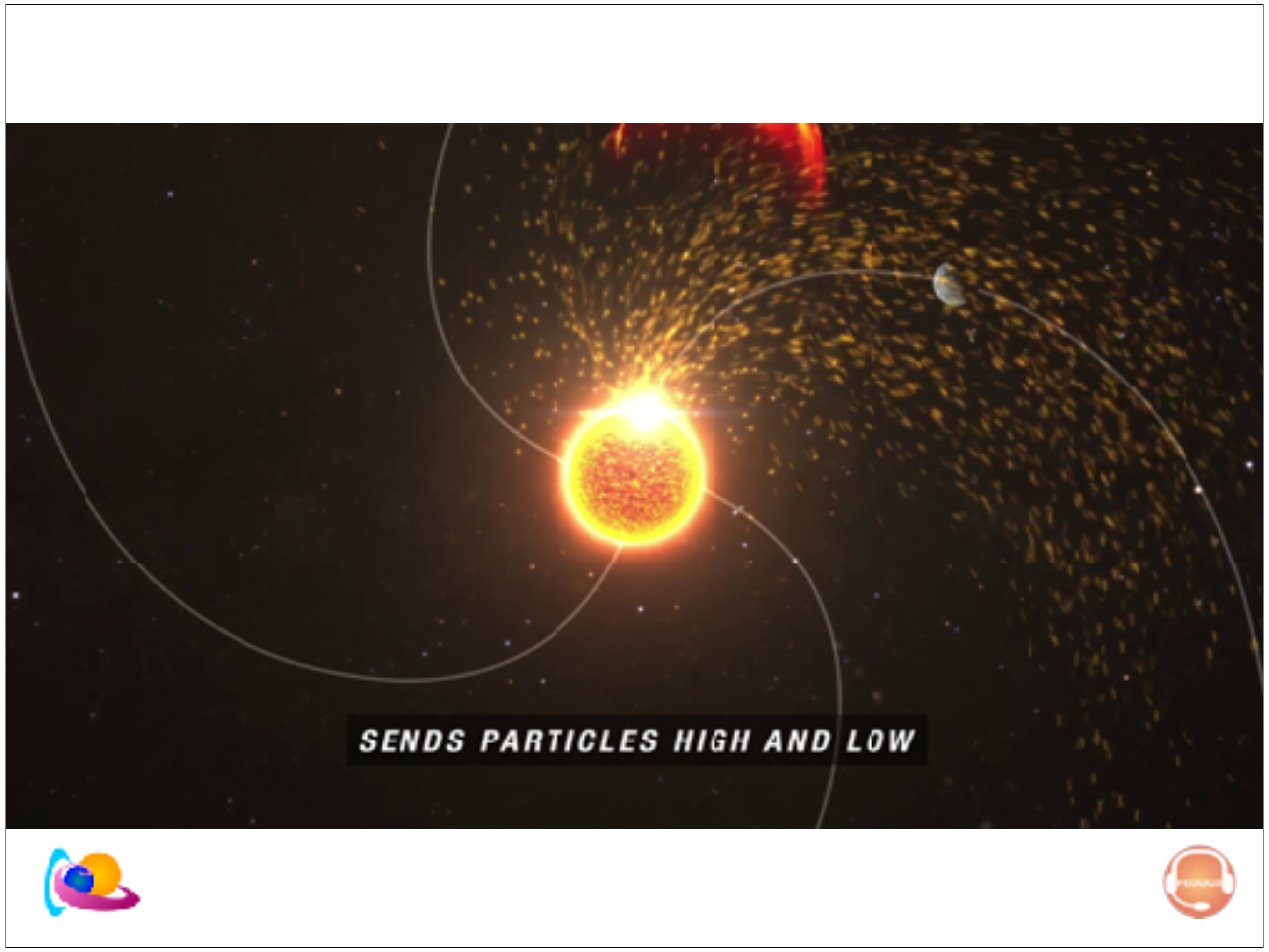
SPACE WEATHER INTRODUCTORY COURSE

Collaboration of

Solar-Terrestrial Centre of Excellence

Koninklijke luchtmacht

Koninklijk Nederlands Meteorologisch Instituut
Ministerie van Infrastructuur en Milieu



https://svs.gsfc.nasa.gov/13853/

SOLAR WIND

What

The solar wind is a continuous, low density flow of energetic **charged** particles (ions, electrons, neutrons) radiating outwards from the Sun in every direction due to the very hot corona.
As such it can interact with the magnetic structures e.g. at Earth
Our focus is on the interaction of the magnetic field carried by the wind with the Earth's magnetosphere.

https://www.youtube.com/watch?v=dRpXiwS41Z4 starting 29:30

3 SPACE WEATHER PHENOMENA

The sun’s energy reaches the earth in 3 forms: light, moving gas and particle precipitation. This energy interacts with the magnetosphere and the atmosphere of the earth. This is space weather.

How and where the interaction occurs depends on the type of energy.

LIGHT	WIND	RAIN

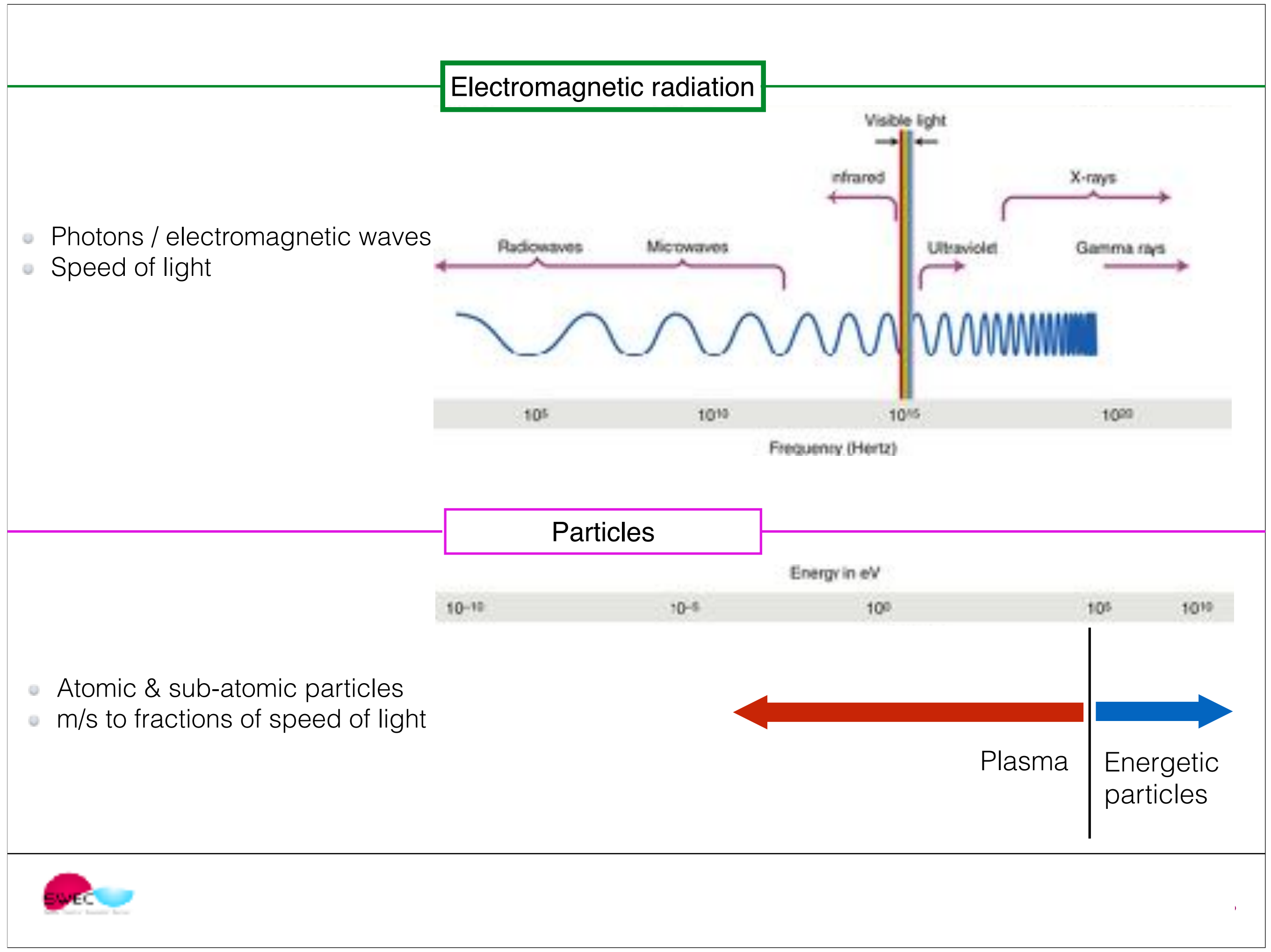
Wind = Expanding, moving gas; in this case moving plasma

light= electromagnetic waves, energy transmitted in the form of photons/ EM waves

EPP = particle has high energy and precipitates along the geomagnetic field.

<100 kEV : plasma

Particle precipitation - energy transmitted in the form of fast-moving atomic or sub-atomic particles —> drizzle



Where does the wind (plasma) end and do the energetic particles begin?
Energy threshold of 100 kEV

100 kEV – corresponds to the kinetic energy of a particle

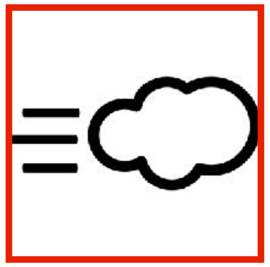
Solar wind is moving plasma, expanding (ionised) gas

Energetic particles, 5th state of matter defined by temperature,

States of matter: from solid to plasma: adding more energy causes particles to become 'loser'
For a plasma: atoms start to split into sub-atomic particles

Energetic particles are individuals, gas laws don't apply
Plasma can hold currents and magnetic field

Solar wind plasma has very low density so nearly collisionless

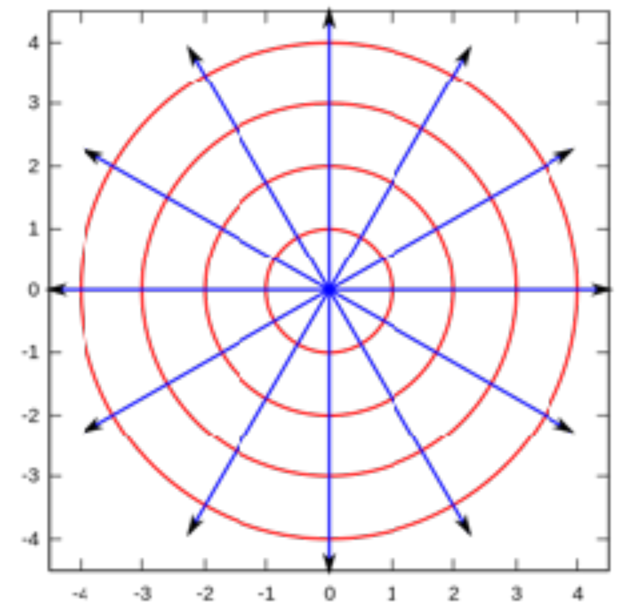


Outward moving plasma

Density decreasing: wind becomes thinner as you move away from the sun because there is more volume (space) for the same amount of matter (particles)

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.

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.

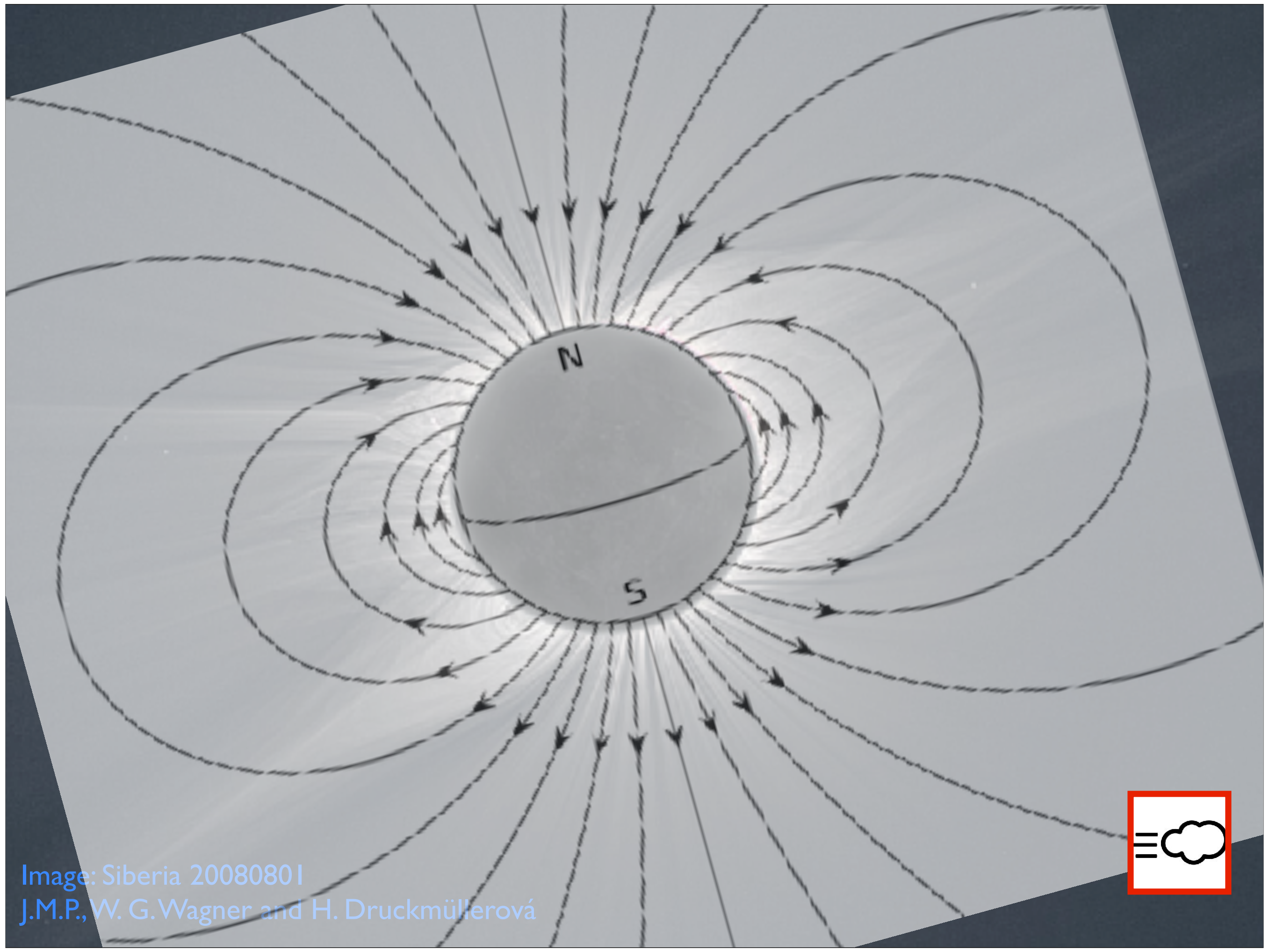
Corona is structured - you see magnetic field lines

This is during solar minimum, during solar max the field is more complex

It is the magnetic field that lies at the base of all solar activity.

