Interplanetary CMEs and shocks

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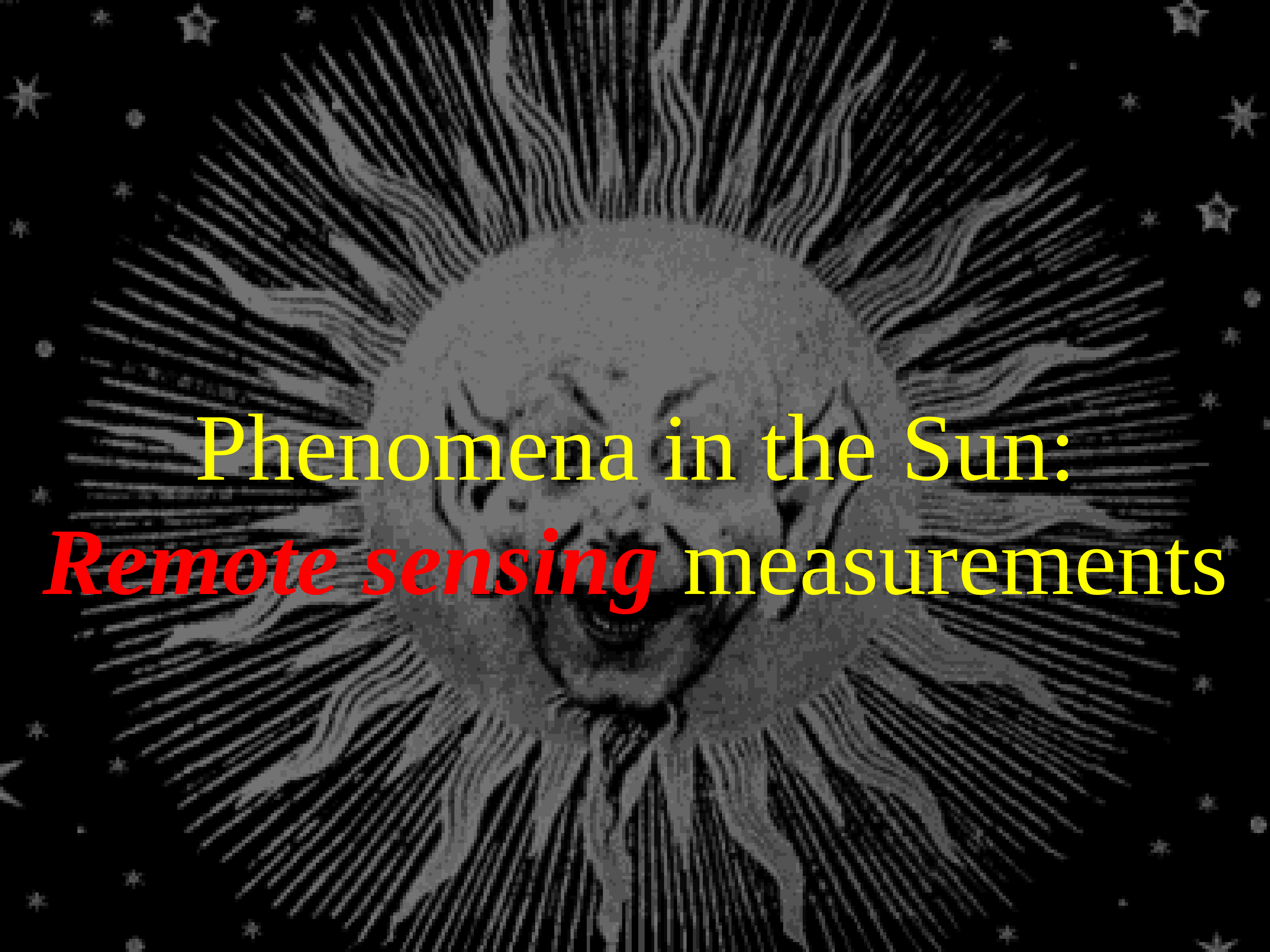
Headlines of the talk

- Phenomena in the Sun: *Remote sensing* measurements

- Phenomena observed in the interplanetary medium coming from the Sun: *In-situ* measurements

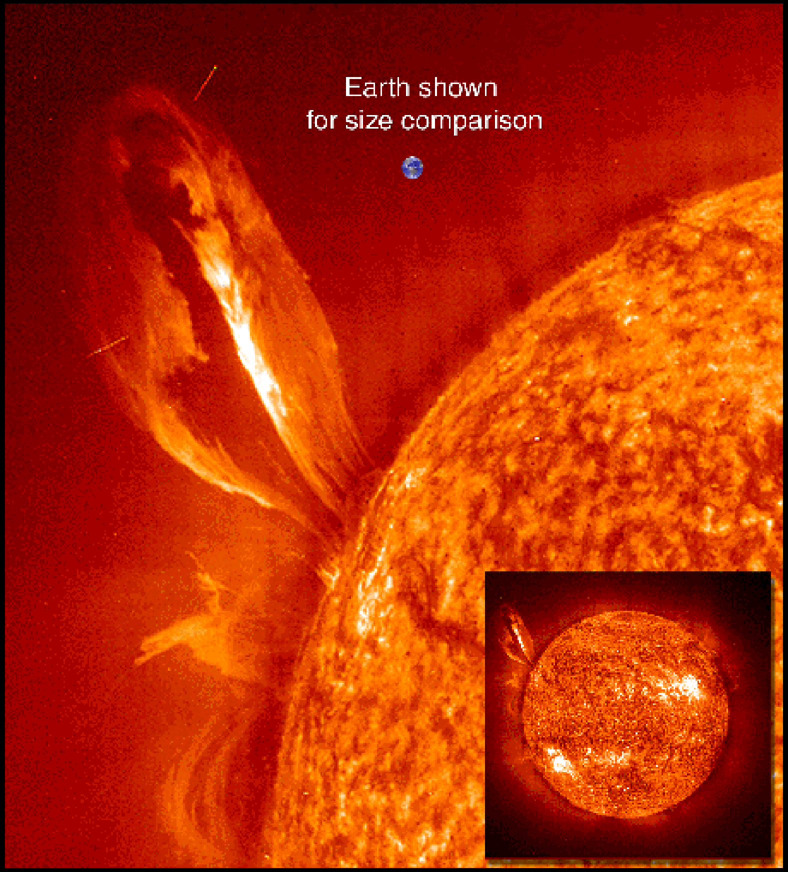
- Analytical approaches to the physics of the phenomena in the interplanetary medium, an example: Magnetic clouds

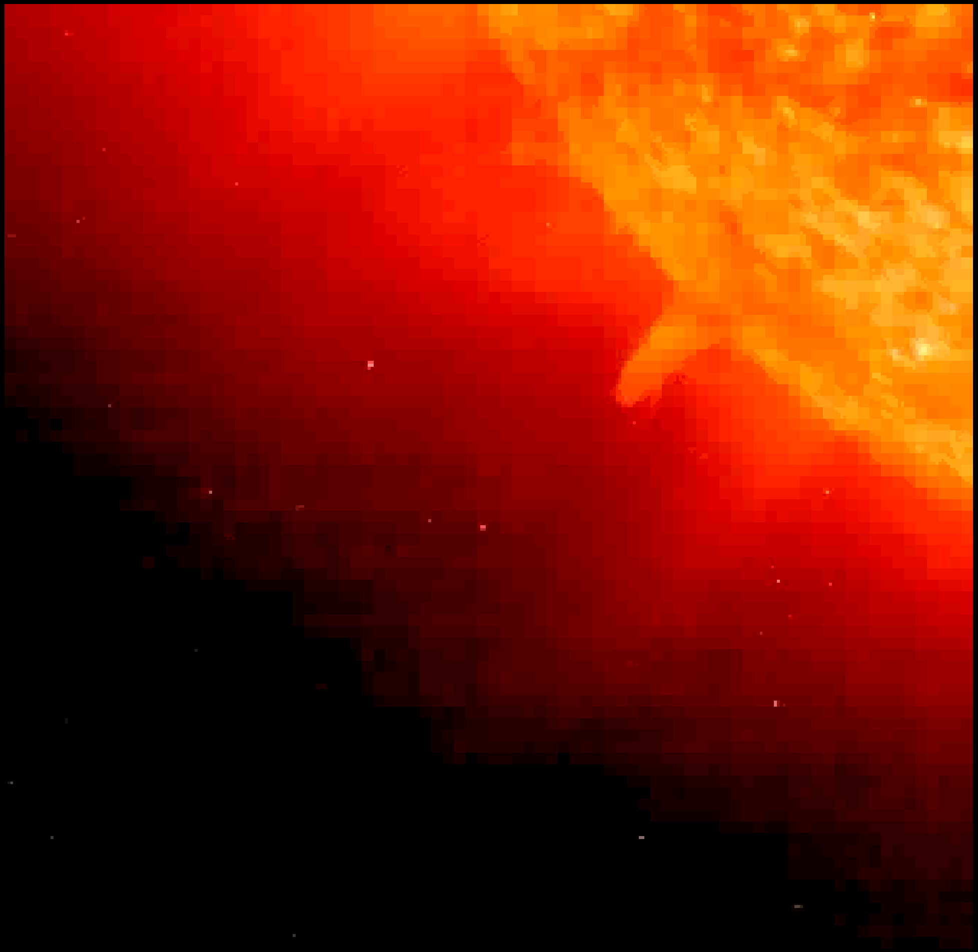


Phenomena in the Sun:
Remote sensing measurements

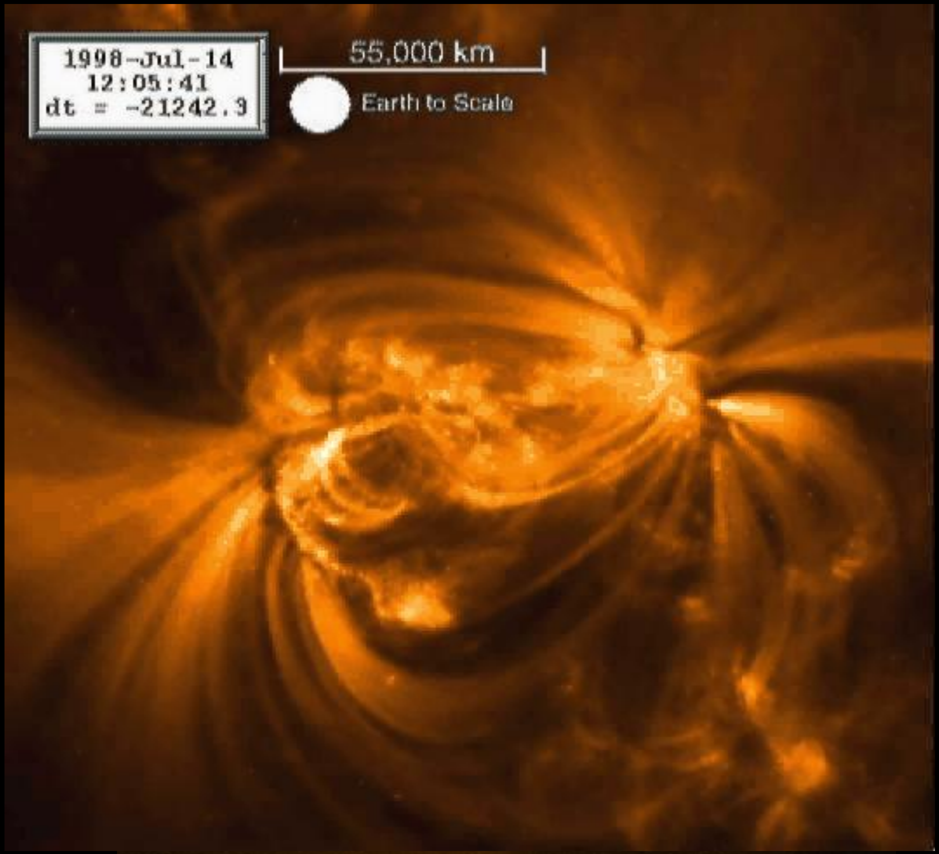
Prominences

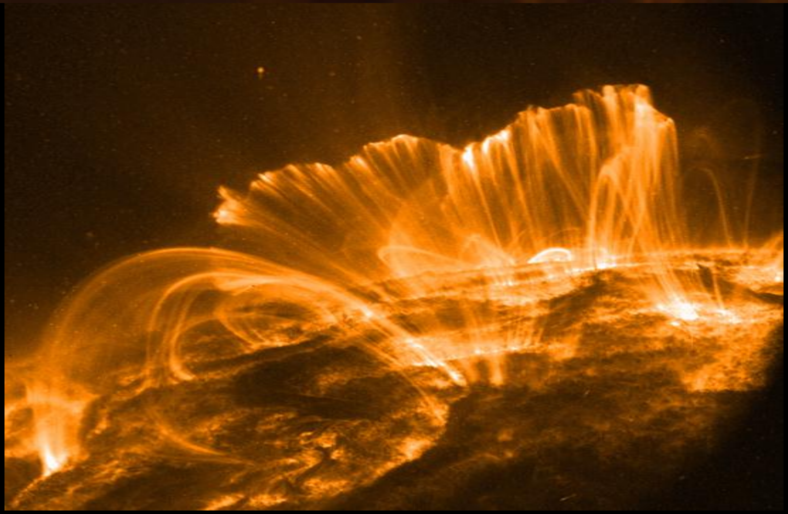
Plasma clouds suspended over the Sun surface. They are loops magnetic field lines

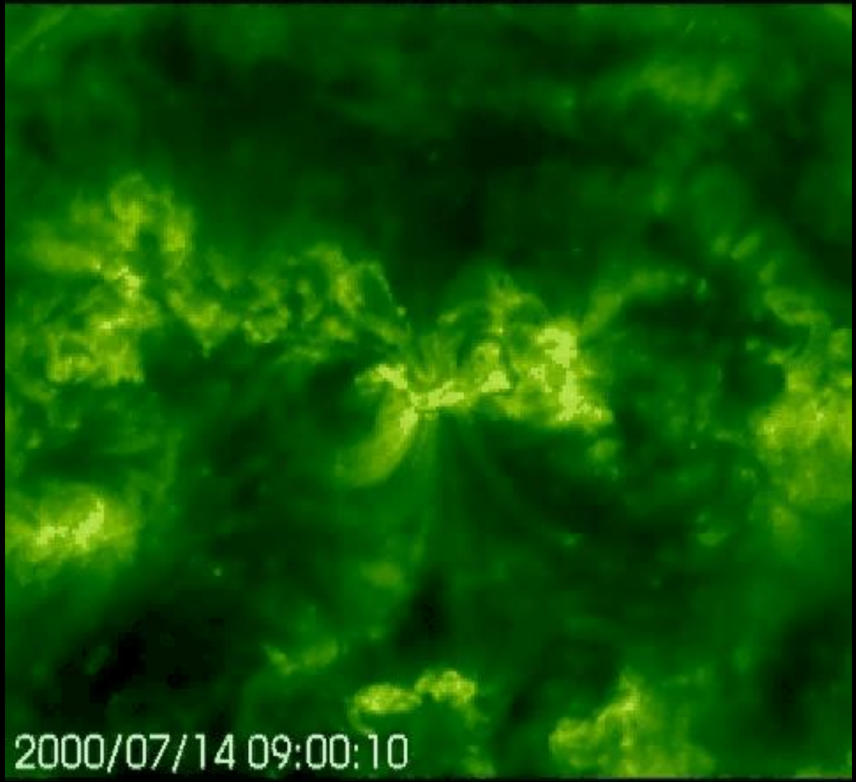




Phenomena at Sun surface



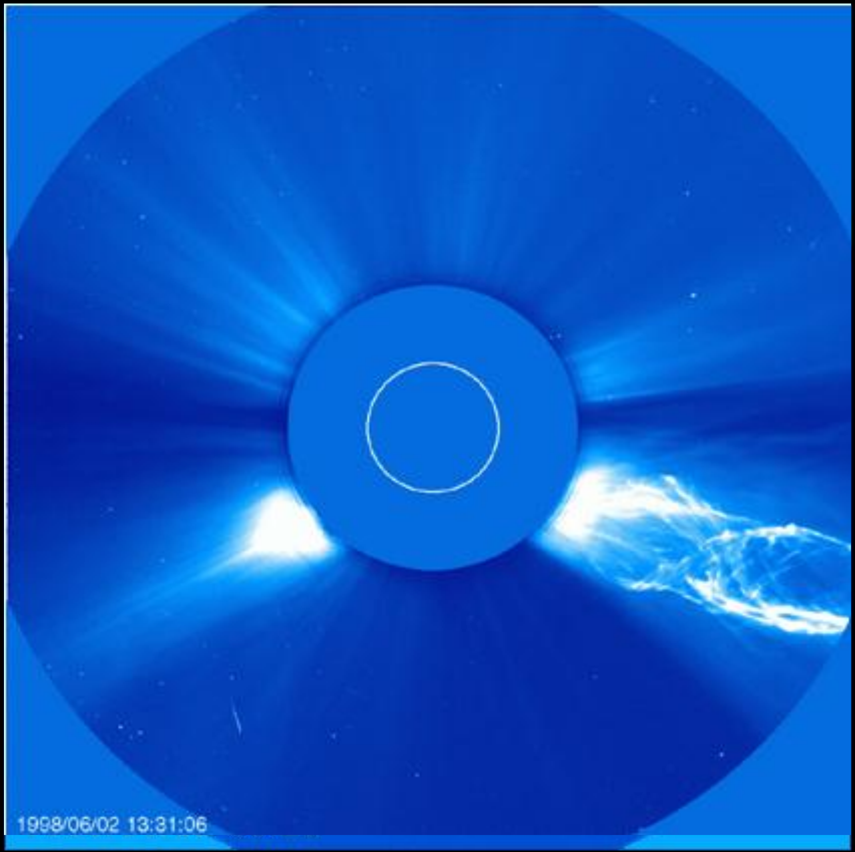




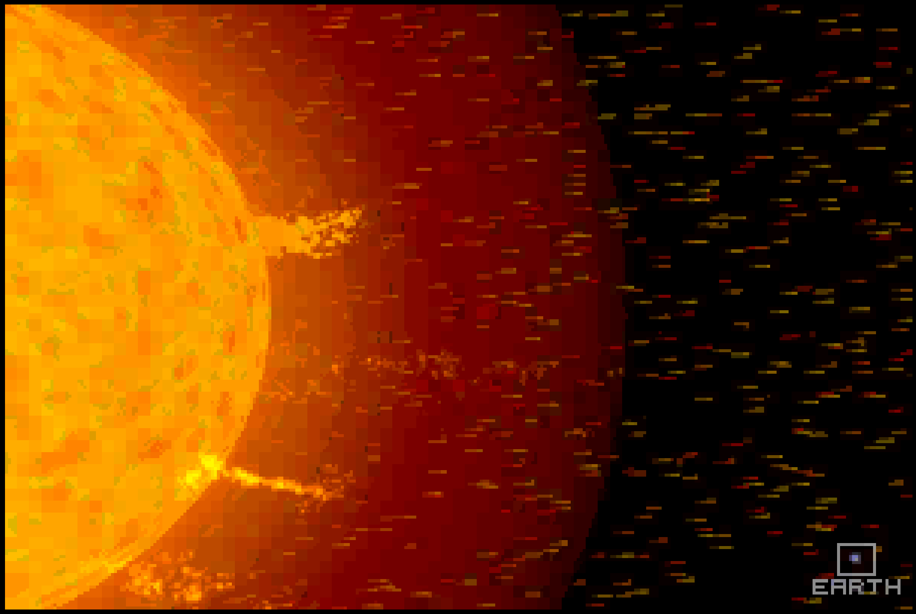
Coronal Mass Ejection

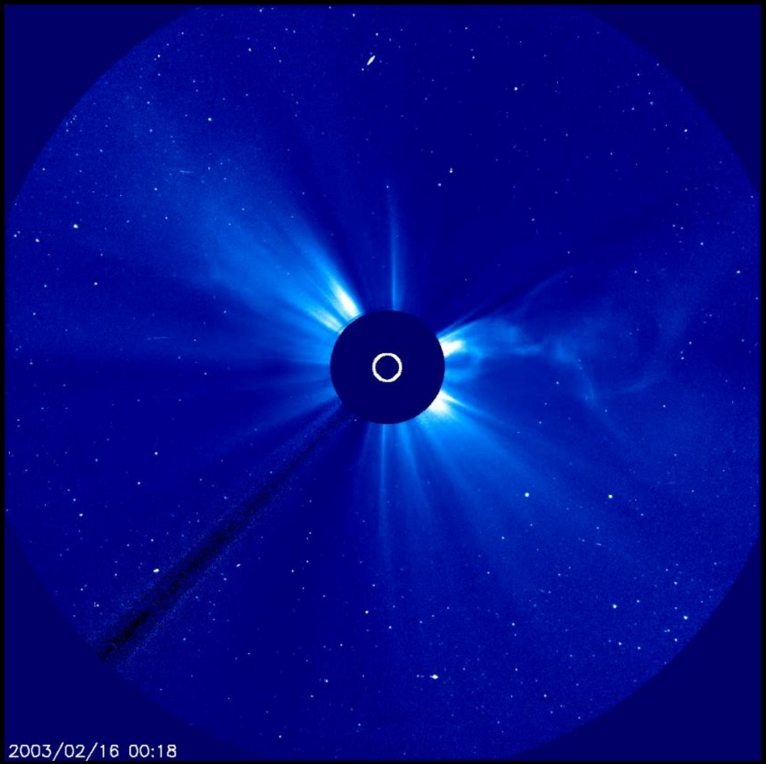
Plasma emission from the Sun surface

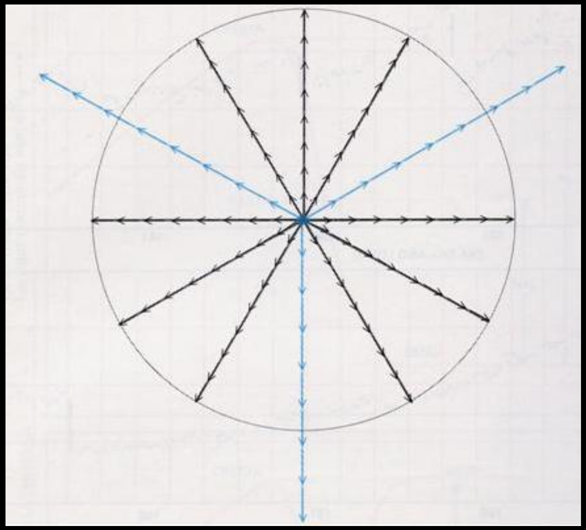
During solar maximum (2.5 per a day)
During solar minimum (0.5 per a day)

