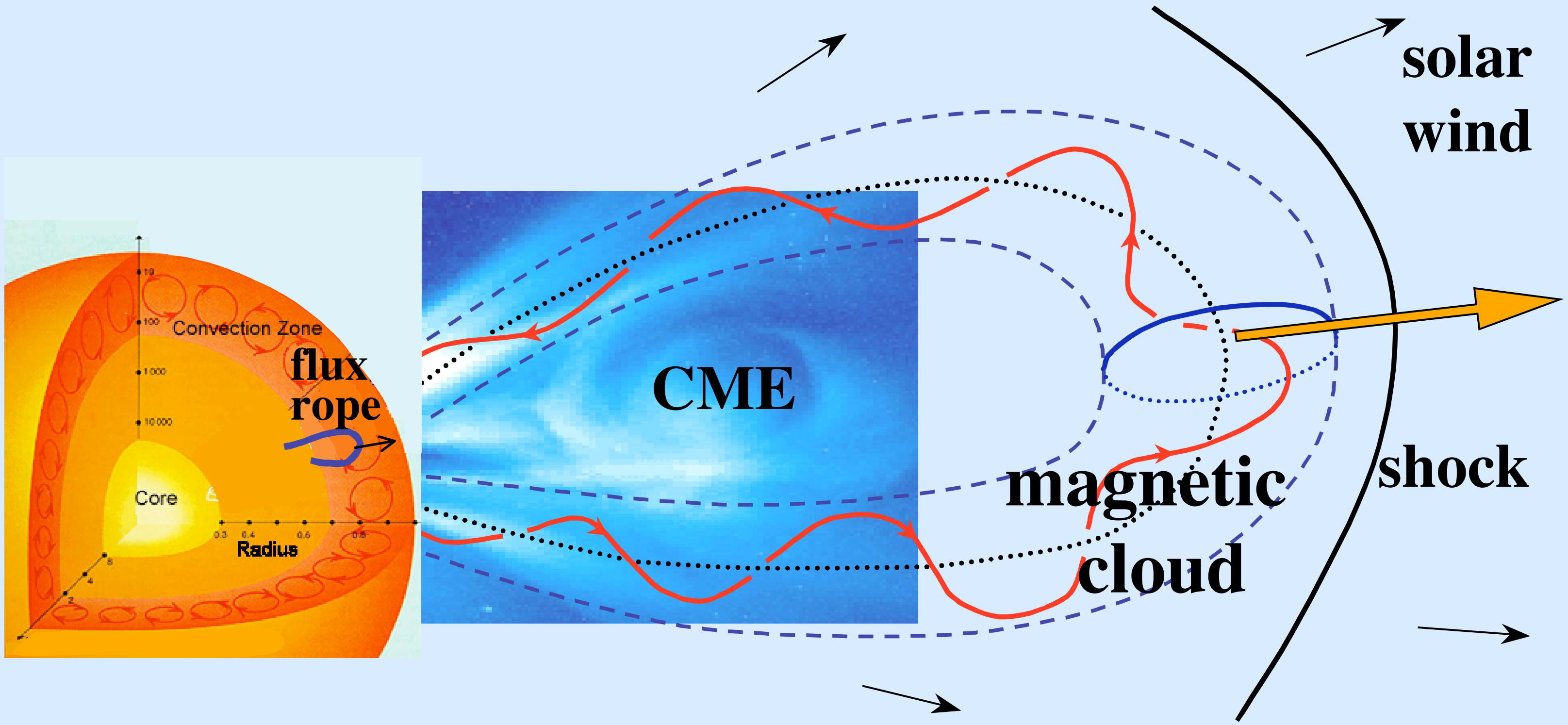
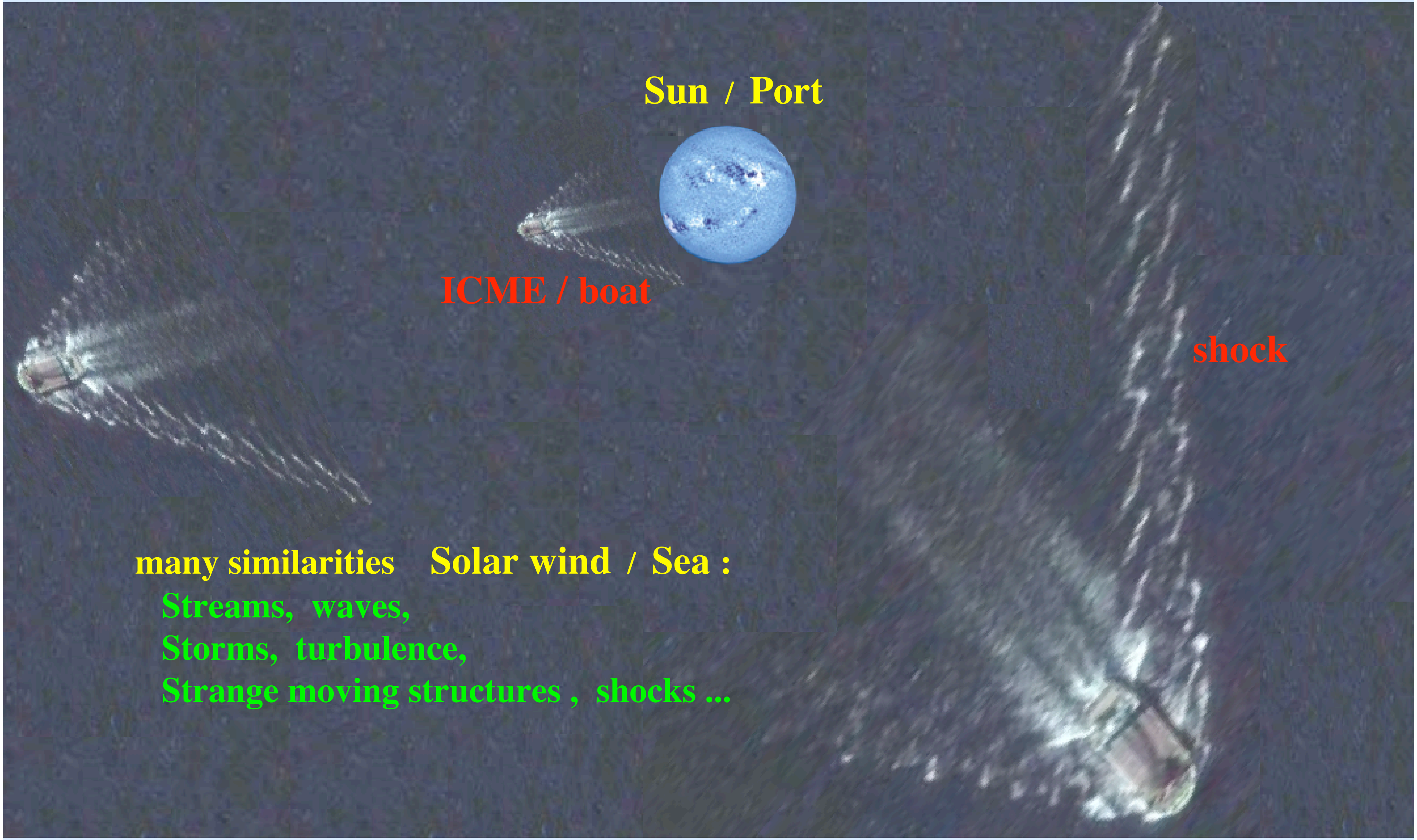
Interaction of ICMEs / MCs with the Solar Wind

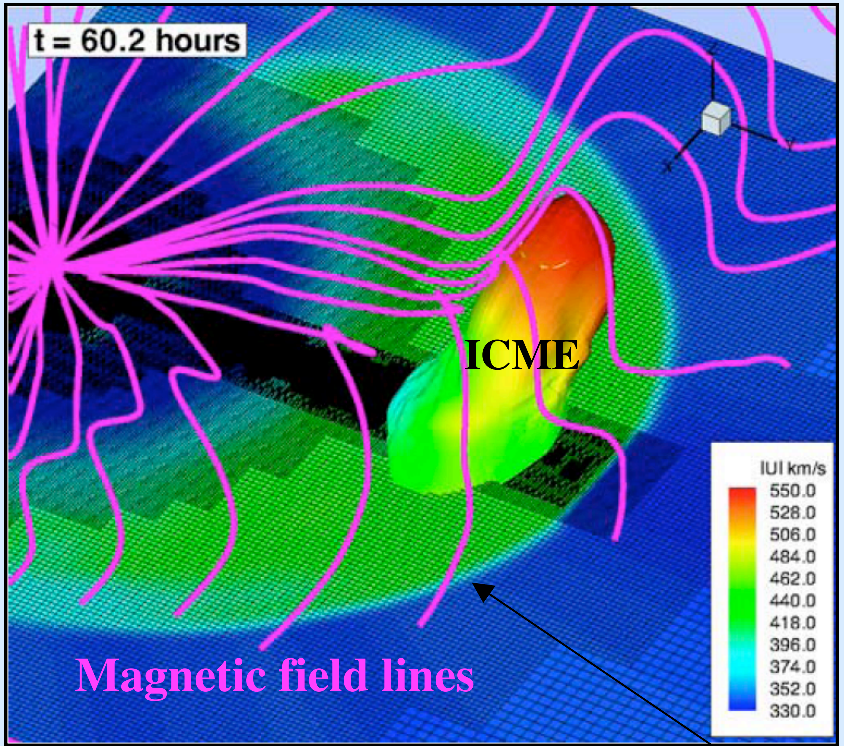


Pascal Démoulin

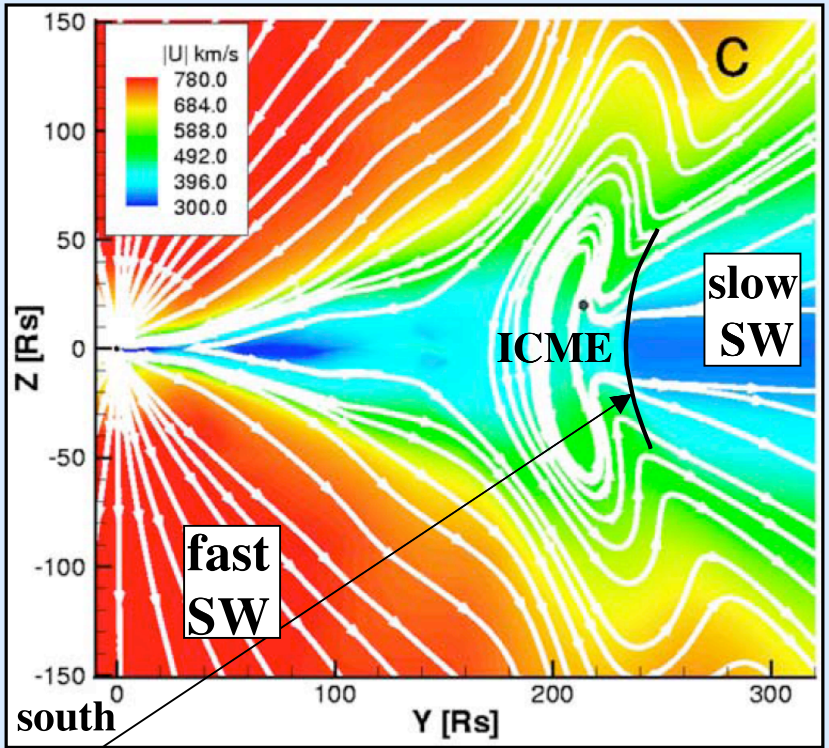
A crude analogy



Large scale implications of MCs / ICMEs



north



equatorial plane

meridional plane

shock

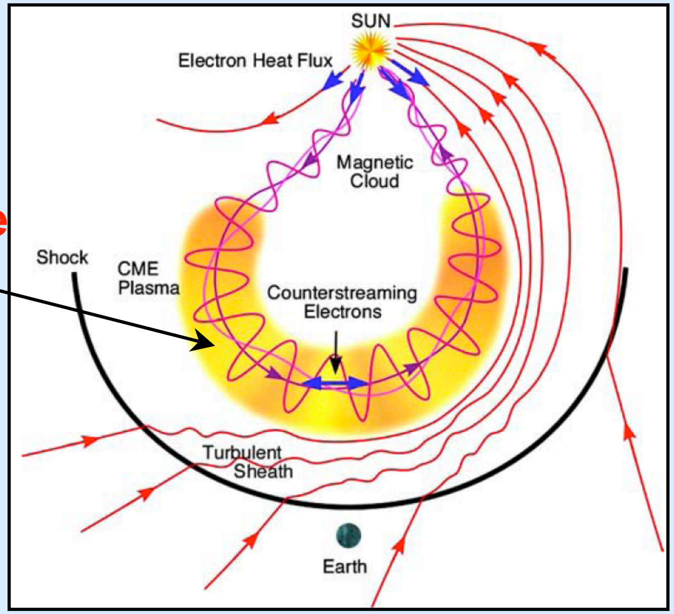
(shock surface: saddle shape)

3D MHD simulation (Manchester et al. 2004)

Main properties of MCs and ICMEs

Definition of Magnetic Clouds :

smooth & large rotation of enhanced B → **flux rope**
and **low proton plasma β (β_p)**
and **low proton temperature (T_p)**
(Klein & Burlaga 1982;
Burlaga, 1988; Lepping et al. 1990)



(Zurbuchen & Richardson 2006)

