SPACE WEATHER INTRODUCTORY COURSE

SWIC

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

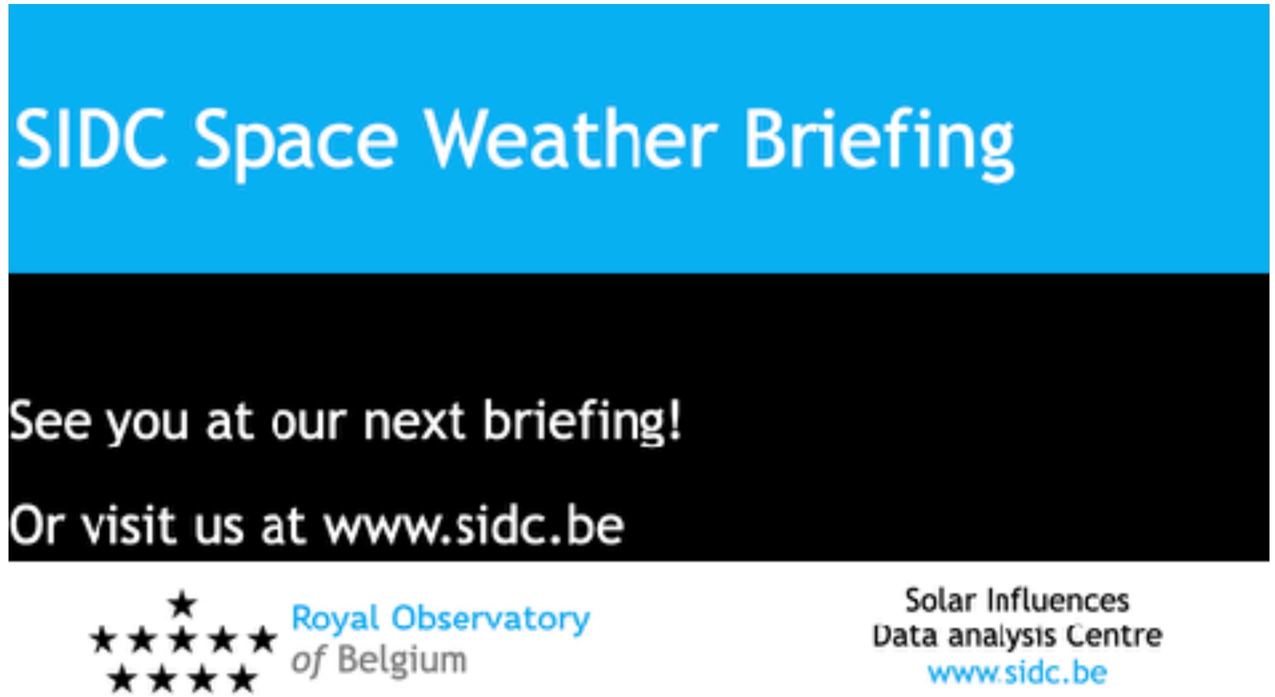
Koninklijk Nederlands
Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu

SPACE WEATHER

Basic Concepts

Elke D'Huys, Jan Janssens & Petra Vanlommel

SPACE WEATHER BRIEFING



We will soon take part in the weekly space weather briefing where our forecaster on duty reports on the current and expected space weather conditions.

SPACE WEATHER BRIEFING

Summary Report

Solar activity from 2021-04-18 12:00 to 2021-04-25 23:59

Active regions	7 ARs (NOAA AR 2814, 2815, 2816, 2817, 2818, 2819 & 2820)
Flares	# C-class flare: 20 # M-class flare: 1 # X-class flare: 0
Filament eruptions	No big filament eruptions
Coronal Holes	One small equatorial coronal hole (negative polarity)

Proton flux	quiet
Electron flux	the greater than 2MeV electron flux was mostly above the 1000 pfu threshold.

Solar wind and geomagnetic conditions

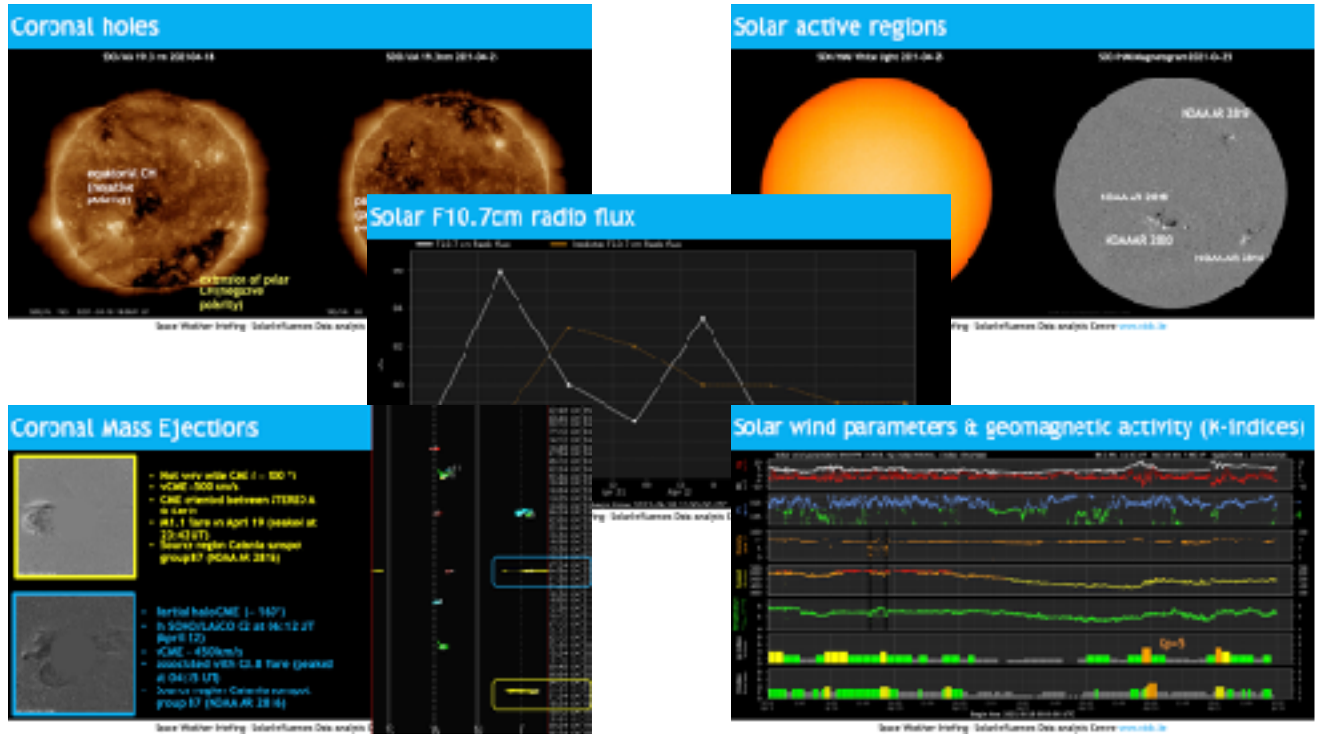
ICME	In situ shock and CME observed on April 24 (22:27 UT)
SW Conditions	|B|: 0.95 - 11.05 nT // Bz: -10.63 nT to 7.38 nT // Speed: 368.3 - 1153.6km/s
K-indices	max K-index (Dourbes): 5 max Kp-index (NOAA): 5

All Quiet Alert: none

Space Weather Briefing - Solar Influences Data analysis Centre www.sidc.be

Topics that will be addressed are the space weather ingredients that were presented in the introduction section of this course: solar activity (active regions, filaments, flares, coronal holes), energetic particles, solar wind, geomagnetic conditions.

SPACE WEATHER BRIEFING



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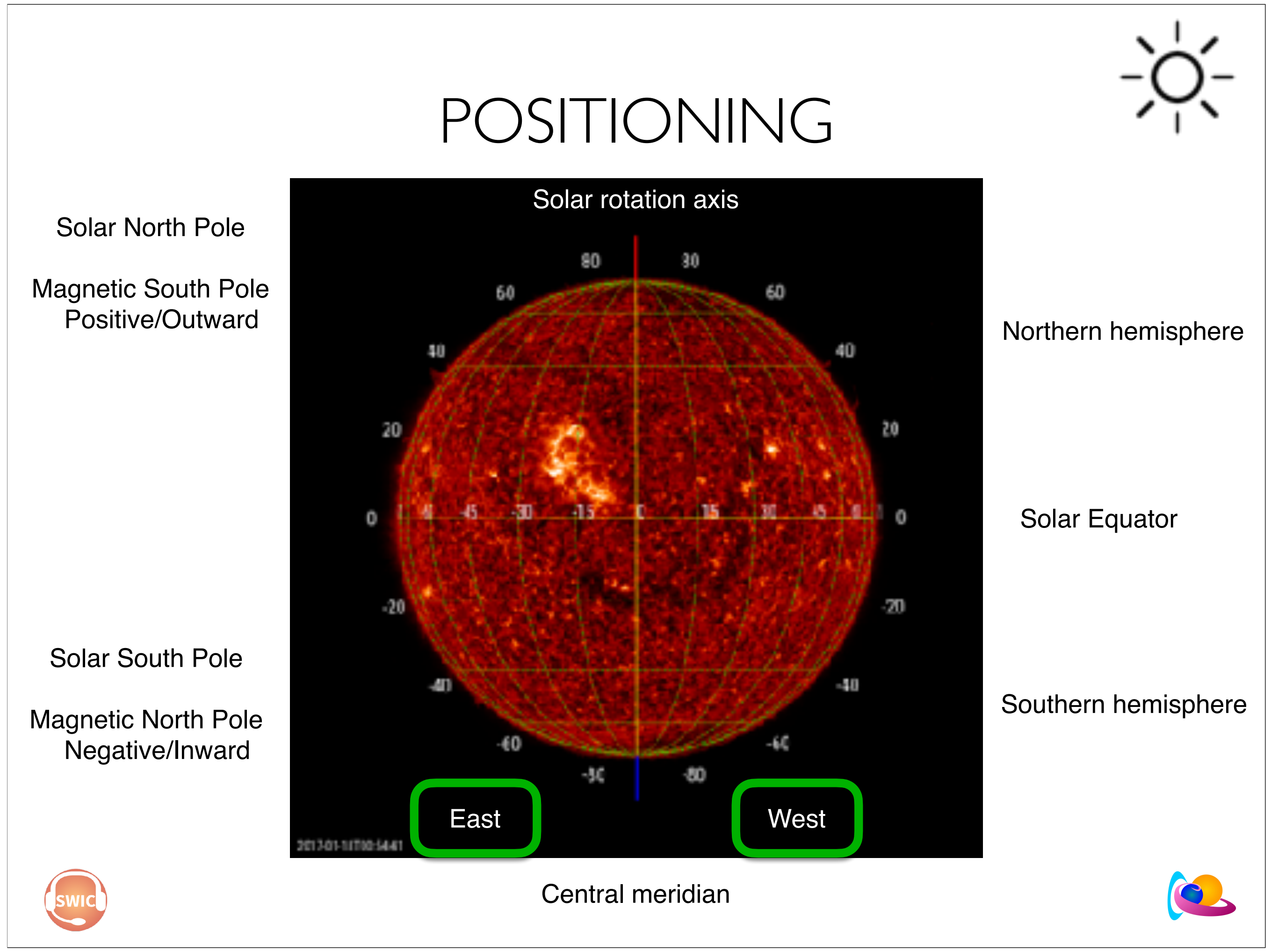
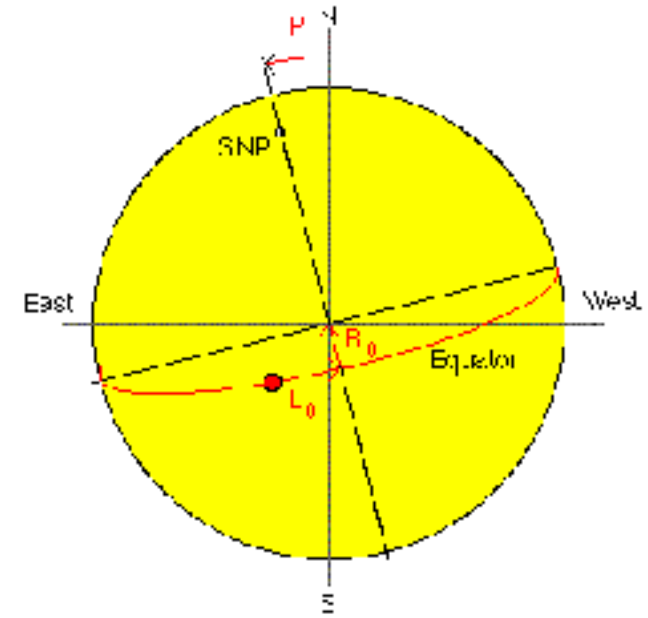


Before going into more detail of the space weather ingredients, we have to be able to 'navigate' on the sun.
Two important lines are the central meridian and the solar equator. With these, you determine positions on the solar surface (east/west and north/south, respectively).

Currently (2021), the solar north pole is the magnetic south pole, which means the magnetic field there is positive and outward directed. (See e.g. http://wso.stanford.edu/gifs/Polar.gif)
Every 11 years, there is a magnetic field reversal where the magnetic north pole becomes the magnetic south pole (and vice versa). This happens at the time of solar maximum. This leads to a full magnetic cycle of 22 years (return to original polarities).

During the previous solar cycle (SC 24), there was an unusually long reversal in the field in the northern solar hemisphere: this started as early as June 2012, was followed by a sustained period of near-zero field strength lasting until the end of 2014. Meanwhile, the southern solar hemisphere unambiguously reversed polarity in mid-2013 already.
(https://www.aanda.org/articles/aa/full_html/2018/10/aa32981-18/aa32981-18.html)

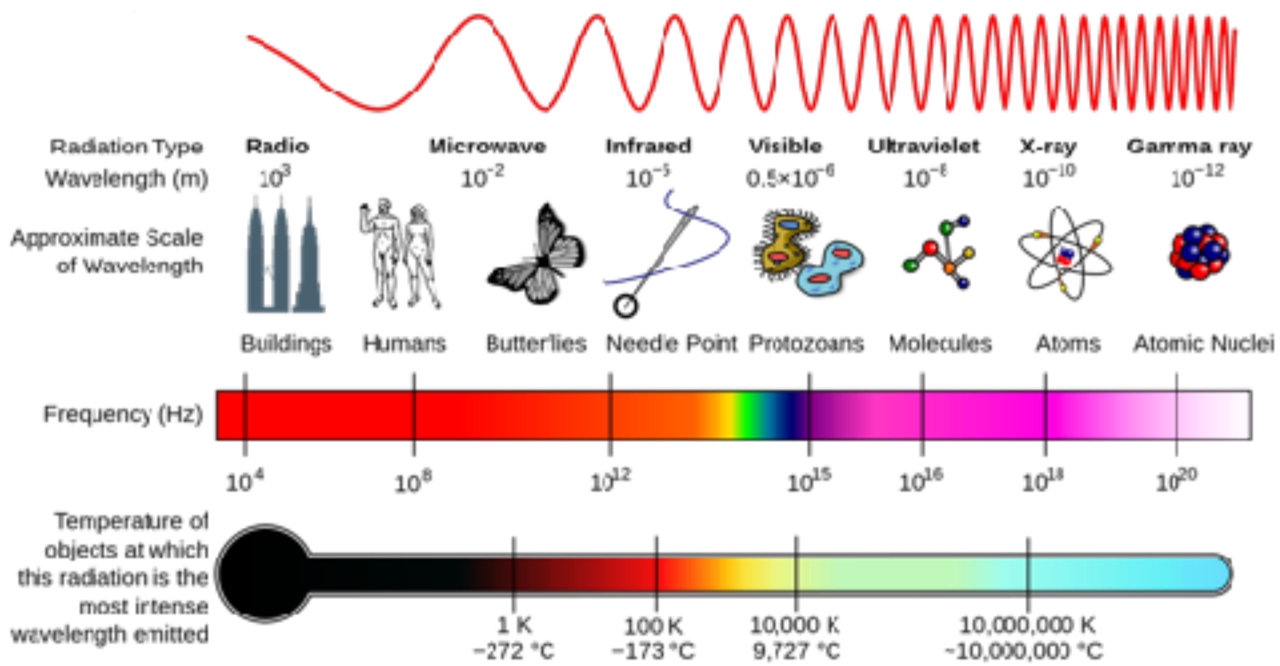
SOLAR ROTATION



The Sun rotates from (solar) East to West, so left to right in approximately 27 days (at the equator). We can see (some types of) activity coming on the East limb and predict the effects of possible related space weather.

The solar rotation axis is tilted compared to the ecliptic (the plane in which the Earth orbits). In other words, the solar equatorial plane does not coincide with the ecliptic. The Earth has a certain heliographic latitude. We have a better view of the solar south pole from February to April, and on the solar north pole from August to October.
(See e.g http://jgiesen.de/sunrot/index.html and the animation on http://www.petermeadows.com/html/sunfromearth.html)

ELECTROMAGNETIC SPECTRUM



The electromagnetic spectrum ranges from radio waves to gamma rays.
As we move to higher temperatures, the wavelengths get shorter.
We can only use longer wavelengths such as radio and visible light to observe the Sun from ground, (E)UV wavelengths are absorbed by the atmosphere. We need satellites to observe in EUV.
Once the space age began, we were given a completely new view of the Sun.

