Investigating mean geometries of interplanetary structures from the statistical analysis of in situ data

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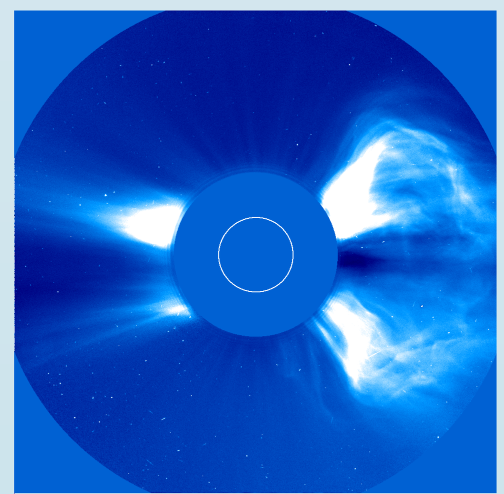
1/ Why a statistical analysis of interplanetary structures?

•Why magnetic clouds and shocks?
Magnetic clouds, and their accompanying shocks, have an **important effect** on interplanetary environments, such as geomagnetic storms and acceleration of particles.

•What do we want to know?
Their 3D structure to better understand/predict their role in space weather. For example, knowing the magnetic field inside magnetic clouds allows:

✧ To understand the role of the field line length in the time delay of energetic particles detection [1,2]
✧ To link it with the 3D configuration of the associated solar source [3]
✧ To determine the magnetic helicity, energy, flux budget [4], [5]



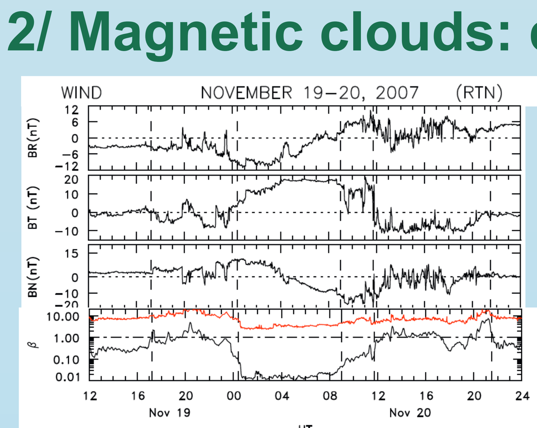
A coronal mass ejection, as seen from SOHO/LASCO

•Why isn't it straightforward?
Because spacecraft only measure the properties of interplanetary structures **LOCALLY**, and because the occurrence of multi-spacecraft crossing at different positions is **RARE**.

•What do we propose to do?
A statistical analysis of samples of events detected by spacecraft at 1AU (Wind, ACE).
Since these events are randomly crossed at different along their structures, one can study the probability distribution of location parameters to deduce their mean shape.

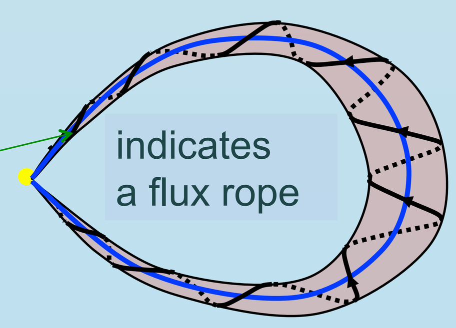
References
[1] Larson et al. 1997, [2] Masson et al. 2012, [3] Nackwacki et al. 2011, [4] Démoulin et al. 2002, [5] Dasso et al. 2005

2/ Magnetic clouds: definition and location parameter

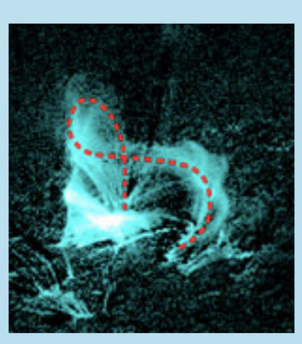


In situ data showing the rotation of the magnetic field inside the MC (Farrugia et al. [2011]).