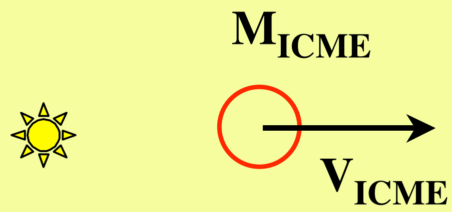
Definition of ICMEs :

lower T_p (e.g. Gosling et al 1973) $T_p/T_{exp} < 0.5$ (e.g. Wang et al. 2005)
or/and **enhanced He** abundance (e.g. Borrini et al. 1982) $N_\alpha/N_p > 0.08$ (e.g. Liu et al. 2005)
or/and **counterstreaming** of suprathermal (> 80 eV) electron beams (e.g. Gosling et al. 1987)
or/and **enhanced ion charge states** (e.g. Fenimore 1980)
or/and **strong B with low variance**
or/and **...**

One or several criteria depending on authors => **ICMEs are not so well defined**

ICMEs include Magnetic Clouds (~ 30 % of ICMEs are MCs, cycle dependence)

interaction 1



<u>Global interaction ICME / SW</u> :

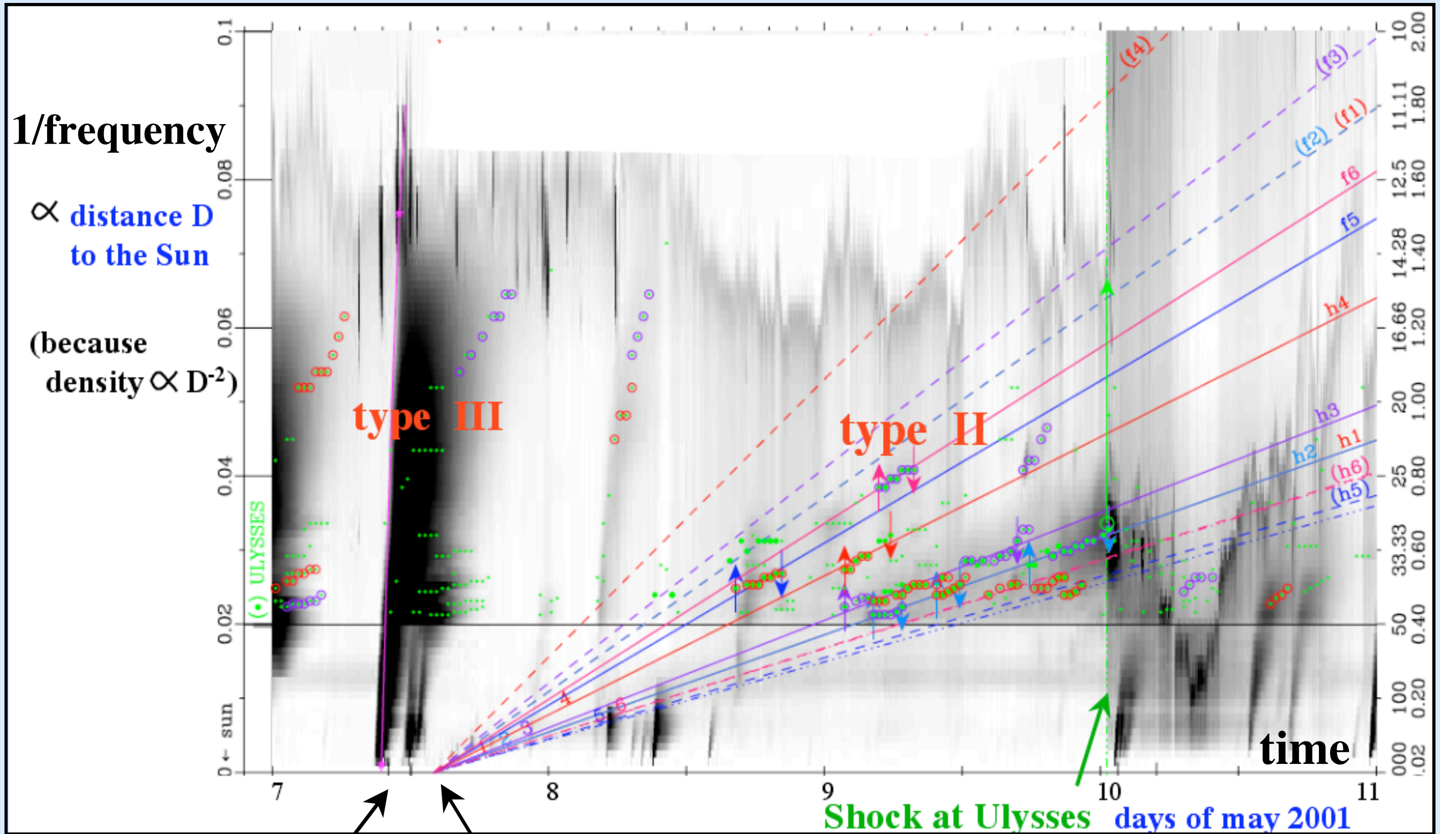
modification of the ICME
mean velocity and mass

acceleration / deceleration of ICMEs (I)

Type II radio emissions + heliospheric density model

=> can track the ICME shock propagation

(Reiner et al. 1998, 2007 Berdichevsky et al. 2002)



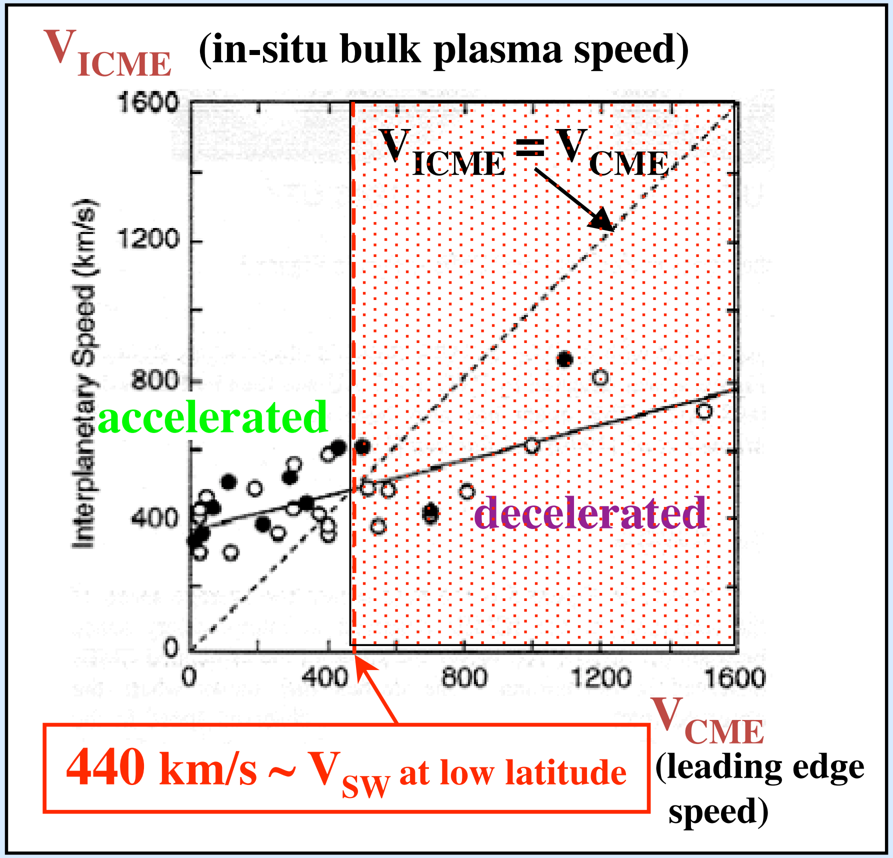
(Hoang et al. 2007)

CME launch time

Convergence of "constant velocity" lines after the type III burst

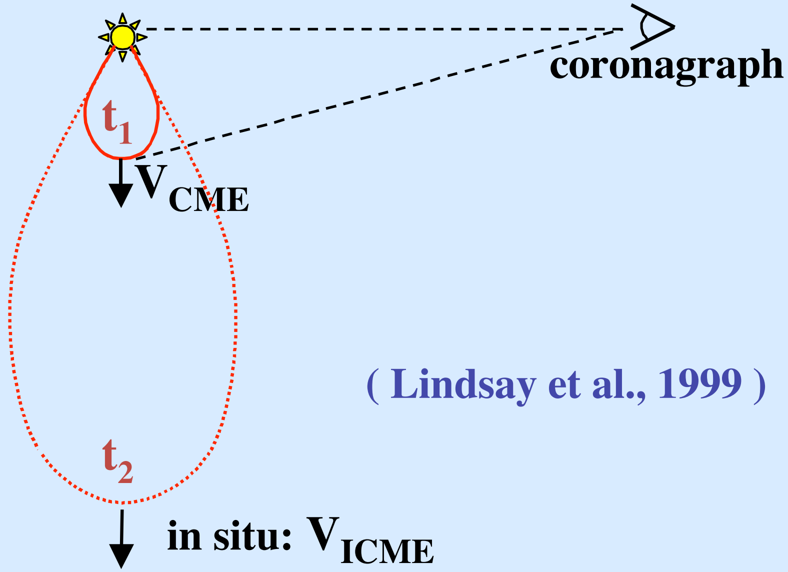
=> small acceleration of the shock (for this case)

acceleration / deceleration of ICMEs (II)



=> drag force from the solar wind

observations in quadrature

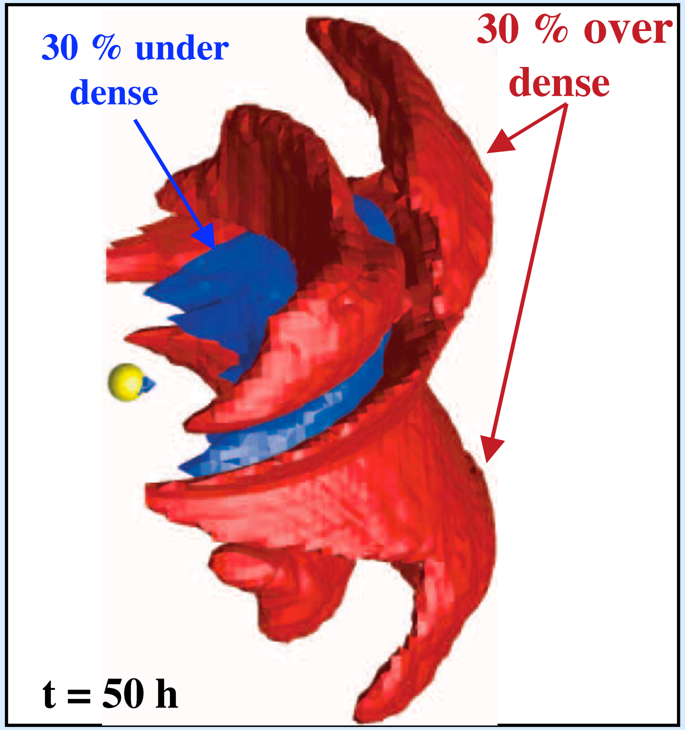


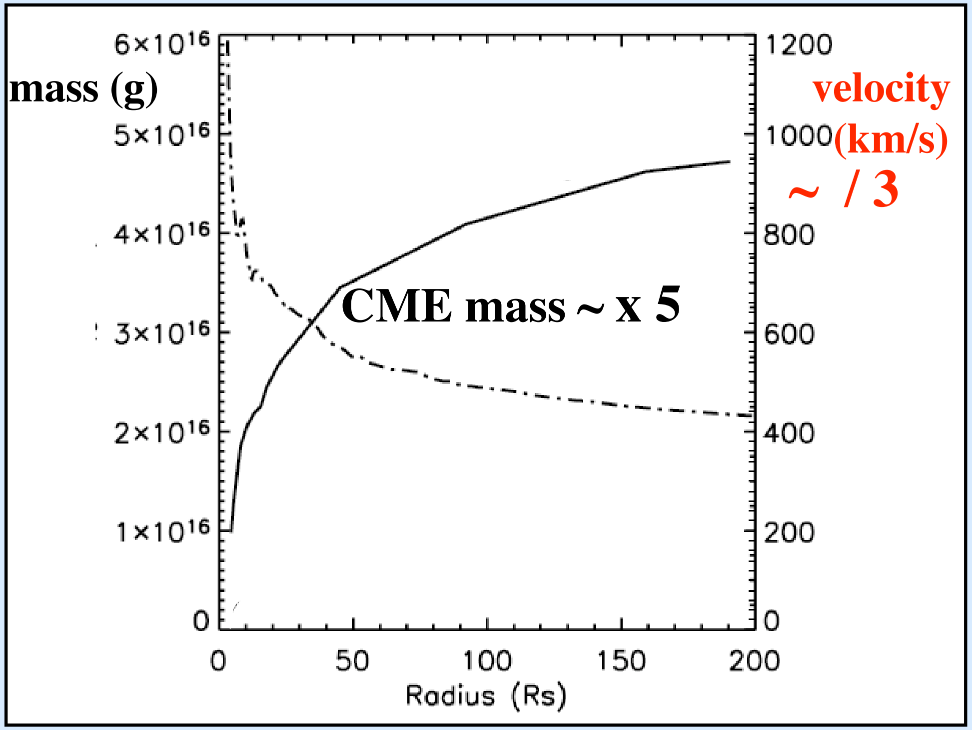
(Lindsay et al., 1999)

