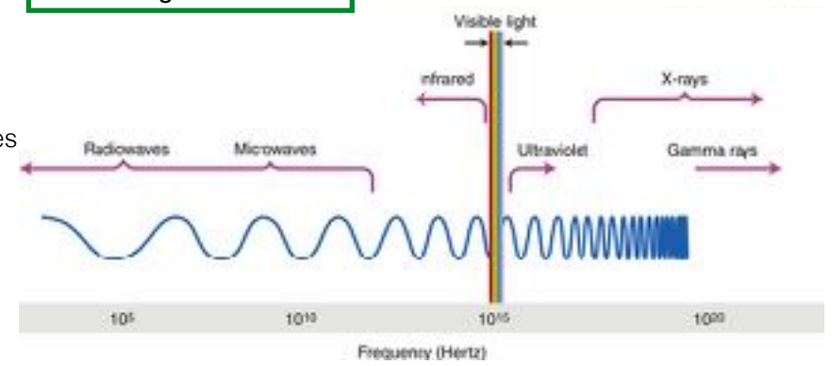
SOLAR WIND

What

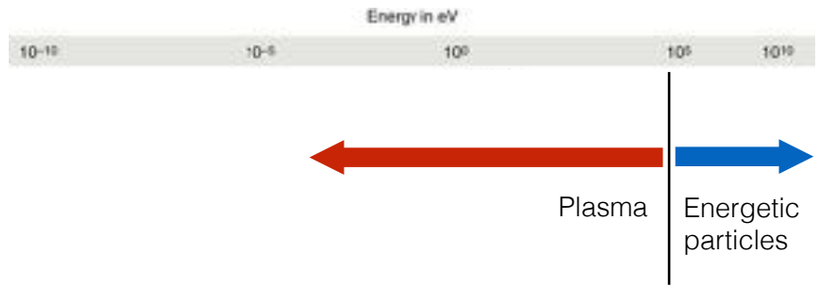
Electromagnetic radiation

- Photons / electromagnetic waves
- Speed of light

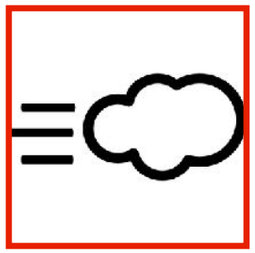


Particles

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



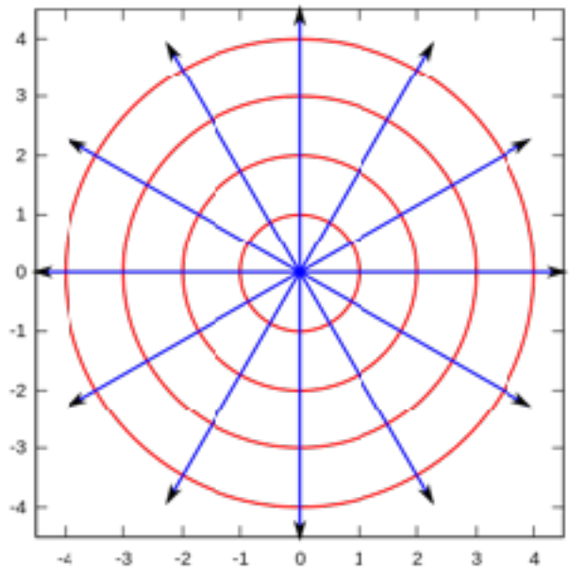
100 kEV

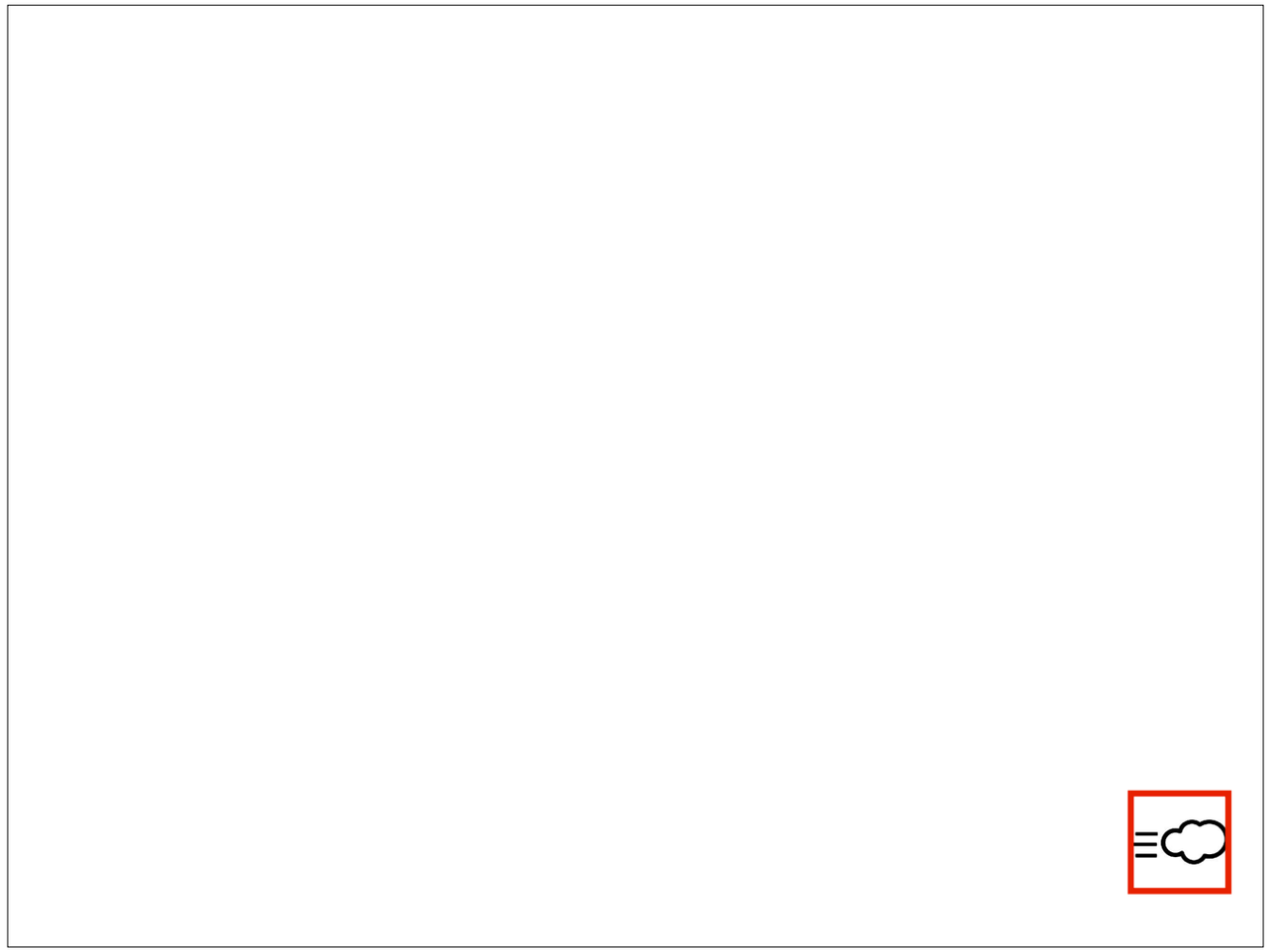


Outward moving plasma

RADIAL SOLAR WIND

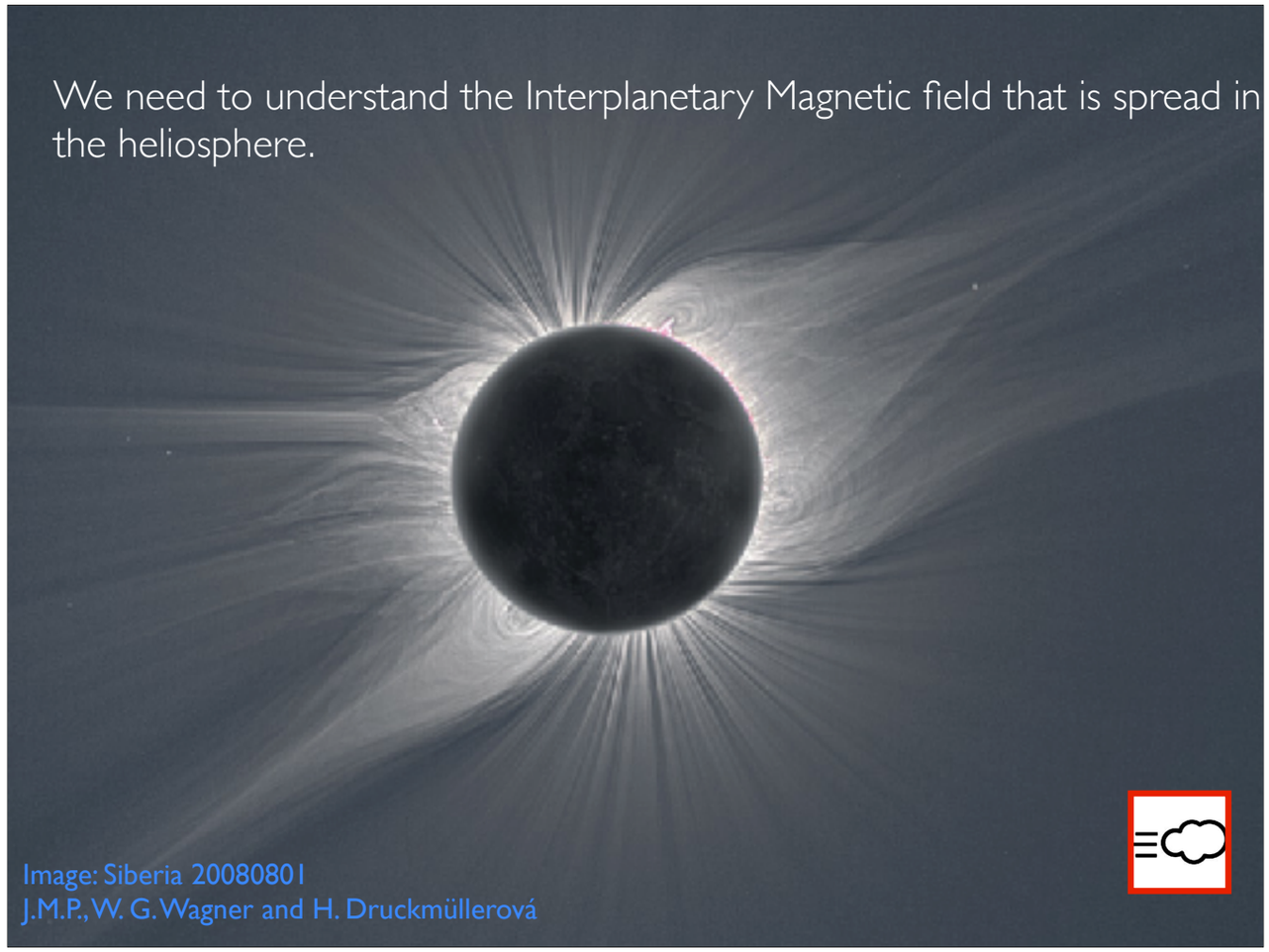
The solar wind carries out solar material and solar magnetic field. The solar material and magnetic field becomes less dense the further away from the Sun.