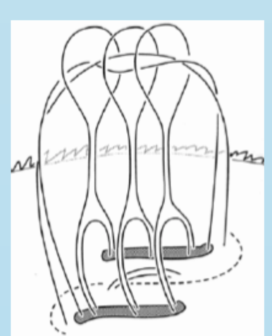
Magnetic clouds criteria: [Burlaga et al. 1981]
✧ Stronger magnetic field than SW
✧ Low proton plasma beta
✧ Smooth and large rotation of MF
✧ Proton temperature lower than SW



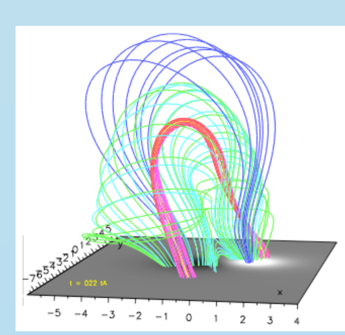
Flux rope structure is similar to: observations, models (theoretical, numerical)



[Moore et al. 1995]



[Zhang et al. 2012]



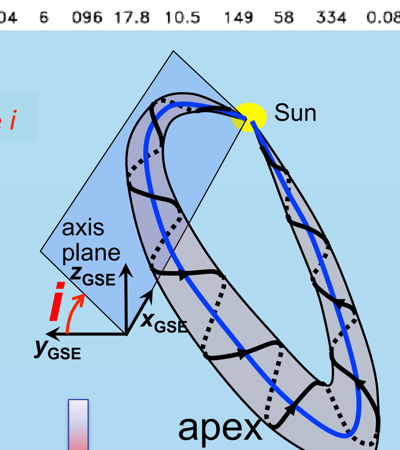
[Aulanier et al. 2012]

Can we define a parameter for the shape of the flux rope axis?

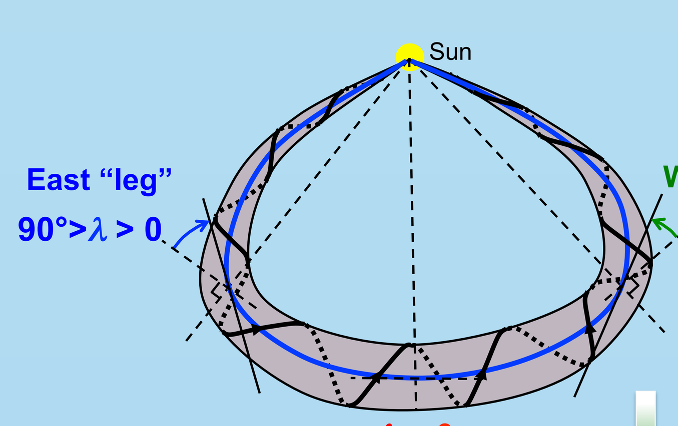
Start					End									
Yr	Mon	Day	DOY	Hr	Mon	Day	DOY	Hr	ΔT^a (Hr)	ϕ_A^b (°)	θ_A^b (°)	V^c km/s	$2Ro^d$ (AU)	B_o^e (nT)
95	02	8	039	5.8	02	9	040	0.8	19.0	100	18	410	0.216	15.2
95	03	4	063	10.8	03	5	064	3.8	17.0	205	−76	443	0.165	14.9
95	04	3	093	7.8	04	4	094	10.8	27.0	96	−22	301	0.303	13.3
95	04	6	096	7.3	04	6	096	17.8	10.5	149	58	334	0.083	14.8

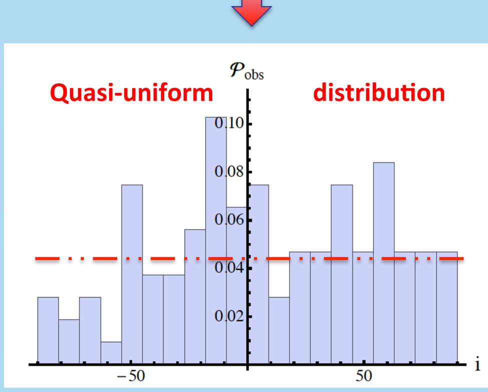
✧ From the data fit with the Lundquist model (force-free model): **local parameters** (speed, radius, …)
[Lundquist 1950, Lepping et al. 2006]