- Confirm with later studies (Gopalswamy et al. 2000, 2001, Zhang et al. 2003, Schwenn et al. 2005)
- More results are coming with the Heliospheric Imager (STEREO) …

mass loading in ICMEs

3D MHD simulation



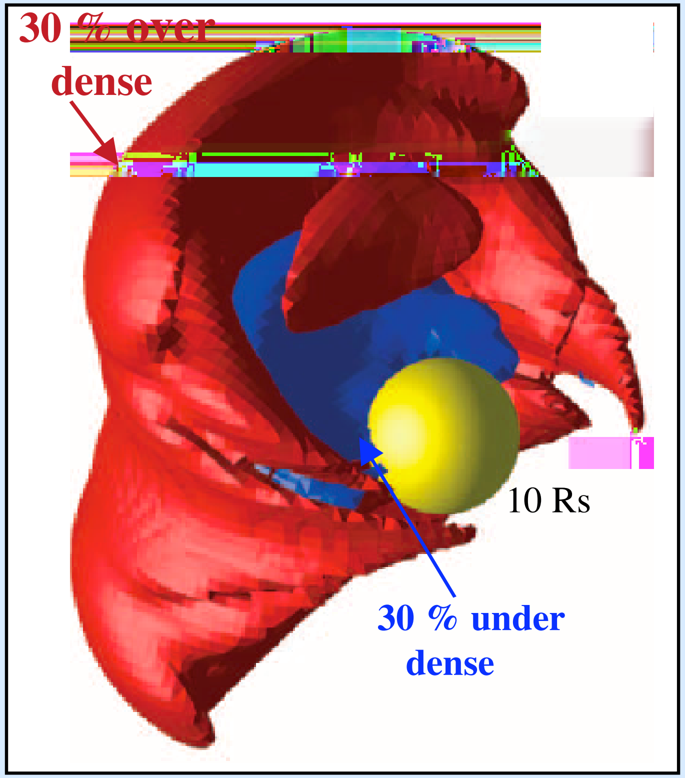


(Lugaz et al., 2005)

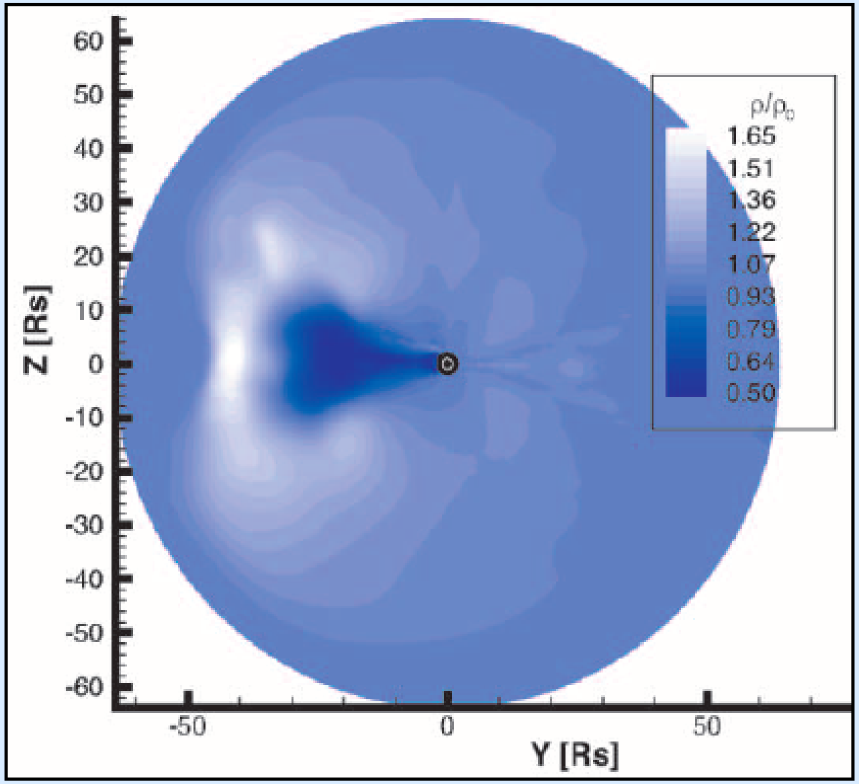
Accumulation of slow plasma => a part of the drag force from the SW

what is observed in a coronagraph ?

3D MHD simulation

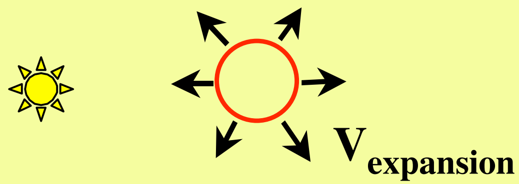


simulated Thomson-scattered light (expected view in HI2 on STEREO A/B)



(Lugaz et al., 2005
Manchester et al., 2008)

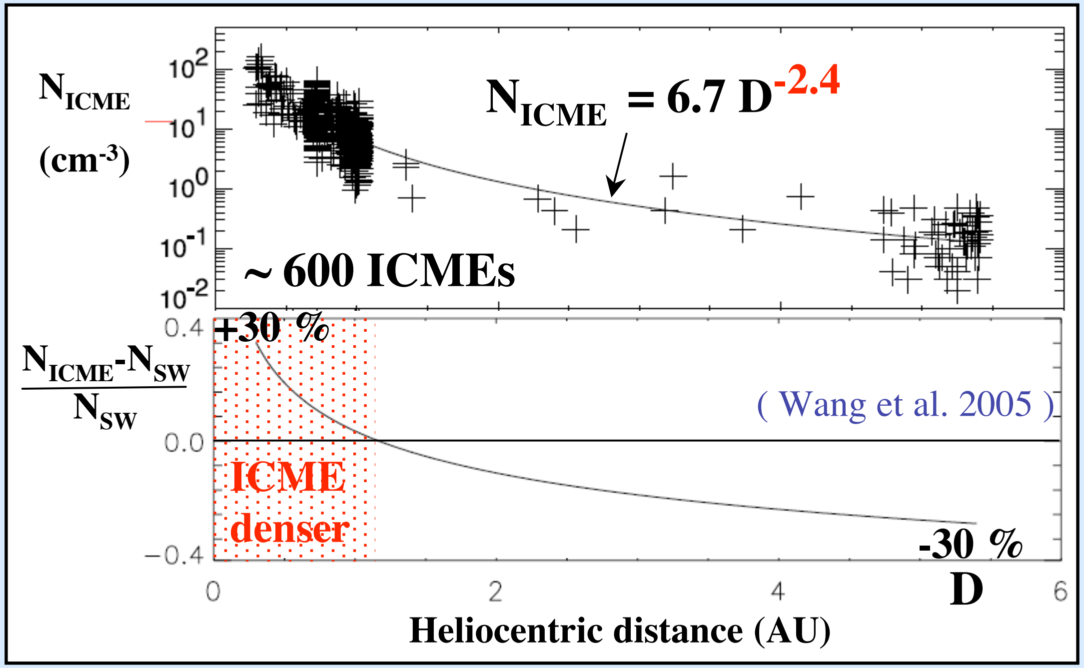
interaction 2



Expansion rate of ICMEs / MCs

How the SW define the ICME expansion rate …

Density (distance) in ICMEs



Faster decrease than in the SW
($N_{SW} \propto D^{-2}$)

=> 3D expansion of ICMEs

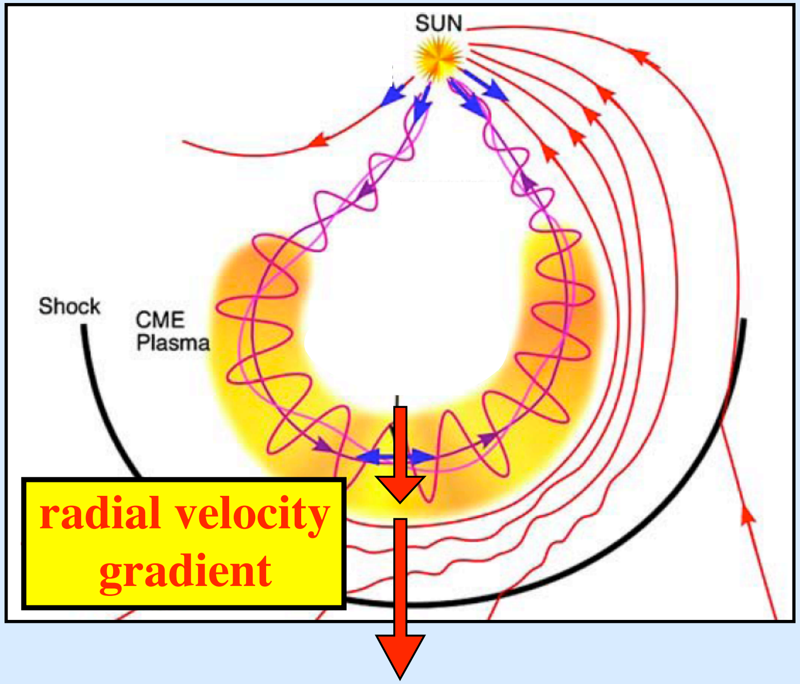
other studies:

216 ICMEs: $N_{ICME} = 6.2\ D^{-2.3 \pm 0.07}$

(Liu et al. 2005)

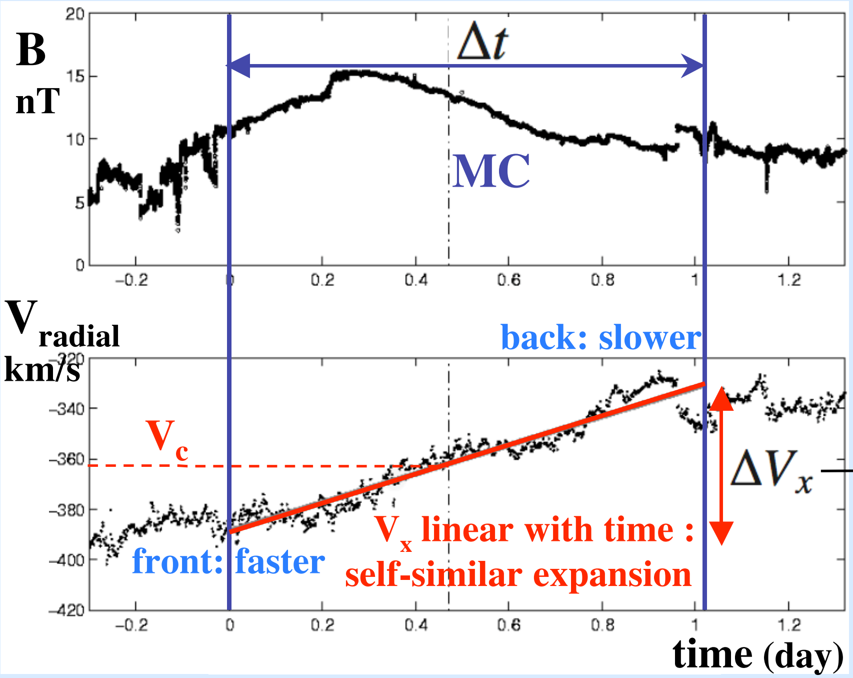
130 MCs: $N_{MC} = 6.6\ D^{-2.6 \pm 0.07}$

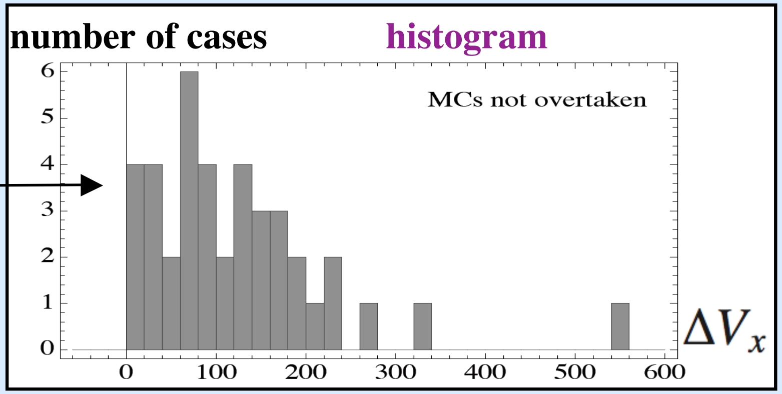
(Leitner et al. 2007)



observed in situ in each ICME

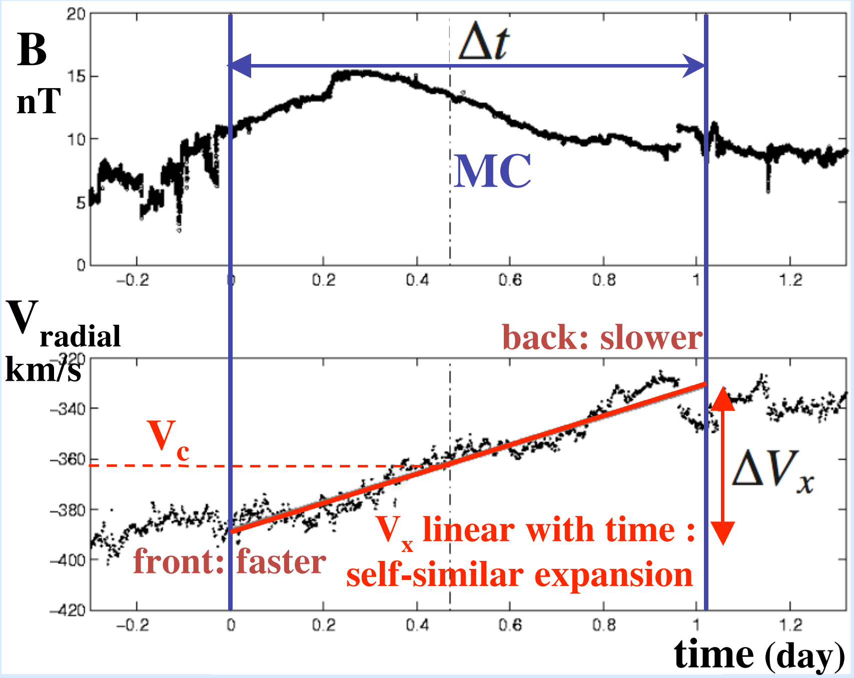
Expansion rate of MCs





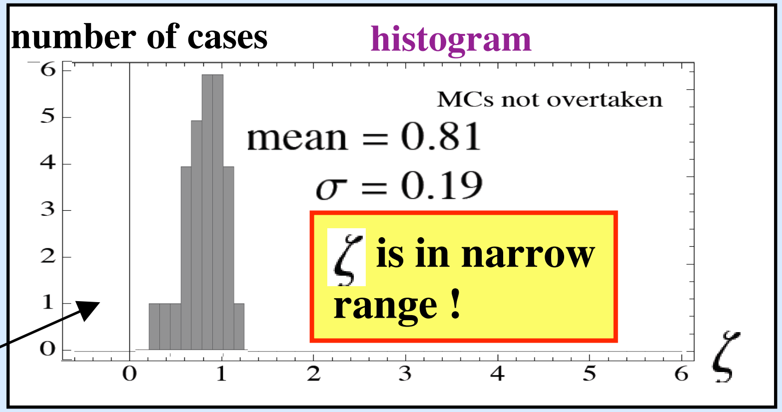
=> broad range of ΔV_x

Expansion rate of MCs



non dimensional expansion rate :

$$\boxed{\zeta = \frac{\Delta V_x}{\Delta t}\frac{D}{V_c^2}}$$



ζ independent of :