Magnetic signature visible here is at large length scales. It changes over a period of 11 years.

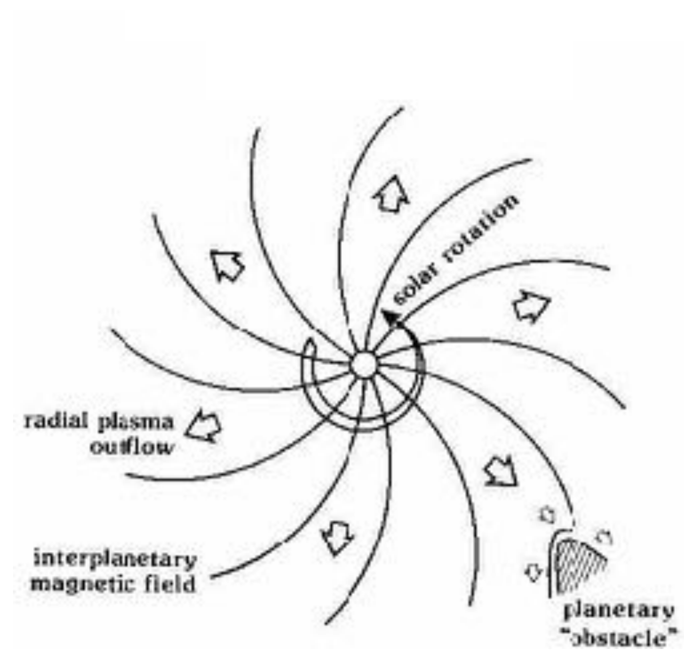
Large spatial and time scale: Solar dipole - visible during a solar eclipse, more pronounced at solar minimum, orientation and geometry vary during the solar cycle.

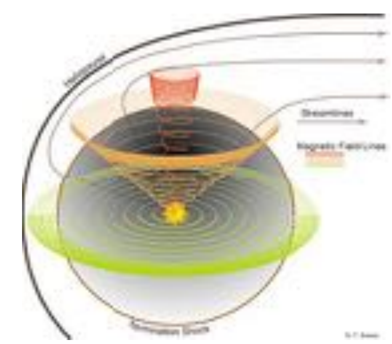


Magnetic forces
The global magnetic field is a dipole, but there is influence of many smaller magnetic fields

PARKER SPIRAL

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

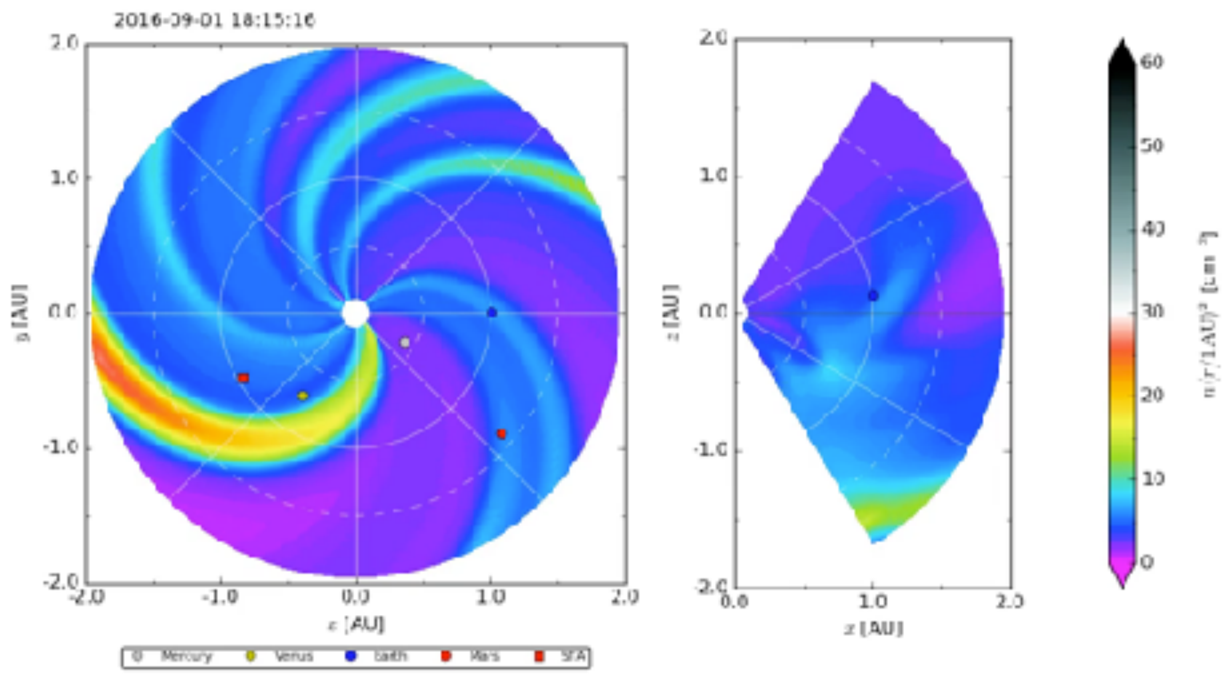




Left: This is a view of the global IMF in the solar equatorial plane.
Right: The IMF and our space is 3D. You have at a particular latitude also IMF lines coming out. Also these lines bend because of the solar rotation. All IMF lines at a particular latitude form a magnetic cone. The solar equatorial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

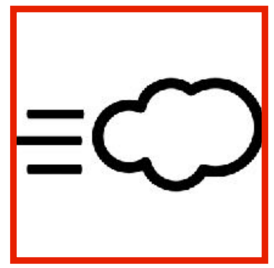
The frozen-flux theorem: IMF and plasma are glued.
The footpoints of the magnetic field lines are attached to the sun. At the same time, the plasma of the solar wind on the further distance is glued to that same magnetic field line. When the sun rotates, the IMF is forced to bend.



EUHFORIA, realtime simulations of the inner heliosphere

EUHFORIA simulation showing the Parker spiral
Left: top view
Right: side view

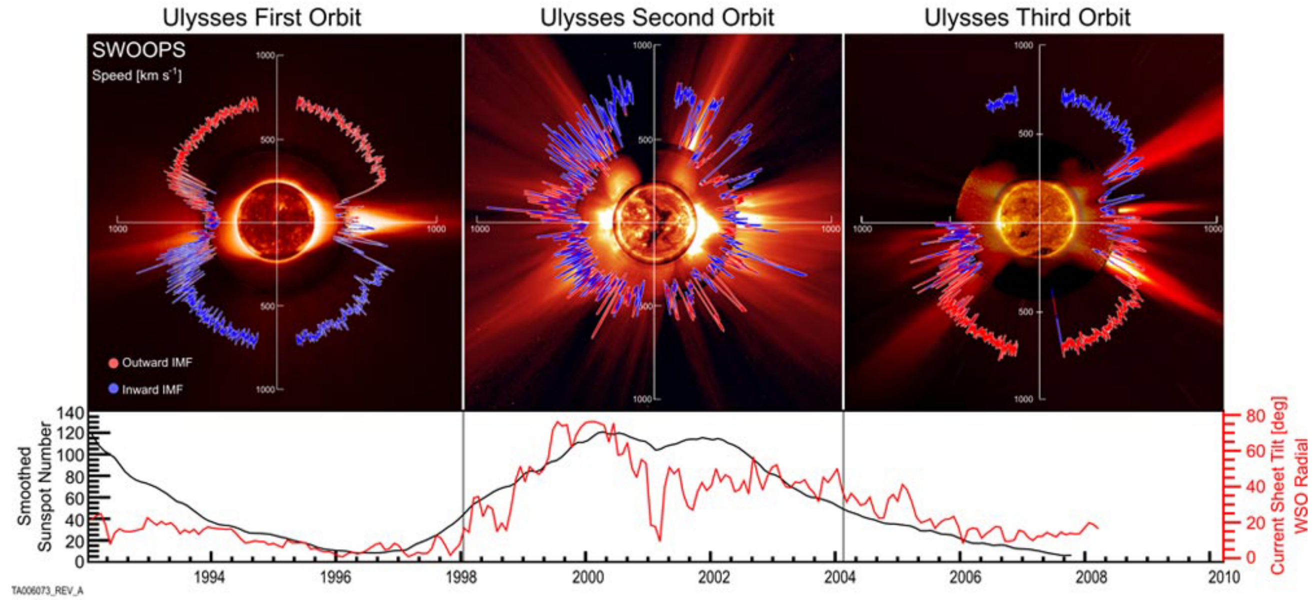
EUHFORIA (EUropean Heliospheric FORecasting Information Asset) is a space weather modeling tool that computes the time-evolution of the inner heliospheric plasma environment using a combination of empirical and physics-based modeling approaches.
https://euhforia.com/



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 everywhere.

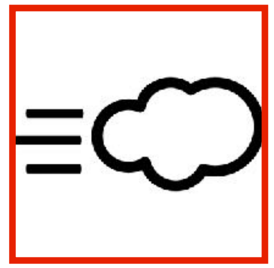
Larger areas with fast solar wind streams. Fast solar wind streams are associated with coronal holes. These are regions with open magnetic field regions of the corona. While slow streams are associated with closed field regions primarily concentrated near the equatorial (or streamer) belt.

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

SLOW versus FAST

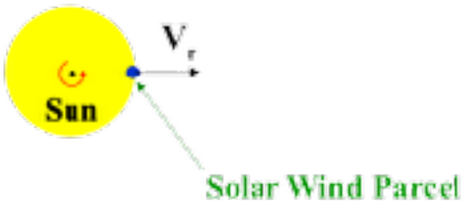
250-400	km/s	400-800
High: ~10	Density, cm^{-3}	Low: ~3
Low: ~10^4K, ~1eV	Temperature	High: ~10^5K, ~10eV
Variable	Behaviour	Stationary

Faster wind has a higher temperature (more kinetic energy)



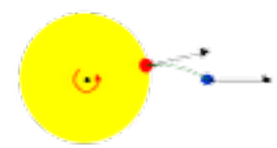
IMF is bent and the plasma flow is radial.
Euh?