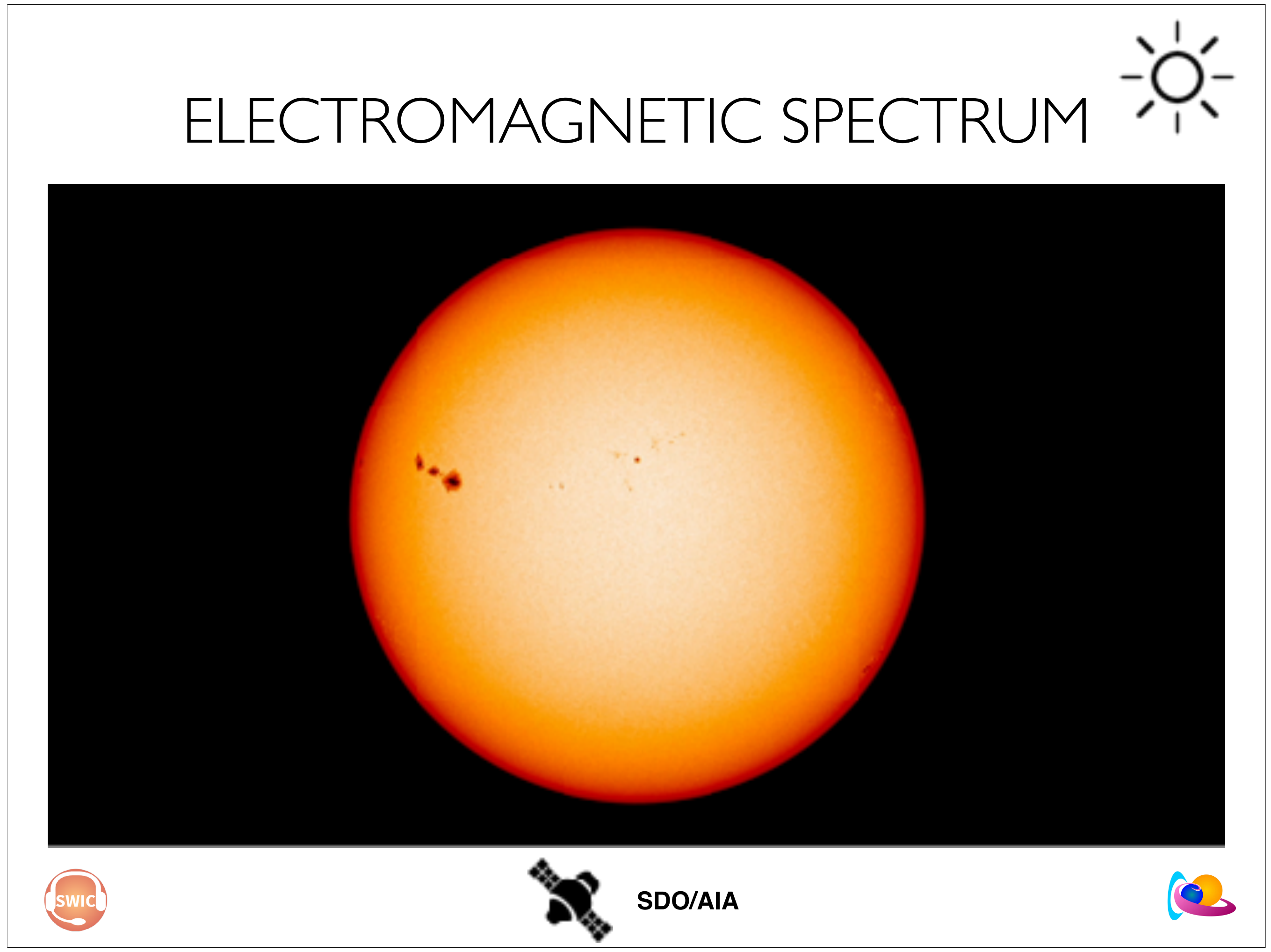
H-alpha 656.28 nm - red - 9000 °K
C II K 3933.7Å - 393.37 nm - blue
Visible light: 780 - 380 nm / 7800- 3800 Angstrom / rainbow
UV: 380 - 10 nm / 3800 - 100 Angstrom
EUV: 100 - 10 nm / 1000 - 100 Angstrom

ELECTROMAGNETIC SPECTRUM

To study a distant object, we can not take in-situ measurements, but we can take pictures (remote sensing).
Similarly, a doctor can use an x-ray camera to image your bones. In fact, an x-ray picture shows the shadow of your bones which are not transparant for x-rays. The softer parts of your hand are partly transparant for x-rays, and are thus less visible in the image.

These pictures can show doctors parts of your body that they can't normally see.
Each wavelength gives complementary information.

Right image: temperature measured using infrared waves, red=cold and blue=warm in this color scale.



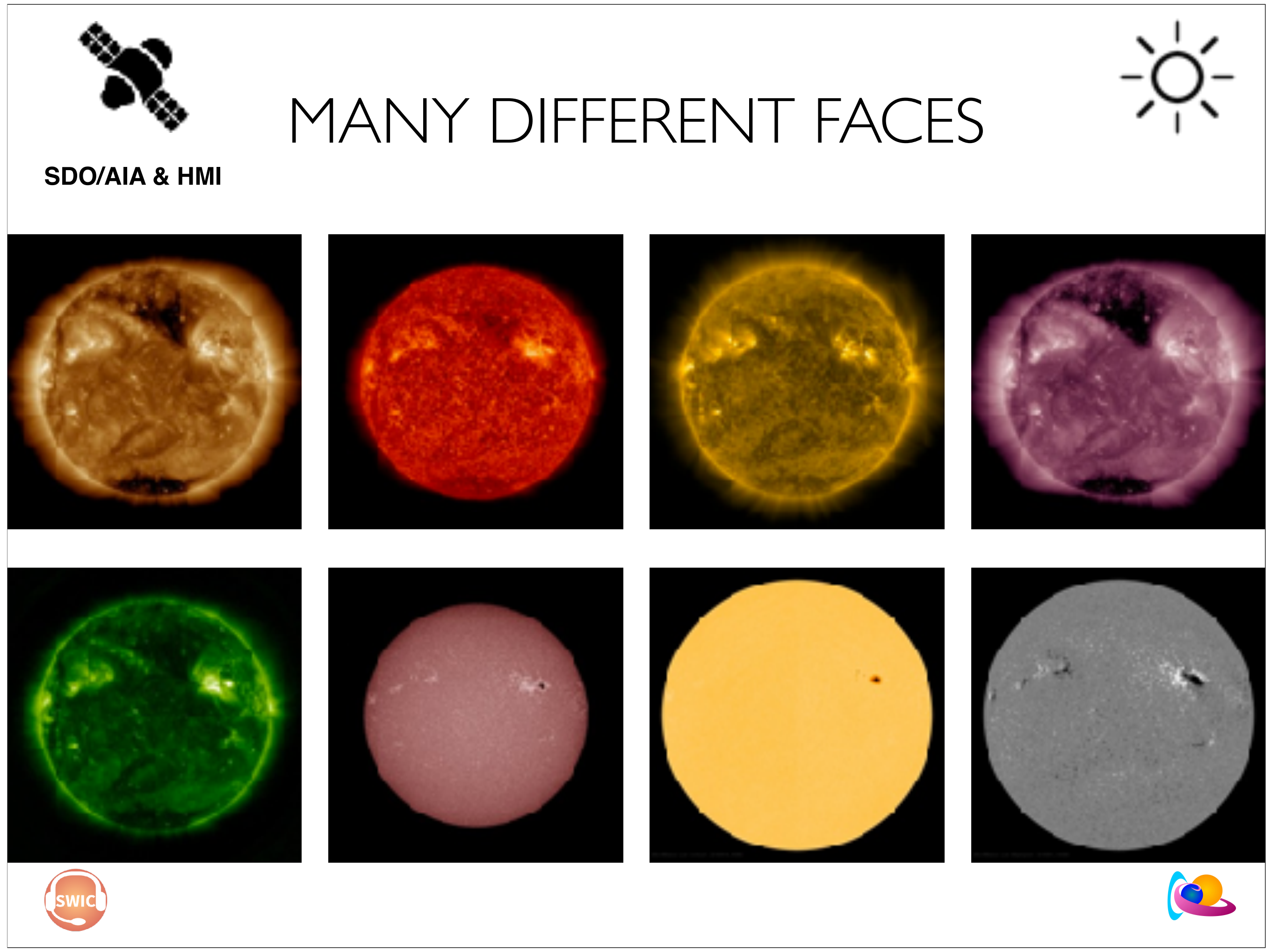
The Sun has a hidden region that became only visible at the start of the space age. From the moment we could inspect the Sun in other wavelengths, the Sun showed its dynamic, explosive and magnetic personality.

Indeed, we use many tricks to observe the Sun and its activity. One of them is to look at the Sun using different parts of the light spectrum, thus in different wavelengths. From Earth, with the naked eye, we see the surface of the Sun in white light like this.

However, when the movie starts, you can see how looking at the Sun in other wavelengths (from space) reveals very different structures and complexity. For this we mainly use extreme ultraviolet wavelengths because we are studying the hot outer region of the Sun, the corona. We see active regions, these are the bright patches, that show up in EUV wavelengths where the sunspots were first seen in white light. We also see the effects of the sun's magnetic field in the many loops above these sunspots. Each wavelength shows us different aspects and different layers of the solar atmosphere and by combining them, we try to build a complete picture of the solar activity.

Therefore, we have many instruments in space to observe the solar atmosphere.

Credits: This movie was made combining different observations from the Atmospheric Imaging Assembly (AIA) telescope on board the Solar Dynamics Observatory (SDO).
https://youtu.be/g08XKIz2SD0



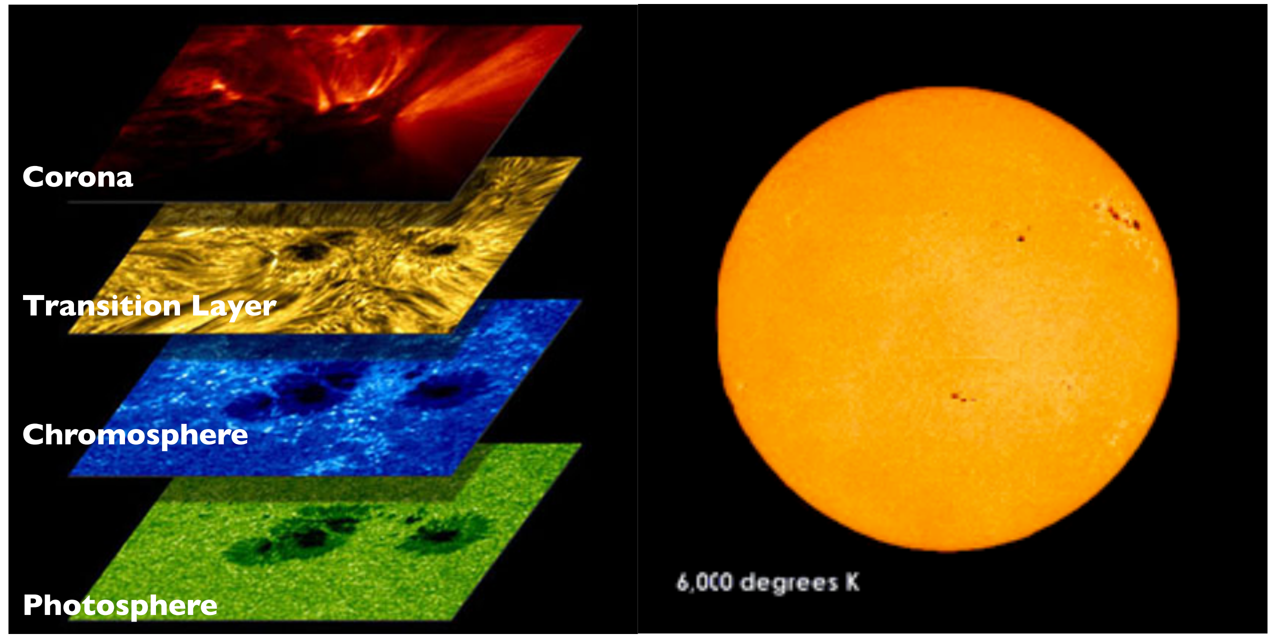
The Sun has many different faces. Here you see images taken of the Sun in different wavelengths at approximately the same time by the Atmospheric Imaging Assembly (AIA) and the Helioseismic and Magnetic Imager (HMI) on-board the Solar Dynamics Observatory (SDO). Each wavelength reveals a different aspect of the solar activity, e.g. bright regions called active regions or dark spots called sunspots.

At the bottom right you see a magnetogram, which shows you the strength of the solar magnetic field. You immediately see that the field is very strong at the location of the sunspot seen in the photospheric image just to the left of the magnetogram.

So both sunspots and active regions are different features indicating the same area of strong magnetic field.

Another example: flaring in active region 1158
https://www.youtube.com/watch?v=u6PSejWooNM

LAYERS OF THE SUN

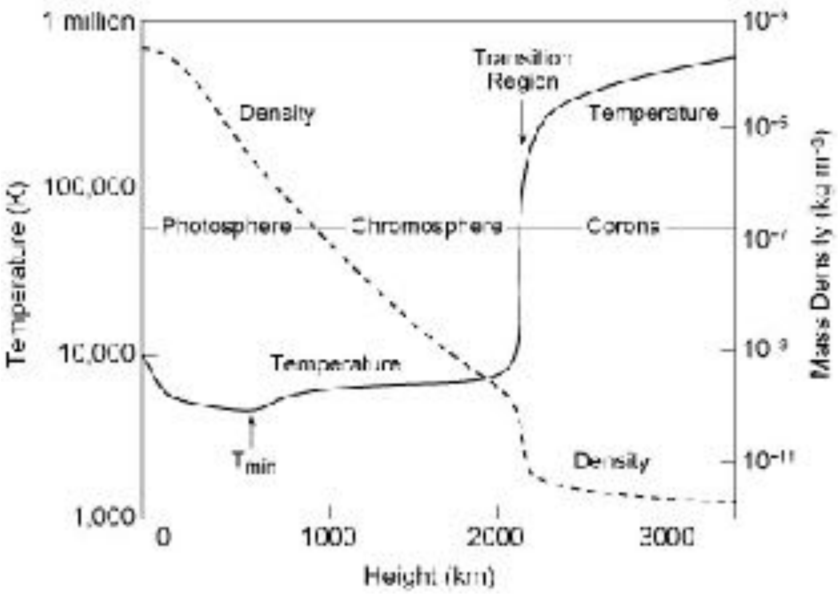


The solar atmosphere is formed by the most outer layers of the Sun from where the solar radiation can escape freely, in contrast to the un-transparant inner layers.
The solar atmosphere has 4 basic layers: photosphere - chromosphere - transition layer - corona.

Temperature increases as you go higher up to the outer layers, which is sort of strange. Normally you would think that the temperature decreases if you go further away from the heat source. Why is the corona so hot? This is a hot topic in solar research and still subject of debate.

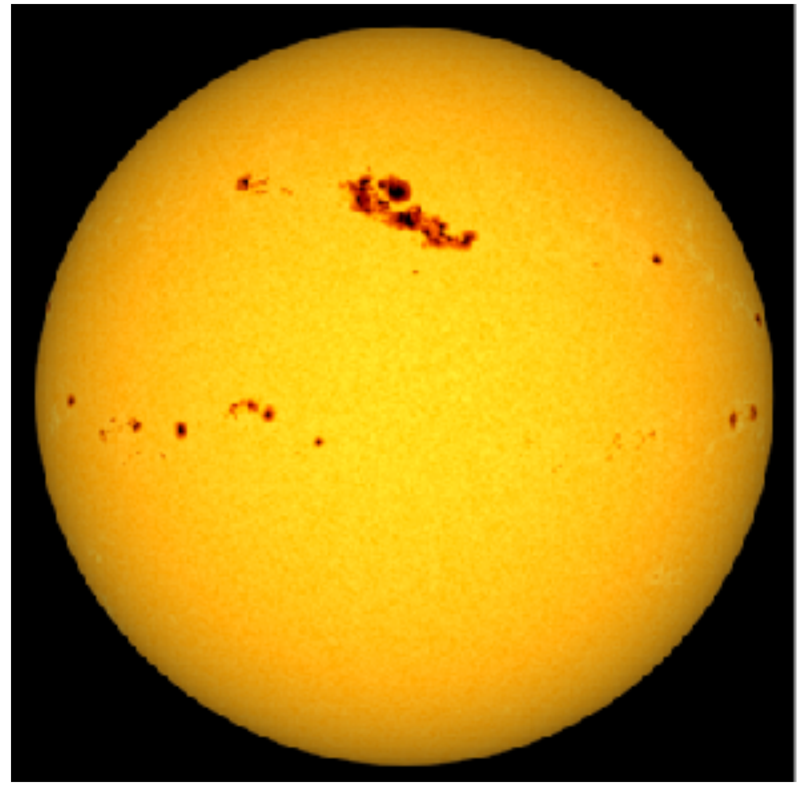
The name photosphere comes from the greek work photon which means ‘light’. The photosphere radiates mostly in visible light, which we can see from ground.
In contrast, the corona radiates in (E)UV and X-rays, wavelengths which we can not see with our eyes. That’s why we see the Sun as a non-dynamic structure. The coronal loops and dynamic structures in the corona are invisible to us unless we observe them in the EUV using special filters translating the EUV into a picture which we can see.

LAYERS OF THE SUN



But, although the corona is a million degrees Kelvin hot, satellites don't burn up. This is because the corona is not dense at all. Compare this with a sauna and a bath. You can sit in a sauna of 90°C but not take a bath of 90°C. The air is the sauna is less dense than the water in the bath, which is why you don't get burned in the sauna.

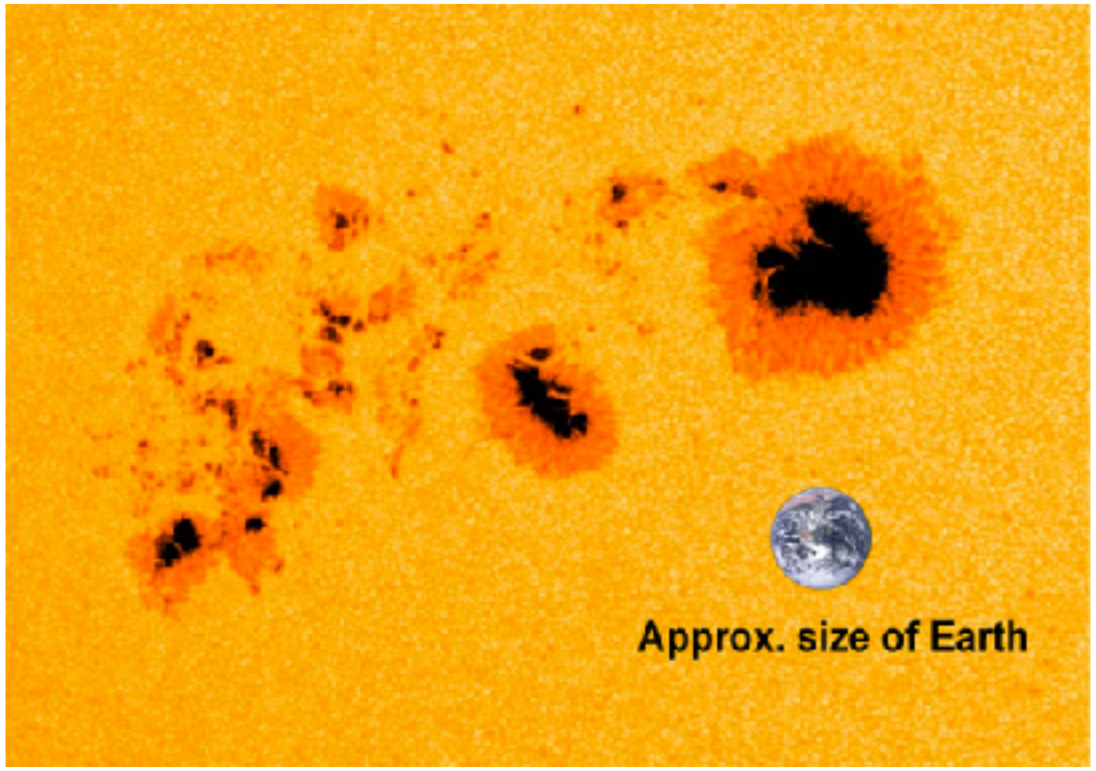
SUNSPOTS



From ground we can image the photosphere in white light. The Sun then appears as a rather dull yellow ball, but sometimes shows dark spots called sunspots.