- B strength
- MC size

=> MCs have a typical expansion rate !

meaning: if ζ independent of D,

size = $\text{size}_0\,(D/D_0)^{\zeta}$

(Démoulin et al. 2008, Gulisano et al. 2009)

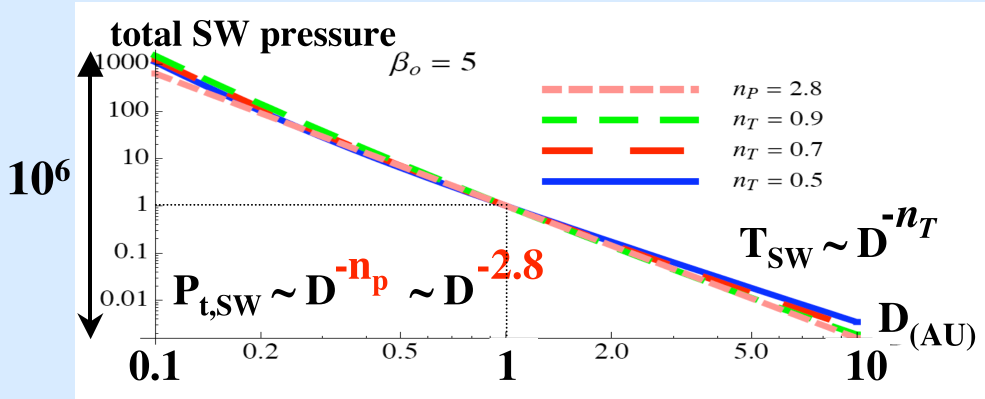
Why a typical expansion rate for MCs ?

simple estimation of the pressure balance

$$P_{MC} \sim c \; P_{t,SW}$$

few units

main source of P_B evolution



=> self-similar expansion : $r = r_0 \, D^{n_p/4} \sim r_0 \, D^{0.7}$

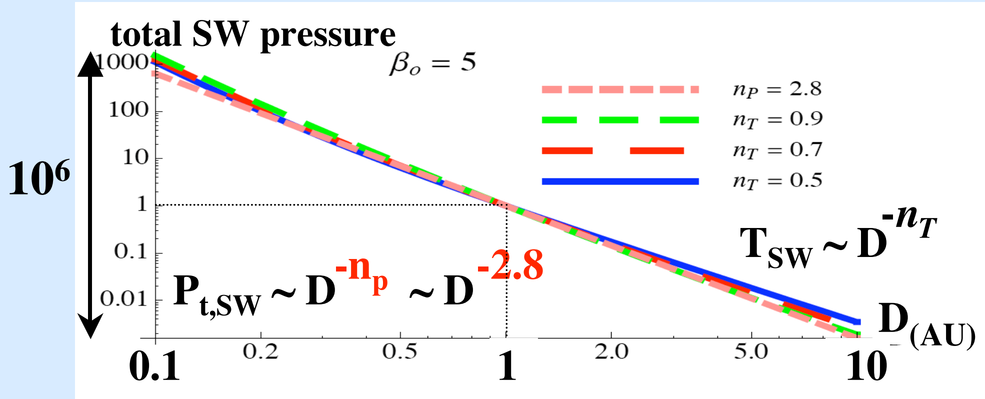
The SW total pressure defines the cross-section expansion rate

simple estimation of the pressure balance

$P_{MC} \sim c\, P_{t,SW}$

few units

main source of P_B evolution

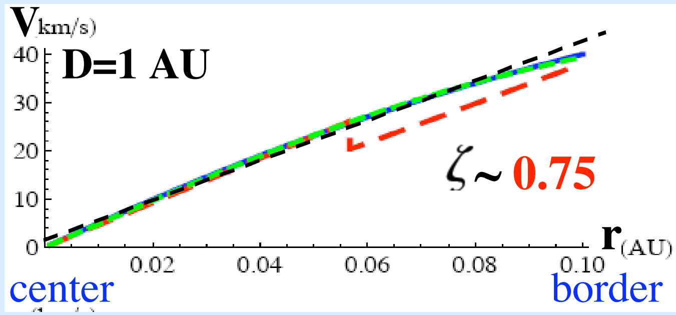


=> self-similar expansion : $r = r_0\, D^{n_p/4} \sim r_0\, D^{0.7}$

Model of flux rope evolution

ideal MHD + force-free field
($V_{expansion} \lesssim V_A$)

Velocity profile across the flux rope

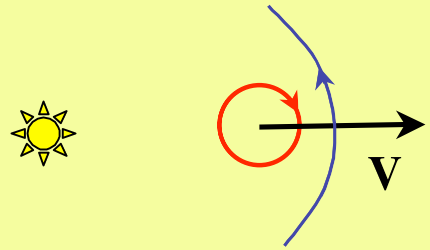


different field models :
- Lundquist
- Gold & Hoyle
- splitted

ζ and linear V profile as observed

(Démoulin & Dasso 2009)

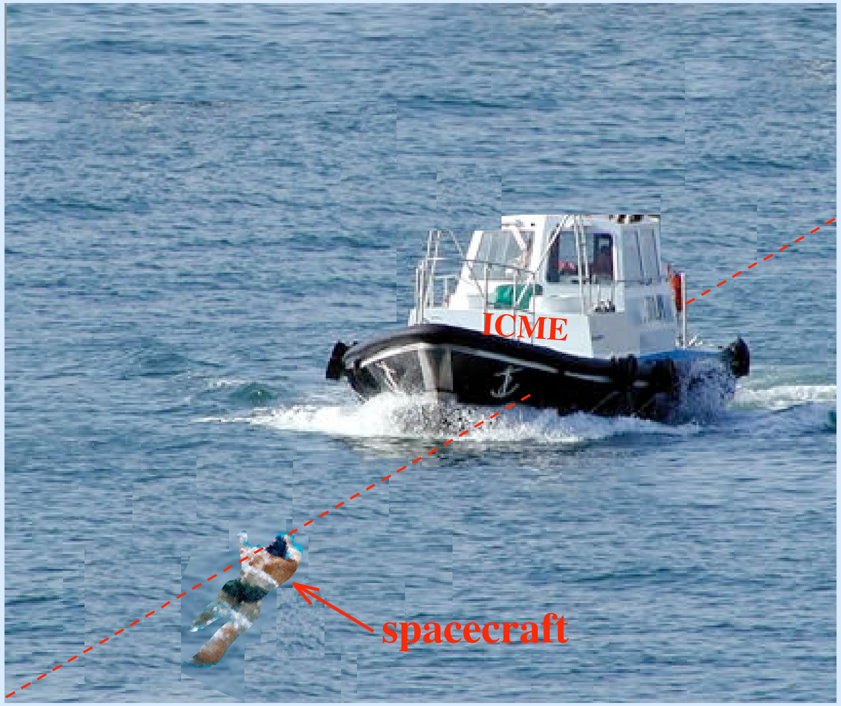
interaction 3

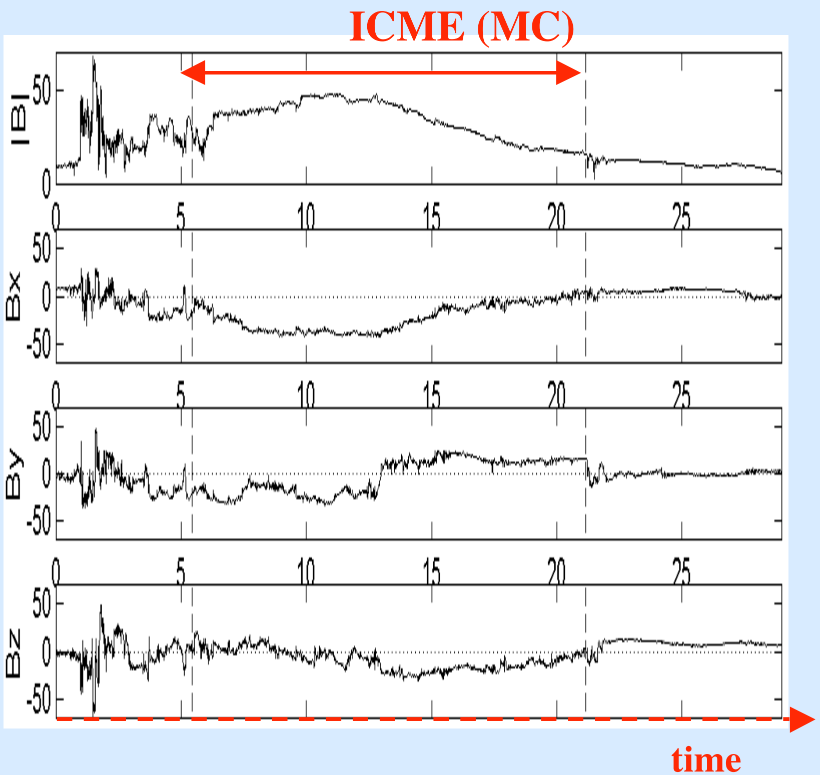


Magnetic interaction ICME / SW

Loss of magnetic flux

in situ measurements in ICMEs / MCs





Notice: do not worry about the spacecraft-swimmer, it will cross the ICME-boat without damage !

The solar wind is a parallel world
…. like in the "**the matrix**" movie… **:)=**

1D : plasma & B data only along a line

=> we need models to have a more global view

Defining the MC axis & frame

* **Minimum variance analysis**

(e.g. Sonnerup & Cahill 1967)

* **Relate the in/out bound physical properties of the flux rope**

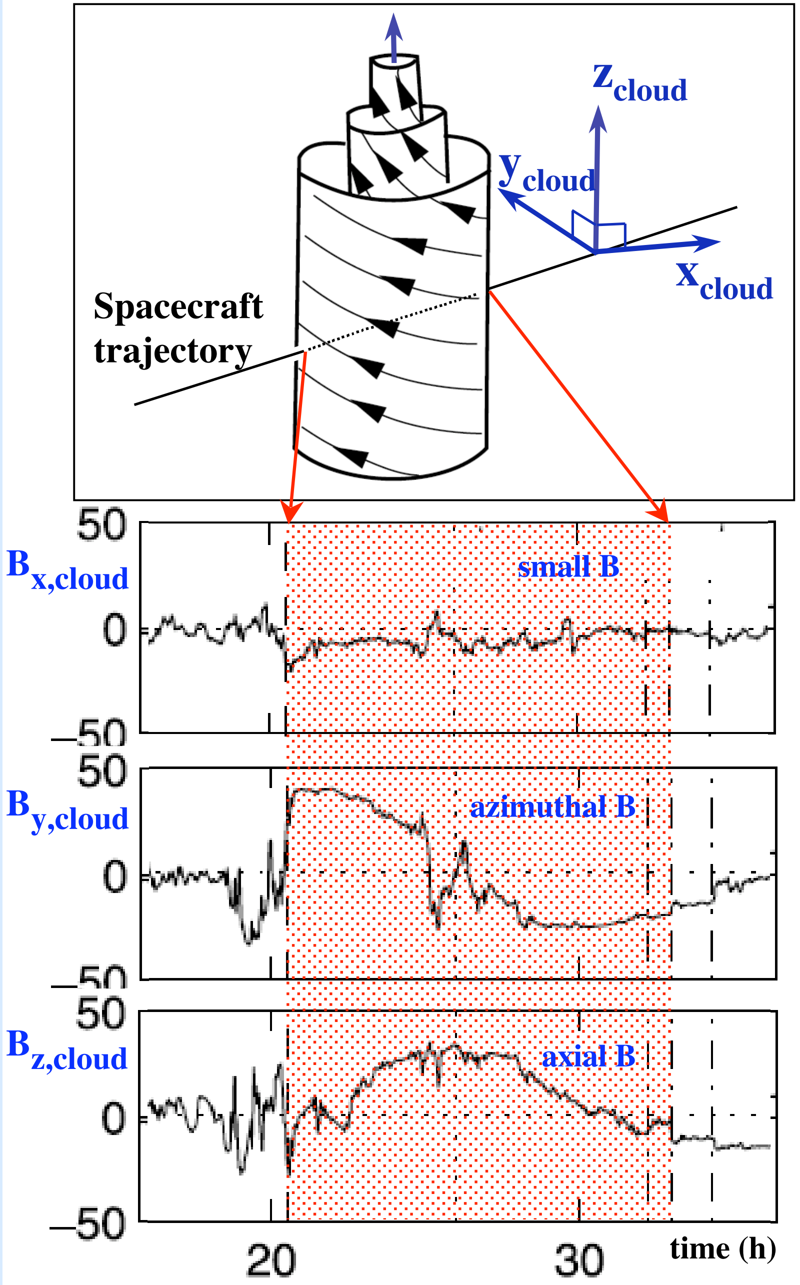
- plasma + B_{axial} pressure: $P_t(A)$ (Hu & Sonnerup 2002)
- conservation of azimuthal flux: (Dasso et al. 2005)

