

Flux and Helicity of Magnetic Clouds from a model-independent method. A Statistical Study

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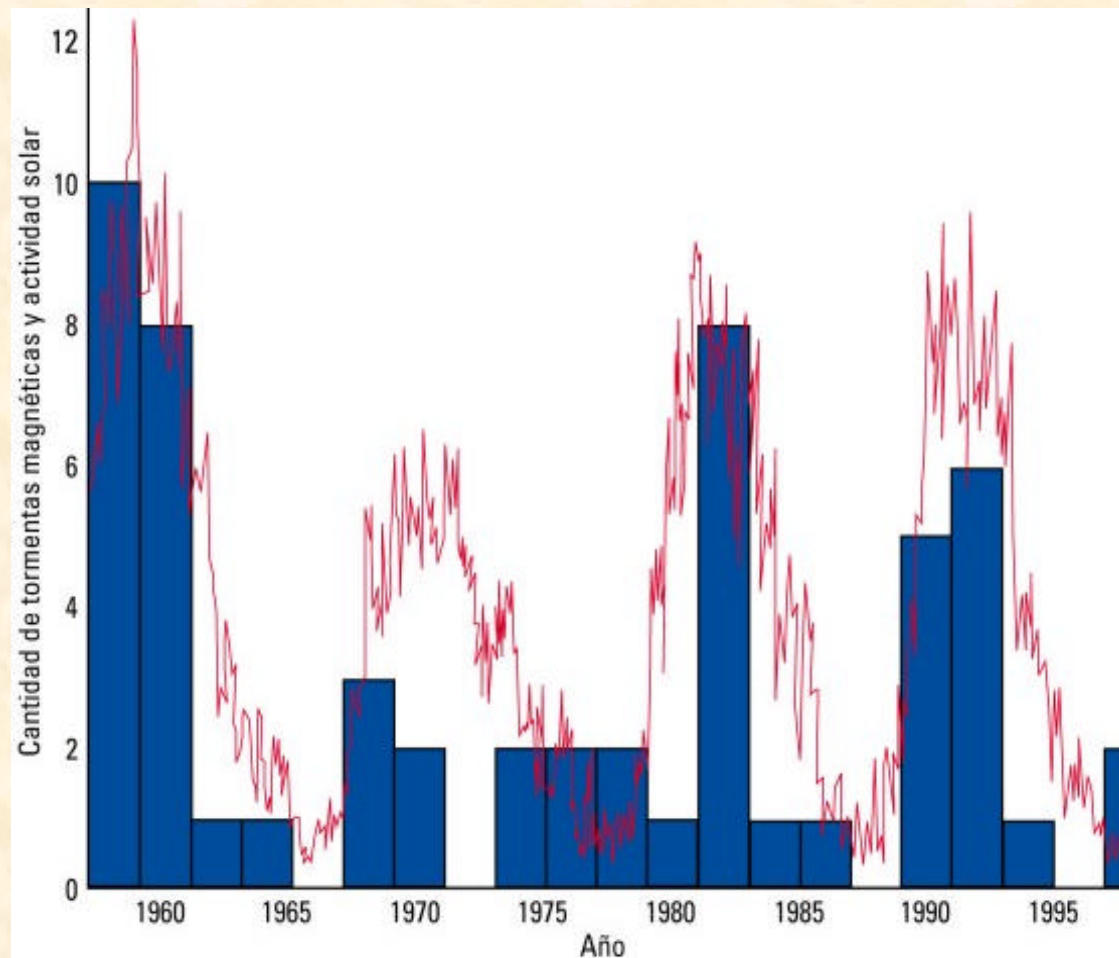
CAWSES Meeting, Sep 12, 2004, Beijing, China

Outline

- Brief Introduction to ICMEs/MCs and their major role in the Sun-Earth Coupling
- Importance of Magnetic Helicity
- Estimation of H for MCs from *in situ* observations
- Results of Studied Events and Comparison of H in MCs with estimations of release of H from their coronal source
- Conclusions

- E. Sabine shown [1851] a direct relationship between geomagnetic fluctuations and the solar cycle
- In particular, Carrington [sept 1859] observed a white solar brightness (a solar flare), and 18 hs later one of the most strong magnetic storms happened at Earth.

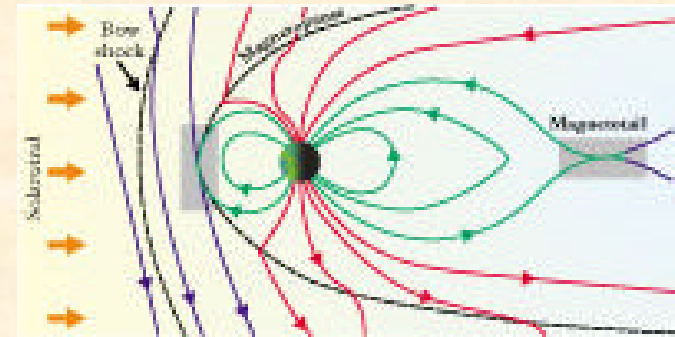
Interplanetary Magnetic Clouds as the most powerful drivers of space weather, playing a unique role in Sun-Earth coupling



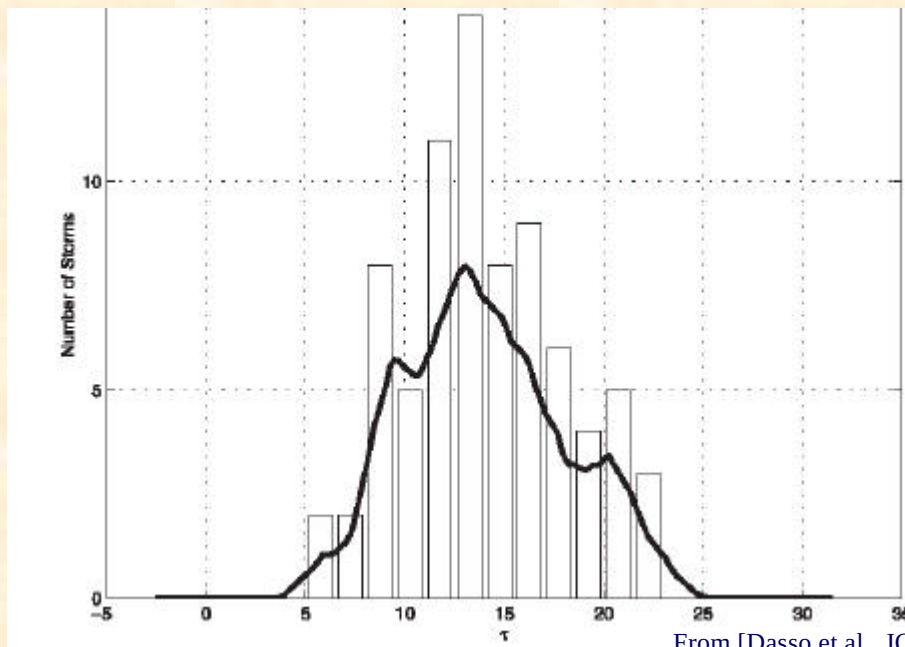
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When an MC has $B_z < 0$ (Magnetic Reconnection): Opening of Magnetosphere [Dungey, 1961]