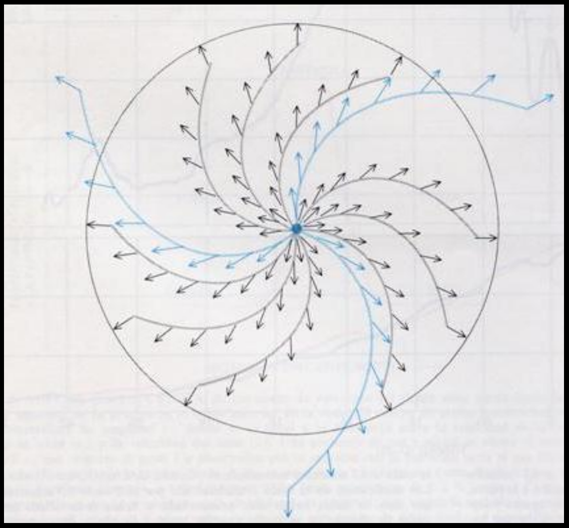


Solar wind



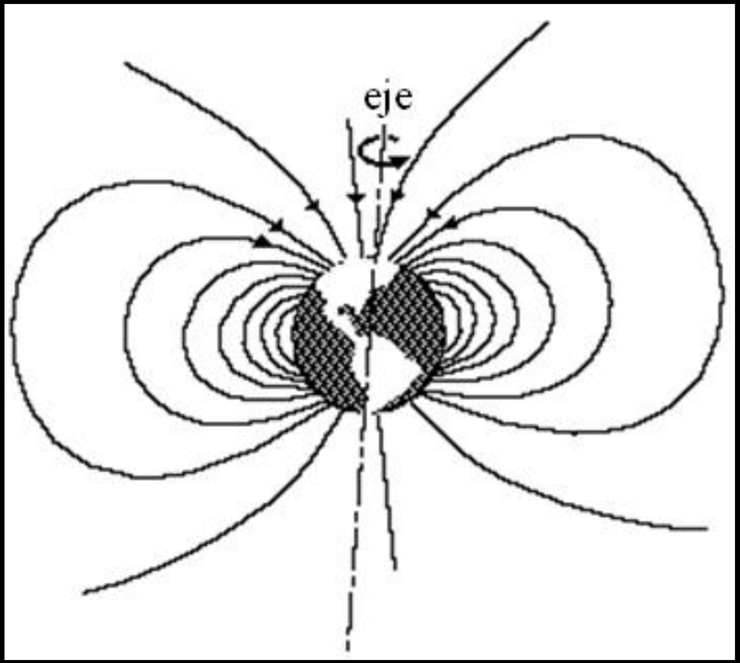




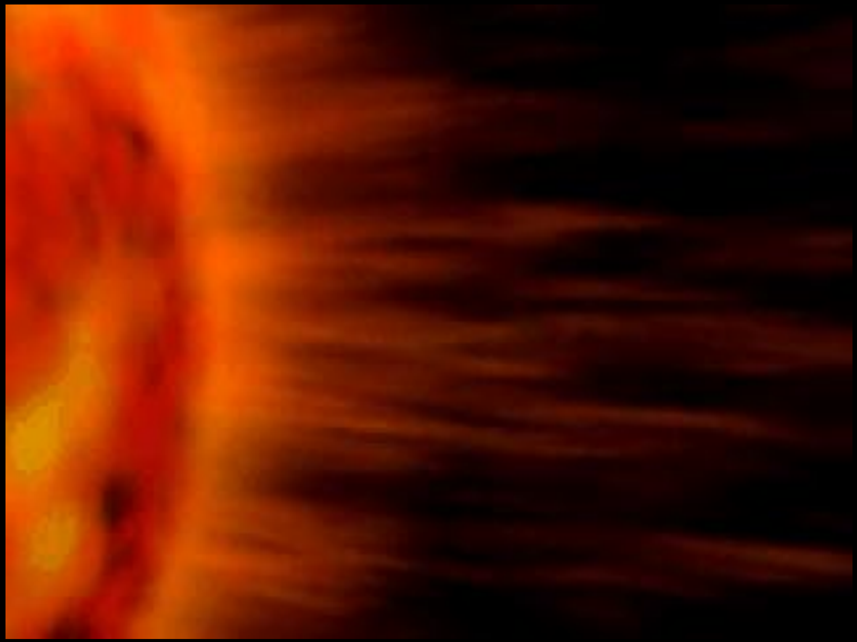


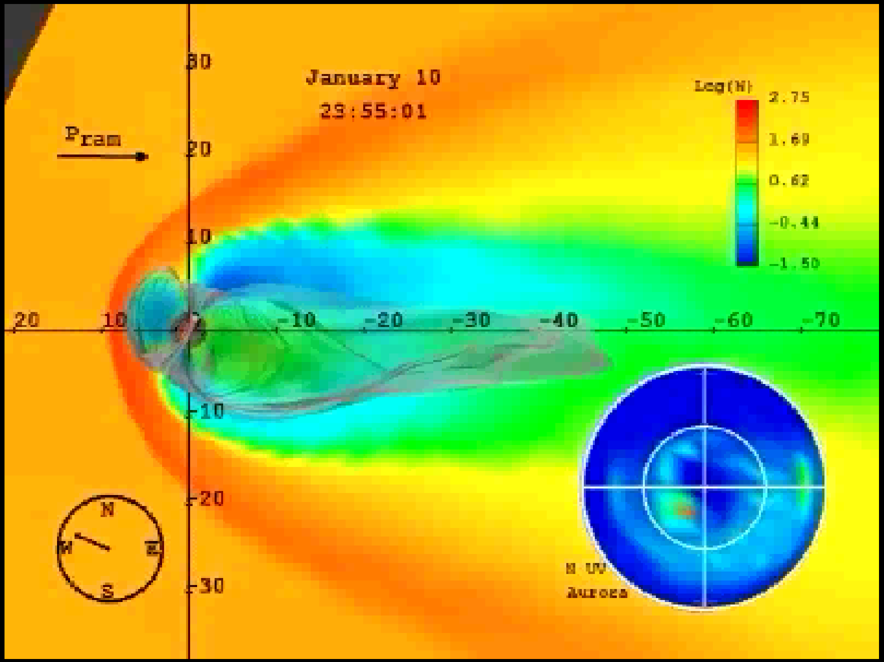
Magnetic field of The Earth

B ≈ 0,5 G

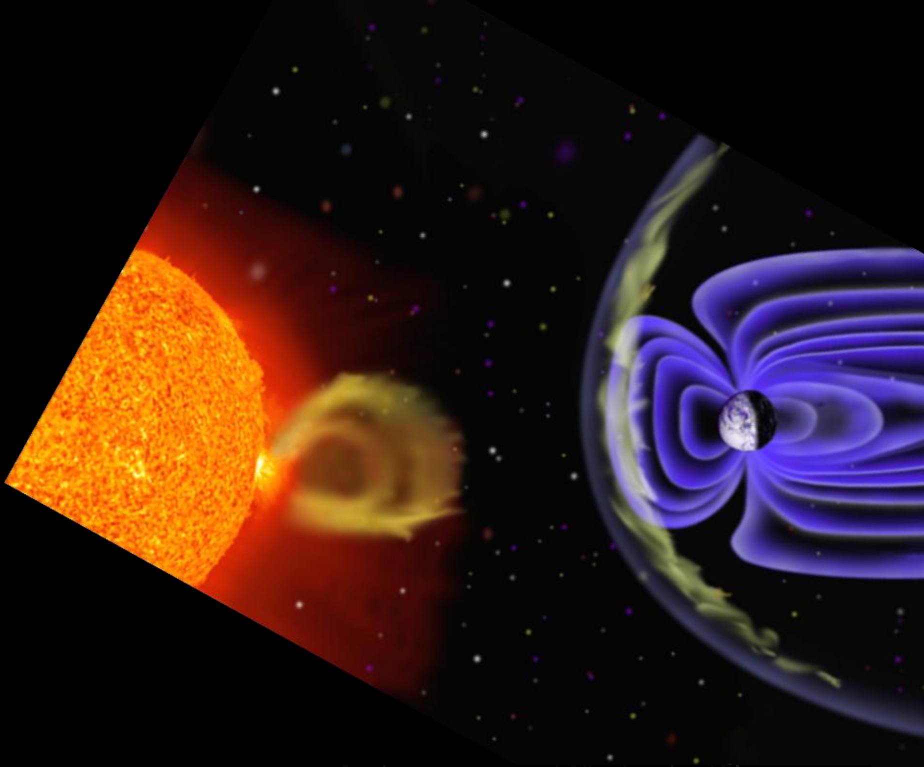


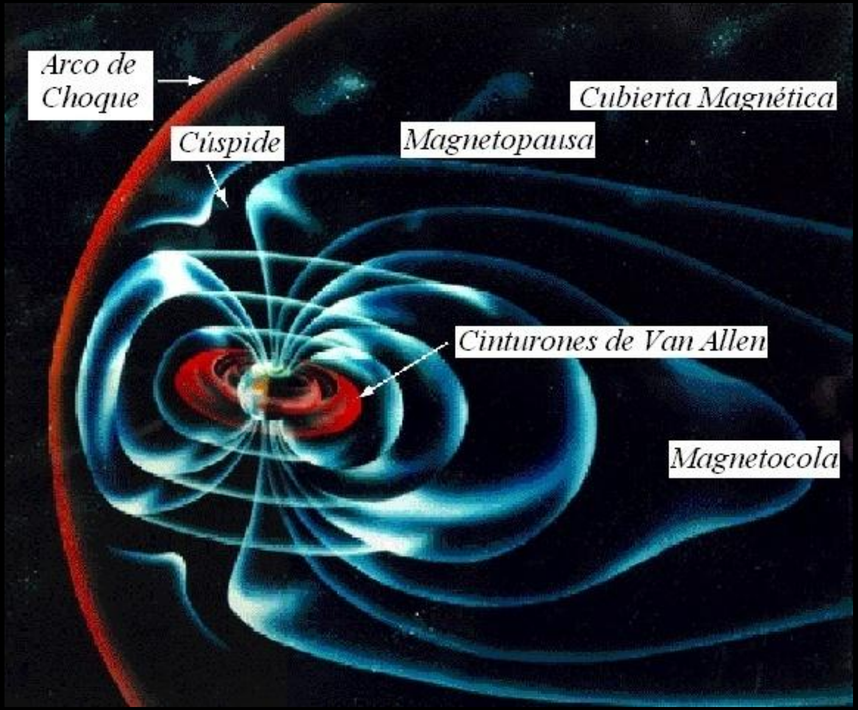
Solar wind effect on the magnetosphere

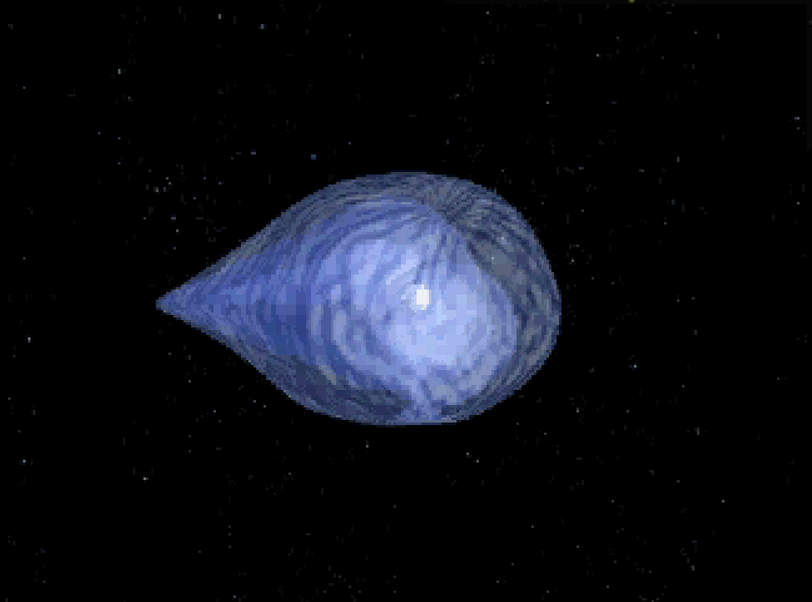




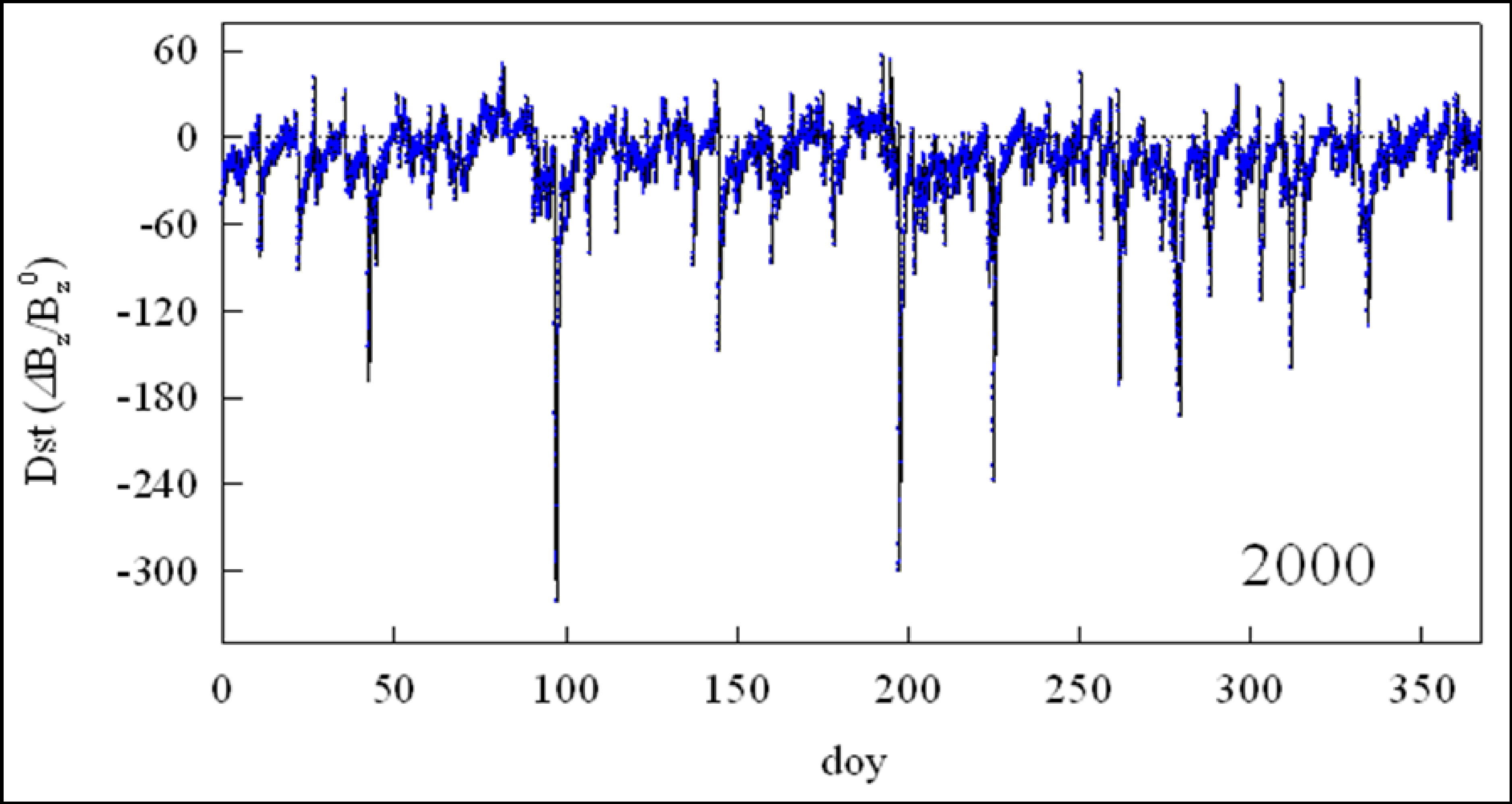
Structure of magnetosphere





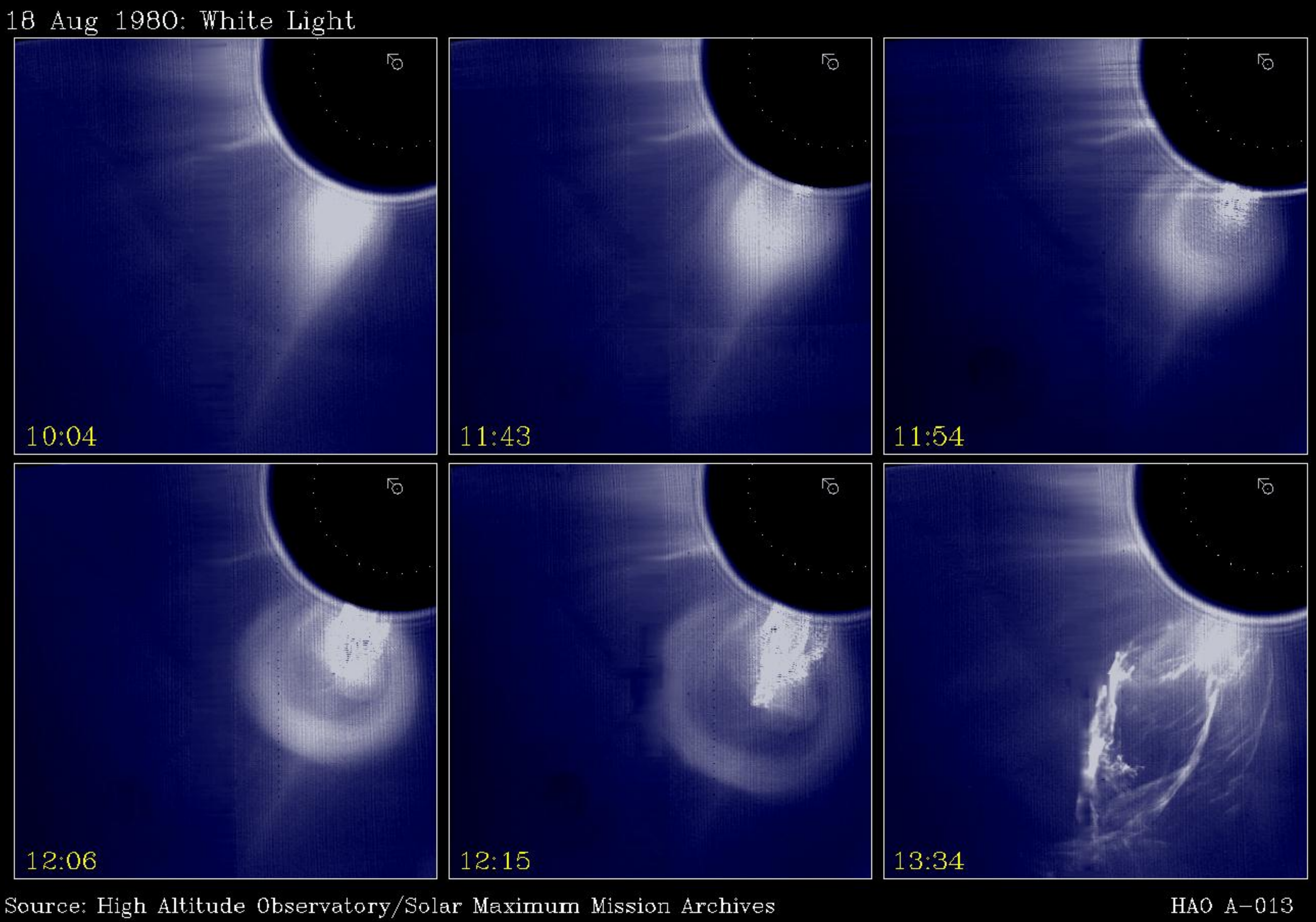


Geomagnetic storms

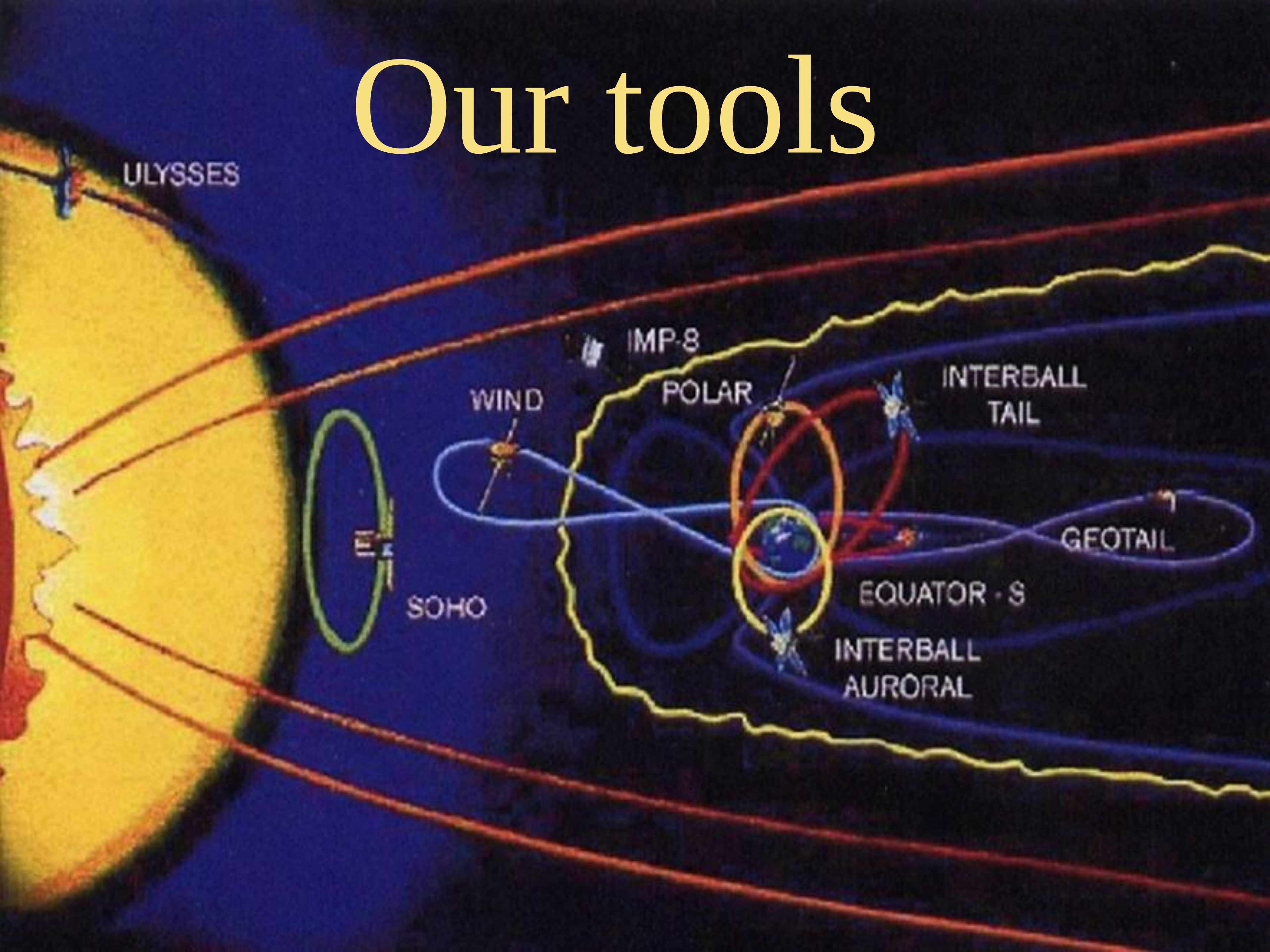


Phenomena observed in the interplanetary medium coming from the Sun: *In-situ* measurements

Sequence of different phases in the evolution of a Coronal Mass Ejection



Our tools

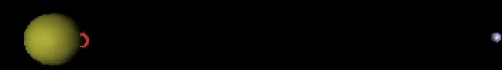

ULYSSES
IMP-8
WIND
POLAR
INTERBALL
TAIL
SOHO
GEOTAIL
EQUATOR - S
INTERBALL
AURORAL

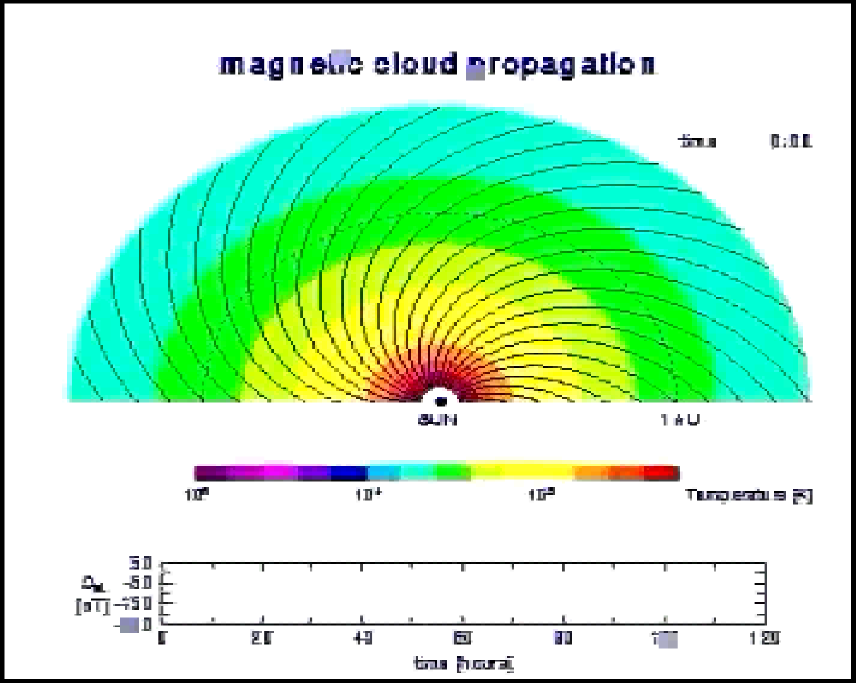
Main characteristics in the interplanetary medium

Physical magnitud	*Minimum value*	*Medium value*	*Máximun value*
Flux ($cm^{-2}\ s^{-1}$)	1	3	100
Velocity (kms^{-1})	200	400	900
Density (cm^{-3})	0.4	6.5	100
B ($\times 10^{-5}$ G)	0	5	40
Helium (%)	0.2	6	80

Interplanetary space inside our galaxy	**Density, (atoms/cm^3)**	**Temperature (K)**
Heliosphere, near The Earth	5	10,000
The cloud around Heliosphere	0.3	7,000
The best vacum obtained at the laboratory	1000	
Atmosphere inside a room	2.7×10^{19}	288
Outside Milky Way the density of particles is around 10^{-6}/cm^3		

Time taken by the light	**Distance**	**Example**
3 seconds	900.000 km	~ Distance Earth-Moon
8.3 minutes	149.600.000 km	Distance Sun-Earth (1 UA)
13.5 hours	98 UA	Position Voyager-1 (January, 2006)
1 year	~ 63.000 UA	Light year
4.2 years	~ 265.000 UA	Closest star to our solar system



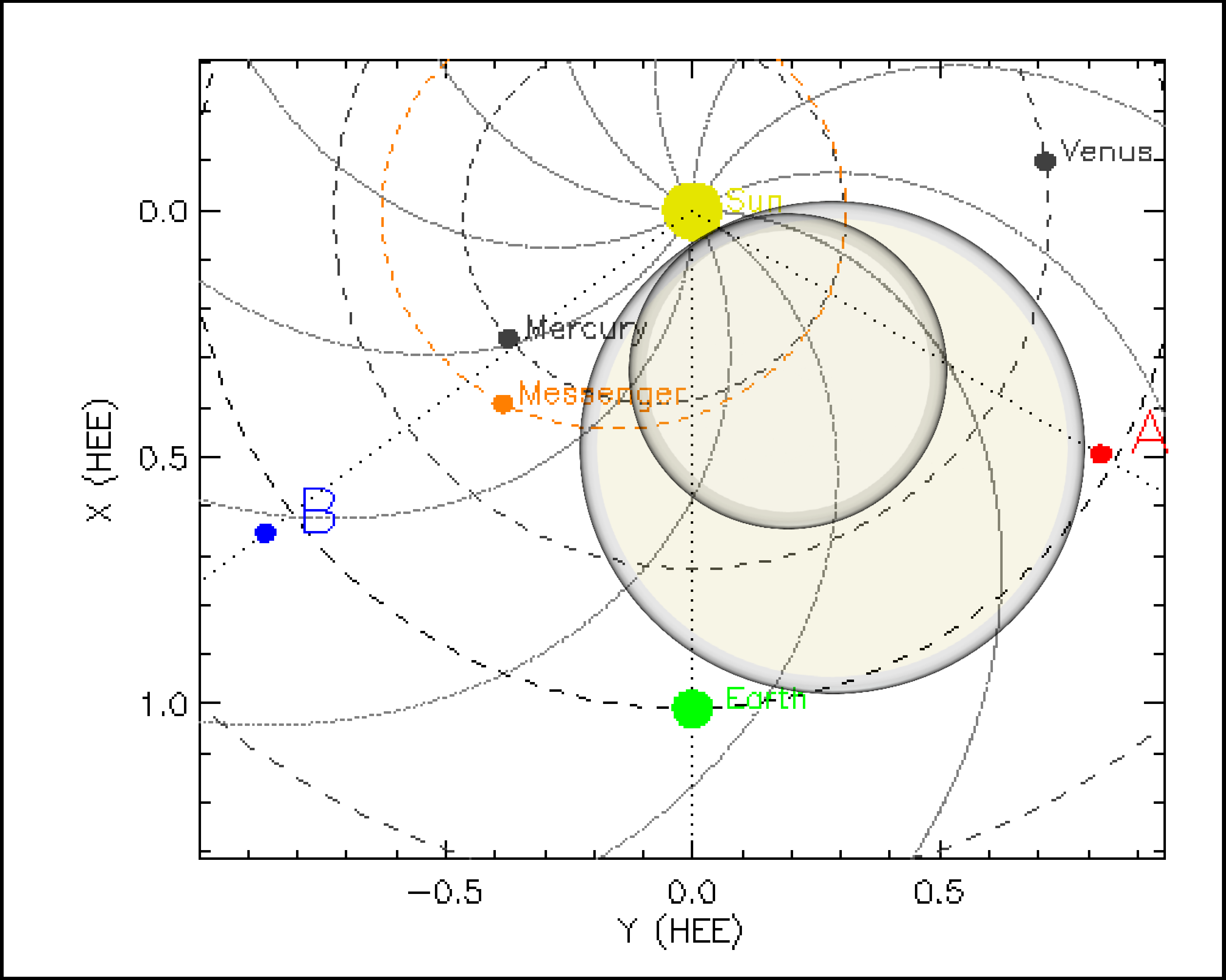


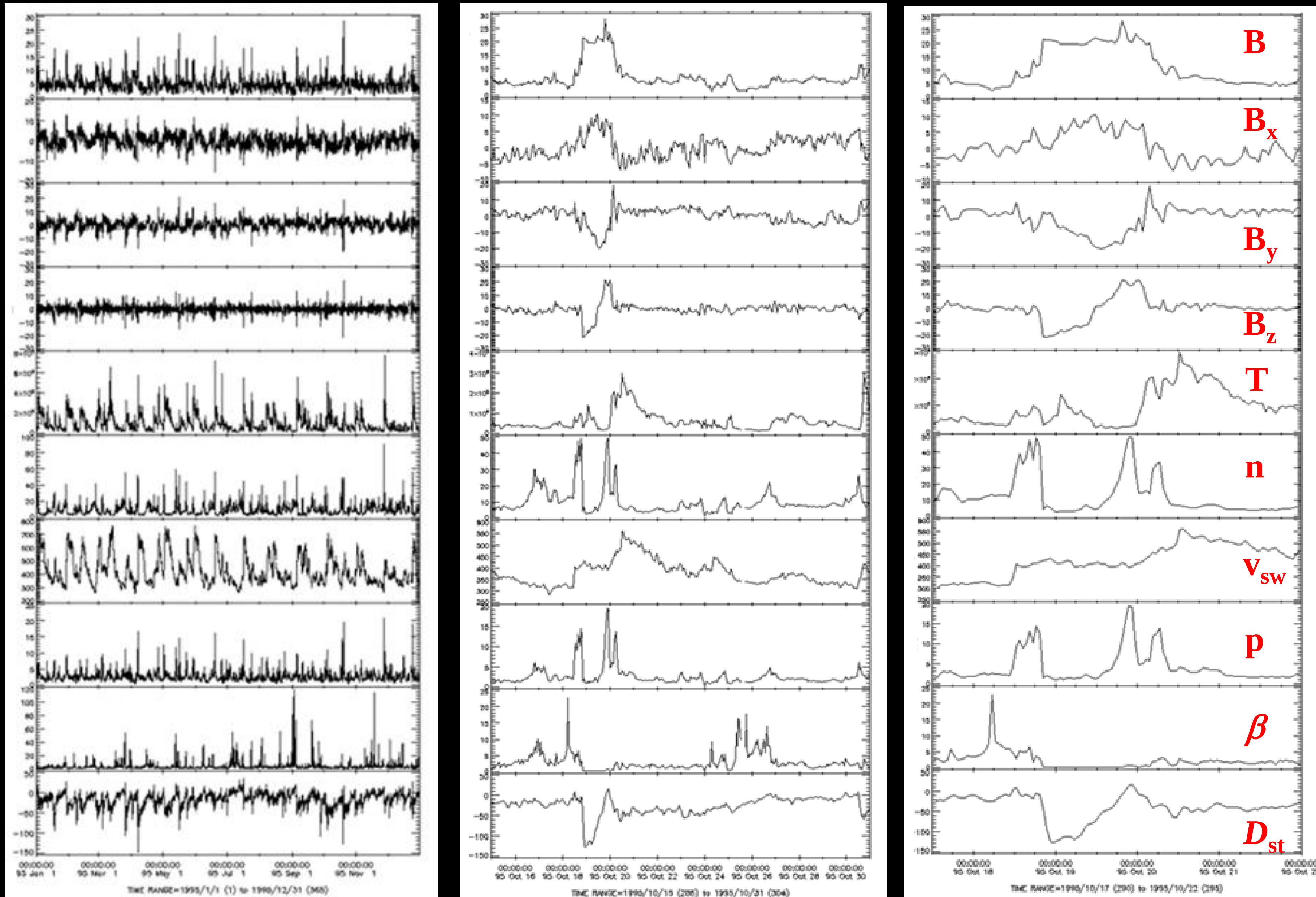
Dynamic of any CME in the interplanetary medium

A CME propagating in the interplanetary medium is called ICME

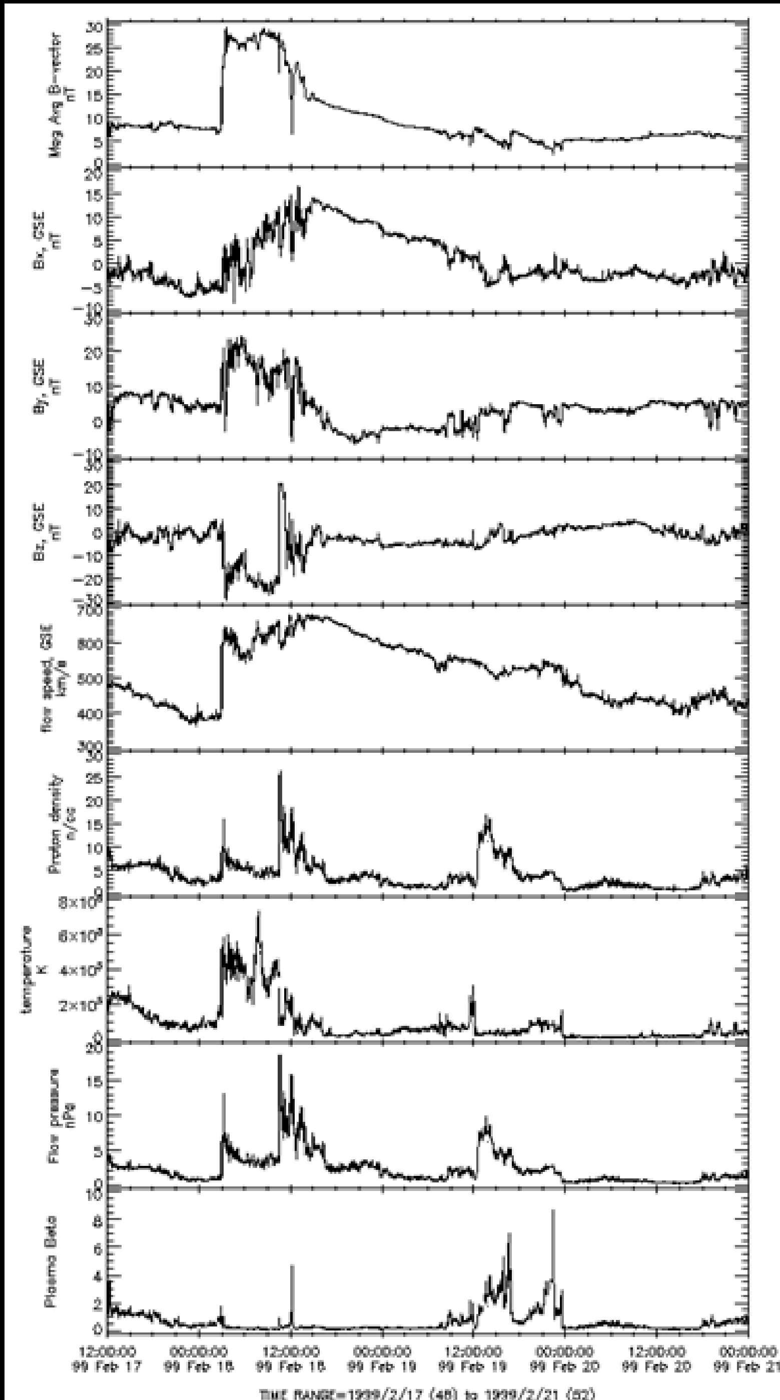
Up to more recently years the only possible data for the study of these structures come from measurements taken from the passage of one spacecraft

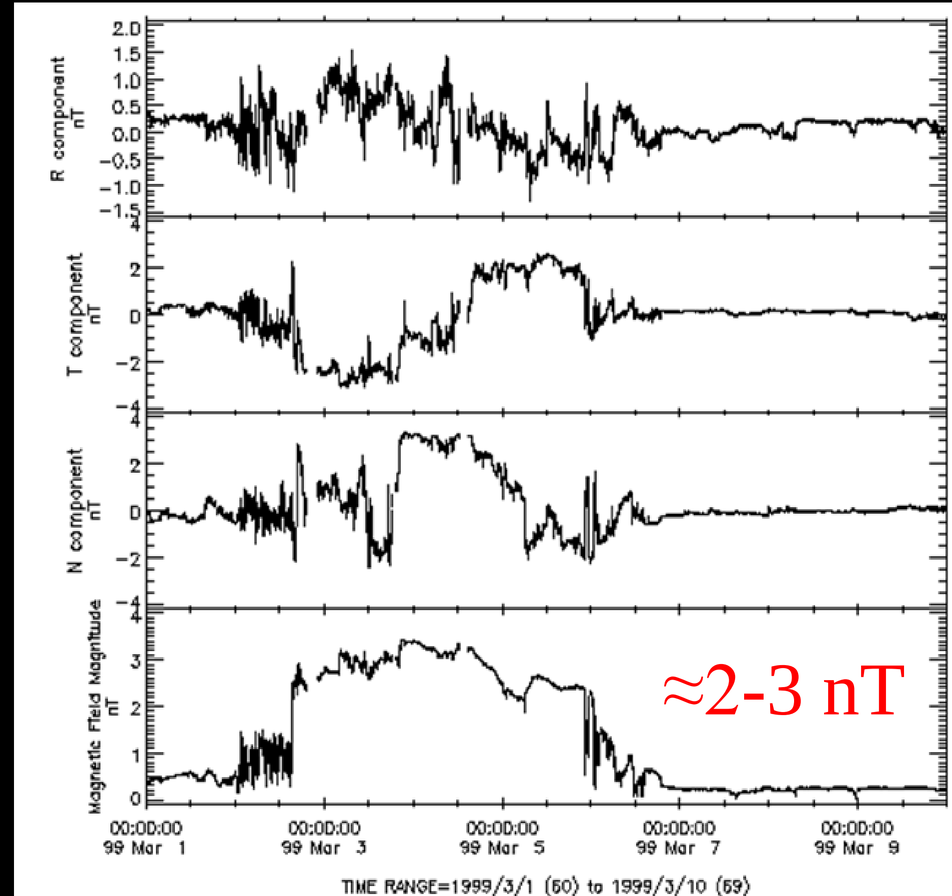
Measurements obtained from several spacecrafts



