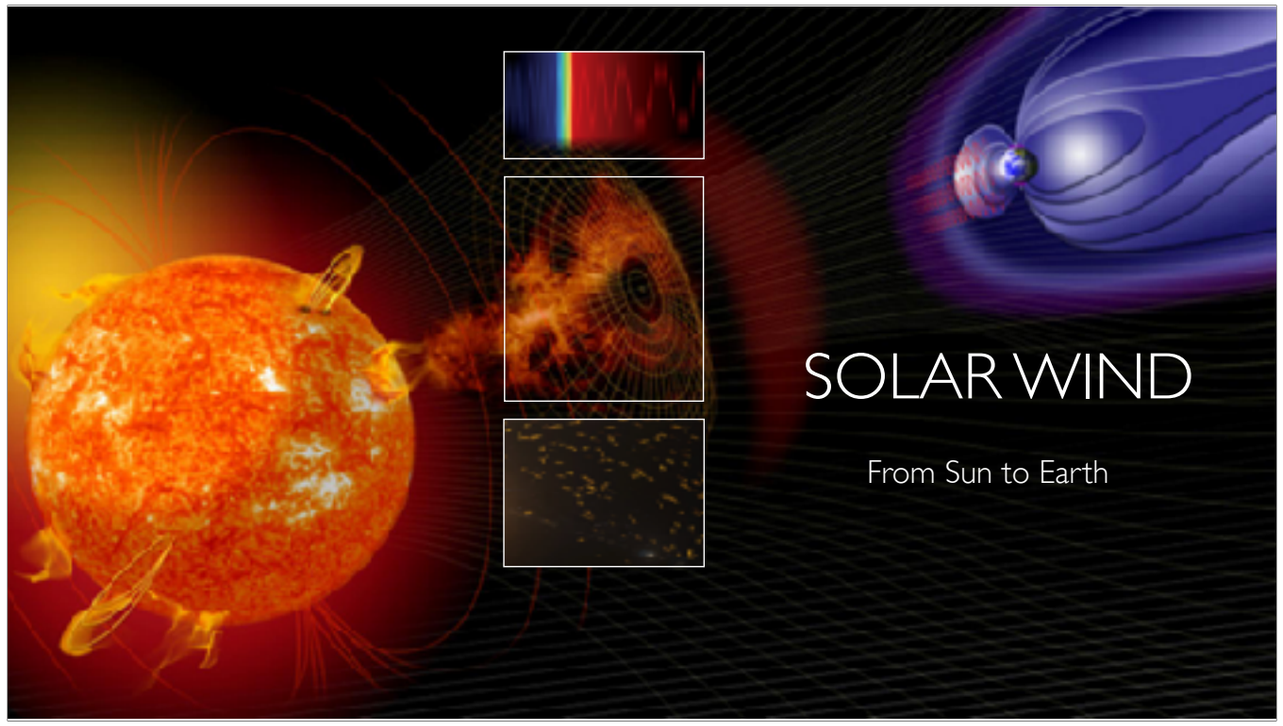

SOLAR WIND
From Sun to Earth

SOLAR WIND

What

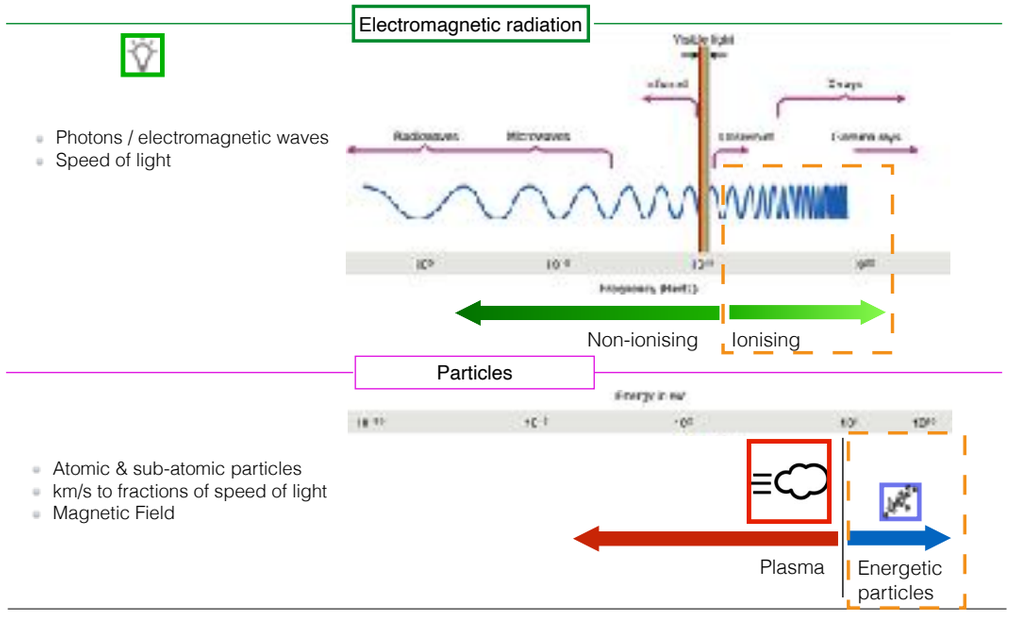


Photo-ionisation — green
Impact ionisation — blue

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.

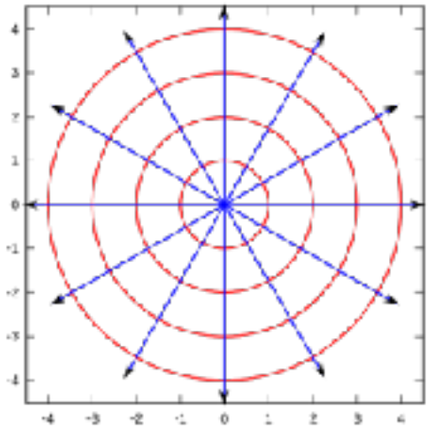
Expanding gas

—>

Outward moving plasma

RADIAL SOLAR WIND

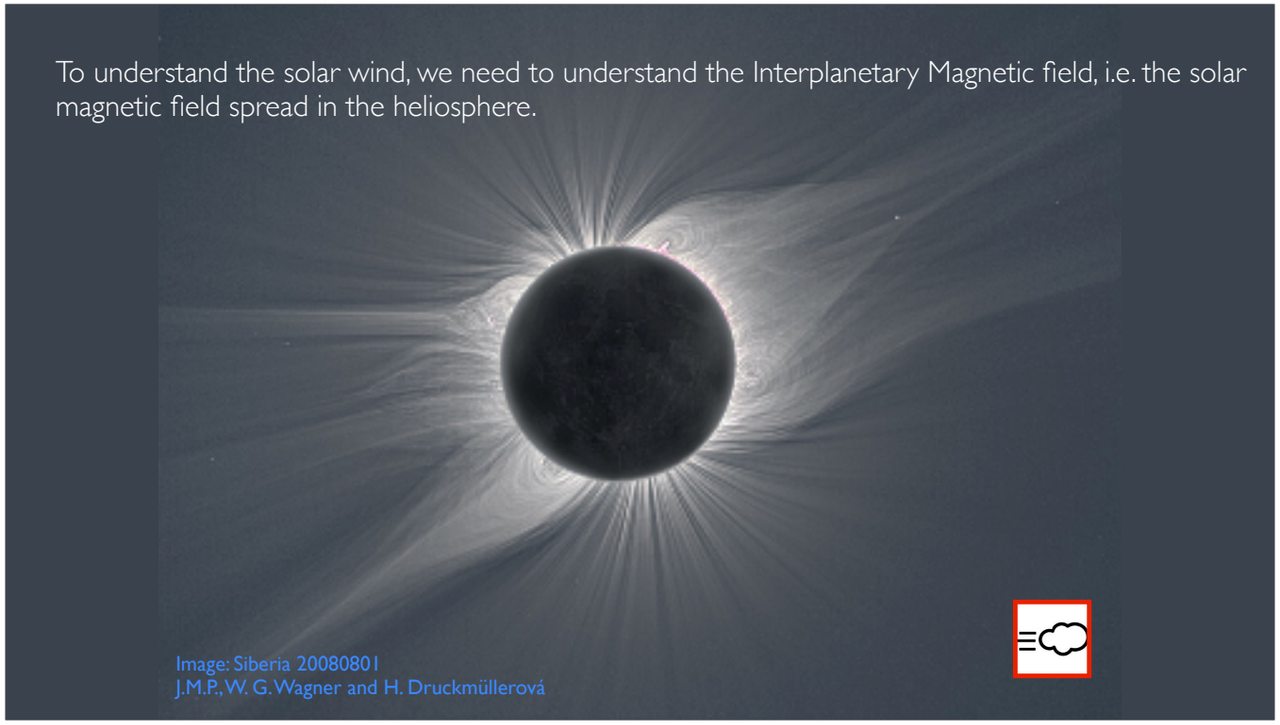
The solar wind carries out solar material and solar magnetic field. The solar material and magnetic field becomes less dense the further away from the Sun.



2D cross section – valid over all cuts

For this, we need first to understand the Interplanetary Magnetic field that is spread in the heliosphere. The Sun is the source of this magnetic field. The moving plasma and the IMF together form the solar wind.

Corona is structured - you see lines



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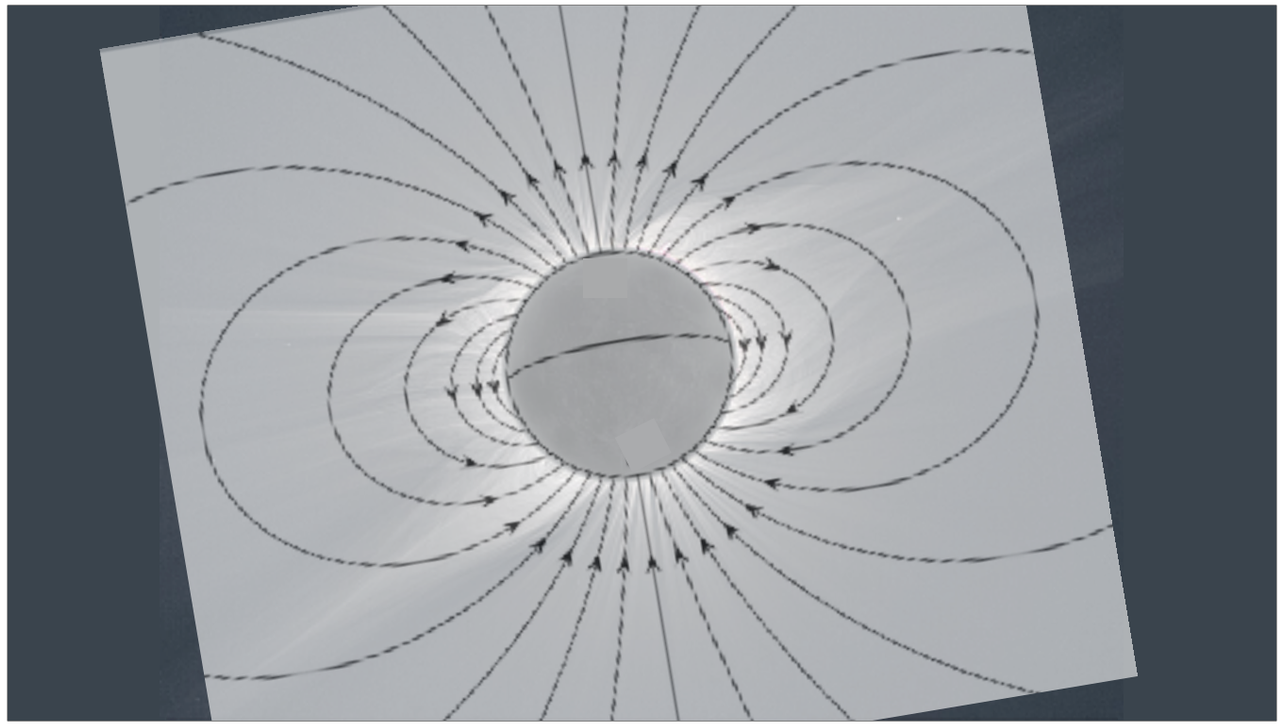
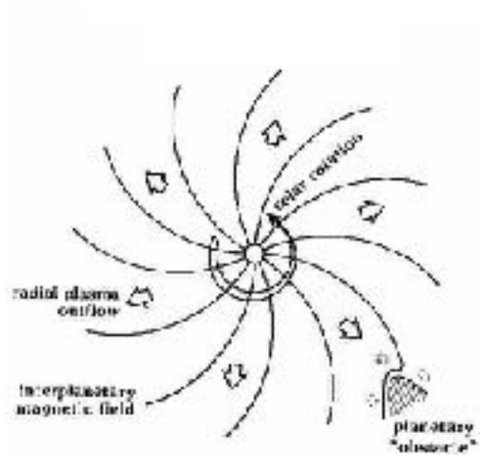
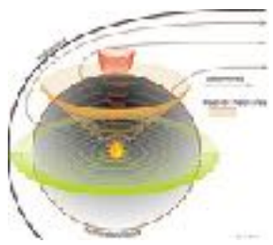


Magnetic forces
`

PARKER SPIRAL

The magnetic field stays connected to the Sun. As the Sun rotates, the magnetic field gets bent.