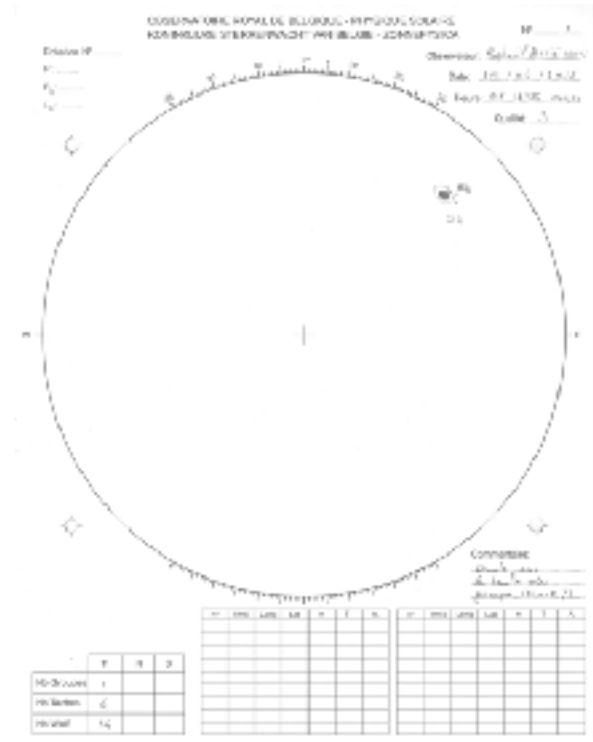
Sunspots ar relatively dark area's on the solar surface that indicate cooler regions in the solar photosphere. These area's are slightly cooler compared to their surroundings because the intense magnetic fields in these regions inhibit the convection of plasma. This means that the heat that is produced in the core of the Sun is radiated outwards less efficiently in these locations, and thus they are somewhat cooler and appear dark. Note that sunspots are still very hot: their dark core has a temperature of ~4000K, while the bright photosphere has one of ~5800K.

Sunspots appear, change and evolve and then disappear again in time spans of days up to months. They usually come in pairs, each with a different polarity. The number of sunspots on the solar disk is an important measure of solar activity.



Sunspots are huge!

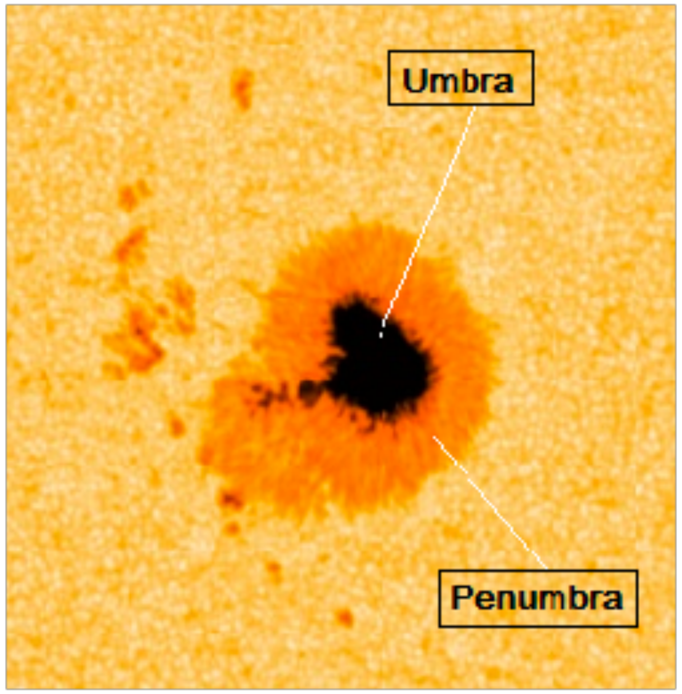
DRAWINGS



The Royal Observatory of Belgium hosts the World Data Center for the production, preservation and dissemination of the international sunspot number. (http://sidc.oma.be/silso/)

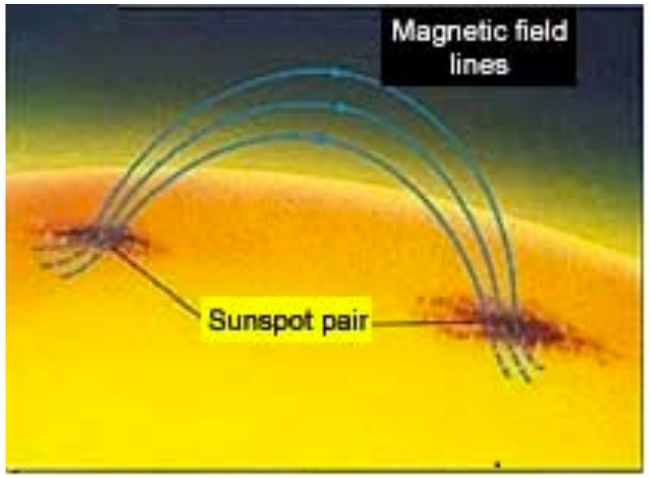
Each day (when weather permits) we make drawings of the sunspots that are seen on the solar disk. At ROB we have done this since 1955, but sunspot records go back centuries. Some very big sunspots were observed with the naked by the ancient Greeks, but systematic observations began when the telescope was invented (think e.g. of Galileo Galilei)
This long record allows us to study the evolution of solar activity over very long time scales. We now have satellites with much clearer observations of this activity, but to be able to properly correlate current with older observations, we keep on making drawings.

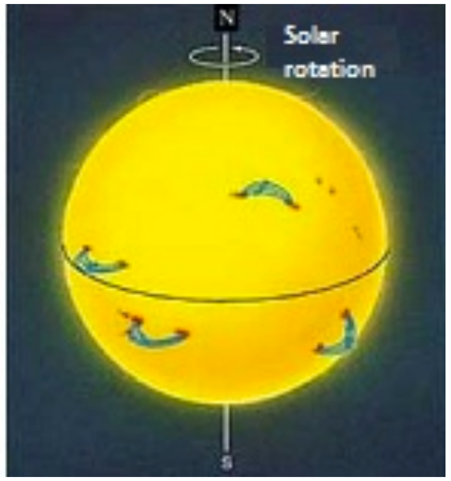
NOMENCLATURE



Often two distinct regions can be seen in a sunspot: the dark core called the umbra (shadow in Latin) and the slightly less dark surroundings, called the penumbra.

MAGNETIC FIELD



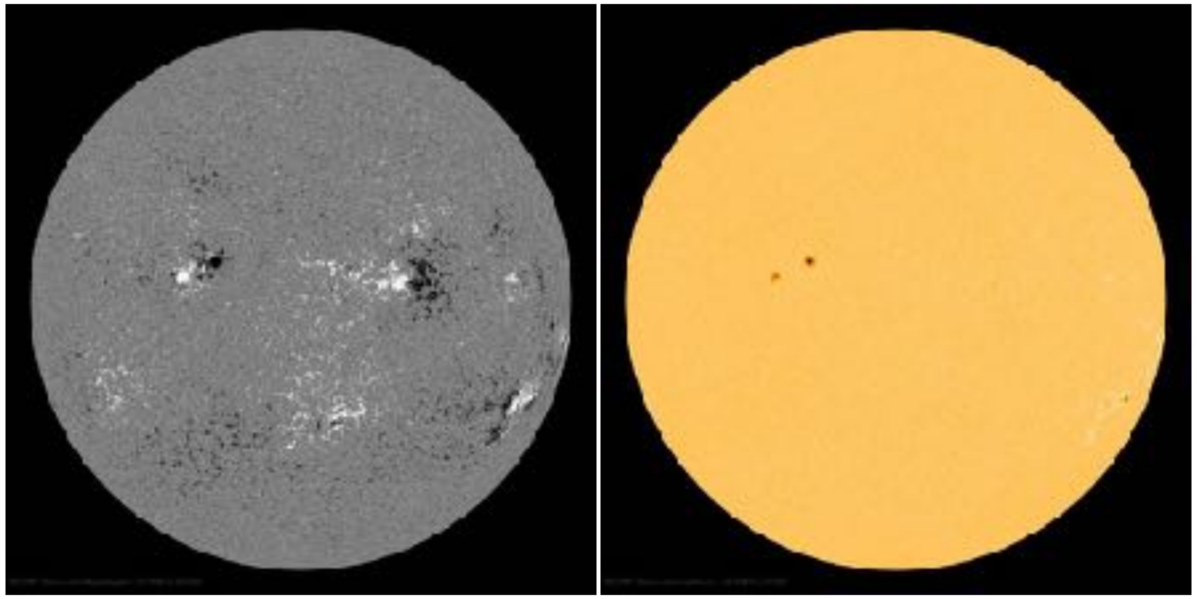


The solar magnetic field lines are made visible by the plasma that is attached to them (frozen in theorem). Think of the typical physics experiment where you can trace the fields lines of a magnet with iron filings.

The magnetic field lines connect the different polarities (From the positive to the negative pole).

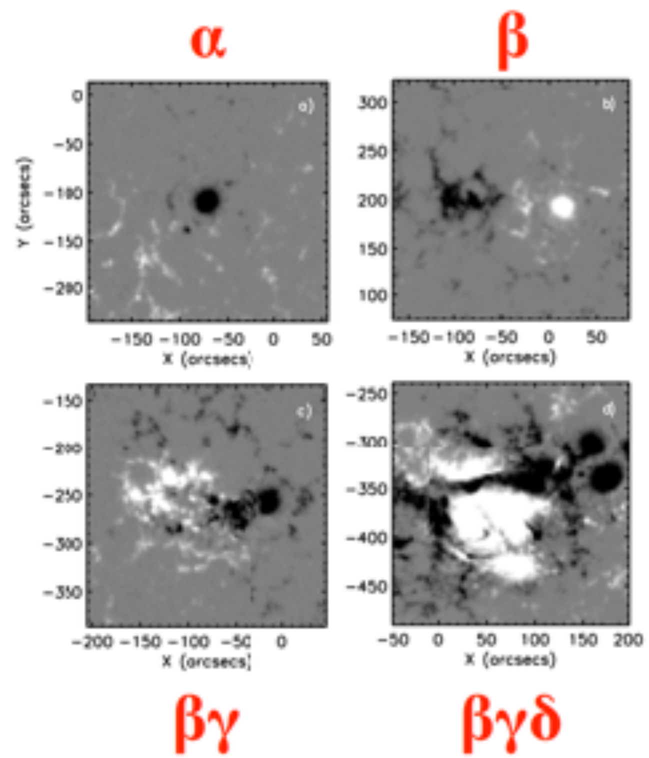
MAGNETOGRAM

SDO/HMI



A magnetogram images the strength of the magnetic field. When you compare them to the photospheric images you can clearly see the relation between magnetic field strength and the sunspots: sunspots are regions of very strong magnetic field.

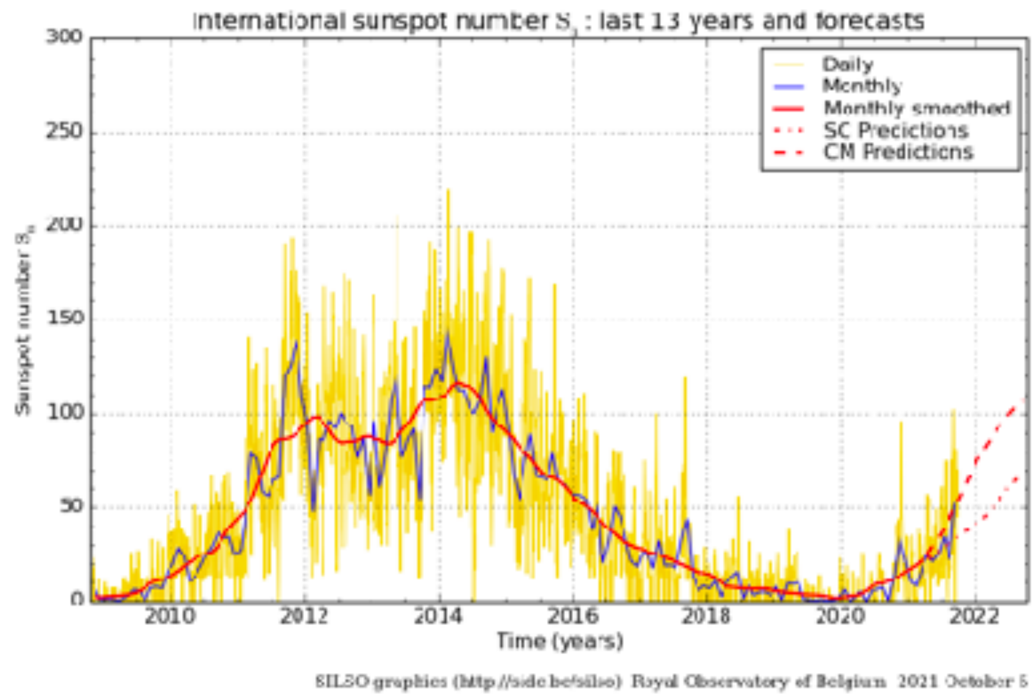
SUNSPOT COMPLEXITY



Sunspots can show a variety of complexity. From a single polarity spot to a monster region where polarities are intermixed. There are various systems in place to classify sunspots, which we will discuss later. Know for now that the complexity of a sunspot is related to its likelihood to produce significant solar activity.

SUNSPOT NUMBER AND SOLAR CYCLE

$$R = K\,(10g + s)$$



Every day we count the number of sunspots, combining different observations on different locations and correcting for the specifics of the observations. This is a weighted count: one single sunspot has much less weight than a complex group (the complex group is much more likely to cause activity).

The relative sunspot number is defined as R = K (10g + s), where g is the number of sunspot groups and s is the total number of distinct spots. The scale factor K (usually less than unity) depends on the observer and is intended to convert the observation back to the scale originated by Wolf in 1848. This weighing factor combines corrections for the observer, location, and instrumentation.

Combining all observations leads to a daily sunspot number. When we plot this number over time, we see a clear cyclical behaviour. The solar activity, for which the sunspot number is a proxy, increases and decreases over a time span of approximately 11 years. This is called the solar cycle.

The red lines indicate different predictions for the behaviour of the next solar cycle. As you can see, there is quite some discrepancy/uncertainty for the various predictions.

THE 10.7CM RADIO FLUX

Measured at Penticton, Canada

STAFF viewer, http://www.staff.oma.be

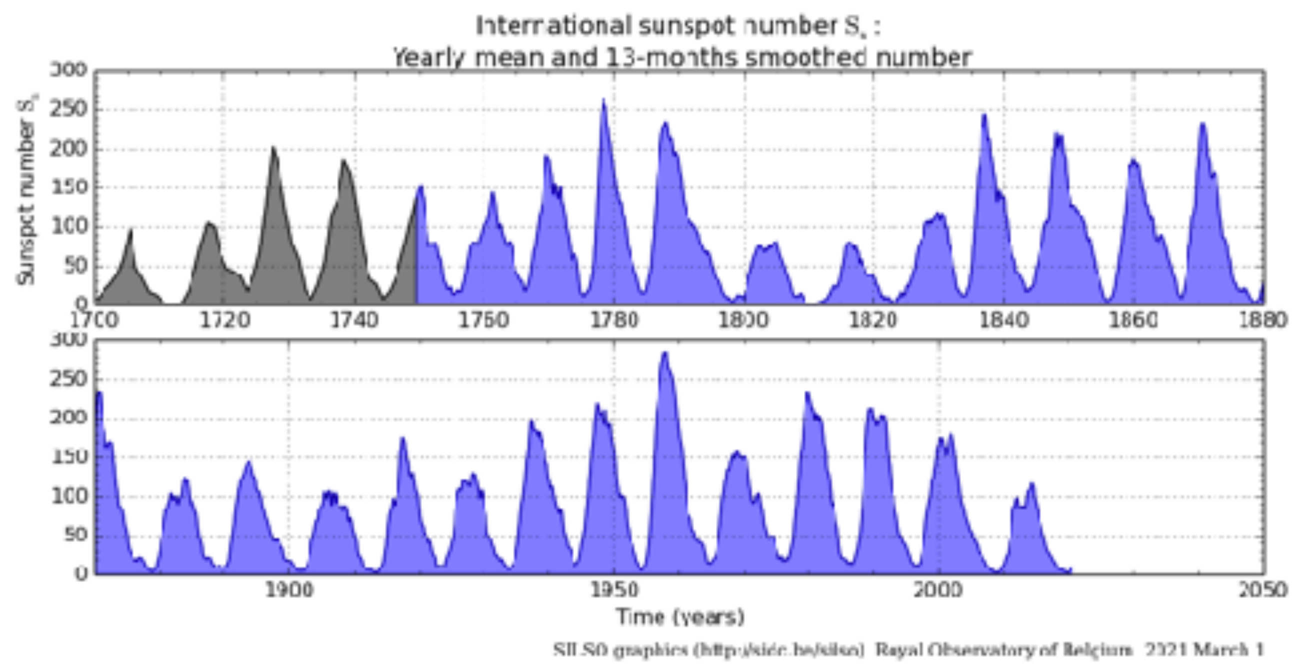
A 10.7 cm solar flux measurement is a determination of the strength of solar radio emission in a 100 MHz-wide band centered on 2800 MHz (a wavelength of 10.7 cm), averaged over an hour. It is expressed in solar flux units (sfu), where 1 sfu = 10-22 W m-2 Hz-1.
The F10.7 is well correlated with the sunspot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

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.