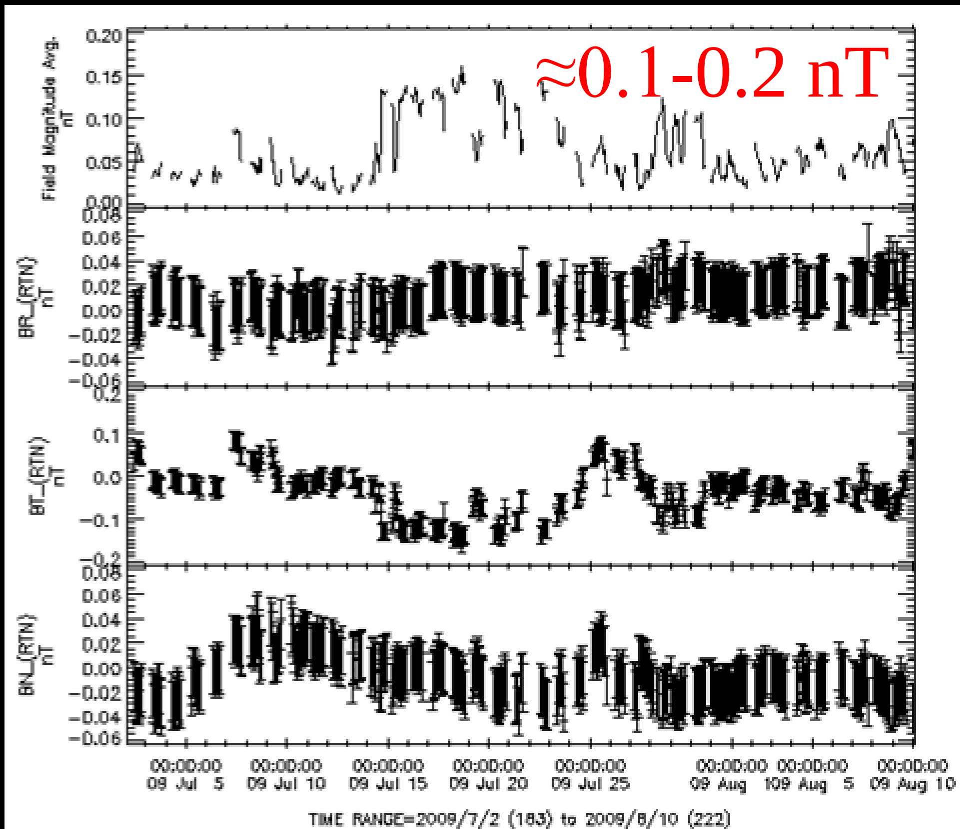


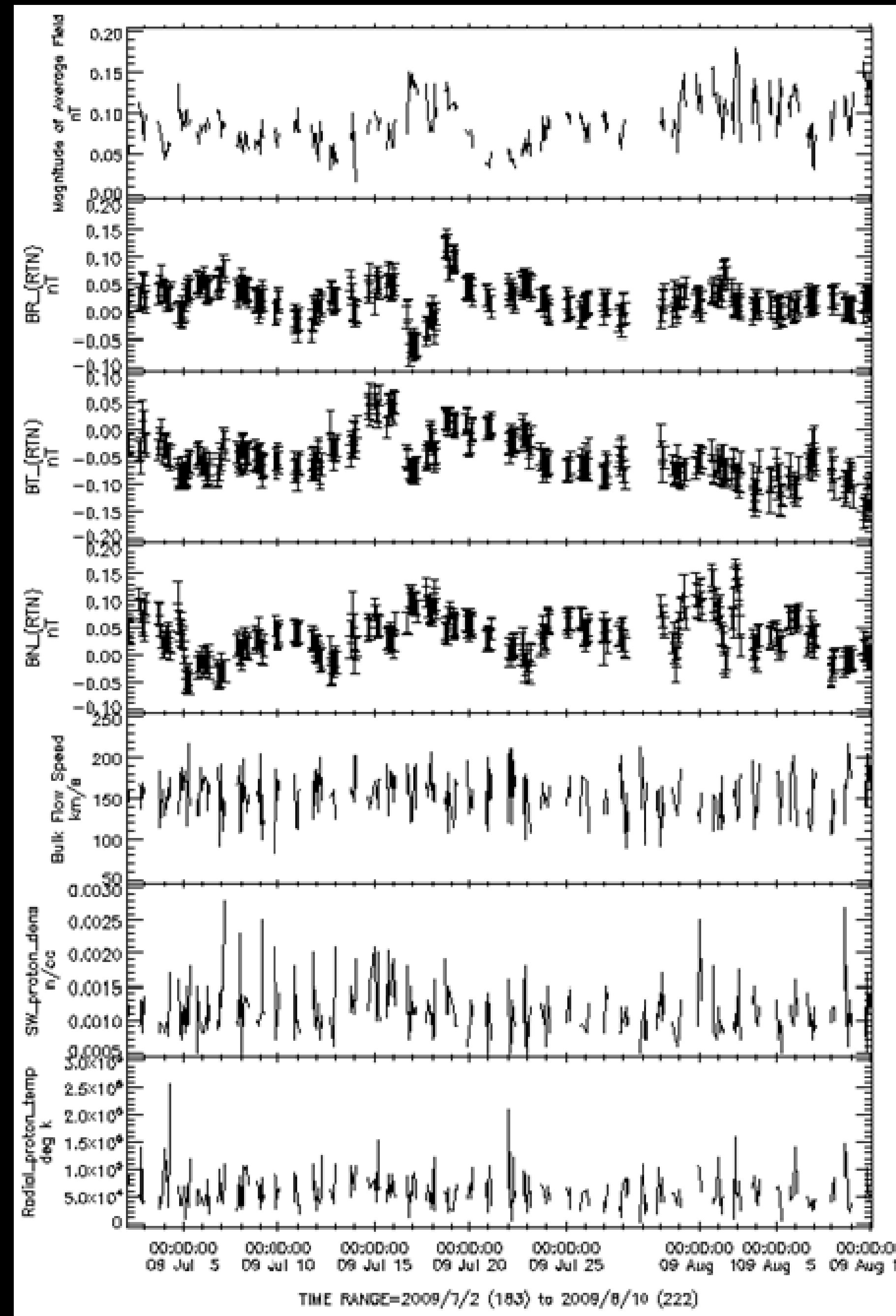
http://cdaweb.gsfc.nasa.gov/istp_public





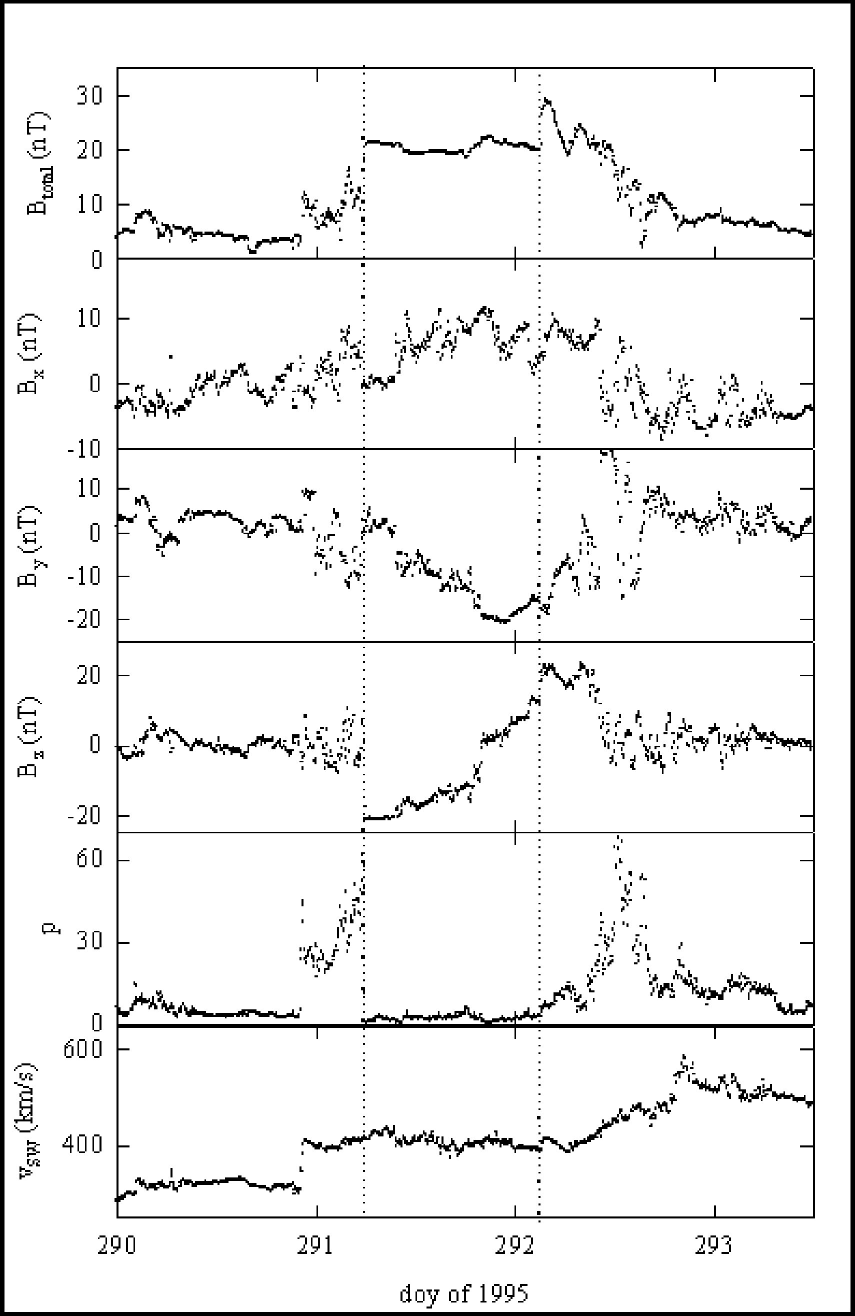
Phenomenon seen by two spacecrafts (ACE and Ulysses)





Voyager 1

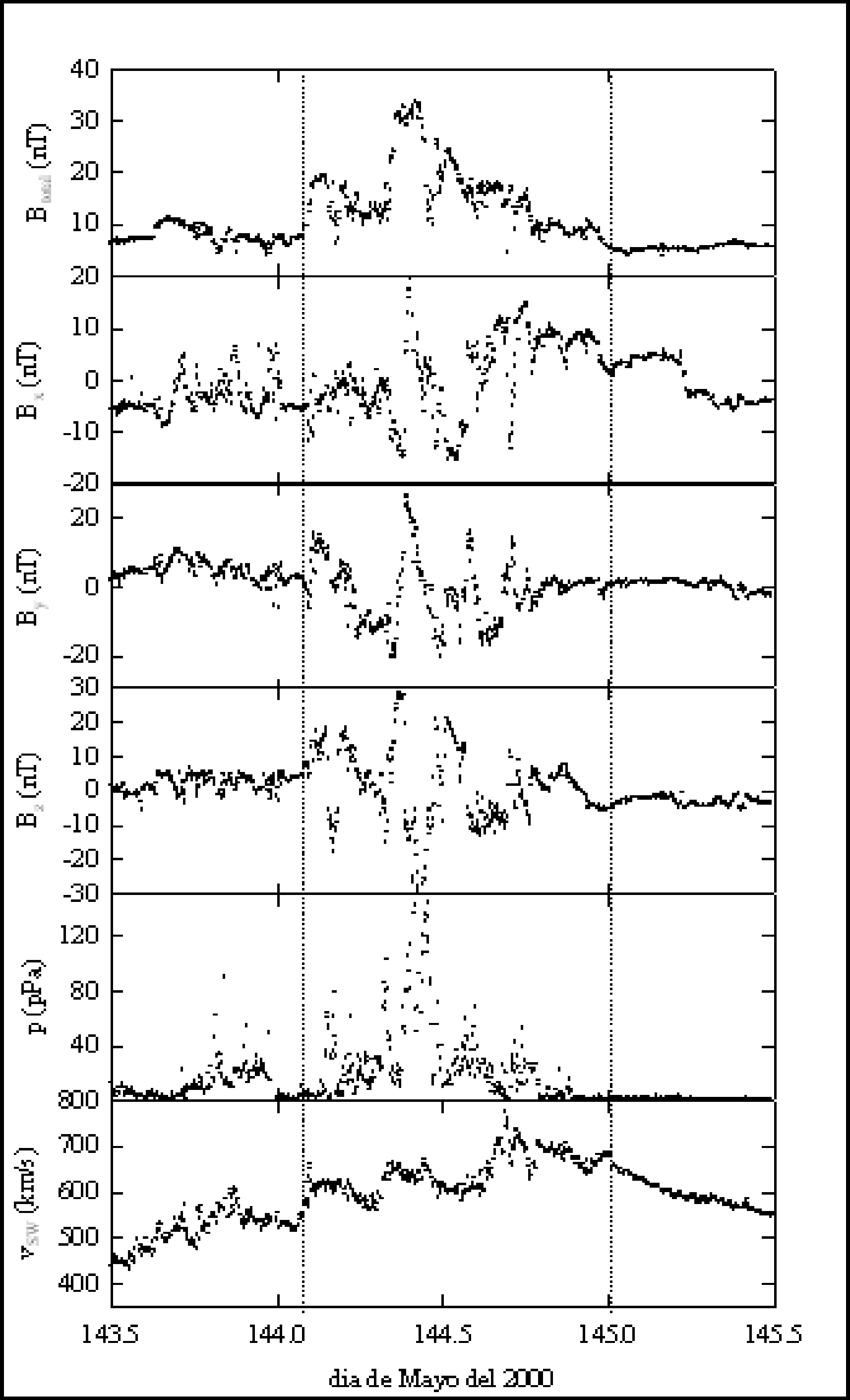
Voyager 2



Magnetic clouds (MCs) as seen in the interplanetary medium

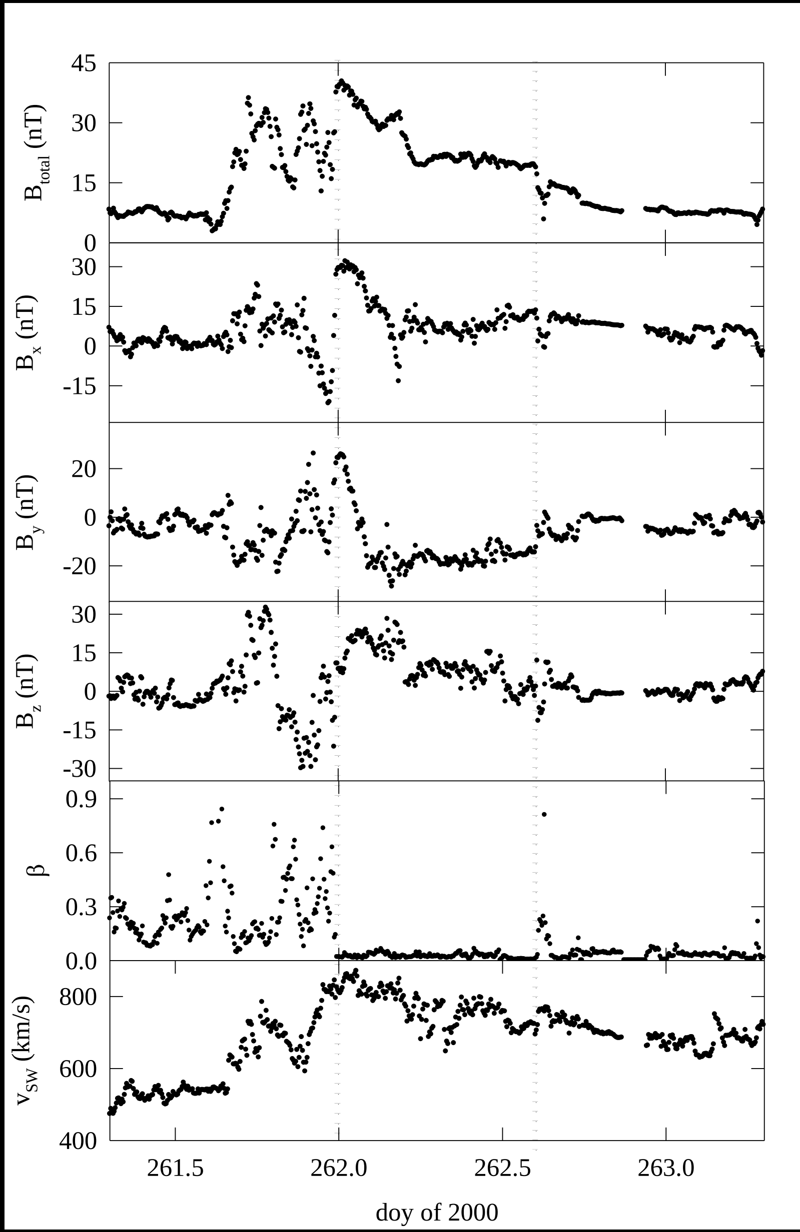
1 AU

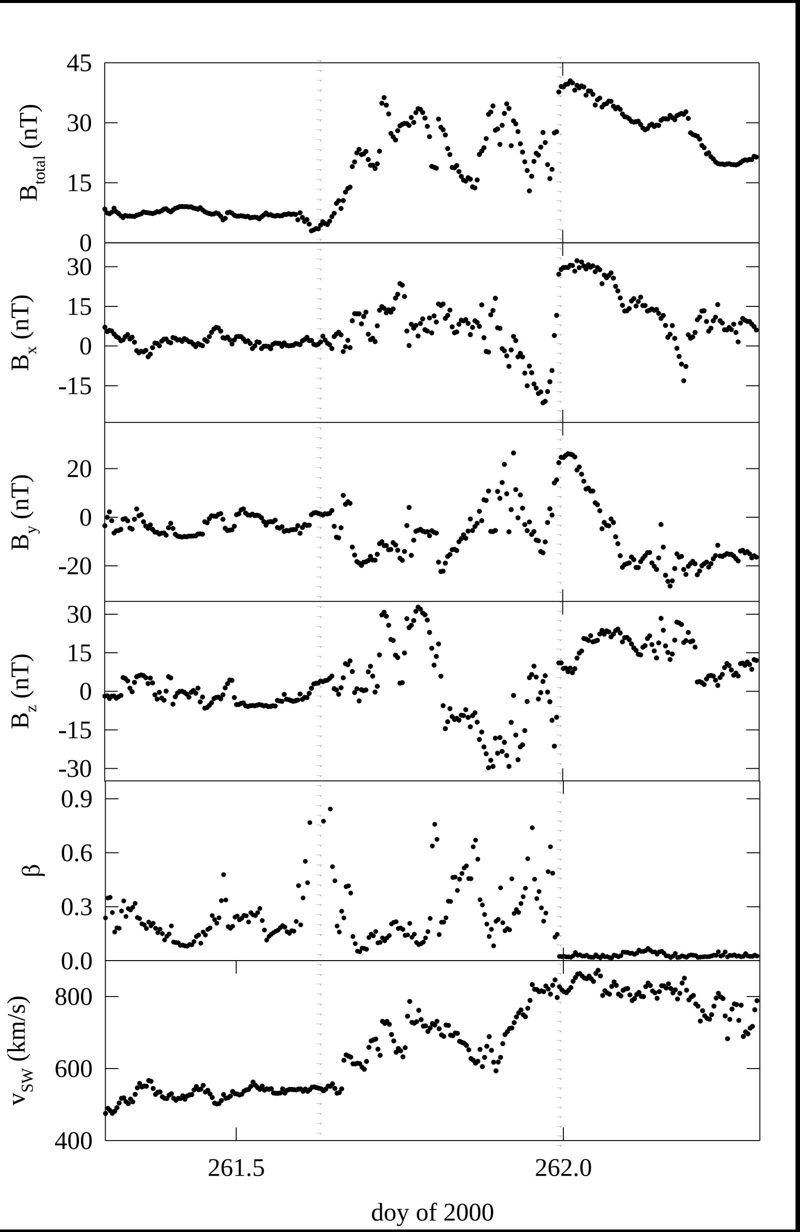
Corotating Interaction Region (CIR)



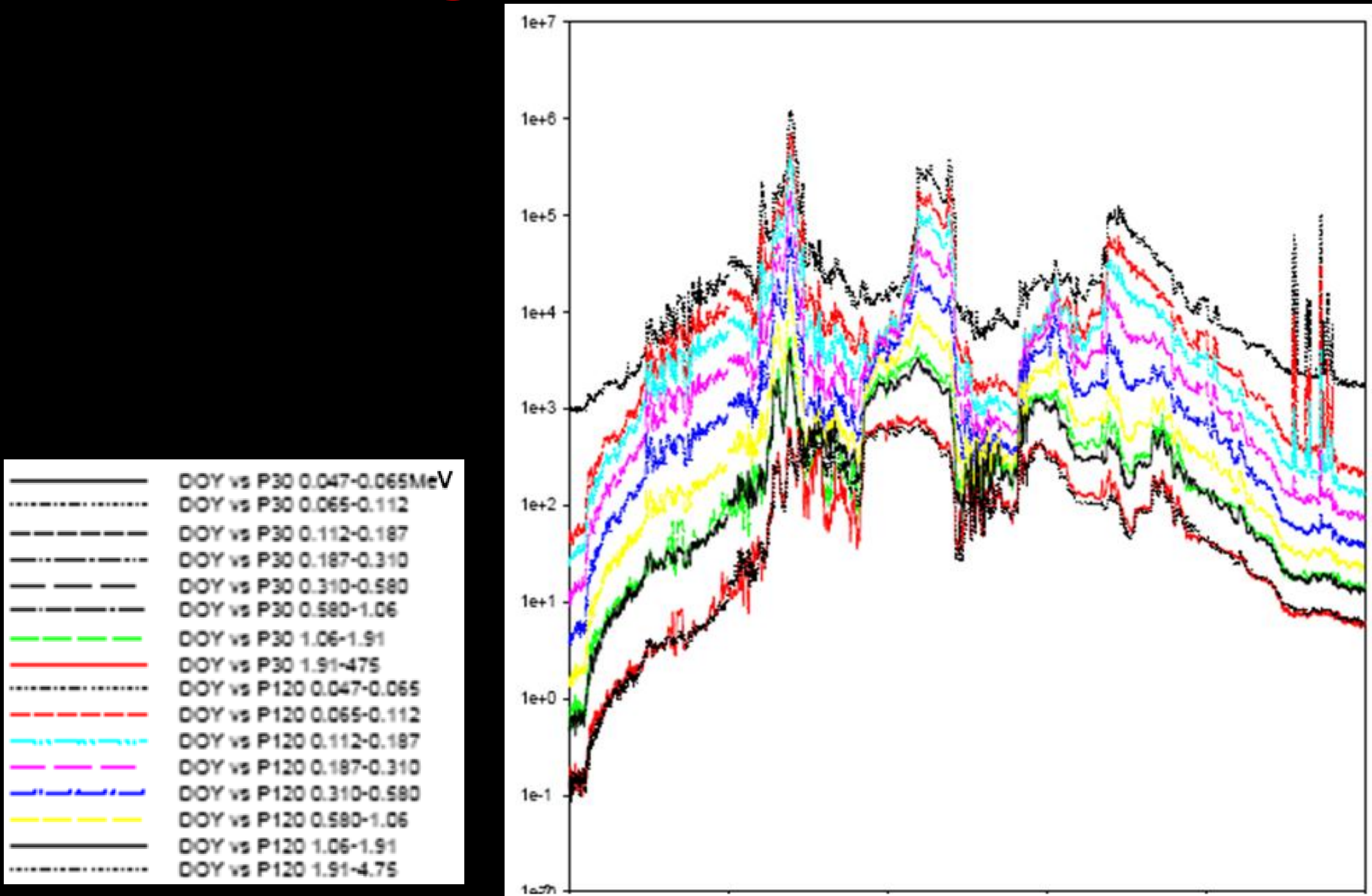
1 AU

Shock associated with a magnetic cloud



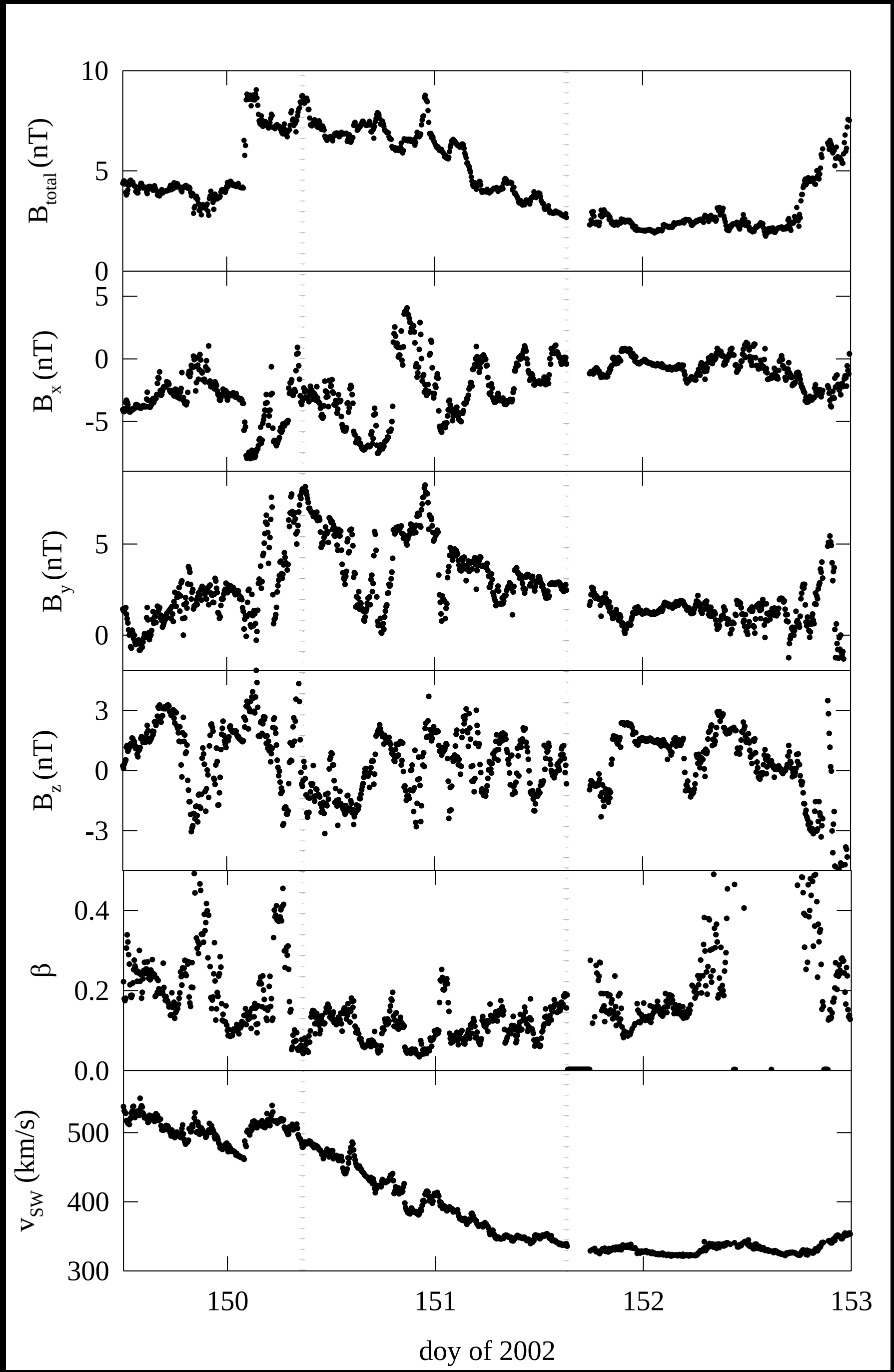


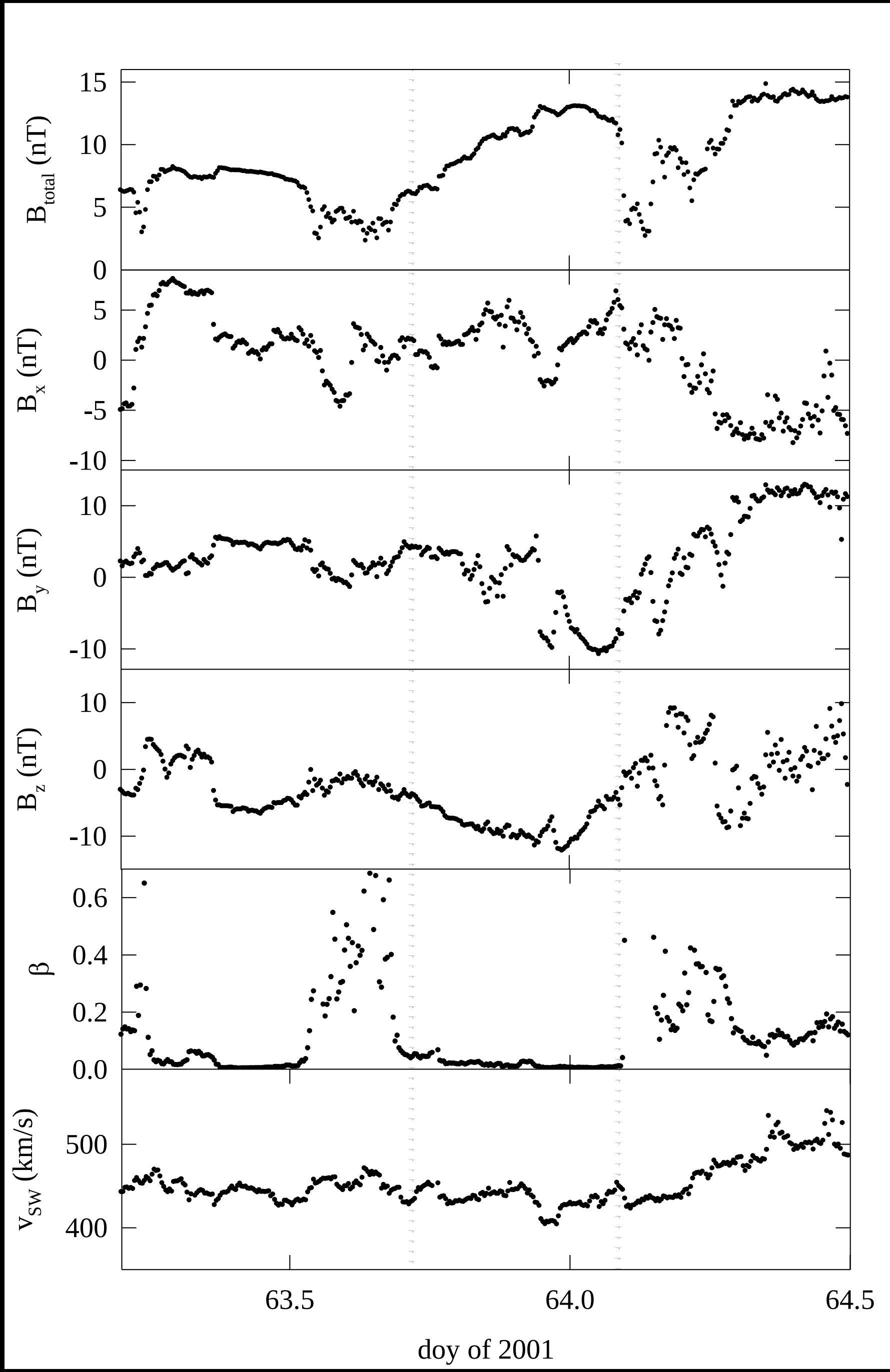
Solar Energetic Particles



Complex Ejecta (event 20020530)

Complex behaviour of the magnetic field components and plasma. (Resulting from the interaction of successive CMEs or from the interaction of CMEs with complex solar wind structures and streams.)