Inclination angle *i*

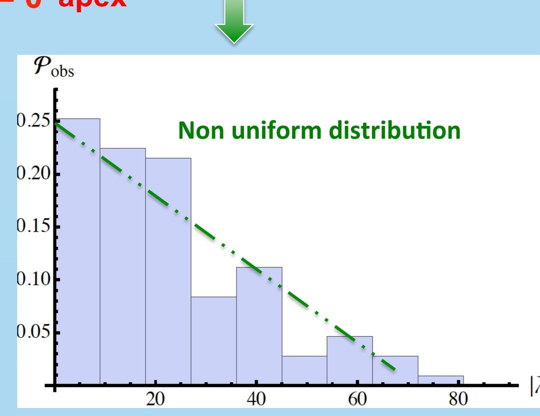


Location angle λ: location of the spacecraft along the flux rope axis



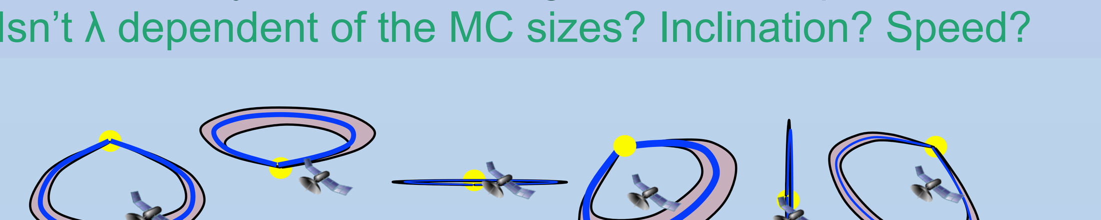


→ The MC detection is independent of the angle *i*
→ The distribution of λ is non uniform:
➢ **Deduce shape?**

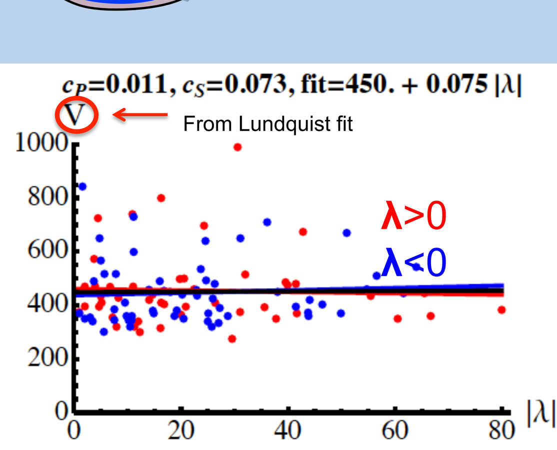


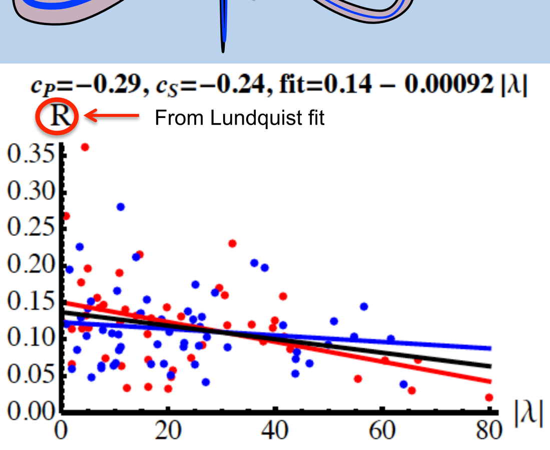
3/ Correlation study

Can we study the location angle over a sample of >100 events? (Wind data)
Isn't λ dependent of the MC sizes? Inclination? Speed?