See notes at:
STCE news item: http://www.stce.be/news/374/welcome.html
SWS: http://www.sws.bom.gov.au/Educational/2/2/5
SWS: http://www.sws.bom.gov.au/Educational/2/2/6

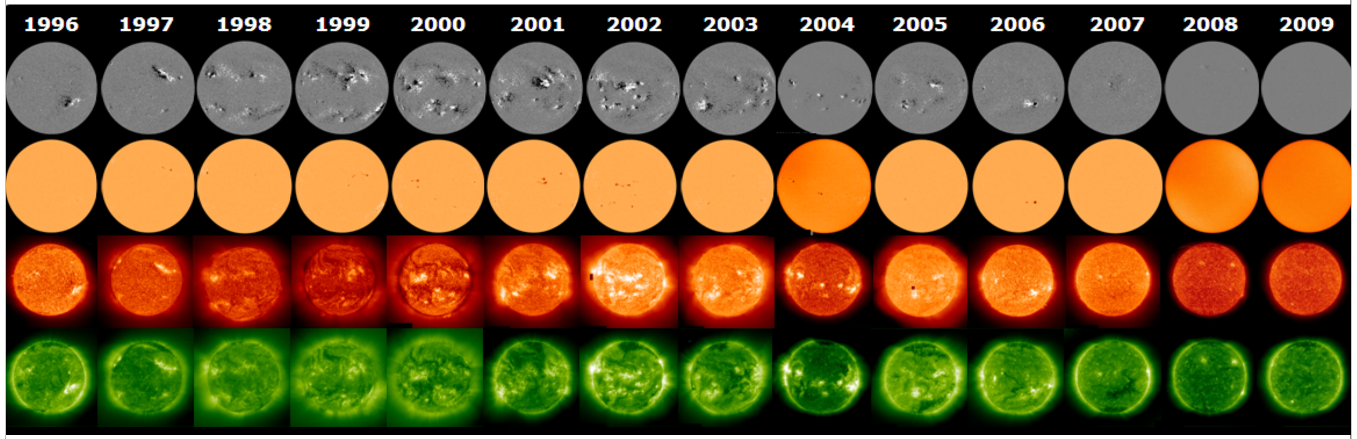
Tapping, K. (2013): The 10.7 cm solar radio flux ($F_{10.7}$)
http://adsabs.harvard.edu/abs/2013SpWea..11..394T

LONG TERM SOLAR ACTIVITY



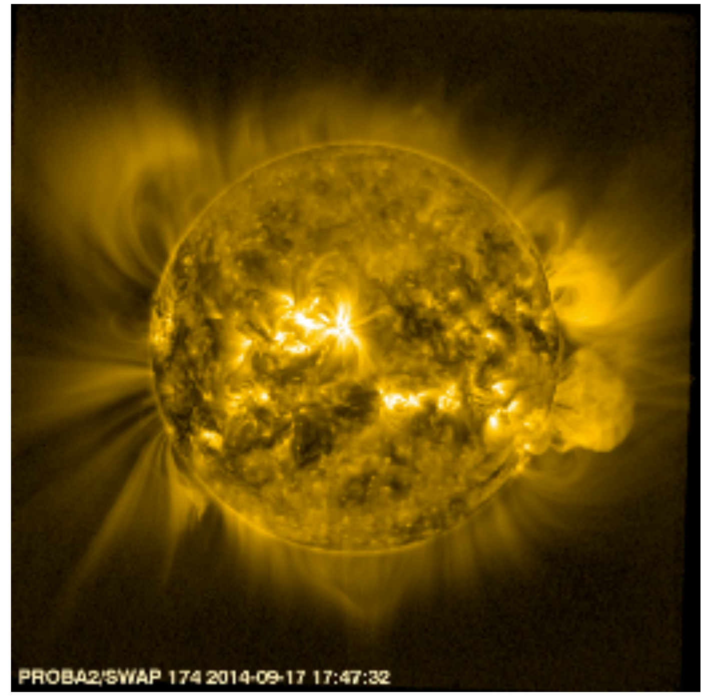
This graph shows you the solar activity over the last three centuries. Clearly, there is a large variation in solar cycles, some are shorter that others (more narrow), some are much stronger than others (higher).
To create this type of graph, we rely heavily on the old sunspot drawings as these are our main indication of how active the Sun was in the distant past.

SOLAR CYCLE



This composition illustrates a solar cycle as seen in various wavelengths. As the magnetic complexity increases (see the magnetograms), also the number and size of active regions in EUV wavelengths and the number of sunspots in white light images increases.

SOLAR ACTIVITY WITH SWAP



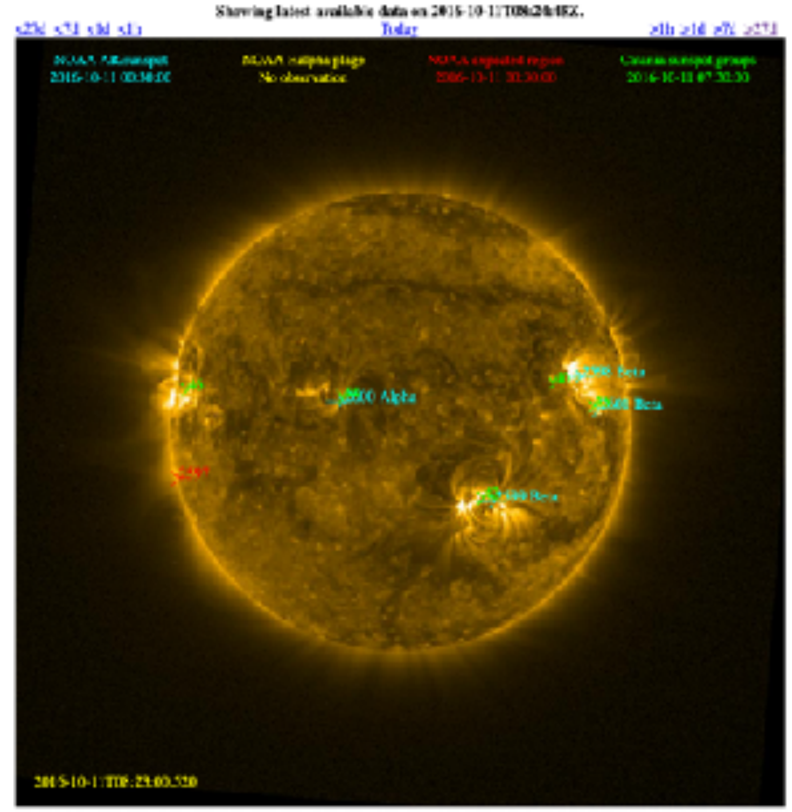
PROBA2/SWAP

This is a movie made with images from the SWAP telescope onboard the PROBA2 satellite. It shows the solar corona at 174 A over a time period of one solar rotation (so approximately a month).

Clearly, the Sun is no longer that quiet yellow ball, but is bursting with activity. We see flashes of light, plasma being hurled away from the Sun, field lines, darker and brighter regions, … These are the main ingredients of what we call space weather.

https://proba2.sidc.be/swap/data/mpg/movies/carrington_rotations/swap_cr_2155_yellow.mp4

ACTIVE REGION NUMBERING



PROBA2/SWAP

An active region is an area on the Sun with especially strong magnetic field. In white light images we often see sunspots on these locations, in EUV it is a bright region with visible plasma loops.

Active regions are numbered by the US National Oceanic and Atmospheric Administration (NOAA). The present numbering system started on January 5, 1972, and has been consecutive since then. An example of an active region "name" is "AR5128" (AR for Active Region) or "NOAA Region 5128". Since we only see active regions when they are on the side of the Sun facing the Earth, and the Sun rotates approximately once every 27 days (the equator rotates faster than the poles), the same active region may be seen more than once (if it lasts long enough). In this case the region will be given a new number. Hence, a long-lived active region may get several numbers.
On June 14, 2002, active region number 10000 was reached. For practical, computational reasons, active region numbers continue to have only four digits. Therefore, the sequence of numbers is 9998, 9999, 0000, 0001, and so on. Active region number 10030, for example, is AR0030. This region will often simply be referred to as region number 30, with 10030 implied.

The Catania solar observatory also names regions with sunspots. This sunspot group number can usually be linked to a NOAA AR number, however, sometimes there is an active region without a visible sunspot, or a sunspot without a clear counterpart in EUV. There is no one to one correlation.

http://sidc.oma.be/spaceweatherservices/solarmap/

Source: https://hesperia.gsfc.nasa.gov/sftheory/questions.htm#AR_numbers

FLARE

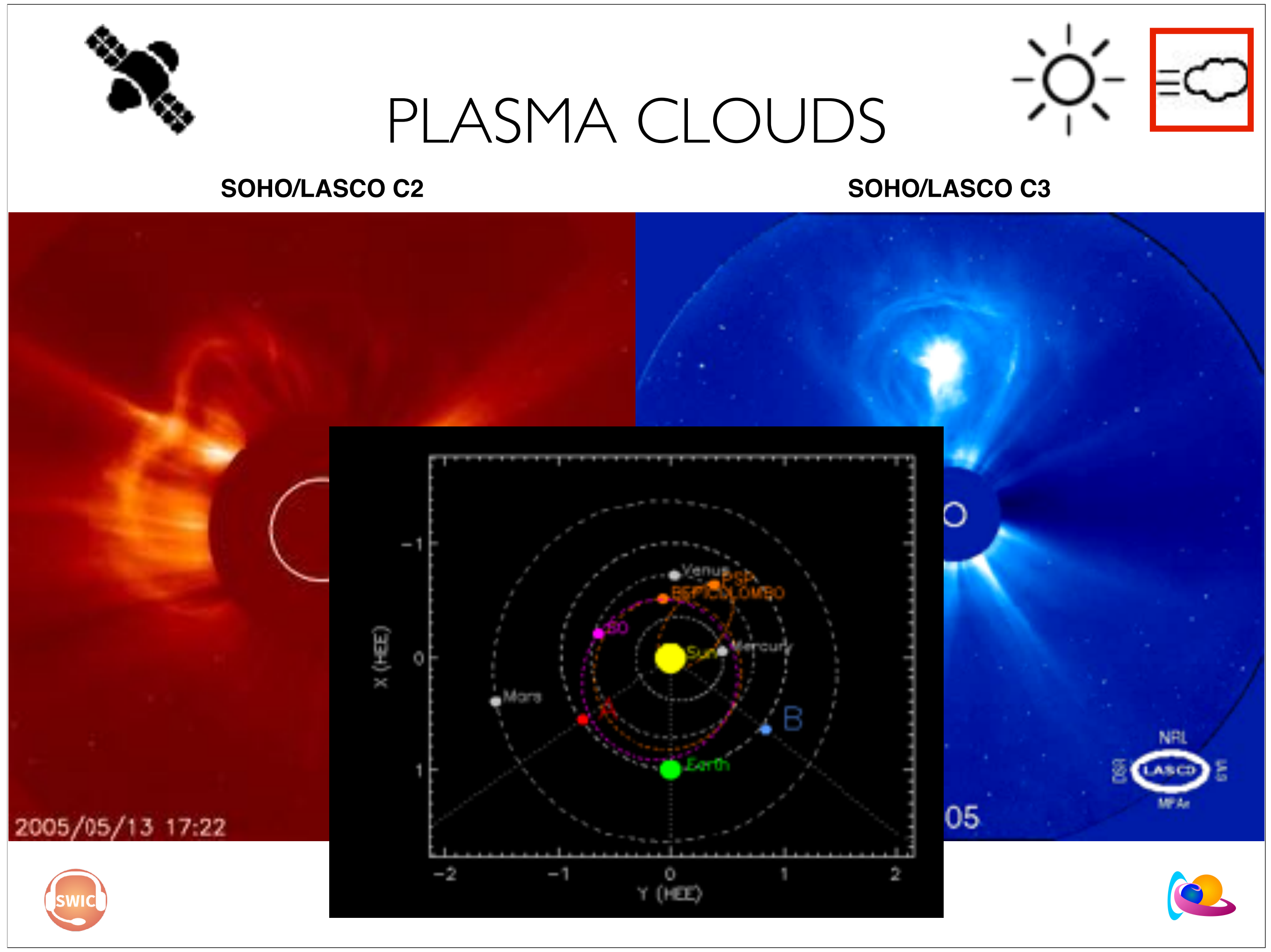
CORONAL MASS EJECTION

CORONAL HOLE

SOLAR ENERGETIC PARTICLES

INGREDIENTS OF SPACE WEATHER

The Sun as a magnetic structure



These coronagraph images show coronal mass ejections (CMEs) which are huge clouds of highly energised plasma that are hurled away into space. When these are directed towards Earth, they may have all kinds of space weather effects.

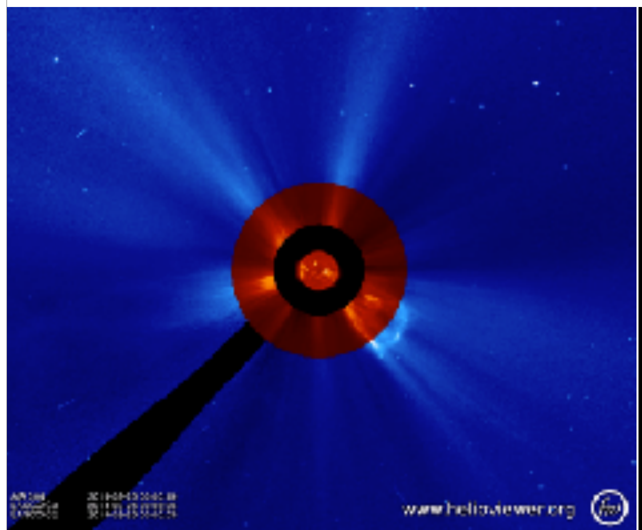
A coronagraph is a telescope with a plate that covers the Sun to block the overpowering light of the solar disk. This allows us to image the solar surroundings, it's corona. The white circle in the middle indicates the position and size of the Sun. A coronagraph creates an artificial eclipse, allowing us to study the far corona without having to wait and travel for an eclipse that can be observed from ground.

How can we know the direction these clouds are travelling in? Look at the shape in the picture and think of a balloon that is being blown. When you look straight at it, you see it expand in all directions, as in the picture on the left. When you look from the side, and the balloon is dus not expanding towards you, it looks more like the picture on the right.

To really be able to estimate the direction and speed of CMEs we need observations from two different view points. This is where the STEREO A and STEREO B spacecraft come in. These spacecraft are in the same orbit as Earth, but one is lagging behind, while the other is ahead of Earth. This is how we can get a side view of plasma clouds. Unfortunately, contact with STEREO B was lost on October 1, 2014.
https://stereo-ssc.nascom.nasa.gov/where.shtml

Very fast plasma clouds may bridge the distance from Sun to Earth in less than a day. These are exceptional, fortunately. Most often plasma clouds take around 3 days to reach us, the slow ones up to 5 days.

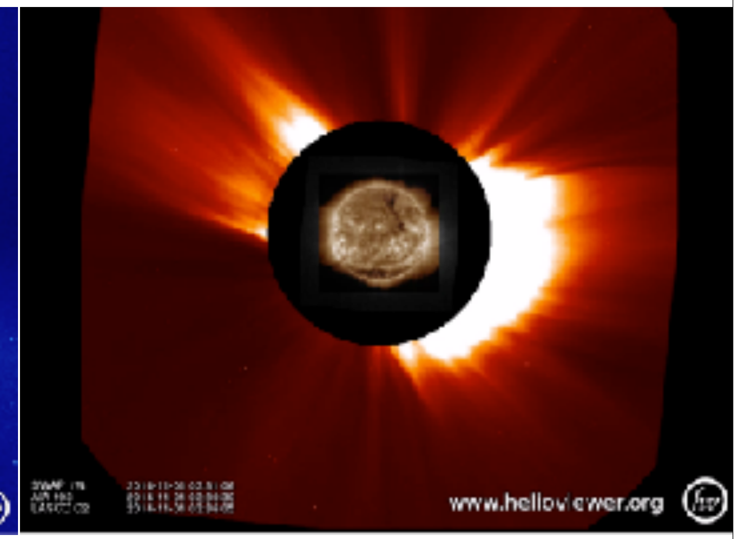
PLASMA CLOUDS



SDO/AIA

SOHO/LASCO C2

SOHO/LASCO C3



SDO/AIA

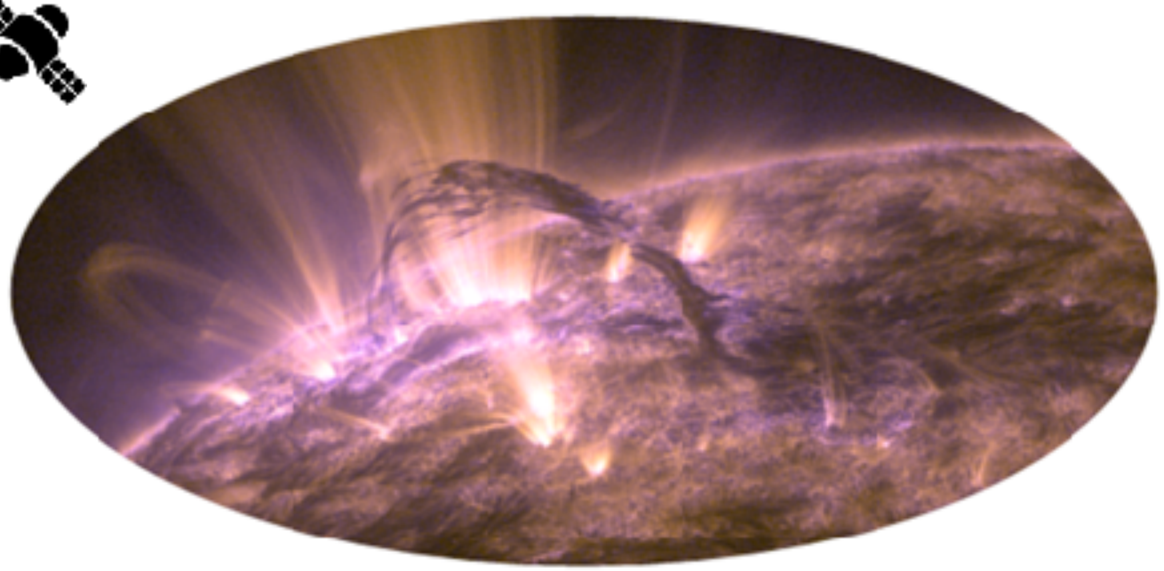
PROBA2/SWAP

SOHO/LASCO C2

Combining images allows us to relate the events on the solar disk to what we see in the different coronagraphs (that image different regions in the heliosphere).

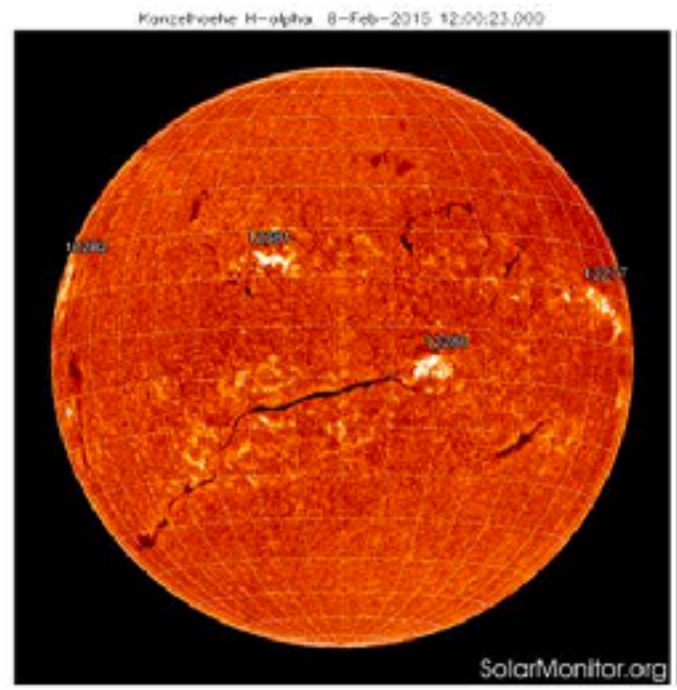
PROMINENCE

SDO/AIA



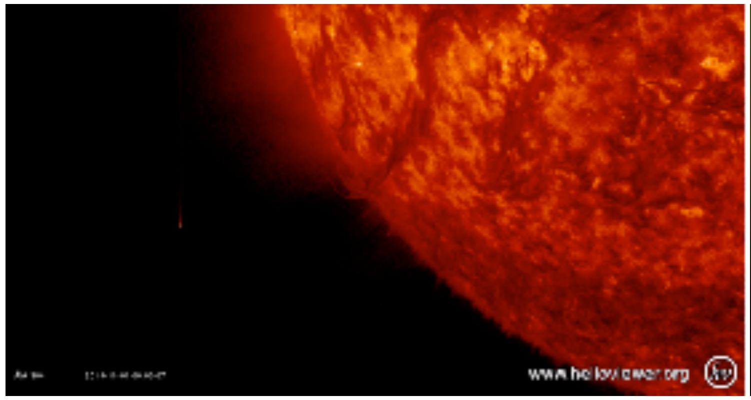
A prominence or filament is a dark loop seen on the edge of the Sun. It shows you the loops of the magnetic field due to the plasma that is glued to it. Filaments appear dark because they are slightly colder than their surroundings. A filament is not made of one single magnetic field line, rather it is a bundle of strands that are entangled.