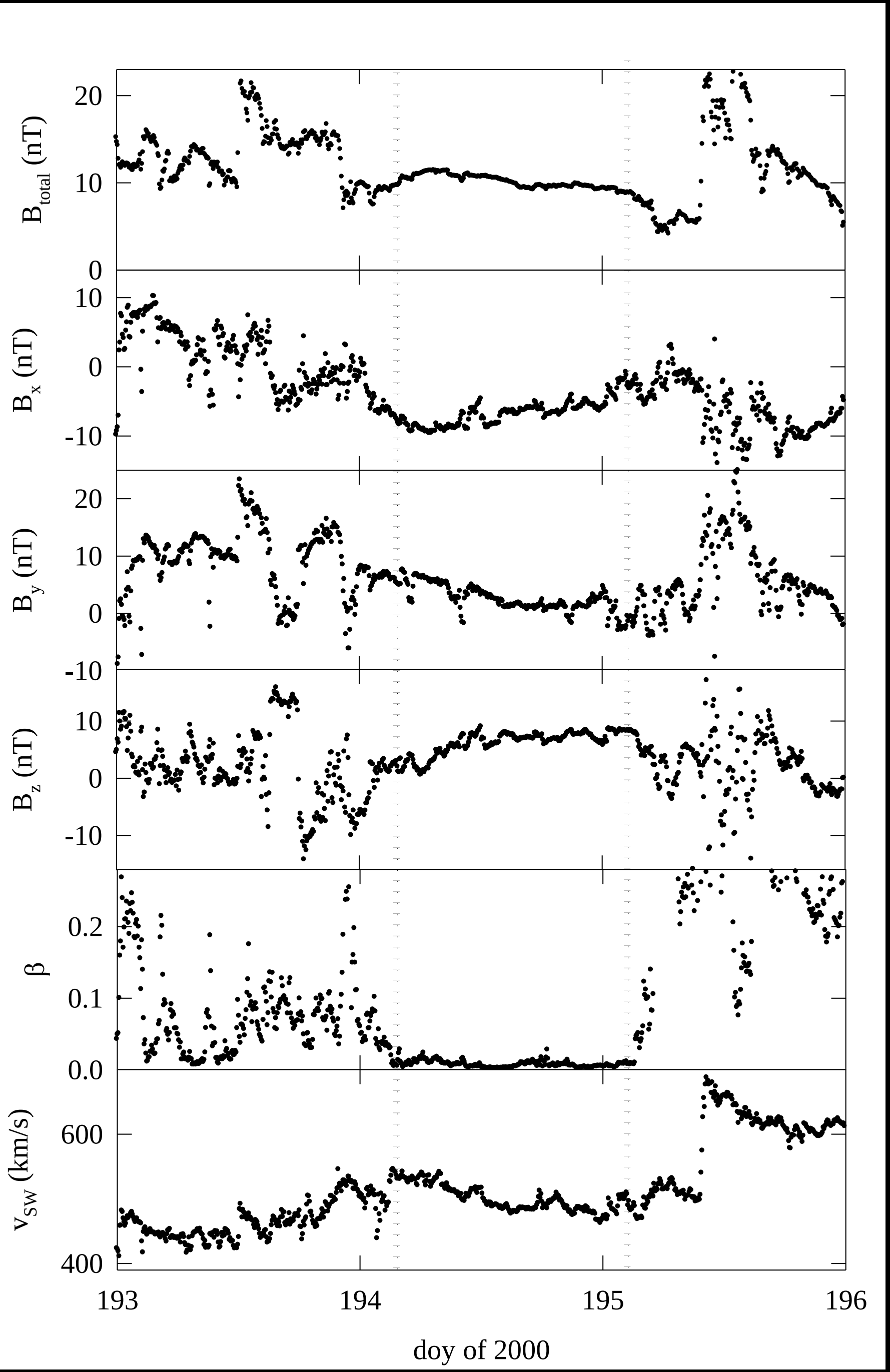




Ejecta (event 20010305)

Non-Flux Rope

Plasma usually presents clear signatures of some well-defined structure but the magnetic field components profile do not present a smooth and regular behaviour (as expected for a flux rope topology)



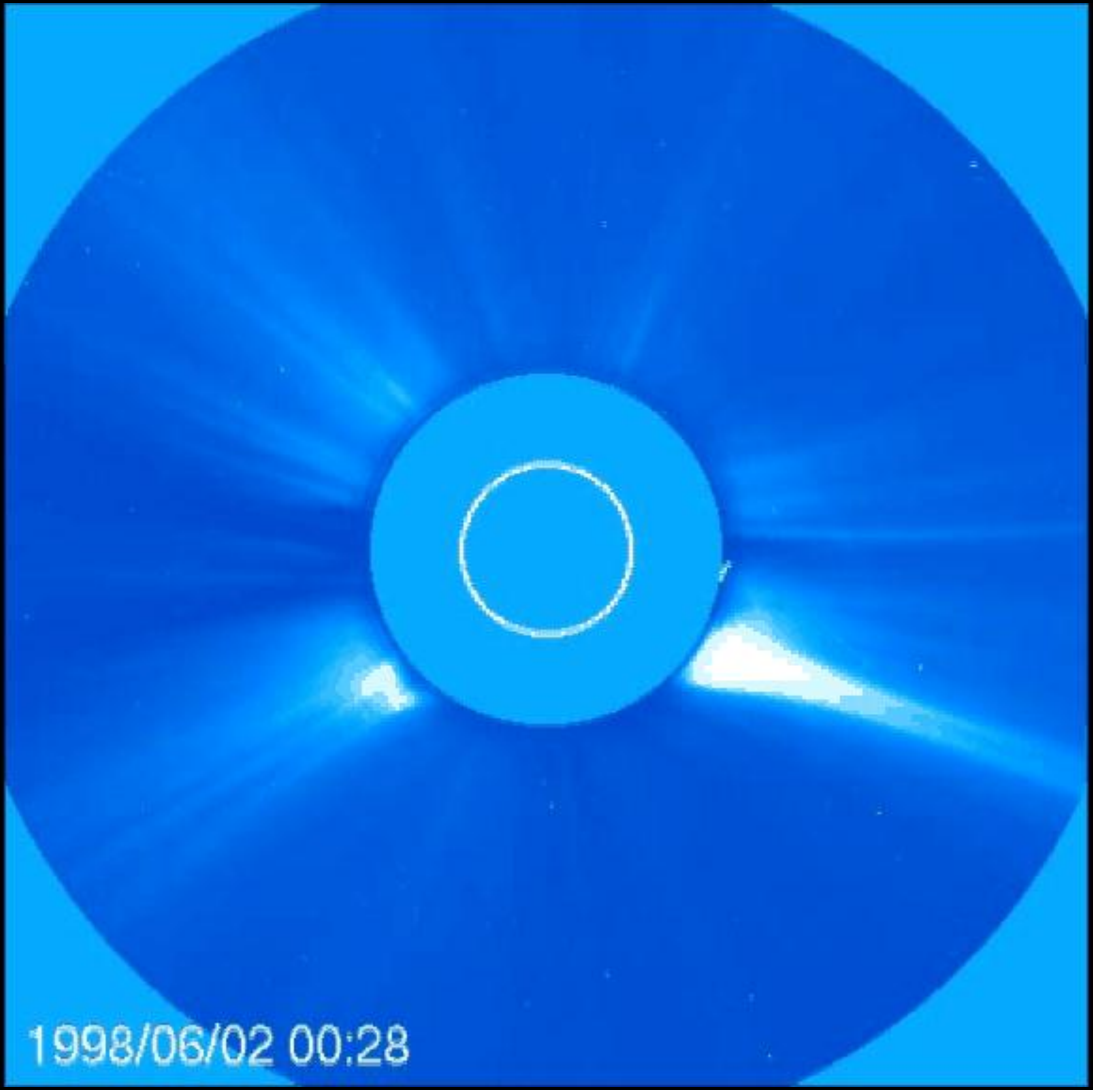
Ejecta (event 20000712)

Flux Rope Ejecta

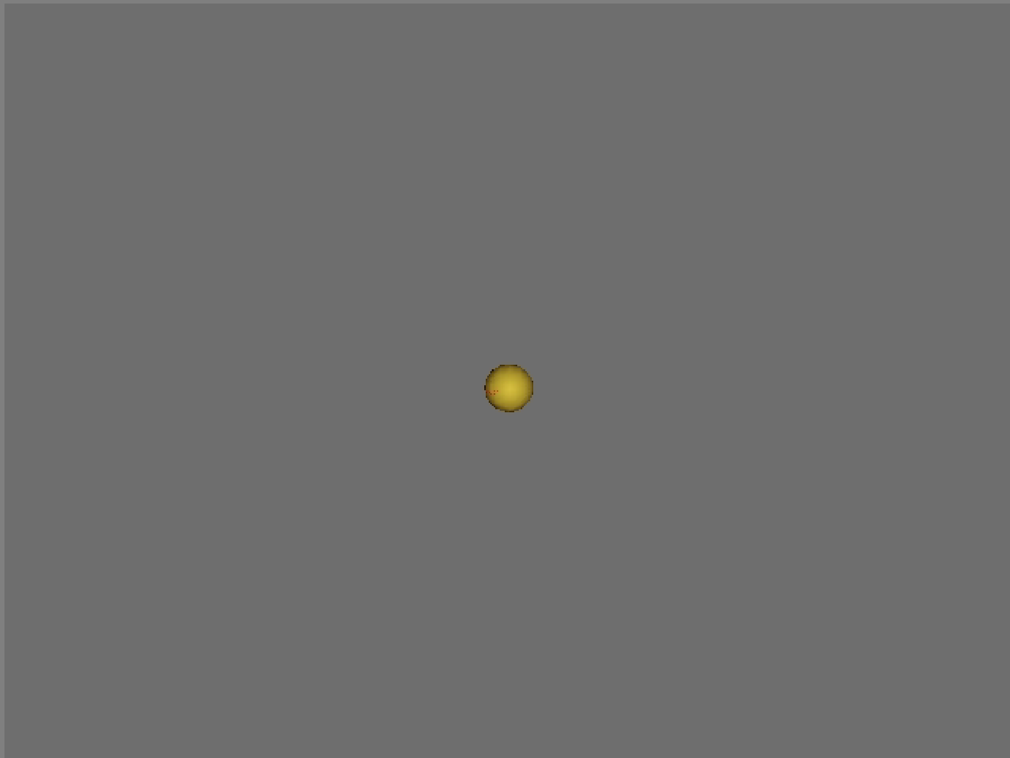
Regular and smooth magnetic field components profiles are shown (with no large fluctuations in the corresponding time interval). The plasma behaviour (temperature, pressure or beta) are well defined

Analytical approaches to the physics of the phenomena in the interplanetary medium, an example:
Magnetic clouds

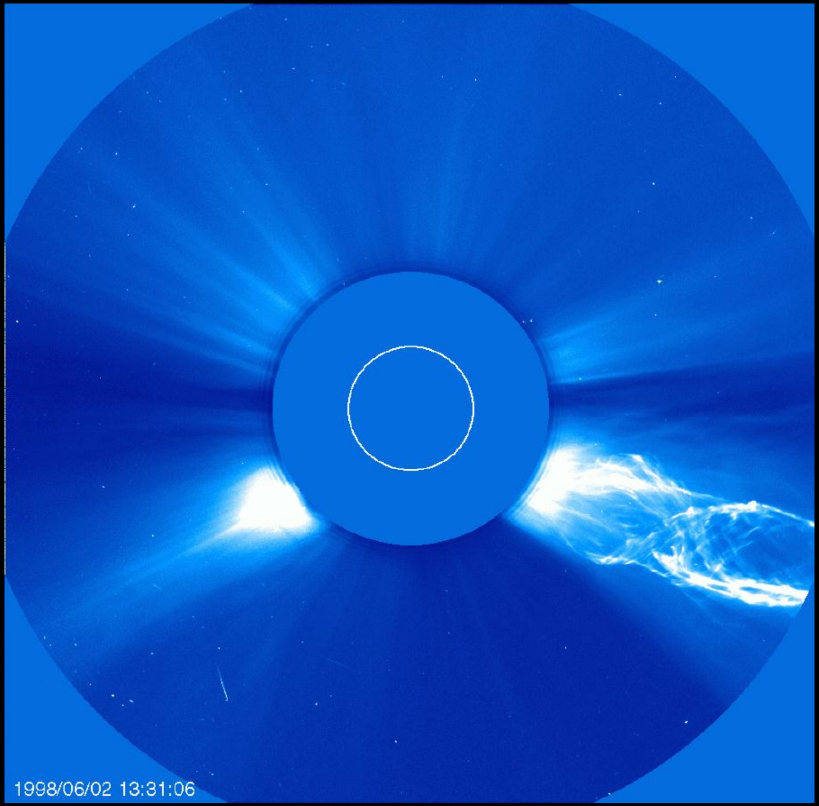
Coronal mass ejection



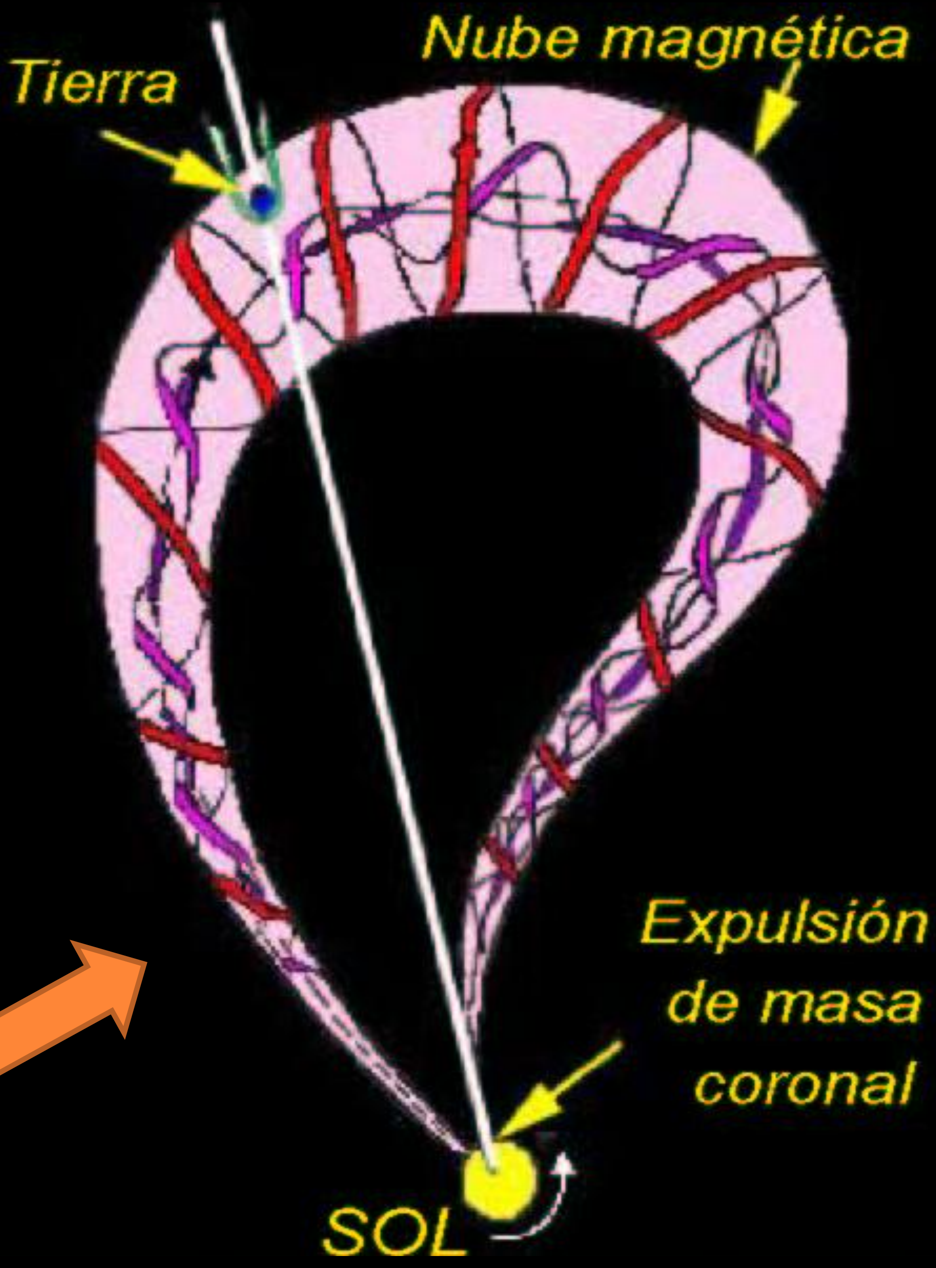
http://cdaw.gsfc.nasa.gov/CME_list

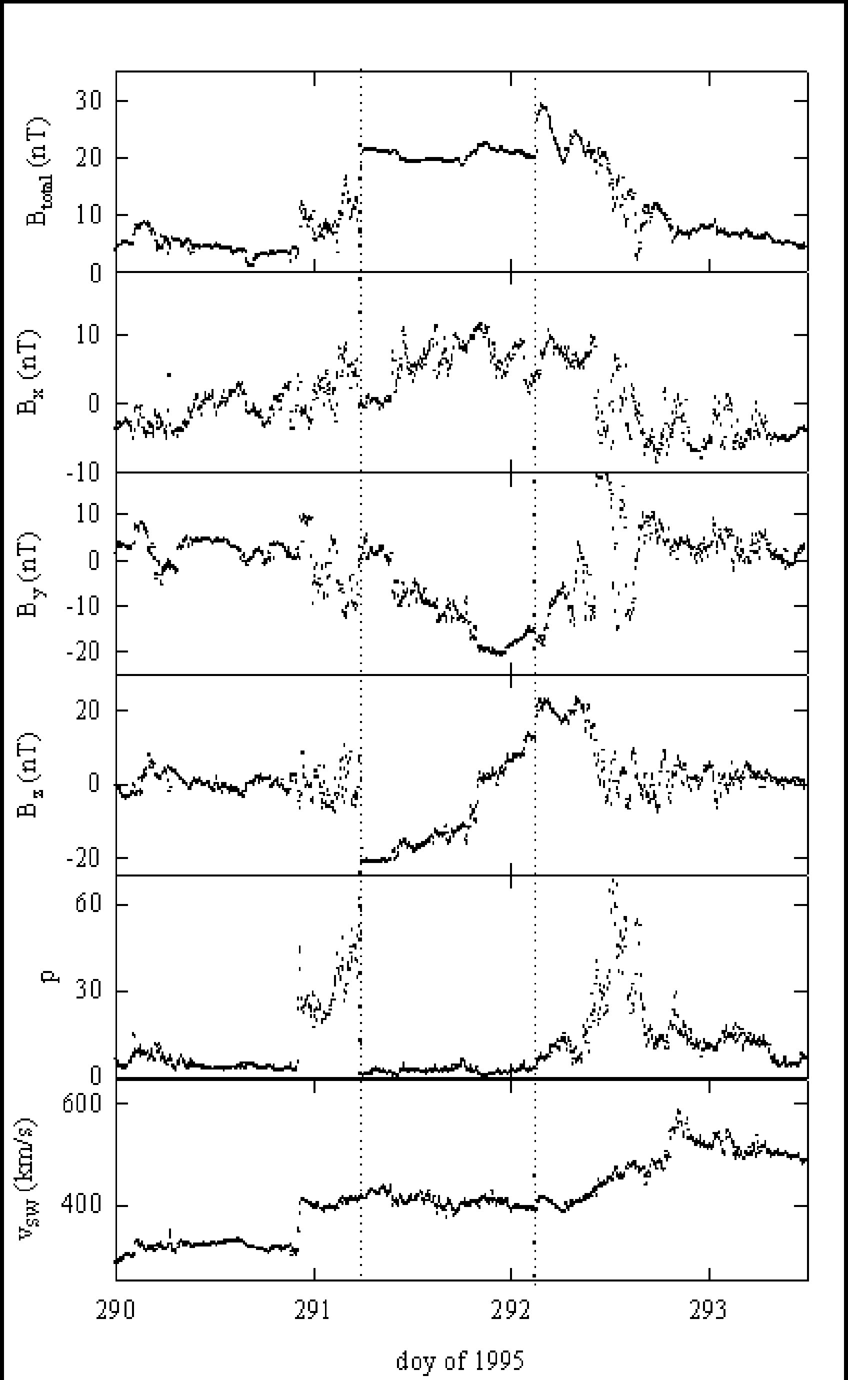


The expansion of a magnetic cloud



Artistic picture of a flux rope structure corresponding to a MC propagating in the interplanetary medium





Magnetic cloud

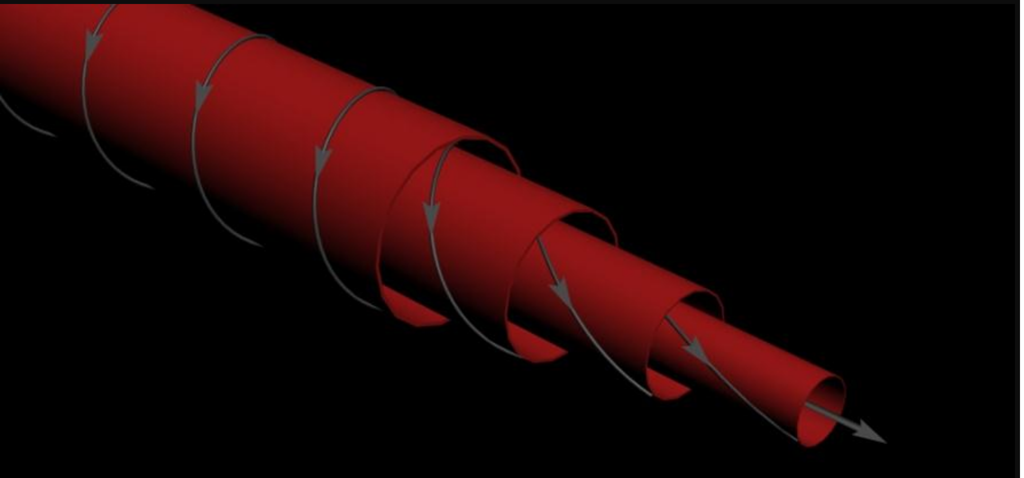
Structures showing clear signatures in the magnetic field components and plasma behaviour (temperature, pressure or beta)

¡One of the main difficulties is the determination of the boundaries of the MC!

Magnetic cloud

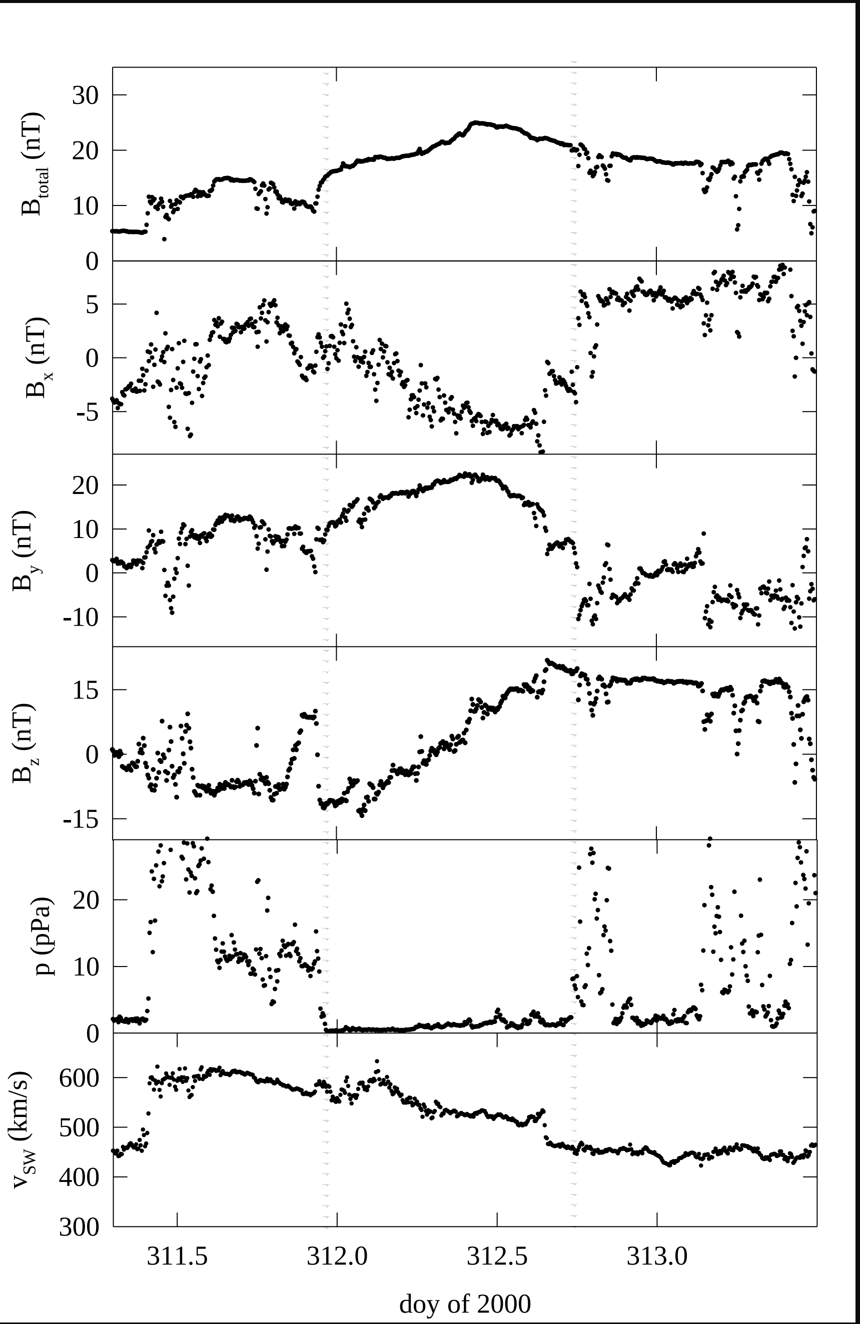
(Burlaga *et al*. 1981)

1) Higher magnetic field comparing the usual values in the solar wind
2) Magnetic field rotation
3) Low-temperature of protons