We need to check the **correlation** between **λ and other MC parameters**

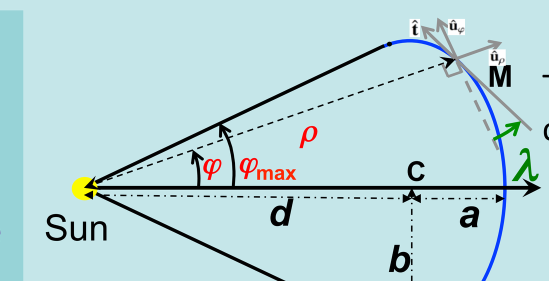




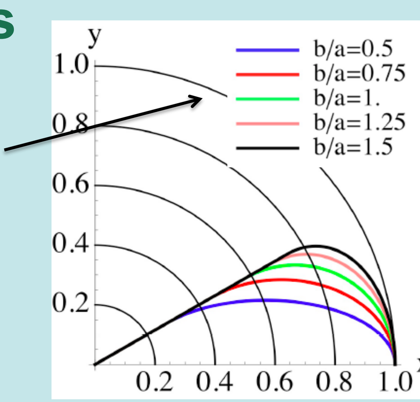
✧ **λ>0 and λ<0 give similar results: independent of the "legs"**
✧ **λ is weakly correlated with other MC parameters**
➽ We can therefore perform a statistical analysis
➽ It *seems* that there is a similar shape for all the MCs

4/ Method 1: Comparison with synthetic distributions

Model for a MC axis shape
1. Expressed in cylindrical coordinates (ellipse shape)
2. Give analytical probability distribution (in function of the ellipse **aspect ratio**)

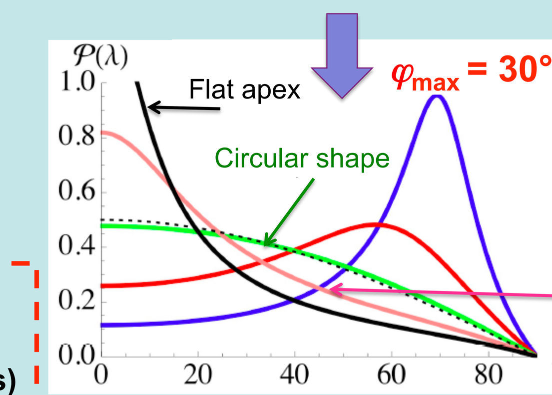


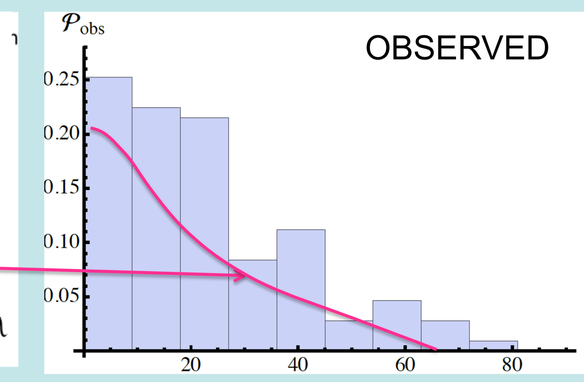
The aspect ratio can be changed



$$\mathcal{P}(\lambda) = \mathcal{P}_\varphi \, |d\varphi/d\lambda|$$
$$1/(2\,\varphi_{max})$$

Angles φ and λ are expressed in function of b/a



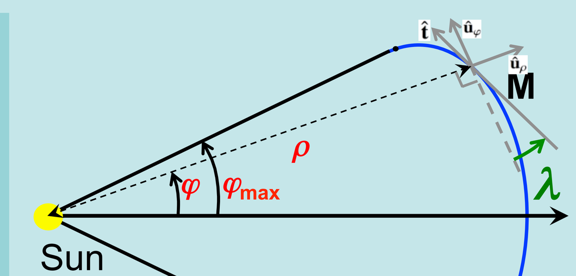


Satisfying aspect ratios:
1<b/a≤1.3
(➽only a small interval of possible shapes)
We have found the most probable MC shapes

Comparison between the synthetic probability distributions and the "real" distribution obtained from the Wind data