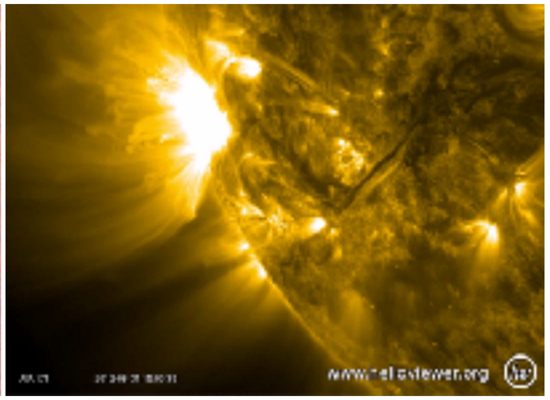
FILAMENT



When prominences are observed face on, they look like dark snake-like structures on the solar disk, and they were called filaments. Both are names for the same feature. When a filament becomes unstable and erupts due to reconnection of its magnetic field, its is hurled into space and takes the plasma with it, forming a plasma cloud or coronal mass ejection.

FILAMENT AND CLOUD



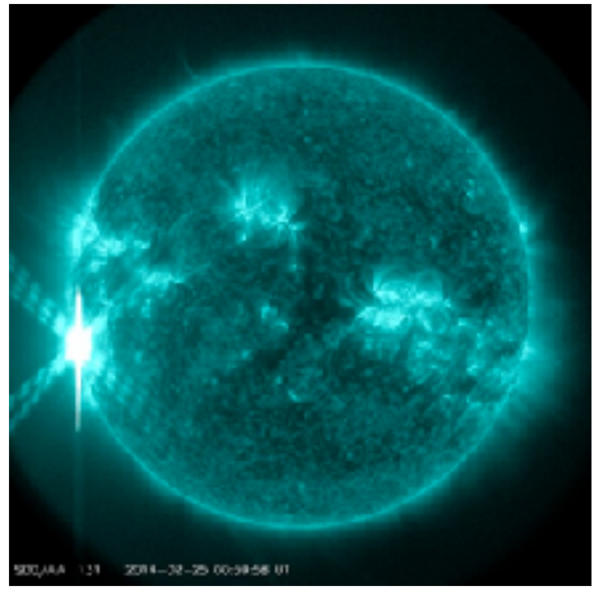


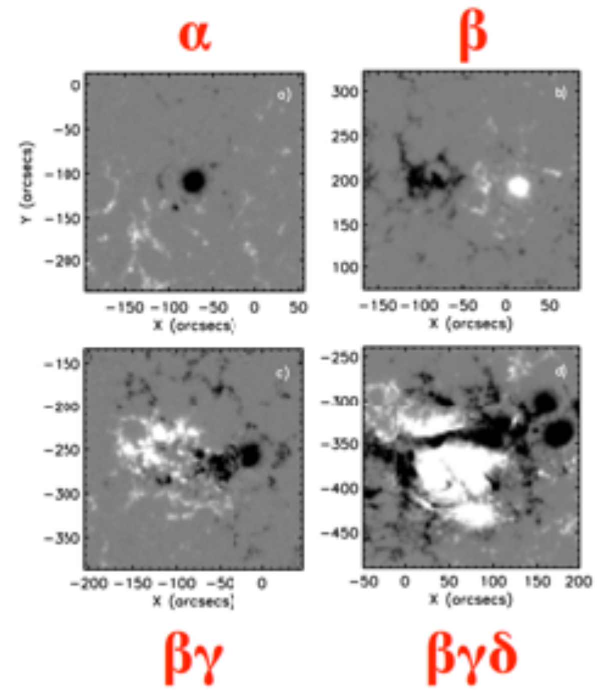
SDO/AIA

These movies are close-ups of erupting filaments. You see that the filament start to move, becomes unstable and eventually erupts, dragging the plasma that is glued to the magnetic field lines with it, forming a plasma cloud.

FLARES

SDO/AIA

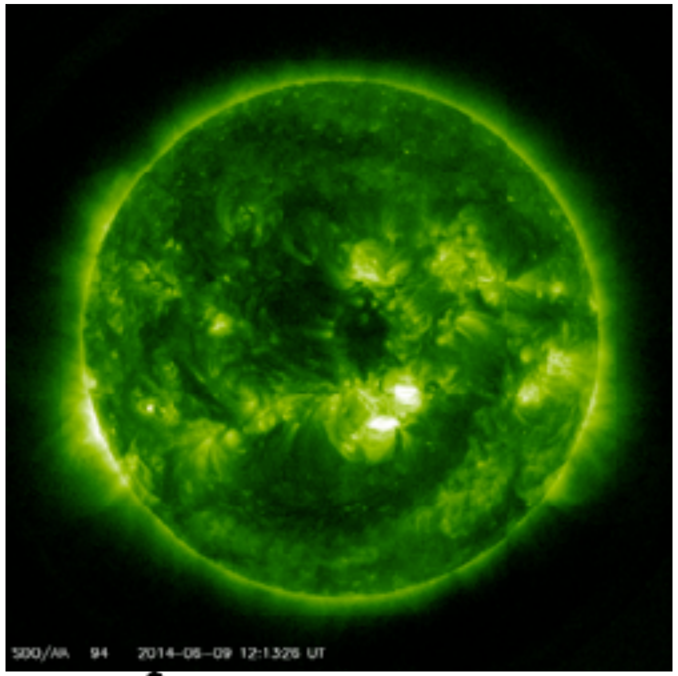




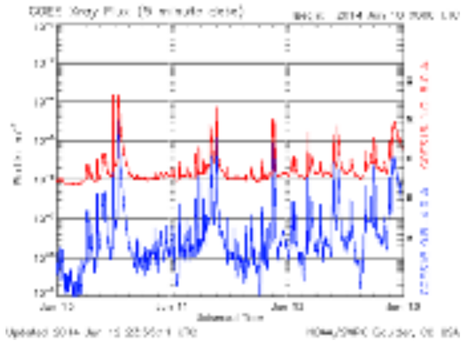
A solar flare is a bright flash of light, caused by a reconfiguration of the solar magnetic field. This so-called reconnection can also send a plasma cloud into space. Solar flares and coronal mass ejections often, but not always, form part of one event.

Chances for a strong flare are highest when the Sun is very active. Solar flares often occur in regions with rapidly changing and complex magnetic field, which we can see in the magnetogram observations.

FLARE OBSERVATION



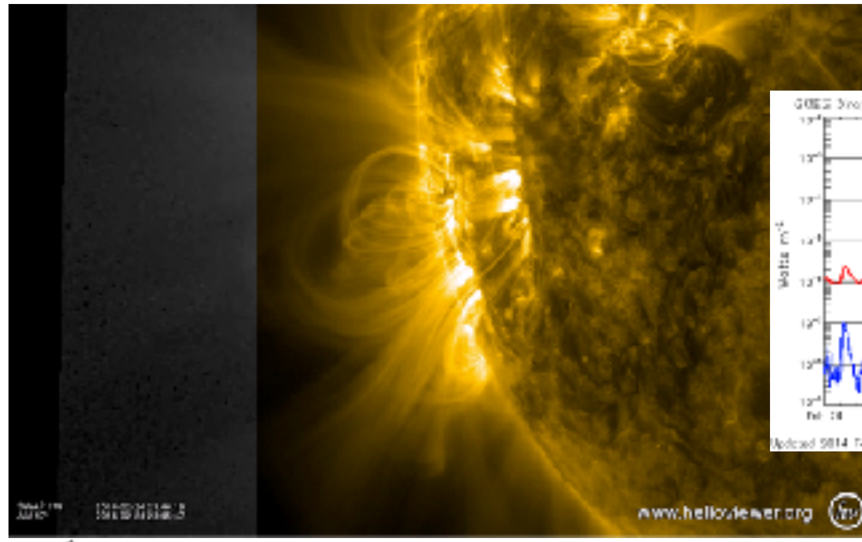
SDO/AIA

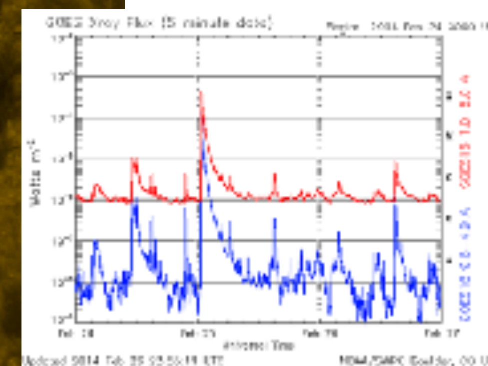


GOES

This movie show a very active period with many M-class flares as measured by the GOES satellite. Remember that the solar flare radiation only takes 8 min to arrive at earth.

FLARE AND PLASMA CLOUD





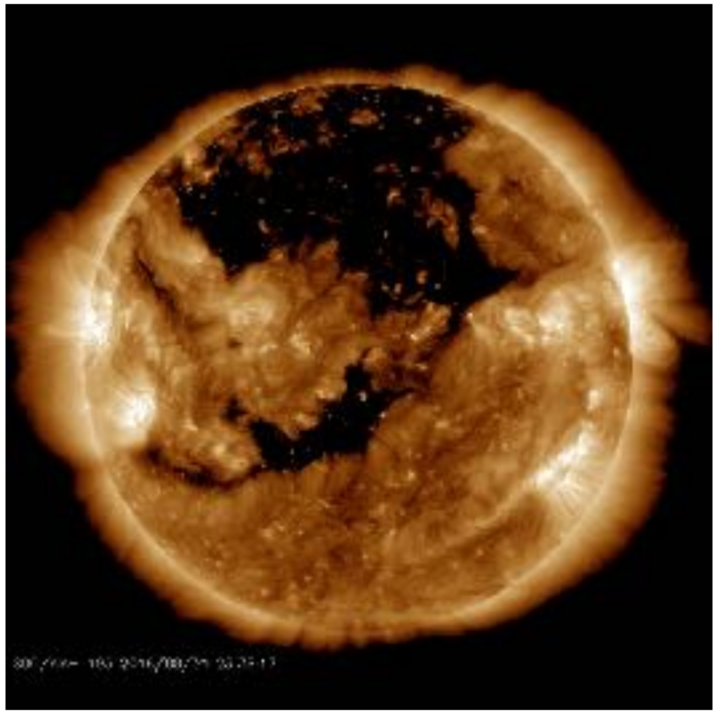
SDO/AIA
PROBA2/SWAP

GOES

A solar flare is a bright flash of light, caused by a reconfiguration of the solar magnetic field. This so-called reconnection can also send a plasma cloud into space. Solar flares and coronal mass ejections often, but not always, form part of one event.

CORONAL HOLE

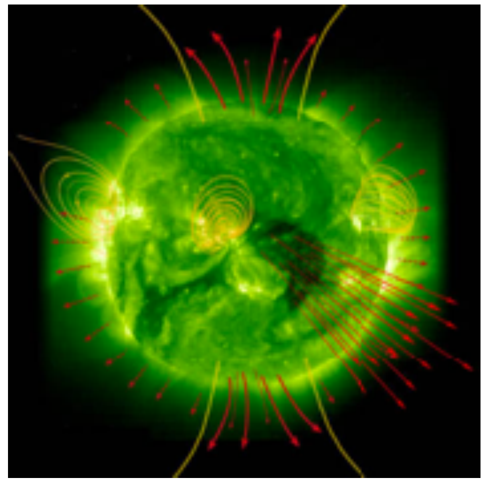
SDO/AIA

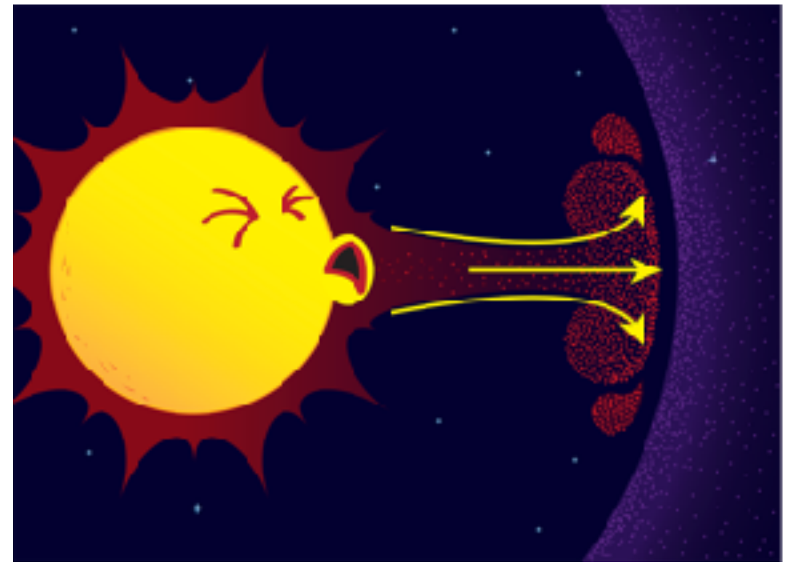


A coronal hole is a structure in the solar corona that you see as a black area in the EUV. In these regions, the magnetic field in less strong and the magnetic field lines are open, which allows plasma to escape.
There is thus less plasma present to radiate and the region appears black in images.

SOLAR WIND

SOHO/EIT



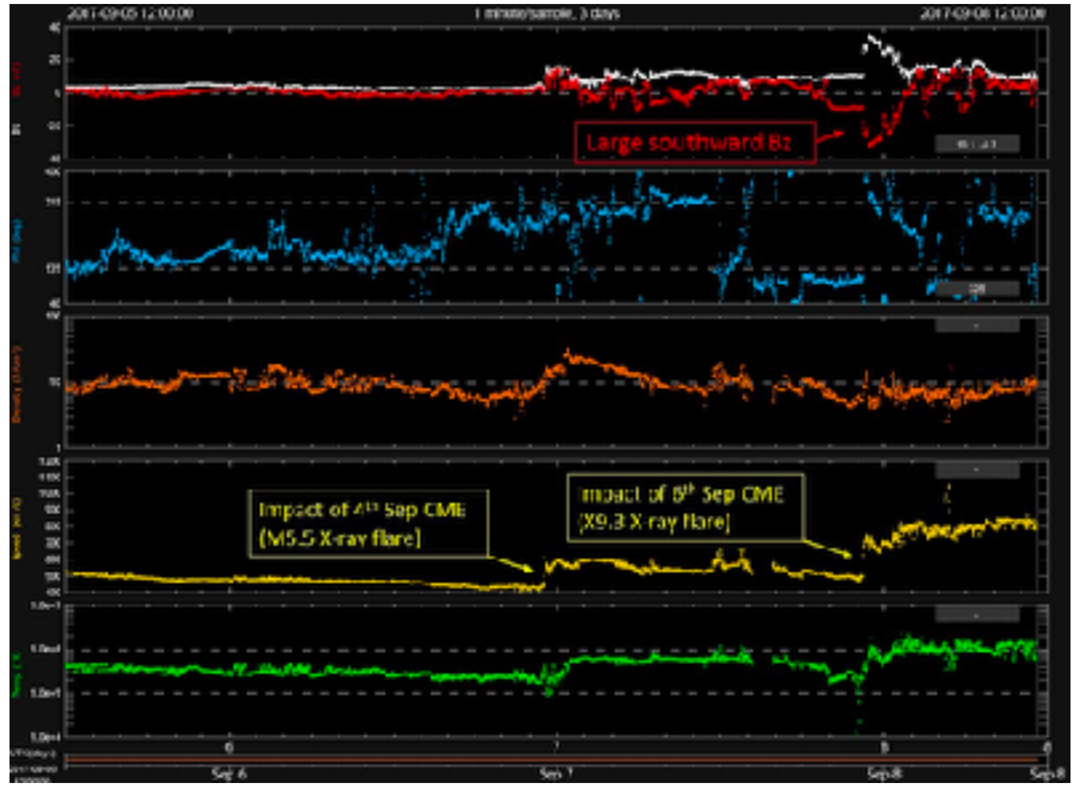


The magnetic field lines of a coronal hole fan out into space, there are no closed magnetic loops above. This gives rise to a solar wind that is faster (~800 km/s) than the regular solar wind (~450 km/s).

In determining how strong the impact of a coronal hole will be, the latitude of the coronal hole on the solar disk is important. It is the plasma that leaves at the central meridian that will reach Earth. Polar coronal holes only have an impact when they extend to lower latitudes.

DSCOVR

SOLAR WIND

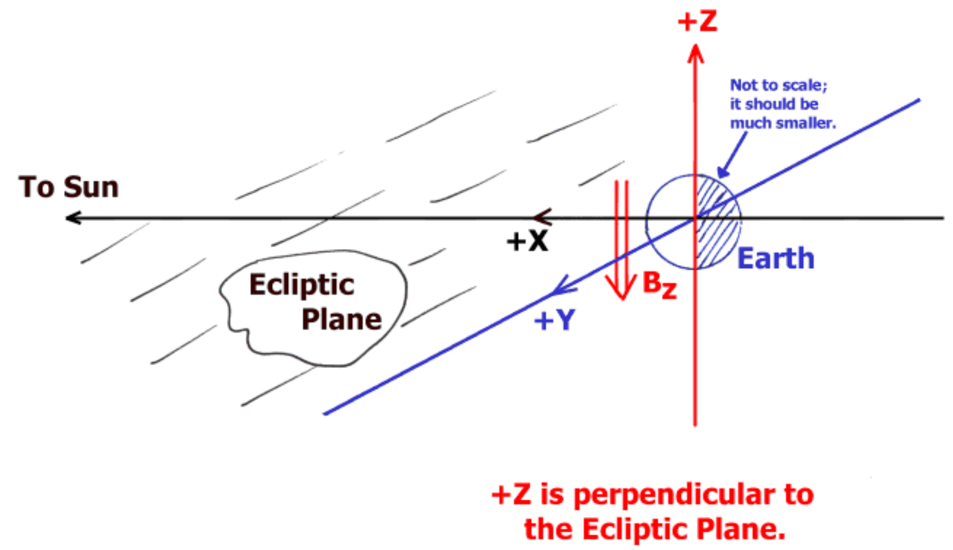


These measurements are made by the DSCOVR satellite. They characterise the solar wind.
From top to bottom there are measurements of: the magnetic field, the phi angle, the density, the speed, and the temperature.

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.