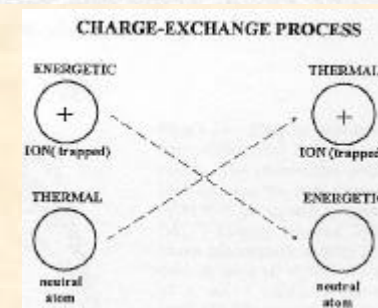
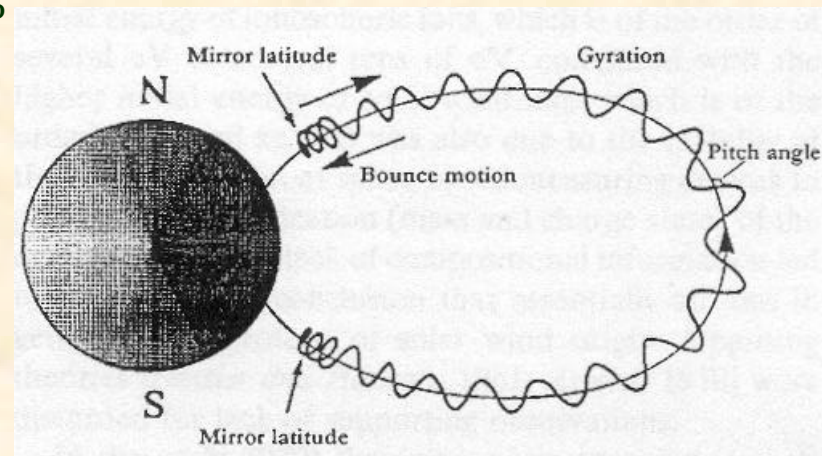
- MCs as a trigger of Most Intense Geomagnetic Storms
 $dDst/dt + Dst/t = V(t)Bs(t)$ [Gonzalez et al., 1989]
- The Hall effect can modify classical driven reconnection rates during the injection of particles into the magnetosphere [Morales et al., JGR submitted 2004]
- The MCs properties determine the level of the storm.
Could their properties determine also t ? How?



Statistical Study (1957-1998)



From [Dasso et al., JGR 2002]



Signatures of Interplanetary Coronal Mass Ejections (ICMEs) observed *in situ* at $\sim 1\text{AU}$

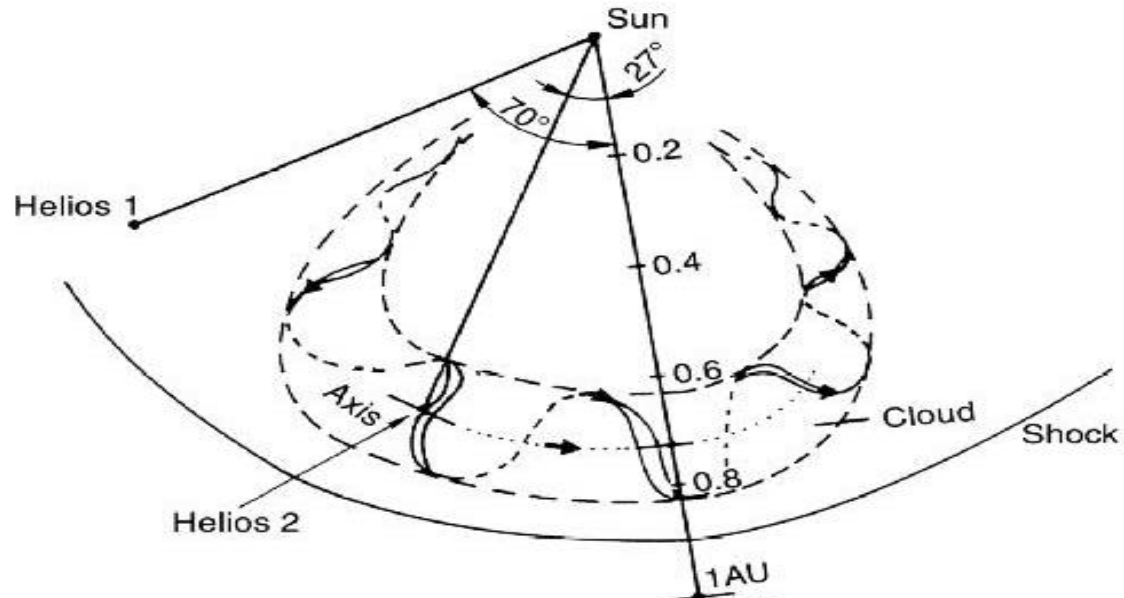
- **Strong magnetic field** [Burlaga & King, JGR 1979] **(known as Magnetic Cloud)**
- **Low proton temperature** [Gosling et al., JGR 1973; Richardson & Cand, JGR 1995]
- **Large and coherent rotation of the magnetic vector (helix)**
[Bulaga et al., JGR 1981]
- **Bi-directional flows ($E > 80\text{eV}$) electron fluxes**
[Montgomery et al., JGR 1974; Gosling, JGR 1987]
- **Bi-directional flows ($E \sim \text{KeV-MeV}$) proton fluxes**
[Mardsen et al., JGR 1987; Galvin et al., JGR 1987]
- **Highly variable abundance of Helium (0-20%)**
[Borrini et al., JGR 1982; Galvin et al., JGR 1987]
- **Unusual ionization states** [Galvin et al., JGR 1987]