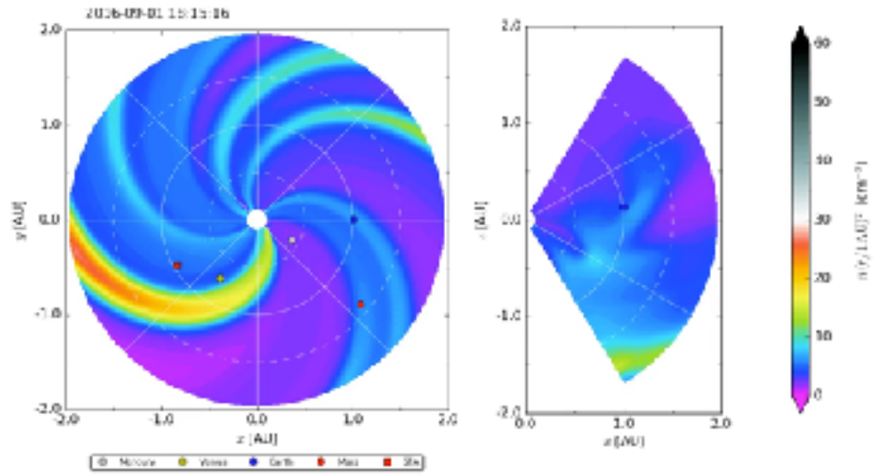




Left: This is a view of the global IMF in the solar equatorial plane.
Right: The IMF and our space is 3D. You have at a particular latitude also IMF lines coming out. Also these lines bend because of the solar rotation. All IMF lines at a particular latitude form a magnetic coin. The solar equatorial plane is a flat cone, a plane.

This is the ideal IMF.
left: It has no component perpendicular on the solar equatorial plane.
right: it has no component perpendicular to the surface of the magnetic cone.

The frozen-flux theorem: IMF and plasma are glued.
The food points of the magnetic field lines are attached to the sun. At the same time, the plasma of the solar wind on the further distance is glued to that same magnetic field line. When the sun rotates, the IMF is forced to bend.

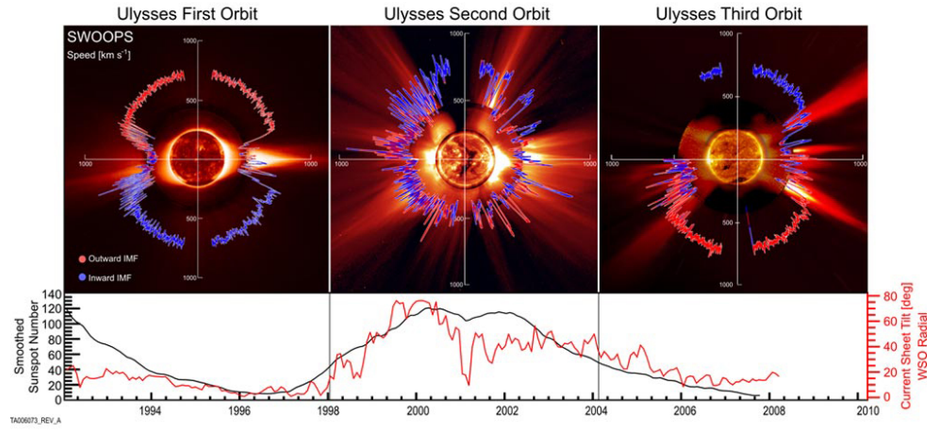


EUHFORIA, realtime simulations of the inner heliosphere

The moving plasma and the IMF together form the solar wind.

The solar wind is linked to open solar magnetic field lines.

SLOW versus FAST



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

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

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

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

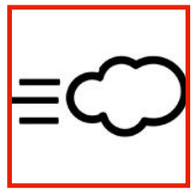
Larger areas with fast solar wind streams. Fast solar wind streams are associated with coronal holes. These are regions with open magnetic field regions of the corona. While slow streams are associated with closed field regions primarily concentrated near the equatorial (or streamer) belt.

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

SLOW versus FAST

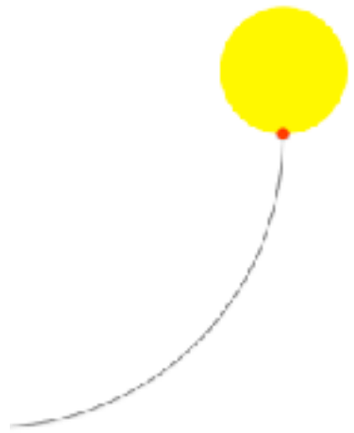
250-400	km/s	400-800
High: ~10	Density, cm^{-3}	Low: ~3
Low: ~10^4K, ~1eV	Temperature	High: ~10^5K, ~10eV
Variable	Behaviour	Stationary

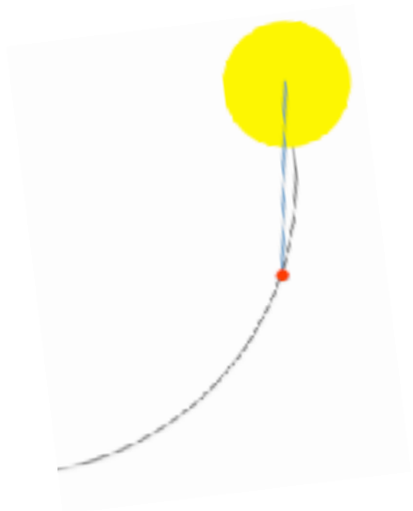
Coronal holes are the source of a fast solar wind.
Solar wind varies within these boundaries.

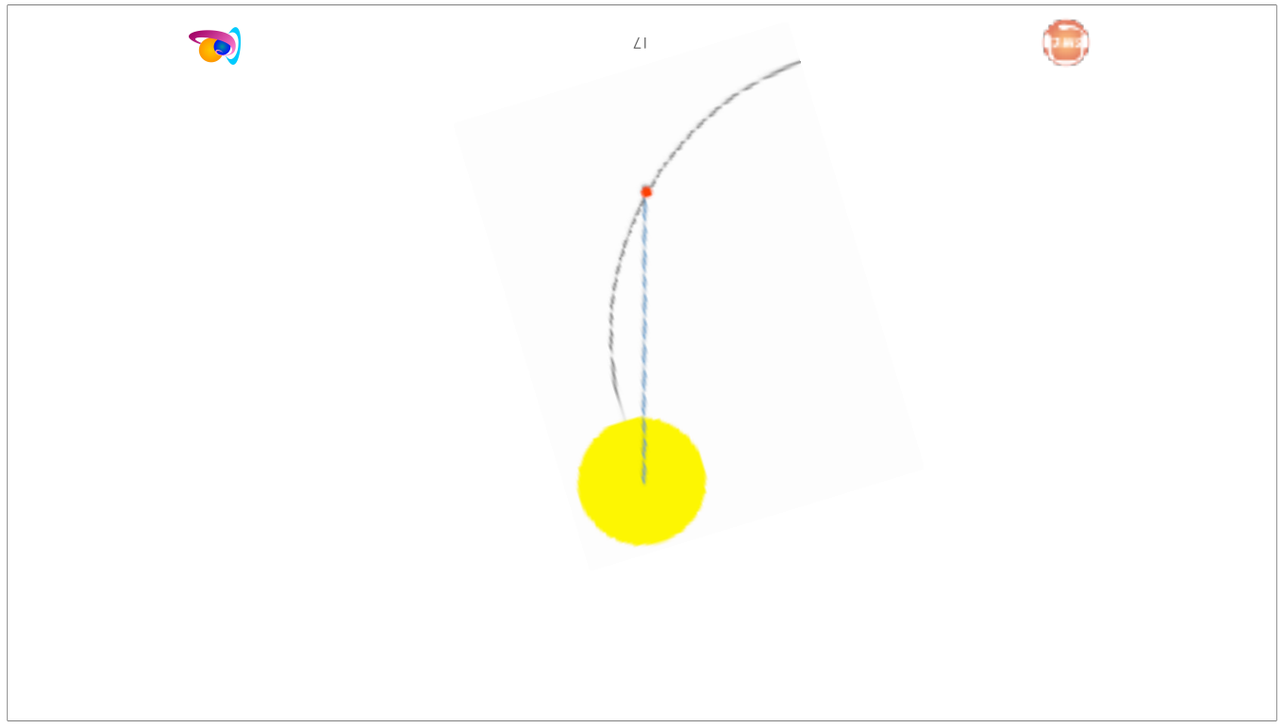


IMF is bent and the plasma flow is radial. Euh?

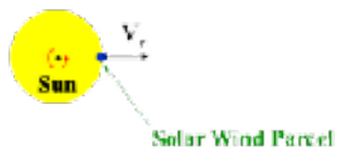
SOLAR WIND IS RADIAL & IMF BENDS?







The Solar **Wind** and the **Interplanetary** Magnetic **Field**
(**Formation** of the Parker **Spiral**)



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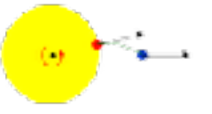

Ange, 2018

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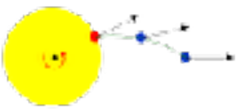

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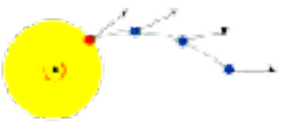

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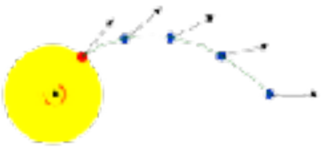

Arge, 2018

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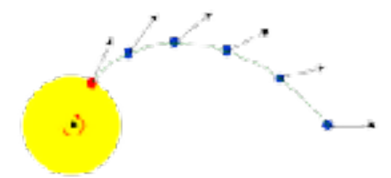
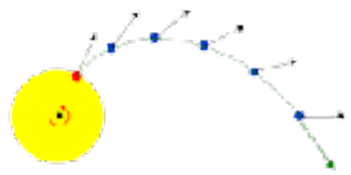


Aug., 2018

The Solar **Wind** and **the** **Interplanetary** Magnetic **Field**
(**Forma**tion of **the** Parker **Spiral**)



Augc, 2018

Because (1) the solar wind flows away from the Sun radially AND (2) the magnetic field and solar wind plasma flow together (i.e., frozen in flux condition), (some) magnetic field lines attached to the Sun are dragged out into space forming a spiral pattern called the Parker Spiral.

Continuous radial outflow of gas - Consists of charged particles

Shapes the IMF - Can carry magnetic structures.

The IMF is bent.

IMF are open magnetic field lines.