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

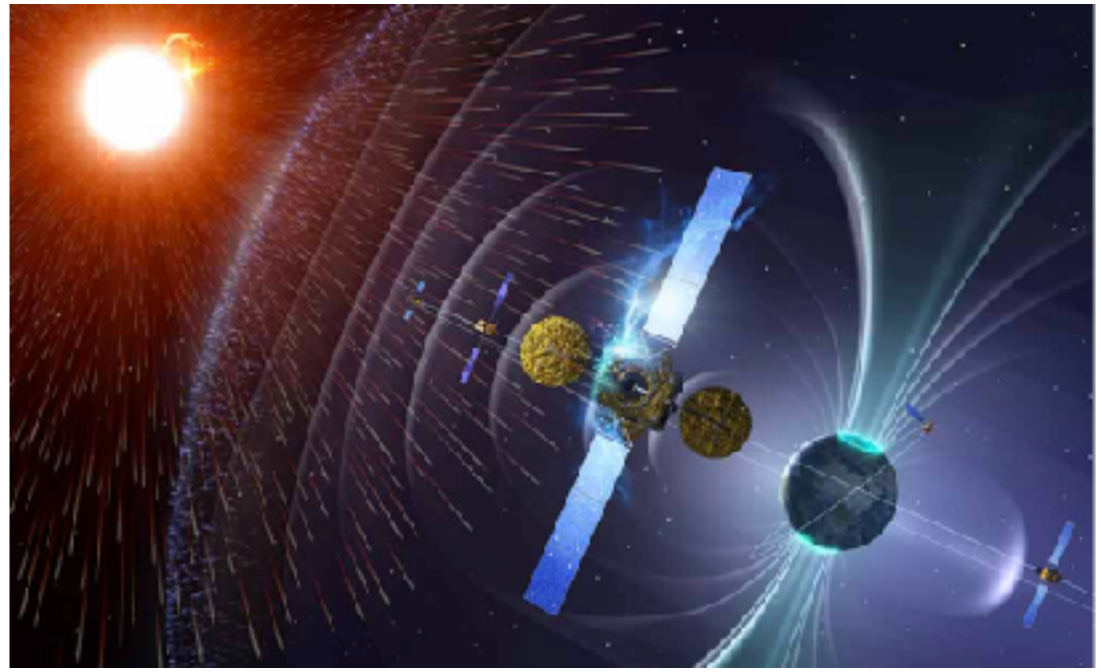
COORDINATE SYSTEM



The coordinate system used for solar wind observations is GSE: the Geocentric Solar Ecliptic system. This system has its X-axis pointing from the Earth toward the Sun and its Y-axis is chosen to be in the ecliptic plane pointing towards dusk (thus opposing planetary motion). Its Z-axis is parallel to the ecliptic pole. Relative to an inertial system this system has a yearly rotation.

The most important thing to remember is the Bz parameter. Whenever Bz is negative (downwards pointing magnetic field), the magnetic field in the solar wind can reconnect with the Earth's magnetic field, leading to a geomagnetic storm.

ENERGETIC PARTICLES

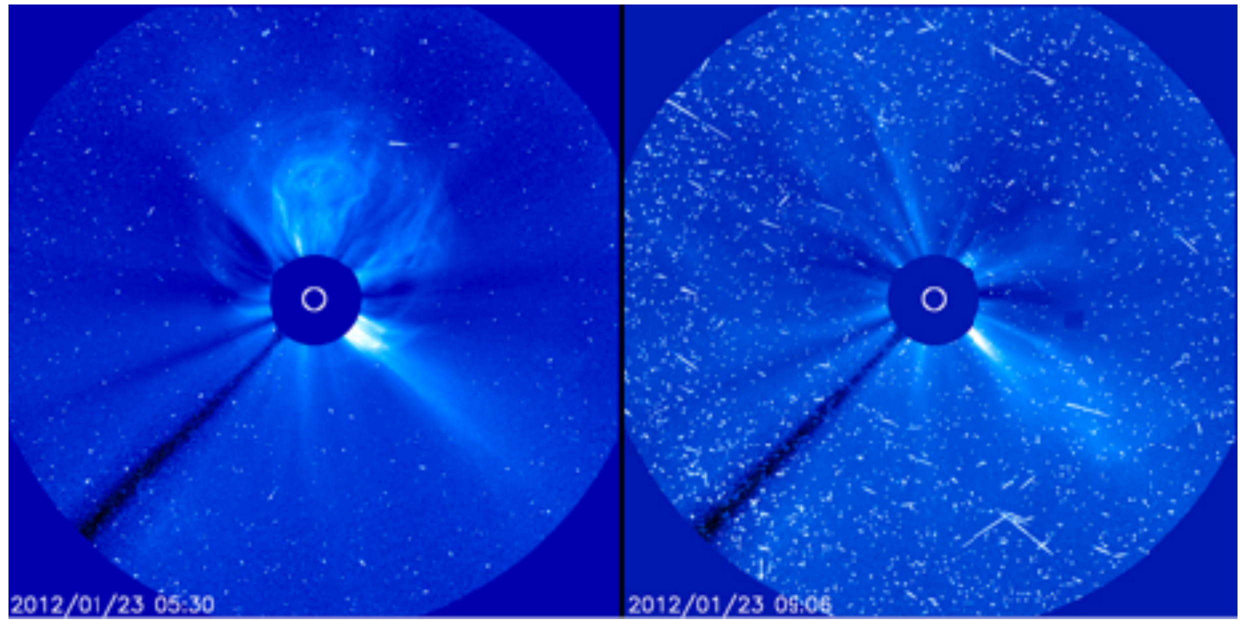


Along with the ejected plasma, highly energetic and very fast particles may escape into space during a solar eruption. Because they are charged particles, they follow the interplanetary magnetic field lines.

Solar radiation storms occur when a large-scale magnetic eruption, often causing a coronal mass ejection and associated solar flare, accelerates charged particles in the solar atmosphere to very high velocities. The most important particles are protons which can get accelerated to 1/3 the speed of light or 100,000 km/sec. At these speeds, the protons can traverse the 150 million km from sun to Earth in just 30 minutes.

PARTICLE IMPACT

SOHO/LASCO C3



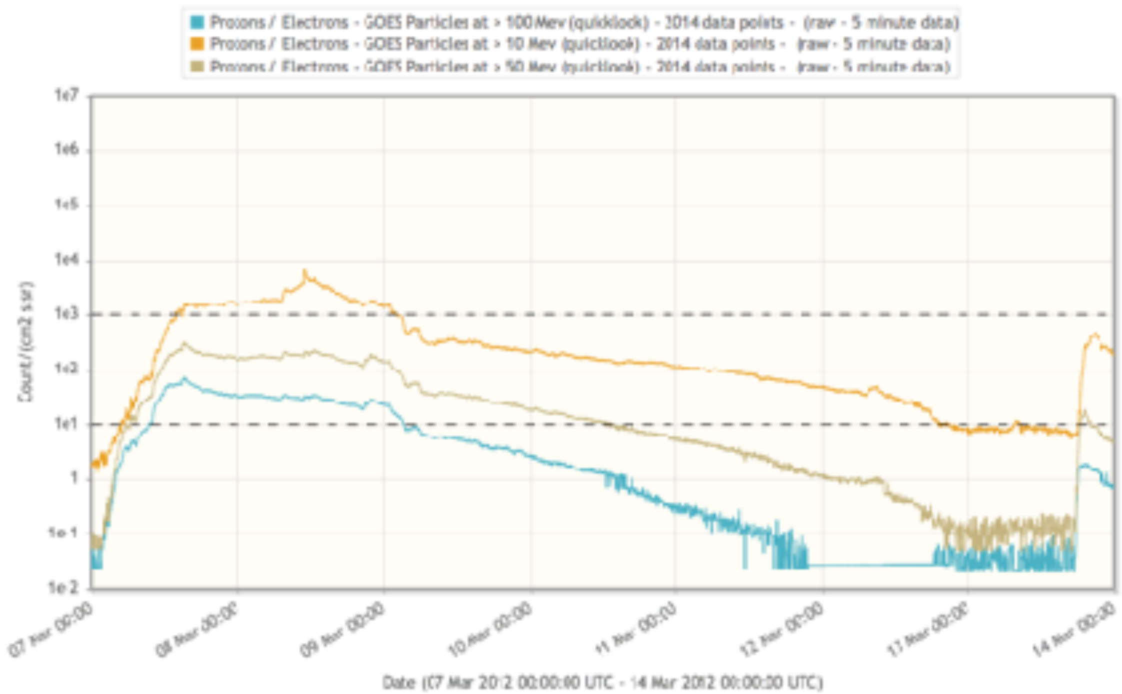
Here are two examples of where coronagraph observations were impacted by high energetic protons. These are a sure indication that the plasma cloud is headed our way.

Energetic particles may impact/damage satellites and their instruments. They are seen as white stripes and dots: these 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 locally. Remote sensing indicates that you look at something from a distance.)

GOES

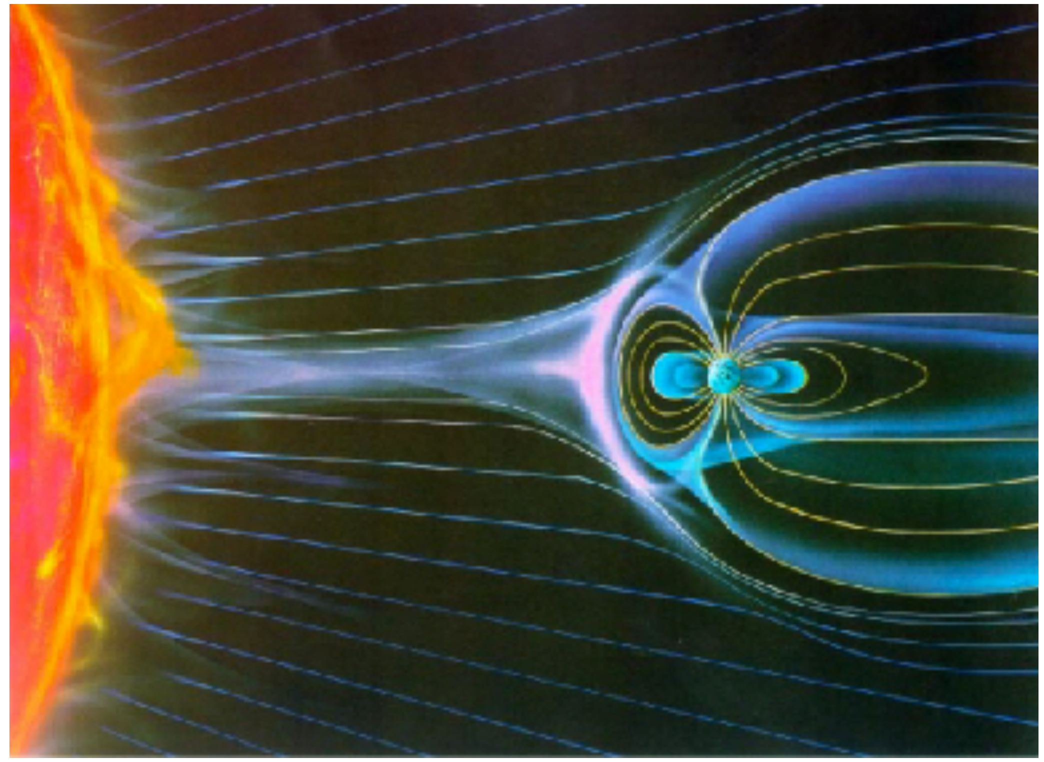
MEASURED BY GOES



The GOES satellite is a geostationary satellite that measures the protons at different energy levels.
http://www.swpc.noaa.gov/products/goes-proton-flux

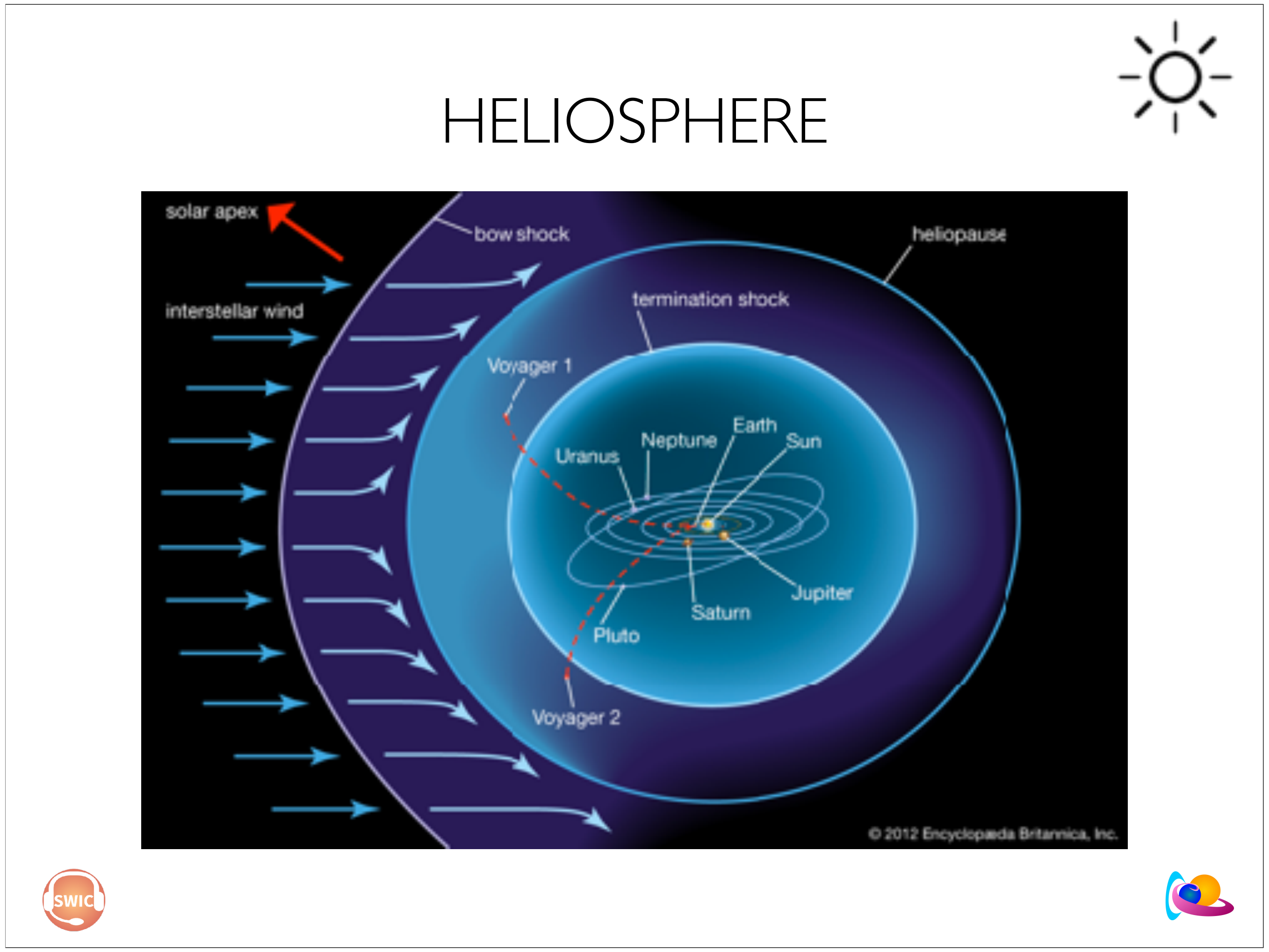
The protons may be accelerated by a the shock of a coronal mass ejection (gradual event) or a flare (impulsive event). Some solar energetic particle events have two peaks- a prompt one arriving 10s to minutes after the solar activity, and a second one, arriving with the interplanetary CME shock.

MAGNETOSPHERE



This image shows that we are somewhat protected from the solar activity by the Earth's magnetosphere. Due to the solar wind, the sun-facing side of the Earth's dipole is compressed and the other side is stretched into a long magnetotail.
In front of the Earth's magnetosphere, there is a shock region, very similar to the shock in front of a fast boat moving in the water.

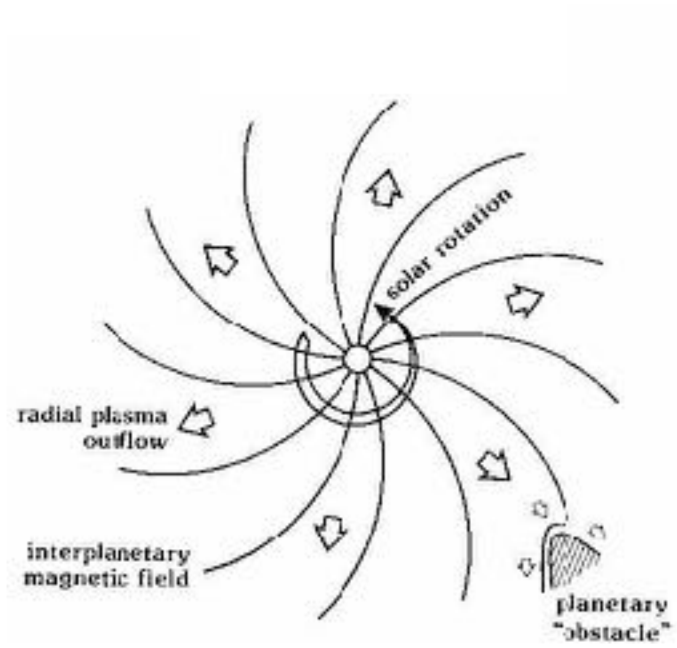
A magnetic field is embedded in the solar wind. This magnetic field can interact with the magnetic field of the Earth at the boundaries of the Earth's magnetosphere. This interaction is called reconnection and only happens when the magnetic fields of Earth and that of the solar wind are oppositely directed, causing a geomagnetic storm.



The heliosphere is the region surrounding the Sun and the solar system that is filled with the solar magnetic field and the protons and electrons of the solar wind.

The solar wind flows outward through the solar system into the interstellar medium (ISM) and begins to feel the effects of the ISM at the termination shock, where the solar wind starts to lose speed. The region beyond the termination shock in which the solar wind slows is called the heliosheath. At the outward boundary of the heliosheath is the heliopause, where the outward pressure of the solar wind balances the pressure of the incoming ISM. The heliopause is usually considered to be the boundary of the solar system and is about 123 astronomical units (AU; 1 astronomical unit = 150 million km) from the Sun. (By comparison, Neptune, the outermost planet, is 30 AU from the Sun.)
(https://www.britannica.com/science/heliosphere)

INTERPLANETARY MAGNETIC FIELD

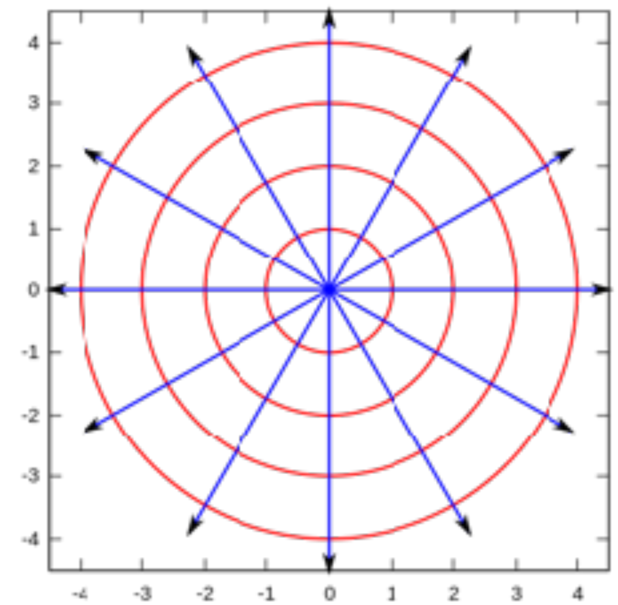


The interplanetary magnetic field (IMF) is the component of the solar magnetic field that is dragged out from the solar corona by the solar wind flow to fill the Solar System.