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



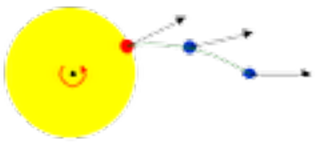
Arge, 2018

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



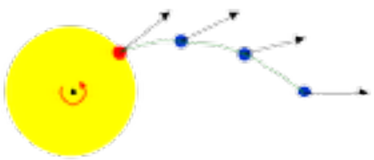
Arge, 2018

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



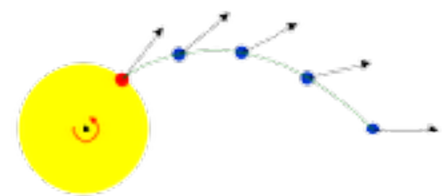
Arge, 2018

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



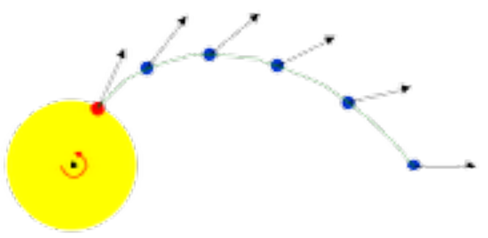
Arge, 2018

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

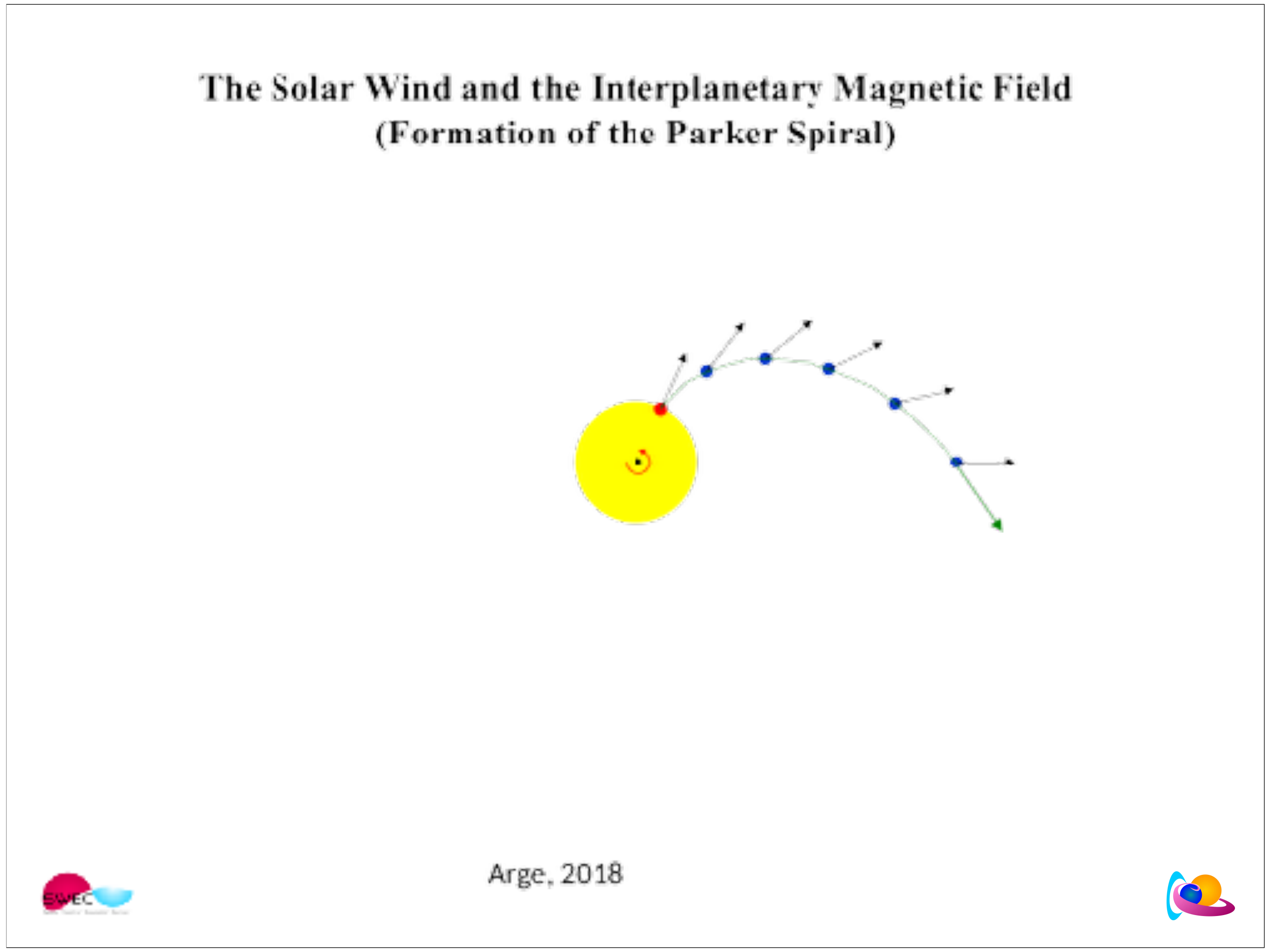


Arge, 2018

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/Bent?

IMF are open/closed magnetic field lines?

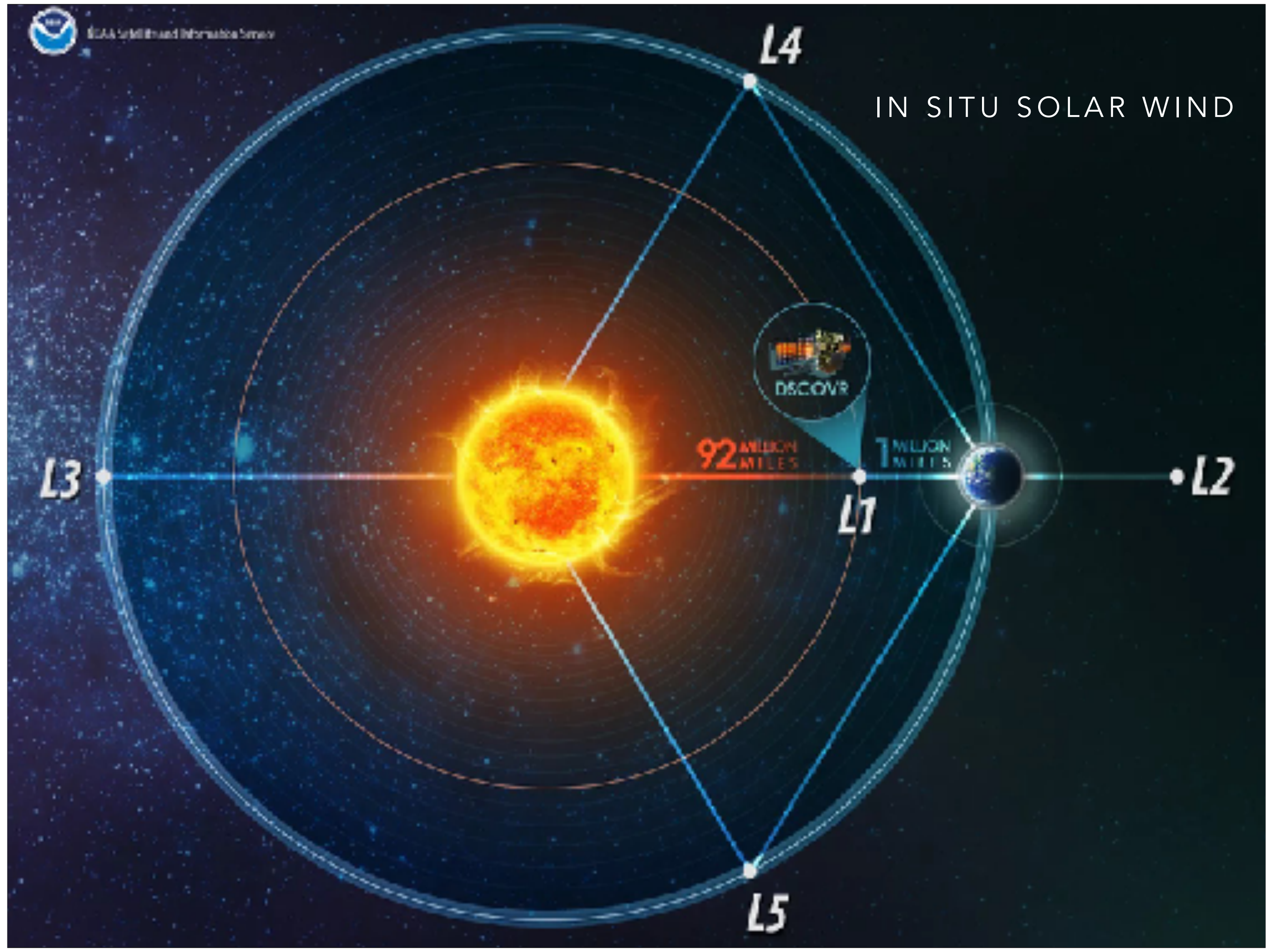
Radial outflow: linked to open magnetic field lines
Example of a Magnetic structure: a CME

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

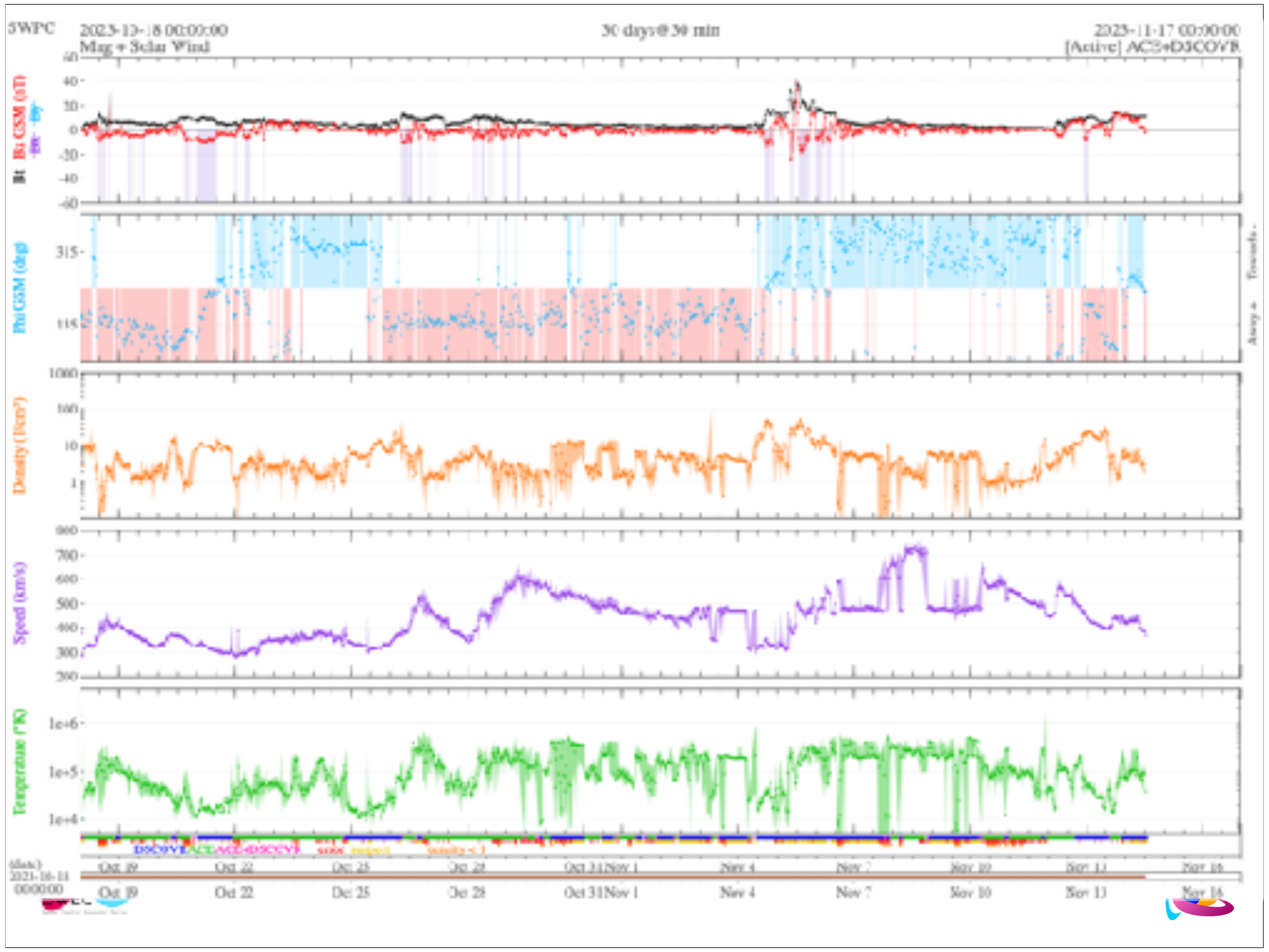
The solar wind is a continuous radial stream of solar plasma that leaves the sun and moves away from it. It fills the space between the planets with solar mass. The solar wind reaches the boundaries of the heliosphere, a magnetic shield around the Sun. In the heliosphere, the Sun sets the rules and you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