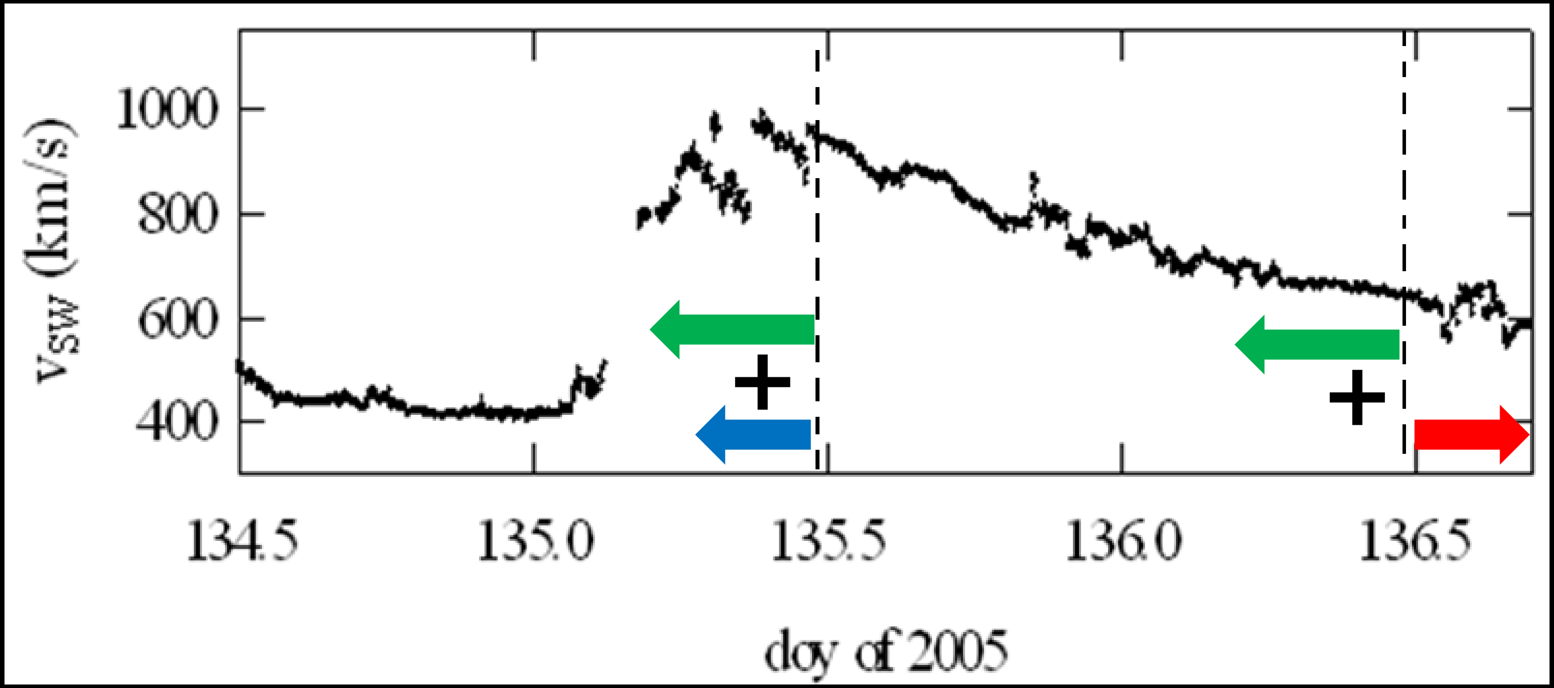


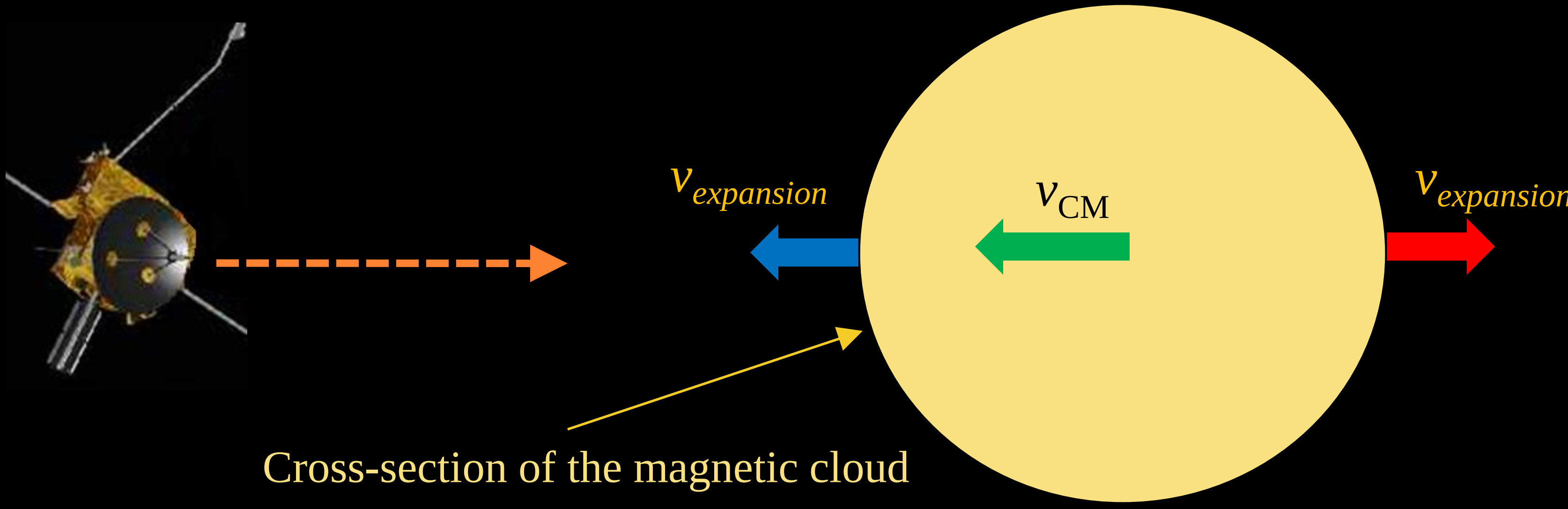
Flux rope structure

$B_{poloidal}$, B_{axial}

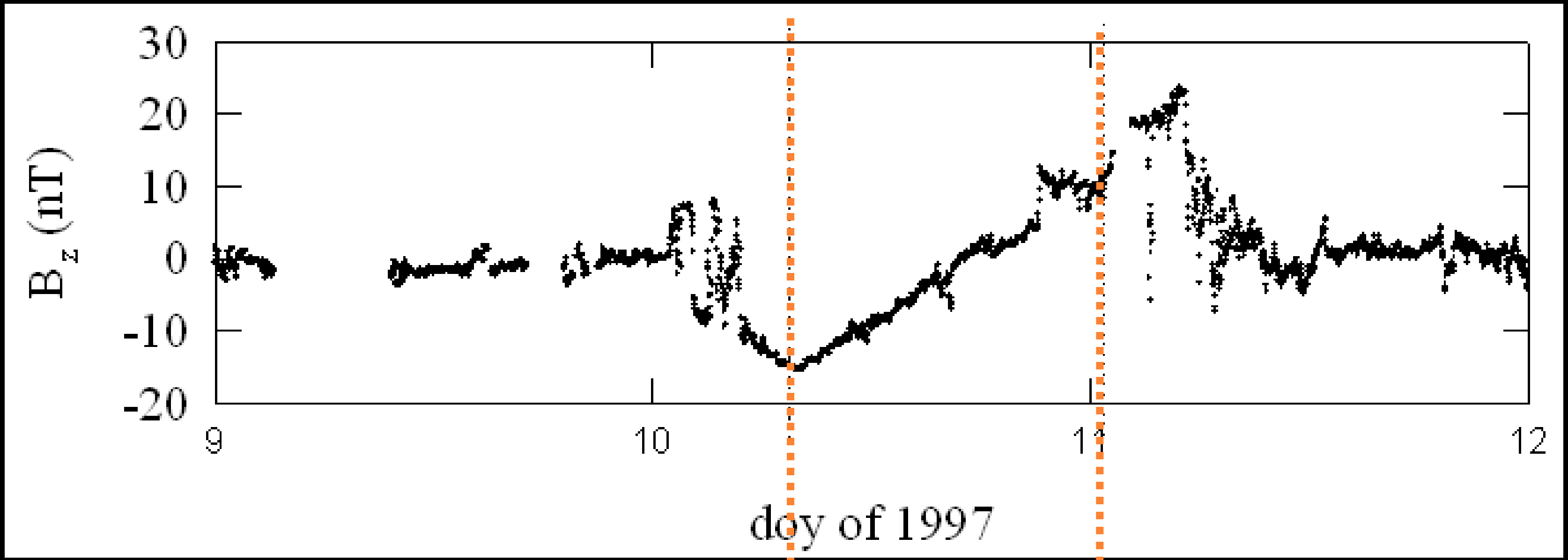


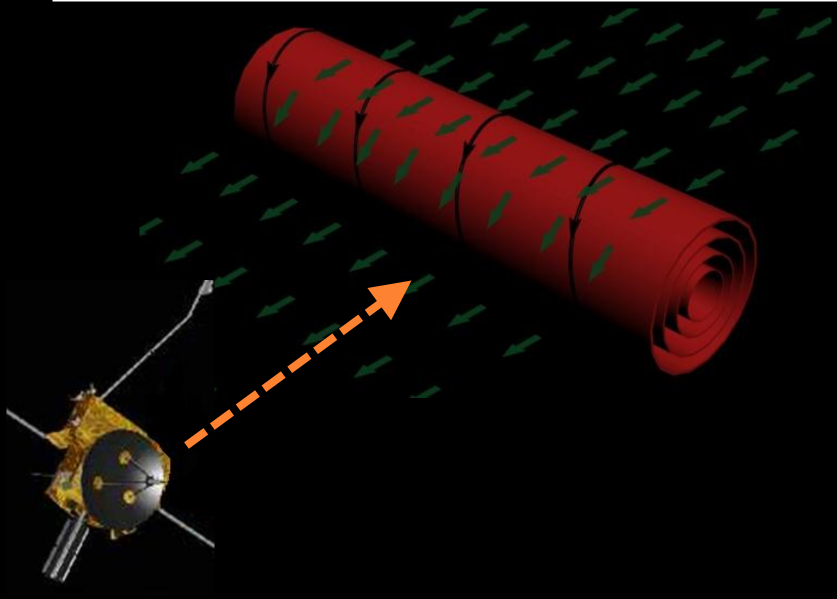
Expansion of the cross-section of the magnetic cloud

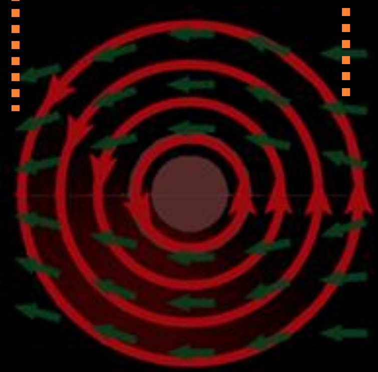


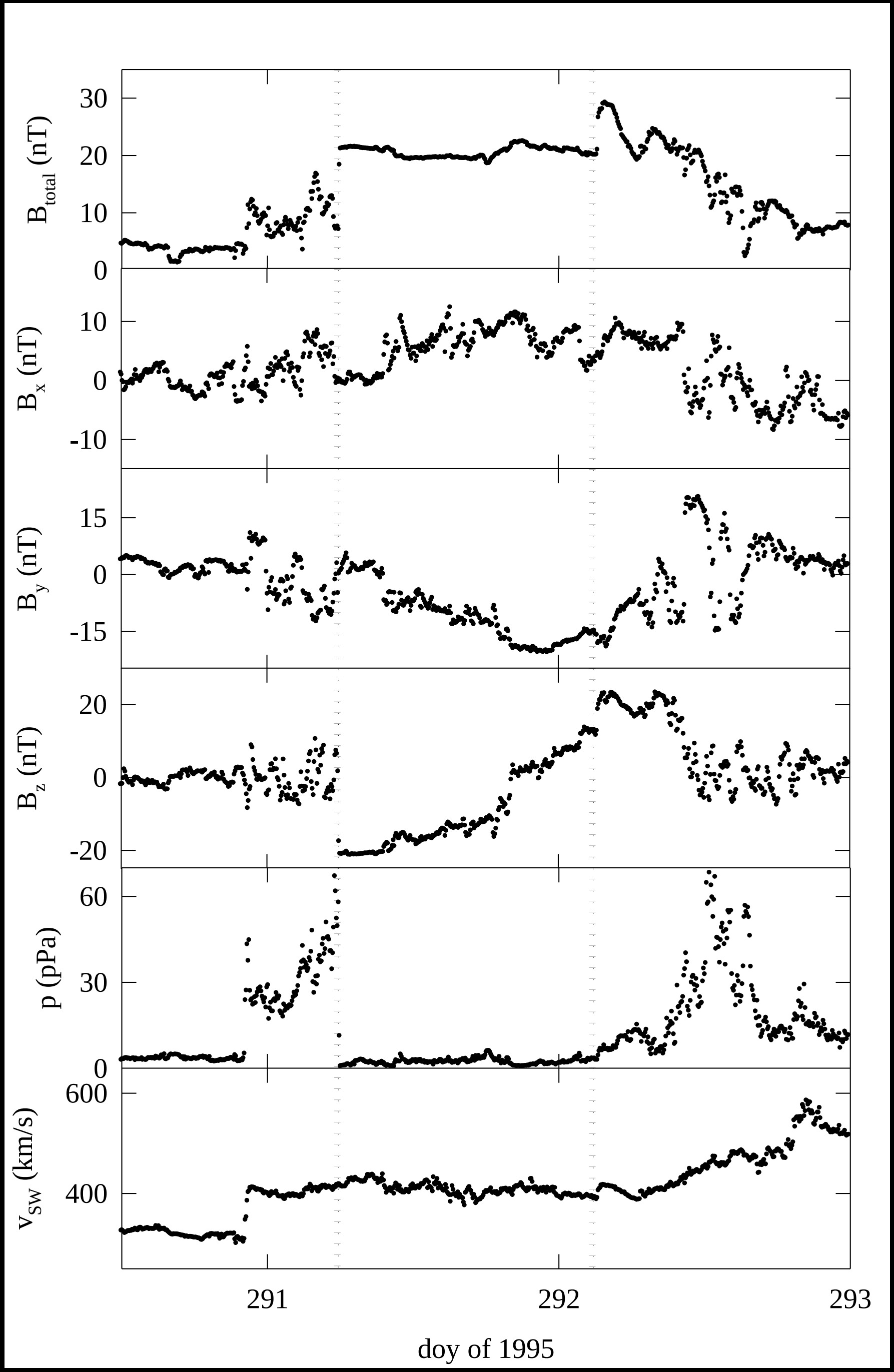


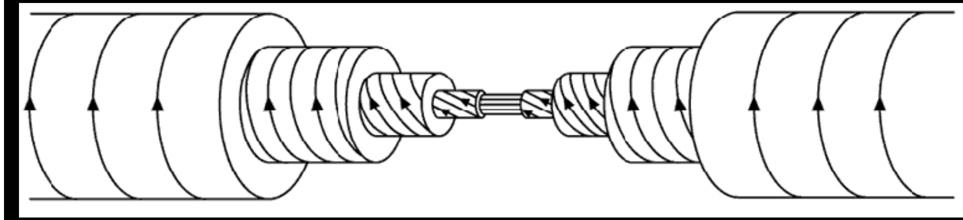
Topology of the magnetic field lines





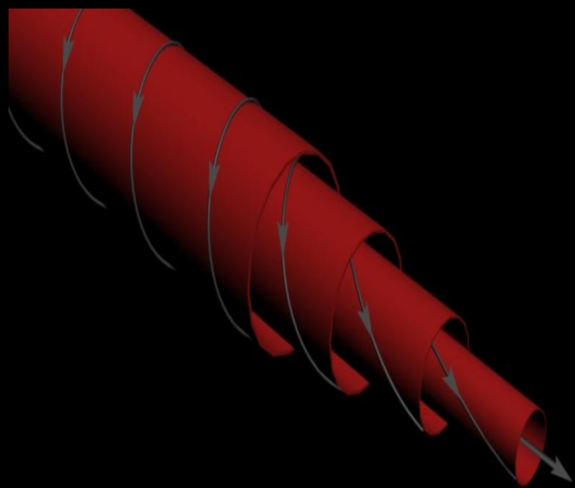


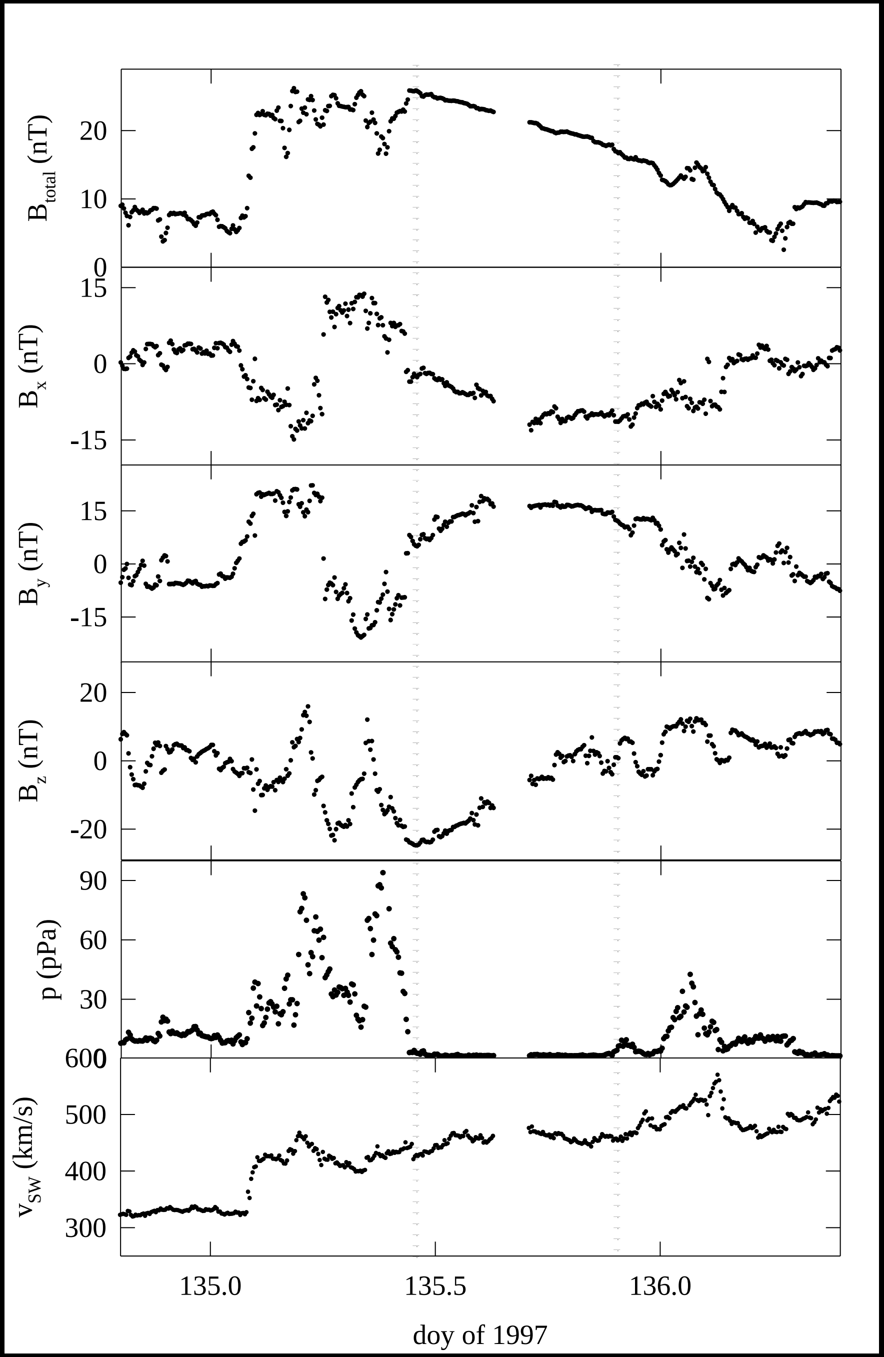




Circular cross-section

Distortion of the magnetic cloud as a consequence of its interaction with the solar wind

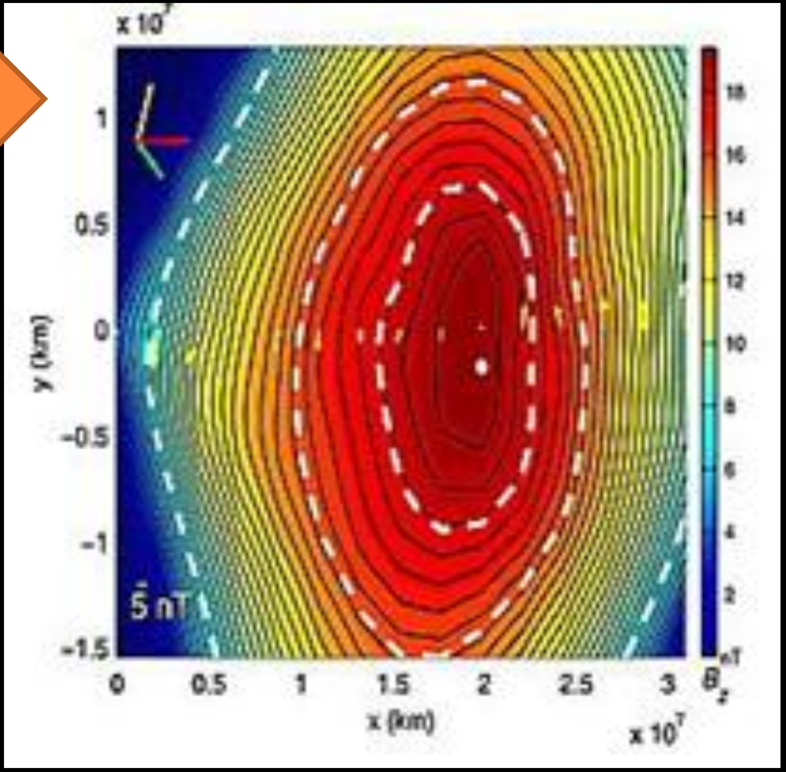




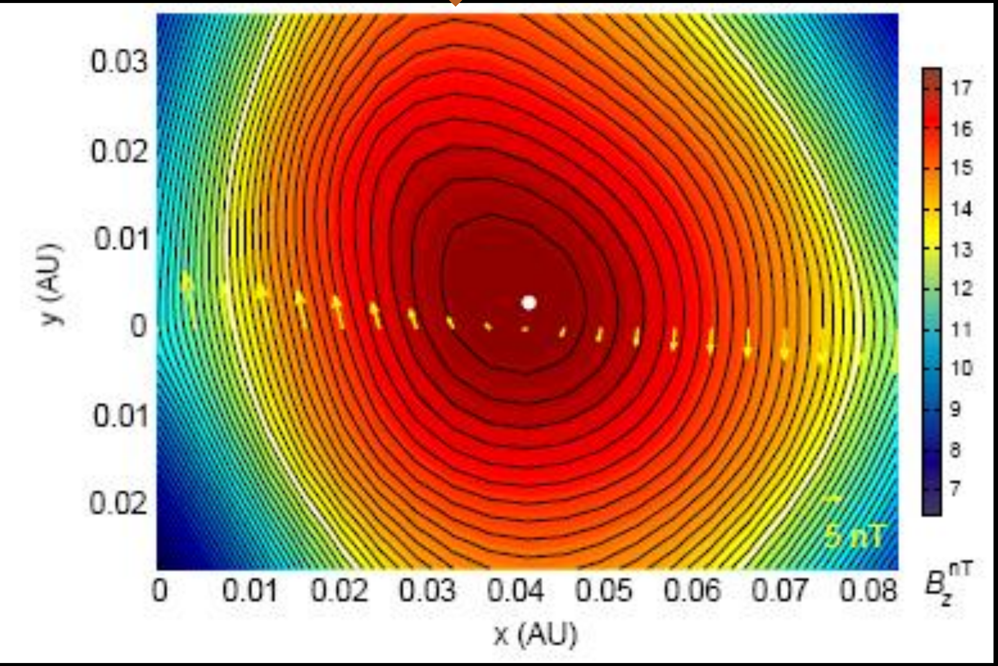
Elliptical cross-section

Numerical tecniques

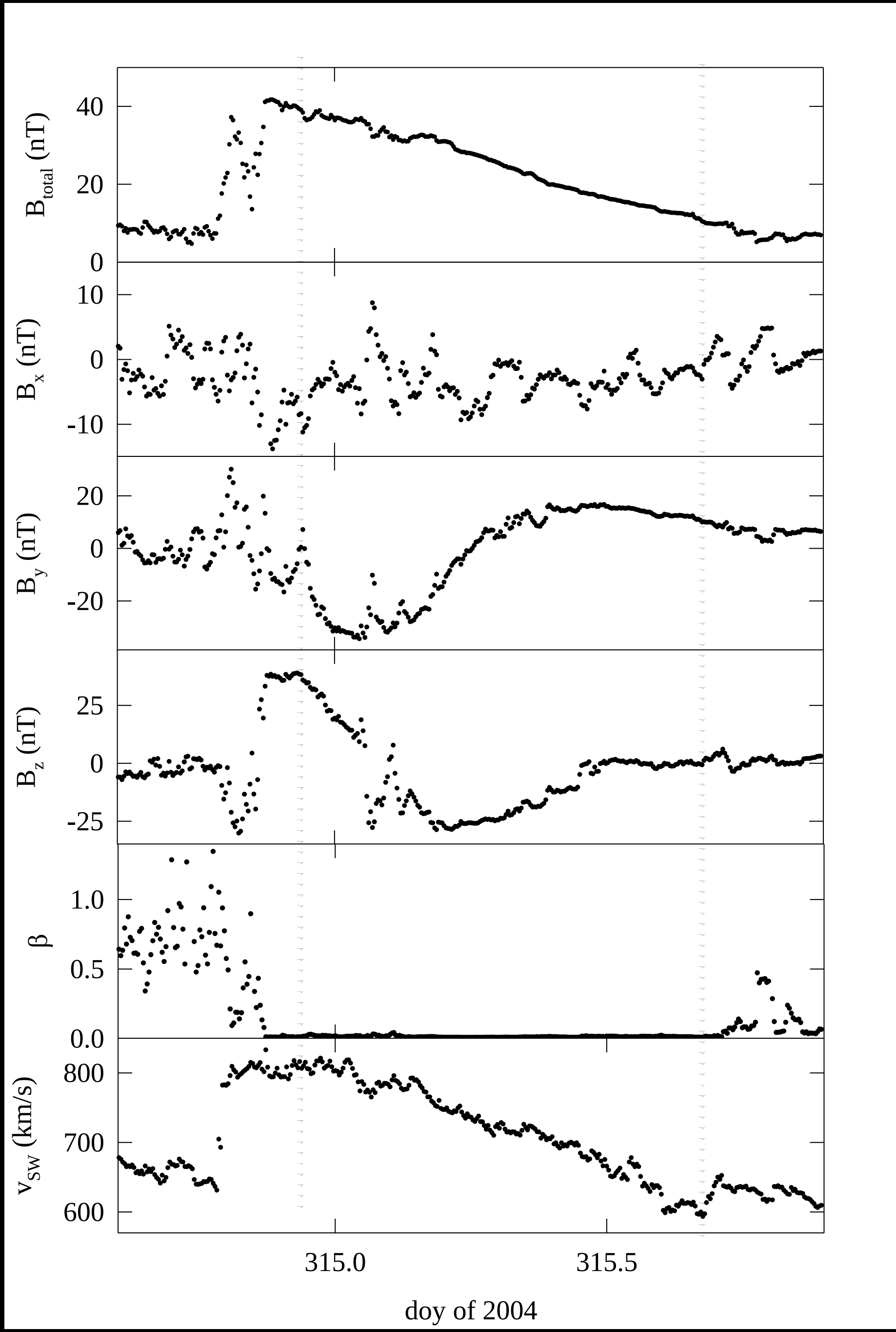
Elliptical cross-section



Circular cross-section



Hu and Sonnerup 2002



The most general case

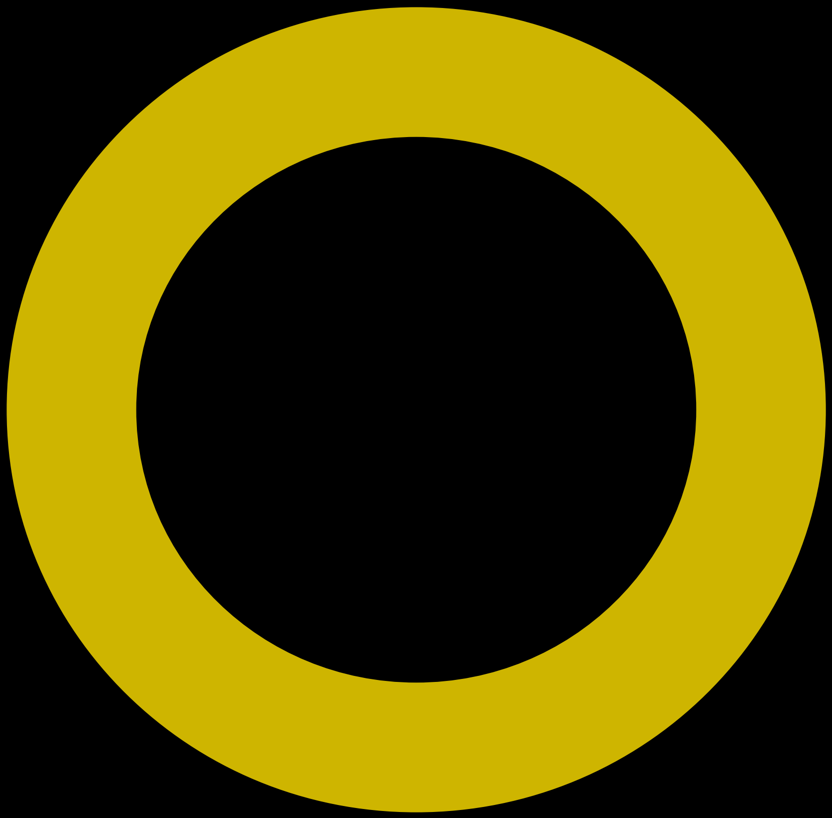
distortion

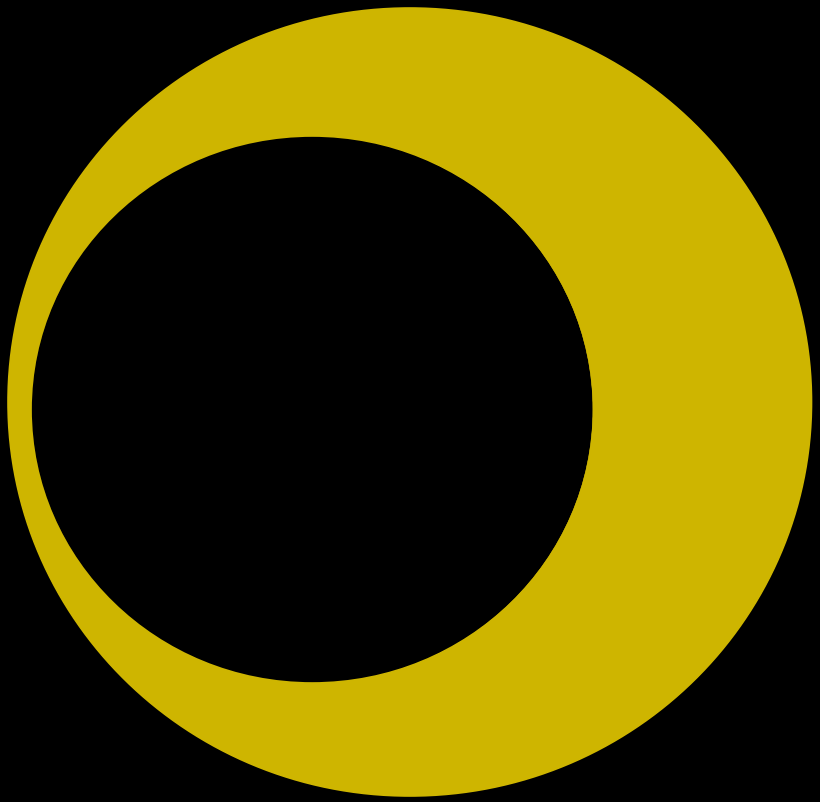
+

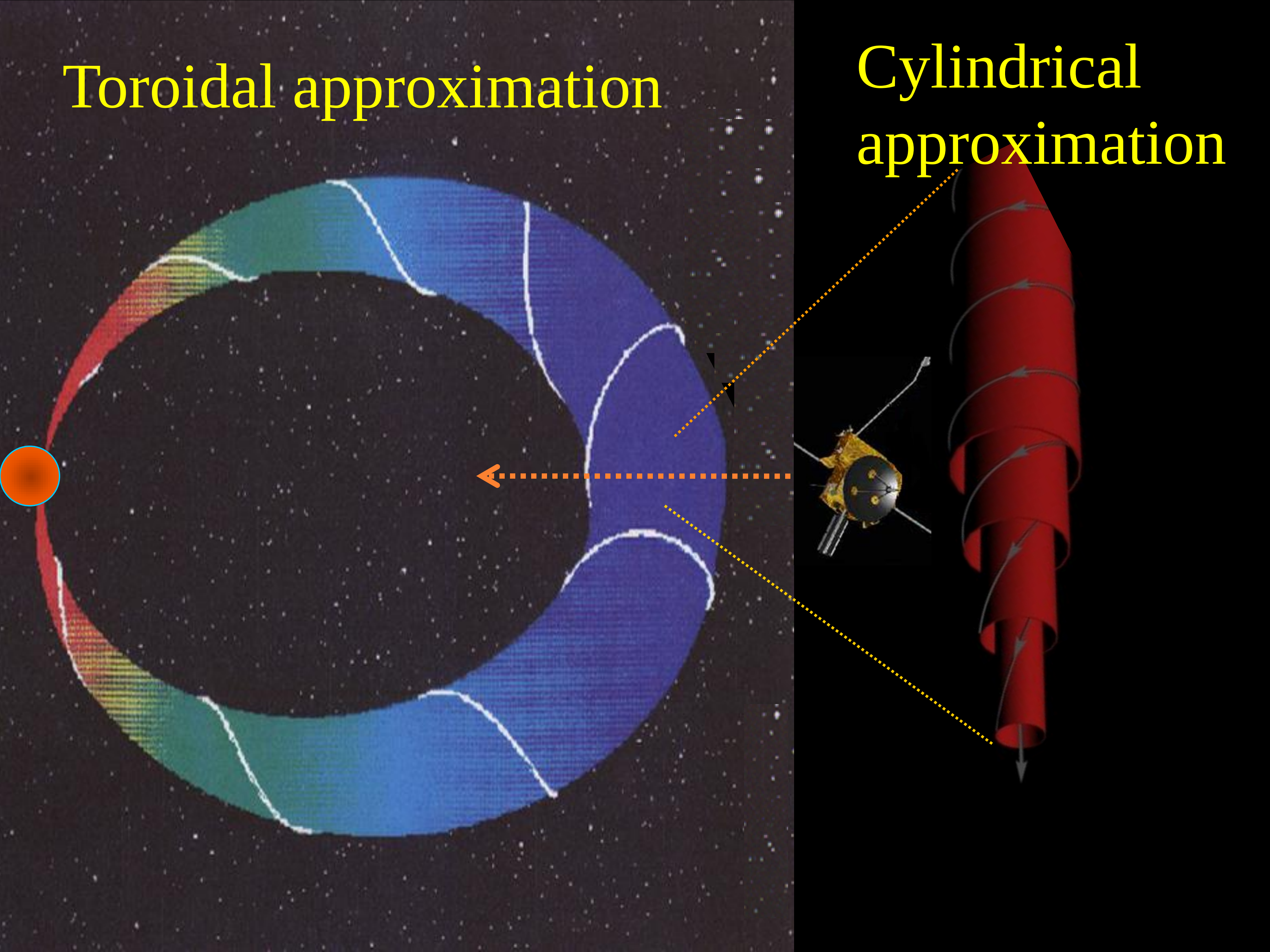
expantion

Developing the analytical approach for the magnetic clouds

Toroidal topologies
(circular cross-section)






Toroidal approximation
Cylindrical approximation

Electromagnetic phenomena in a space plasma

$$\nabla \cdot \vec{B} = 0$$

$$\nabla \times \vec{B} = \mu_0 \vec{j}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \vec{j} = 0$$

The electric field equations are not taken into account!