Because the Sun rotates (once every 27 days) the interplanetary magnetic field has a spiral shape -- named the "Parker spiral", after the scientist who first described it.

Indeed, the magnetic field stays connected to the Sun because of the frozen-flux theorem: the magnetic field and the plasma are glued together. The footpoints of the magnetic field lines are attached to the Sun. As the Sun rotates, the interplanetary magnetic field is forced to bend.

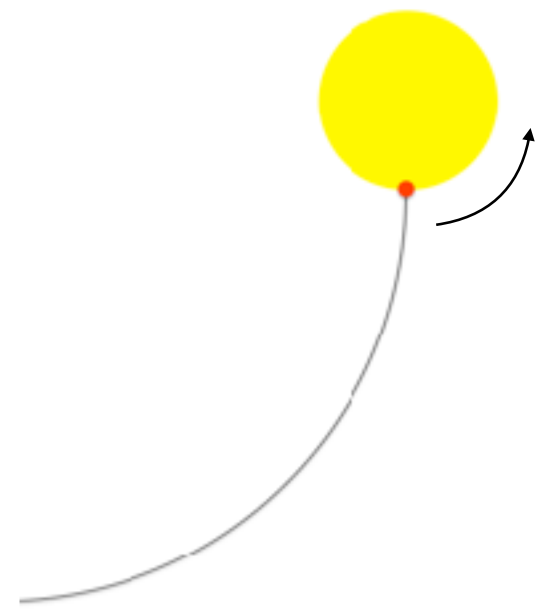
RADIAL SOLAR WIND



The solar wind carries out solar material and solar magnetic field. The solar material and magnetic field become less dense further away from the Sun. Near Earth, the interplanetary magnetic field still controls the solar wind and its movement.

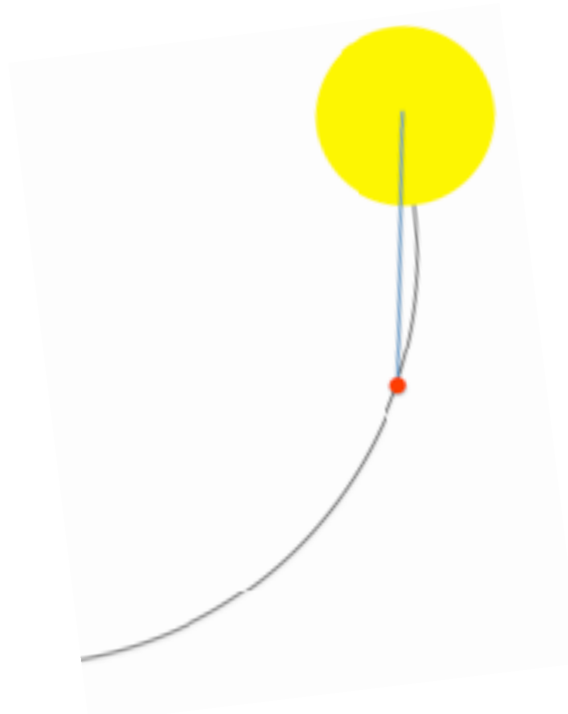
The solar wind is radial. Plasma moves radially.

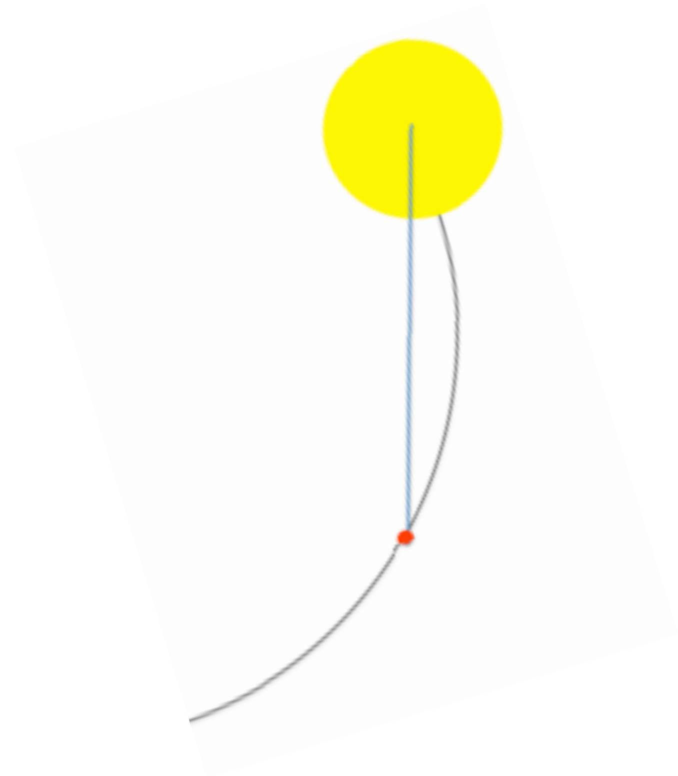
SOLAR WIND IS RADIAL & IMF BENDS?

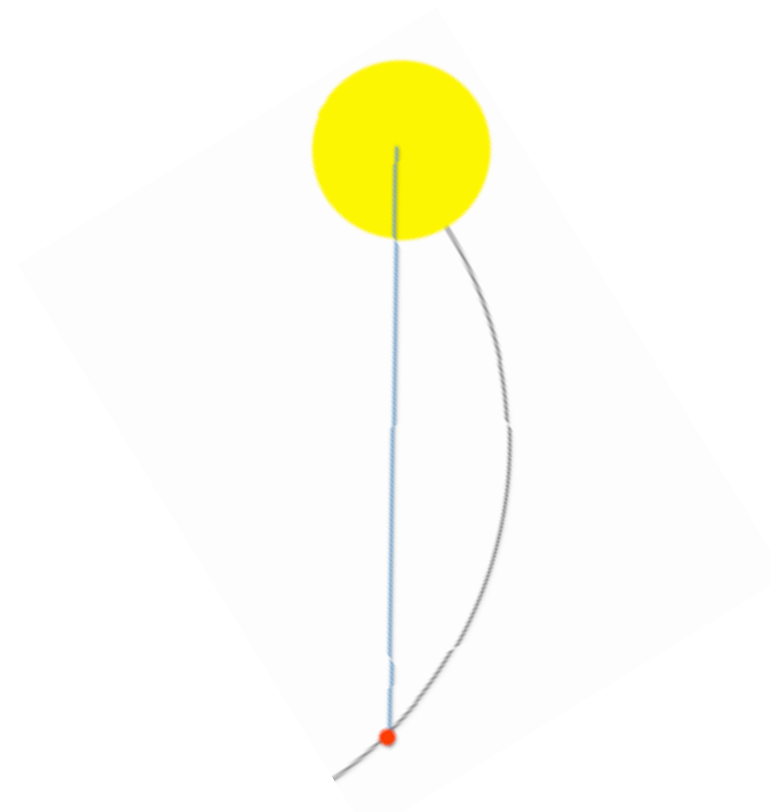


How is it possible that the solar wind (plasma) moves radially while the interplanetary magnetic field is bent into the Parker spiral?

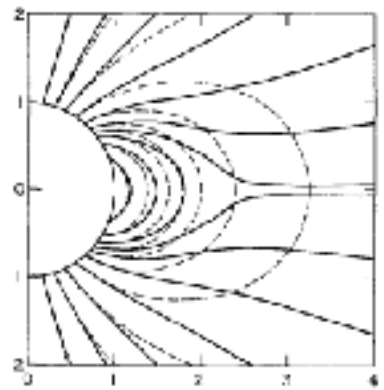
Due to the solar rotation, the plasma blob moves out radially, but stays on the same magnetic field line.

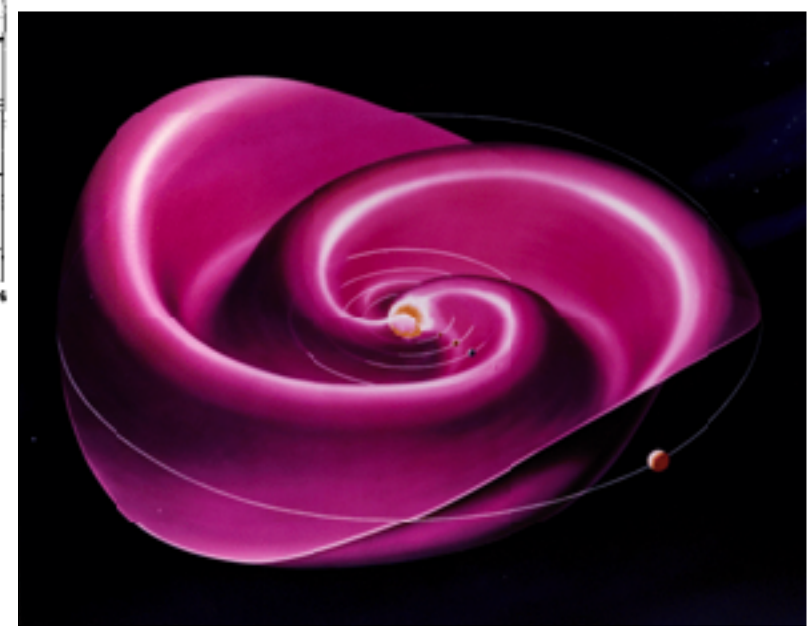






HELIOSPHERIC CURRENT SHEET



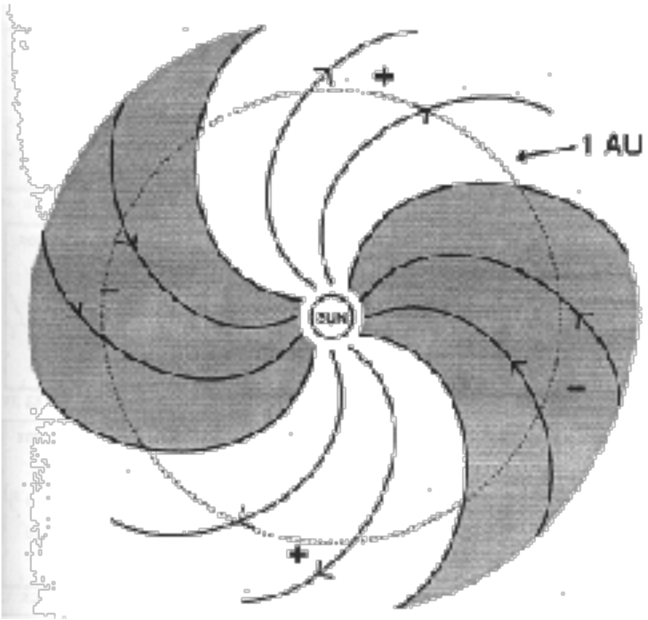


The influence of the spiral-shaped magnetic field on the interplanetary medium (solar wind) creates the largest structure in the Solar System, called the heliospheric current sheet.

The heliospheric current sheet is a layer between regions with opposite magnetic field lines. In an idealised situation, the heliospheric current sheet would be a flat sheet, perpendicular to the magnetic axis of the Sun. However, since the magnetic axis is not the same as the solar rotation axis, the heliospheric current sheet gets a wavy shape, also referred to as the ballerina skirt.
Indeed, the Sun's rotation causes the heliospheric current sheet to move up and down at a fixed observer's position, with associated changes in the plasma density and the direction of the magnetic field.

Left image from Pneuman, G.W., Kopp, R.A. Gas-magnetic field interactions in the solar corona.
Sol Phys 18, 258–270 (1971). https://doi.org/10.1007/BF00145940

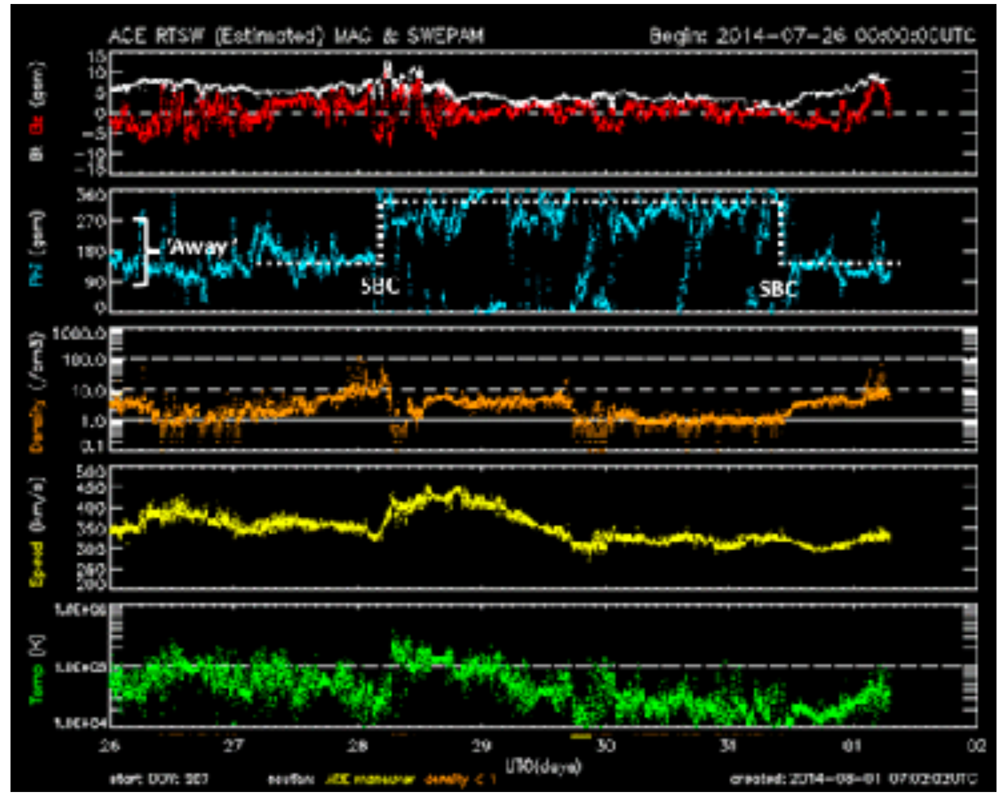
SECTOR BOUNDARY CROSSING



Because the Sun's rotational axis and its magnetic axis are not always aligned, the heliospheric current sheet gets warped. When the Earth traverses such a "fold" in the ballerina skirt, a change in the orientation of the magnetic field of the solar wind occurs, which is called a Sector Boundary Crossing (SBC). It quite abruptly changes either from "towards" to "away" from the Sun, or from "away" to "towards" the Sun. This orientation is measured by the "Phi angle", which is oriented "away" when values are between 90 and 270 degrees. Though such a crossing often may be accompanied by a slight change in e.g. solar wind speed or magnetic field strength, the effect is usually minor.

SECTOR BOUNDARY CROSSING

ACE

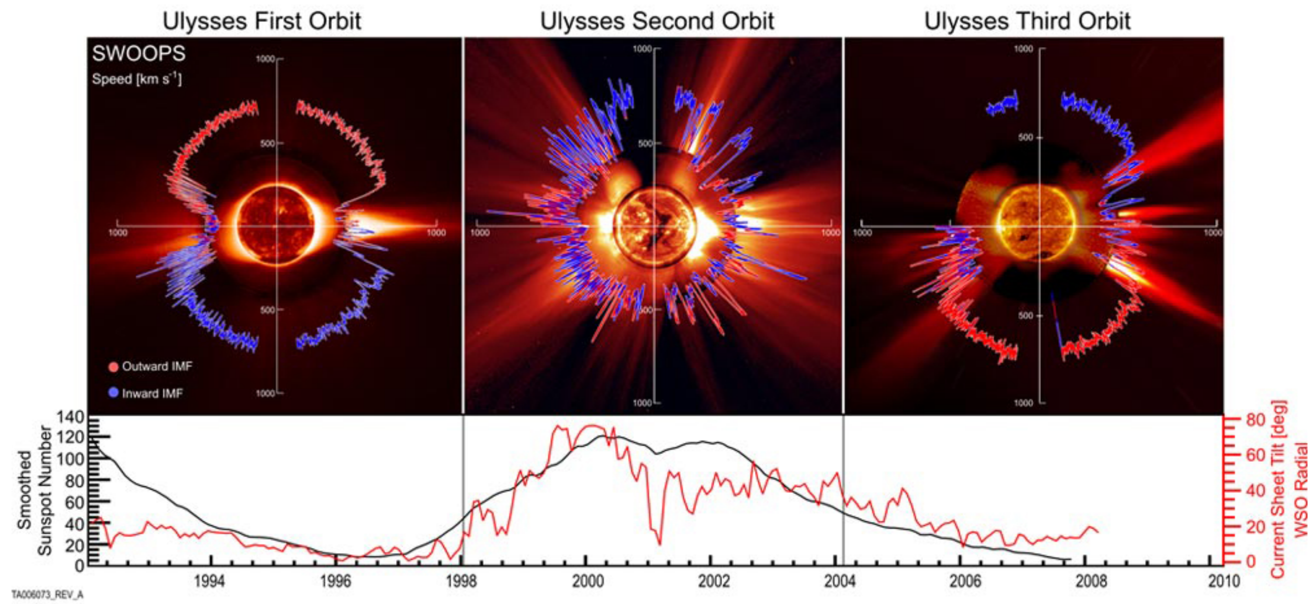


Sector boundary crossings are usually not associated with big disturbances in the geomagnetic field. A nice example of an SBC occurred late July 2014, when early on 28 July the magnetic field changed from "away" to "towards" the Sun, and a few days later (31 July around noon) back to "away" (Phi angle, blue). Though some changes can be seen in the speed (yellow), density (orange) and magnetic field strength (white) of the solar wind, the geomagnetic remained quiet to unsettled.

https://www.stce.be/news/269/welcome.html

SOLAR WIND

ULYSSES



The Ulysses spacecraft orbited the Sun, passing all latitudes and measuring the solar wind speed at these locations. Ulysses made 3 orbits around the Sun. It showed clearly that the solar wind strongly depends on the latitude.

During solar minimum the solar wind is quite structured, with higher wind speed at the poles compared to the equator. During solar maximum the global and local magnetic fields get intertwined and the solar wind becomes unstructured.

Fast solar wind streams are associated with coronal holes. These are regions with open magnetic field lines. Slow streams are associated with closed field regions primarily concentrated near the equatorial (or streamer) belt.

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

SLOW VERSUS FAST

250-400	km/**s**	400-800
High: ~10	Density, cm^{-3}	Low: ~3
Low: ~10^4K, ~1eV	Temperature	High: ~10^5K, ~10eV
Variable	Behaviour	Stationary

These are some characteristics of typical slow and fast winds.