More Signatures of ICMEs at $\sim 1\text{AU}$

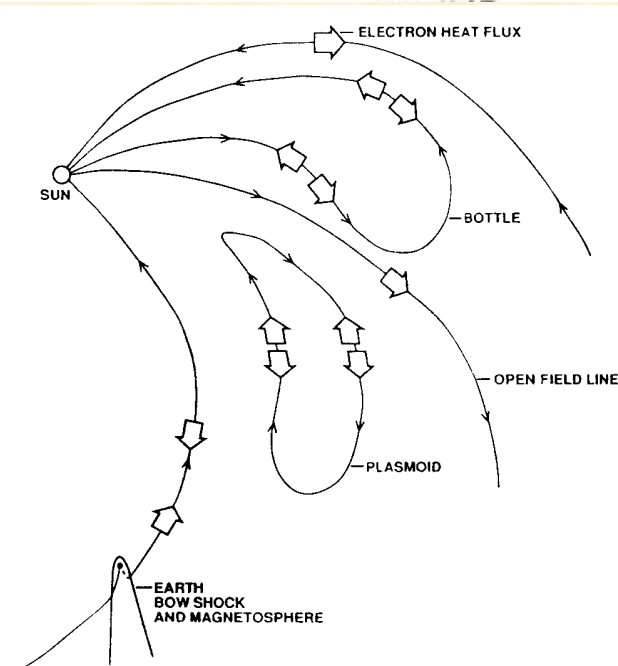
- $T_e \gg T_p$ [Osherovich et al., JGR, 1993; Richardson et al., JGR 1997]
- $T_{p\parallel} > T_{p\perp}$ ($T_{p\parallel} \sim 10 T_{p\perp}$) [Galvin et al., JGR 1987]
- $T_e \parallel > T_e \perp$ ($T_e \parallel \sim 3 T_e \perp$) [Pillip et al., JGR 1987; Gosling et al., JGR 1987]
- Level of magnetic fluctuations lower than in SW [Pudovkin et al., JGR 1979]. Magnetic Clouds as a highway of energetic particles [Torsti et al., ApJL 2004]
- Theoretical reasons to the excitation of EM Waves ($\omega \sim W_p \sim 1\text{Hz}$) [Dasso et al., JGR 2003]
- Wide range of mean bulk velocity, depending of initial condition and on solar wind environment. Typically $\sim 300\text{-}600\text{ km/s}$ [Cane & Richardson, JGR 2003]

Magnetic Clouds in the Interplanetary Medium

• *In situ* observations indicate that the field of a Magnetic Cloud can be described as a (locally) cylindrical flux tube [Farrugia et al., JGR, 1995]

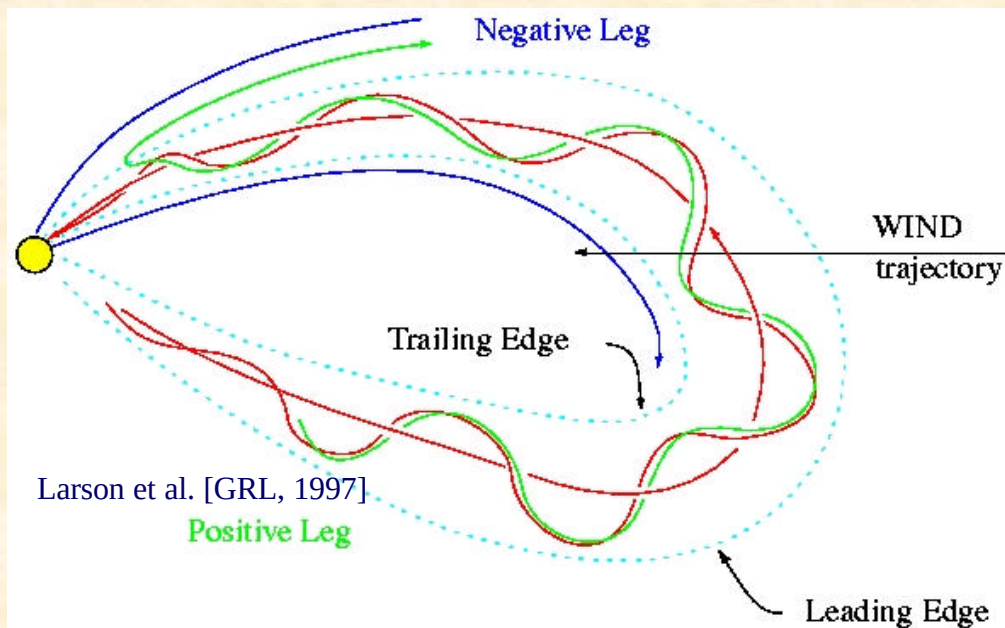
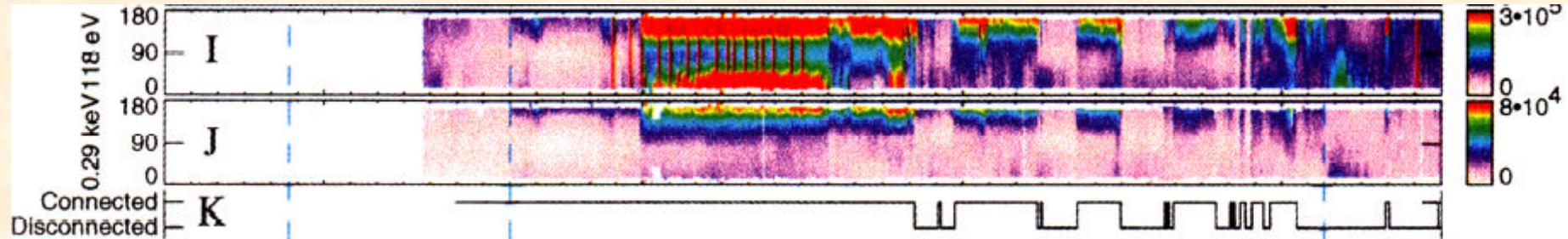


- How is its magnetic structure?
- How is its magnetic connectivity with the Sun?
- What is the right meaning of the observed bidirectional flux of electrons and protons?



Connection of the magnetic cloud to the Sun

Larson et al. [GRL, 1997]



Estimation of one leg's length:

$$L \sim 1.2 \text{ AU} \quad L = v_{\text{elec}}(t_f - t_0)$$

t_0 : type III burst
(e- beam: Lungmuir)

t_f : in situ
(e-: 20KeV)

$$w_e \sim n_e^{1/2}$$

(14MHz $\rightarrow$ 10KHz)

- Correlation between **absence of e⁻ flux** and **high β value**
- When suprathermal e⁻ fluxes are not observed ...
disconnection or scattering due to wave-particle interaction?

Large Scale Magnetic Helicity: a Key. Why?

$$(H = \int_V dV \mathbf{A} \bullet \mathbf{B})$$

- **In 3D-MHD ® inverse cascade (to the largest scales)**

[e.g., Biskamp 1997]

- **Well conserved in corona (even better than the energy)**

[Berger, Geophys Astrphys Fluid Dyn 1984]