Method 2: Direct integration from observed distribution

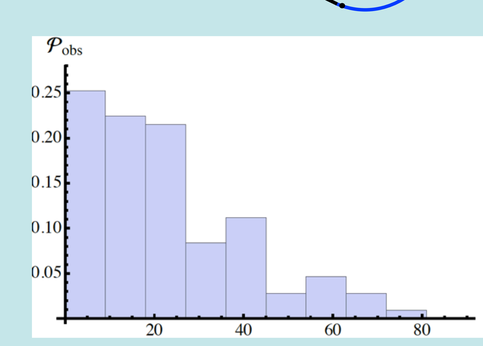
Model for a MC axis shape
1. Expressed in cylindrical coordinates (no shape given)
2. Use the integration of observed probability distribution function

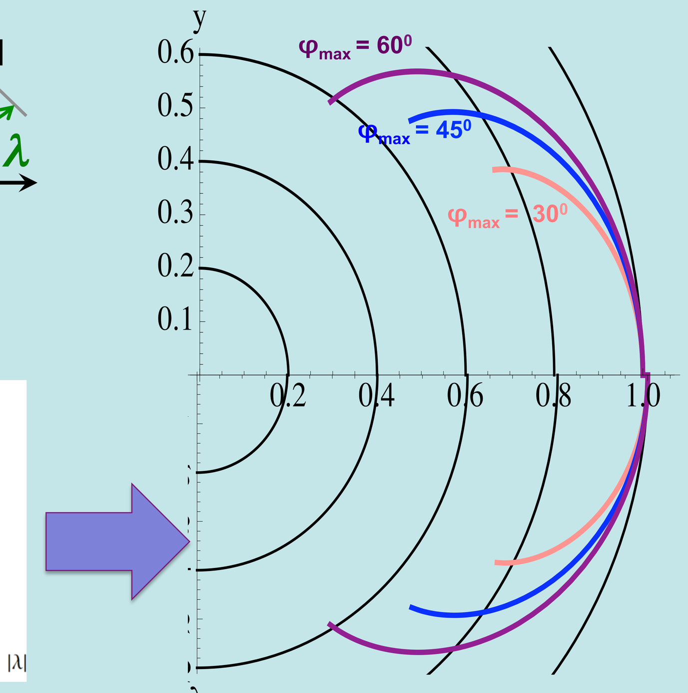


$$\varphi(\lambda) = \varphi_{max} \int_0^{\lambda} \mathcal{P}_{obs}(|\lambda'|)\,d\lambda'$$

Free parameter

ρ(φ) is expressed in similar ways



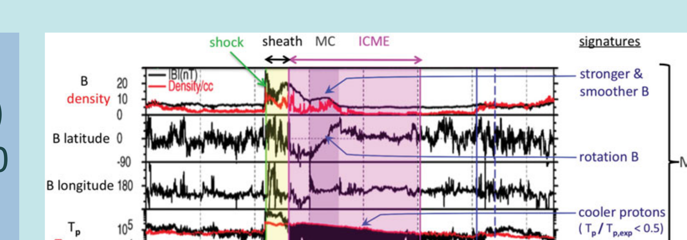


➔Integrating P_{obs} gives similar results as the 2nd method
➔**Consistent results**
(although φ_{max} remains a free parameter)

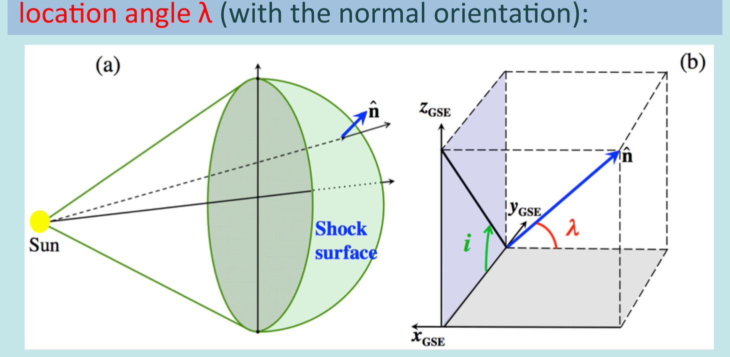
Integrating the observed distribution directly gives the possible shapes for the magnetic cloud axis