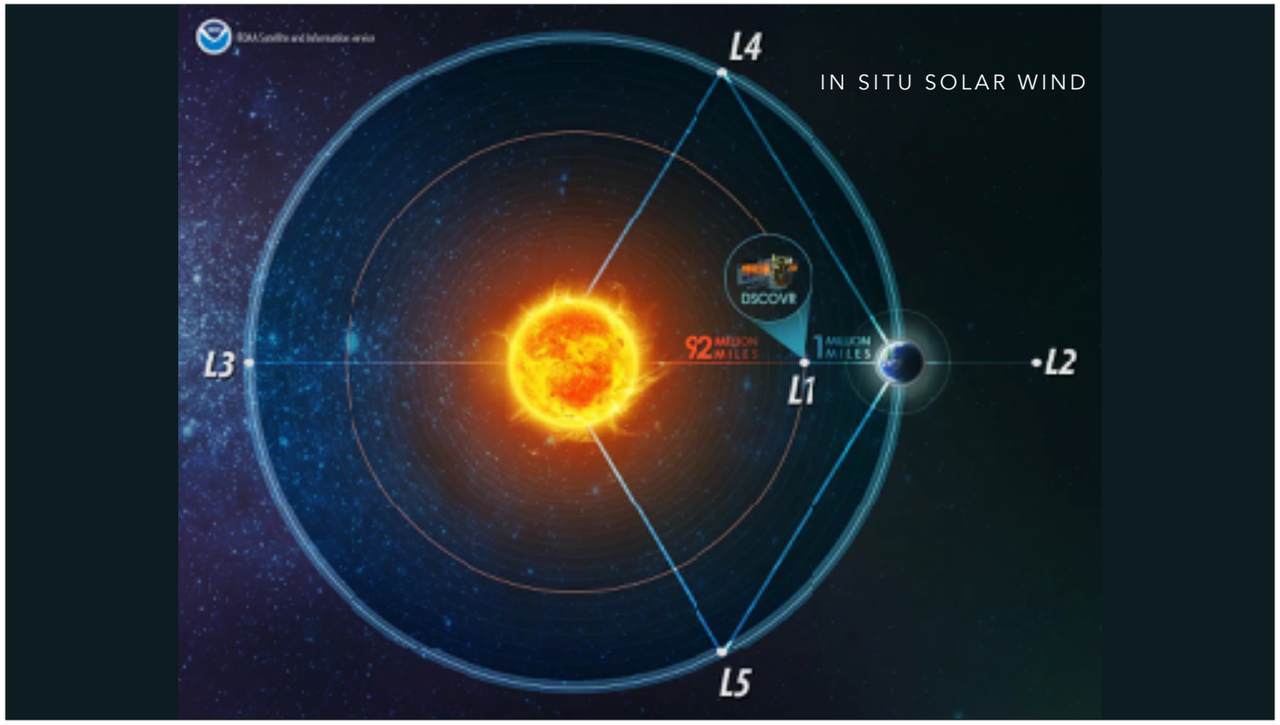
Radial outflow: linked to open magnetic field lines
Example of a Magnetic structure: a CME

The solar wind plasma is glued to the IMF - or the IMF is glued to the plasma.

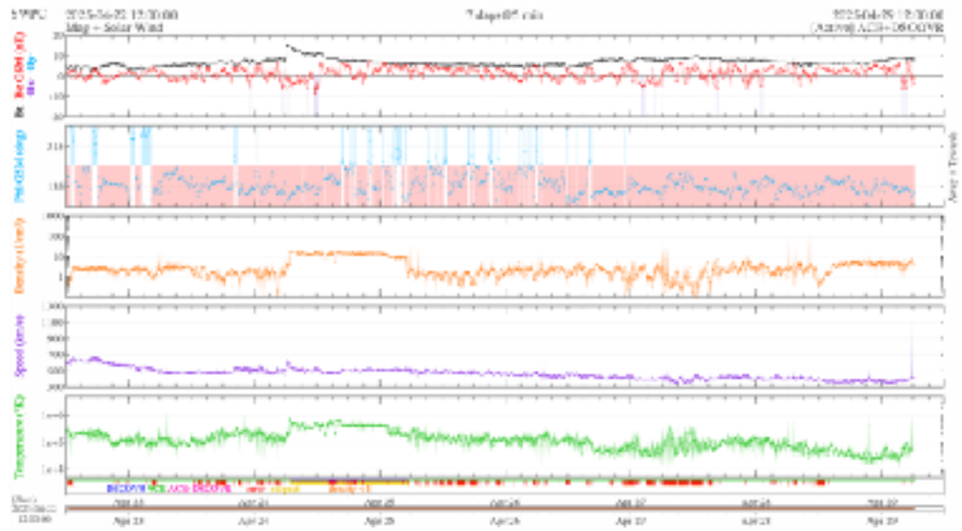
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you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

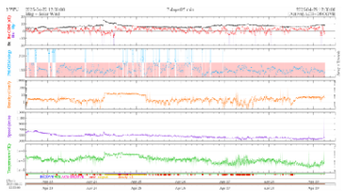
SOLAR WIND

Near Earth

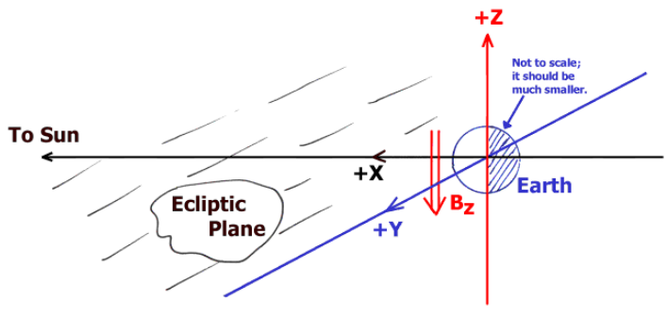

L4
IN SITU SOLAR WIND
DSCOVR
92 MILLION MILES
1 MILLION MILES
L3
L1
L2
L5

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





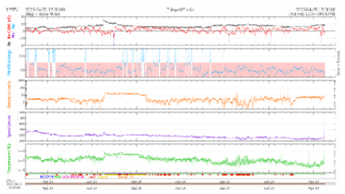
COORDINATE SYSTEM



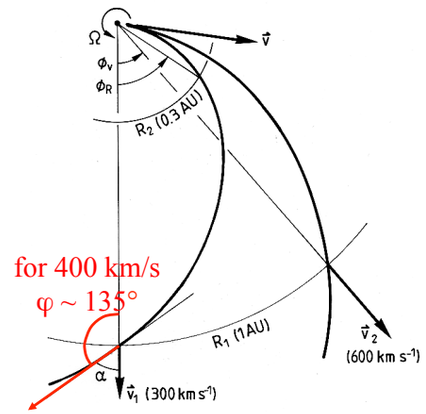
+Z is perpendicular to the Ecliptic Plane.

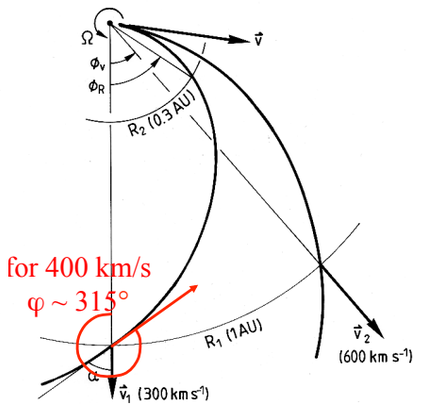
GSM: Geocentric Solar Magnetospheric System. This has its X-axis pointing from the Earth toward the Sun and its Y-axis is chosen to be in the ecliptic plane pointing towards dusk (thus opposing planetary motion). Its Z-axis is parallel to the ecliptic pole. Relative to an inertial system this system has a yearly rotation.

GSM: Geocentric Solar Magnetospheric coordinate system.
The x-axis of the GSM coordinate system is defined along the line connecting the center of the Sun to the center of the Earth. The origin is defined at the center of the Earth, and is positive towards the Sun. The y-axis is defined as the cross product of the GSM x-axis and the magnetic dipole axis; directed positive towards dusk. The z-axis is defined as the cross product of the x- and y-axes. The magnetic dipole axis lies within the xz plane.



IMF POLARITY

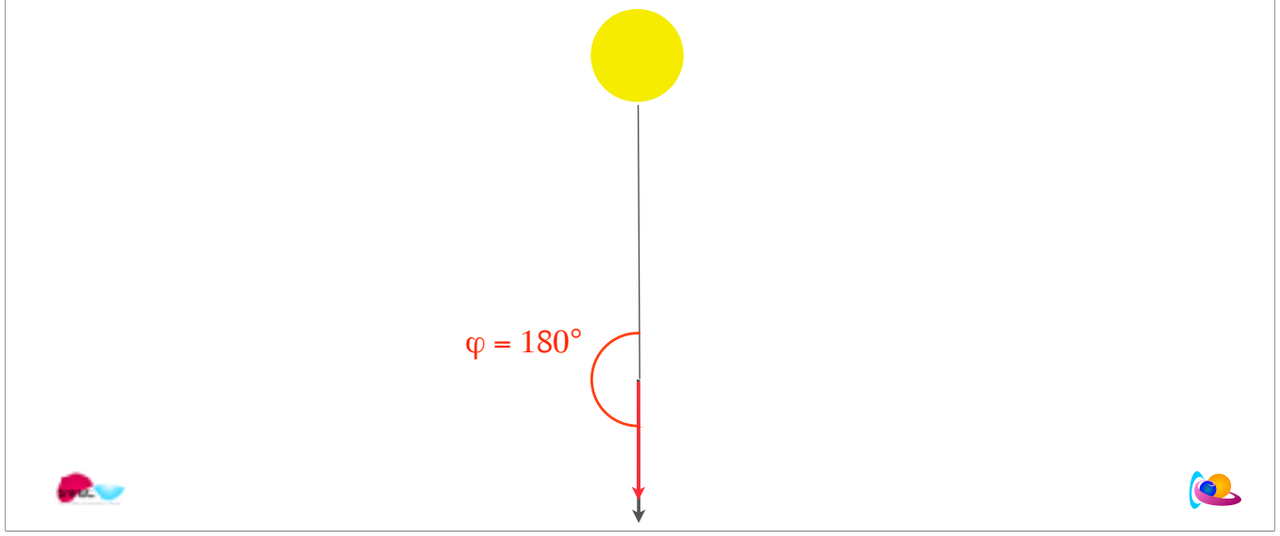




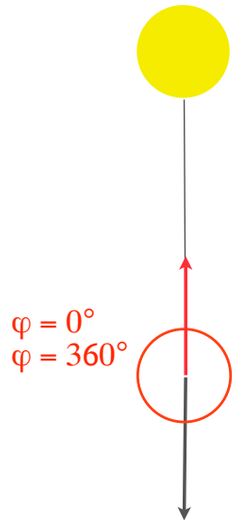
This is the IMF

Phi is a value between
90° and 180°
270° and 360°

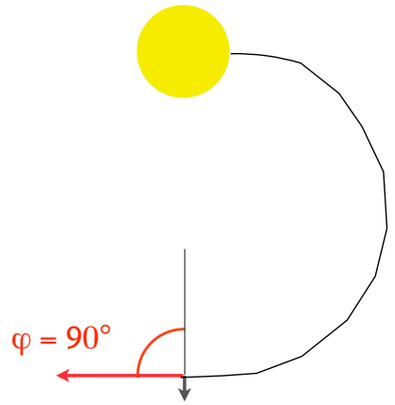
EXTREME FAST



EXTREME FAST



EXTREME SLOW



SOLAR WIND

Transients

lasting only for a short time; impermanent.
Kortstondig, vergankelijk

Transients

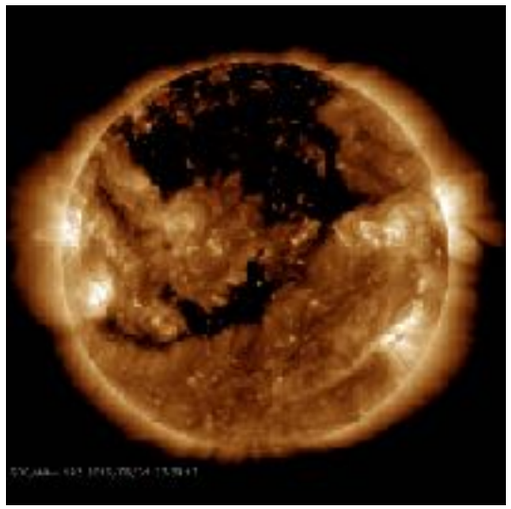
High Speed Streams (HSSs)