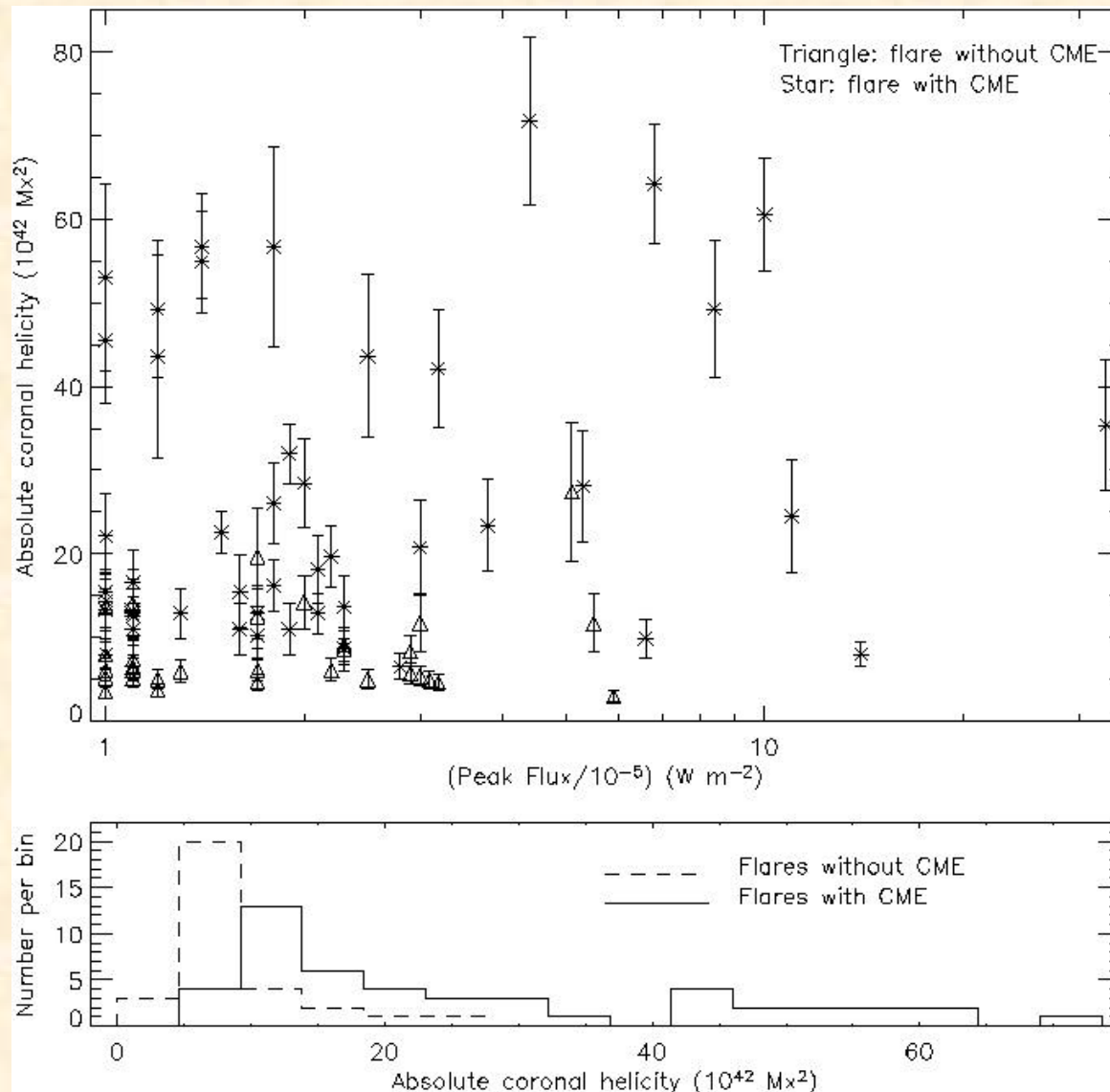
- **Useful to track Magnetic Field (from its formation to the heliosphere):
the convective zone ® the corona ® the interplanetary medium (IM)
(in particular, MCs carries H from corona to IM)**

- **H not yet sufficiently analyzed in MCs**

Some promising and recent results on magnetic helicity in CMEs and MCs

- **Estimations of H in corona** [e.g., Démoulin et al., A&A 2002]
- **Conservation of H have been found, from simulations for the evolution of CMEs (formation of flux rope from an arcade type field)** [Amari et al., ApJ 2003]
- **Important role of H during merging of coronal flux ropes**
[Zhang&Low, ApJ 2003]
- **From the study of an interplanetary flux rope, H resulted to be a well defined MHD quantity** [Dasso et al., JGR 2003]

- The amount of the Pre-flare coronal H may determine if an AR with big flare will (or not) produce a CME [Nindos & Andrews, AAS 2004]



Preflare Coronal Helicity of A.Rs that Produced Big Flares

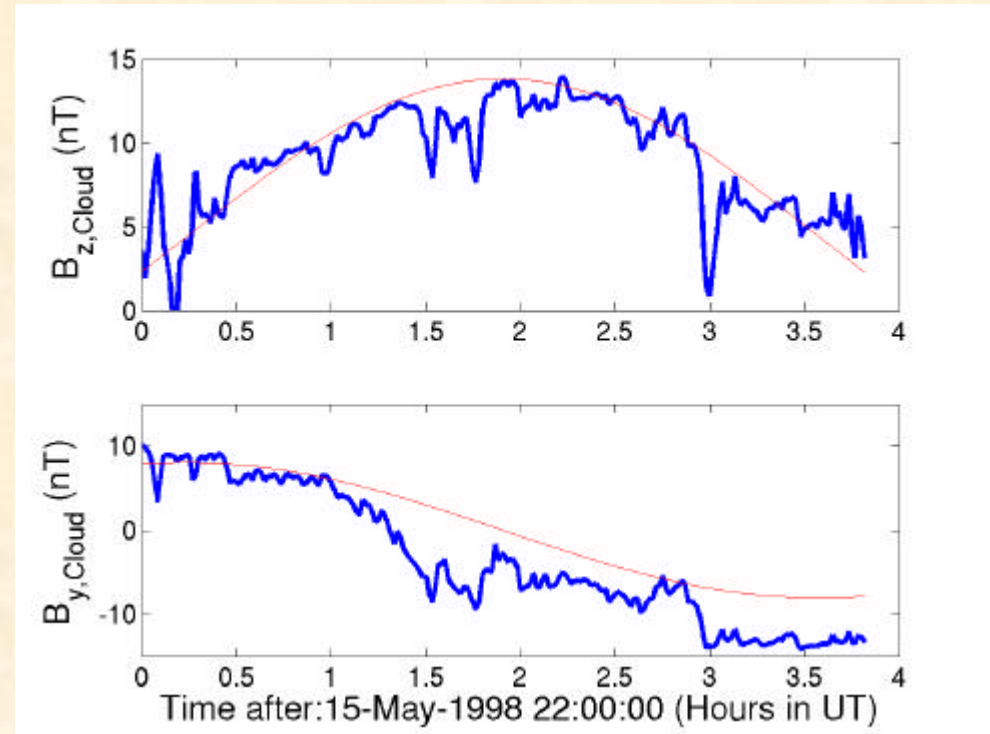
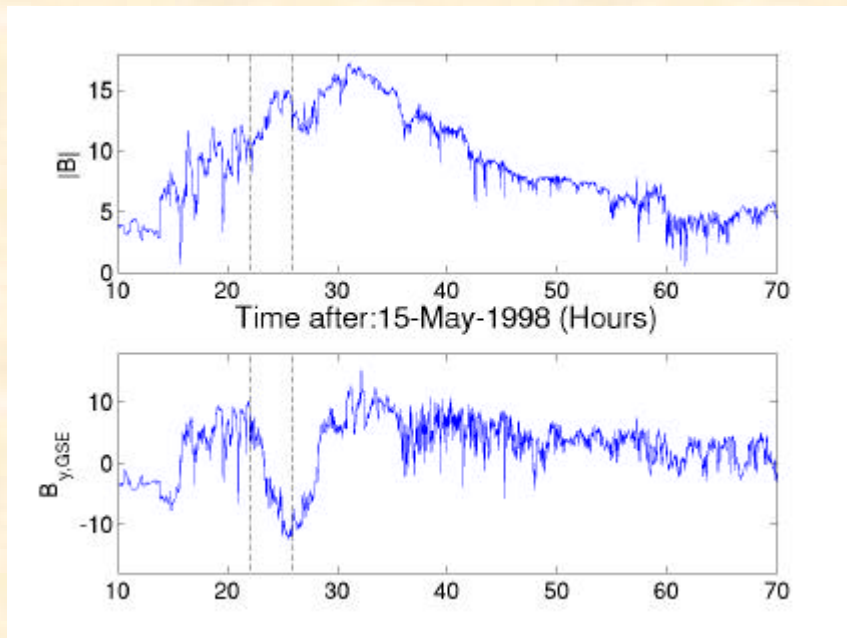
[From Nindos & Andrews, Chapman Conference, Turku, Finland, August, 2004]