=> Constraints on the MC orientation

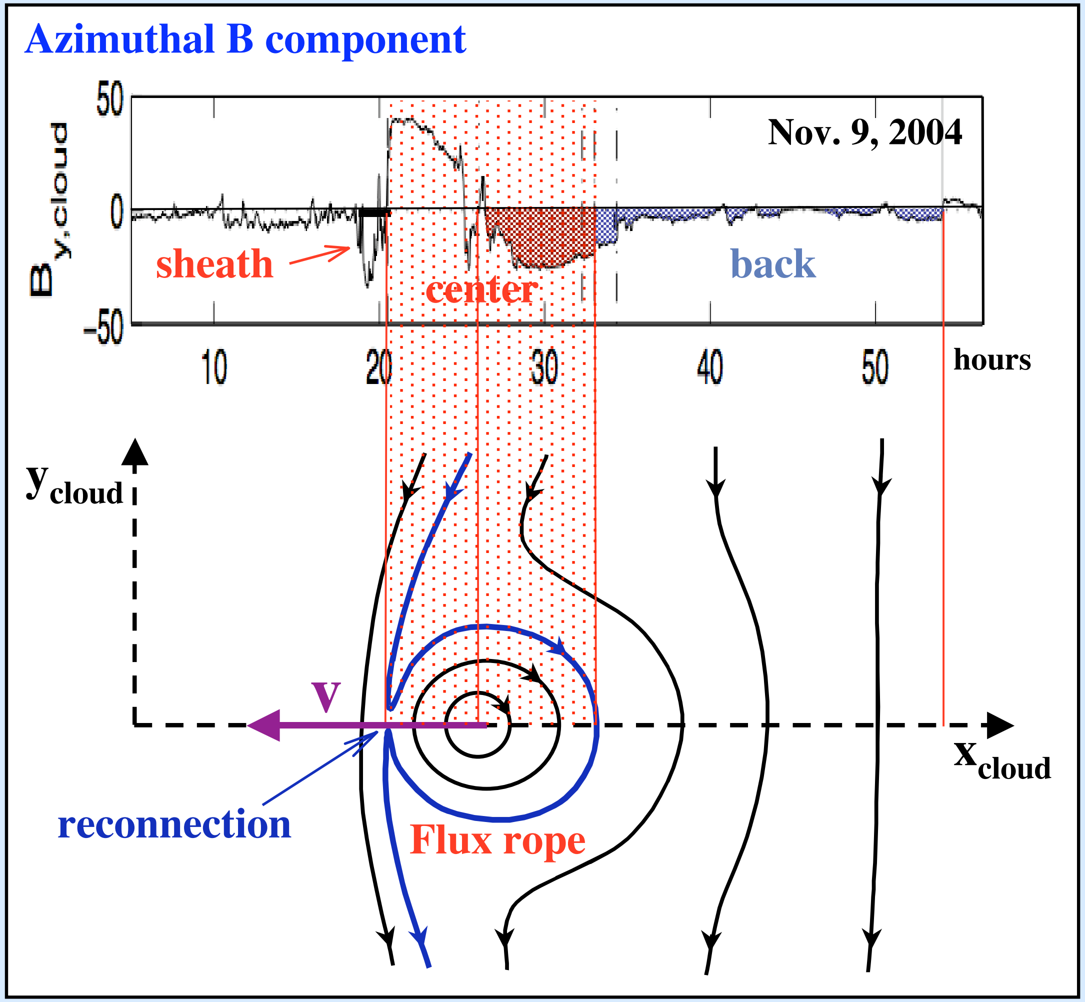
* **Fit data with a model** large variety !

- Force-free field (Burlaga et al. 1981, Lepping et al. 1990, Farrugia et al. 1999, …)
- Magneto-hydrostatic (Hu & Sonnerup 2001, Mulligan & Russell 2001, Hidalgo et al. 2002, …)
- Include self-similar expansion (Marubashi 1997, Vandas & Romashets 2003, …)

Uncertainty on the axis orientation ~ +/- 10^0



Loss of magnetic flux by reconnection



The amount of reconnected flux depends on the amount of overtaken flux during the MC transit from the Sun

Percentage of azimuthal flux lost :

Oct. 18, 1995 : ~ 60 %
Oct. 28, 2003 : small
Nov. 9, 2004 : ~ 25 %

Highly variable with the MC considered !

(Dasso et al. 2006, 2007)

One origin of MC asymmetry
(others: aging, front compression, overtaken by SW, intrinsic)

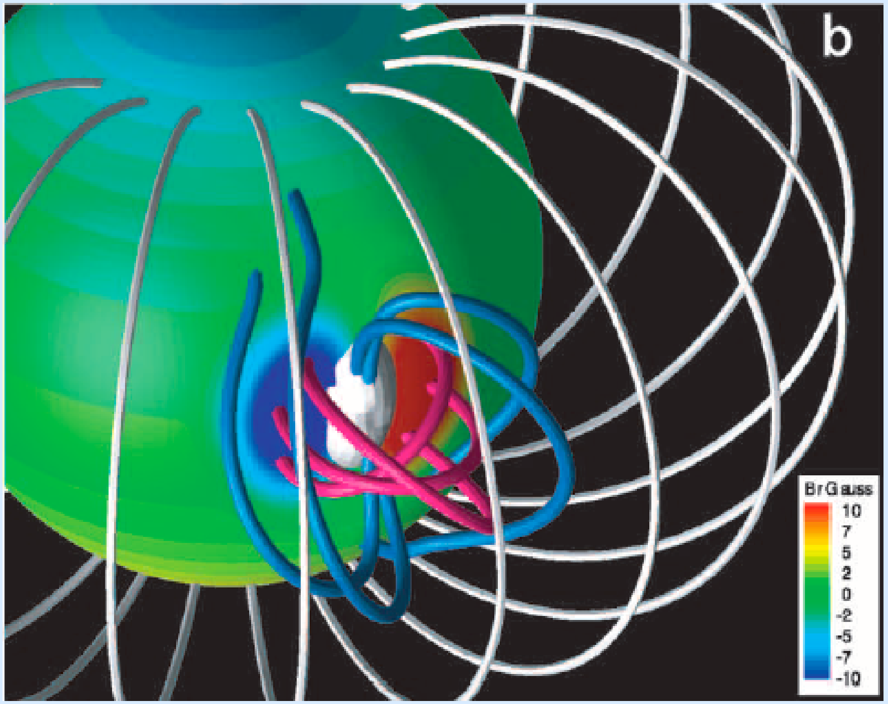
interaction 4

Deformation of the flux rope

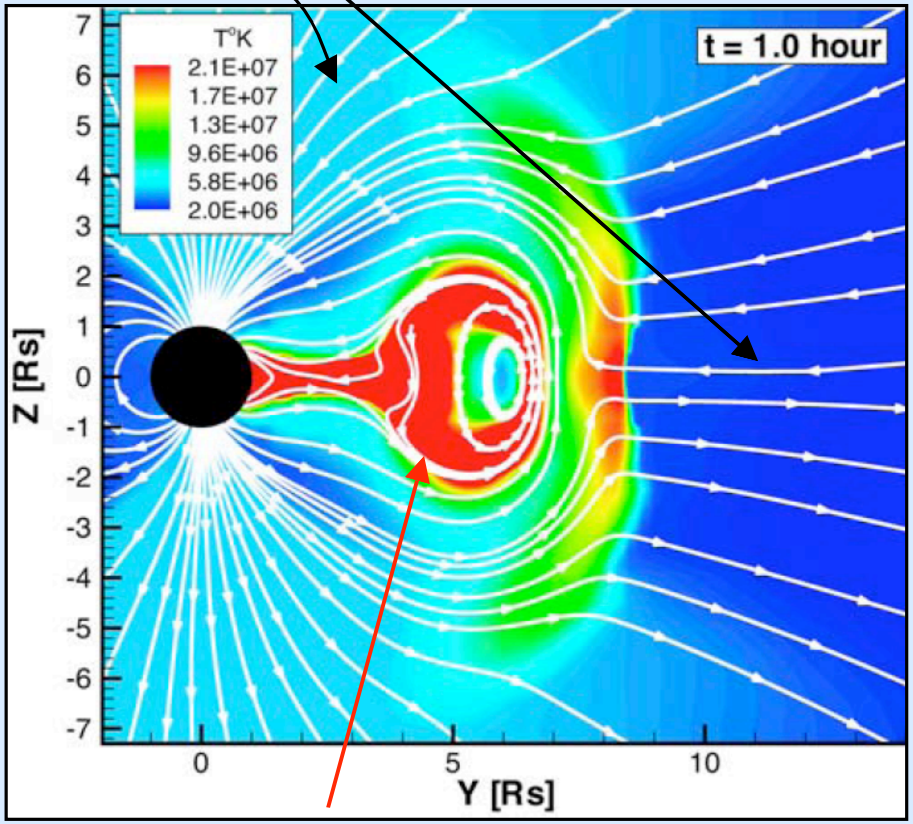
MHD simulations + observational clues

<u>3D MHD simulations</u> (I)

* Steady SW (fast/slow at high/low latitude)
* Global bipolar field
+ **+ add** Gibson & Low (1998) configuration
  no equilibrium **=>** ejection



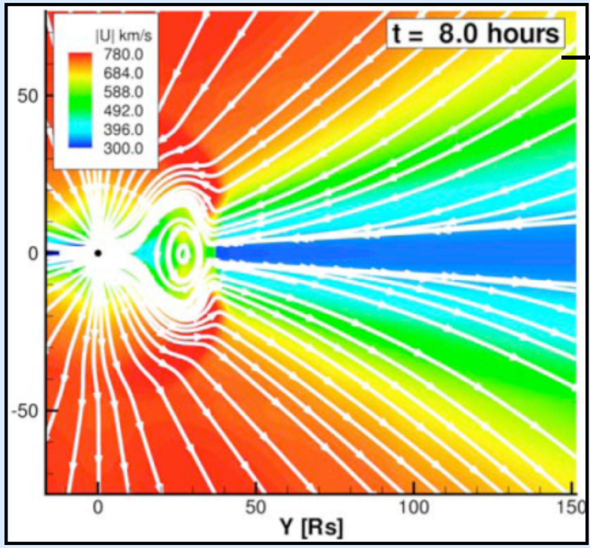
fast SW because $T_p + T_e \sim 5 \times 10^6$ K
slow SW " " $\sim 2 \times 10^6$ K



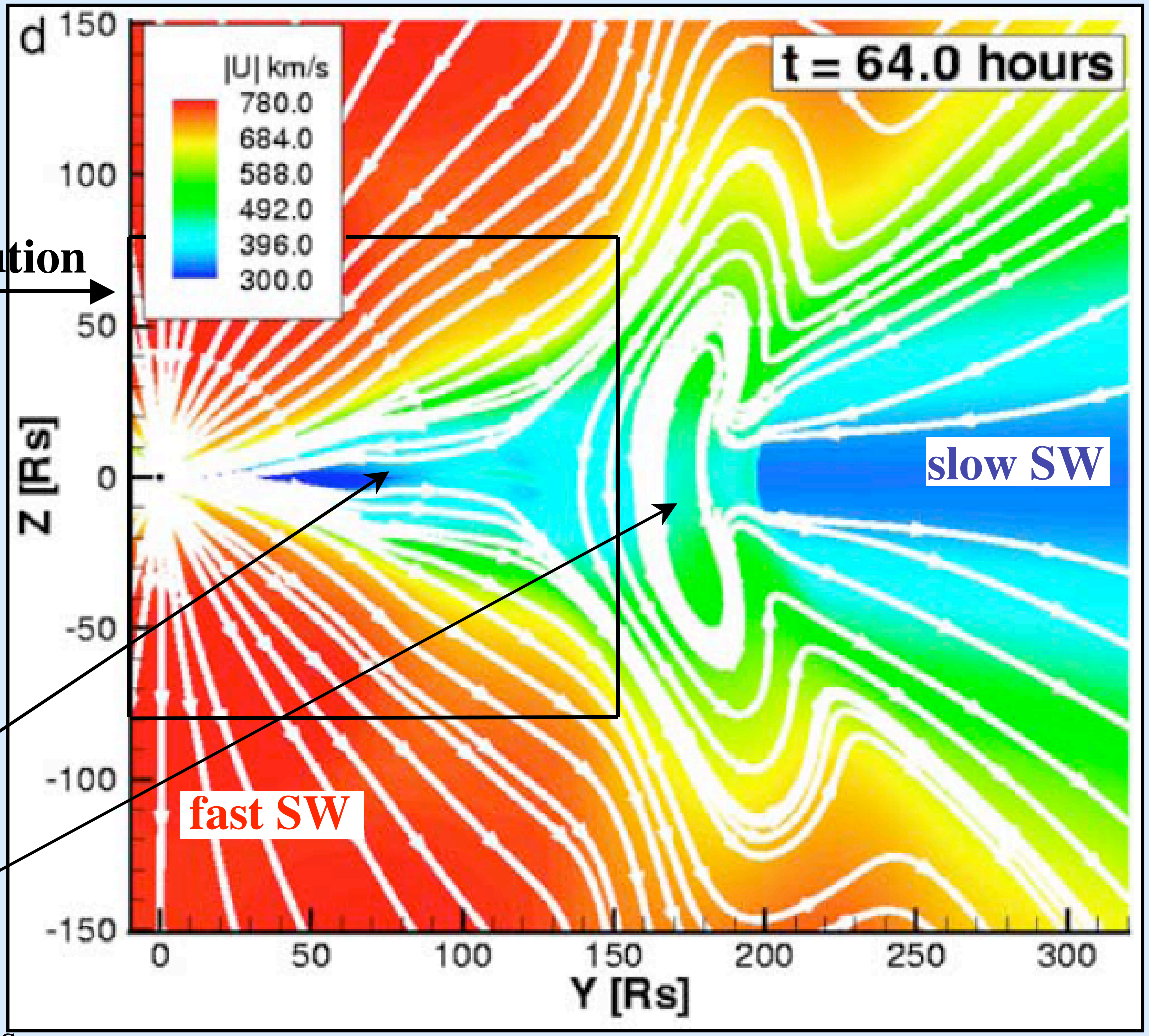
$T_p + T_e \sim 2 \times 10^7$ K !