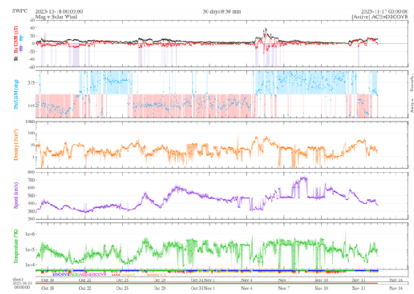
SOLAR WIND

Near Earth

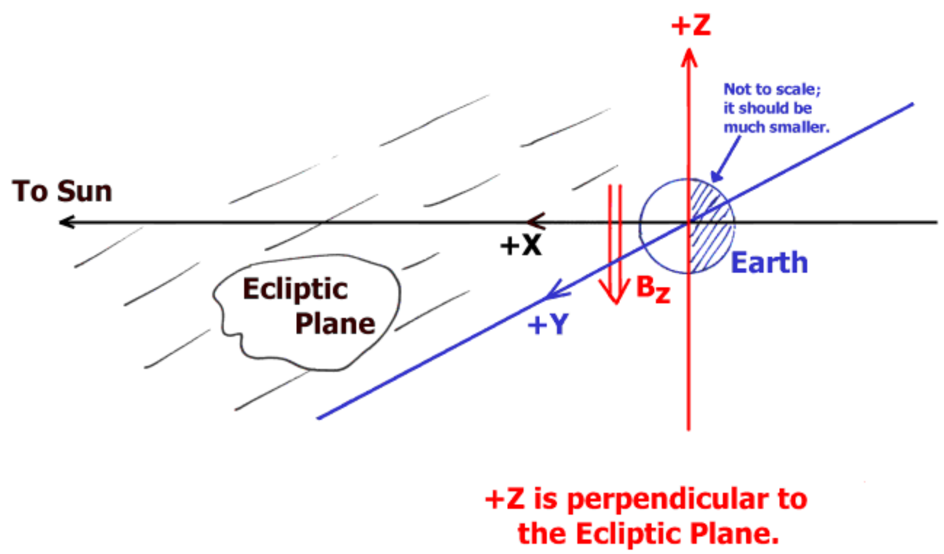


Measured in L1 point
DSCOVR and ACE
1h lead time



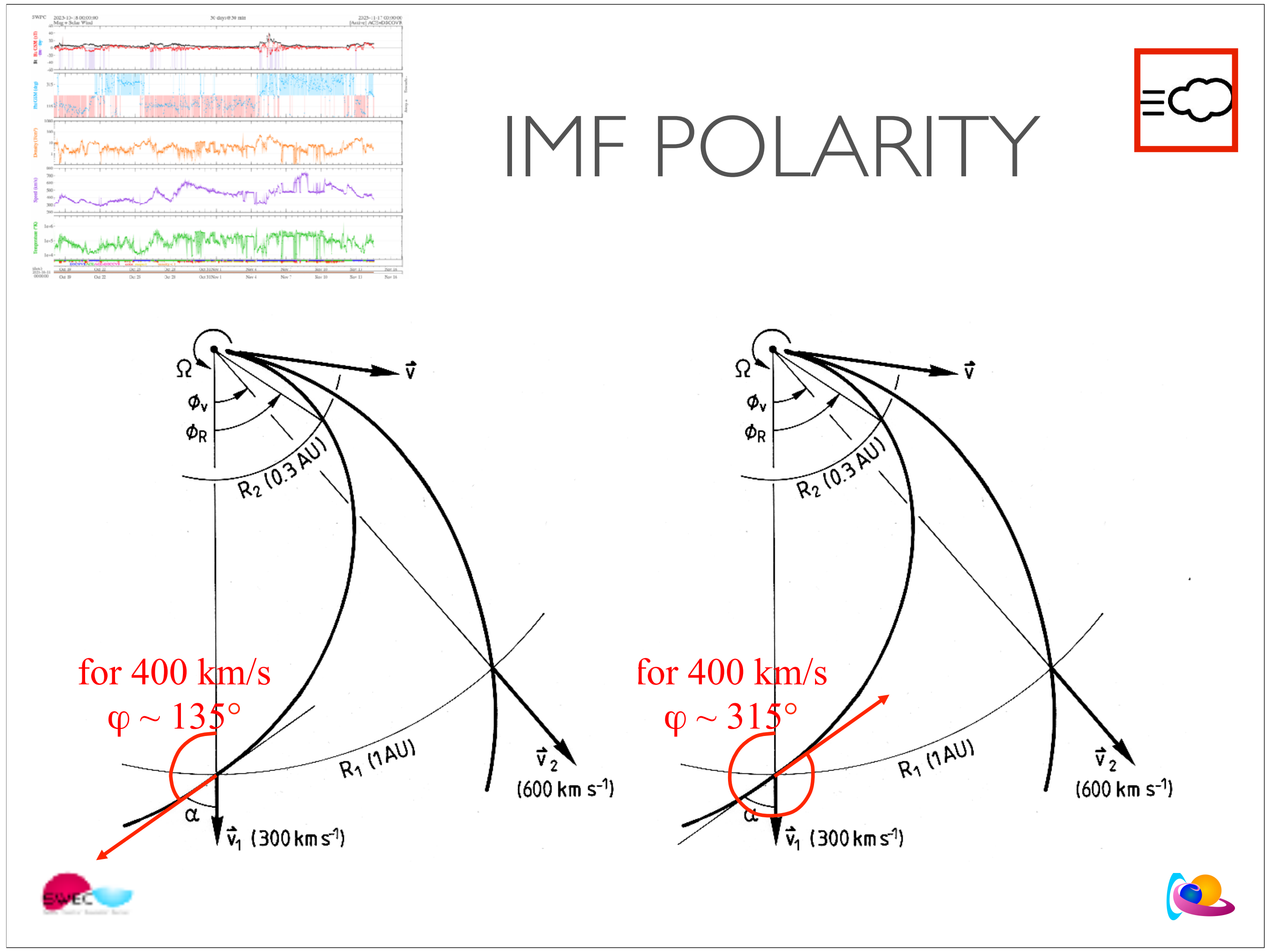


COORDINATE SYSTEM



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.



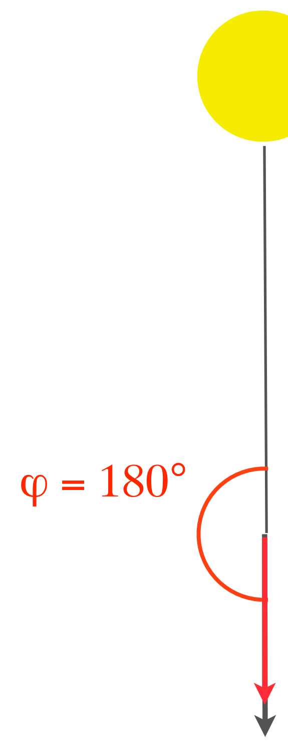
Phi is the angle of the interplanetary magnetic field that is being carried out by the solar wind.

The phi angle indicates the direction of the interplanetary magnetic field.
The vectors indicate the radial solar wind movement.

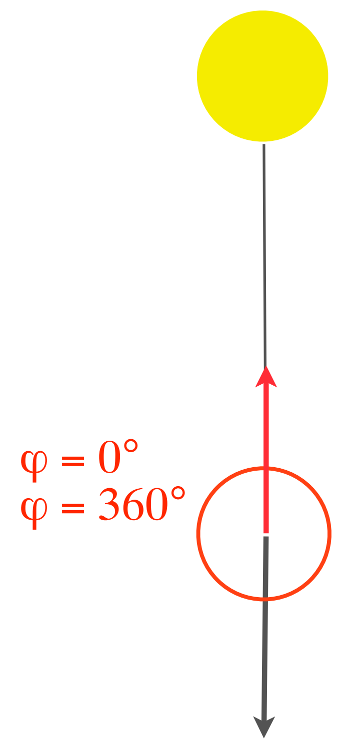
The phi angle is measured counterclockwise from the vector to the line parallel to the magnetic field line at the point of intersection.

The phi determines whether the Interplanetary Magnetic Field (IMF) is pointed towards the Earth or away from the Earth.
Phi is a value between
90° and 180° – outward, away from the sun
270° and 360° – inwards, toward the sun

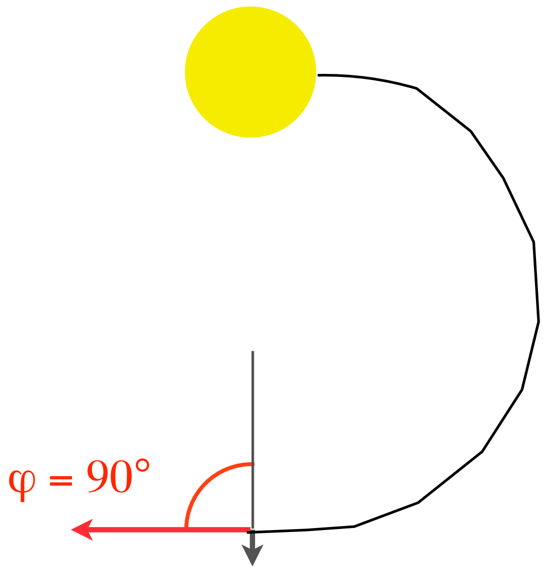
EXTREME FAST



EXTREME FAST



EXTREME SLOW



SOLAR WIND

Transients

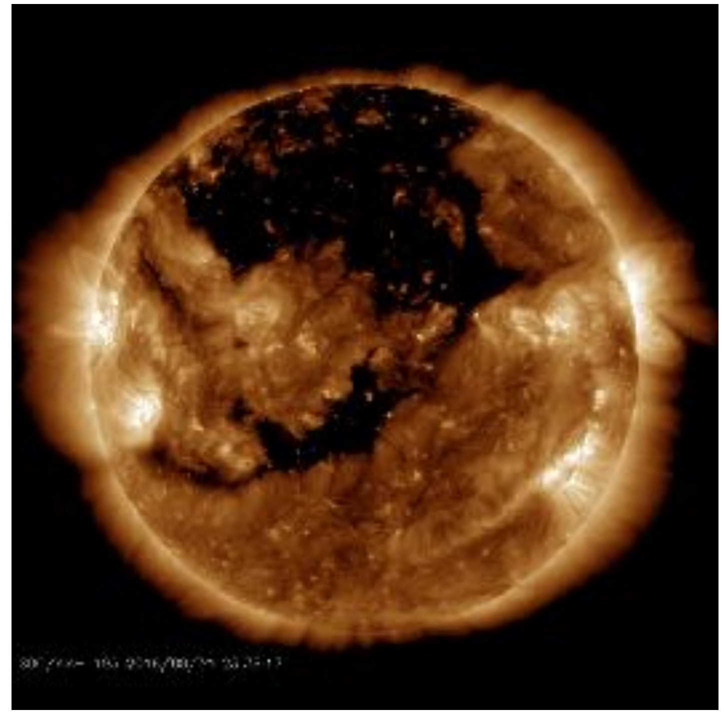
Transients

High Speed Streams (HSSs)

And

Co-rotating Interaction Regions (CIRs)

Coronal Hole



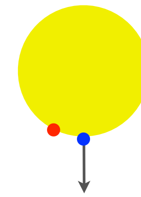
open field structure, source of fast solar wind
non eruptive
radial – plasma leaving when it is at the central meridian, reaches Earth

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.

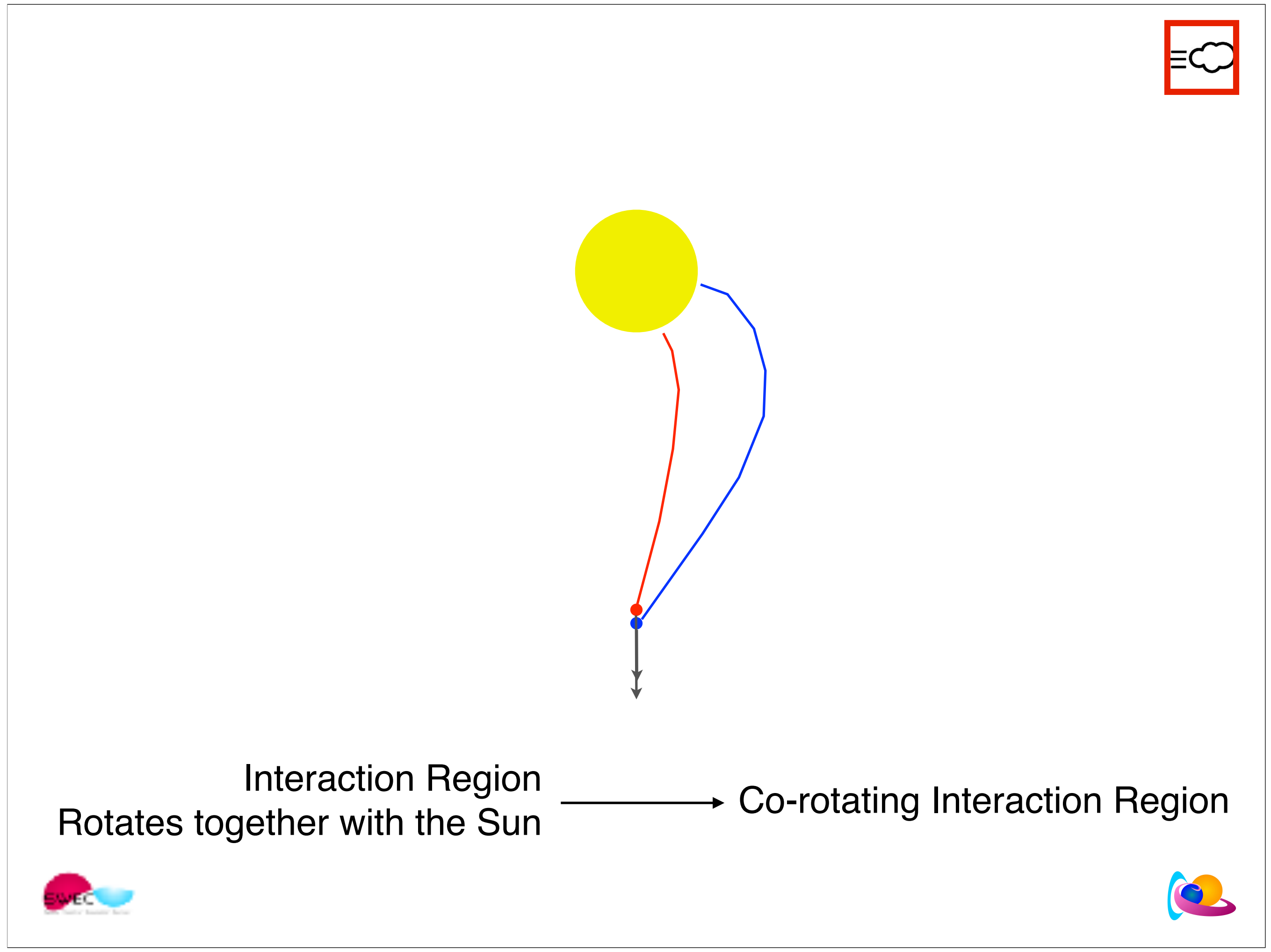
WHAT HAPPENS WHEN FAST CATCHES SLOW?

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.



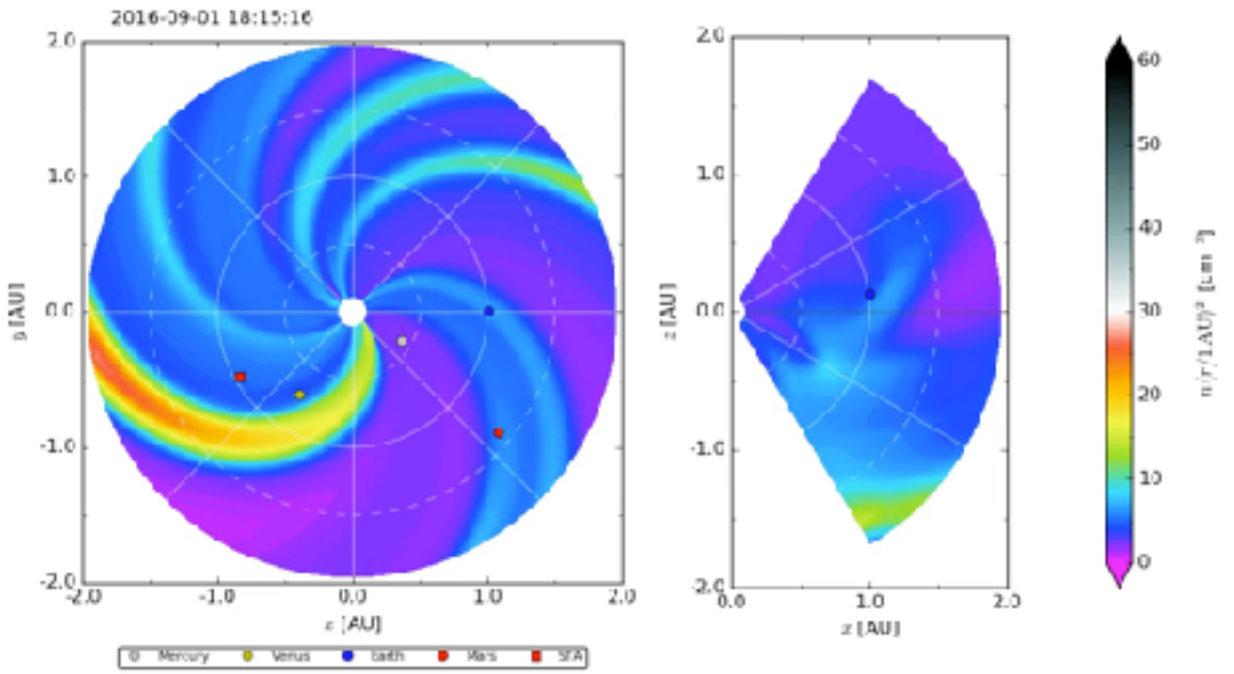
Continuous process – the source of the fast particles, i.e. stays present.