And

Co-rotating Interaction Regions (CIRs)

lasting only for a short time; impermanent.
Kortstondig, vergankelijk

Coronal Hole



open field structure, source of fast solar wind
non eruptive
radial - plasma leaving when it is at the central meridian, reaches Earth

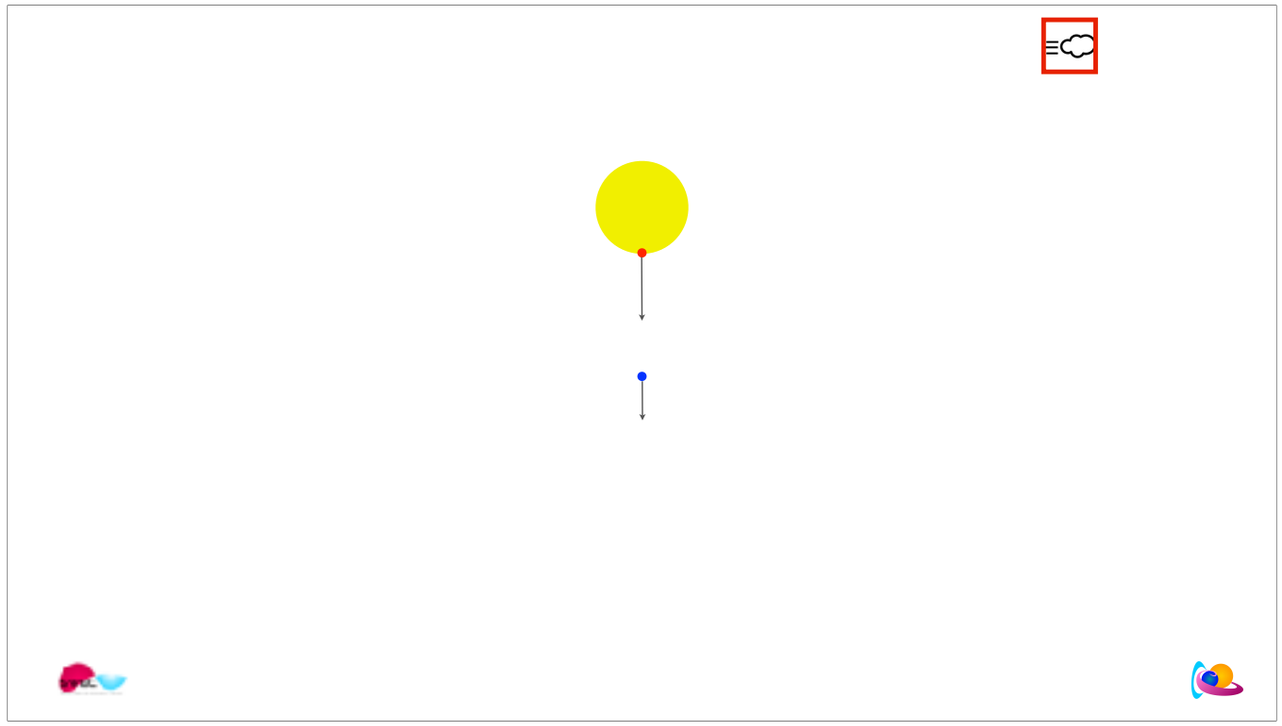
What is important determining when and how strong the impact of a CH will be:
- The heliographic latitude of earth
- The latitude of the CH on the solar disk: the part of a CH with a low latitude is important. Polar coronal holes have only an impact when they extent to lower latitudes.
- It is the material that leave at the central meridian that will reach earth. You have to guess how fast the solar wind is. Calculate the time the material needs to cross the distance 1AU and you have an estimate of the arrival time of the CH wind near Earth.

at the central meridian

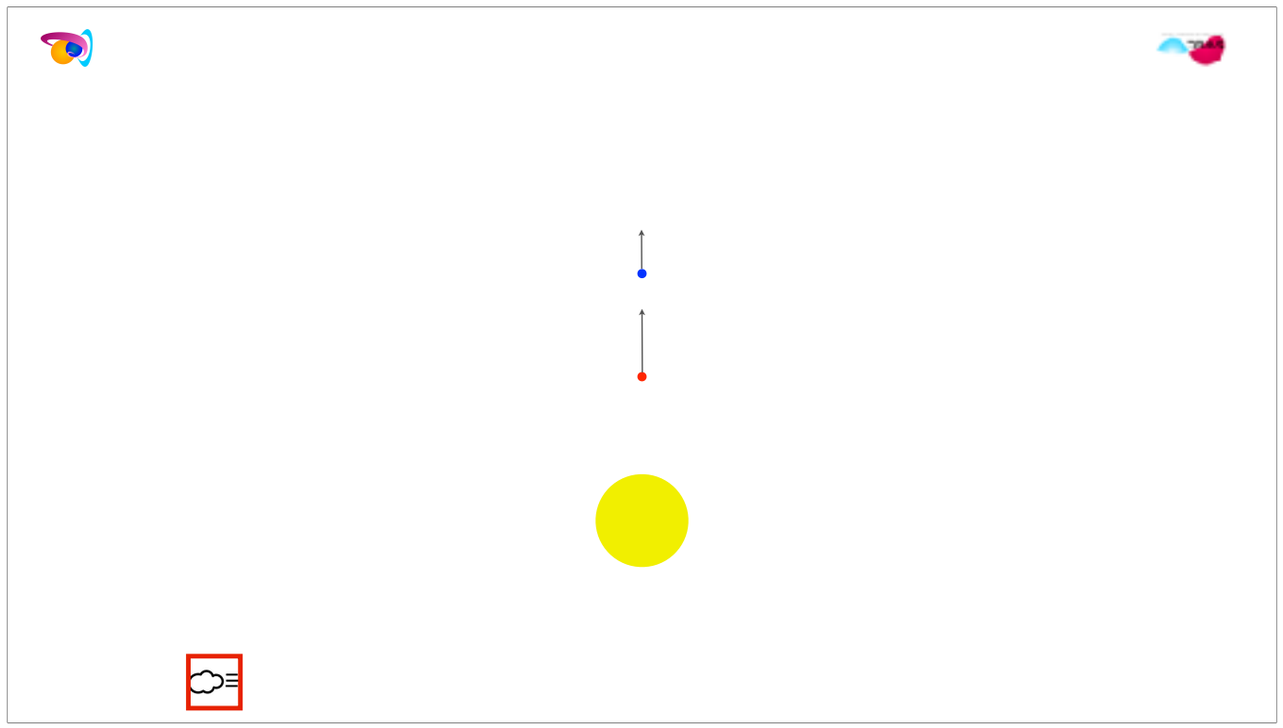
WHAT HAPPENS WHEN FAST CATCHES SLOW?

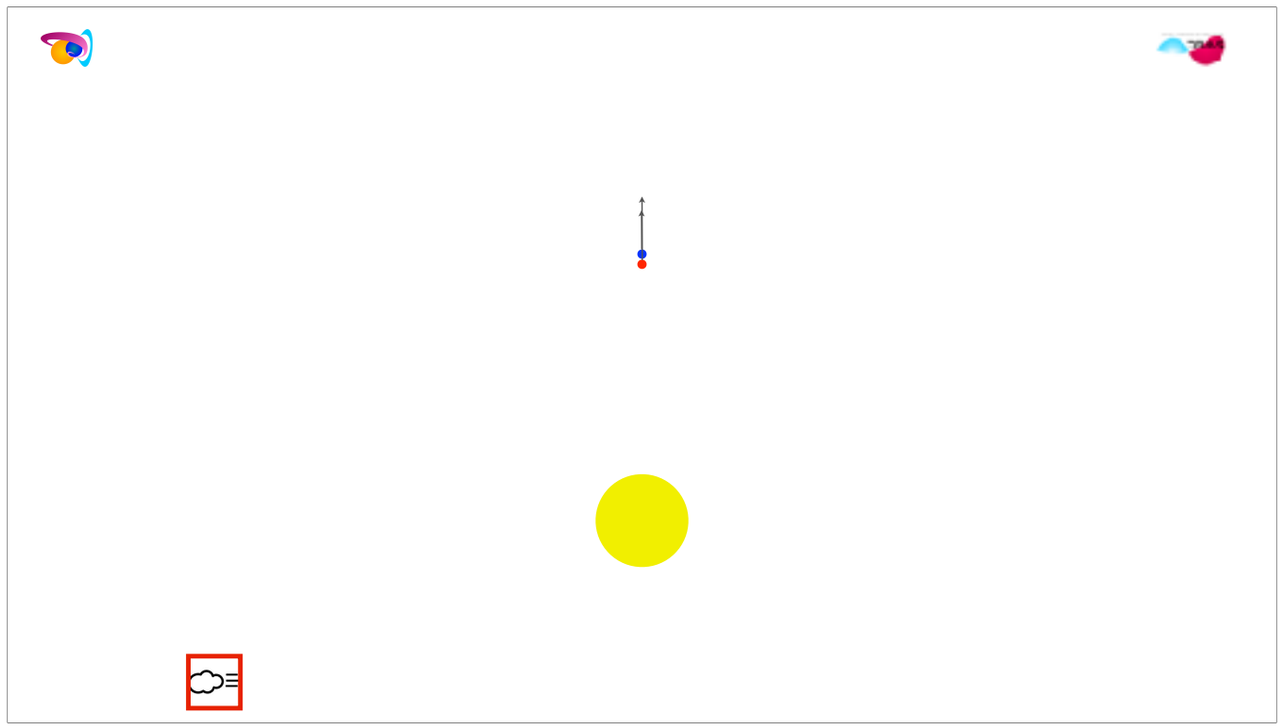
Top View

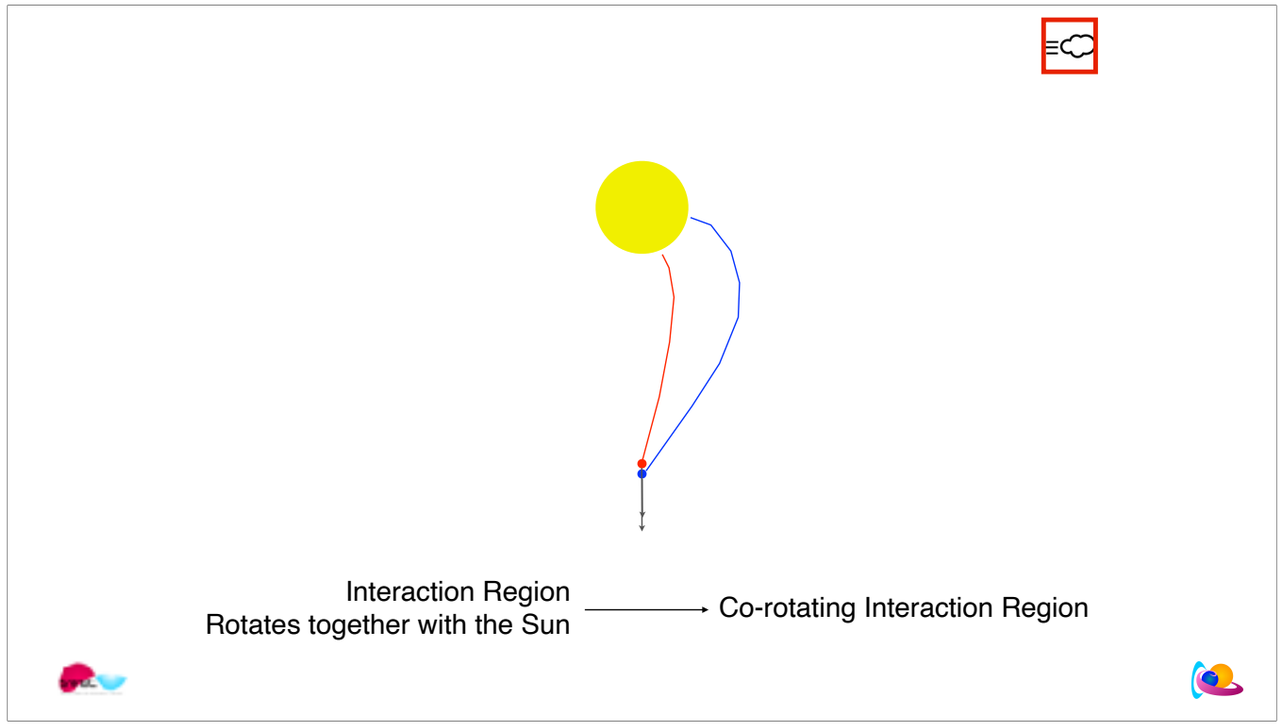
What happens when fast catches slow solar wind material?