(Manchester et al. 2004, Lugaz et al. 2005)

3D MHD simulations (II)



evolution



magnetic reconnection

important deformation of the flux rope

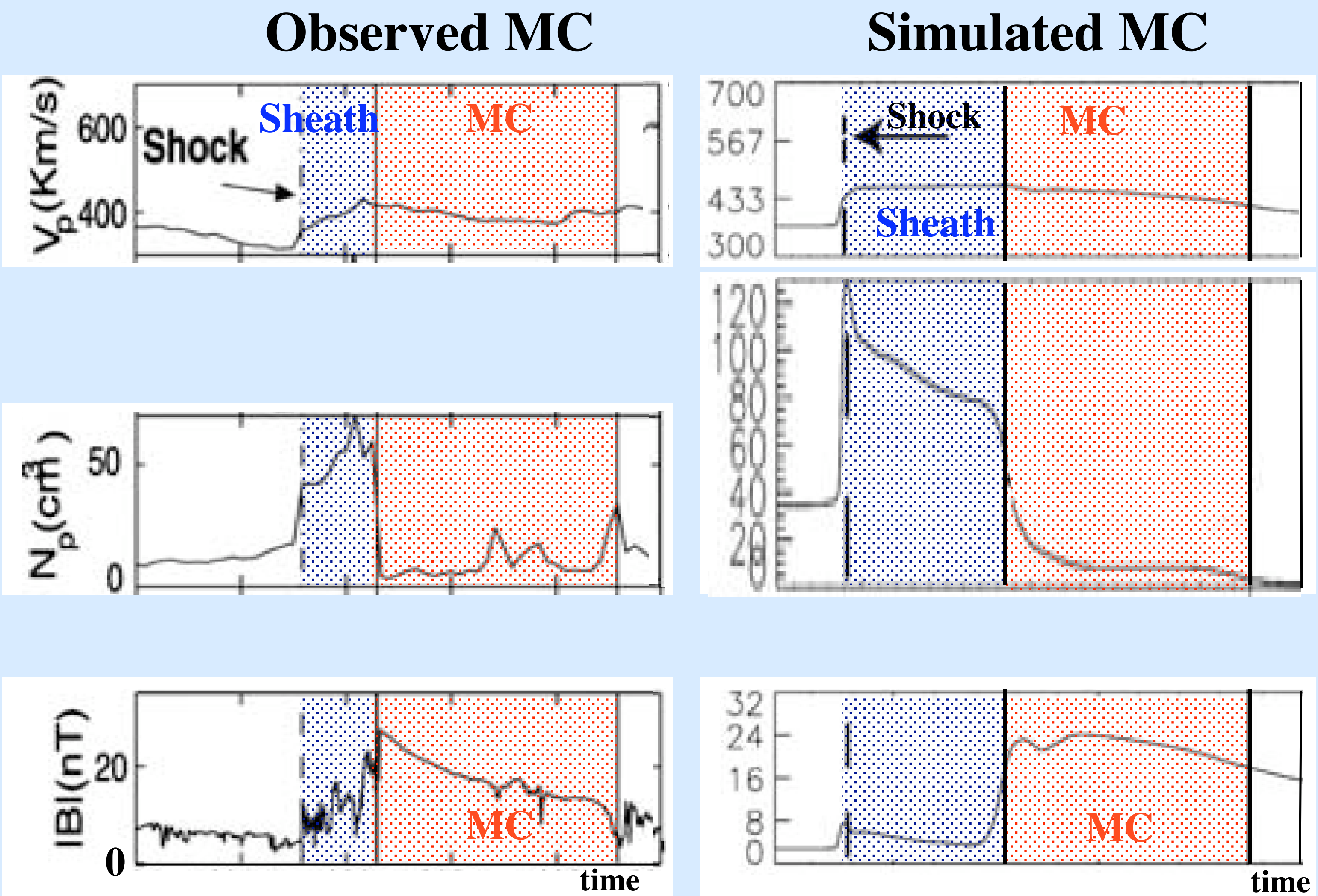
more than in previous simulations (e.g. Riley et al. 2002)

Strong effect of the slow / fast wind

(Manchester et al. 2004b)

Comparison: simulations / observations

Comparison at 1 AU with similar <V>, size & B_{max}



(Manchester et al. 2004b)

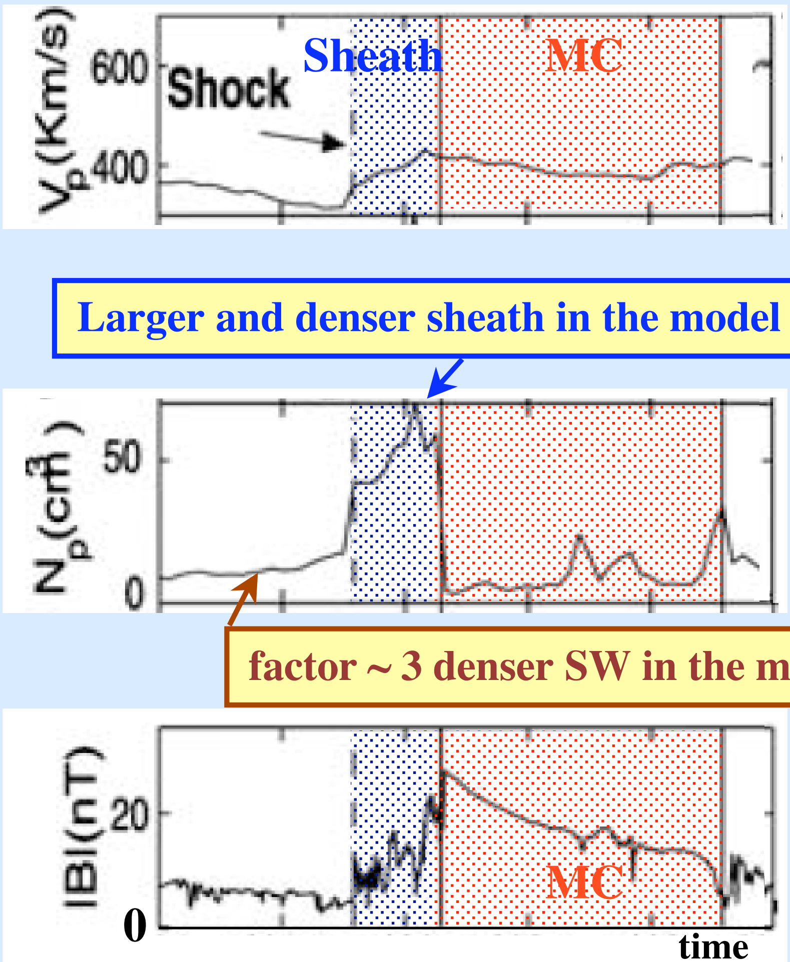
Comparison: simulations / observations

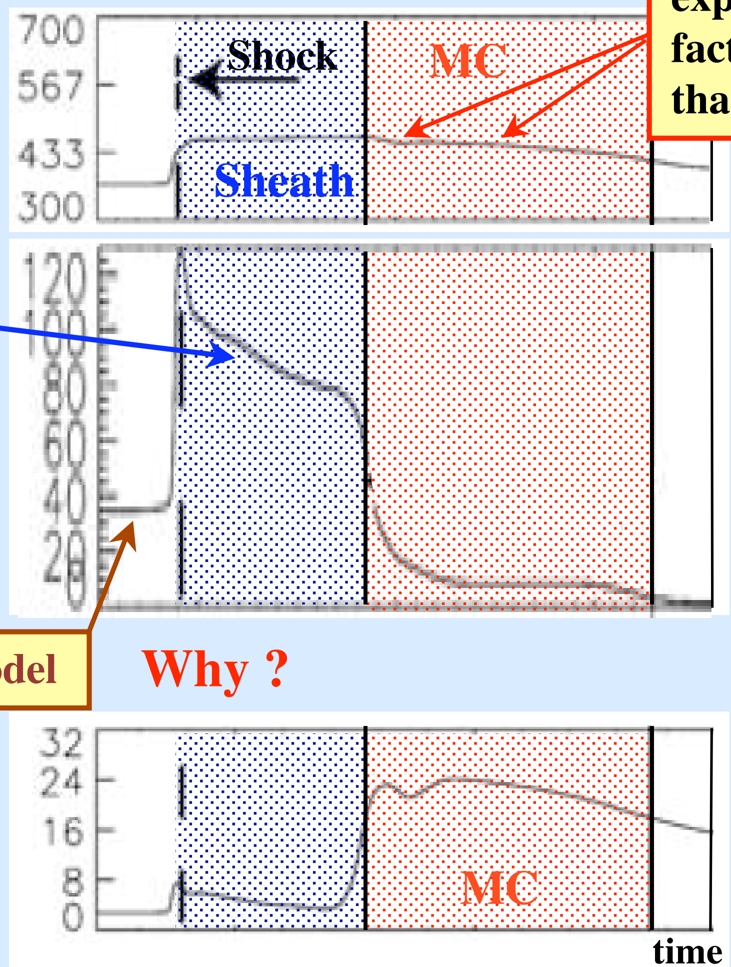
Comparison at 1 AU with similar <V>, size & B_{max}

Observed MC

Simulated MC

expansion rate: factor 2 to 3 lower than observed





Larger and denser sheath in the model

factor ~ 3 denser SW in the model

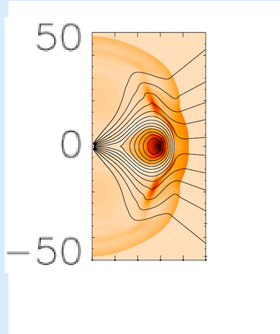
Why ?

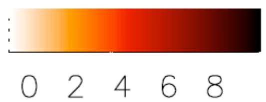
(Manchester et al. 2004b)

axisymetric MHD simulations (2.5 D)

* Same SW model as Manchester et al. (2004)
* Add a flux rope in the corona with v=1000 km/s
  (5 times denser, $R_{rope} \sim 0.3\ R_{sun}$)

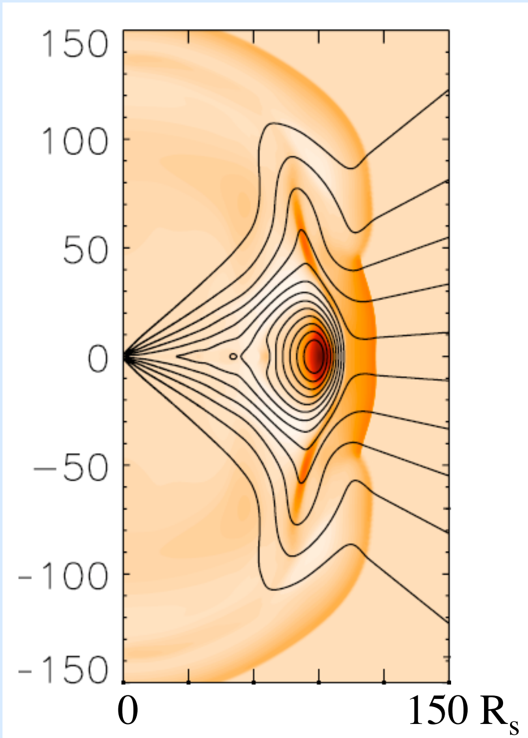
t=10 h



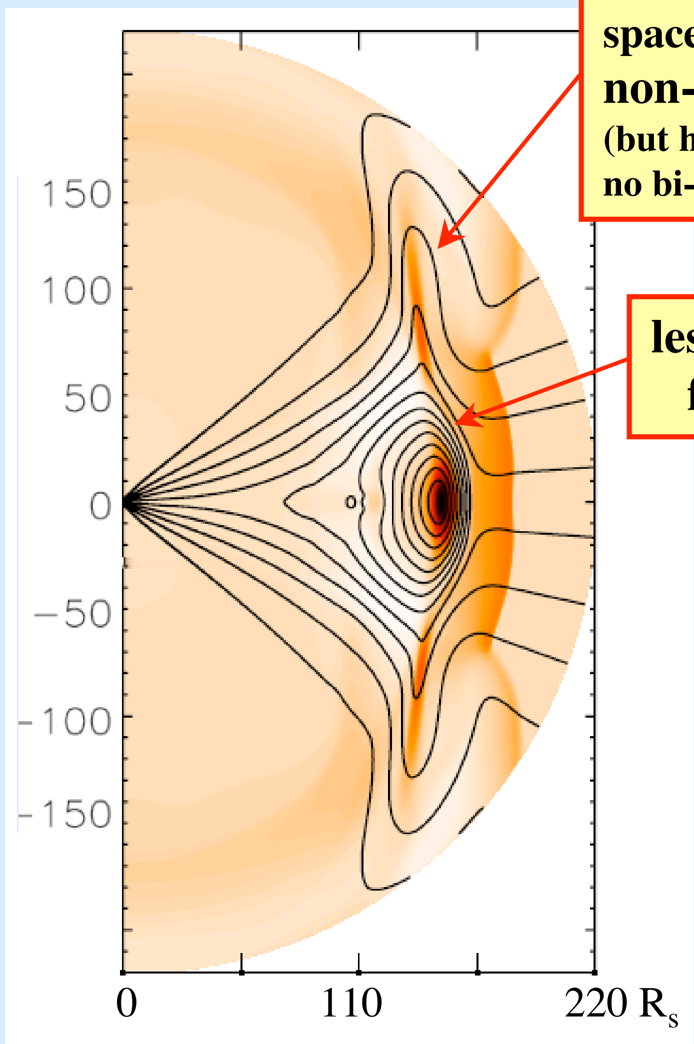


relative density :
$(n-n_{SW})/\ n_{SW}$

t=32 h



t=55 h



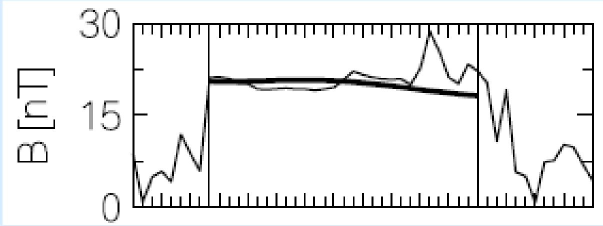
if crossed by a spacecraft :
non-MC ICME
(but hotter, no bi-streaming e⁻…)

less distorted flux rope

(Chané et al. 2006)