- In a statistical sense, the pre-flare coronal H of the A.Rs producing confined big flares is smaller than the coronal H of those producing eruptive big flares.

**However ..., there is a good agreement between difference of H in
a very small AR and H in the associated small magnetic cloud**

[Mandrini et al., A&A 2004, submitted]

22UT, May 15 – 02UT, May 16, 1998 (Wind)



MC Model	R , AU	t_0 , AU^{-1}	B_0 , nT	Flux, M_X	$ H_r $, M_X^2
L	1.6×10^{-2}	-66	13.8	$(1-2) \times 10^{20}$	$(1.5-3.0) \times 10^{39}$

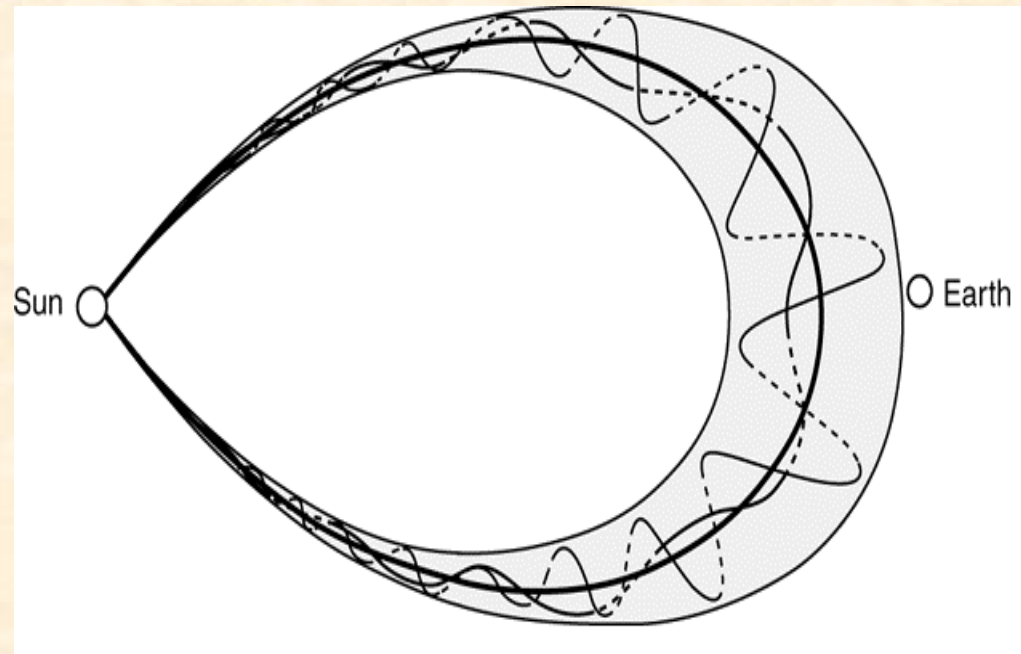
$$2.3 \times 10^{39} M_X^2 < |\Delta H_{cor}| < 3.1 \times 10^{39} M_X^2$$

$$\Phi_{cor} \sim (11-15) \times 10^{20} M_X$$

Cylindrical Helical MHD equilibria

Cloud's Frame: $0 = -\nabla p + \frac{1}{c} \mathbf{J} \times \mathbf{B}, \quad \mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$

- Force Free Field (FFF): $\nabla \times \mathbf{B} = a(\mathbf{r})\mathbf{B}$
- β_p can reach values of $\sim 0.4-0.5$ [Dasso et al., ASR 2001], so non-Force Free Field (NFFF): $\mathbf{J}$ is not parallel to $\mathbf{B}$ (Lorentz Force not null, it is balanced with $\tilde{\mathbf{N}}p$)



Under cylindrical symmetry it is possible to estimate the relative helicity per unit length from Direct Observations, as:

$$\frac{H_r}{L} = 2 \int_0^R dr B_f(r) \Phi_z(r)$$

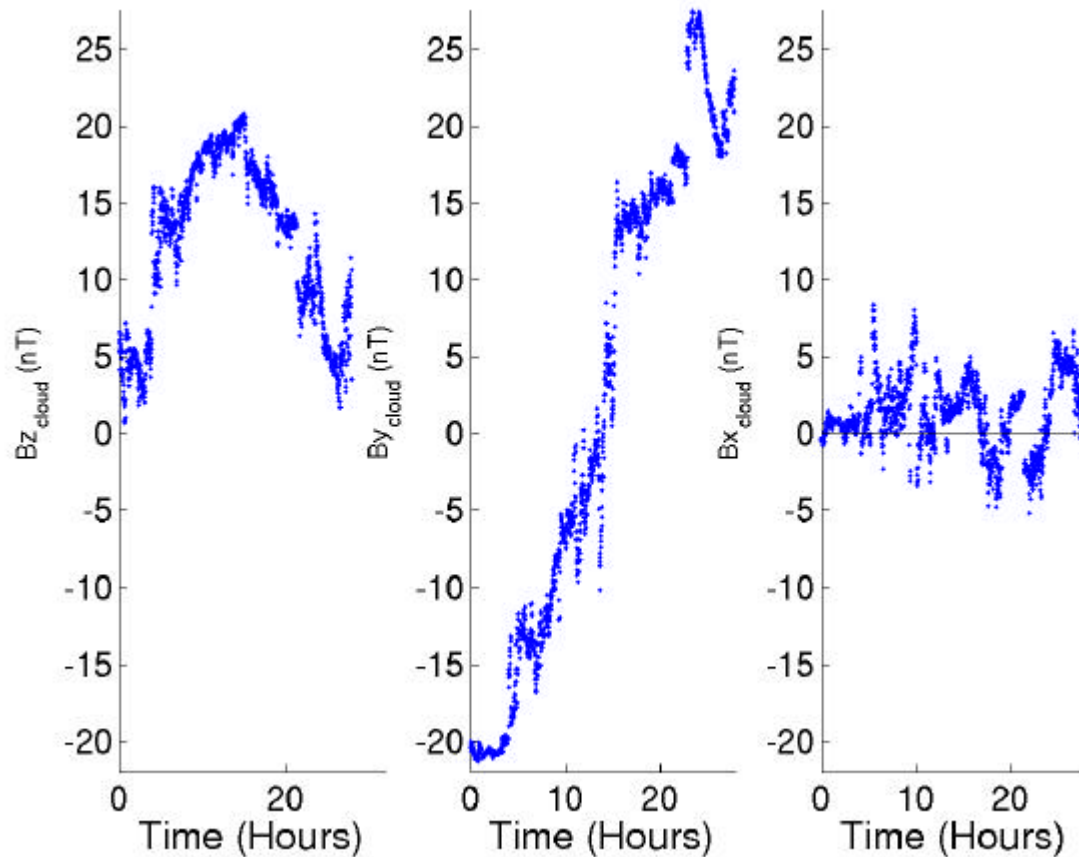
Where $\Phi_z(r) = 2p \int_0^r dr' r' B_z(r')$

The Magnetic Helicity can be expressed as the contribution of the azimuthal field weighted by the accumulated axial Flux (Φ_z)

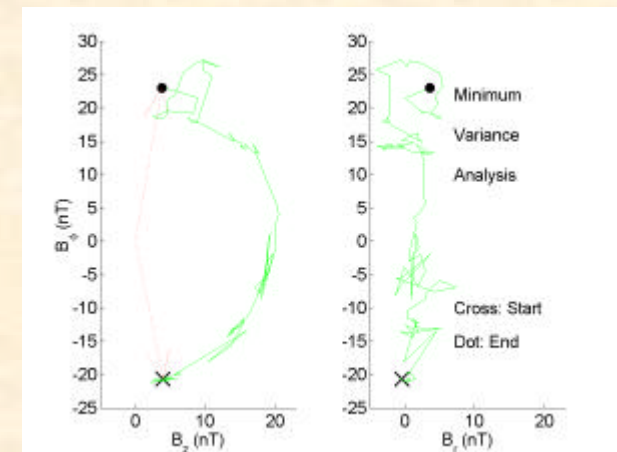
Φ_z and H_r/L can be computed **only** with the assumption of cylindrical symmetry (without any model assumed to the magnetic configuration):

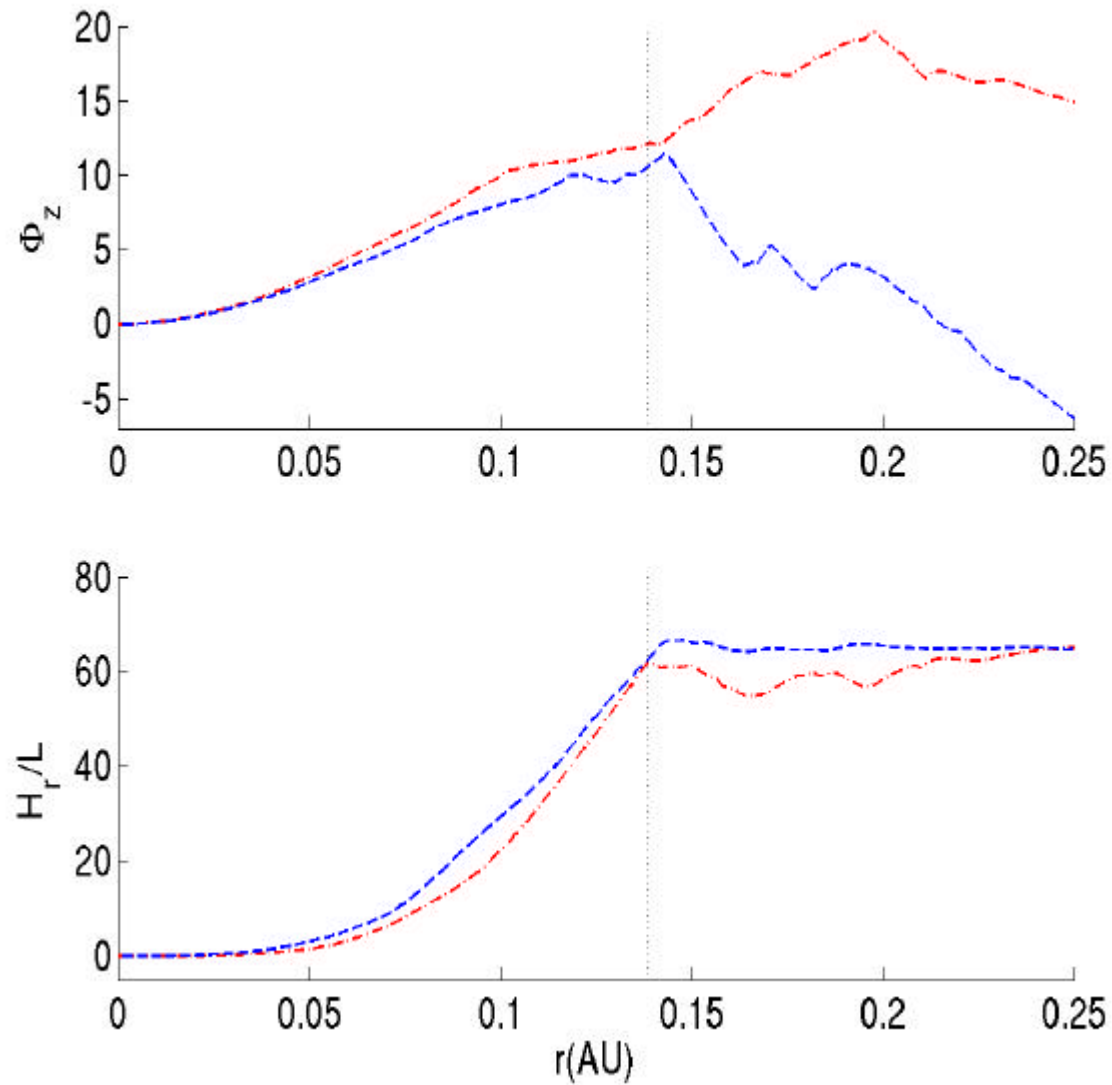
MC of Oct 18-19, 1995 (Wind)