The Sun has turned such that another part of the solar disk is now at the point where previously the blue dot left.
Now, the red can chase the blue.







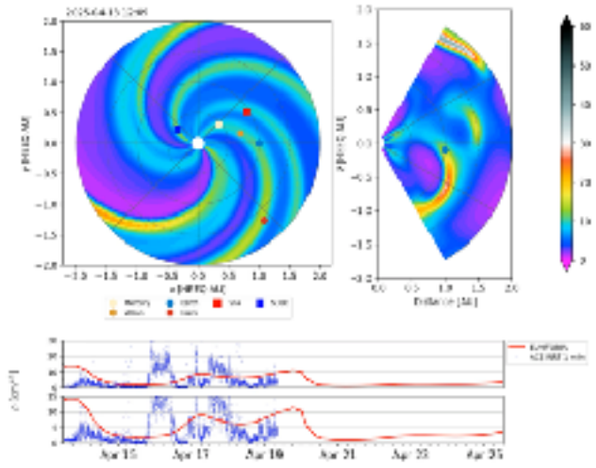
Continuous process - the source of the fast particles, i.e. stays present.

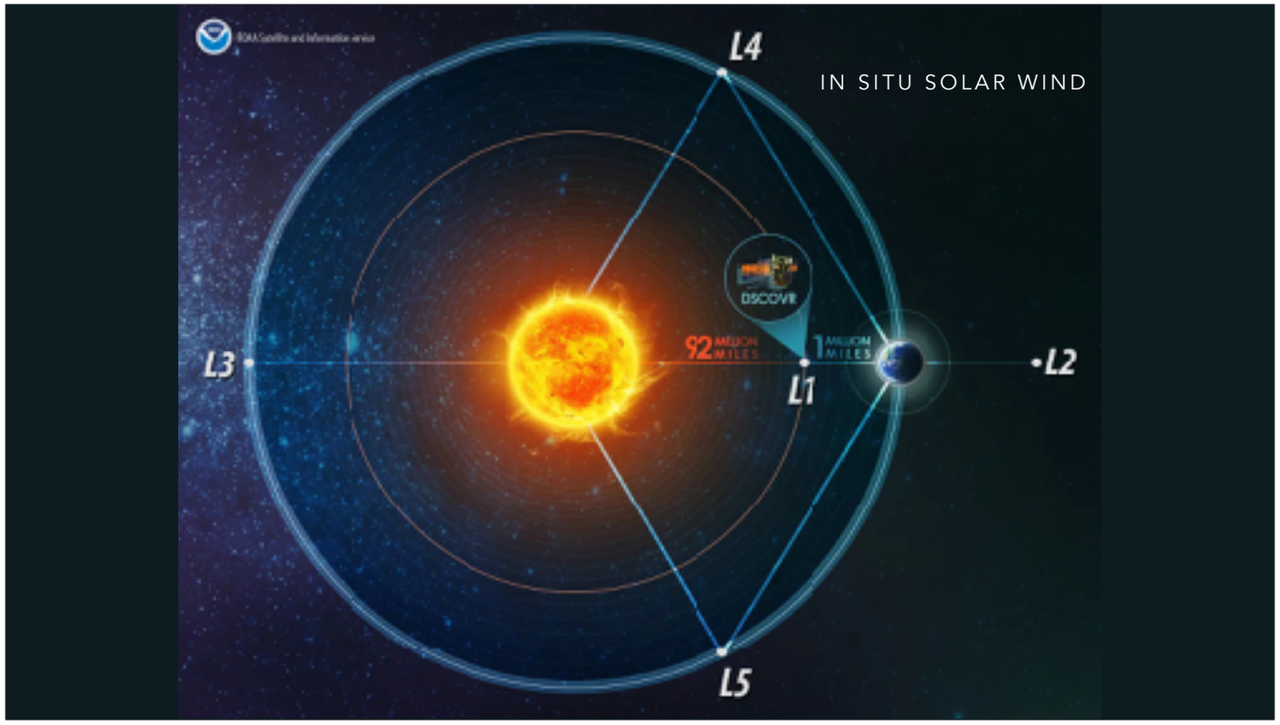
When fast solar-wind streams, emanating from coronal holes, interact with slow streams, they can produce Co-rotating Interaction Regions in interplanetary space. The magnetic fields of the slow streams in the solar wind are more curved due to the lower speeds, and the fields of the fast streams are more radial because of their higher speeds. Intense magnetic fields can be produced at the interface (IF) between the fast and slow streams in the solar wind. The Co-rotating Interaction Regions are bounded by a forward shock (FS) and a reverse shock (RS).

One reason why two shocks are eventually formed at a CIR is due to symmetry about the pressure enhancement caused by compression and entraining of the slow wind ahead of the fast stream (Figure 10.9 [Gosling, 1996]): shocks are driven away from the pressure increase in both directions, resulting in a so-called \Forward-Reverse shock pair" in which the forward shock propagates away from the Sun while the reverse shock propagates towards the Sun but is carried out with the solar wind flow.

http://www.boulder.swri.edu/~deforest/Movies.html

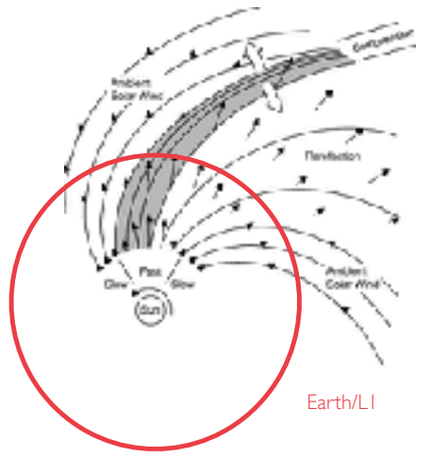
Co-rotating Interaction Region




L4
IN SITU SOLAR WIND
DSCOVR
92 MILLION MILES
1 MILLION MILES
L3
L1
L2
L5

Co-rotating Interaction Region

- A HSS co-rotates with the Sun, generating a CIR
- CH can appear everywhere on the Sun
- If close to the equator, the associated HSS will arrive +- 3 days at Earth (v~ 600 km/s)
- Radial!



als zon niet ronddraait, haalt de snelle zonnewind de trage niet in want die zit er niet achter.

doordat de zon roteert, creëer je dit profiel.

Cartoon showing the interaction of a fast and a slow stream. The fast stream runs into the slow wind, forming a compression region between the two, which results eventually in the formation of a forward-reverse shock pair.

continue toevoer, oorzaak blijft aanwezig

When fast solar-wind streams, emanating from coronal holes, interact with slow streams, they can produce Co-rotating Interaction Regions in interplanetary space. The magnetic fields of the slow streams in the solar wind are more curved due to the lower speeds, and the fields of the fast streams are more radial because of their higher speeds. Intense magnetic fields can be produced at the interface (IF) between the fast and slow streams in the solar wind. The Co-rotating Interaction Regions are bounded by a forward shock (FS) and a reverse shock (RS).

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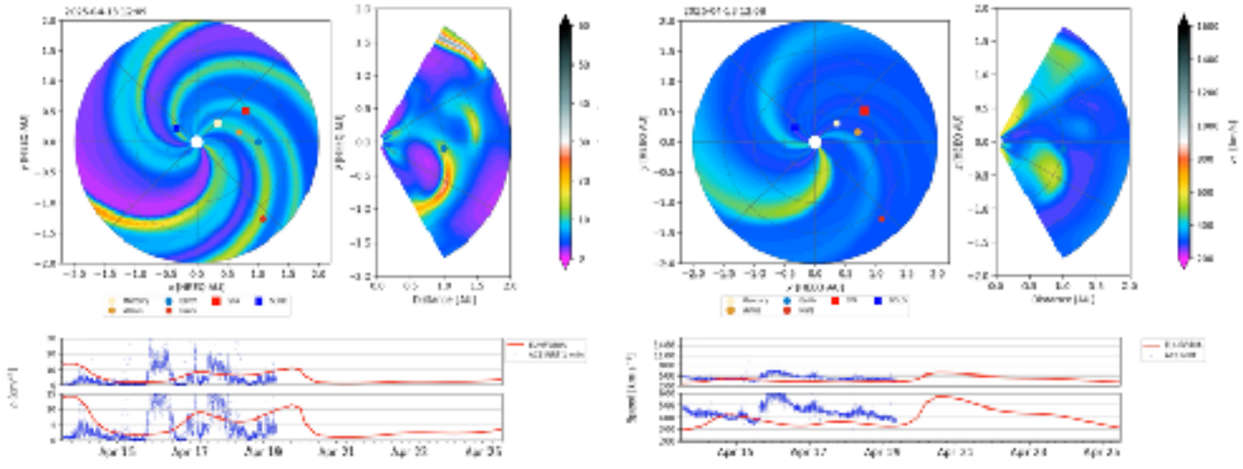
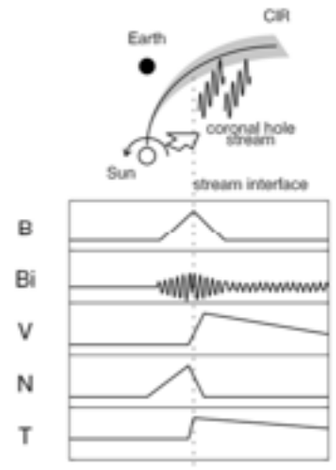
Co-rotating Interaction Region



EUHFORIA, realtime simulations of the inner heliosphere

Co-rotating Interaction Region



Earth

X-axis= where you are on the red circle, Arc length, time
At a point in space, e.g. : the total flux of mass is the same
—> v high, density low
—> v low, density high

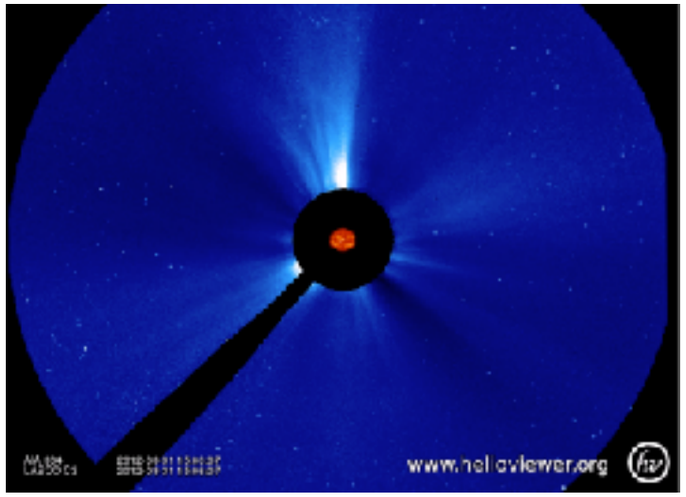
When your plasma is more dense, the closer the magnetic field lines.