To be established: Boundaries conditions
Coordinate system

Current density

$$\vec{j} = e\left(n_p \vec{v}_p - n_e \vec{v}_e\right)$$

$$\frac{\partial(\rho_e + \rho_p)}{\partial t} = 0 \longrightarrow$$

$$\nabla \cdot \left(\vec{j}^{\,e} + \vec{j}^{\,p}\right) = \nabla \cdot \vec{j} = 0$$

The problem of the experimental current density

Obtained from the data corresponding to

n_e	density of electrons
$\vec{v}_e$	velocity of electrons
n_p	density of protons
$\vec{v}_p$	velocity of protons

Models and techniques to study MCs

Force-free

$$\vec{j} \times \vec{B} = 0 \Rightarrow \nabla \times \vec{B} = \alpha \vec{B}$$

Non force-free

$$\vec{j} \times \vec{B} \neq 0$$

Analytical models

Cylindrical approach

Cylindrical topologies (circular cross section and with expansion)

Cylindrical topologies (elliptically distorted cross-section and with expansion)

Other topologies

Plasmoids

Torus topology with uniform circular cross-section

Torus topology with non-uniform circular cross-section

Numerical models

Distortion of the cross-sections elliptic shape

Expansion of the cross-section

Force equation

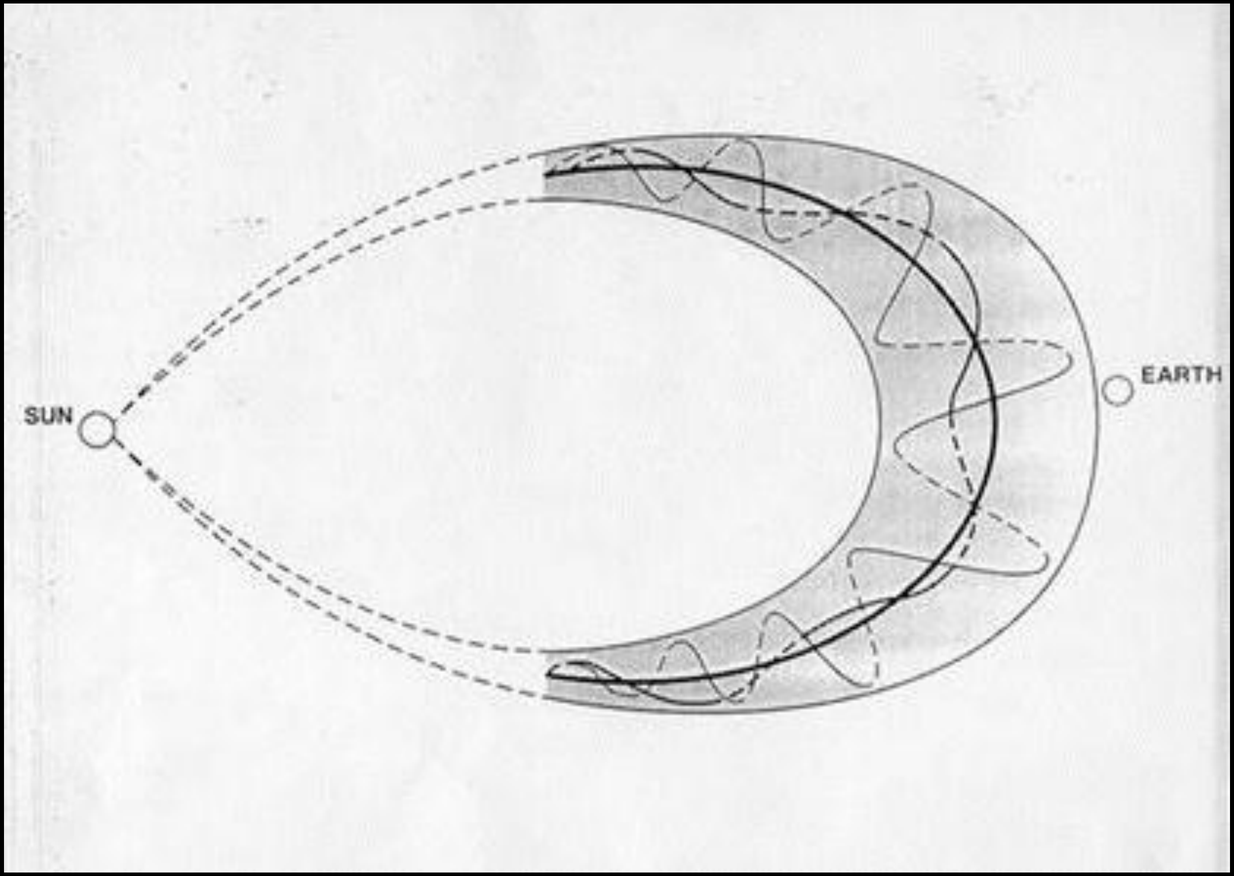
$$mn\frac{d\vec{v}}{dt} = \left(-\nabla\cdot\overline{\overline{p}} + \vec{j}\times\vec{B} + qn\vec{E}\right)$$

$$\frac{d\vec{v}^{e}}{dt} = \frac{d\vec{v}^{p}}{dt} \approx 0$$

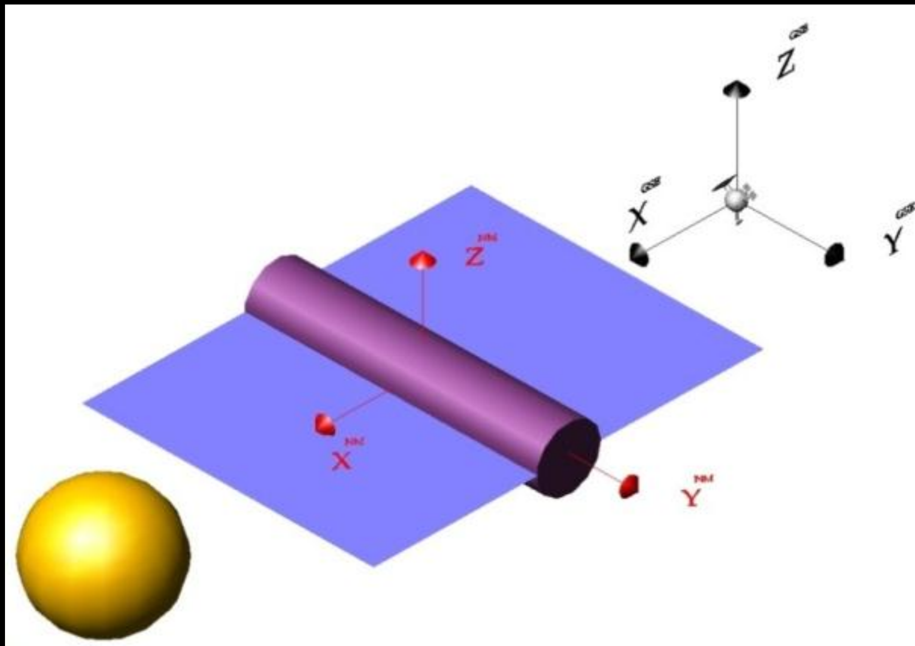
$$-\nabla\cdot\overline{\overline{p}} + \vec{j}\times\vec{B} = 0$$

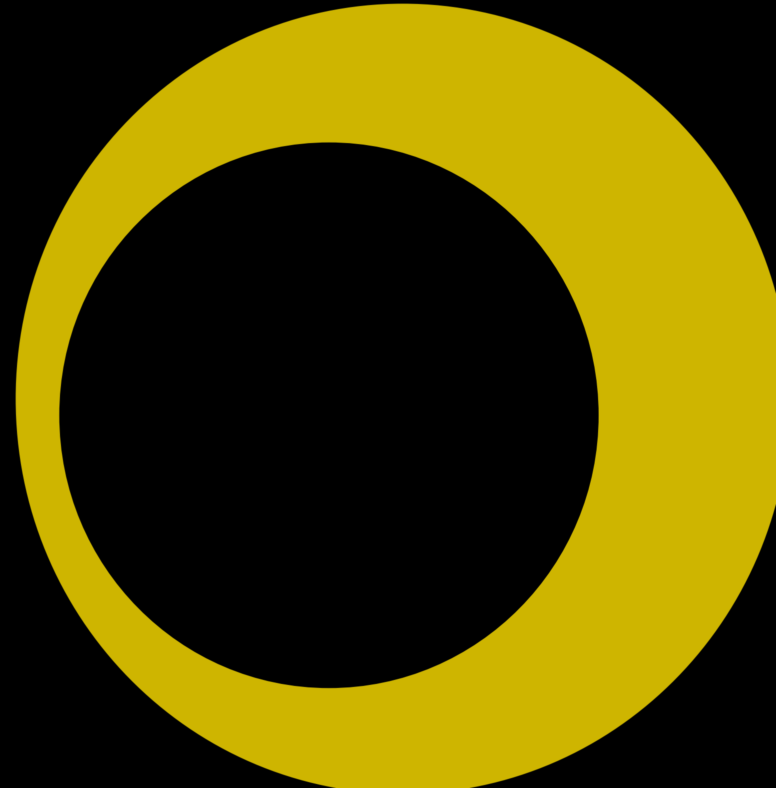
$\overline{\overline{p}} = \overline{\overline{p}}_e + \overline{\overline{p}}_p$ the pressure is in general a tensor

Force free models $\vec{j}\times\vec{B} = 0$ → $\overline{\overline{p}} = cte$



Still an open question: the connection to the Sun during its propagation along the interplanetary medium





$$
\begin{aligned}
x &= r\cos(\varphi) \\
y &= y \\
z &= r\sin(\varphi)
\end{aligned}
$$

$$
\begin{aligned}
x &= \left[\rho_0 + r\sinh(-\rho_0\eta + f)\cos(\varphi)\right]\ \cos(\psi) \\
y &= \left[\rho_0 + r\sinh(-\rho_0\eta + f)\cos(\varphi)\right]\ \sin(\psi) \\
z &= r\cosh(-\rho_0\eta + f)\ \sin(\varphi)
\end{aligned}
$$

To obtain the expressions of the model for describing the phenomenon: cylindrical coordinate system

$$\nabla \cdot \vec{B} = \frac{1}{r}\frac{\partial}{\partial r}\left(rB_r\right) + \frac{\partial B_y}{\partial y} + \frac{1}{r}\frac{\partial B_\varphi}{\partial r} = 0$$

+

$$\nabla \times \vec{B} = \frac{1}{r}\begin{vmatrix} \vec{e}_r & \vec{e}_y & \vec{e}_\varphi \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial y} & \frac{\partial}{\partial \varphi} \\ B_r & B_y & rB_\varphi \end{vmatrix} = \mu_0 \vec{j}$$

+

Boundaries conditions

→ The magnetic field expression of the model

$$\vec{B}^{MC}\left(r, y, \varphi\right)$$

Cylindrical approach

(Boundaries conditions)

(*y*: direction of the axis of the cylinder)

Concerning on the magnetic field

$$B_r = 0 \qquad \frac{\partial B_\varphi}{\partial y} = 0 \qquad \frac{\partial B_y}{\partial y} = 0$$

Concerning on the current density

$$j_\varphi = \alpha r \qquad \frac{\partial j_\varphi}{\partial y} = 0 \qquad \frac{\partial j_y}{\partial y} = 0$$

$$j_y = cte$$

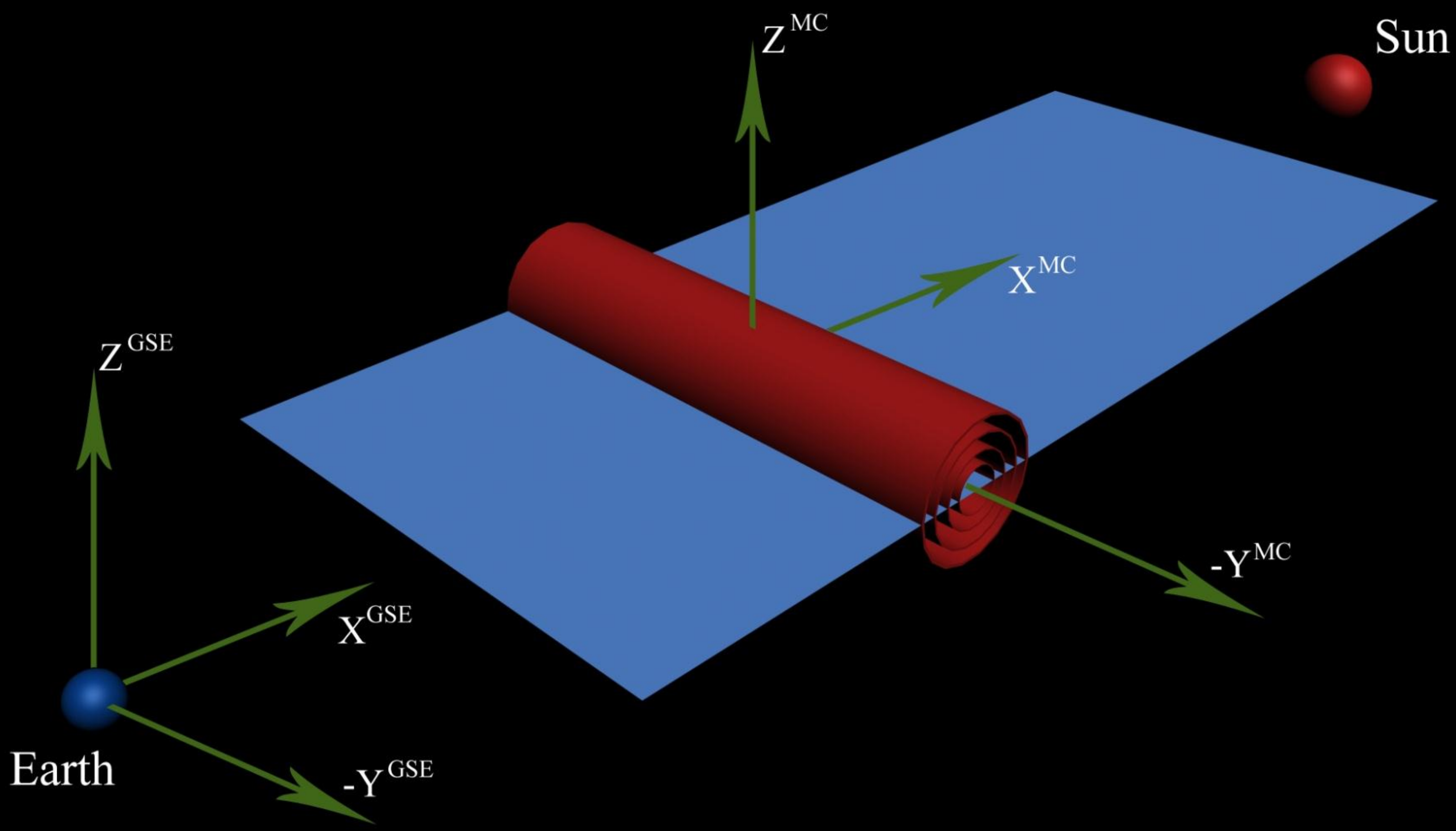
Expressions for the magnetic field components:

$$B_\varphi^{MC} = \frac{\mu_0}{2} j_y r$$

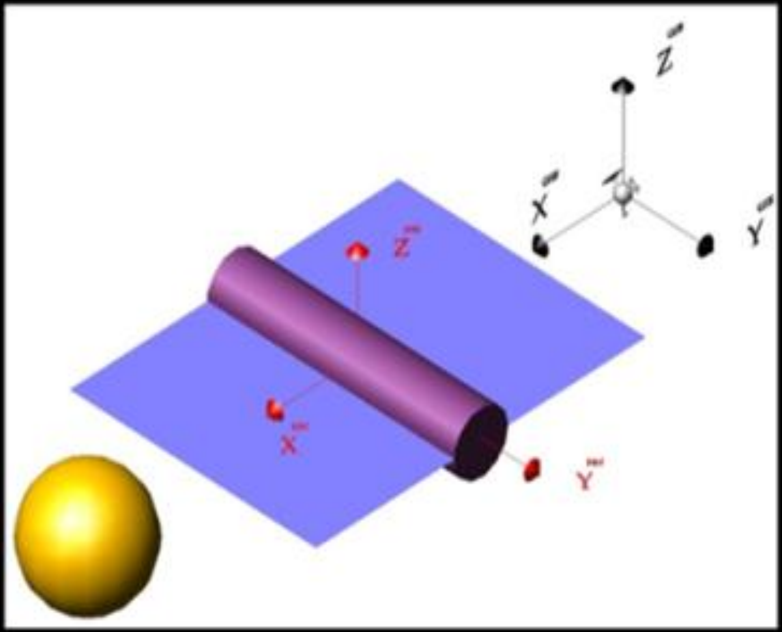
$$B_y^{MC} = B_y^0 - \frac{\mu_0}{2} \alpha r^2$$

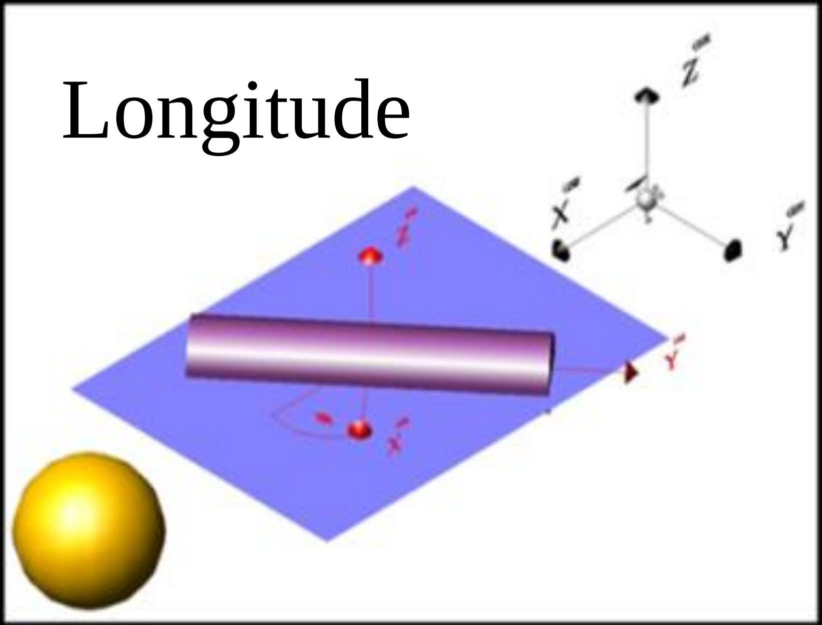
Data expressed in the *GSE* coordinate system

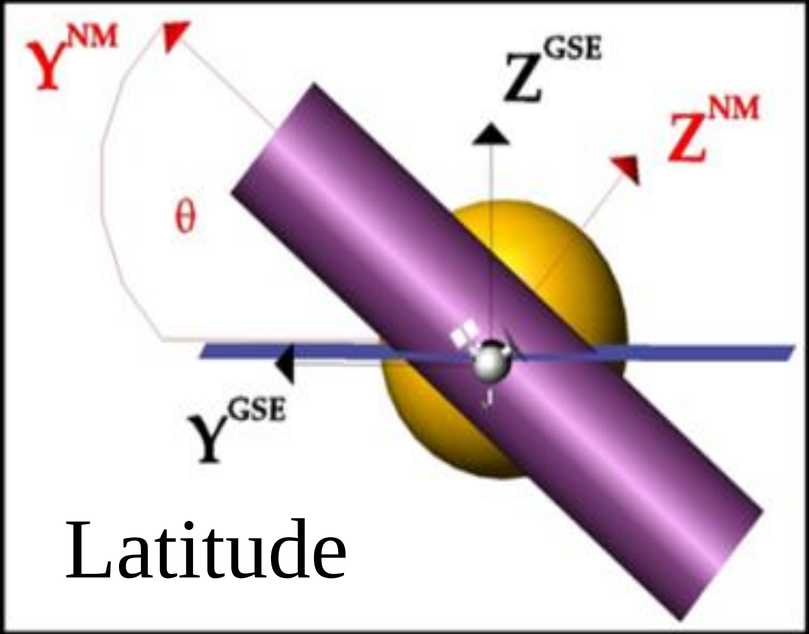
Model expressions determined in the *MC* coordinate system



$$\left(0, B_y^{MC}, B_\varphi^{MC}\right) \Leftrightarrow \left(B_x^{GSE}, B_y^{GSE}, B_z^{GSE}\right) = \left(-B_\varphi^{MC}\sin\varphi, B_y^{MC}, B_\varphi^{MC}\cos\varphi\right)$$







Rotations of a magnetic cloud in the interplanetary medium

Rotation matrices

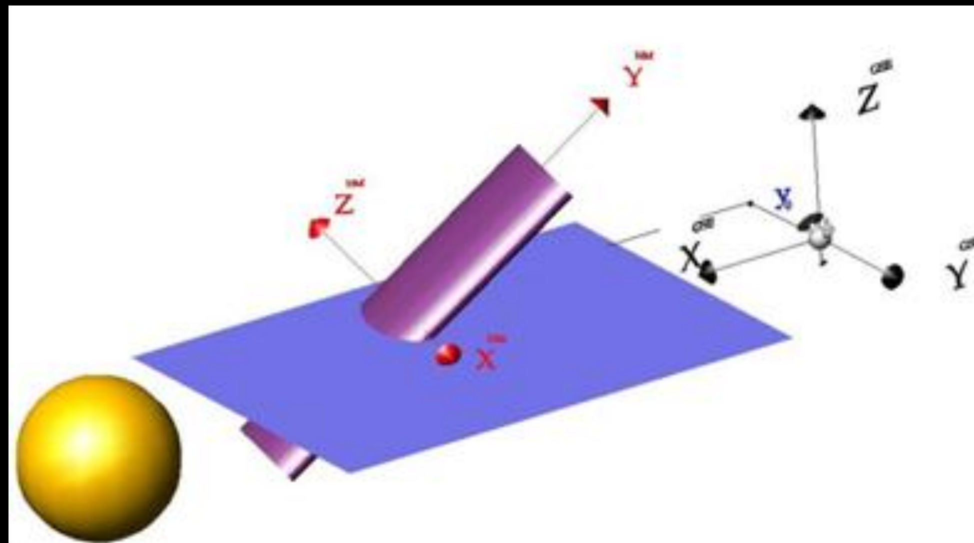
Longitude

$$C_\phi = \begin{pmatrix} cos(\phi) & -sen(\phi) & 0 \\ sen(\phi) & cos(\phi) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Latitude

$$C_\theta = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos(\theta) & -sen(\theta) \\ 0 & sen(\theta) & cos(\theta) \end{pmatrix}$$

$$\vec{B}^{GSE} = C_\phi C_\theta \vec{B}^{MC}$$



$$\left(0, B_y^{MC}, B_\varphi^{MC}\right) \Leftrightarrow \left(B_x^{GSE}, B_y^{GSE}, B_z^{GSE}\right)$$

$$\Uparrow$$

$$\left(\phi, \theta\right)$$

$$B_x^{GSE} = -B_\varphi^{MC} \sin\varphi \cos\phi - B_y^{MC} \sin\phi \cos\theta + B_\varphi^{MC} \cos\varphi \sin\phi \sin\theta$$

$$B_y^{GSE} = -B_\varphi^{MC} \sin\varphi \sin\phi + B_y^{MC} \cos\phi \cos\theta - B_\varphi^{MC} \cos\varphi \sin\theta \cos\phi$$

$$B_z^{GSE} = B_y^{MC} \sin\theta + B_\varphi^{MC} \cos\varphi \cos\theta$$

One more step: Expressions for the spacecraft trajectory inside the magnetic cloud (MC): $r_{spacecraft}$ y $\varphi_{spacecraft}$

Position in *GSE* coordinates $$\vec{r}^{\,GSE}_{spacecraft} = \left(x^{GSE}_{spacecraft}, 0, z_0\right)$$

Assumption: constant velocity inside the MC ⟶ $x^{GSE}_{spacecraft} = \langle v_{SW} \rangle (t - t_0)$

$$\vec{r}^{\,MC}_{spacecraft} = C^t_\theta C^t_\phi \vec{r}^{\,GSE}_{spacecraft} \Rightarrow$$

$$B^{MC}_y = B^0_y - \frac{\mu_0}{2}\alpha\left(r^{MC}_{spacecraft}\right)^2$$

$$B^{MC}_\varphi = \frac{\mu_0}{2} j_y r^{MC}_{spacecraft}$$

Fitting procedure (Regression procedure using, for example, the Marquardt-Leveberg algorithm

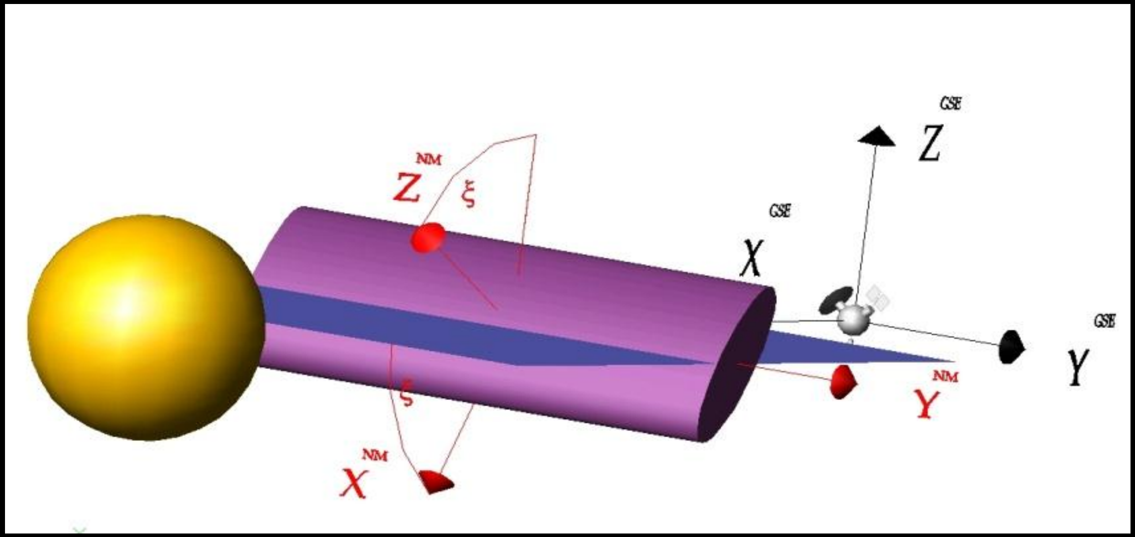
$$\left\{\left(B_x^{GSE}\right)_{theo},\left(B_y^{GSE}\right)_{theo},\left(B_z^{GSE}\right)_{theo}\right\} \longrightarrow \left\{\left(B_x^{GSE}\right)_{observed},\left(B_y^{GSE}\right)_{observed},\left(B_z^{GSE}\right)_{observed}\right\}$$

Five parameters

Parameters of the model of a cylinder with a circular cross-section:

- Associated with the current density: α, j_y
- Determining the orientation of the magnetic cloud axis: latitude (θ) and longitude (ϕ)
- Closest distance of the spacecraft to the magnetic cloud axis, y_0
- Constant term of the axial magnetic field component, B_y^0

$$\chi^2 = \frac{1}{N}\sum\left[\left(\left(B_x^{GSE}\right)_{theo}-\left(B_x^{GSE}\right)_{observed}\right)^2+\left(\left(B_y^{GSE}\right)_{theo}-\left(B_y^{GSE}\right)_{observed}\right)^2+\left(\left(B_z^{GSE}\right)_{theo}-\left(B_z^{GSE}\right)_{observed}\right)^2\right]$$



$$x = r\cosh\eta\cos\varphi$$
$$y = y$$
$$z = r\sinh\eta\sin\varphi$$

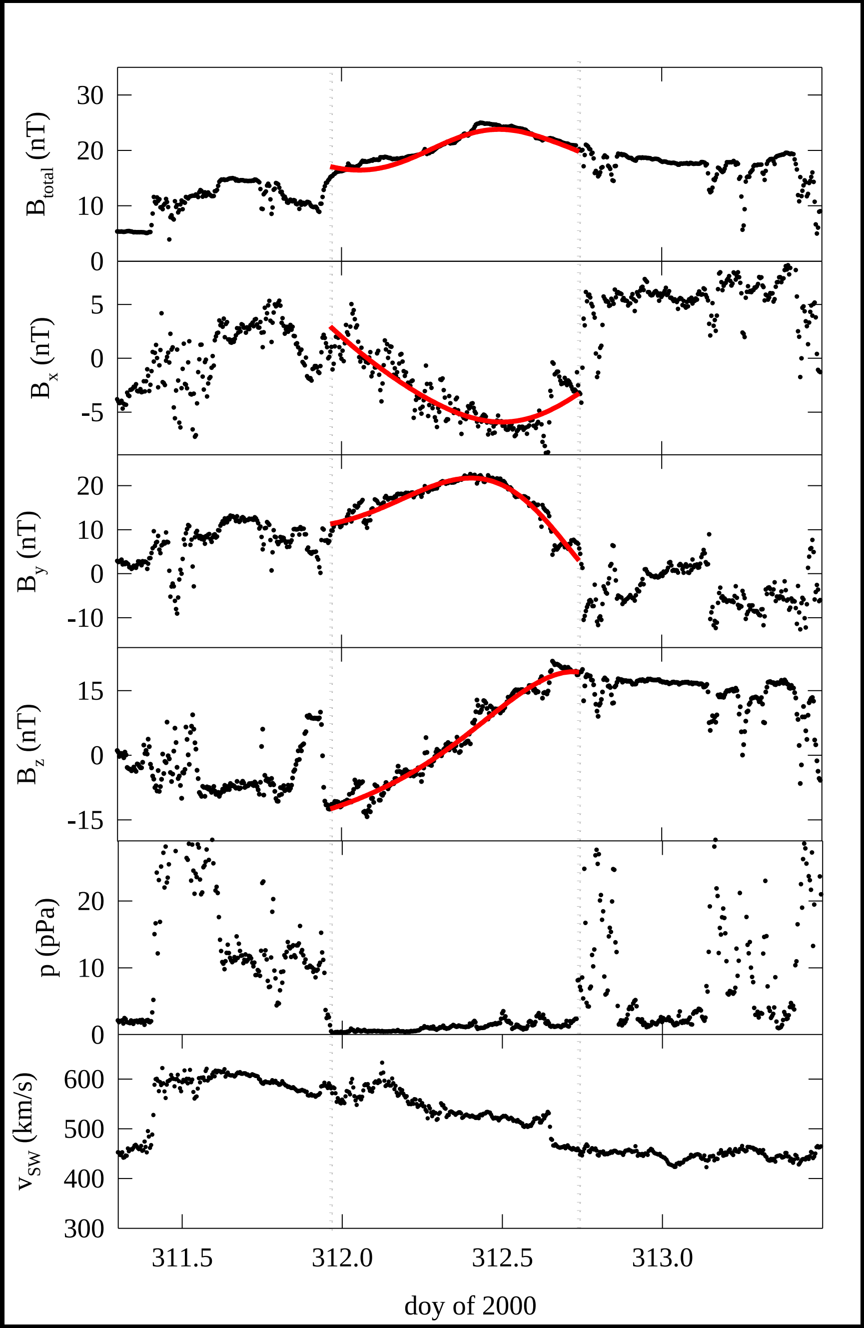
Parameters of the model of a cylinder with a elliptical cross-section:

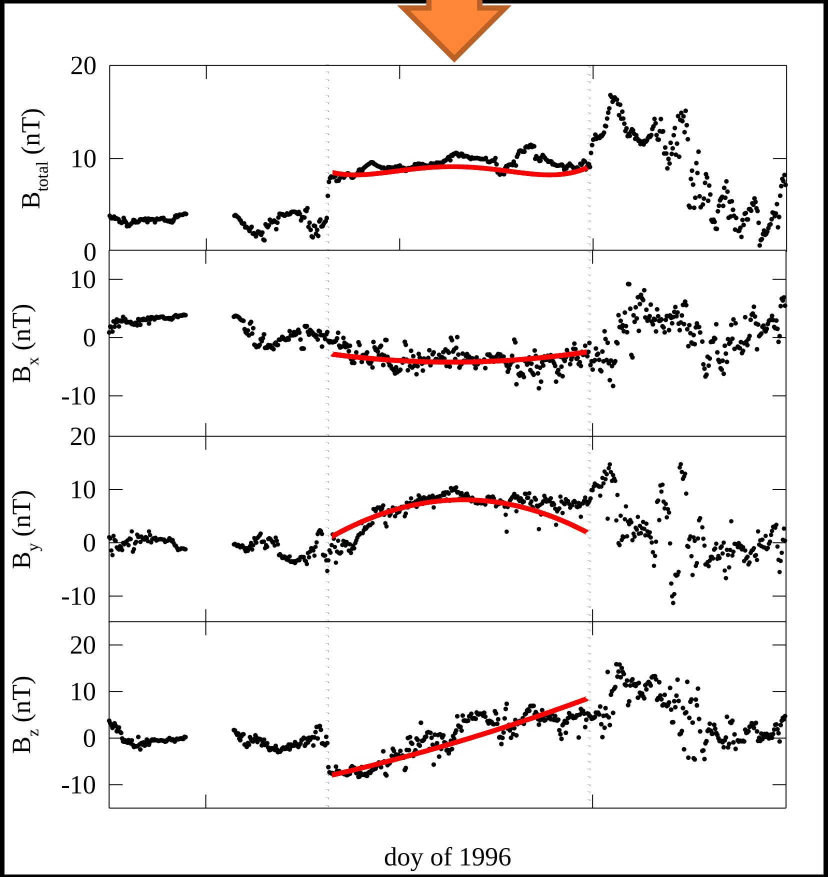
Associated with the current density: α, j_z
Determining the orientation of the magnetic cloud axis: latitude (θ) and longitude (ϕ)
Closest distance of the spacecraft to the magnetic cloud axis, y_0
Constant term of the axial magnetic field component, B_z^0

\+

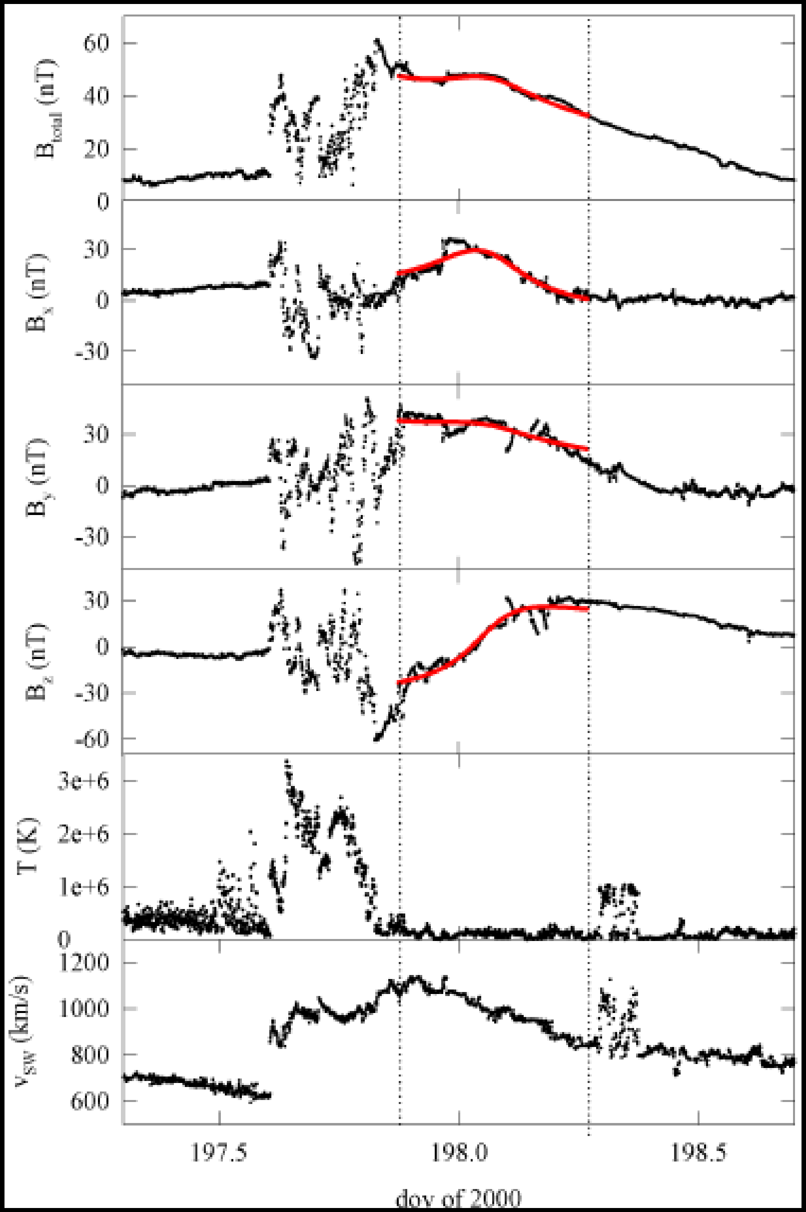
Orientation of the cross-section of the cloud, ζ
Eccentricity of the cross section, η

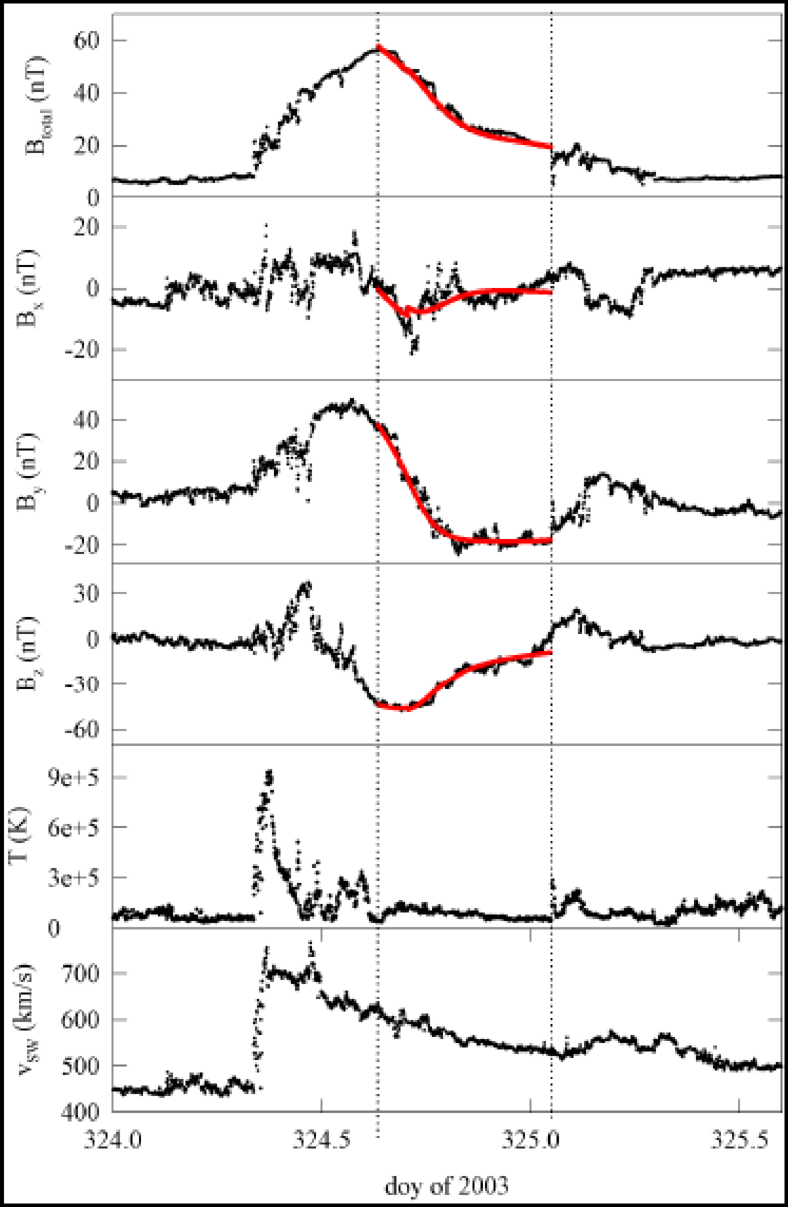
Fits of the cylindrical model with circular cross-section

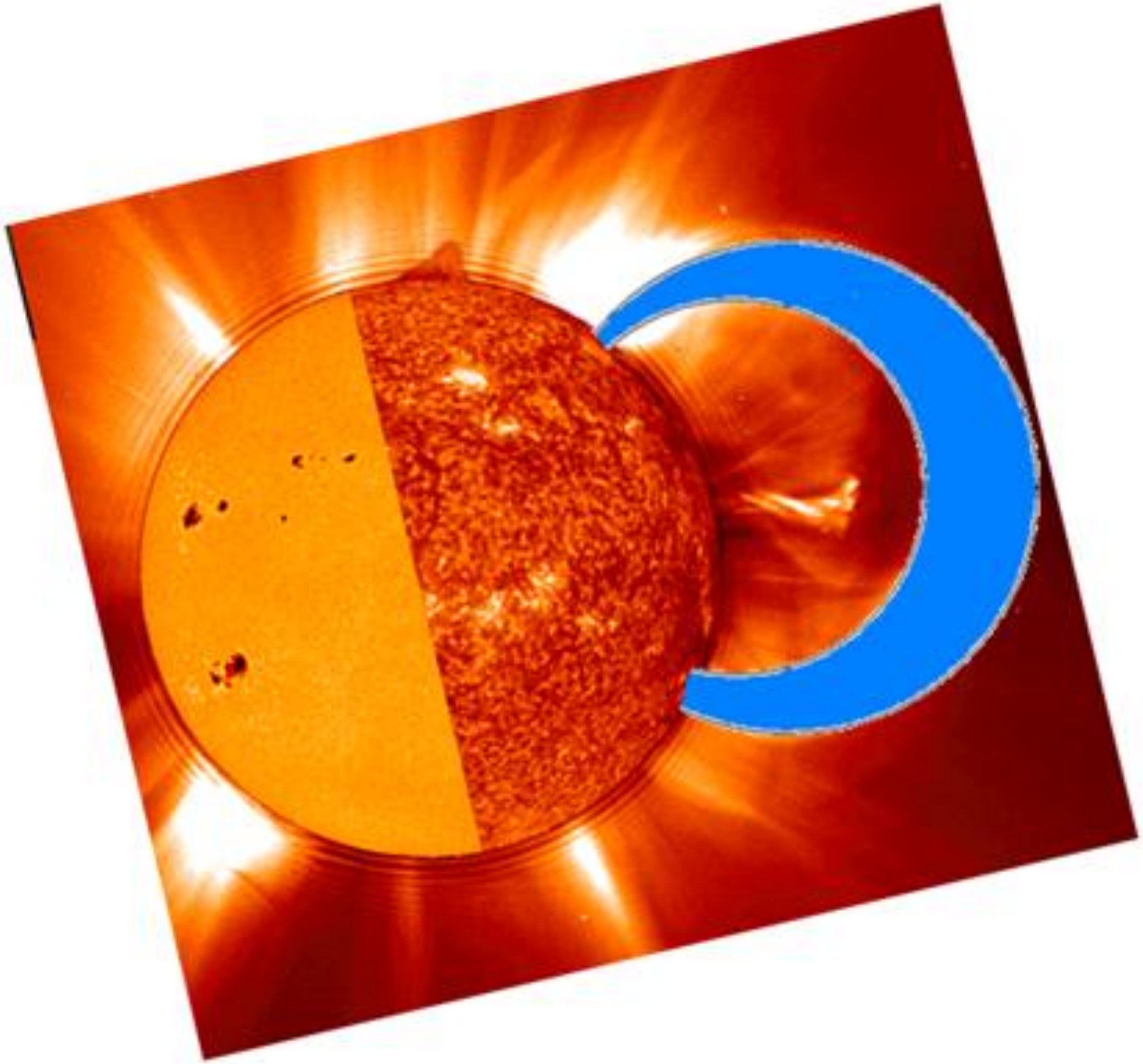


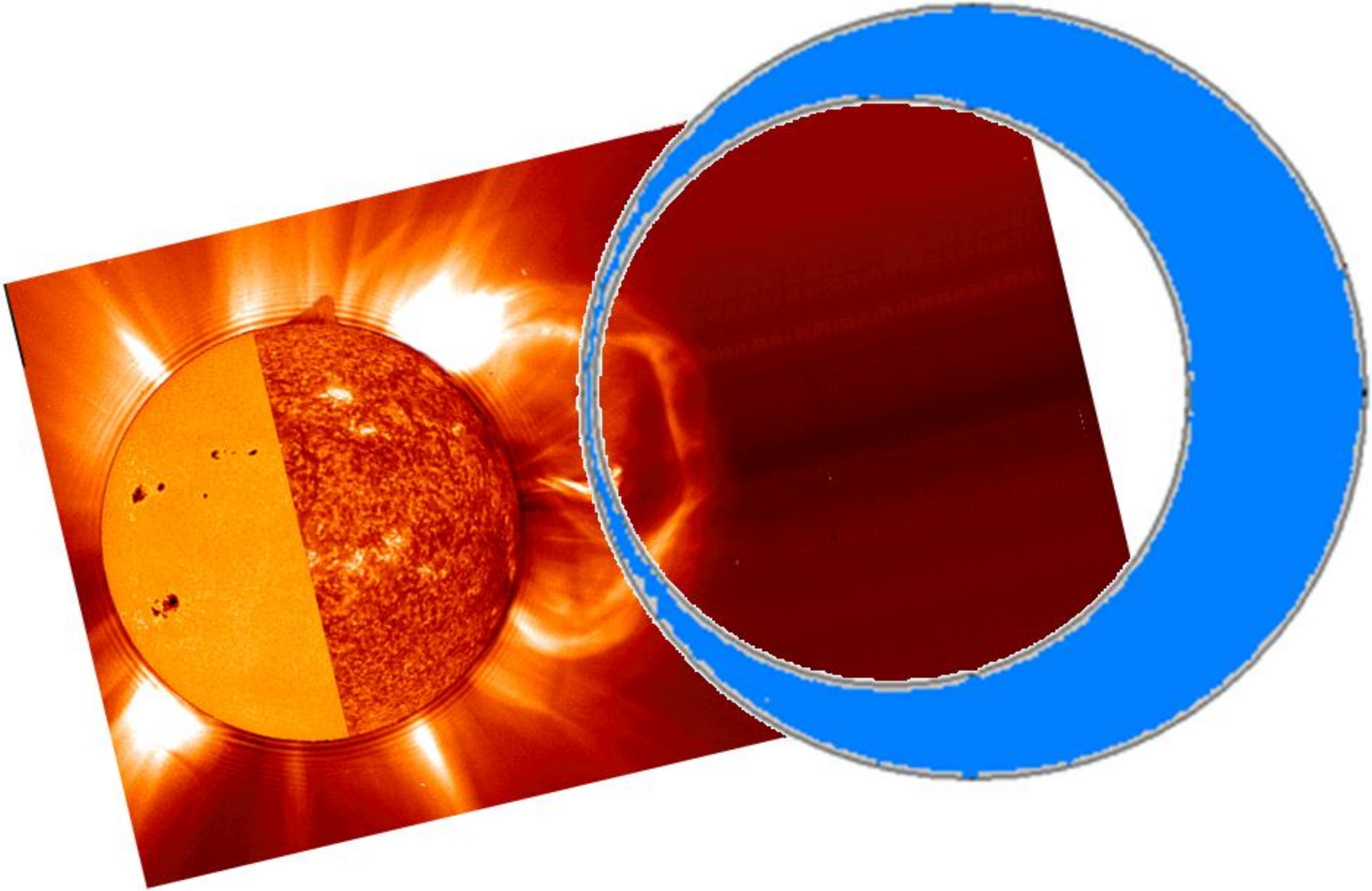


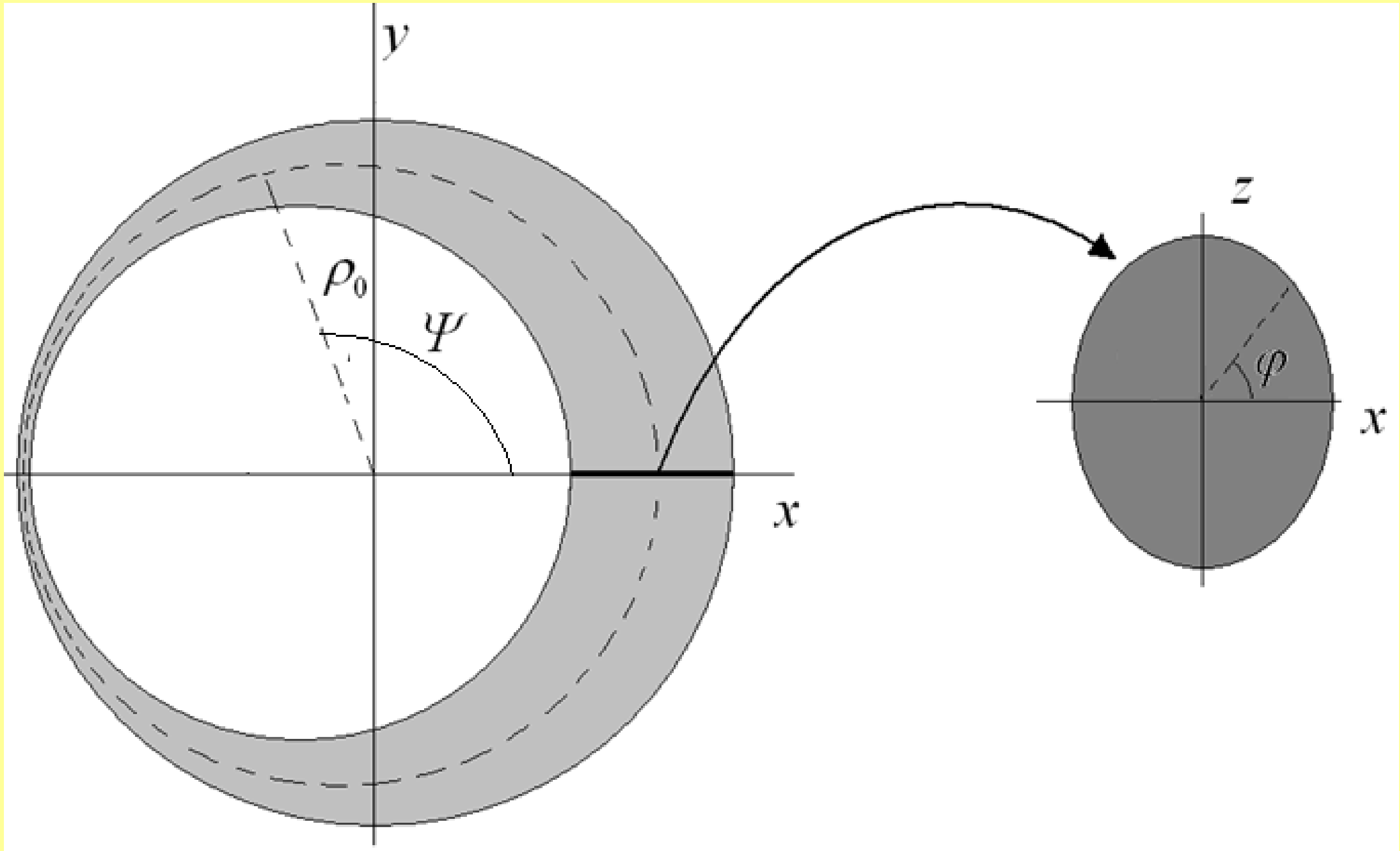
Fits with the cylindrical model with elliptical cross-section model









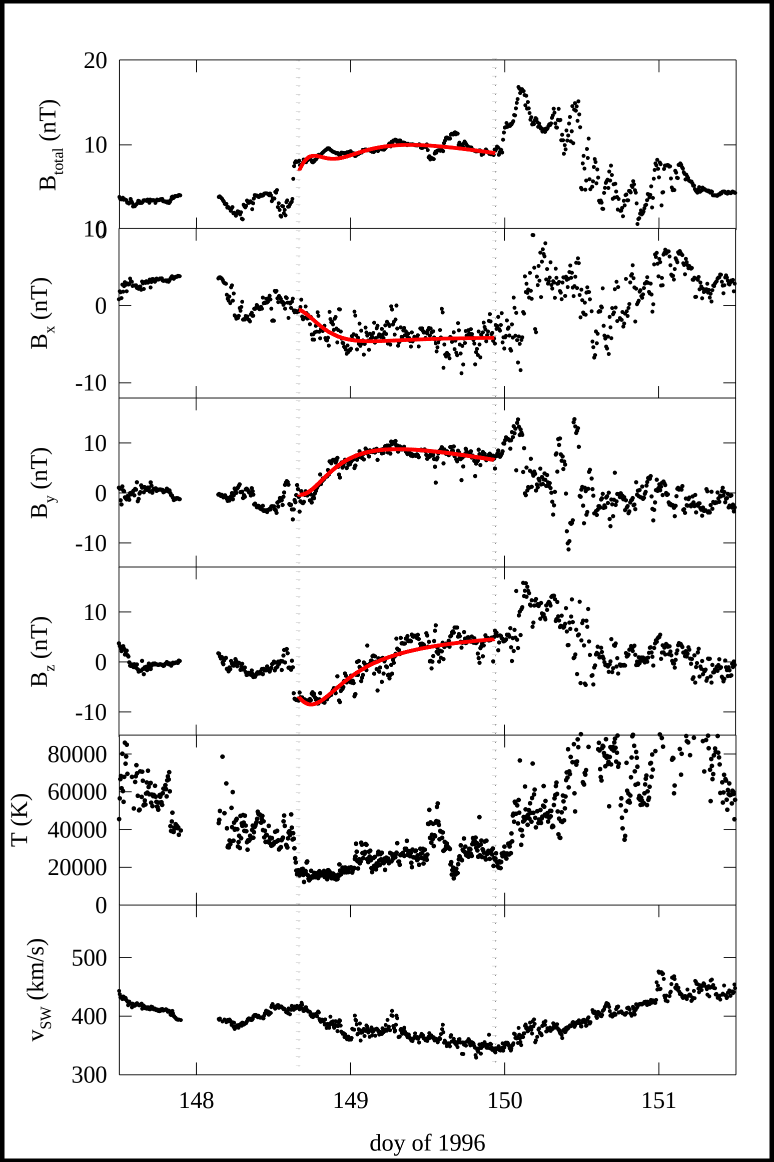


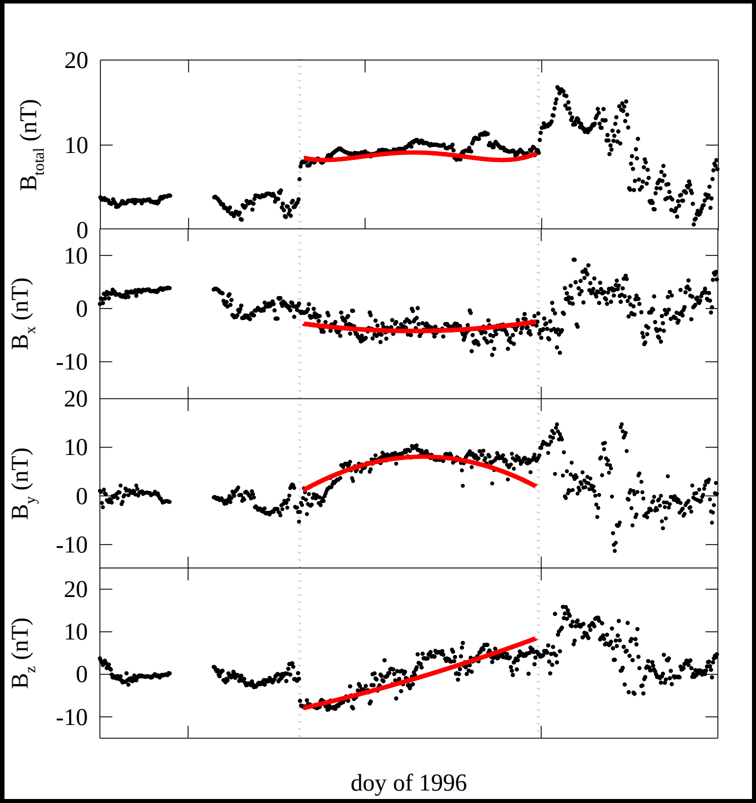
$$x = \left[\rho_0 + r \sinh\left(-\rho_0 \eta + f \right) \cos\left(\varphi \right) \right] \cos\left(\psi \right)$$

$$y = \left[\rho_0 + r \sinh\left(-\rho_0 \eta + f \right) \cos\left(\varphi \right) \right] \sin\left(\psi \right)$$

$$z = r \cosh\left(-\rho_0 \eta + f \right) \sin\left(\varphi \right)$$

Global model vs cylindrical model: circular cross-section (II)





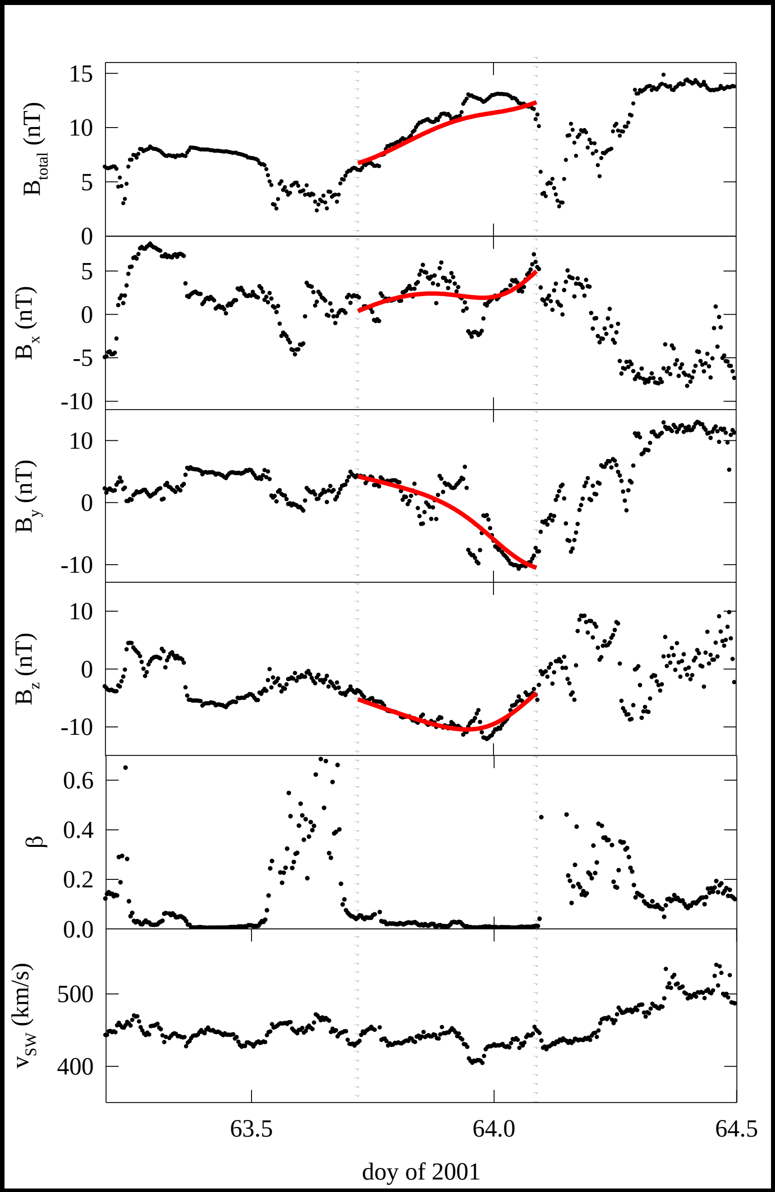
Analytical models answer questions like the following:

- All ejecta seen in the interplanetary medium have flux rope magnetic field configuration?
- Topologies of other magnetic structures in the interplanetary medium (current sheets…)
- …

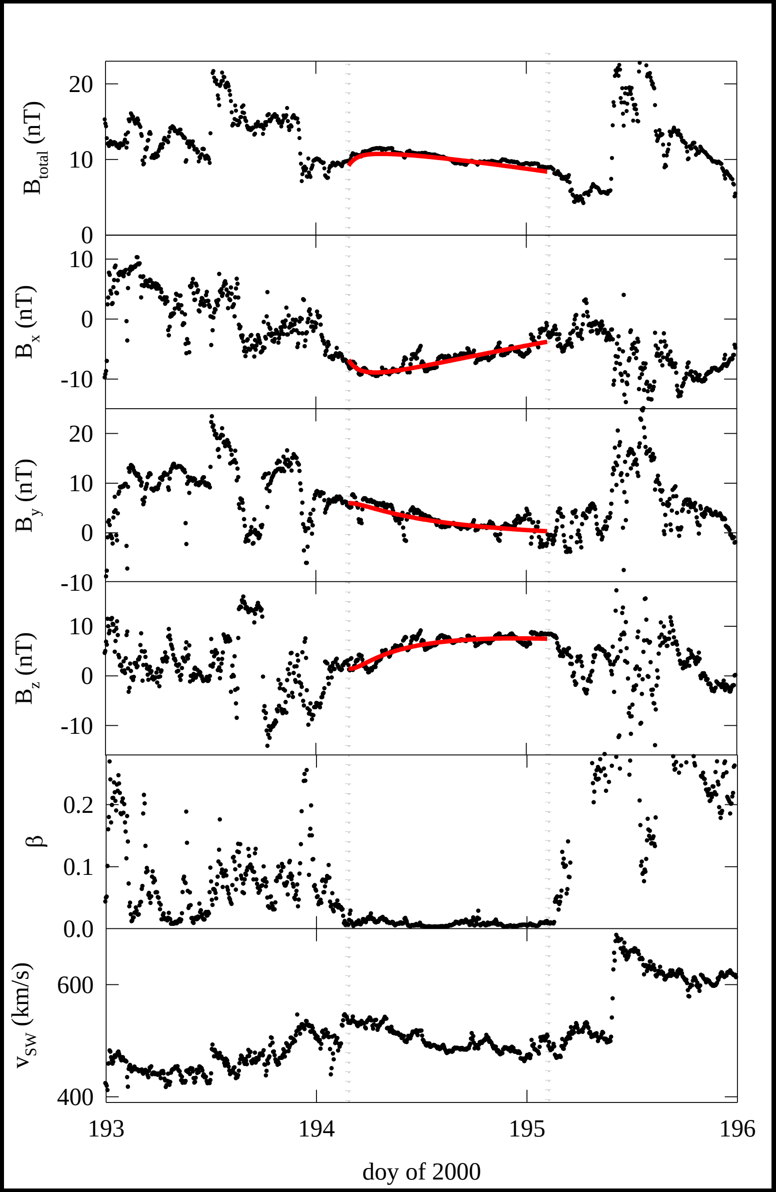
Allow us to analyse every event observed in the interplanetary medium from a physical point of view

Analysis with a model of the flux rope character of some evens

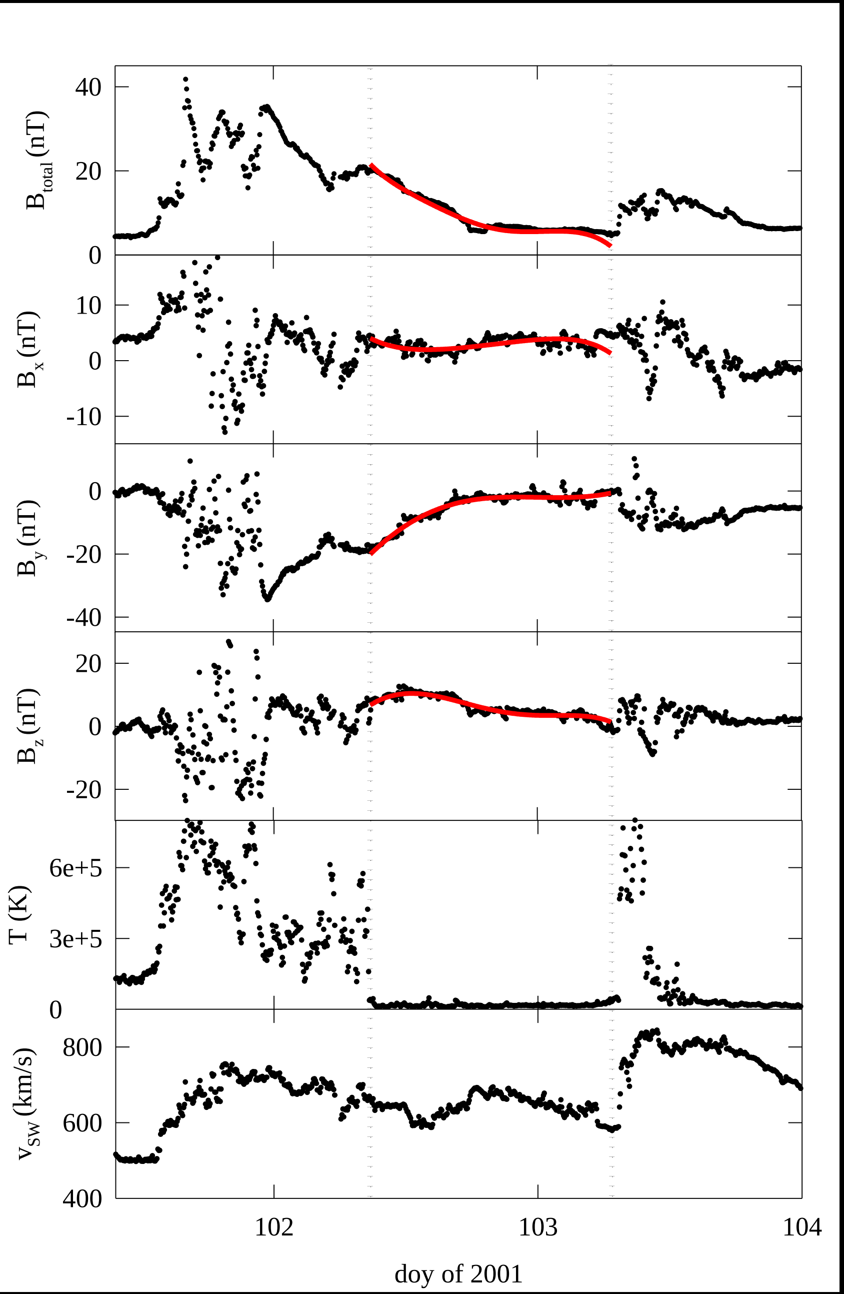
Ejecta without flux rope topology

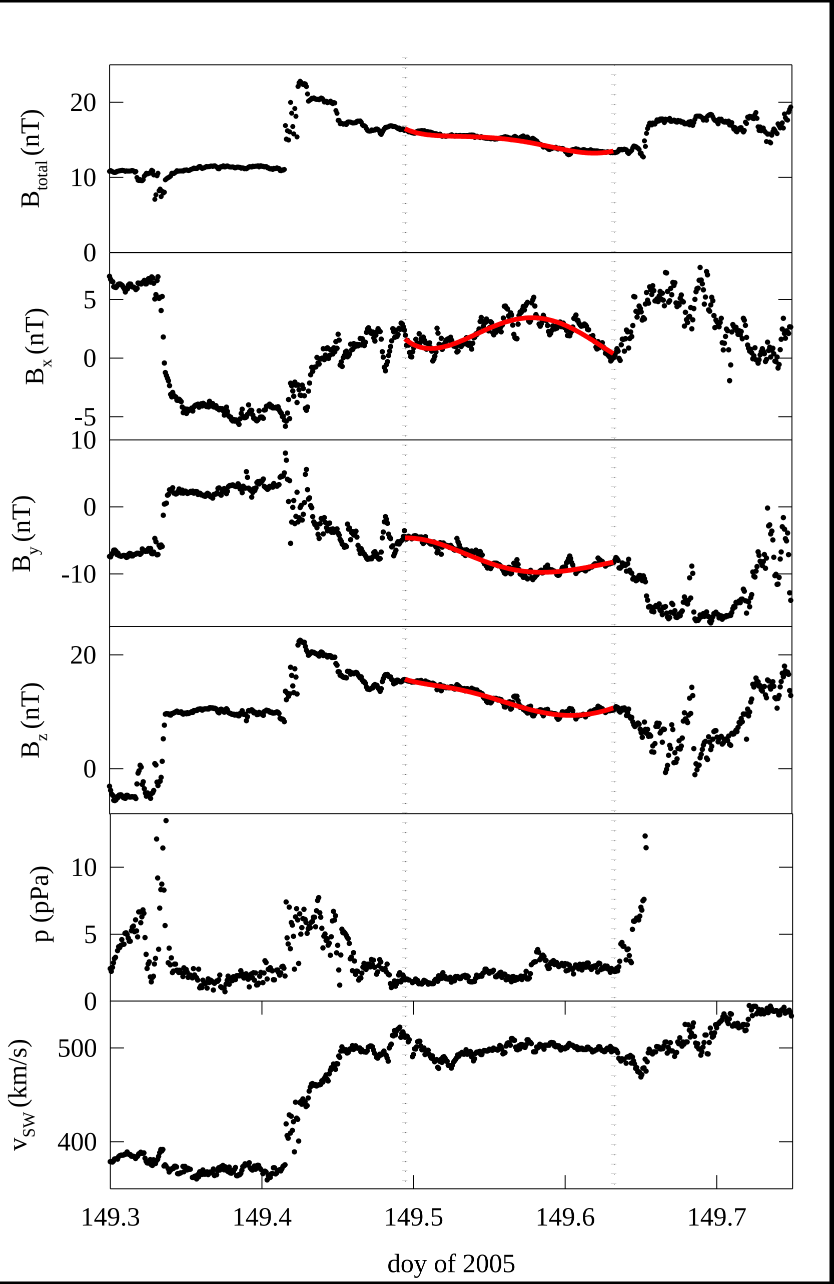


Ejecta with flux rope topology

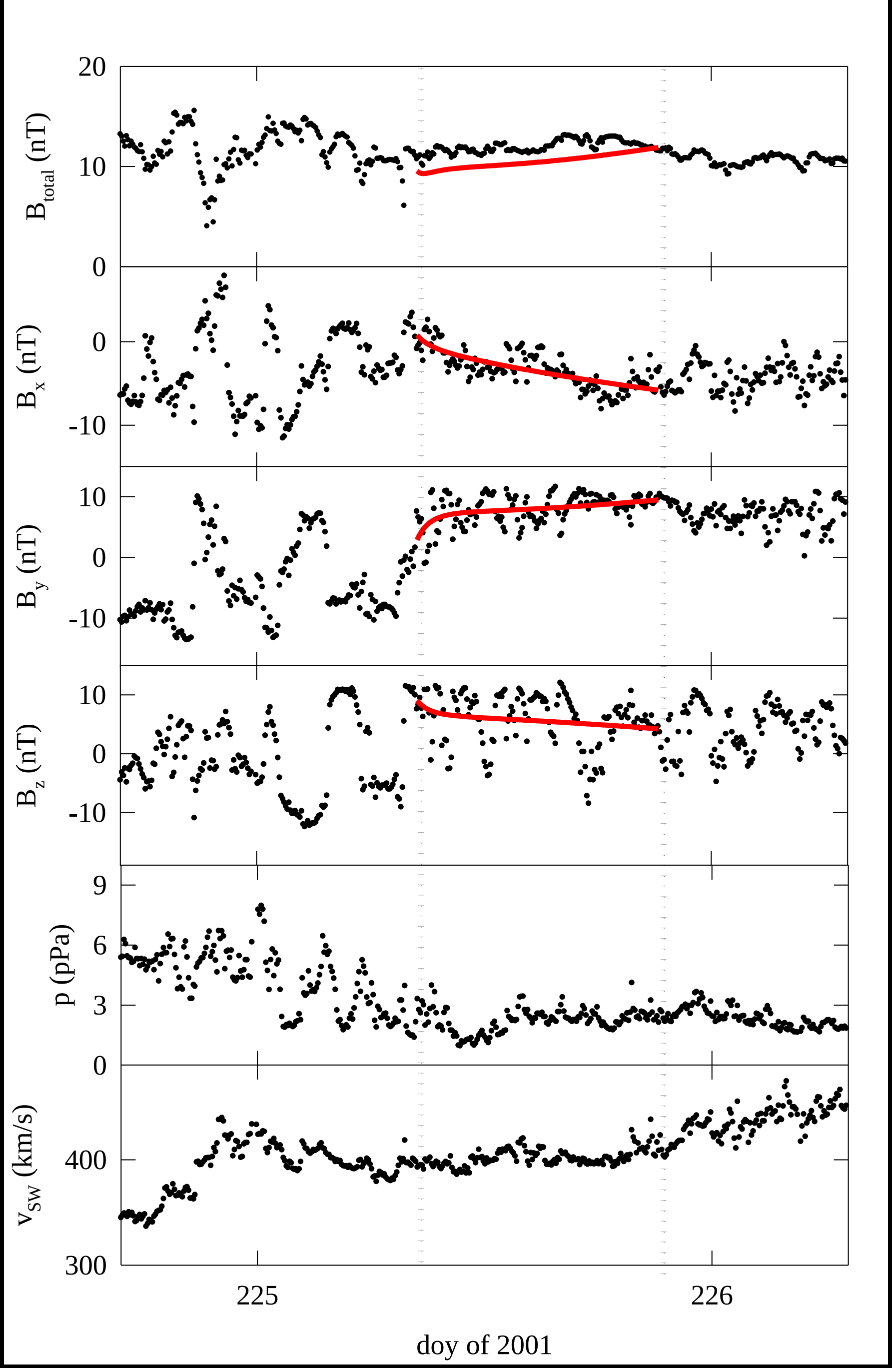


Event 20010412 (Flux rope Ejecta)

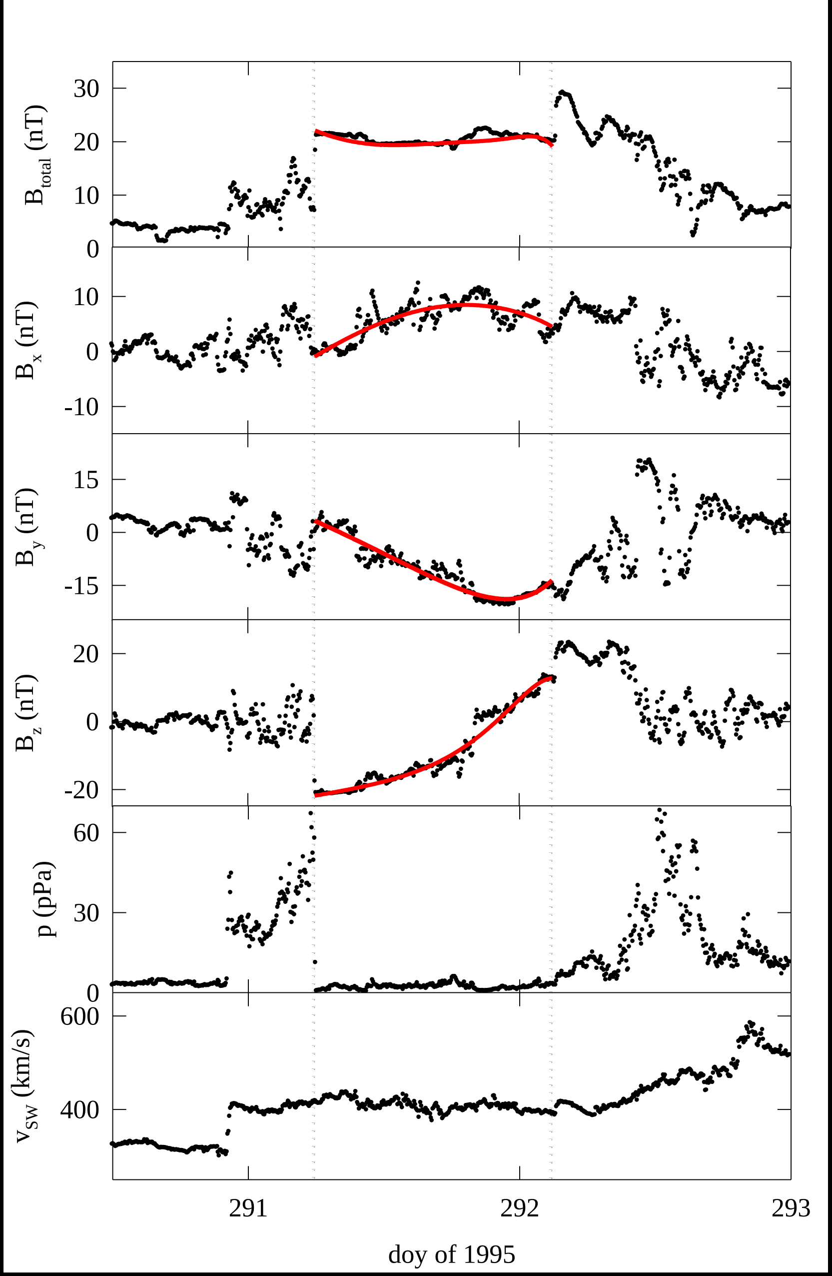




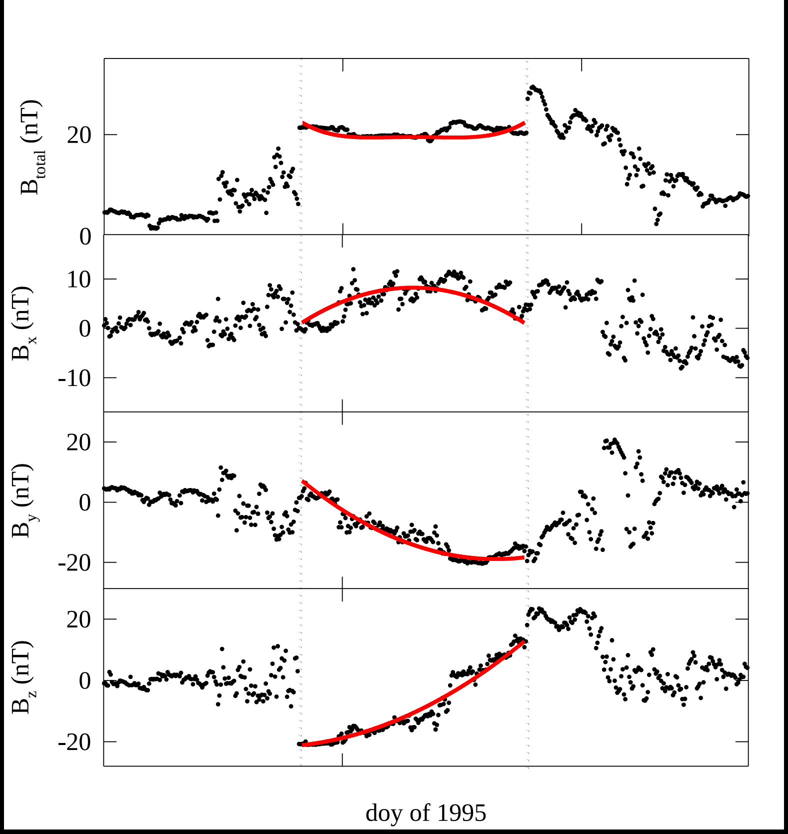
Event 20050529 (Flux rope Ejecta)



Fitting complex ejecta



Analytical models allow us to know, and understand, the physics under the phenomena observed in the interplanetary medium. In all moment the procedure is under control




Thanks a lot for your attention
Muchas gracias por vuestra atención
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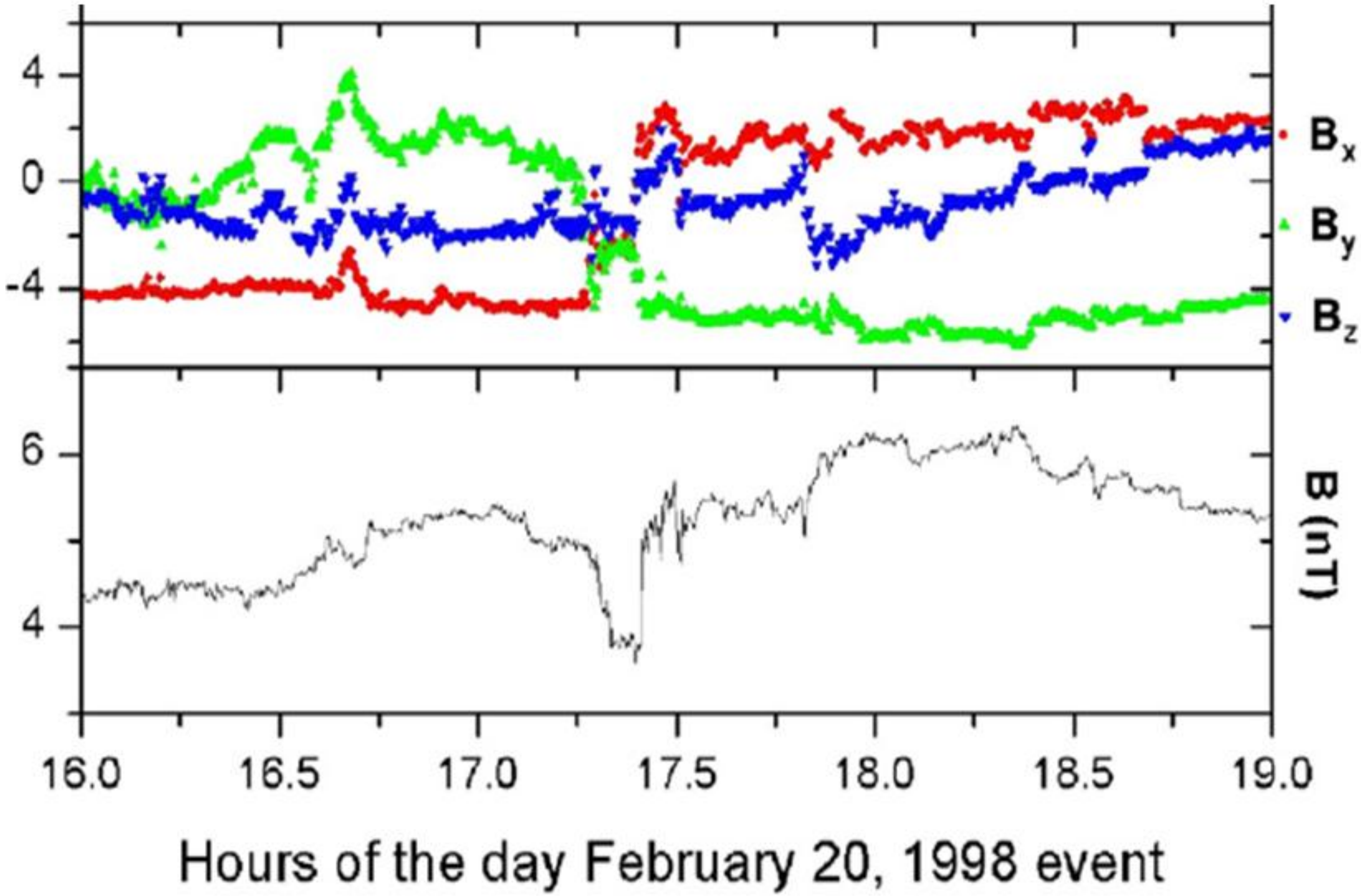
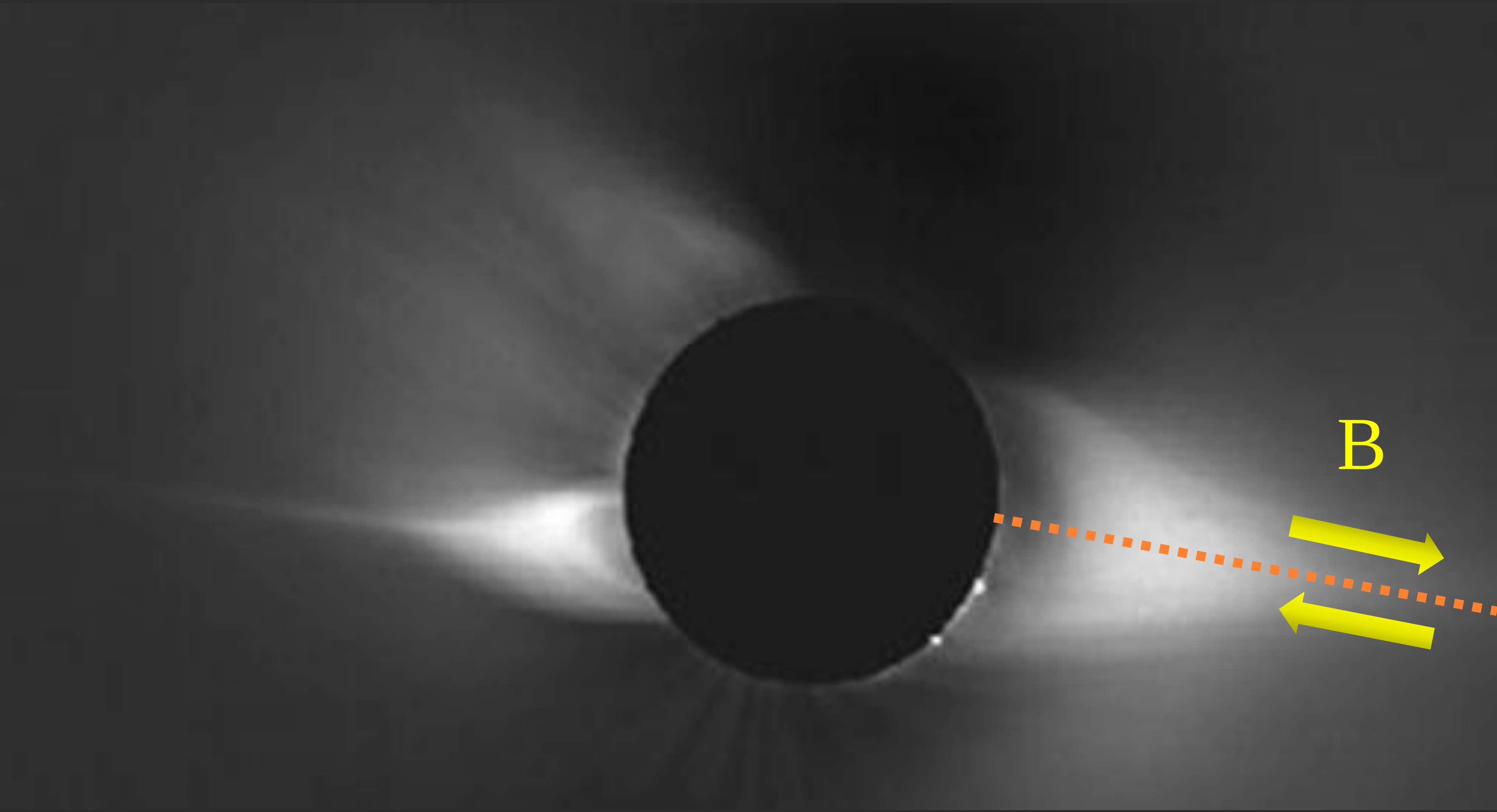
If any of you want to have some of the references, please tell me!

Complementary activity

Development of a current sheet model

The phenomenon



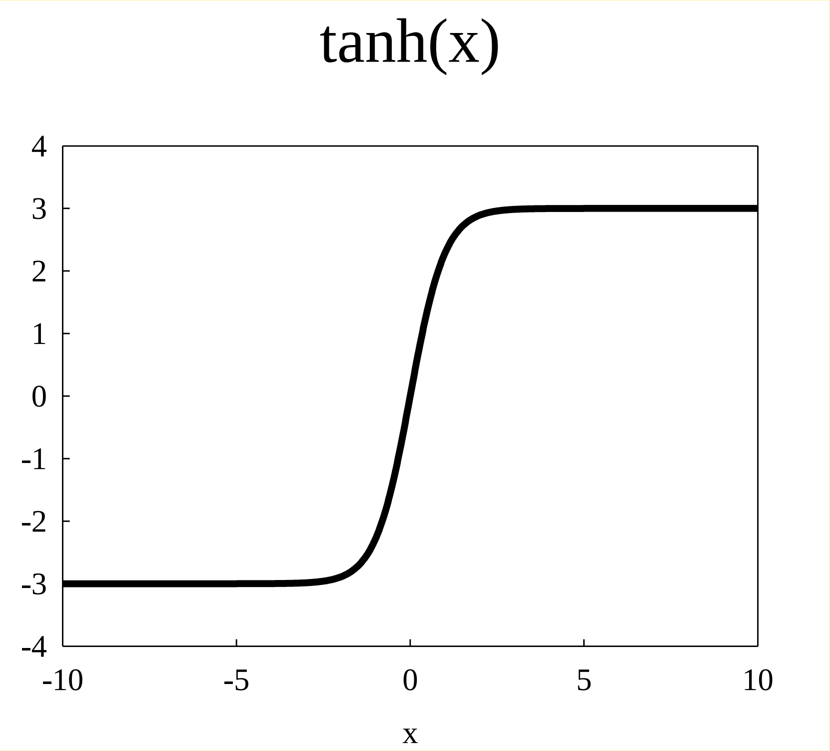

B

The analytical magnetic field model

$$B_x = B_{x0} \tanh\left(\frac{y - y_0}{L}\right)$$

$$B_y = B_{yo}$$

$$B_z = B_{z0}$$



The magnetic field components in the GSE coordinate system

$$B_x = B_{x0} \tanh\left(\frac{y - y_0}{L}\right) \cos\alpha - B_{y0} \sin\alpha$$

$$B_y = B_{x0} \tanh\left(\frac{y - y_0}{L}\right) \sin\alpha \cos\beta + B_{y0} \cos\alpha \cos\beta - B_{z0} \sin\beta$$

$$B_z = B_{x0} \tanh\left(\frac{y - y_0}{L}\right) \sin\alpha \sin\beta + B_{y0} \cos\alpha \sin\beta + B_{z0} \cos\beta$$

Parameters of the model

The three constants components of the background magnetic field

$$\left(B_{x0}, B_{y0}, B_{z0}\right)$$

Local orientation of the current sheet: α and β

y_0

Parameters associated with the spacecraft path