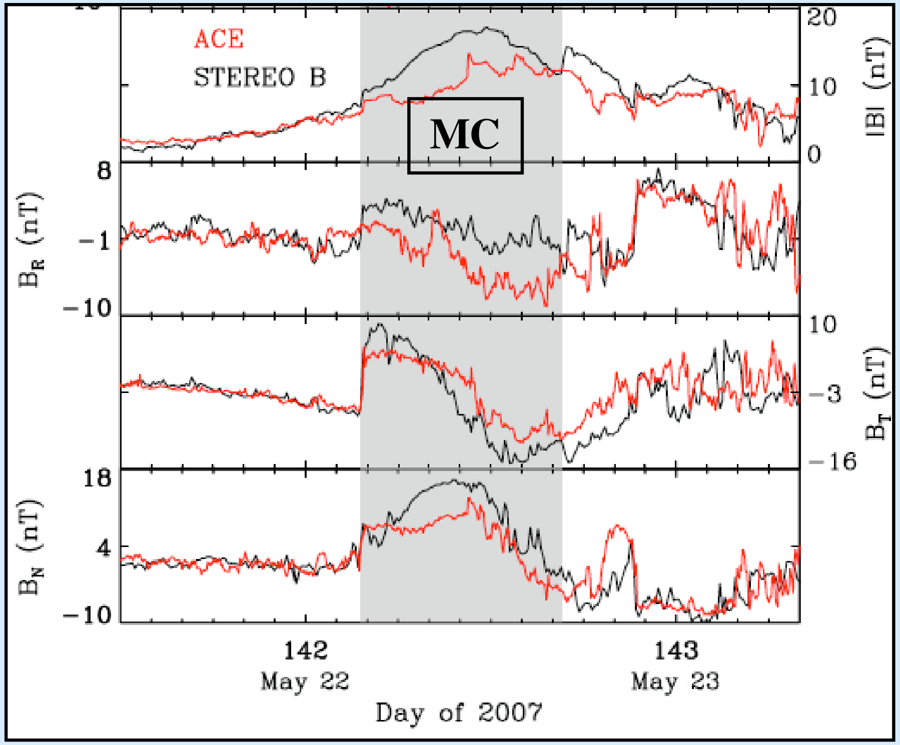
Cross-section shape of MCs

Some MCs are flat : e.g. 18 Oct. 1995
aspect ratio ~ 6
fitting an elliptic flux rope to B observed

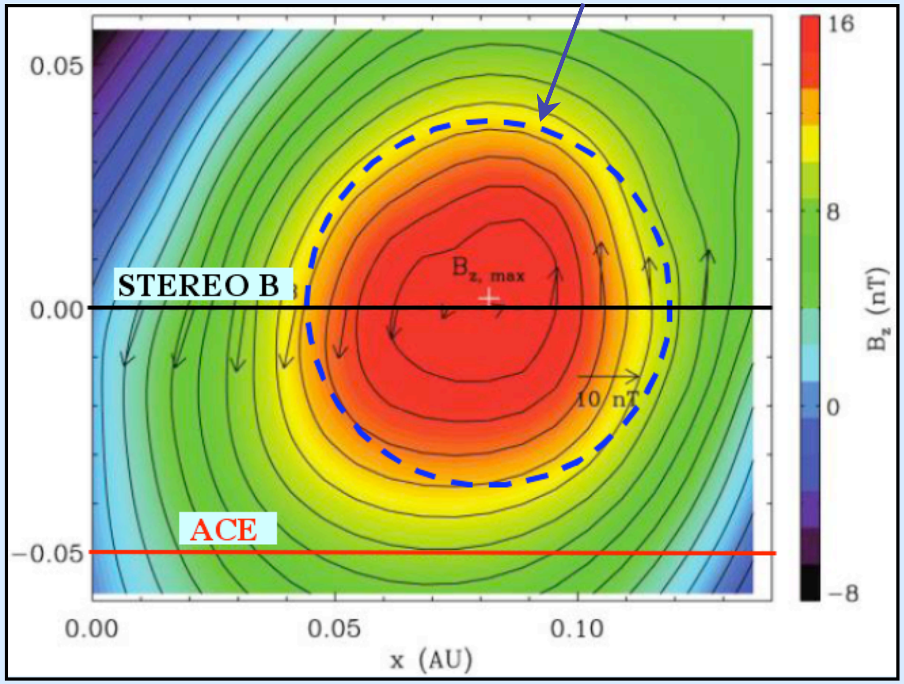


(Vandas et al. 2005)

But this is NOT a generic property !

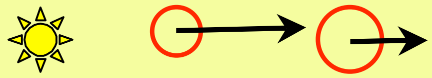


Cross-section: ~ circular
(due to magnetic tension)



reconstruction of the magnetic field from 1D data
(magnetic + plasma pressure balance) **(Liu et al. 2008, Mostl et al. 2009)**

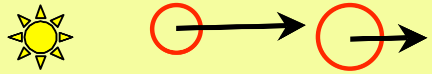
interaction 5



Overtaking of an ICME by another ICME / fast SW stream

beware of corsairs (pirates) !

interaction 5



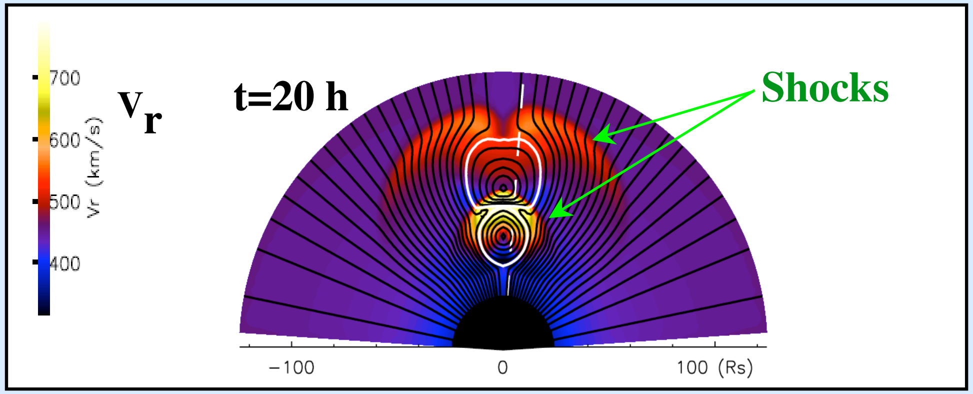
Overtaking of an ICME by another ICME / fast SW stream

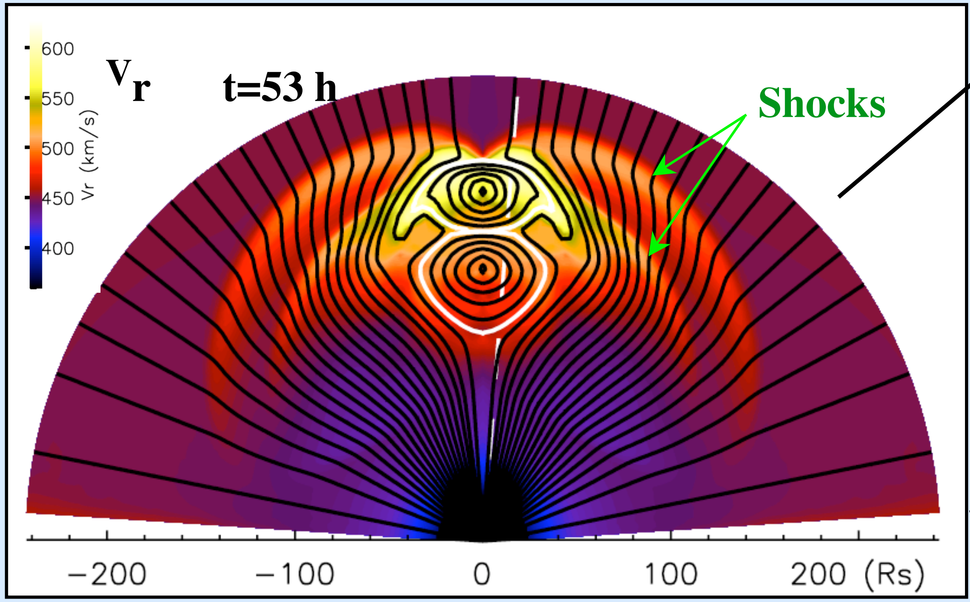
beware of corsairs (pirates) !

Many processes going on during the interaction…
e.g. compression & reconnection

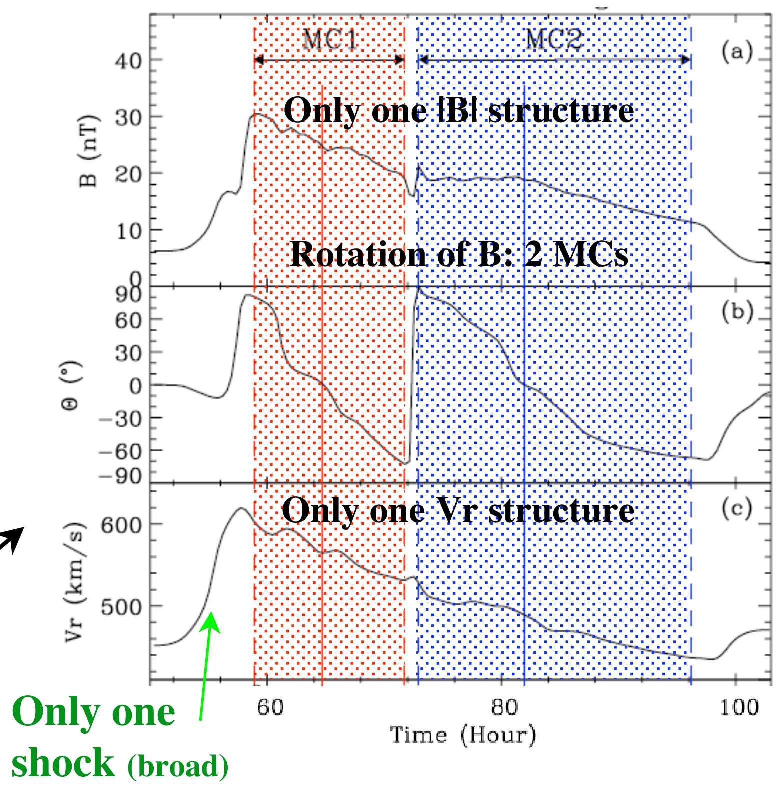
MC overtaken by another MC (simulations)

2.5 D ideal MHD simulation





Results at r = 200 Rs



Interaction => flux rope deformation

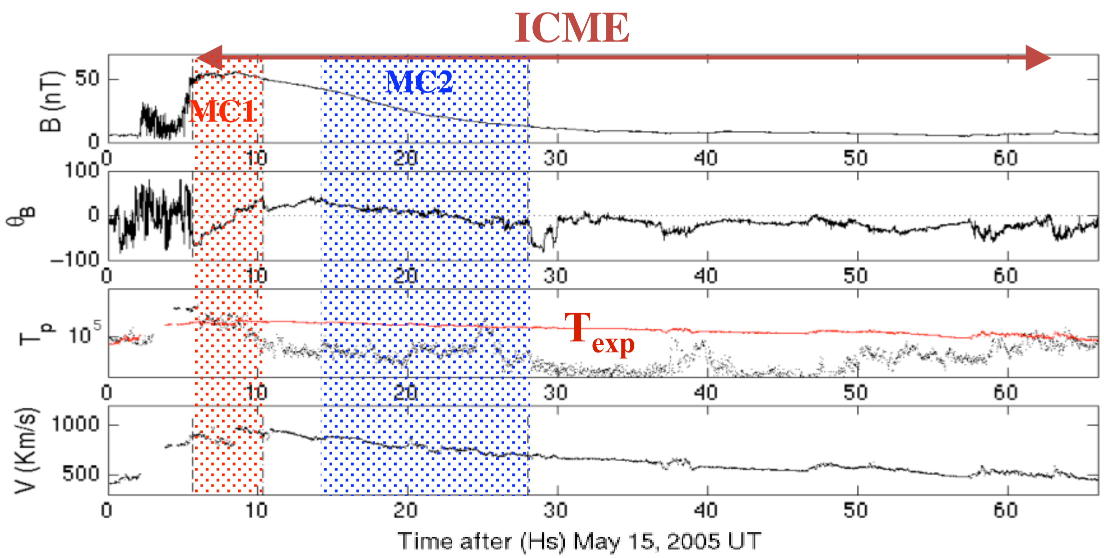
but less than in previous simulations with 1 MC !