5/ Analysis of the shock shape

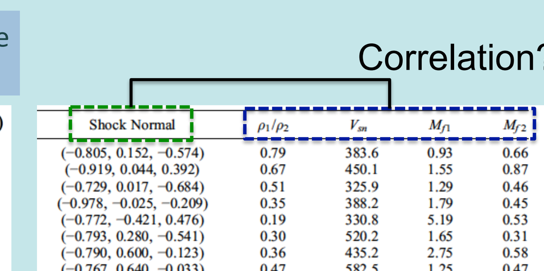
We can do a similar analysis for the shock
✧ Taken from a list of 257 shocks detected by ACE (Wang et al. 2010)
✧ ≈half are associated with ICMEs (association with a list of >300 ICMEs, Richardson & Cane 2010)
✧ Shocks are a **surface** (2D, ≠ MC axis)



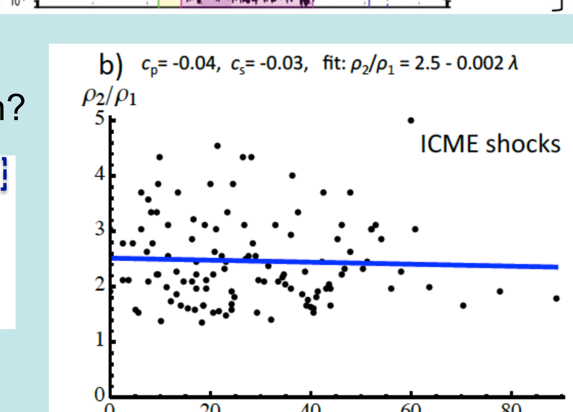
New definitions for the inclination angle *i* and the location angle λ (with the normal orientation):



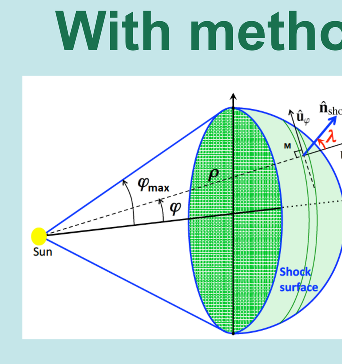
Correlation?



No correlation!
➾ all shocks seem to have a similar shape



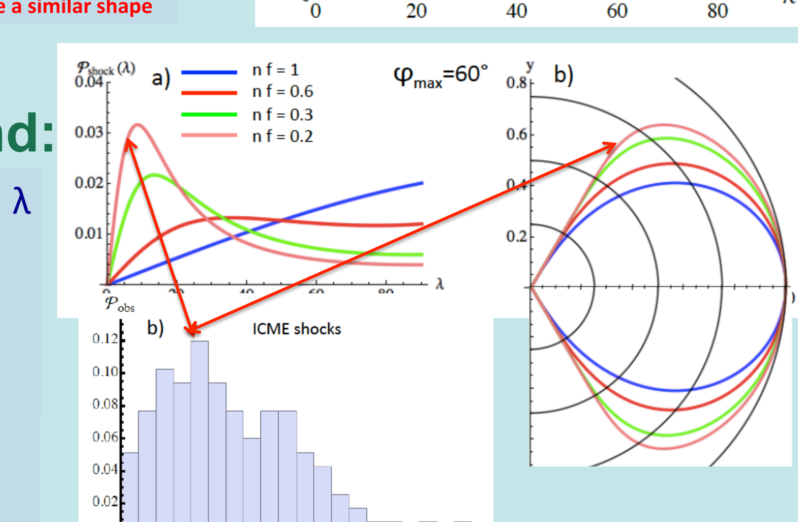
With method 1 and method 2, we found:



➾Method 1: given a shape, the λ distribution can be expressed as (see Janvier et al. 2014 for details):

$$\mathcal{P}(\lambda) = \frac{\sin\varphi}{1-\cos\varphi_{max}} \frac{n\,(1+\tan^2\lambda)}{(nf)^2+\tan^2\lambda}$$