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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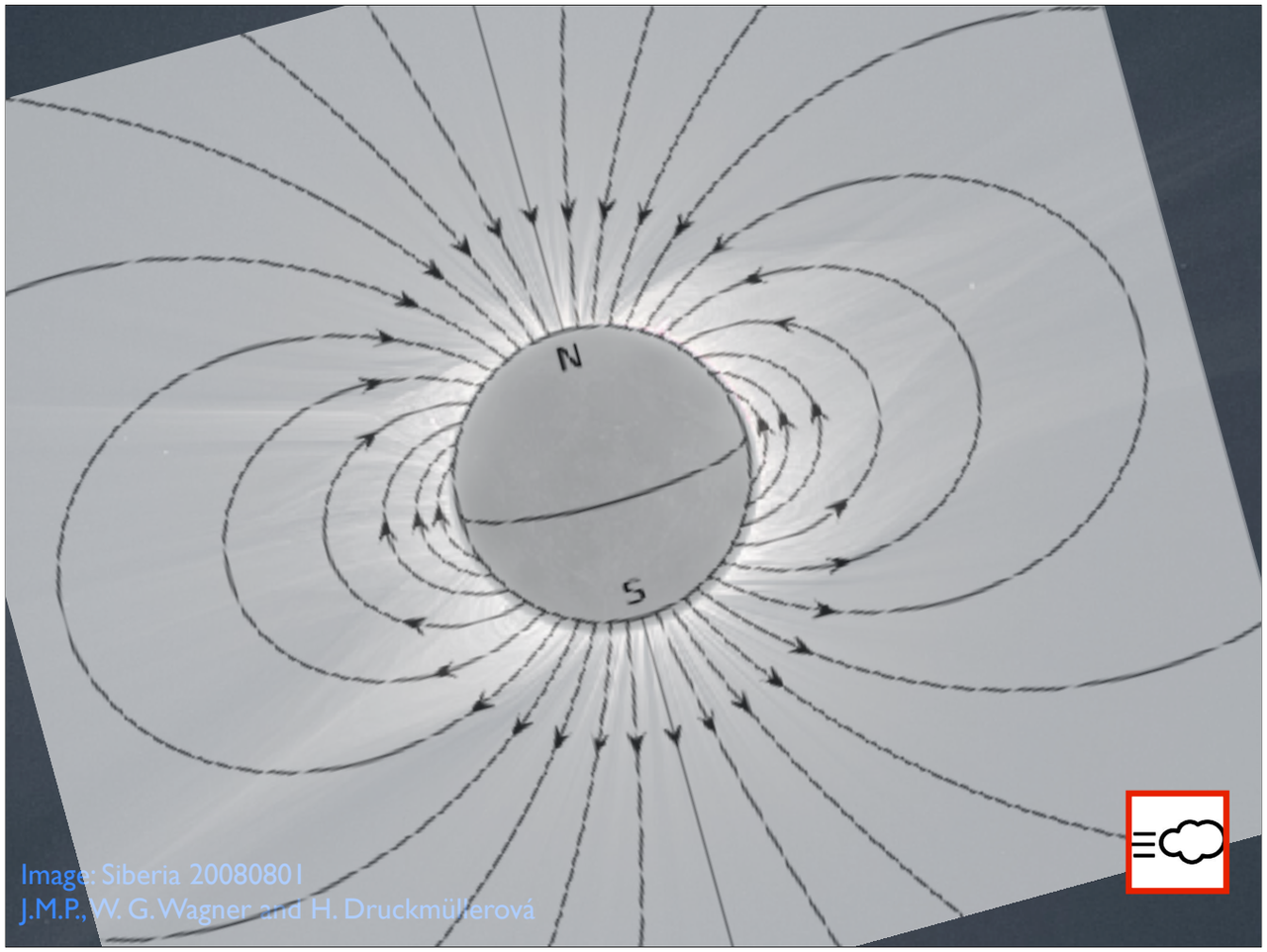
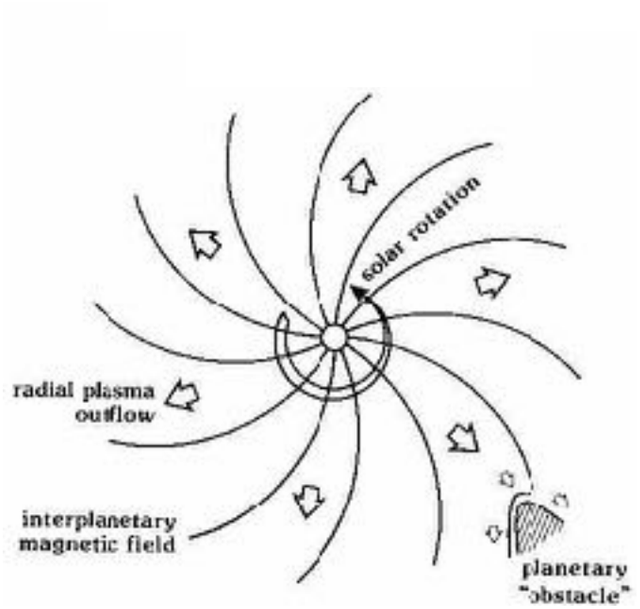


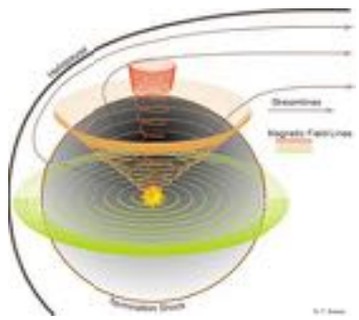
Image: Siberia 20080801
J.M.P., W. G. Wagner and H. Druckmüllerová

Magnetic forces

PARKER SPIRAL

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

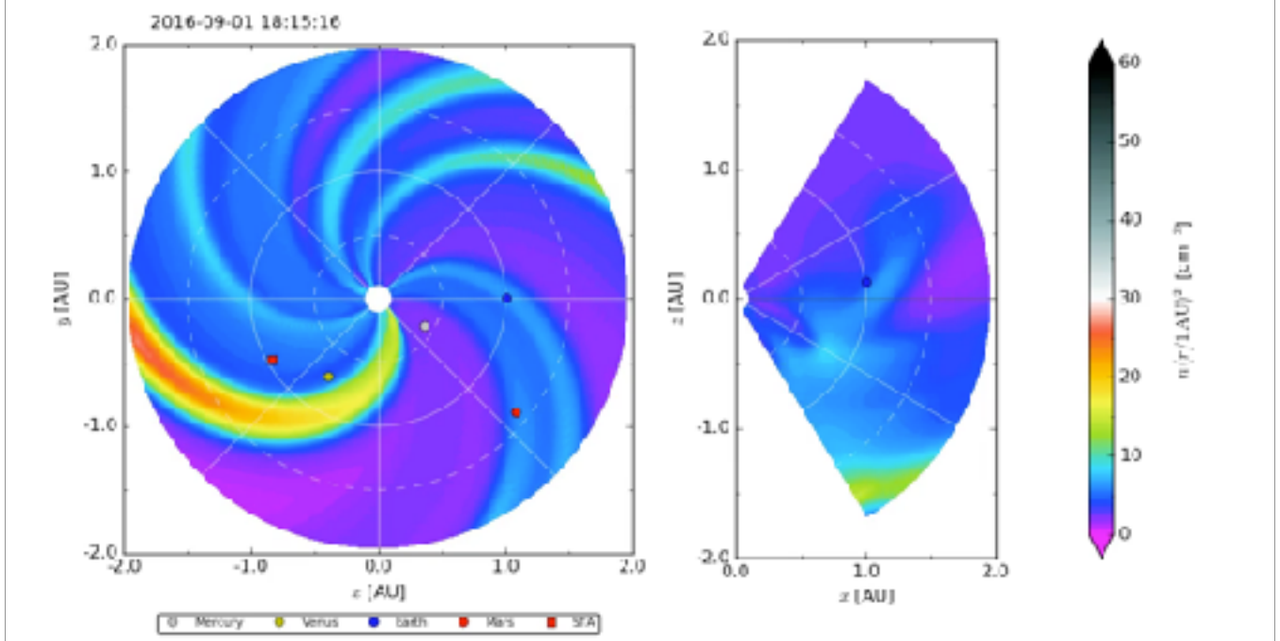




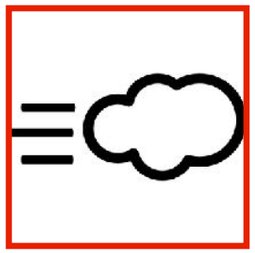
Left: This is a view of the global IMF in the solar equatorial plane.
Right: The IMF and our space is 3D. You have at a particular latitude also IMF lines coming out. Also these lines bend because of the solar rotation. All IMF lines at a particular latitude form a magnetic coin. The solar equatorial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



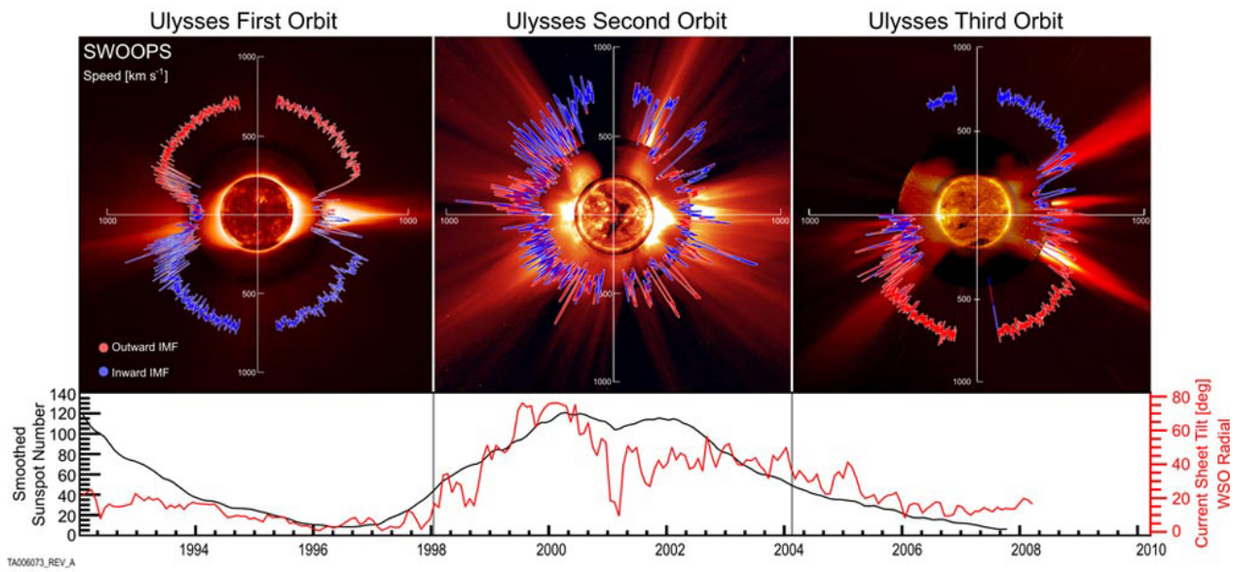
EUHFORIA, realtime simulations of the inner heliosphere



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.

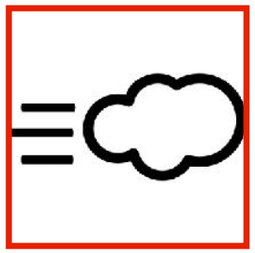
During solar maximum: global and local magnetic field mingle strongly. The solar wind looks more like a mess.

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.

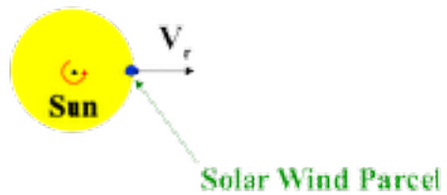
SLOW versus FAST

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



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

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



Arge, 2018

The Solar Wind and the Interplanetary Magnetic Field
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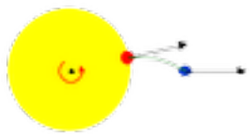

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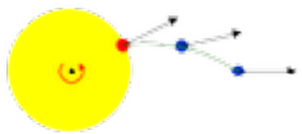

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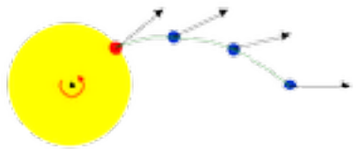

Arge, 2018

The Solar Wind and the Interplanetary Magnetic Field
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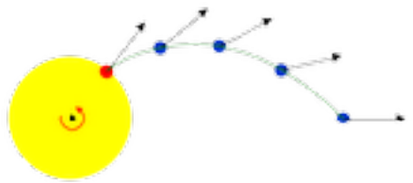

Arge, 2018

The Solar Wind and the Interplanetary Magnetic Field
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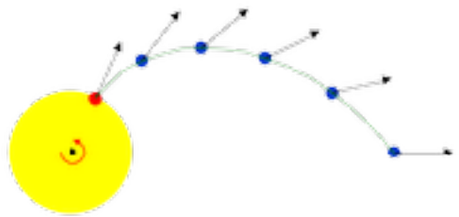
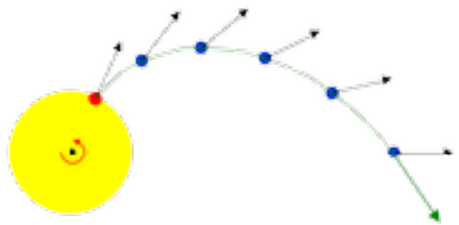


Arge, 2018

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



Arge, 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.

Is the IMF Straight/Bended?

IMF are open/closed magnetic field lines?

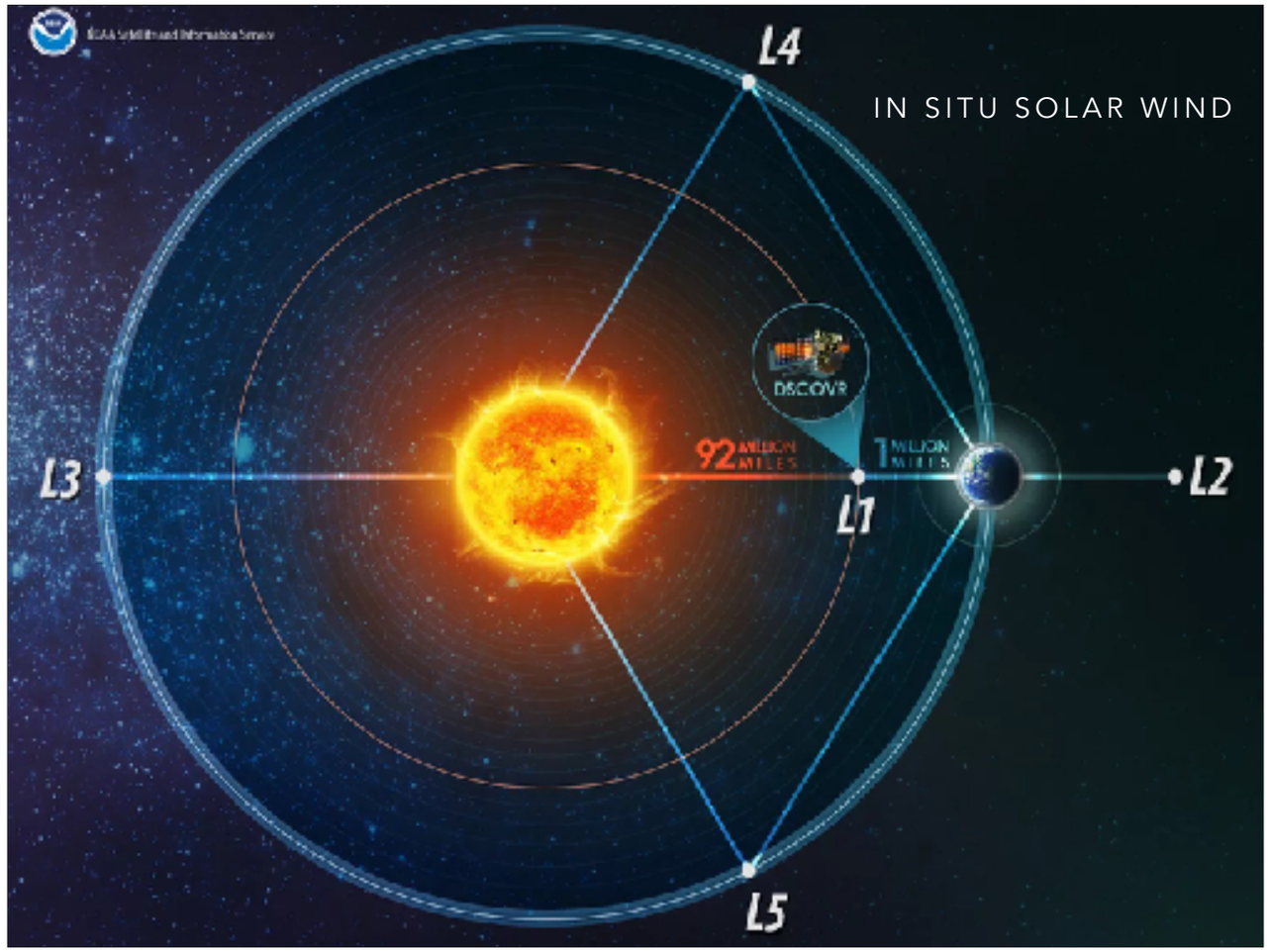
Radial outflow: linked to open magnetic field lines
Example of a Magnetic structure: a CME

