Magnetic Helicity Analysis in Magnetic Clouds: A Key to Link ARs with their IP Manifestation

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Outline

•Brief Introduction to Interplanetary Magnetic Clouds (MCs)

•Magnetic Helicity (H) and Fluxes in Cylindrical Structures

•Technique and Data Analysis (model-dependent and model-independent methods)

•Estimation of Fluxes and H for MCs

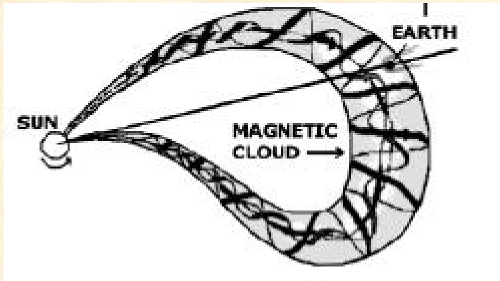
•Comparison of H in MCs with estimations of release of H from their coronal source

•Conclusions

In situ magnetic measurements of MCs can only register data along a unique direction (a linear cut of the 3D structure of the cloud)

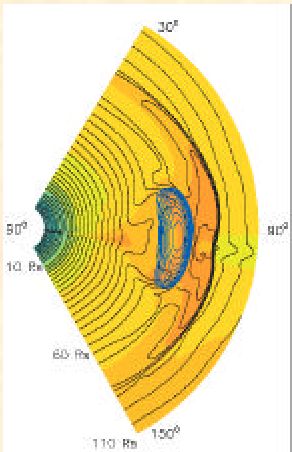
One-point *in situ* **observations of large scale magnetic field in MCs are consistent with helical cylinders structure and symmetry along its axis**

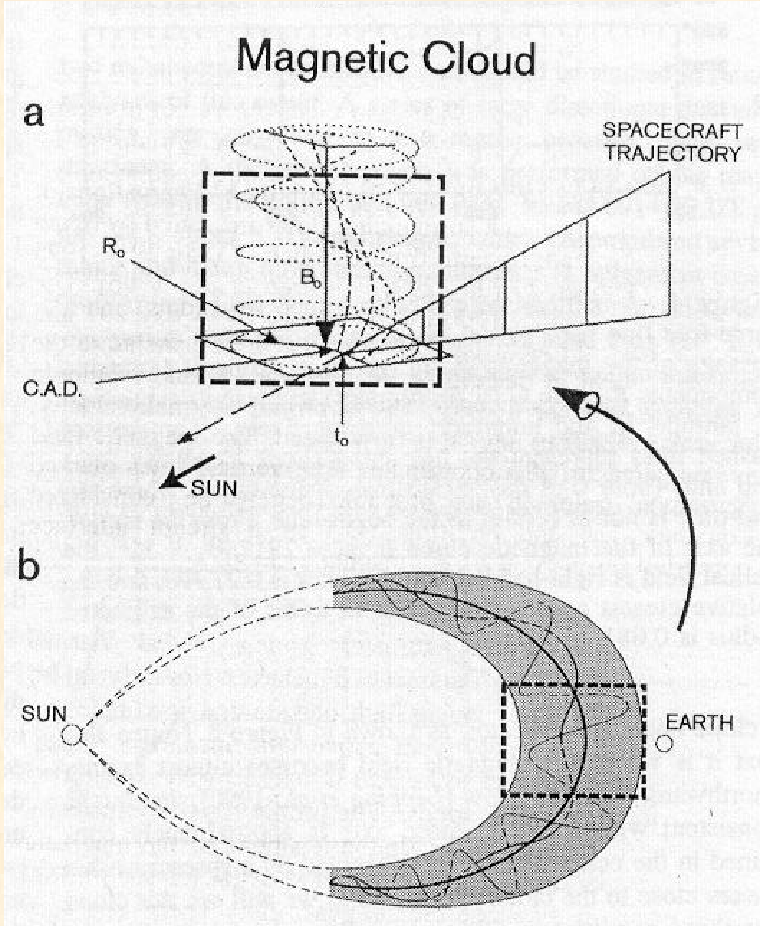
[e.g., Goldstein, SW5 1983; Lepping et al., JGR 1990; Farrugia et al., JGR 1995]



[from Lepping et al., JGR, 2003]

[from Riley et al., JGR, 2003]