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

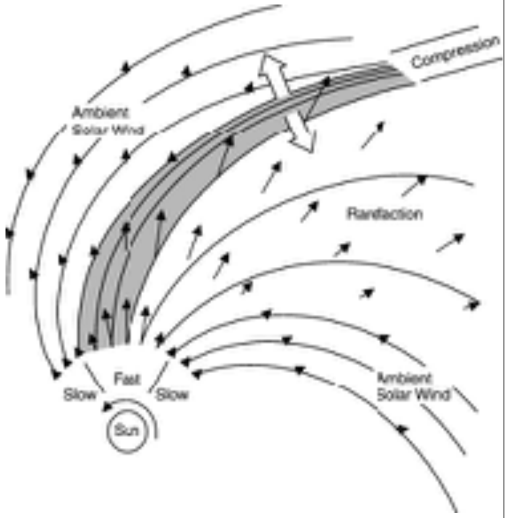


EUHFORIA, realtime simulations of the inner heliosphere

The bright yellow region indicates the CIR
Color scale indicates the density of the solar wind

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!



If the sun would not rotate, the slow wind would not be chased by the fast wind (they would be next to each other, not behind)

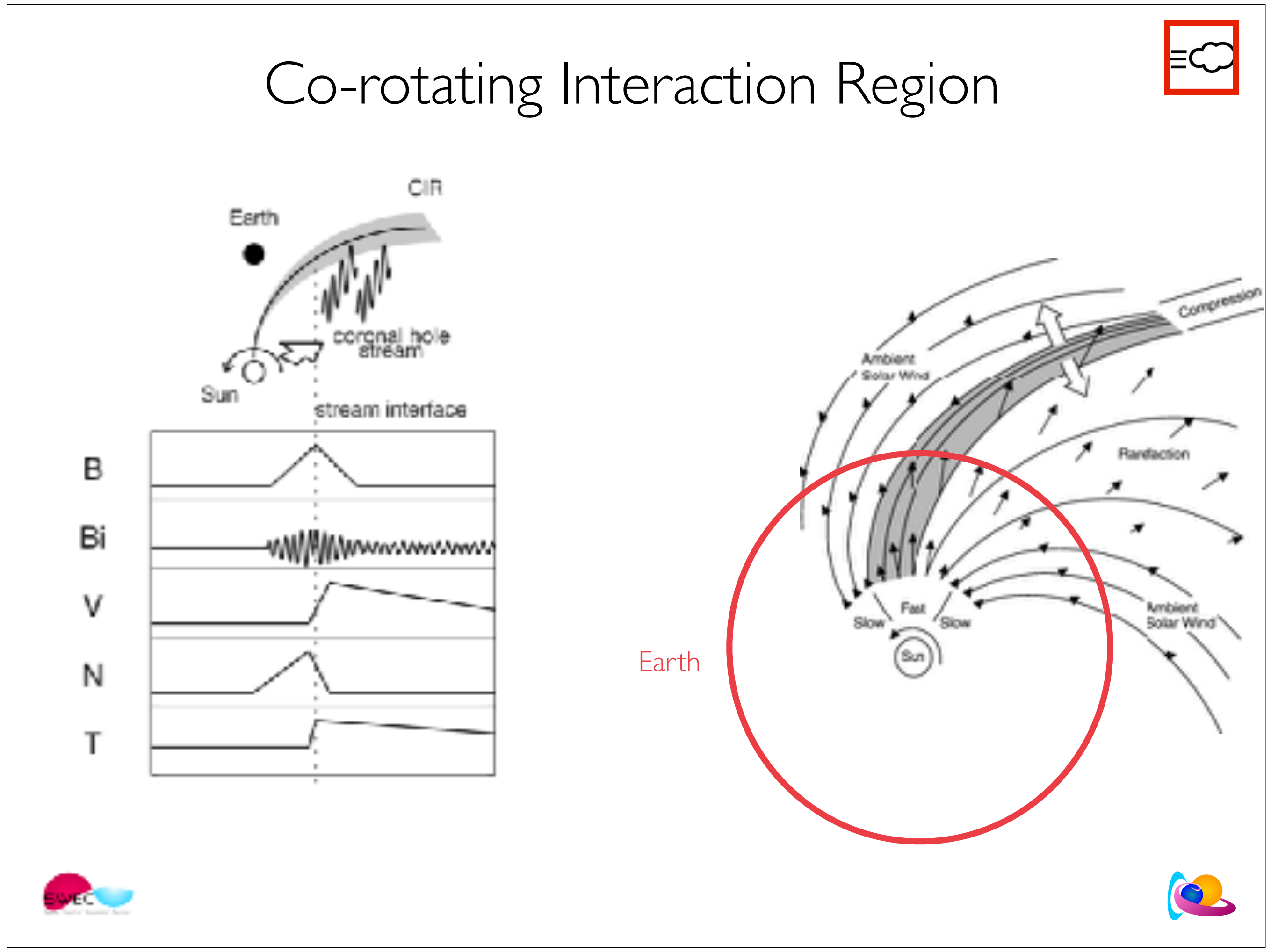
The wind flows continuously so the disturbance is persistent (cause is still present)

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.

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



Where the fast wind catches up with the slow, density and magnetic field strength increase, this is a highly variable zone for B
First we observe the CIR and then the HSS arrives.

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

Behind the compressed interaction region, at the trailing end of the high-speed stream the fast solar wind runs away from the slow solar wind behind it, creating a rarefaction region in which the magnetic field intensity and plasma density are reduced, and the solar wind speed monotonically declines.

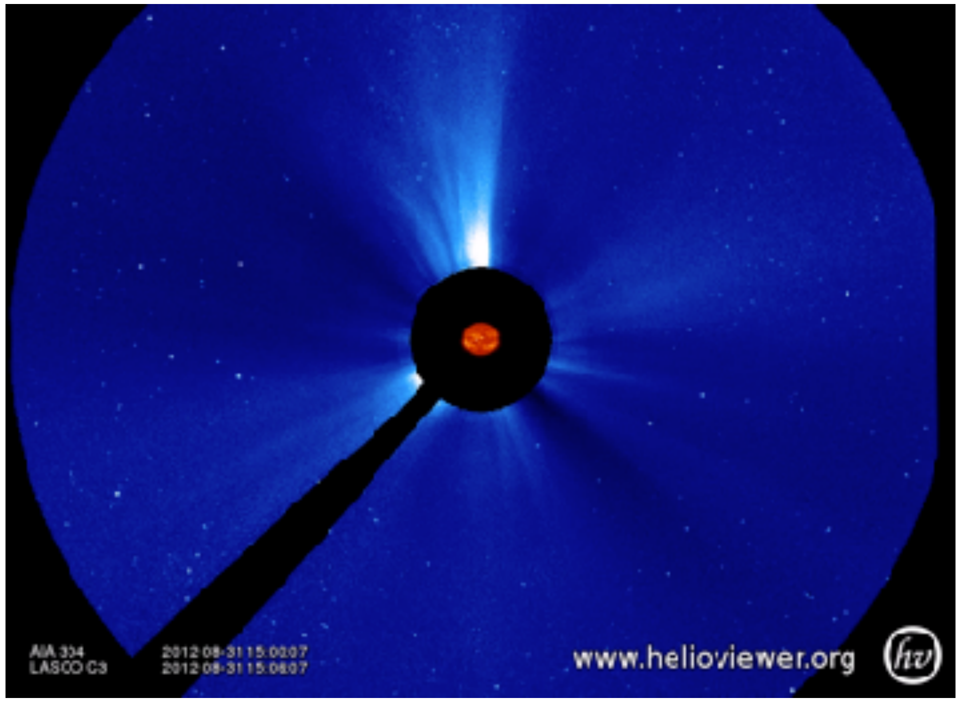
When your plasma is more dense, the magnetic field lines are closer: compression

High temperature

The increases in plasma density N and magnetic field strength B are indicative of compressed plasma in the vicinity of the stream leading edge

Transients

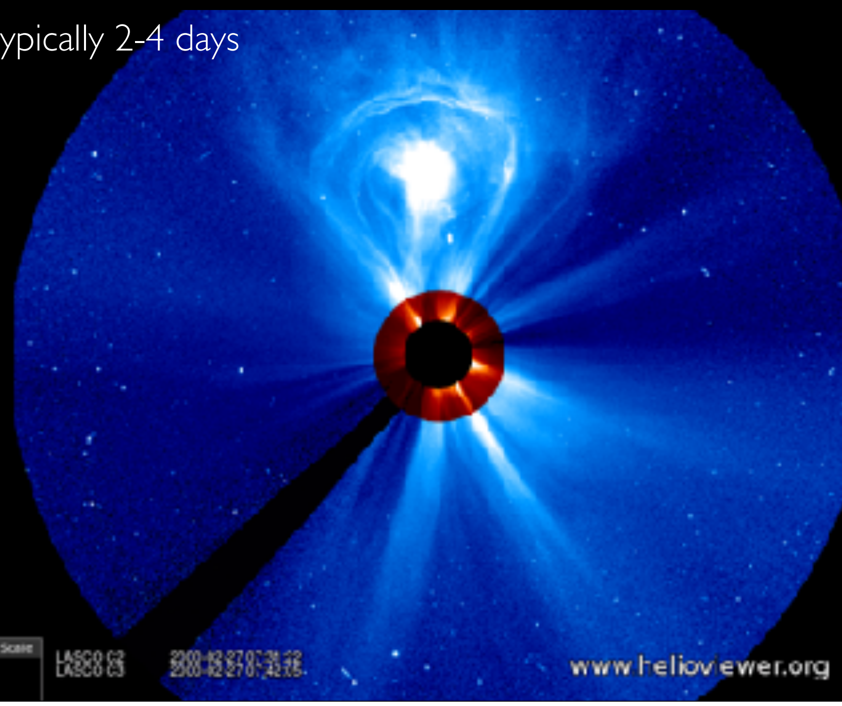
Coronal Mass Ejections



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

Eruptive - transient

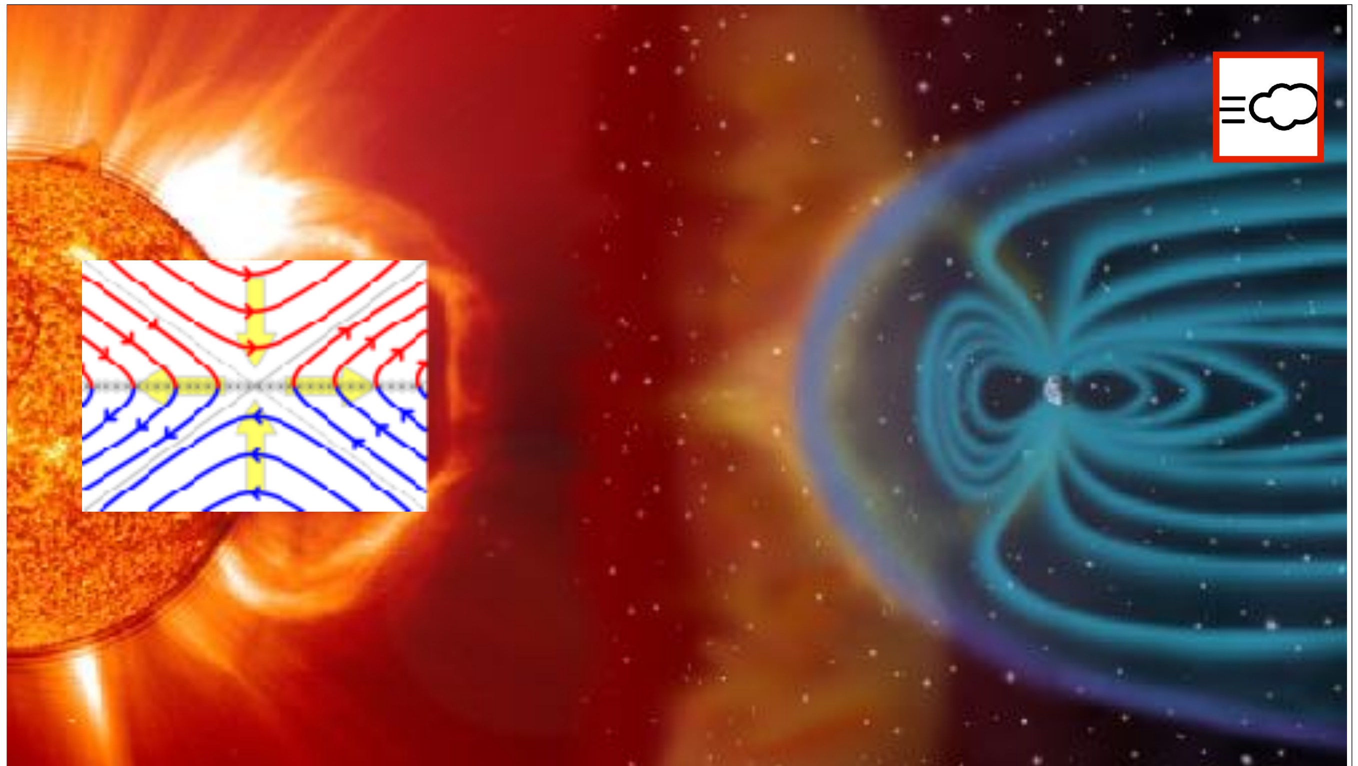
- Trigger the strongest geomagnetic storms
- <1/day during solar min, ~ 3 during solar max
- V between 400 and 2000 km/s
- Travel time typically 2-4 days

