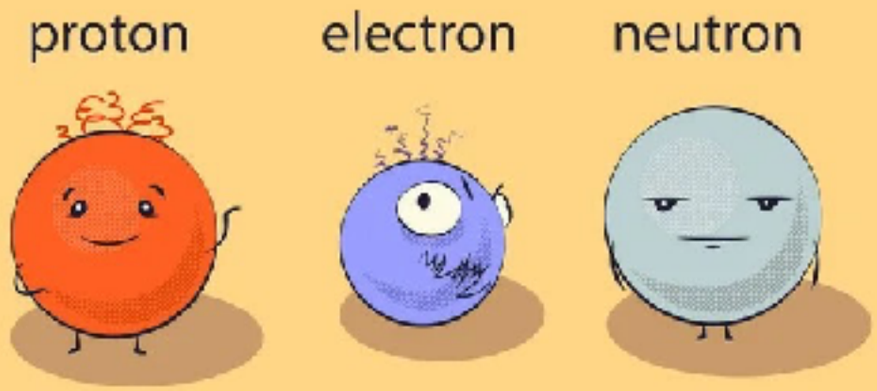


Short Wave Fadeout, auroral absorption, PCA


WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

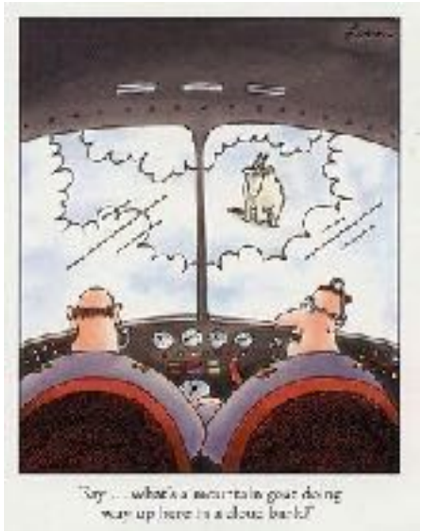
Biological impact






WEEE-WOOO-WEEE-
WOOO-WEEE-WOOO!

Space Weather Warnings and Forecasts do make a difference.



Take away from this presentation

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Enjoy!


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