High temperature

Transients

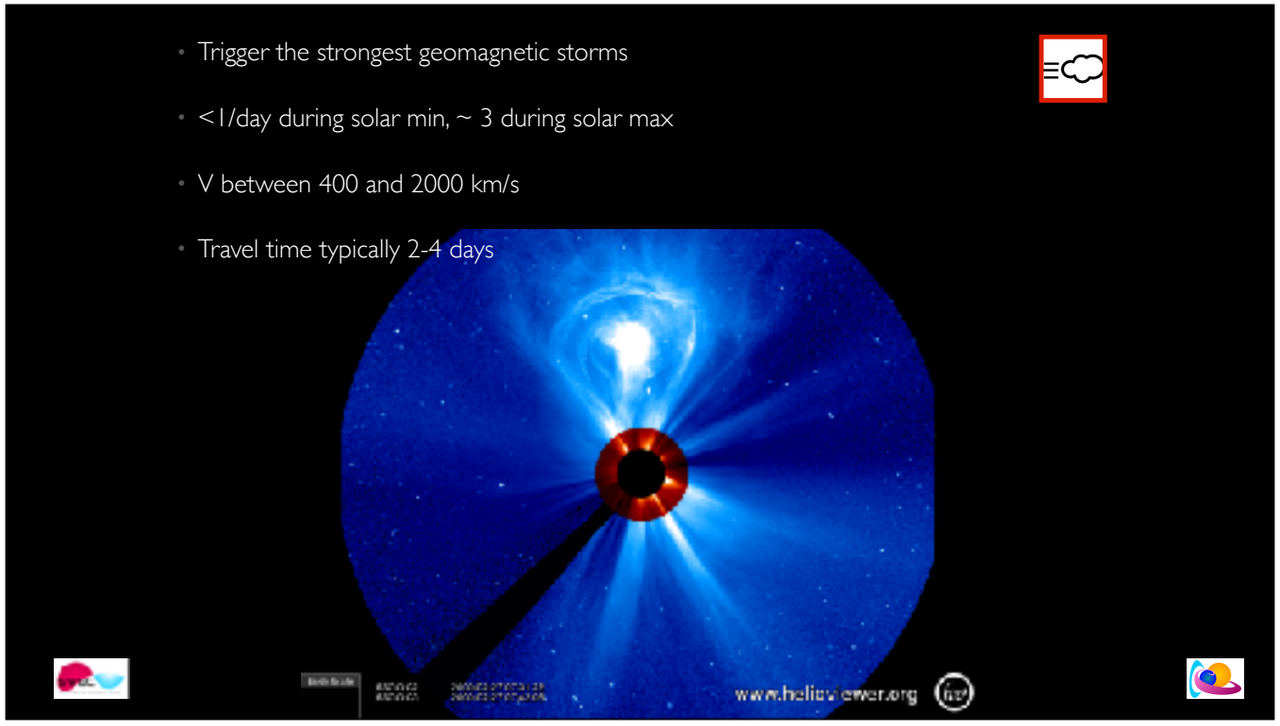
Coronal Mass Ejections

Additional to the background solar wind (fast of slow)
CME can disturb the solar wind well beyond the normal boundaries (of slow and fast)



A new, discrete, bright white light feature in the coronograph field-of-view with a predominantly, radial outward velocity.

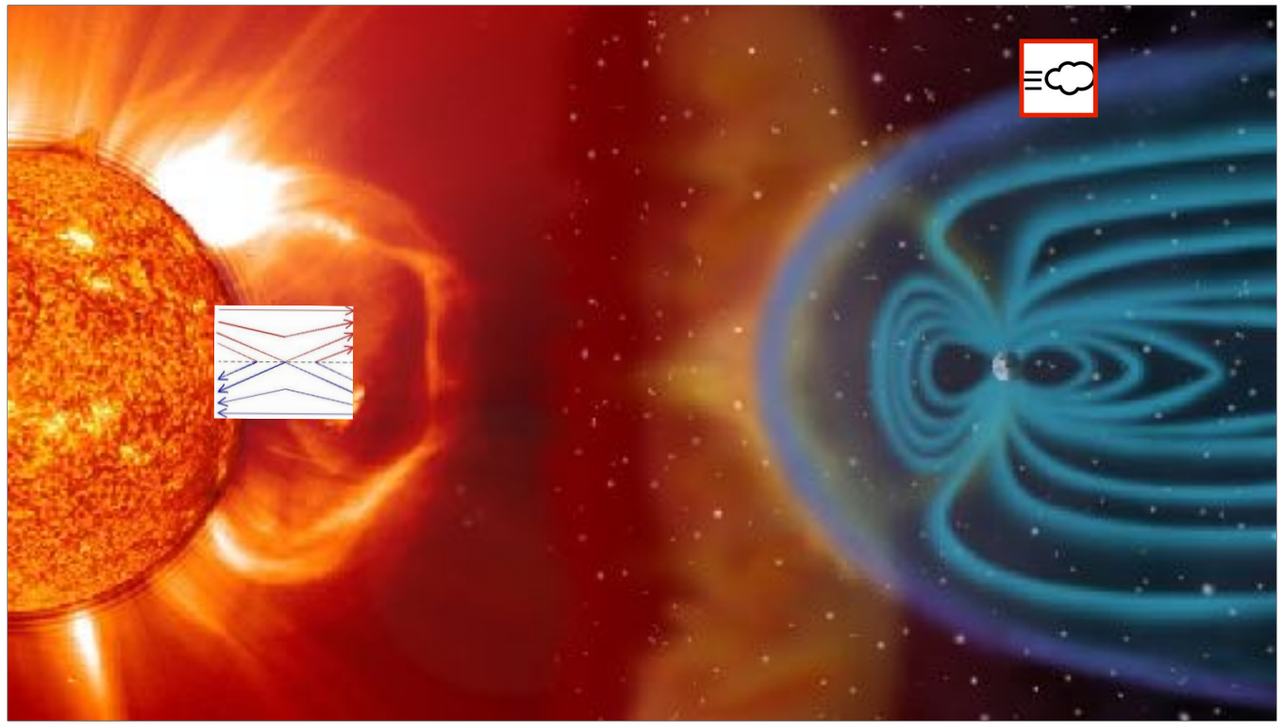
Eruptive - transient



Transient: only lasting for a short time

Low density, but enormous and therefore massive.

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



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

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

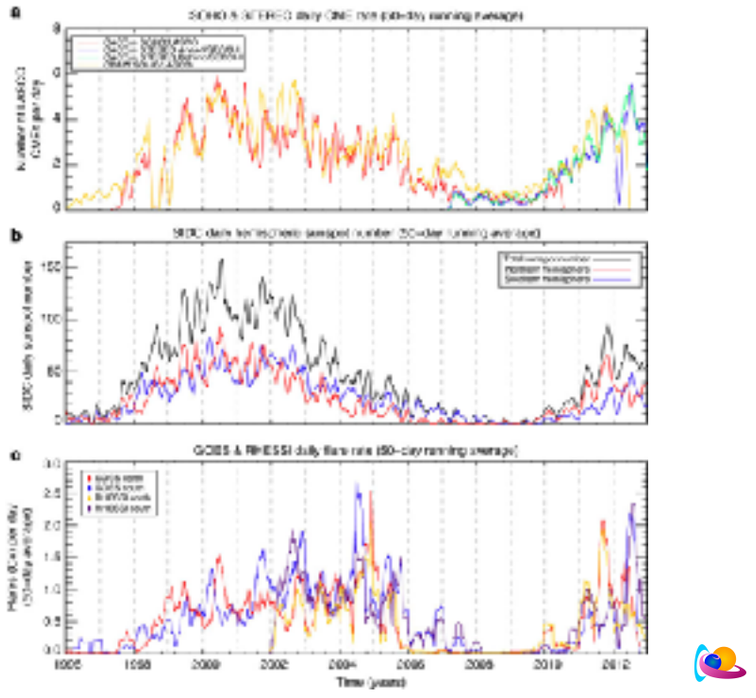
In the case of a speed boat, the boat moves through the water.
In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

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

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

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

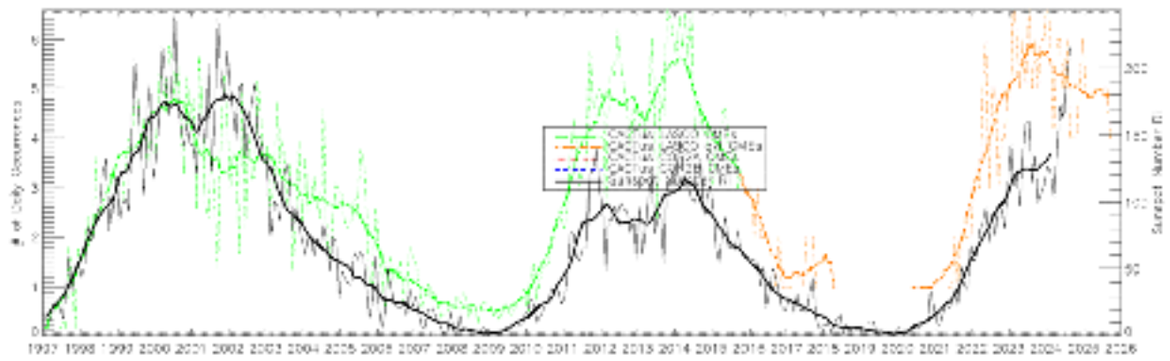
SEASONAL BEHAVIOUR OF CME OCCURRENCE



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

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

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

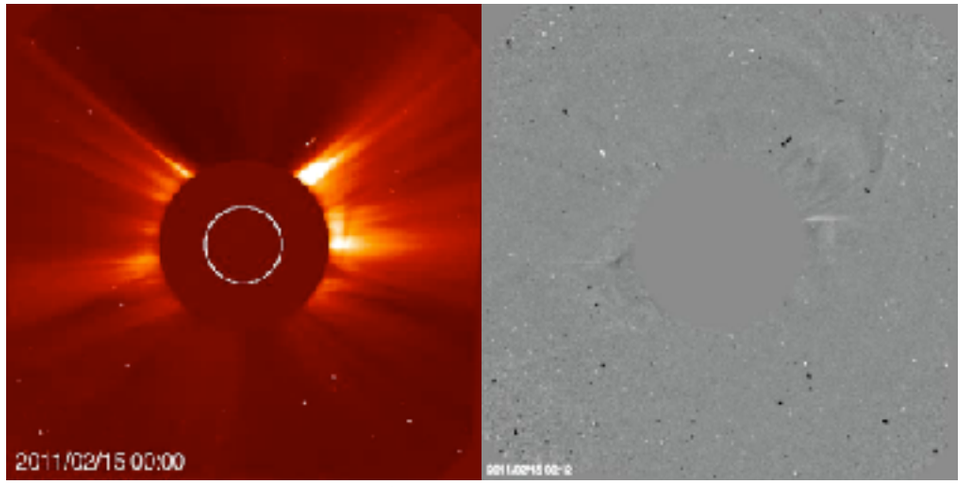


https://www.sidc.be/cactus/catalog/LASCO/2_5_0/dataoverview/CME_and_SSN_rate.png

How do you know there is a CME?