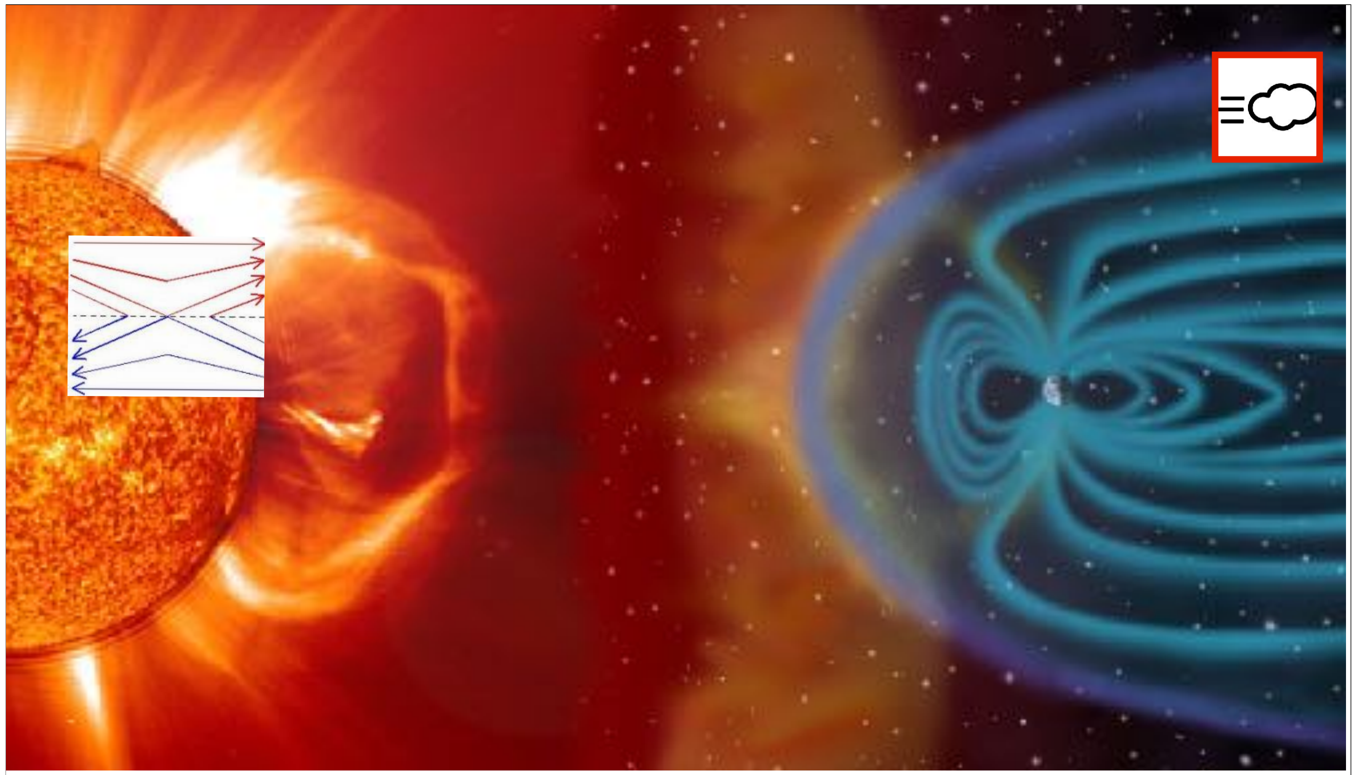


Transient: only lasting for a short time

Low density, but enormous and therefore massive.

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

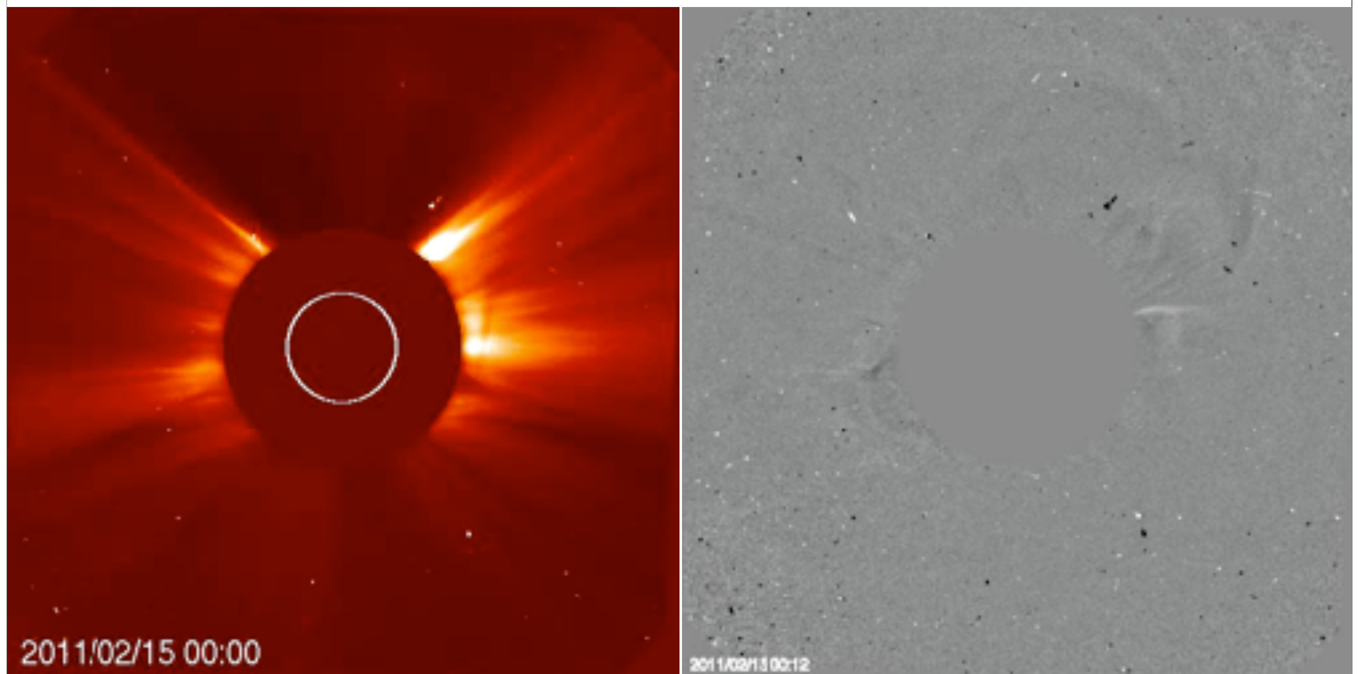




How do you know a CME occurred?

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

IN CORONAGRAPHS



SOHO / LASCO C2

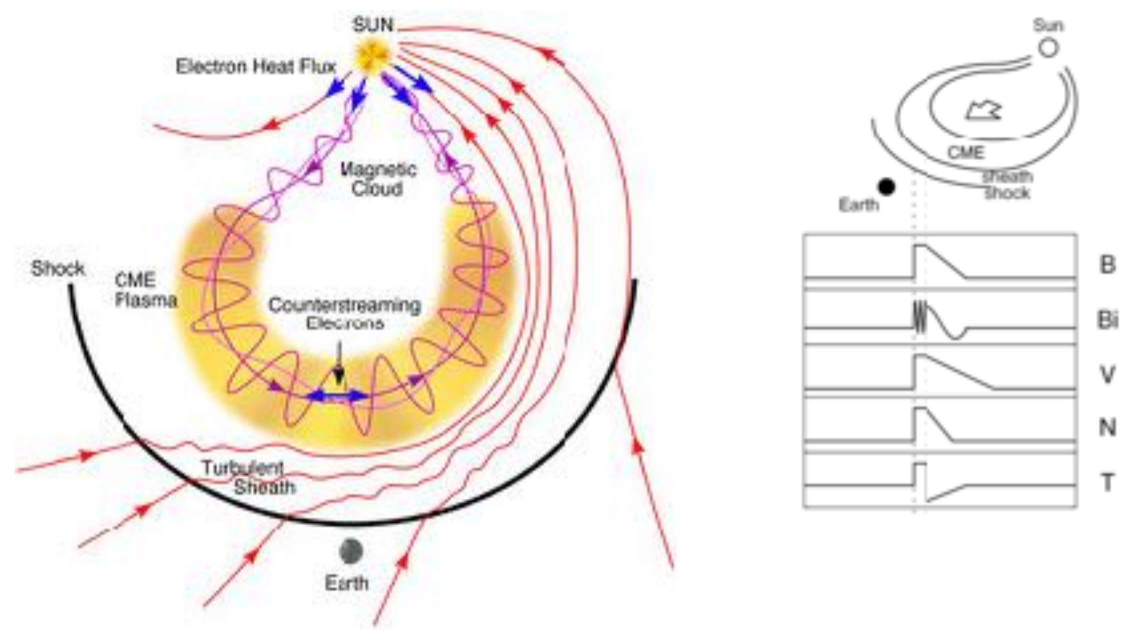
running difference

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.

HALO CME ALERT + PRESTO

SERVICES

INTERPLANETARY CORONAL MASS EJECTION - ICME



Supersonic
CMEs cause a shock in the wind: stepfunctions for all parameters
We mostly keep an eye on B and v

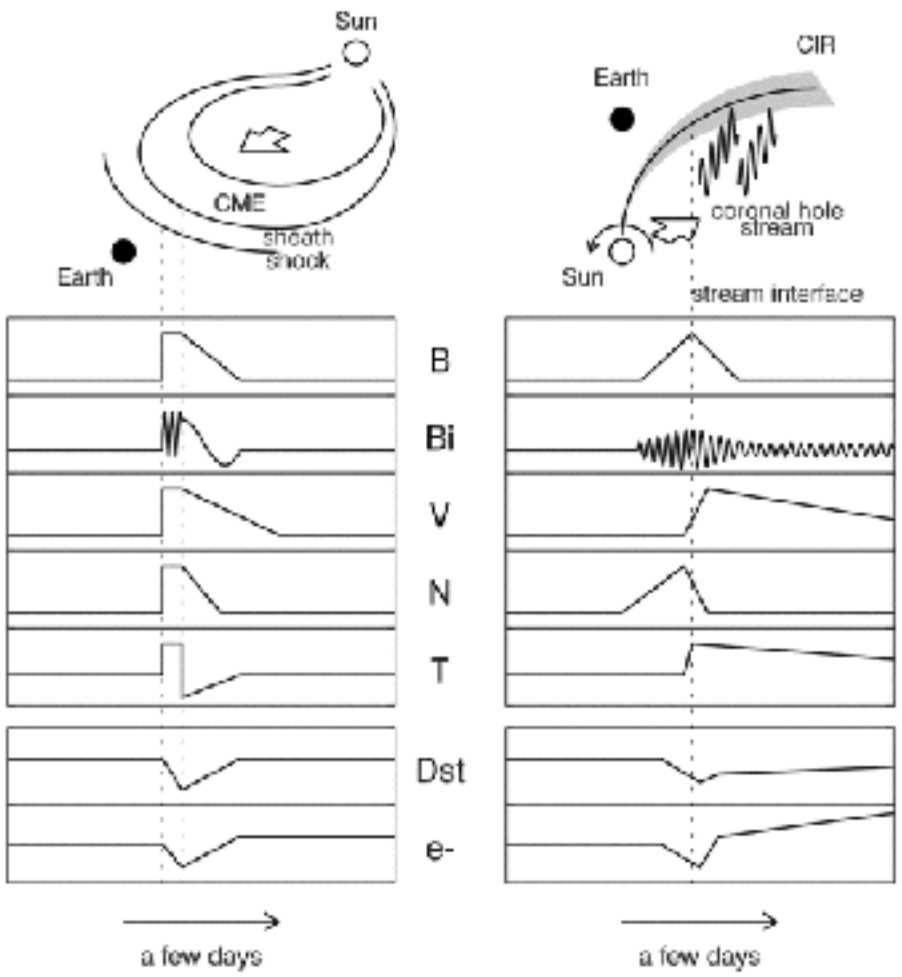
If we pass through the magnetic flux rope, we see a smooth rotation in B

Monotonic decrease in v due to CME expanding as it travels past the observing spacecraft. This expansion leads to low proton temperature.

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	

ICME is expanding gas, so we observe a decrease in T
CIR is fast so T is high
The smooth rotations of the magnetic field components have been often interpreted as indicative of possible magnetic flux-rope (MFR) or magnetic flux-rope-like (MFR-like) structures (Bothmer and Schwenn, 1998).