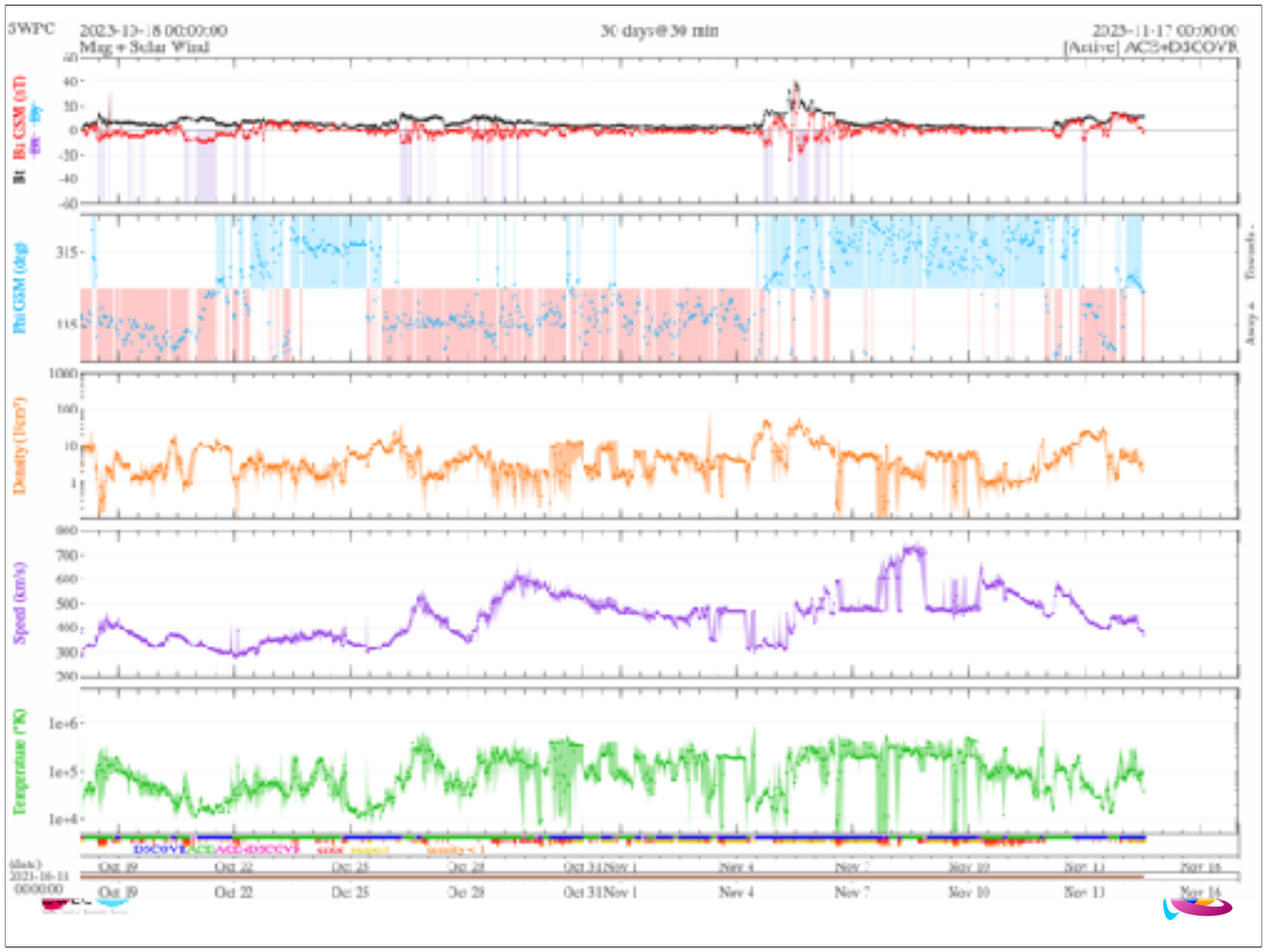
The solar wind plasma is glued to the IMF - or the IMF is glued to the plasma.

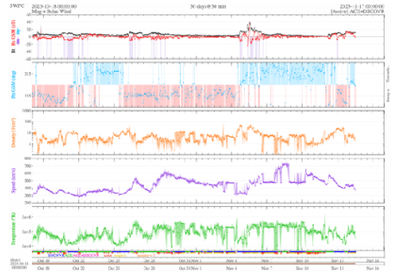
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fils the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you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

SOLAR WIND

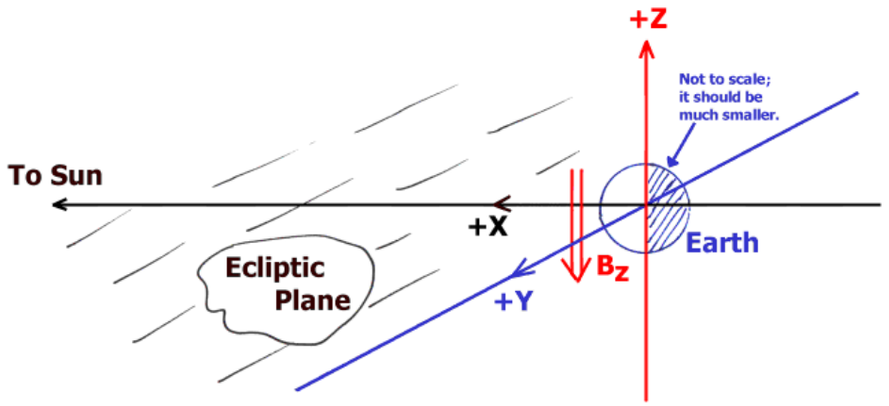
Near Earth


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


SWPC
2023-10-18 00:00:00
Mag + Solar Wind
30 days@30 min
2023-11-17 00:00:00
[Active] ACE+DSCOVR
Bt
Bx GSM (nT)
By
Bz
Phi GSM (deg)
Density (/cm³)
Speed (km/s)
Temperature (K)
Oct 19
Oct 22
Oct 25
Oct 28
Oct 31
Nov 1
Nov 4
Nov 7
Nov 10
Nov 13
Nov 16



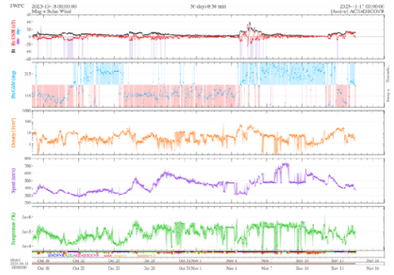
COORDINATE SYSTEM



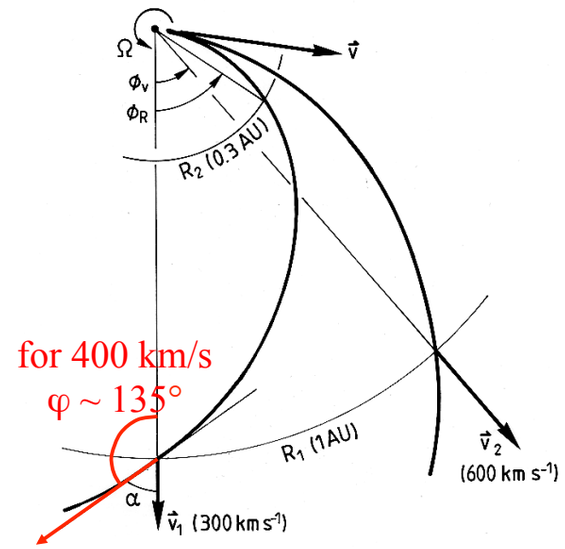
+Z is perpendicular to the Ecliptic Plane.

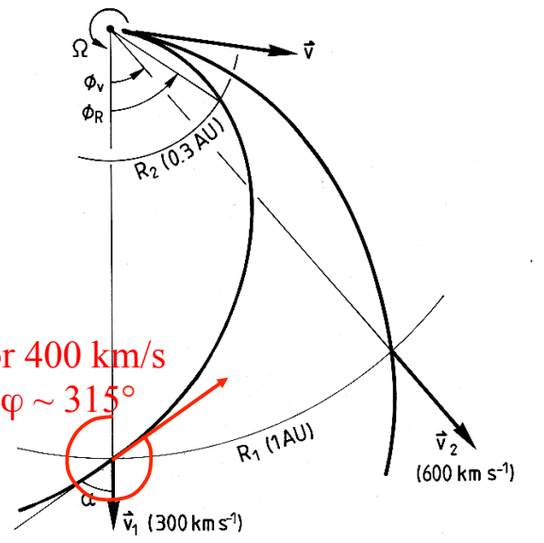
GSM: Geocentric Solar Magnetospheric System. This has its X-axis pointing from the Earth toward the Sun and its Y-axis is chosen to be in the ecliptic plane pointing towards dusk (thus opposing planetary motion). Its Z-axis is parallel to the ecliptic pole. Relative to an inertial system this system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

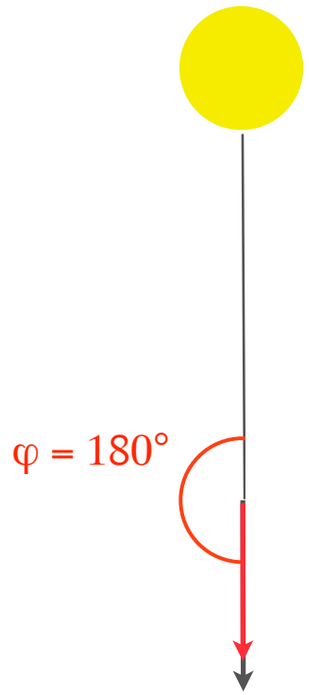




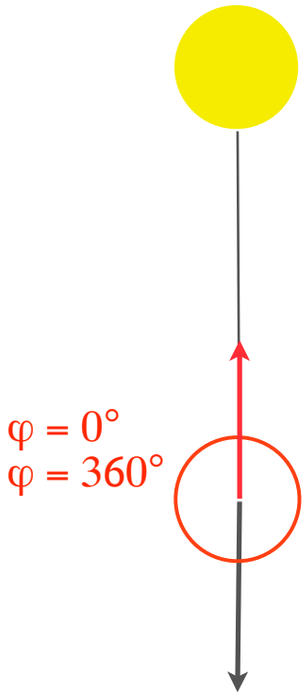
This is the IMF

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

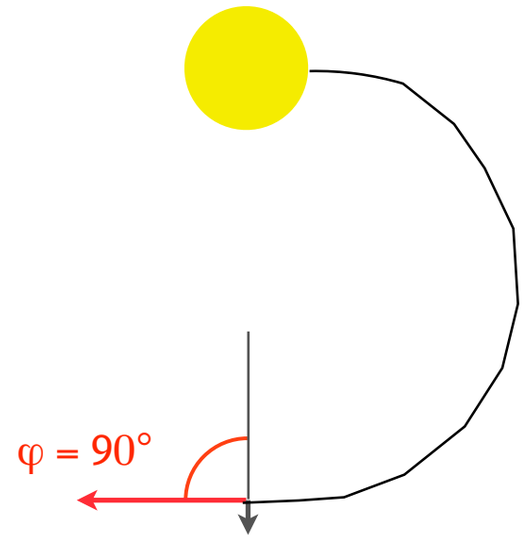
EXTREME FAST



EXTREME FAST



EXTREME SLOW



SOLAR WIND

Transients

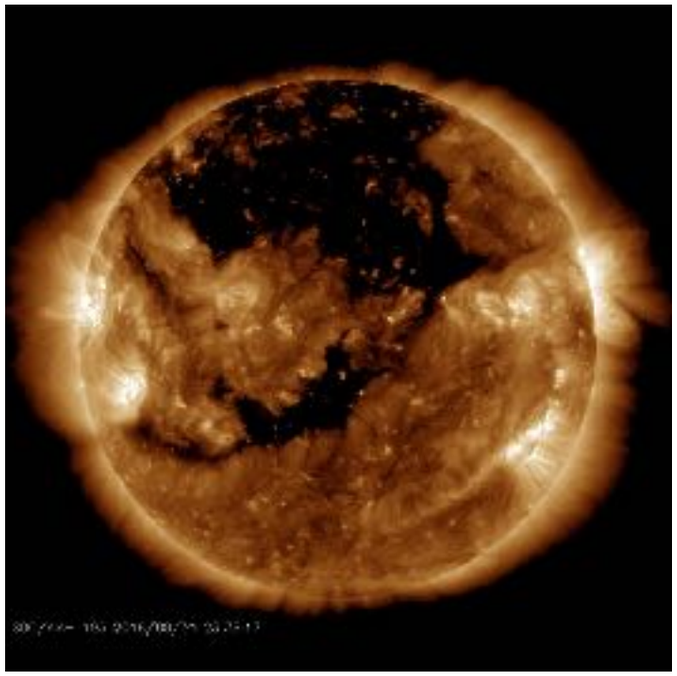
Transients

High Speed Streams (HSSs)