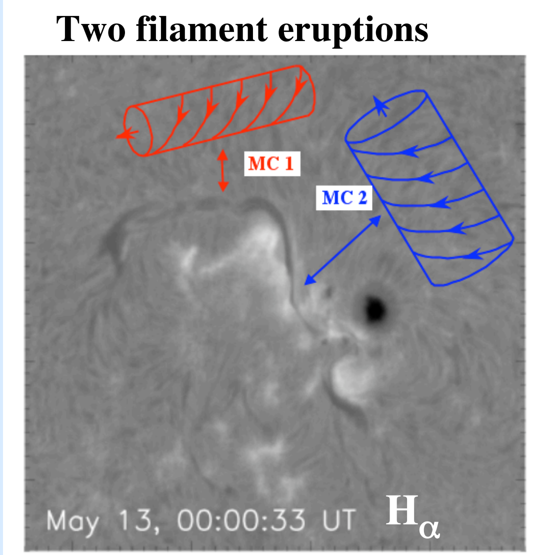
because: - density closer to observed values $N_{(1\ AU)} = 8\ cm^{-3}$

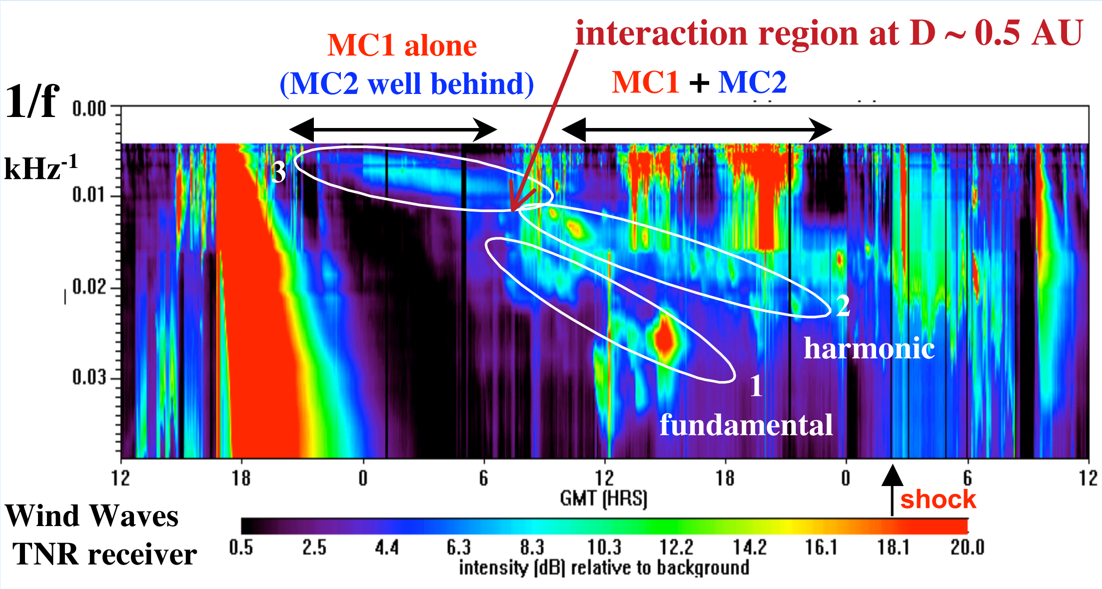
- only slow SW

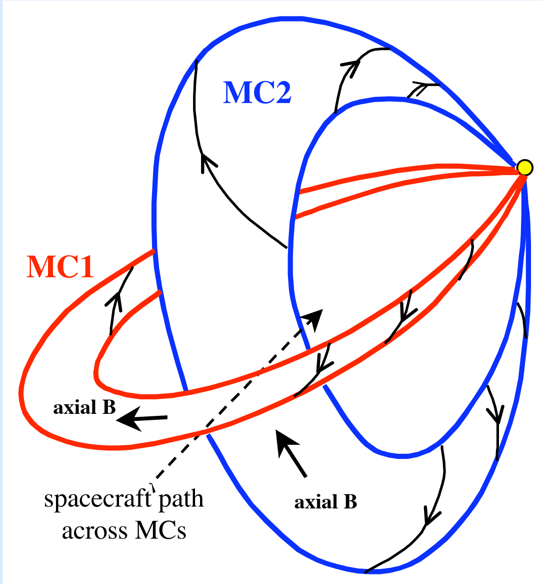
(Xiong et al. 2007)

MC overtaken by another MC (observations)



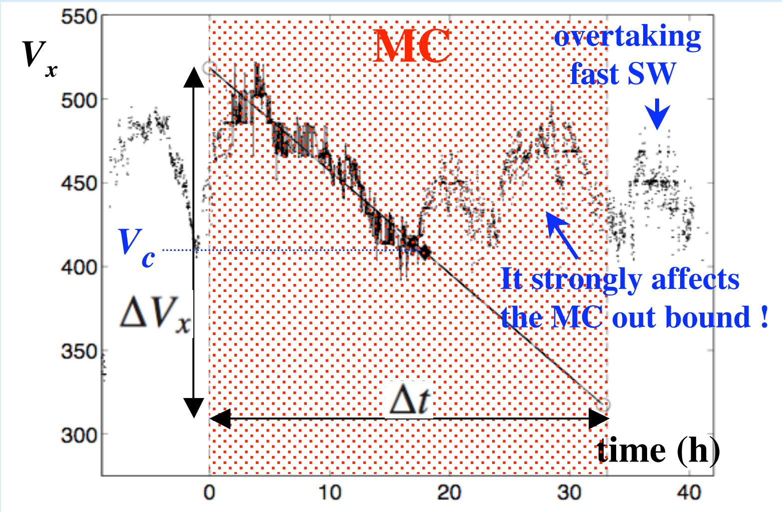


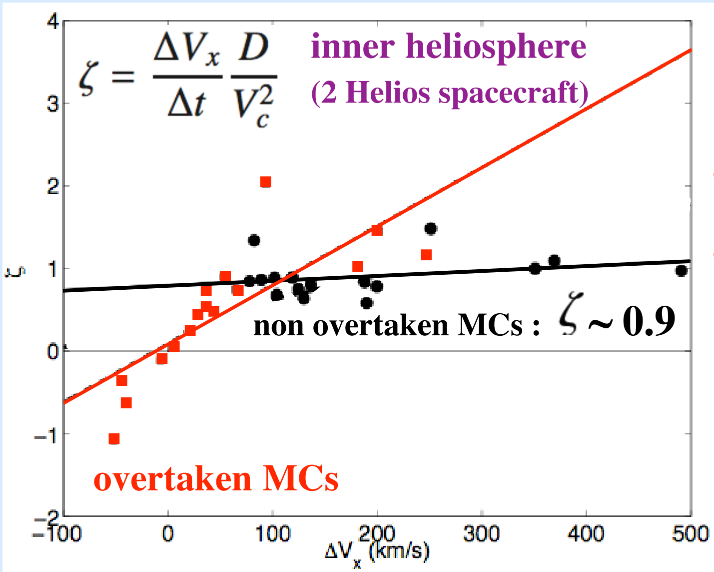




(Dasso et al. 2009)

MC overtaken by a fast SW stream (observations)

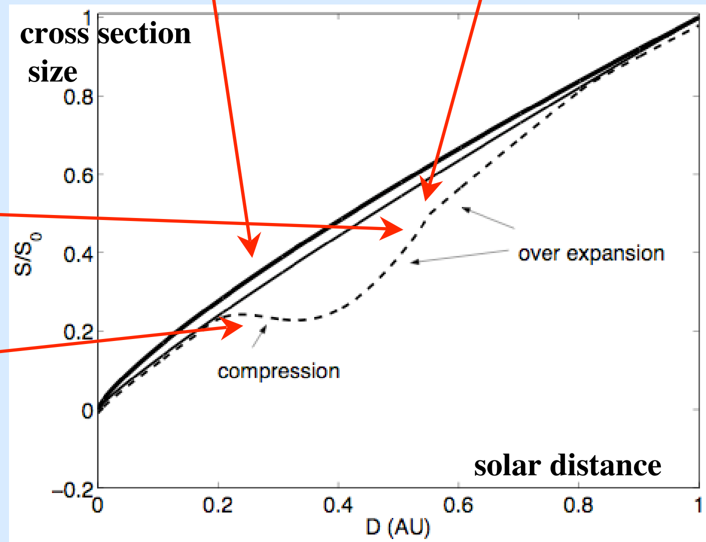




Interpretation :

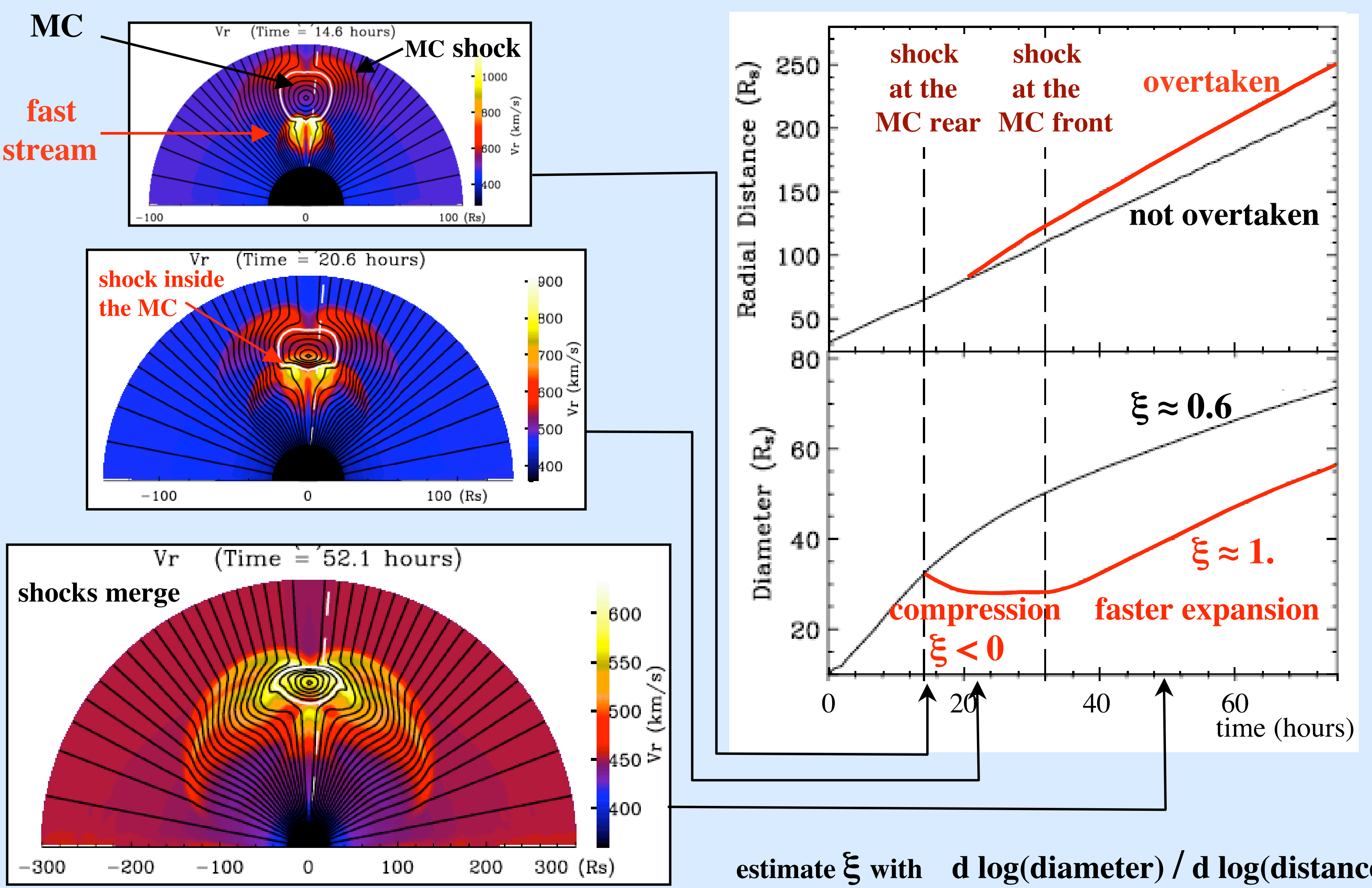
temporal evolution of the interaction

beginning	later on
compression	**over expansion**
	(because over pressure / SW)



(Gulisano et al. 2009)

MC overtaken by a fast SW stream (simulations)



estimate ξ with d log(diameter) / d log(distance)

(Xiong et al. 2006)

Conclusion

The interaction with the SW affects the main ICME / MC properties

- **mass & bulk velocity** (interaction 1)
- **expansion rate** (interaction 2)
- **magnetic flux** (interaction 3)
- **shape of the flux rope** (interaction 4)

all quantities are affected in interaction 5 (overtaken cases)

The boats are shaped / eroded during the trip

and also:

- **magnetic helicity**
- **anchorage to the Sun** (interchange reconnection)

Happy the man who, like Ulysses, has made a fine voyage...

Joachim du Bellay (1522-1560)

It was a trip full of interactions...