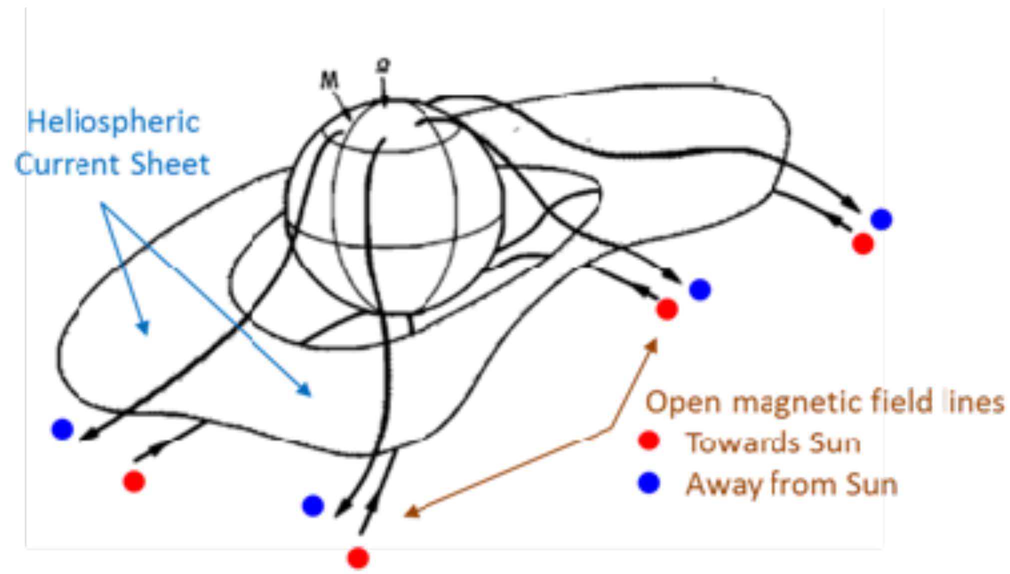


Sun
CME
sheath
shock
Earth
CIR
Earth
coronal hole
stream
Sun
stream interface
B
Bi
V
N
T
Dst
e-
a few days
a few days

Transients

Sector Boundary Crossing

HELIOSPHERIC CURRENT SHEET

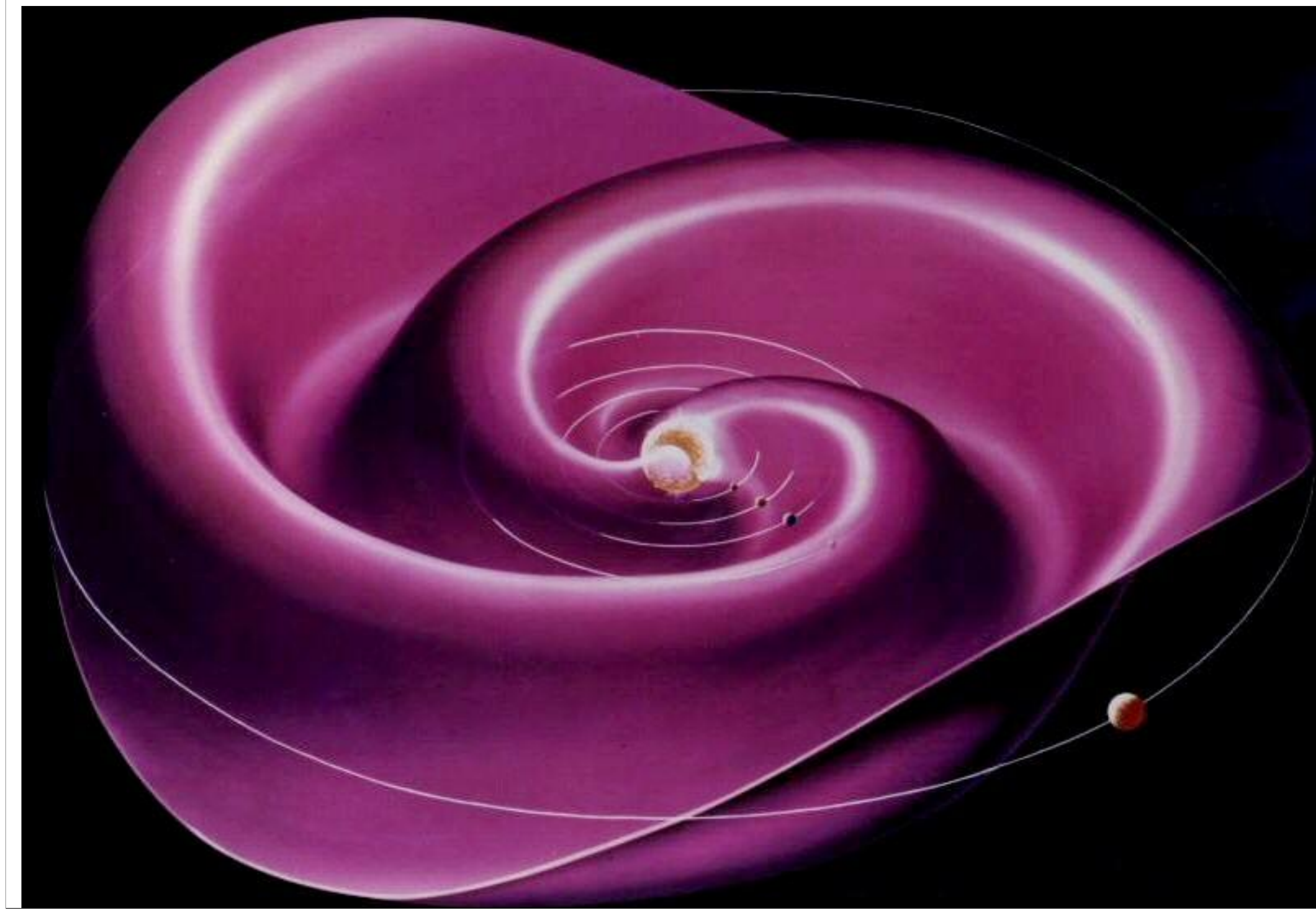


Adapted from Smith et al., 1978

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.

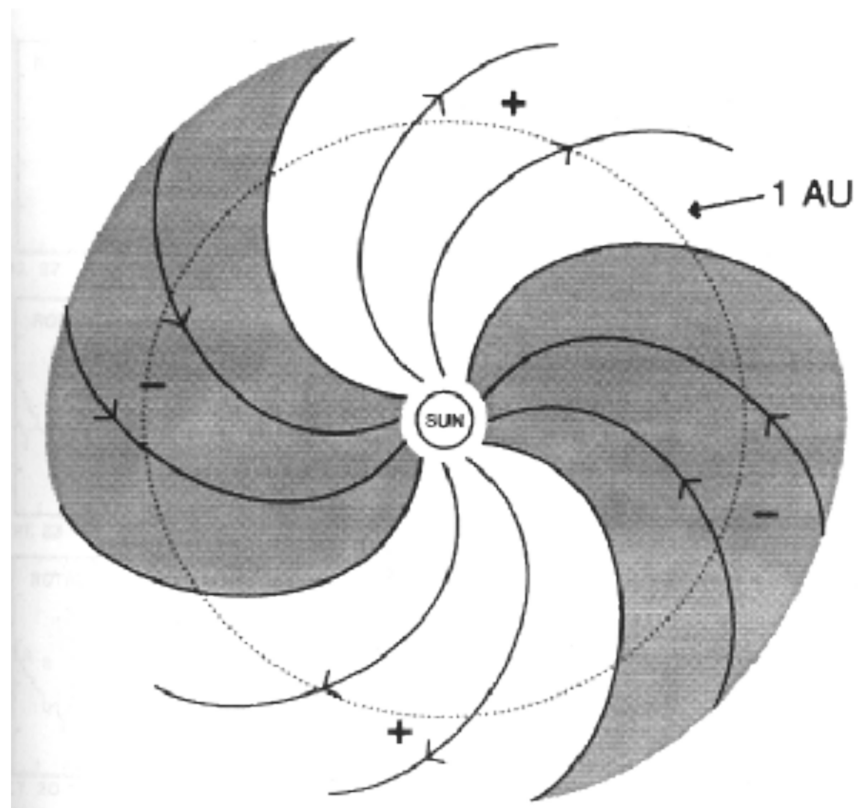
BALLERINA SKIRT



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



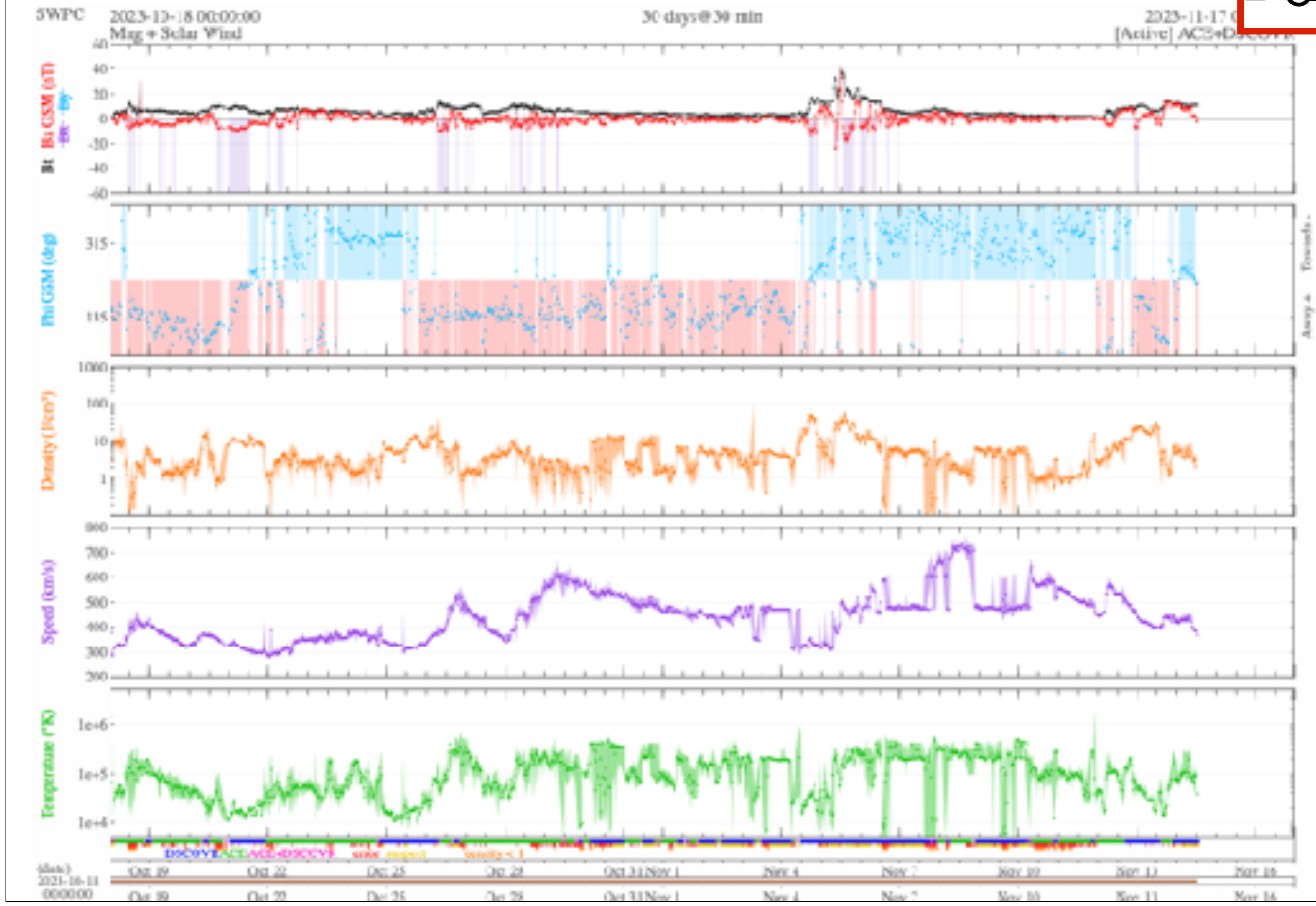
Cravens, 1997

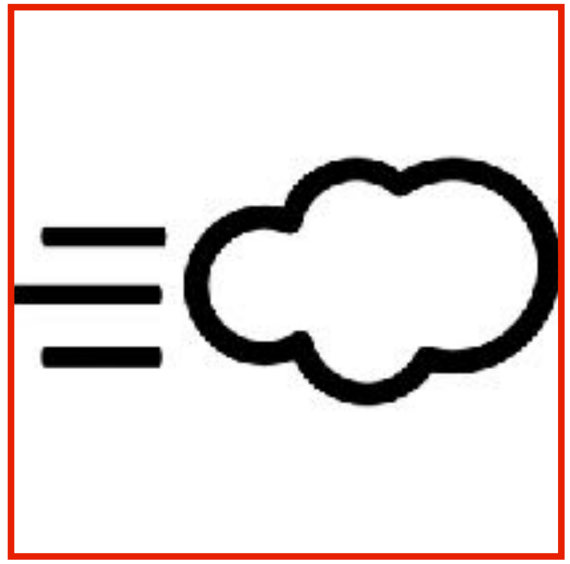
distinct, long-lasting intervals of uniform solar wind field direction exist, called ``sectors''

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 cause large disturbances.

IN SITU


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

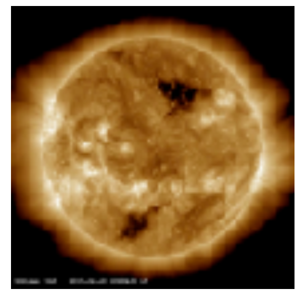


SOLAR WIND

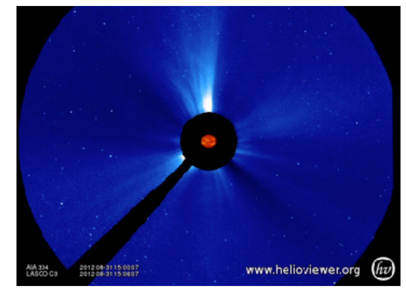
Question

SOLAR WIND VARIATIONS

Coronal Hole



Coronal Mass Ejection



Non-eruptive
Eruptive

Magnetic reconnection
No magnetic reconnection

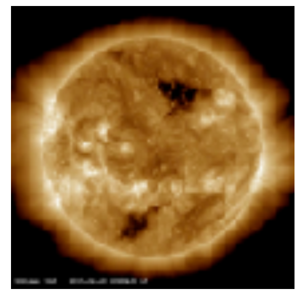
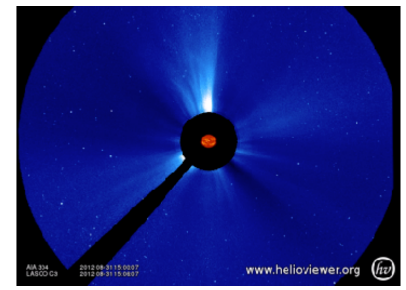
Magnetic reconnection on the SUN

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 emanates from a CH.
—> no magnetic reconnection is involved

SOLAR WIND VARIATIONS

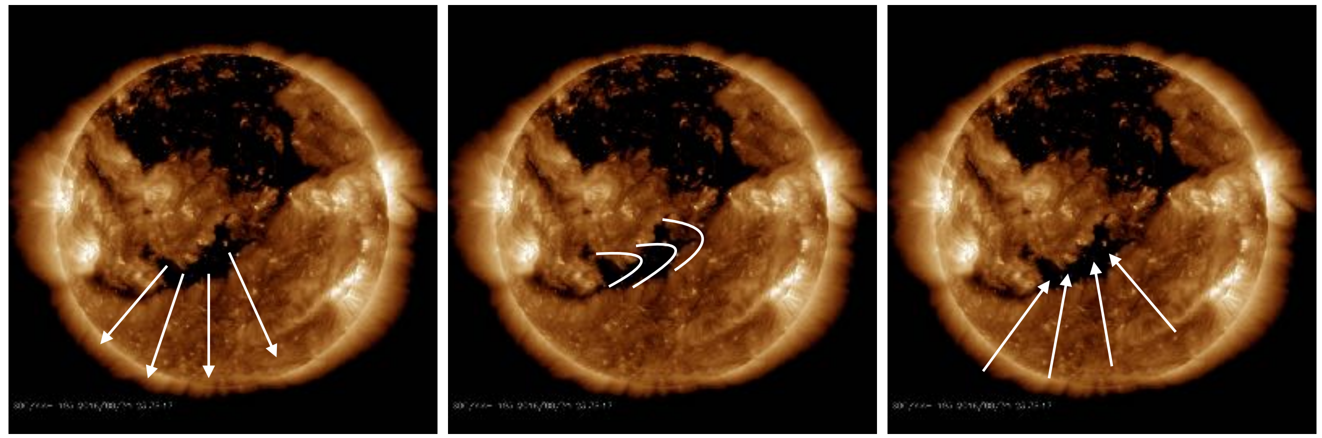
Non-eruptive No B reconnection	Eruptive B reconnection
Coronal Hole	Coronal Mass Ejection
	

The variations in the solar wind introduce space weather events.