And

Co-rotating Interaction Regions (CIRs)

Coronal Hole



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

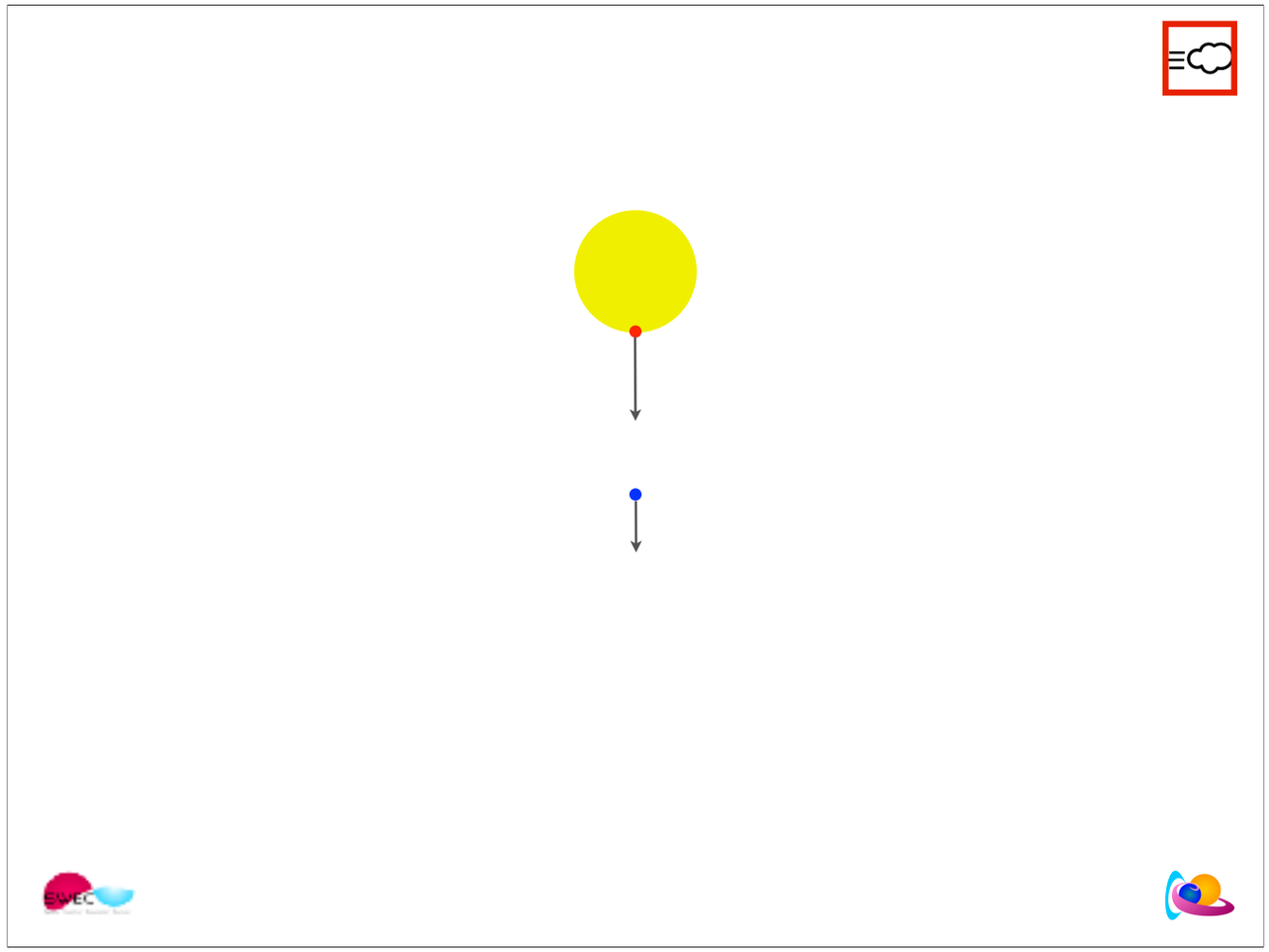
What is important determining when and how strong the impact of a CH will be:
- The heliographic latitude of earth
- The latitude of the CH on the solar disk: the part of a CH with a low latitude is important. Polar coronal holes have only an impact when they extent to lower latitudes.
- It is the material 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

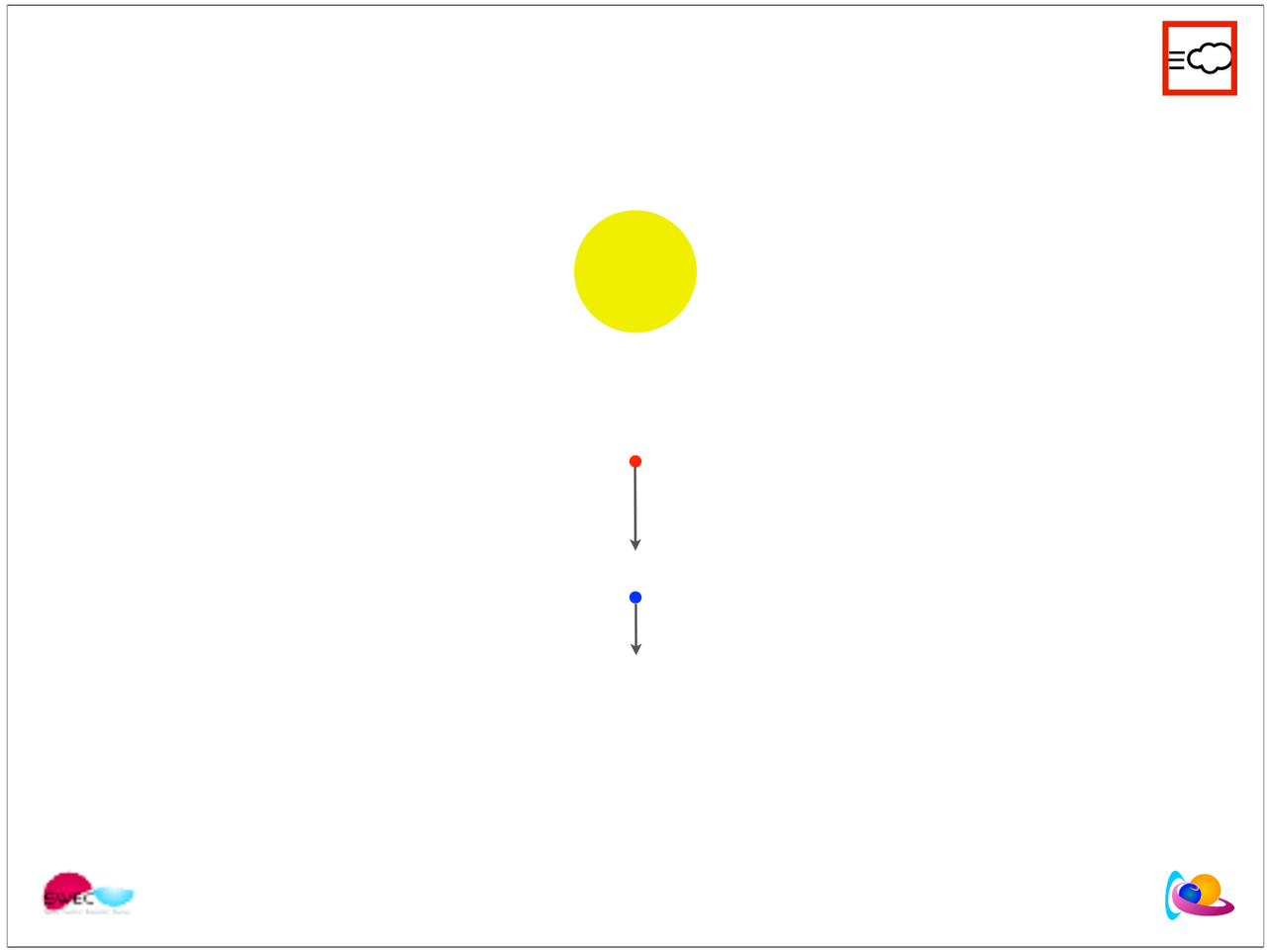
WHAT HAPPENS WHEN FAST CATCHES SLOW?