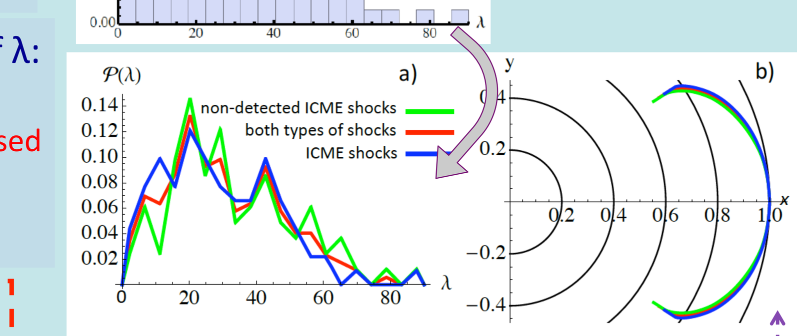
We found the most probable shapes (nf between 0.17 et 0.45)



➾Method 2:Direct integration of the probability distribution of λ:

$$\varphi(\lambda) = \arccos\left(1-(1-\cos\varphi_{max})\int_0^{\lambda}\mathcal{P}_{obs}(\lambda)\,d\lambda\right)$$
$$\ln\rho(\lambda) = -(1-\cos\varphi_{max})\int_0^{\lambda}\frac{\tan(\lambda')}{\sin(\varphi(\lambda'))}\mathcal{P}_{obs}(\lambda')\,d\lambda' + \ln\rho_{max}.$$

✪ φ and ρ expressed with λ and P(λ)

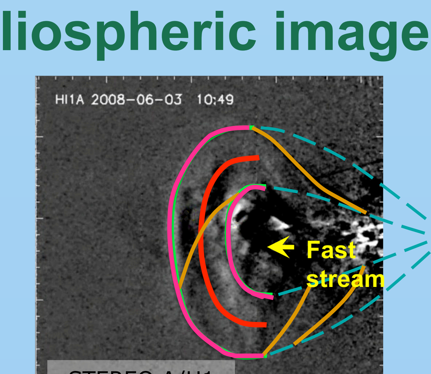


➔Integrating P_{obs} gives similar results as the 2nd method
➔**Consistent results** (although φ_{max} remains a free parameter)

Possible shapes for shocks from direct integration

6/ Comparison with heliospheric imagers

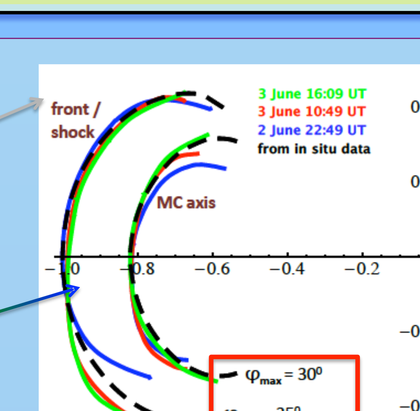
1. Report the shapes from heliospheric imagers
2. Direct comparison with previously found shapes



[Möstl et al. 2009]

Method 2

Imagers



With heliospheric imagers: similar results as obtained with the analytical methods (1 & 2) + allow to constraint the axis elongation
➔Elongation angle: φ_{max}=30° for the magnetic cloud, and φ_{max}=35° for the shock [Janvier et al. 2013b,2014]

6/ Conclusion

We investigate the mean shapes of magnetic cloud axis and shocks deduced from statistical analysis of in situ data

The data we used:
➾ Lepping & Wu (Wind, 14 years)
➾ Richardson & Cane (Ace & Wind, 13 years)
➾ Wang et al. (ACE, 10 years)

Statistical correlations:
➾ **no correlation for λ**
(both for shocks and MC axis)
➾ **there is a mean shape similar to all MCs axis, and shocks**

We proposed 2 statistical methods:
1) Compare the observed distributions with synthetic distributions from models
➔find the shapes that are most suited to explain the observed distributions
2) Directly integrate the observed distributions to express shape parameters
➔ Compare shapes with previous method

➾ **They both give similar results**
➾ **We can compare them with heliospheric imagers**
➾ **We deduced the most probable shapes of magnetic cloud axis and shocks**