- MV method: High variance ratio
- Rotation of $\mathbf{B}$ ($\sim 160^\circ$)
- Positive Helicity, from the sense of rotation, $H_r > 0$



$q, ^\circ$	$f, ^\circ$	R, AU
-5	293	0.12





Accumulative magnetic flux (upper panel), in 10^{20} Mx, and helicity per unit length (lower panel), in 10^{41} Mx/AU, computed from direct observations for the cloud of Oct 18, 1995

$$\Delta H_{Cor} = \Delta H_{Emerg} + \Delta H_{Phot.mot.} - N_{CMEs} H_{CMEs}$$

Comparison: Coronal level and Magnetic Cloud

Longitudinal Magnetograph
(Kitt Peak Solar Observatory)

Coronal loops (Solar X-Ray
Telescope, SXT/YOHKOH)

CORONA Time(UT)	Hr 10^{42}Mx^2
07:30	8.0-16.0
11:58	8.0-10.0

[Luoni et al., in press, 2004]

$\Delta H_{r_{COR}}(7:30 \text{ UT} - 11:58 \text{ UT})$ can reach values $\sim 8 \times 10^{42} \text{Mx}^2$

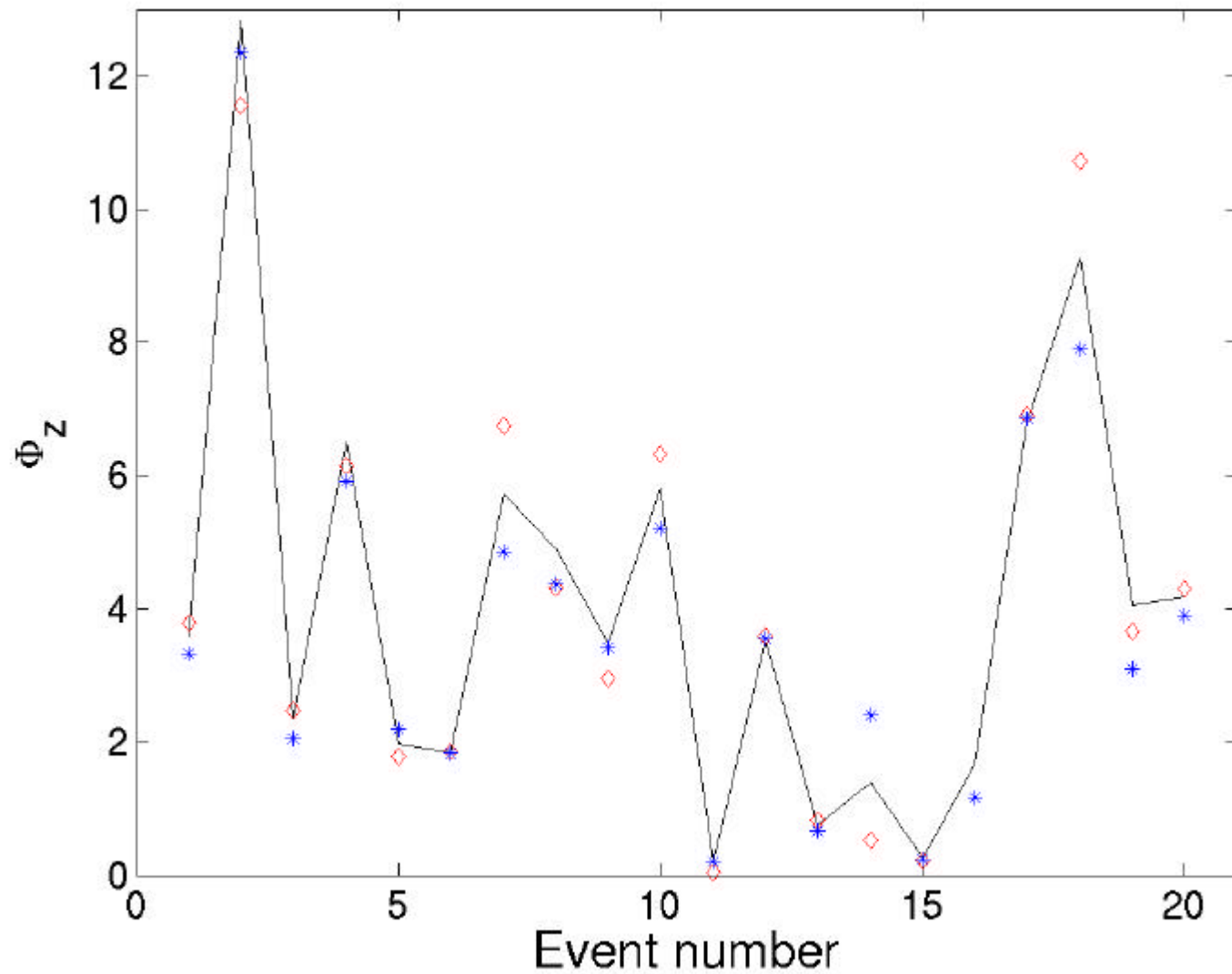
MAGNETIC CLOUD	Hr 10^{42}Mx^2
LFFF and Direct approaches	7-18

Good agreement between the sign and values of $\Delta H_{r_{cor}}$ and $H_{r_{MC}}$

We repeat the analysis for a set of MCs observed by Wind

[From List of MCs http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html]