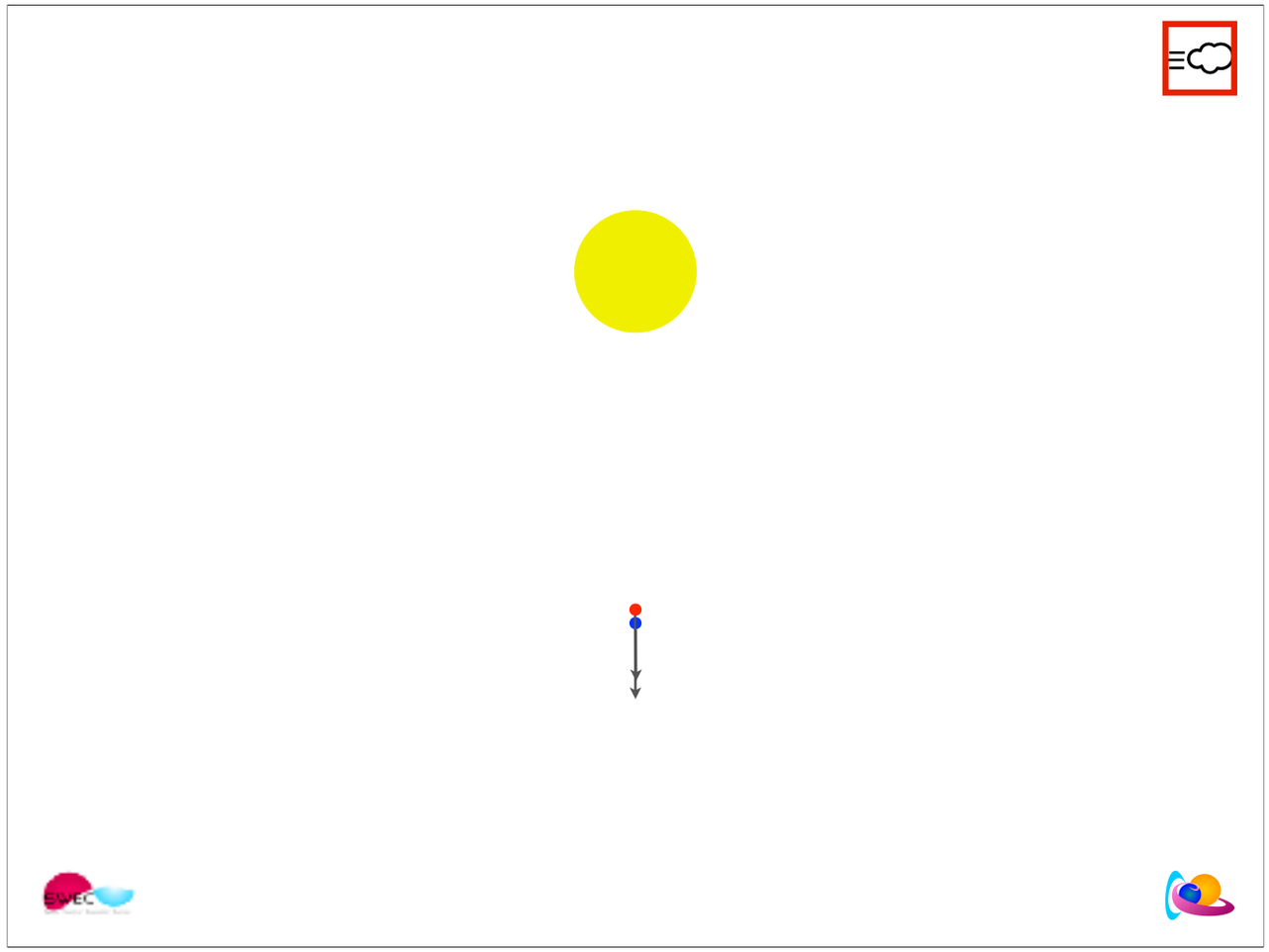
Top View

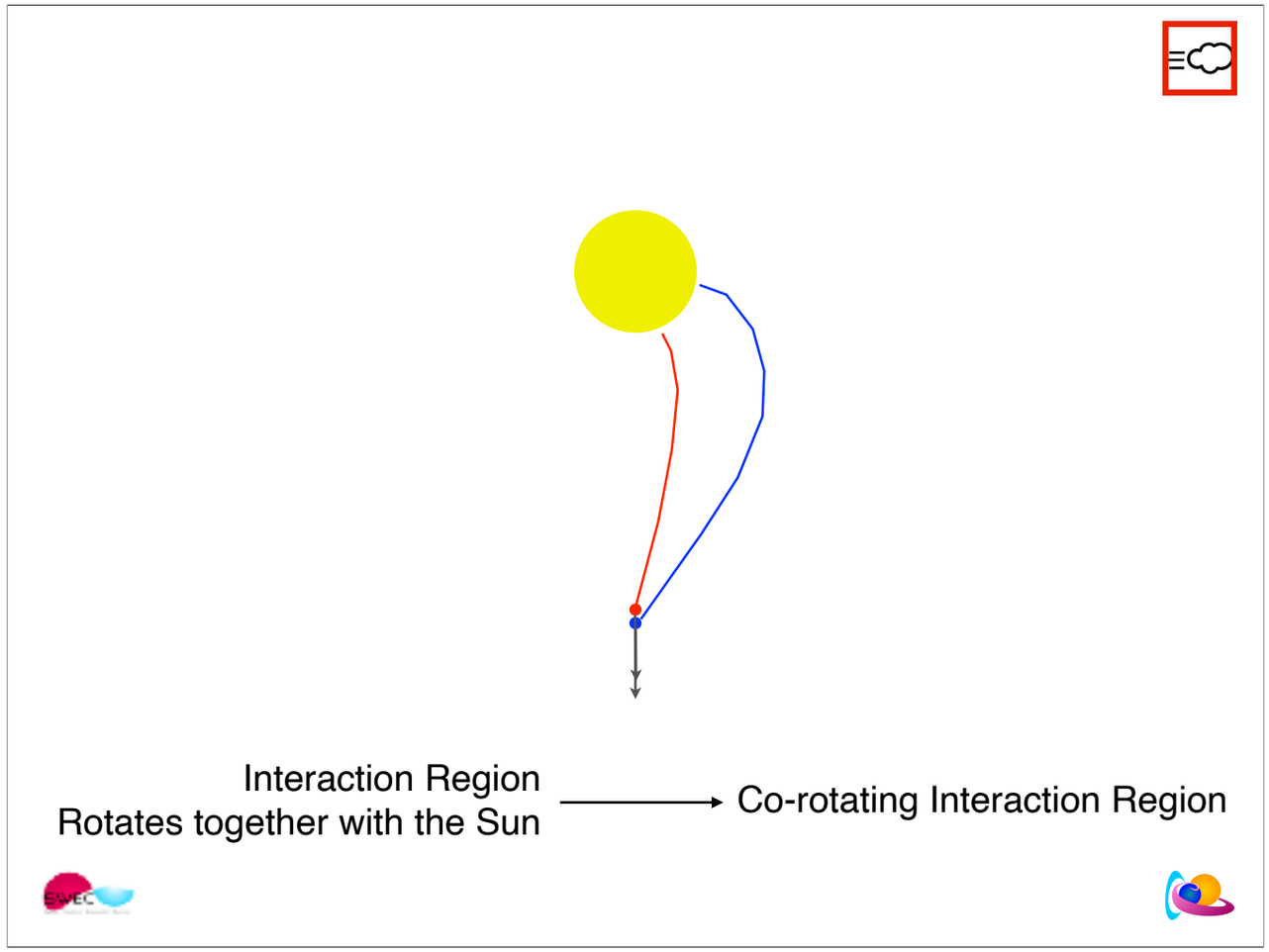
What happens when fast catches slow solar wind material?



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.







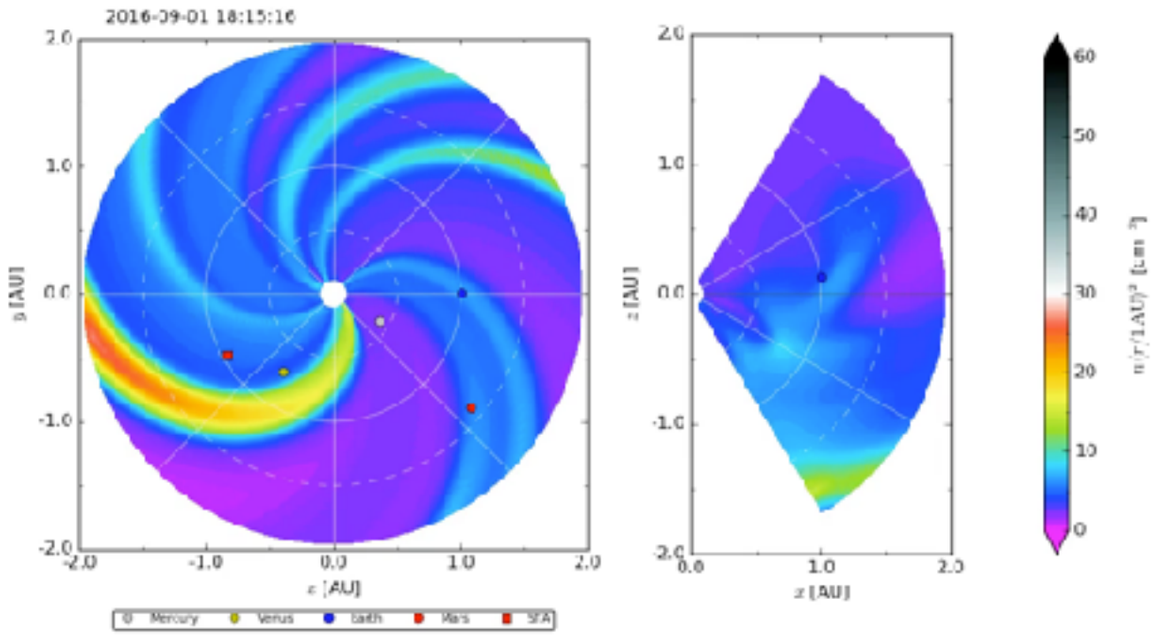
Continuous process - the source of the fast particles, i.e. stays present.

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

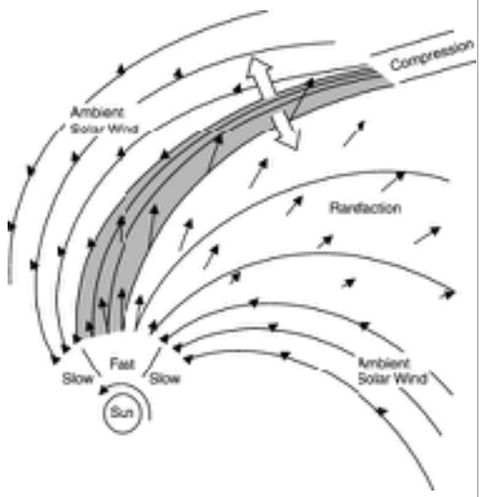
Co-rotating Interaction Region



EUHFORIA, realtime simulations of the inner heliosphere

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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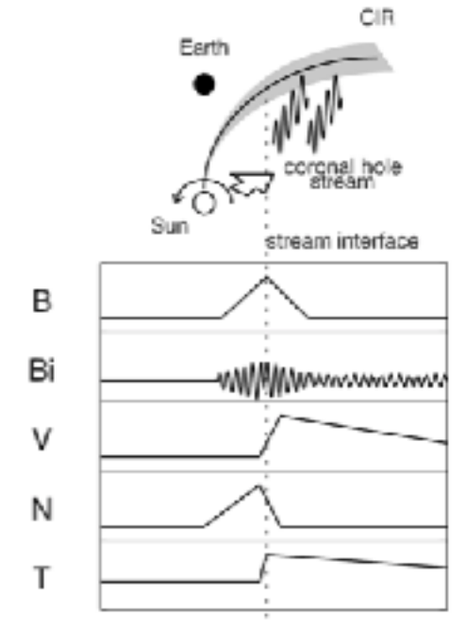
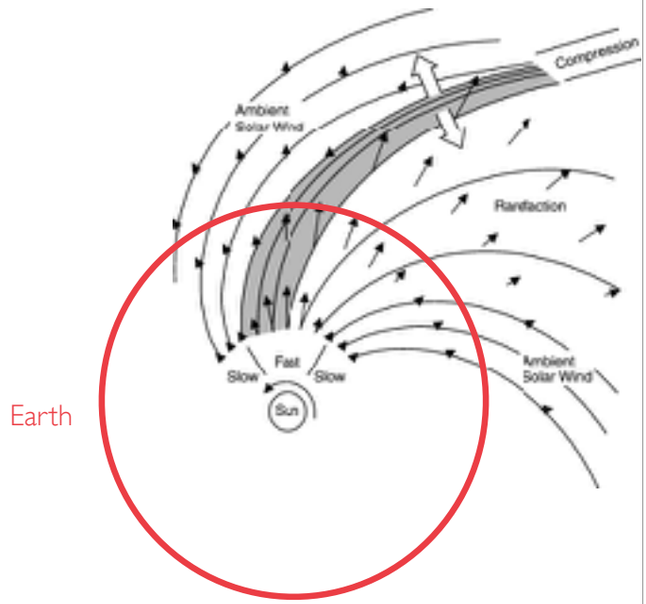
Co-rotating Interaction Region





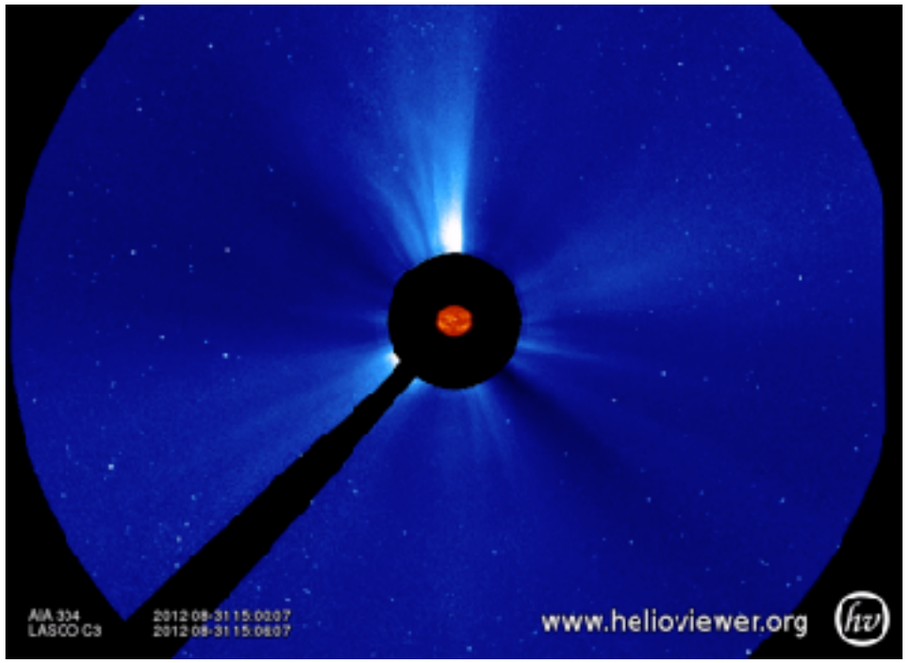
X-axis= where you are on the red circle, Arc length, time
At a point in space, e.g. : the total flux of mass is the same
—> v high, density low
—> v low, density high