Filament eruption
EUV wave
Coronal dimming
Post-eruption coronal loops —> long duration flare

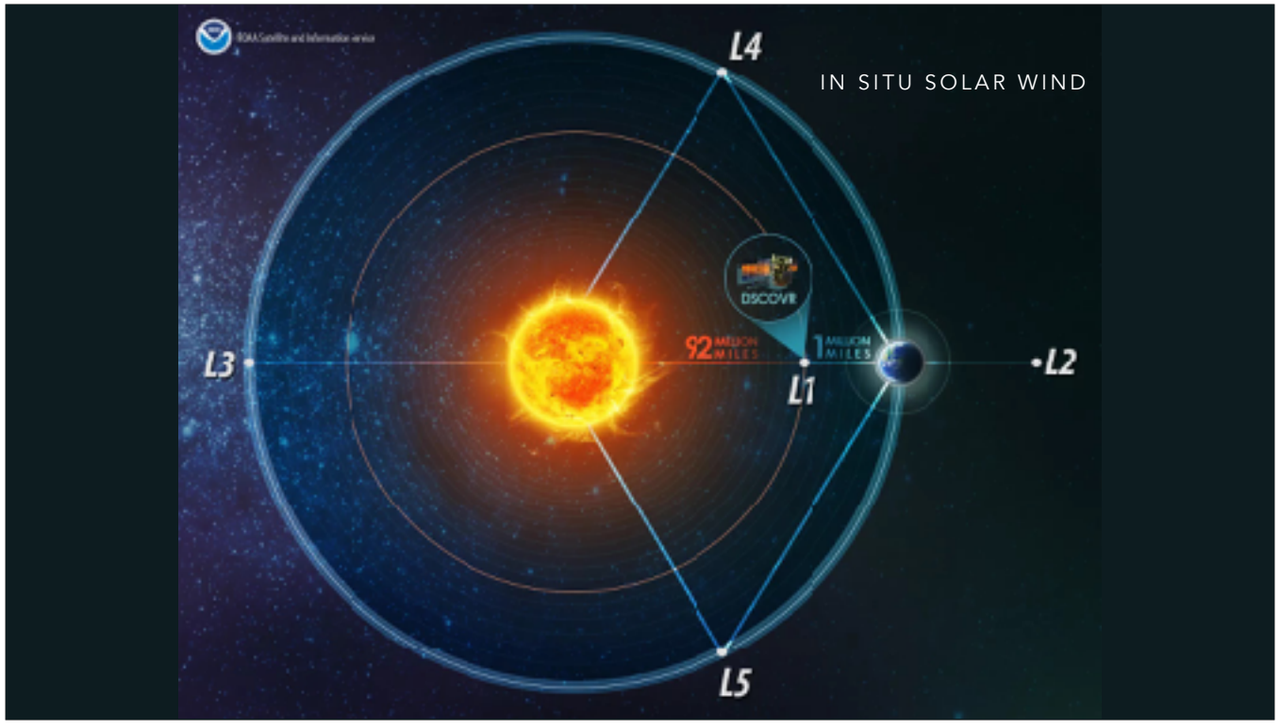
IN CORONAGRAPHS



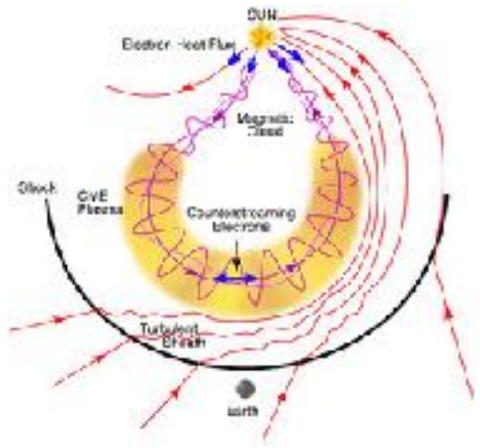
SOHO / LASCO c2

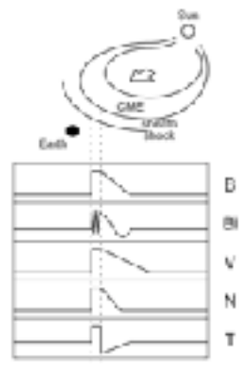
running difference

CMEs cause the most extreme geomagnetic storms. Therefore, there is great interest in understanding the properties of CMEs, especially when they have a halo signature around the solar disk that indicates the CME is aimed at Earth.
Furthermore, if the CME results in a magnetic cloud with a strong and out of ecliptic magnetic field, forecasts are likely for strong to extreme storms.


L4
IN SITU SOLAR WIND
DSCOVR
92 MILLION MILES
1 MILLION MILES
L3
L1
L2
L5

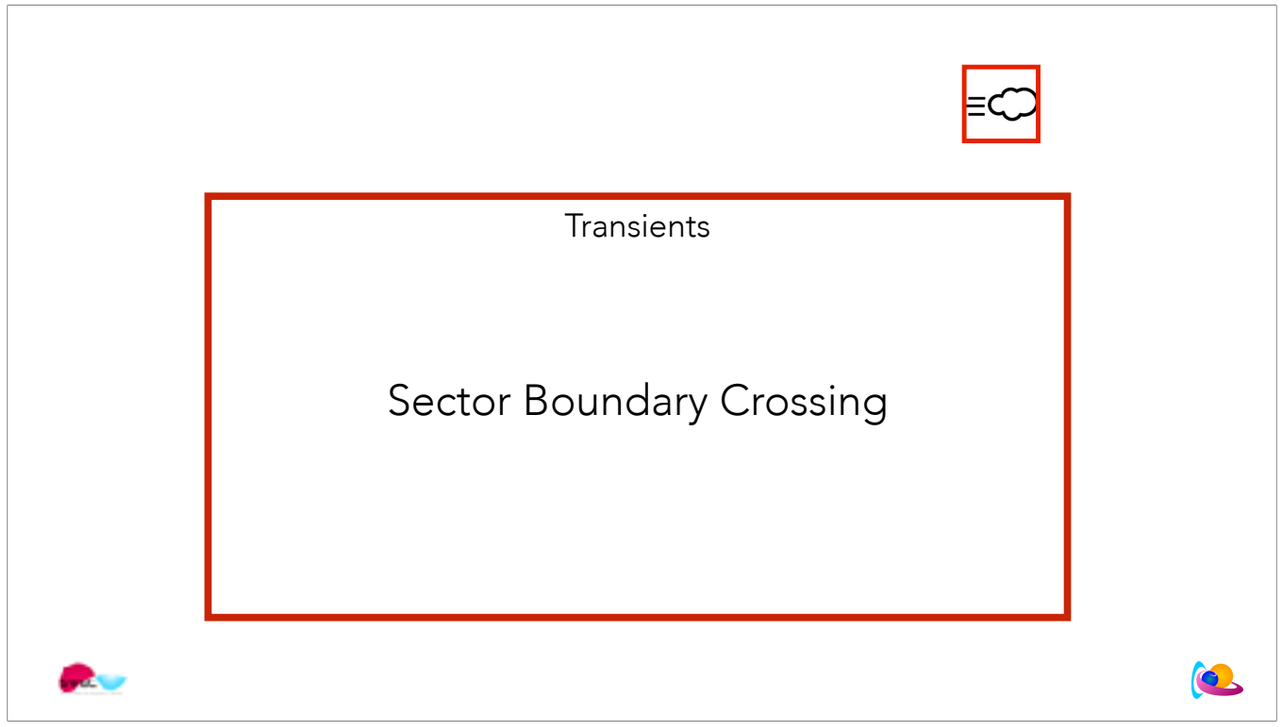
INTERPLANETARY CORONAL MASS EJECTION - ICME



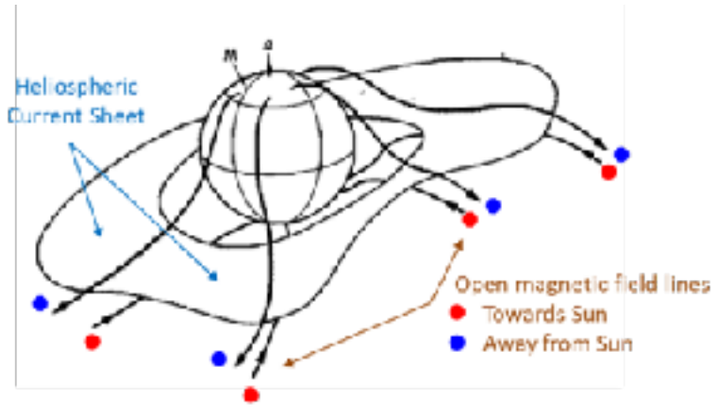


DIFFERENCES

ICME	CIR
Expanding	Compressing
Declining speed profile	Increasing speed profile
Low T (wrt V)	High T
High B (any value above 10 nT)	High B (until ~20nT)
CME	CH (also previous rotation)
Rotation in B	High variation in B
CMEs and CIRs can interact	


Transients
Sector Boundary Crossing

HELIOSPHERIC CURRENT SHEET

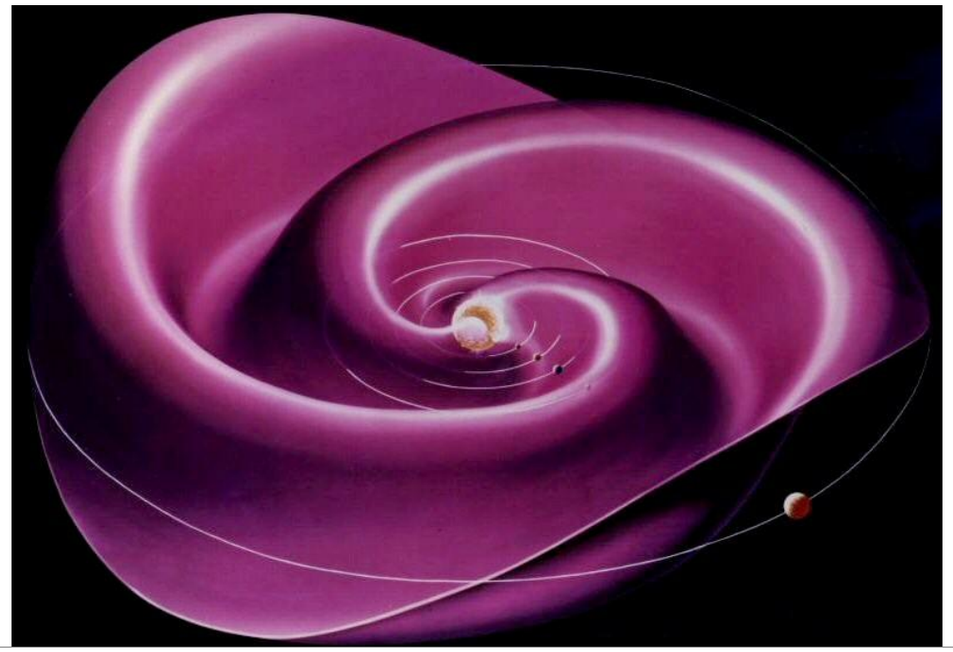


Adapted from Smith et al., 1978

The heliospheric current sheet is a layer between regions with opposite magnetic field lines.
The heliospheric current sheet is in a perfect world a flat sheet, perpendicular on the dipole axis of the Sun.
The dipole axis is not the same as the solar rotation axis. The heliospheric current sheet is therefore not the same plane at the solar equatorial plane.

And there is also the third plane: the ecliptic plane. This is plane in which the earth orbits the sun.

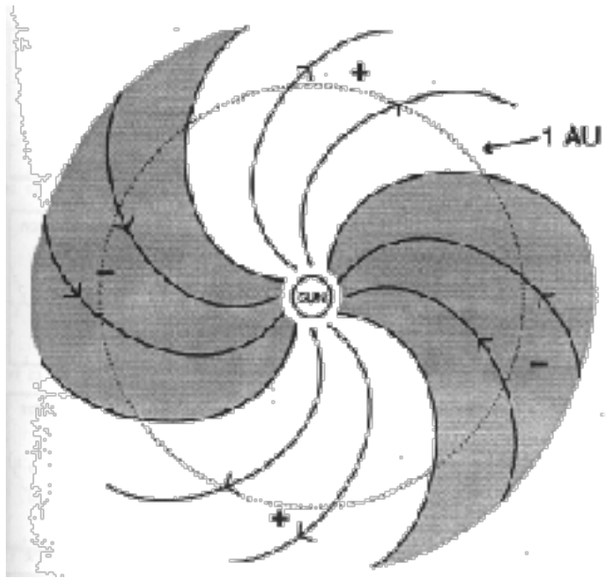
BALLERINA SKIRT



Neither the solar rotation axis nor the effective dipole axis are perpendicular to the ecliptic plane. Accordingly, 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 (towards/away) of the magnetic field. This wavy pattern of the current sheet is sometimes referred to as the “ballerina skirt" .

In this picture, you see 2 waves. There can be more.