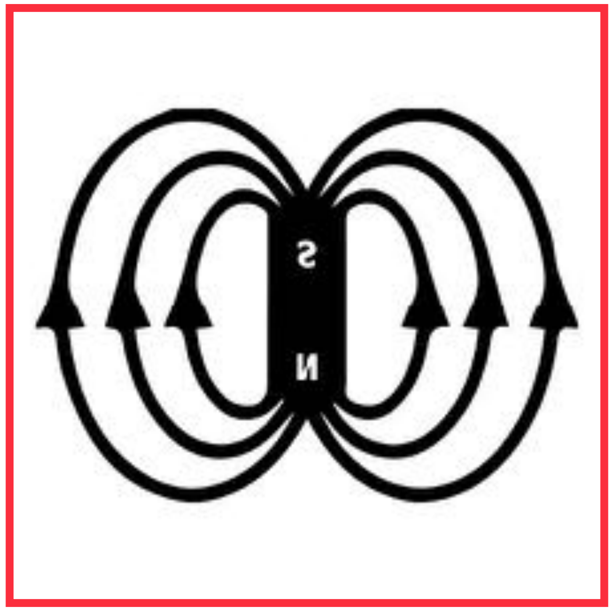
CME – suddenly, a mass is ejected into space. A CME is an eruptive event.
—> magnetic reconnection is involved

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

B OF CORONAL HOLE

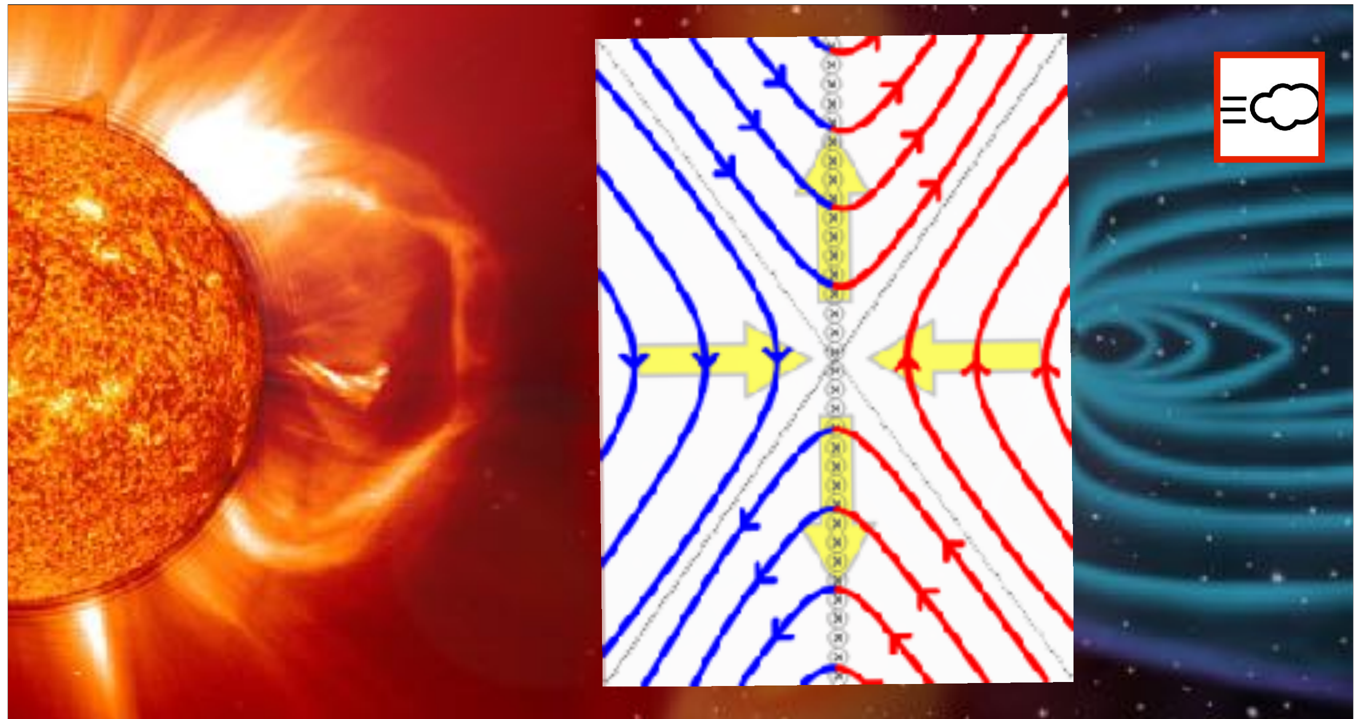


What does the magnetic field of a CH look like?
https://www.stce.be/nl/node/725



SOLAR WIND

Meets the Earth's magnetic field - geo-effectiveness



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.

This is the earths magnetosphere.
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.

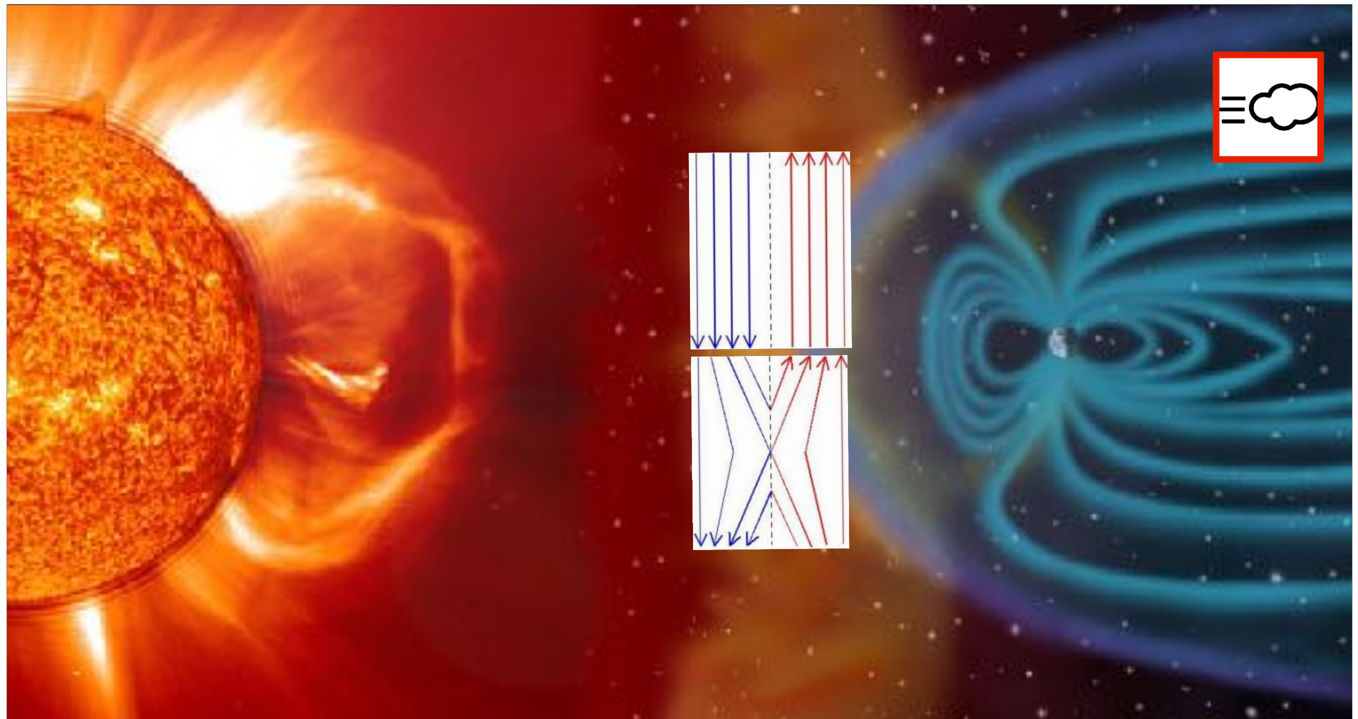
In the case of a speed boat, the boat moves through the water.
In our case, it is the solar wind that blows over the earth. It is just a matter of reference, but the result is the same: a shock.

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.

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



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.

This is the earths magnetosphere.
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's 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's 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.

0.3 T - solar sunspot

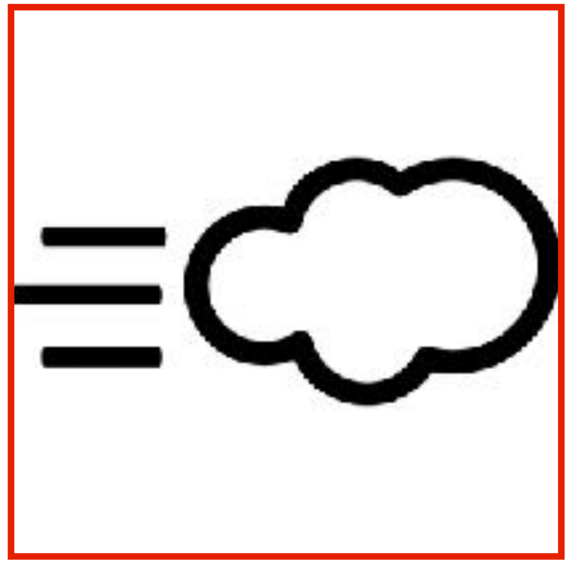
5mT – strength of a typical refrigerator magnet
31.869 μT (3.1×10^{-5} T) – strength of Earth's magnetic field at 0° latitude (North/South), 0° longitude (west/east)
1 to 5 nT – IMF at L1

GEOMAGNETIC CONDITIONS

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

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

The K-index, and by extension the Planetary K-index, are used to characterize the magnitude of geomagnetic storms. Kp is an excellent indicator of disturbances in the Earth's magnetic field and is used to decide whether geomagnetic alerts and warnings need to be issued for users who are affected by these disturbances.



SOLAR WIND

Questions

SOLAR WIND

Name 3 transients

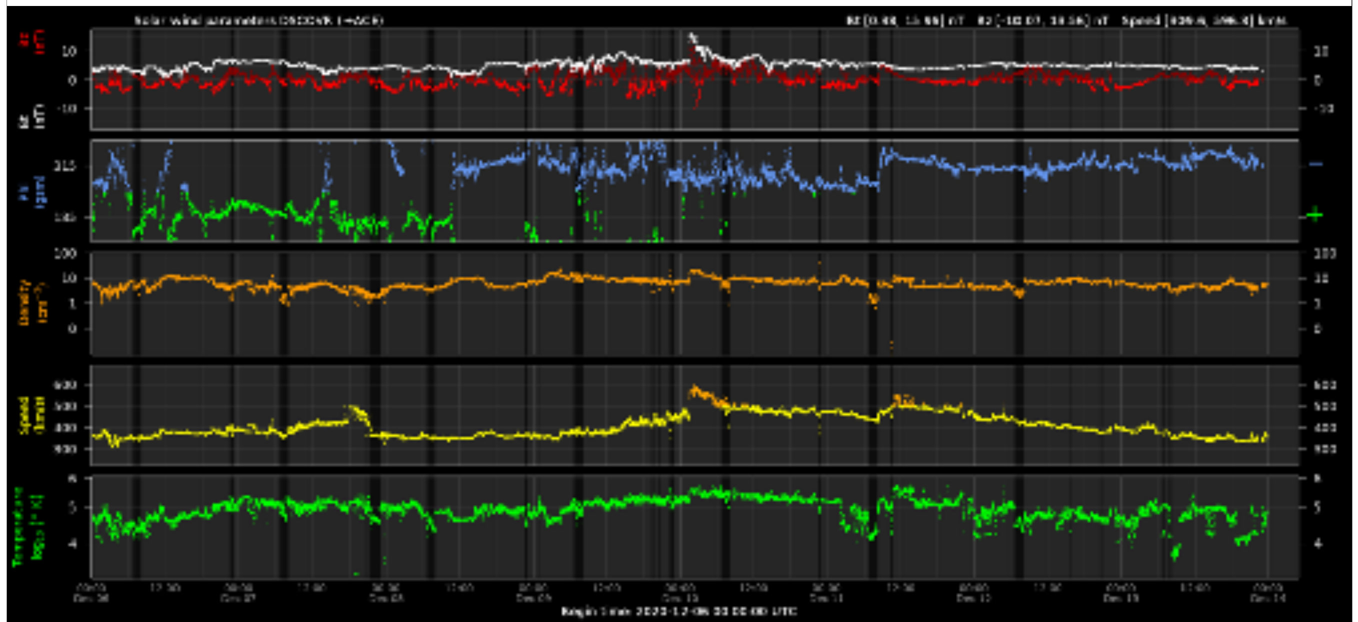
SOLAR WIND

Name a satellite that measures the solar wind at L1

SOLAR WIND

Name the 5 panels in ACE or DSCVR graphs.

CIR



CME

SOLAR WIND

Name 3 clearly distinct places where magnetic reconnection takes place.