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

High temperature

Transients

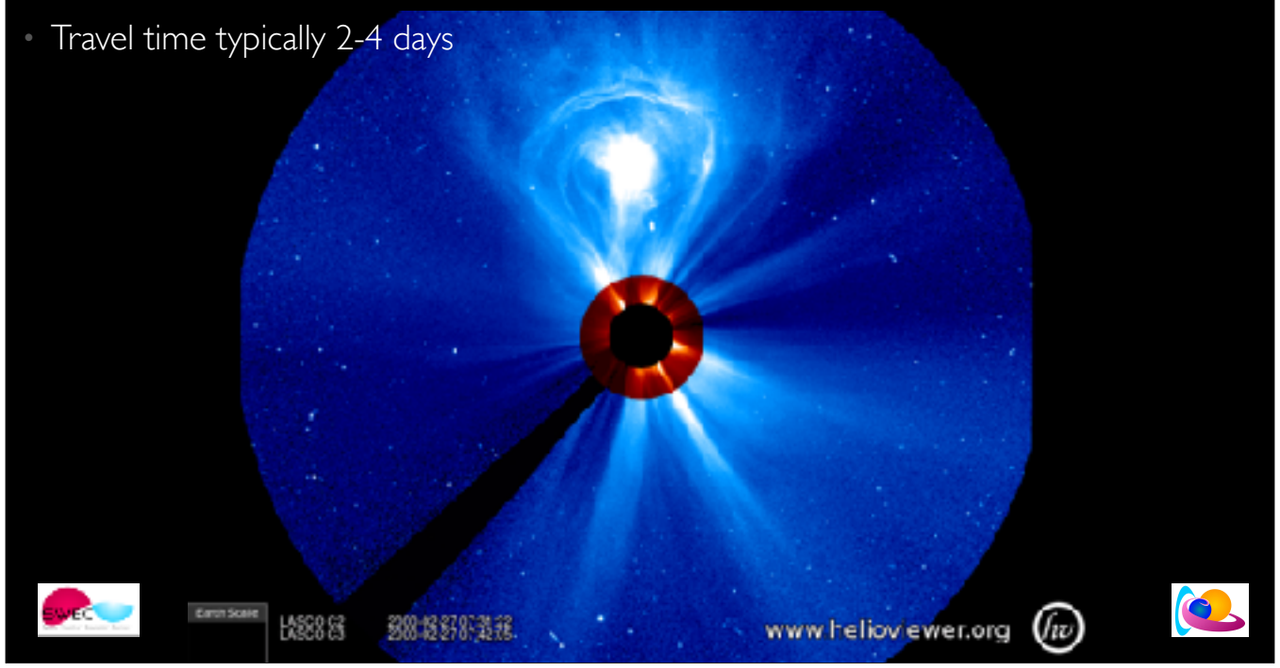
Coronal Mass Ejections



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

Eruptive - transient

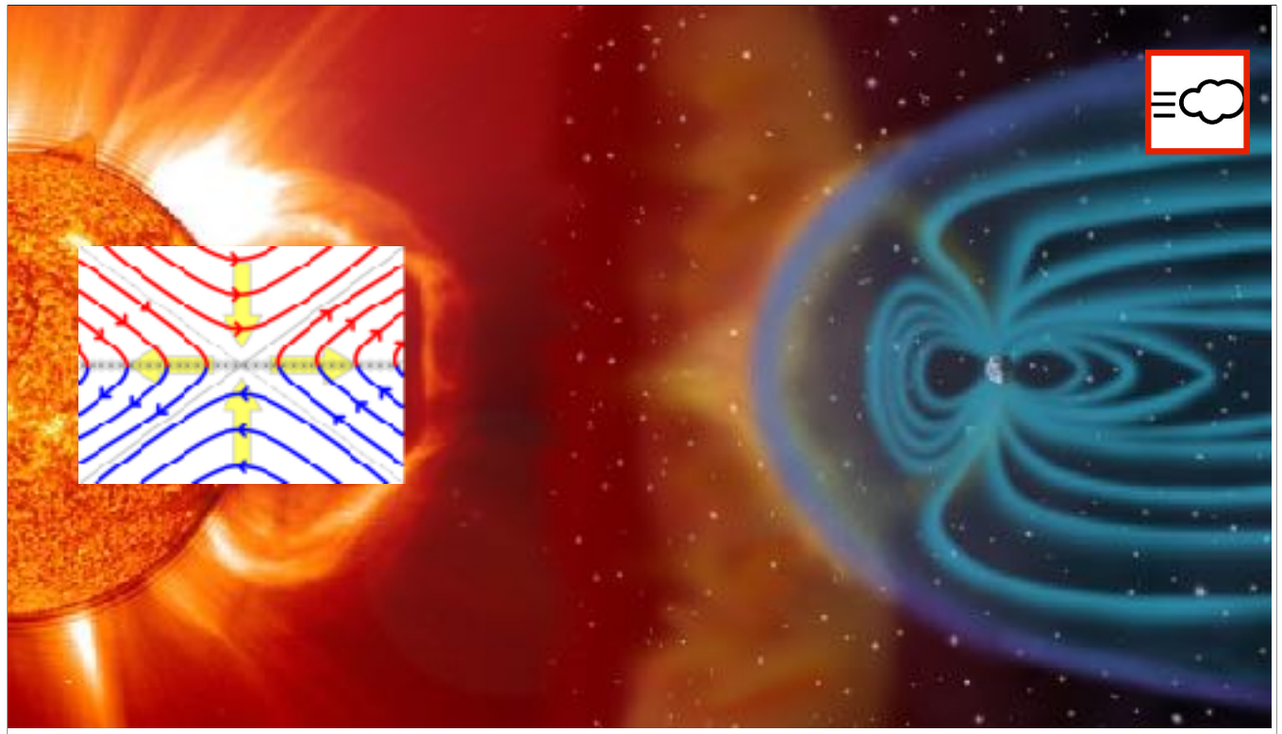
- Trigger the strongest geomagnetic storms
- <1/day during solar min, ~ 3 during solar max
- V between 400 and 2000 km/s
- Travel time typically 2-4 days



Transient: only lasting for a short time

Low density, but enormous and therefore massive.

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



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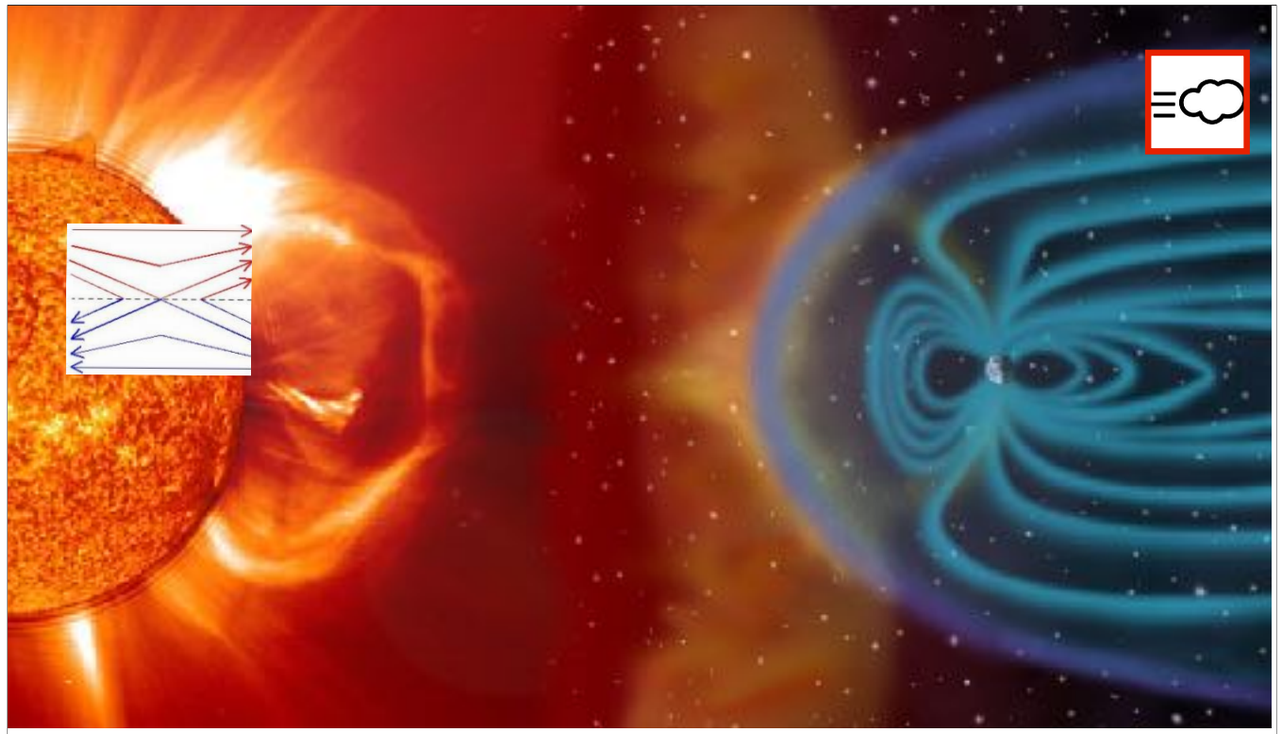

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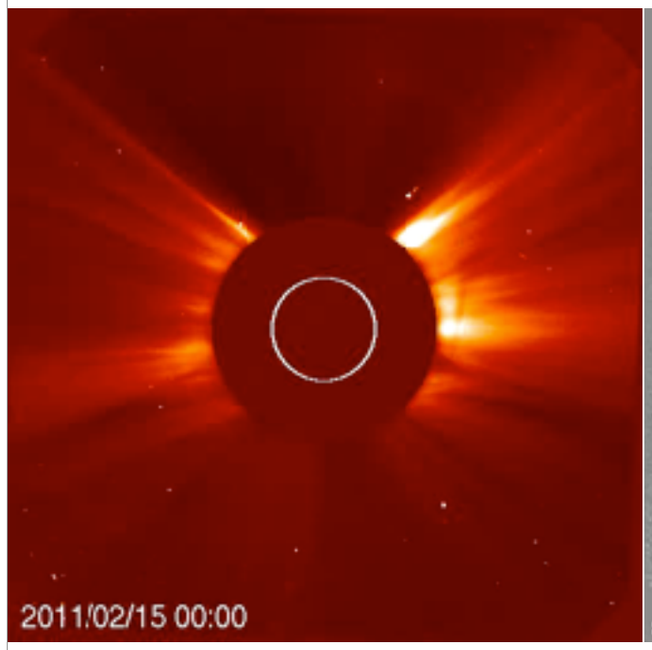
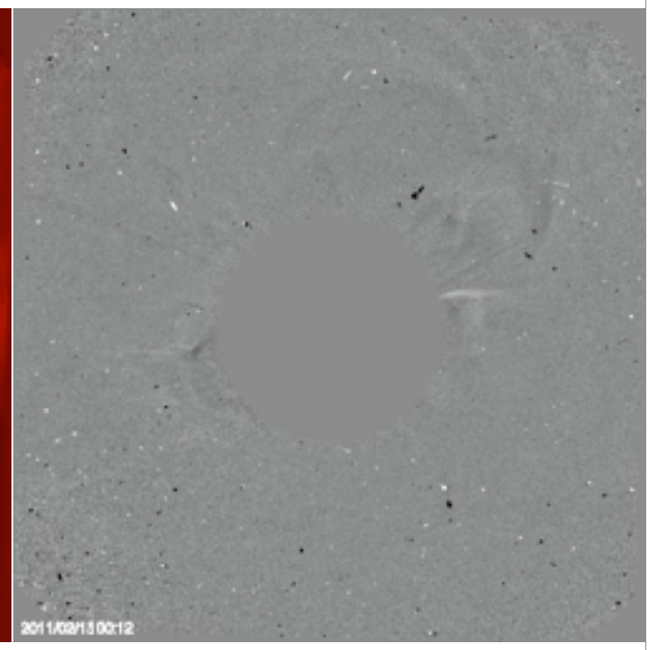
IN CORONAGRAPHS





SOHO / LASCO c2

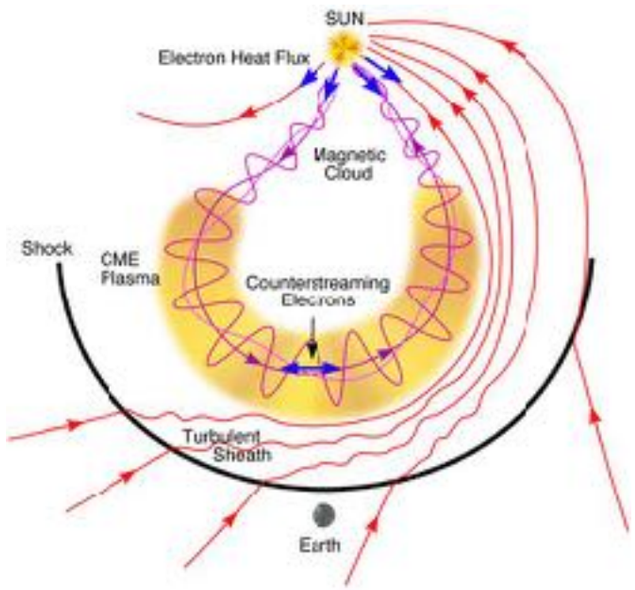
running difference

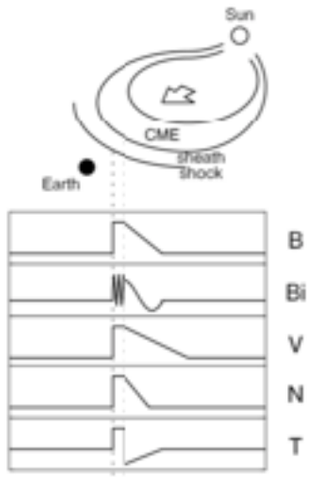
CMEs cause the most extreme geomagnetic storms. Therefore, there is great interest in understanding the properties of CMEs, especially when they have a halo signature around the solar disk that indicates the CME is aimed at Earth.
Furthermore, if the CME results in a magnetic cloud with a strong and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

HALO CME ALERT + PRESTO

SERVICES

INTERPLANETARY CORONAL MASS EJECTION - ICME





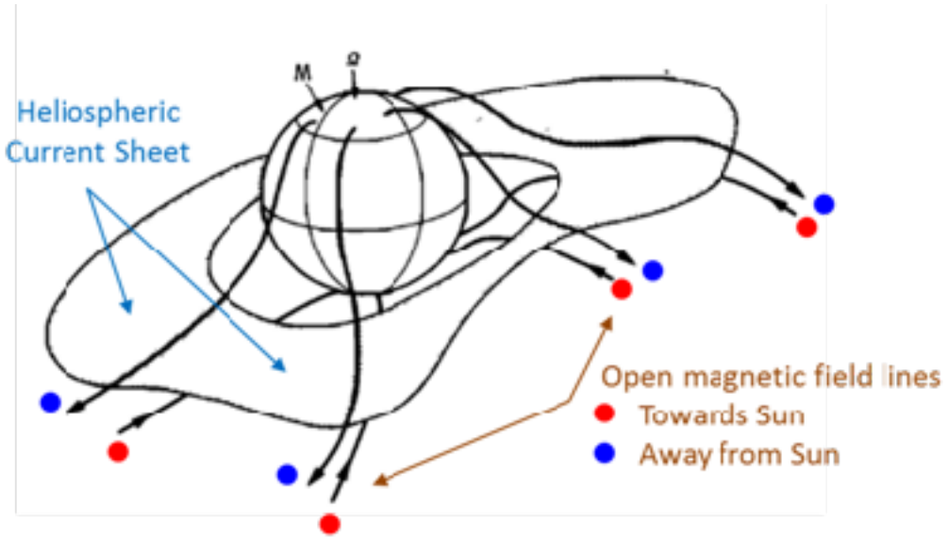
DIFFERENCES

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
ICMEs and CIRs can interact	