Fast solar wind streams are associated with coronal holes. These are regions with open magnetic field lines. Slow streams are associated with closed field regions primarily concentrated near the equatorial (or streamer) belt.

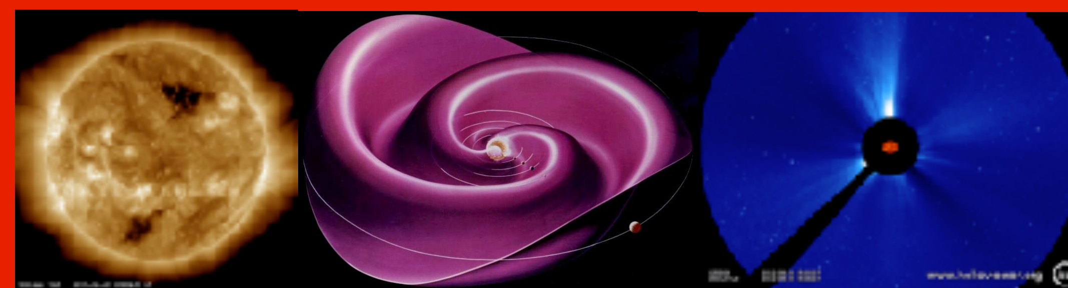
SOLAR WIND VARIATIONS

Non-eruptive

Coronal Hole
Sector Boundary Crossing

Eruptive

Coronal Mass Ejection

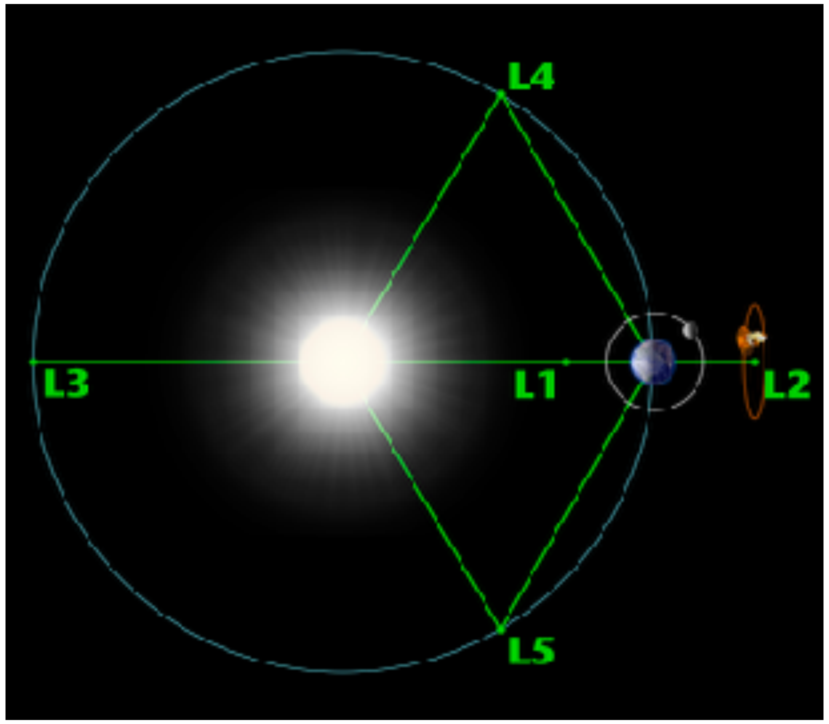


The variations in the solar wind introduce space weather events.

A coronal mass ejection is a sudden, eruptive event. It may or me not be associated with an erupting filament or a flare.

A coronal hole is non-eruptive as it is present for a long time on the solar disk. It can however evolve and grow during its lifetime. The faster wind emanating from a coronal hole is continuous.

LAGRANGE POINTS



The Lagrange points are orbital points near two large co-orbiting bodies, in this case the Sun and the Earth. Normally, the two objects exert an unbalanced gravitational force at any given point, altering the orbit of whatever is at that point. At the Lagrange points, the gravitational forces of the two large bodies and the centrifugal force balance each other. This can make Lagrange points an excellent location for satellites, as few orbit corrections are needed to maintain the desired orbit.
(https://en.wikipedia.org/wiki/Lagrange_point)

(Image not to scale)

SPACECRAFT ORBITING EARTH

PROBA2
- ➡ SWAP - LYRA

SDO
- ➡ AIA - HMI - EVE

GOES
- ➡ SUVI - EXIS - SEISS

We list here some of the most frequently used space weather satellites that are orbiting in different locations: Earth, L1 and then the ones with more exotic orbits.

When orbiting around Earth, satellites are relatively well shielded from the adverse effects of space weather. To be able to observe the Sun in other wavelengths than the visible spectrum, they need to be orbiting above the Earth's atmosphere since that absorbs (E)UV light. However, in their low-earth orbits, they are still protected by the magnetosphere.

These satellites provide solar imaging, irradiance measurements, magnetograms, …

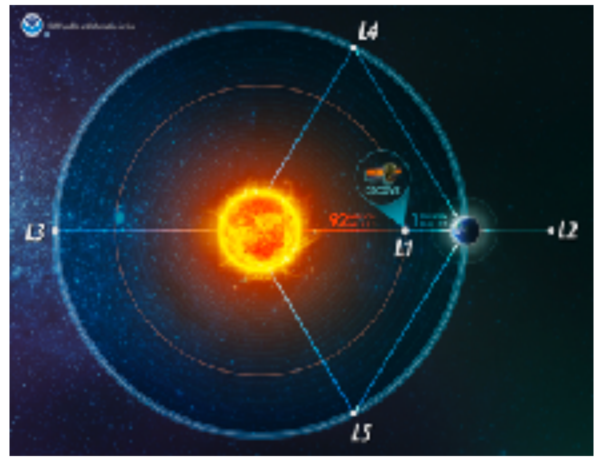
PROBA2: PRoject for Onboard Autonomy
  LYRA: Large Yield RAdiometer
  SWAP: Sun Watcher using Active Pixel System detector and Image Processing

SDO: Solar Dynamics Observatory
  AIA: Atmospheric Imaging Assembly
  HMI: Helioseismic and Magnetic Imager
  EVE: Extreme Ultraviolet Variability Experiment

GOES: Geostationary Operational Environmental Satellite
  SUVI: Solar Ultraviolet Imager
  EXIS: Extreme UV and X-Ray Irradiance Sensor
  SEISS: Space Environmental In-Situ Suite

Image credit: https://www.nesdis.noaa.gov/content/currently-flying

SPACECRAFT ORBITING L1



SOHO
- ➡ EIT - LASCO - MDI

DSCOVR
- ➡ PLASMAG

ACE
- ➡ SWEPAM - MAG

WIND
- ➡ MFI - SWE

L1 is especially interesting for solar observations. We place satellites there that measure the solar wind and the particles in situ. This give us a lead time of 1h approximately.

Satellites SOHO – ACE – DSCOVR – WIND are at L1.

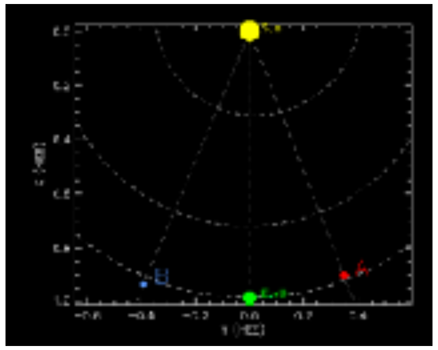
Imaging
SOHO: Solar and Heliospheric Observatory
    EIT: Extreme ultraviolet Imaging Telescope
    LASCO: Large Angle and Spectrometric Coronagraph
    MDI: Michelson Doppler Imager (magnetogram)

Solar Wind Measurements
DSCOVR: Deep Space Climate Observatory
    PLASMAG: Plasma–Magnetometer, Measures solar wind particles and magnetic field vector

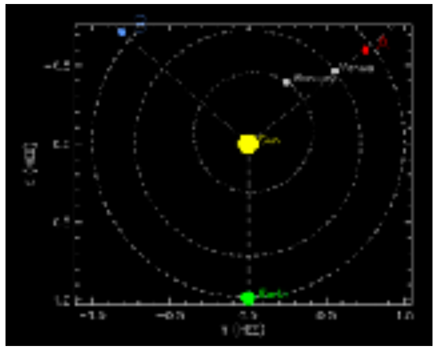
ACE: Advanced Composition Explorer (Solar Wind Measurements)
    SWEPAM: Solar Wind Electron, Proton, and Alpha Monitor
    MAG: Magnetometer

WIND: Comprehensive Solar Wind Laboratory for Long–Term Solar Wind Measurements
    MFI: Magnetic Field Investigation
    SWE: Solar Wind Experiment

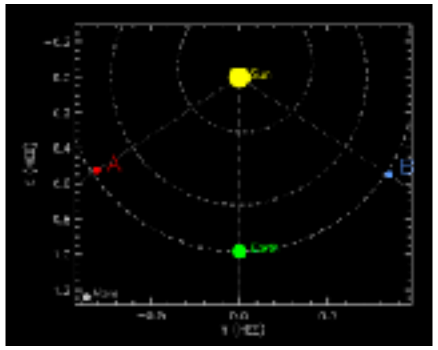
EXOTIC ORBITS: STEREO



January 1, 2008



January 1, 2013



January 1, 2021

SECCHI: EUVI - COR1 - COR2 - HI
SWAVES - IMPACT PLASTIC

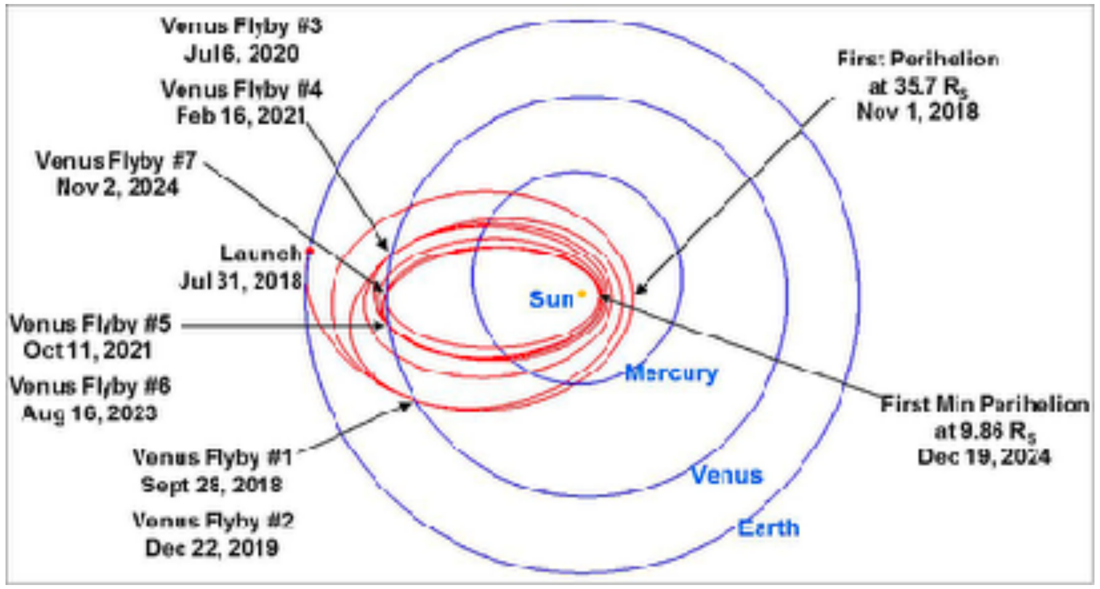
The STEREO (Solar TErrestrial RElations Observatory) mission consists of two nearly identical spacecraft in heliocentric elliptical orbit in the ecliptic plane at approximately 1 AU from the sun: one drifting ahead of the Earth and one behind. Simultaneous measurements are obtained by the satellites instruments at gradually increasing separations over the course of the mission, allowing for stereoscopic observations and e.g. triangulation of solar events as well as following eruptions along the Sun-Earth line.

The STEREO spacecraft were launched in 2006. For a brief period, from 2011 to 2014, scientists had the unprecedented opportunity to see the Sun's entire atmosphere at once. During that time, observations from NASA's SDO (Solar Dynamics Observatory) were supplemented by measurements from NASA's STEREO mission, which included two spacecraft orbiting the Sun. Collectively, the three observatories provided a 360° view of the Sun.

Communications with Solar Terrestrial Relations Observatory-B (STEREO-B) were lost on Oct. 1, 2014, due to multiple hardware anomalies affecting control of the spacecraft orientation. Communications with STEREO-B were re-established on Aug. 21, 2016, during a monthly attempt to reach the spacecraft using NASA's Deep Space Network. During the next weeks, the NASA and the Johns Hopkins APL STEREO teams worked tirelessly to discover the spacecraft's current conditions and to recover the spacecraft fully. The attempt to recover the spacecraft was not successful. STEREO-B has now been out of contact since Sept. 23, 2016. Four years after the initial loss of communications anomaly with the Behind observatory, NASA directed that periodic recovery operations cease with the last support on October 17, 2018.
(https://directory.eoportal.org/web/eoportal/satellite-missions/s/stereo)

Instruments
- SECCHI: Sun Earth Connection Coronal and Heliospheric Investigation
  - SECCHI EUVI: Extreme UltraViolet Imager
  - SECCHI COR1: Inner Coronagraph
  - SECCHI COR2: Outer Coronagraph
  - SECCHI HI: Heliospheric Imager
- SWAVES: STEREO/WAVES
- IMPACT: In-Situ Measurements of particles and CME transients
- PLASTIC: Plasma and Suprathermal Ion Somposition

EXOTIC ORBITS: PSP



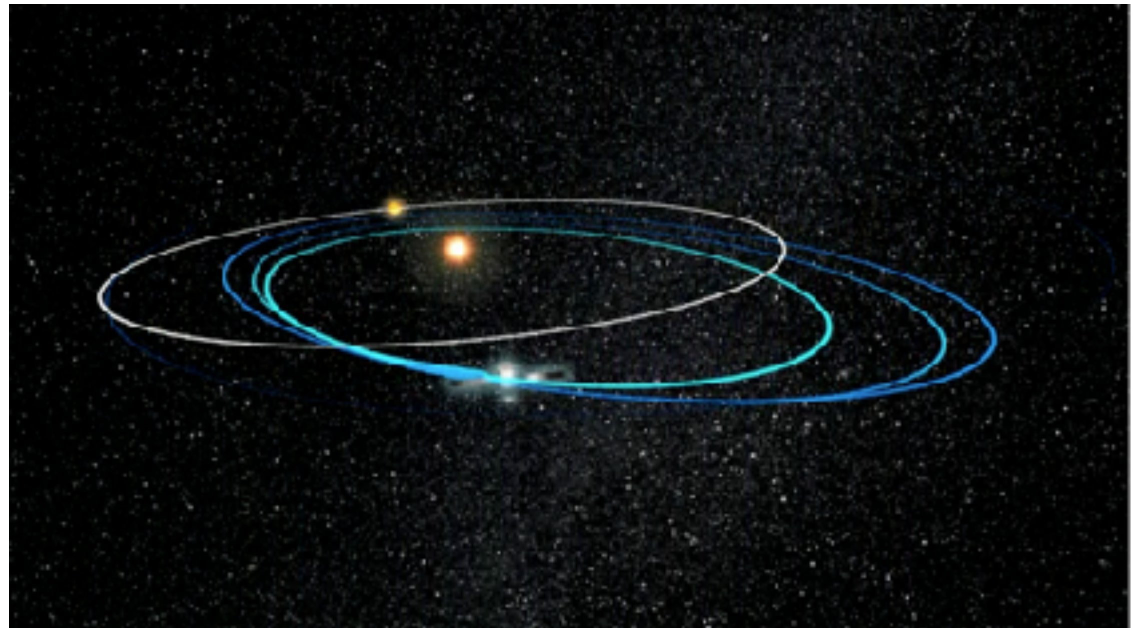
Parker Solar Probe was launched in 2018. The spacecraft will fly through the Sun's atmosphere as close as 6 million km to our star's surface, well within the orbit of Mercury and more than seven times closer than any spacecraft has come before. (Earth's average distance to the Sun is 149 million km.)

In 2017, the mission was renamed for Eugene Parker. In the 1950s, Parker proposed a number of concepts about how stars -including our Sun- give off energy. He called this cascade of energy the solar wind, and he described an entire complex system of plasmas, magnetic fields, and energetic particles that make up this phenomenon. Parker also theorized an explanation for the superheated solar atmosphere, the corona, which is - contrary to what was expected by physics laws -- hotter than the surface of the sun itself. This is the first NASA mission that has been named for a living individual.
https://www.nasa.gov/content/goddard/parker-solar-probe-humanity-s-first-visit-to-a-star

Instruments

- FIELDS measures the electric field around the spacecraft with five antennas
- WISPR: Wide-Field Imager for Parker Solar Probe
- SWEAP: Solar Wind Electrons Alphas and Protons investigation
- ISOIS: Integrated Science Investigation of the Sun

EXOTIC ORBITS: SOLAR ORBITER



Solar Orbiter was launched in 2020 and takes images of the Sun from closer than any spacecraft before and for the first time look at its uncharted polar regions. By combining observations from Solar Orbiter's six remote-sensing instruments and four sets of in situ instruments, scientists hope to find answers to some profound questions: What drives the Sun's 11-year cycle of rising and subsiding magnetic activity? What heats up the upper layer of its atmosphere, the corona, to millions of degrees Celsius? What drives the generation of the solar wind? What accelerates the solar wind to speeds of hundreds of kilometres per second? And how does it all affect our planet?
(http://www.esa.int/Science_Exploration/Space_Science/Solar_Orbiter)

The movie shows several gravity assist manoeuvres (slingshot) with planets to travel to final operational orbit using much less propellant than would otherwise be needed. Each one is designed to change the trajectory of the spacecraft targeting the next planet in the sequence, while reducing the orbital energy and bringing the spacecraft closer and closer to the sun. The orbit also becomes more and more inclined, allowing (for the first time ever) to observe the solar poles directly.

Once the satellite will be in its operational mission (>November 2021), the in-situ instrumentation will be permanently active. The remote-sensing instruments will only be operational during 3 distinct science windows: at minimum and maximum latitude and during the closest approach. Of these, the closest approach is scientifically most interesting. At this point in the orbit, the angular velocity of the spacecraft approaches the angular velocity of the sun, which means we can perform co-rotating observations, allowing continuous observations of the same regions on the solar surface for extended periods.

In-situ instruments:

- EPD: Energetic Particle Detector
- MAG: Magnetometer
- RPW: Radio and Plasma Waves
- SWA: Solar Wind Plasma Analyser

Remote-sensing instruments:

- EUI: Extreme Ultraviolet Imager
- METIS: Coronagraph
- PHI: Polarimetric and Helioseismic Imager (photospheric vector magnetic field and line-of-sight (LOS) velocity)
- SoloHI: Heliospheric Imager
- SPICE: Spectral Imaging of the Coronal Environment
- STIX: X-ray Spectrometer/Telescope