AWAY/TOWARDS SECTORS

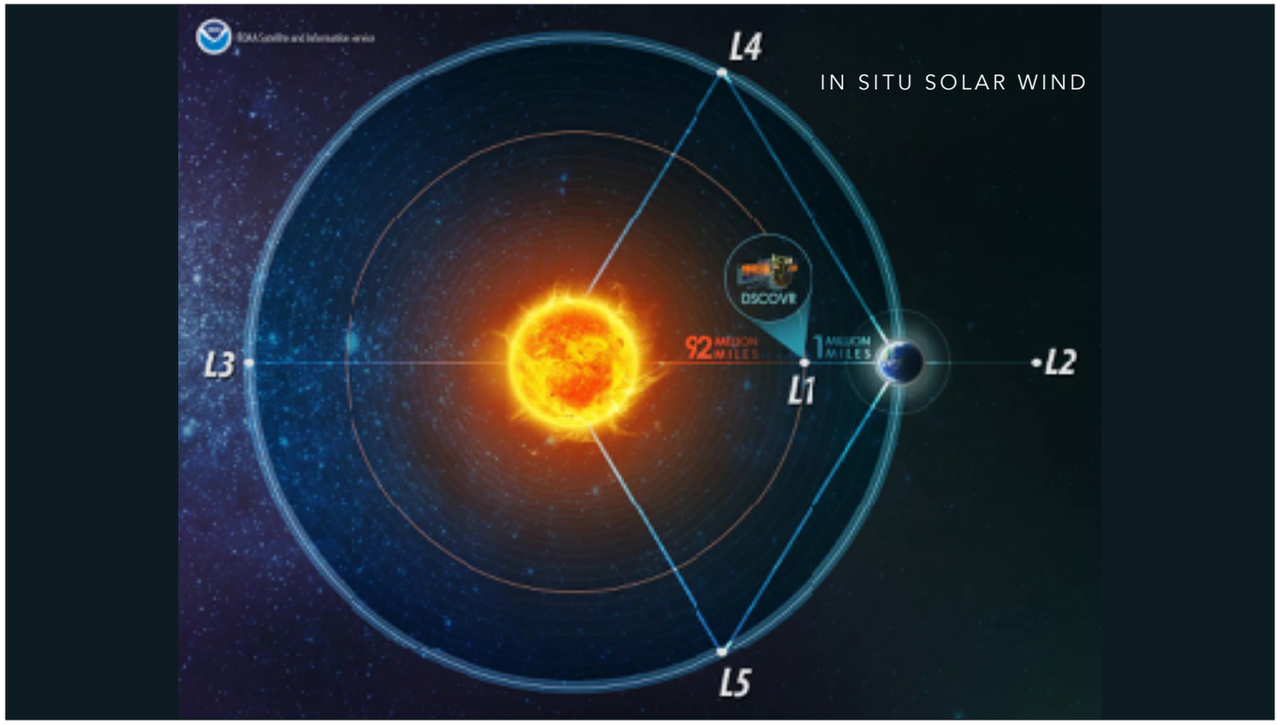


Cravens, 1997

distinct, long-lasting intervals of uniform solar wind field direction exist, called ``sectors''

Going from one sector to another, changes in the **plasma density** and the **direction (towards/away) of the magnetic field** occur.

When you pass from one sector to another sector, the density and Bz of the solar wind measured at the L1 point by ACE or DSCVR can change and have a geomagnetic impact. But in general, sector boundary crossings do not do much.


L4
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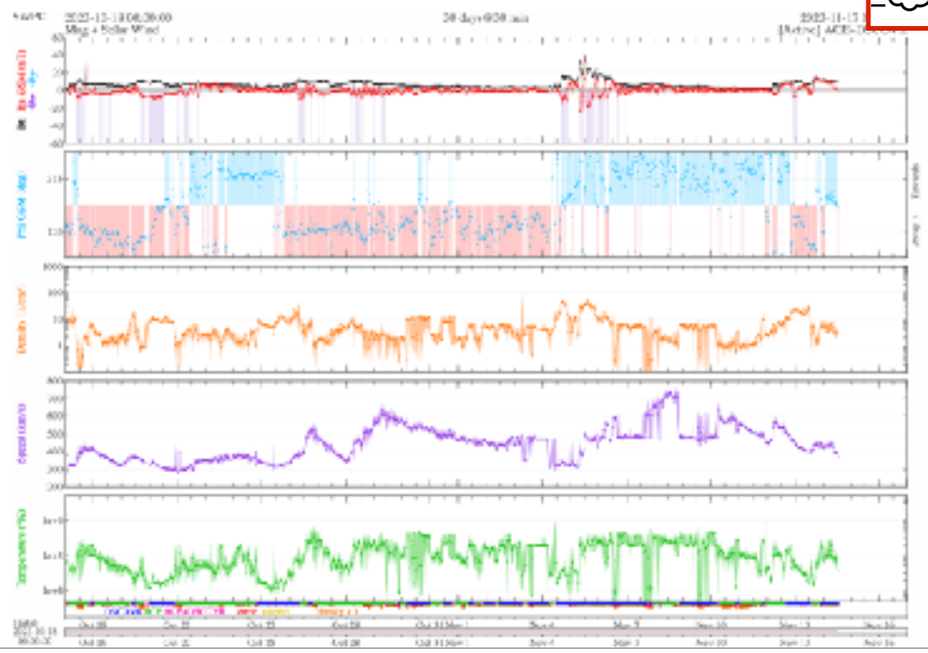
IN SITU

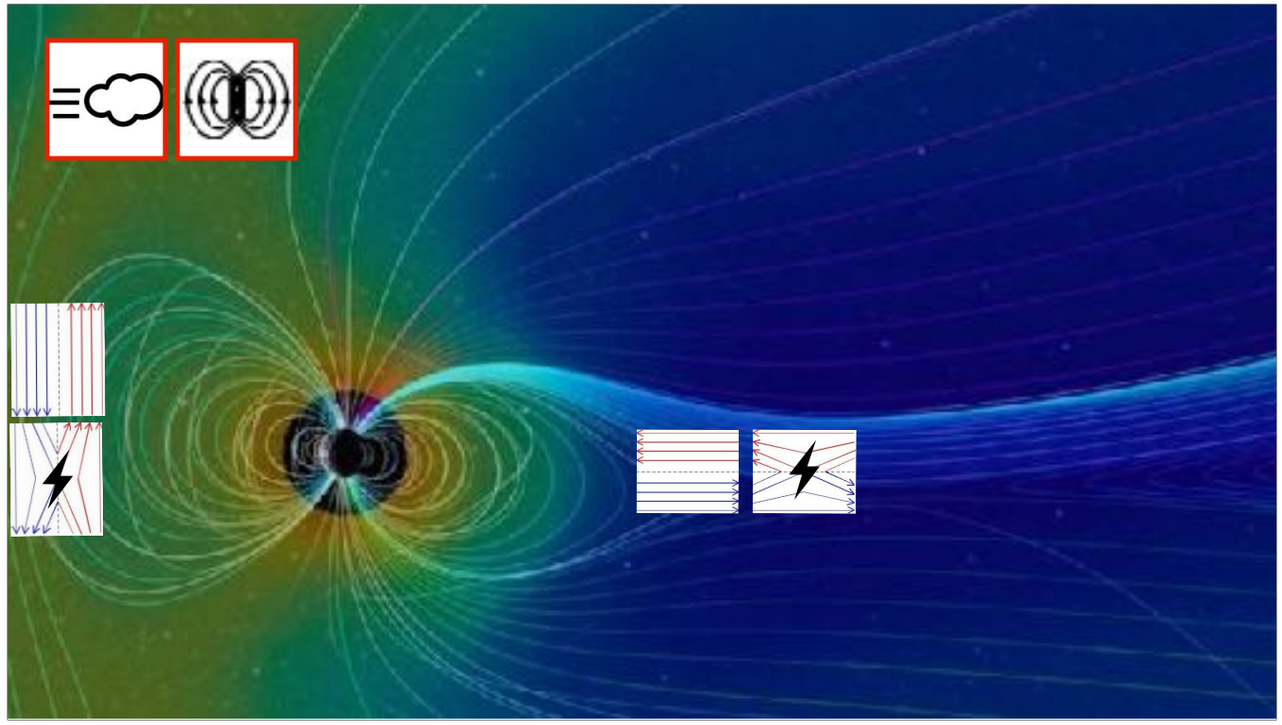


GEOMAGNETIC STORM

Solar wind meets the Earth
Geoeffectivity

Ap Kp Dst

Can you give a few ‘markers’/geomagnetic indices for the strength of a geomagnetic storm



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.

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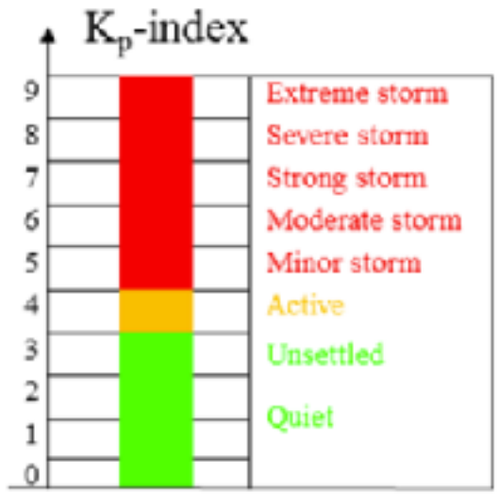
1 to 5 nT – IMF at L1

STORM SCALE - GEOMAGNETIC CONDITIONS



GEOMAGNETIC CONDITIONS

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

http://ionosphere.meteo.be/geomagnetism/K_BEL/

SOLAR WIND

Questions

SOLAR WIND

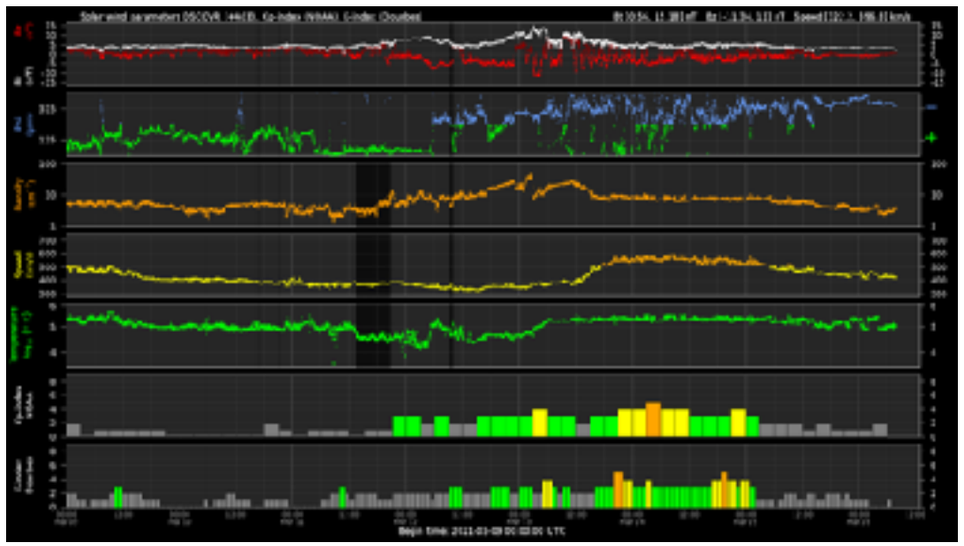
Name 3 transients

SOLAR WIND

Name a satellite that measures the solar wind at L1

SOLAR WIND

Name the 5 panels in ACE or DSCVR graphs.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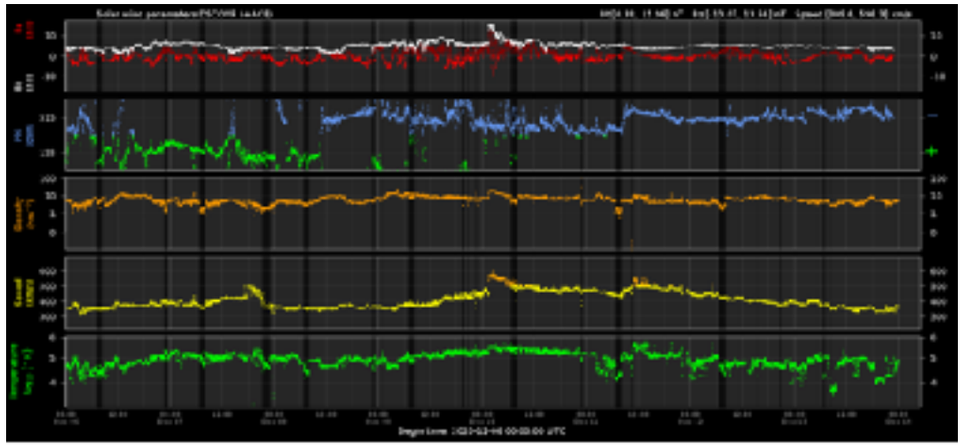

SOLAR WIND

Name 3 clearly distinct places where magnetic reconnection takes place.