Transients

Sector Boundary Crossing

HELIOSPHERIC CURRENT SHEET

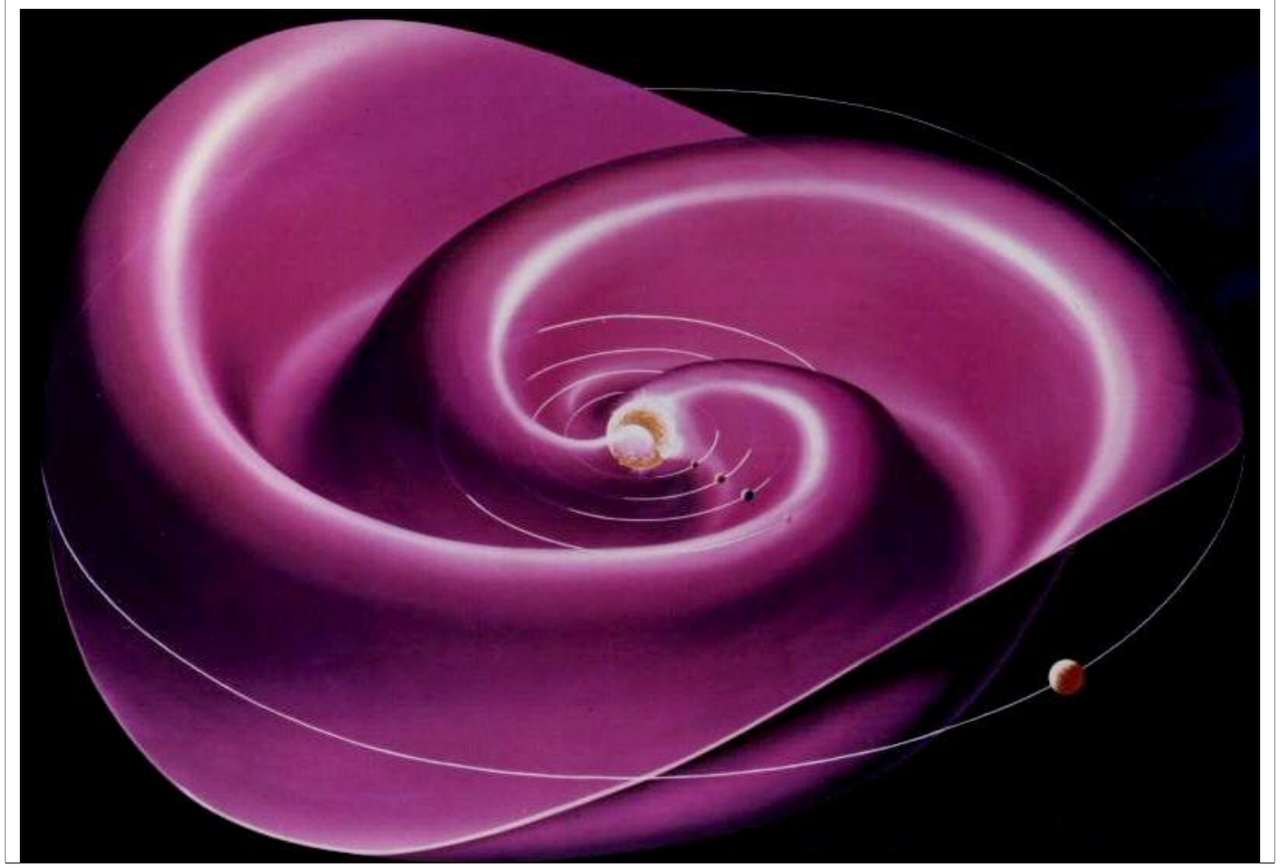


Adapted from Smith et al., 1978

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.

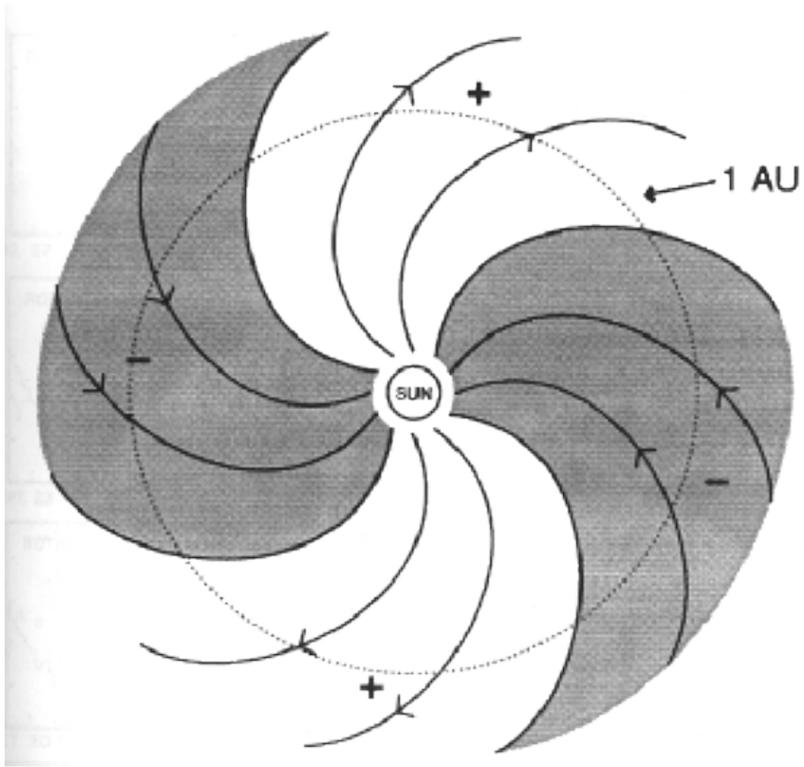
BALLERINA SKIRT



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



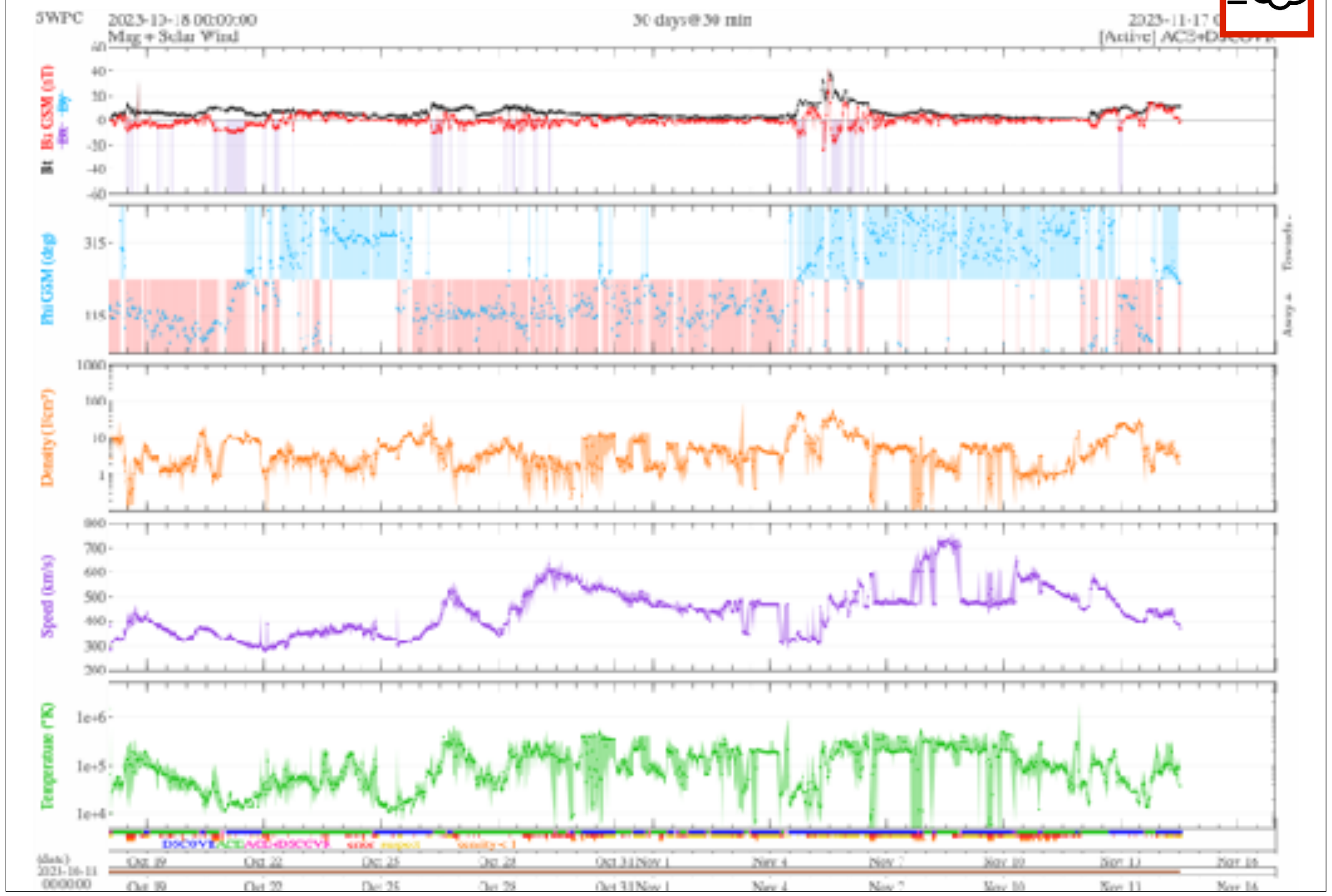
Cravens, 1997

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.

IN SITU

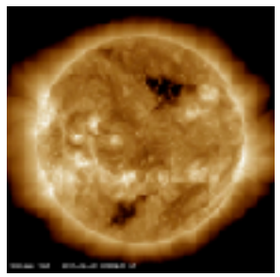

SWPC
2023-10-18 00:00:00
Mag + Solar Wind
30 days@30 min
Speed (km/s)
Temperature (°K)

SOLAR WIND

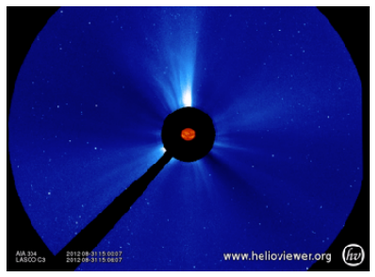
Question

SOLAR WIND VARIATIONS

Coronal Hole



Coronal Mass Ejection



Non-eruptive
Eruptive

Magnetic reconnection
No magnetic reconnection

B reconnection on the SUN

The variations in the solar wind introduce space weather events.

CME - suddenly, a mass is ejected into space. A CME is an eruptive event.
—> magnetic reconnection is involved

A CH is not eruptive. A CH is present, it doesn't pop up suddenly. A CH can of course slowly appear or disappear, become bigger, become smaller but not on time scale of a few minutes. It is also not the case that a CH ejects material and a little bit later, not any more. The solar wind continuously emanate from a CH.
—> no magnetic reconnection is involved

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Non-eruptive
No B reconnection

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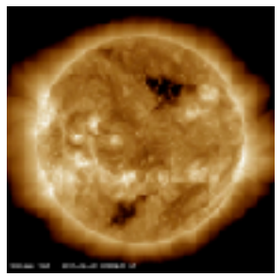
B reconnection

Coronal Hole



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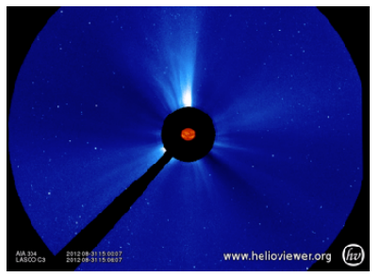

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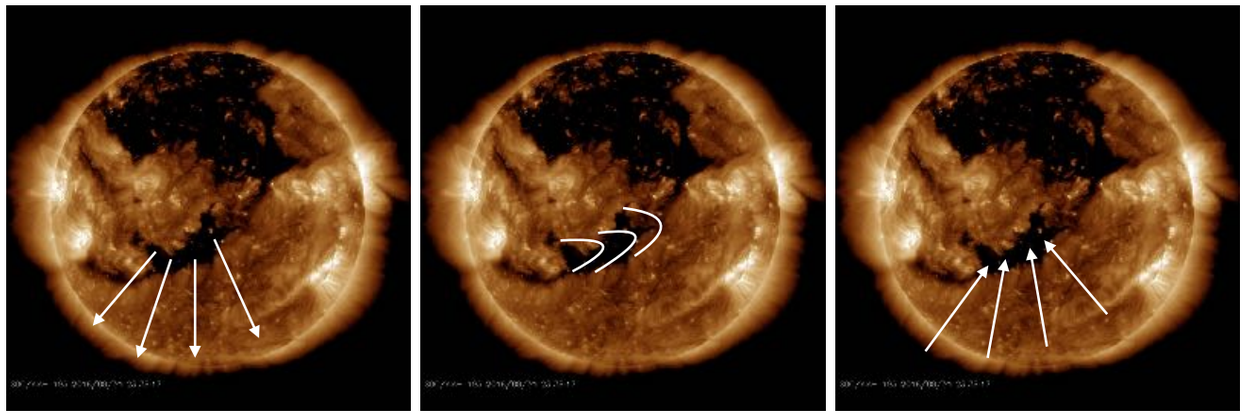
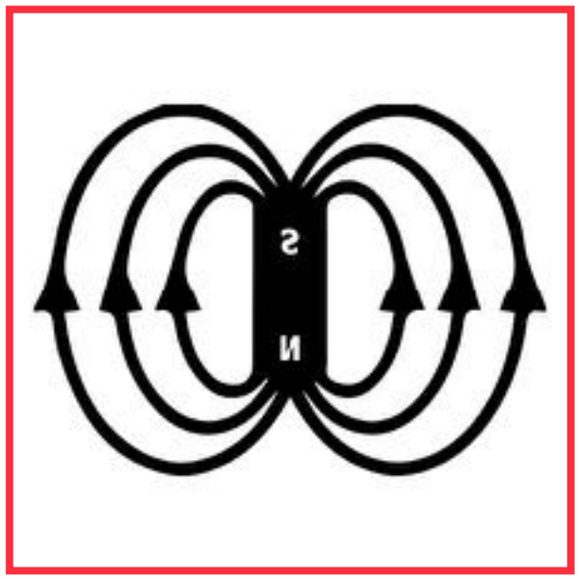
B OF CORONAL HOLE