Event	Start	End	Theta (Deg)	Phi (Deg)	Radius (10 ⁻² AU)	Helicity Sign
#1	22-Aug-1995 22:00:00	23-Aug-1995 19:00:00	-22,7	271,2	9,1	+
#2	18-Oct-1995 19:00:00	20-Oct-1995 00:00:00	-13,7	286,9	13,7	+
#3	16-Dec-1995 05:00:00	16-Dec-1995 22:00:00	-12,1	51,2	6,5	-
#4	27-May-1996 15:00:00	29-May-1996 07:00:00	-2,3	132,2	13,2	-
#5	01-Jul-1996 17:00:00	02-Jul-1996 09:00:00	3,0	105,1	6,5	-
#6	07-Aug-1996 13:00:00	08-Aug-1996 10:00:00	-64,6	292,4	8,6	+
#7	24-Dec-1996 03:00:00	25-Dec-1996 10:00:00	50,9	80,3	13,0	+
#8	10-Jan-1997 05:00:00	11-Jan-1997 02:00:00	-18,1	244,4	10,1	+
#9	21-Apr-1997 15:00:00	23-Apr-1997 07:00:00	16,6	333,3	8,9	+
#10	15-May-1997 09:00:00	16-May-1997 01:00:00	-15,9	111,9	8,4	-
#11	16-May-1997 07:00:00	16-May-1997 14:00:00	-30,3	303,0	3,6	-
#12	09-Jun-1997 02:00:00	09-Jun-1997 23:00:00	-17,8	238,1	8,2	+
#13	19-Jun-1997 05:06:00	19-Jun-1997 17:54:00	-61,0	216,8	4,7	+
#14	15-Jul-1997 06:00:00	16-Jul-1997 01:00:00	-63,8	124,6	8,2	-
#15	03-Aug-1997 14:00:00	04-Aug-1997 01:00:00	-11,5	31,5	3,2	-
#16	18-Sep-1997 00:00:00	20-Sep-1997 12:00:00	60,1	203,5	20,5	+
#17	21-Sep-1997 22:00:00	22-Sep-1997 18:00:00	72,1	163,5	9,9	-
#18	01-Oct-1997 16:00:00	02-Oct-1997 23:00:00	35,3	127,8	14,8	-
#19	10-Oct-1997 23:00:00	12-Oct-1997 00:00:00	-15,0	256,9	12,0	+
#20	07-Nov-1997 05:48:00	08-Nov-1997 04:18:00	-5,2	225,7	8,4	+

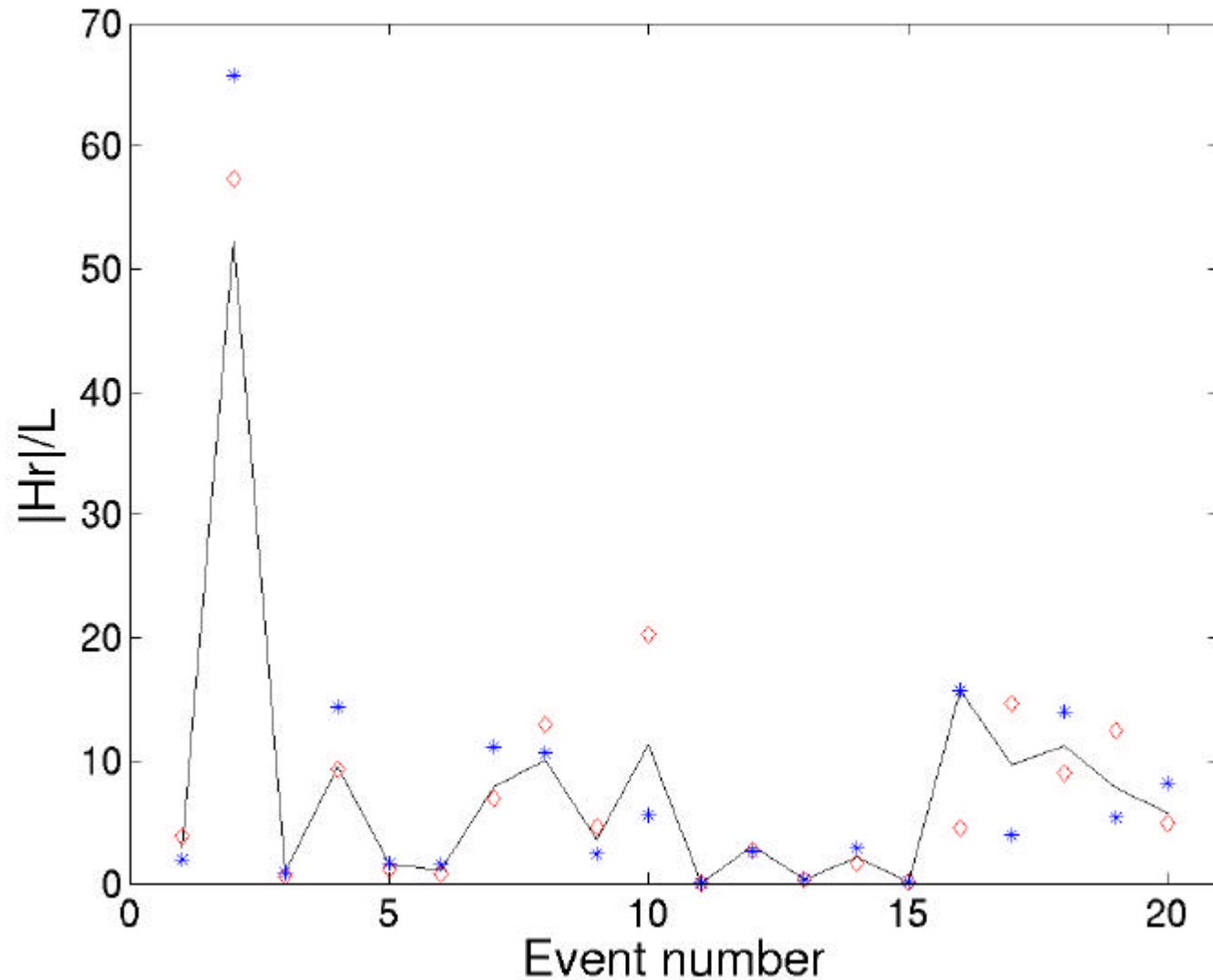


$\phi_{z,L}$ between
 $\phi_{z,in}$ and $\phi_{z,out}$
 for 14 MCs

$\phi_{z,L} \sim \phi_{z,in} \sim \phi_{z,out}$
 for 6 MCs

$\phi_{z,L} > \phi_{z,in/out}$
 for 6 cases

Magnetic flux (ϕ_z) accross a surface perpendicular to the cloud
 axis (z) for each event, in units of 10^{20} Mx



H_L between H_{in}
and H_{out} for 18
MCs

$H_L \sim H_{in} \sim H_{out}$ for
6 MCs

$H_L < H_{in/out}$
for 2 cases

Absolute value of the magnetic helicity per unit length ($|Hr|/L$) in units of $10^{41} \text{ Mx}^2/\text{AU}$. Blue stars, and red diamonds correspond to direct observations, in-bound and out-bound respectively.
Black line corresponds to Lundquist's model

Summary and Conclusions

- MCs are the most geoeffective solar objects, and it is necessary to improve the knowledge of their global features and the link with their solar sources.
- H is the most important MHD magnitude to gain insight about the physics during the ejection/travel of CMEs/MCs (MHD invariant, better conserved than Energy in the corona and interplanetary medium)
- We showed a method to analyze the content of H in Magnetic Clouds
- We compared our results with that obtained from a LFFF model, giving similar values of H in 30% of MCs.
- However, we found that H is very sensitive to the size (radius) of MCs, so it is very important to improve the determination of their boundaries, orientation, and impact parameter, and our method can help us to improve them
- Our comparisons of H in two MCs with the (respective) release of H from coronal level of the associated AR (with a change of H of four order of magnitude between both events!), showed a good agreement

Thanks for your attention !