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

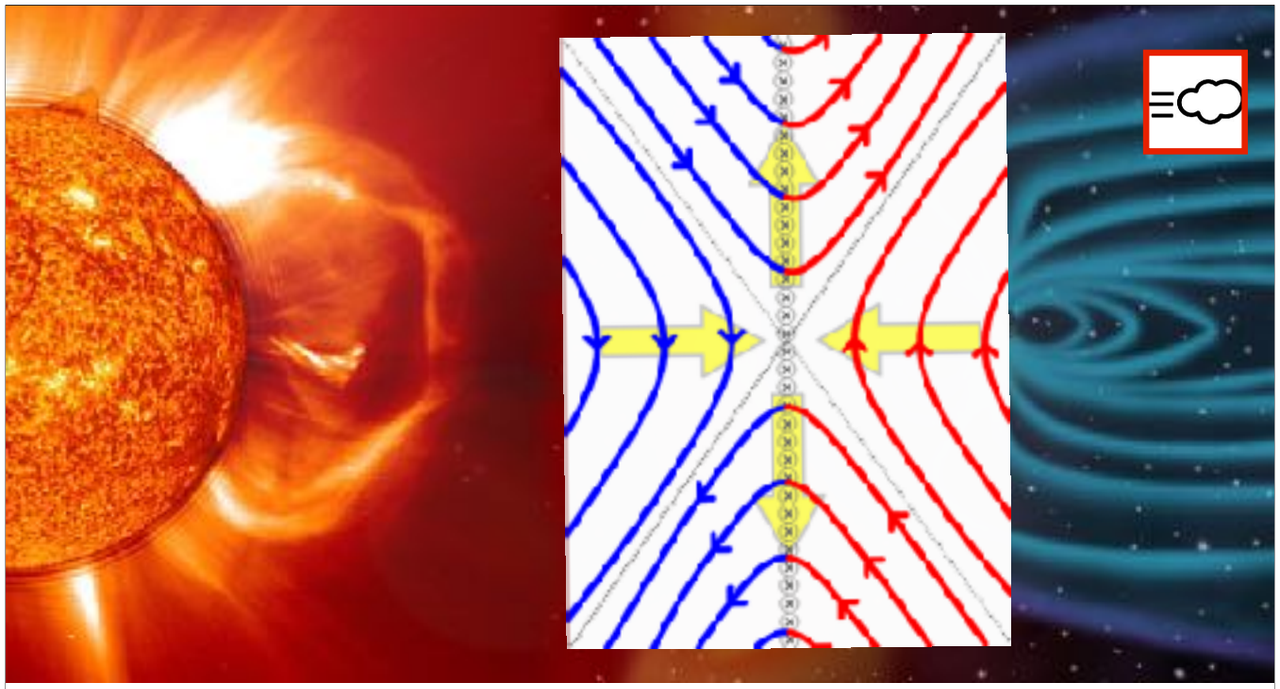
What is important determining when and how strong the impact of a CH will be:
- The heliographic latitude of earth
- The latitude of the CH on the solar disk: the part of a CH with a low latitude is important. Polar coronal holes have only an impact when they extent to lower latitudes.
- It is the material 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



SOLAR WIND

Meets the Earths magnetic field - geoeffectivity



RECONNECTION

The magnetic field carried by the solar wind can couple with the magnetic field of Earth. This coupling is stronger when the solar wind magnetic field is opposite to the magnetic field of Earth.

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

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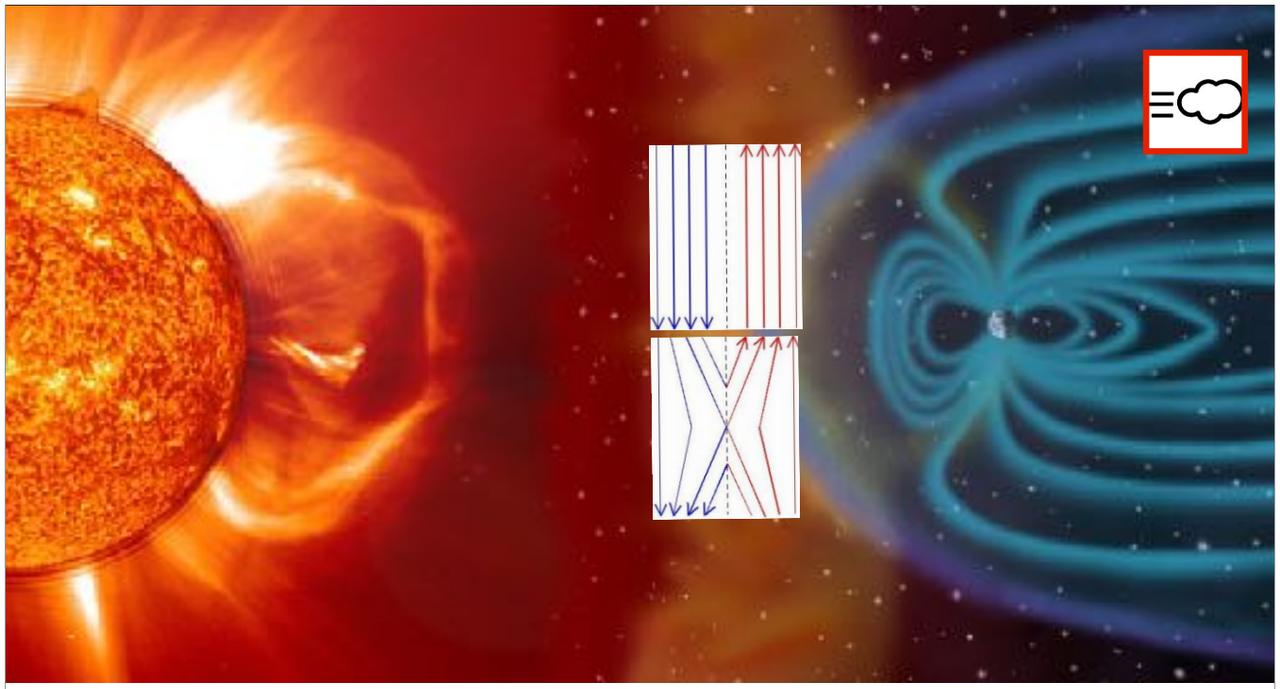

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GEOMAGNETIC CONDITIONS

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

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

SOLAR WIND

Questions

SOLAR WIND

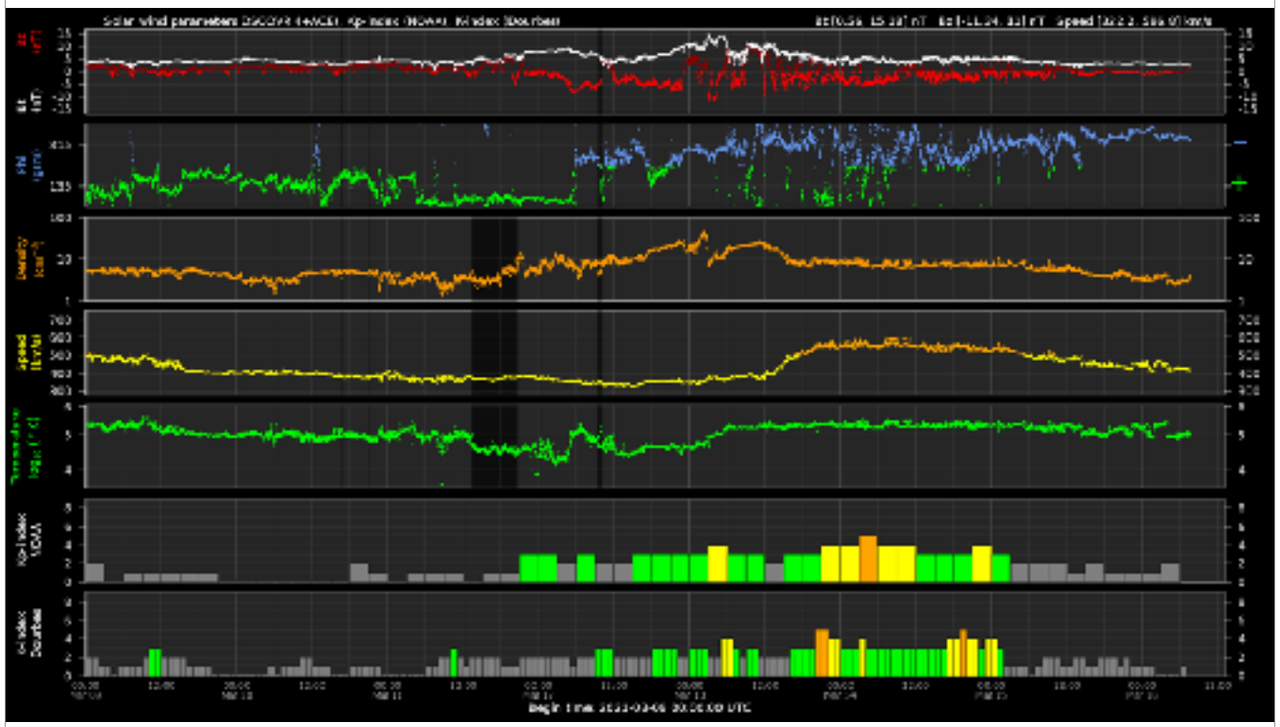
Name 3 transients

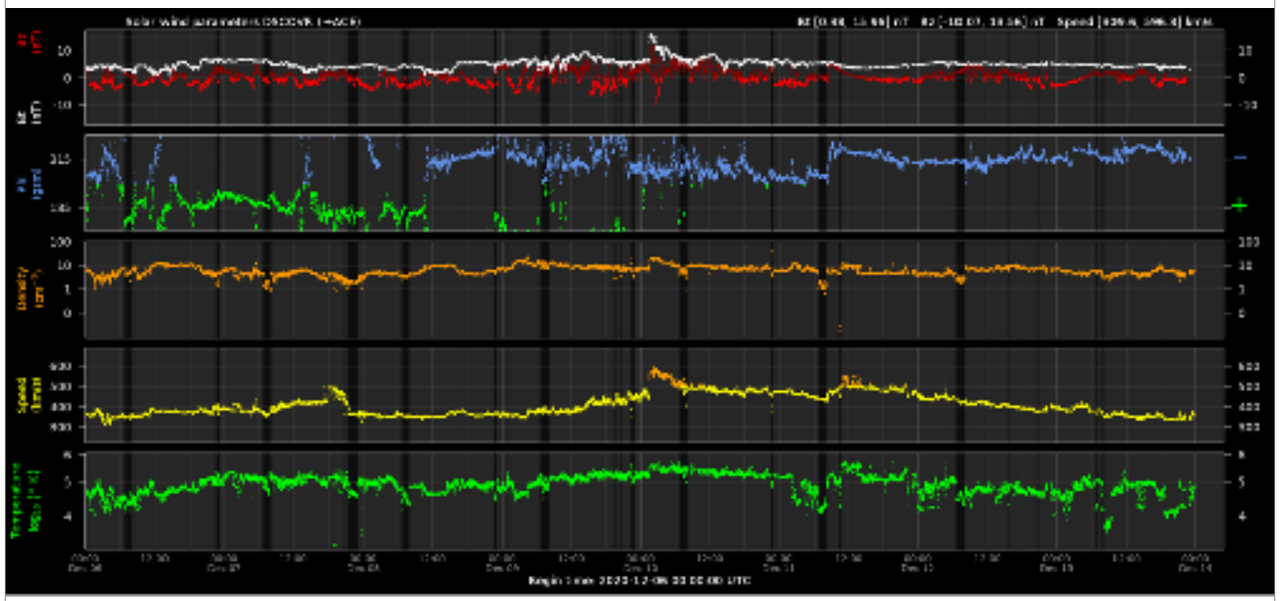
SOLAR WIND

Name a satellite that measures the solar wind at L1

SOLAR WIND

Name the 5 panels in ACE or DSCVR graphs.


Solar wind parameters
Bz (nT)
Bt (nT)
Density (cm-3)
Speed (km/s)
Temperature (10^4 K)
Kp Index NOAA
Ap Index Boulder
Begin Time


Bangkok Urban 2023-12-06 00:00:00 UTC

SOLAR WIND

Name 3 clearly distinct places where magnetic reconnection takes place.