From [Lepping et al., JGR 1990]

We assume the local section of the MC as a Cylindrical Flux Rope:

$$\mathbf{B} = B_z(r)\mathbf{z} + B_f(r) f$$

Magnetic Helicity (H) is one of the keys to track CMEs-MCs

•**In 3D-MHD ® inverse cascade (to the largest scales)** **[e.g., Biskamp 1997]**

•**Well conserved in corona and heliosphere (even better than the energy)**
[Berger, Geophys Astrphys Fluid Dyn 1984]

•**Useful to track magnetic structures from its formation to the heliosphere:**

the convective zone ® the corona ® the interplanetary medium (IM)

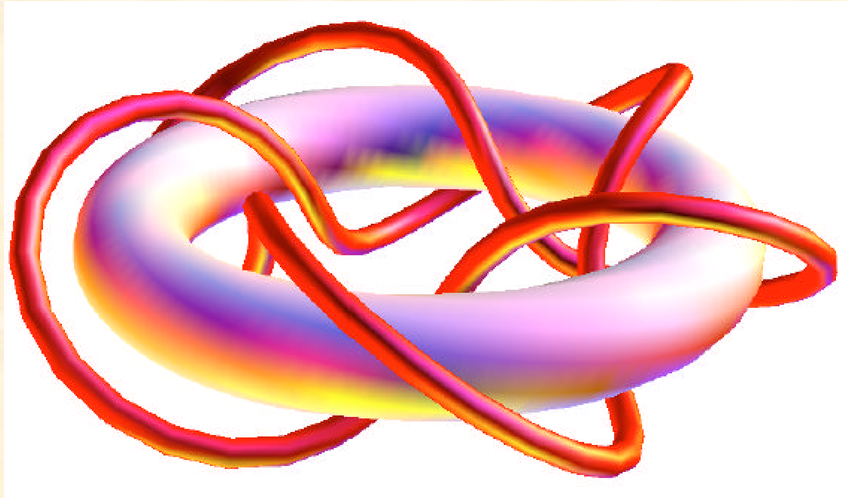
In particular, MCs carry H from corona to IM

•**Estimations of H in corona** **[e.g., Dèmoulin et al., A&A 2002; Nindos et al., ApJ 2003]**

•**Recent Studies of Magnetic Helicity in ICMEs and MCs** **[e.g., Dasso et al., JGR 2003; Ruzmaikin et al., JGR 2003; Leamon et al., JGR 2004; Lynch et al., JGR 2005, Nakwacki et al., SW11 2005, Gulisano et al., JAST 2005; Dasso et al., A&A, in press 2006]**

•**Link between the release of helicity in ARs and content of helicity in MCs**
[e.g., Mandrini et al., A&A 2005; Luoni et al., JASTP 2005]

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



H as ‘Linking Number’, from Berger [Plasma Phys Control Fusion, 1999]

When $\mathbf{B} \bullet \mathbf{n} \neq 0$ on $S(V)$,
a **Relative Helicity** (H_r) is well defined
(both, gauge and ideal invariant)

[Berger&Field, JFluidMech 1984]

$$(H_{rel} = H - \int_V dV\ \mathbf{A}_{ref} \bullet \mathbf{B}_{ref})$$

Taking an appropriate reference field, for cylindrical flux ropes:

$$\frac{H_r}{L} = 4p \int_0^R dr\ r\ A_f(r)\, B_f(r)$$

Different models to MCs. Main parameters: {R, t_0 and B_0}

Force Free Field (Lundquist, ArkFys, 1960)

$\nabla \times \mathbf{B} = 2\tau_0 \mathbf{B}$ $(\tau_0 = cte)$ $\quad \mathbf{B} = B_0 J_0(2\tau_0 r)\mathbf{z} + B_0 J_1(2\tau_0 r)\boldsymbol{\varphi}$

$\mathbf{A} = \mathbf{B}/(2\tau_0)$

$$\frac{H_r}{L} = \frac{\pi B_0^2 R^2}{\tau_0}\left[J_0^2(2R\tau_0) + J_1^2(2R\tau_0) - \frac{J_0(2R\tau_0)J_1(2R\tau_0)}{R\tau_0}\right]$$

$$F_z = \left[\pi B_0 R J_1(2R\tau_0)\right]/\tau_0$$

$$F_\varphi = \frac{B_0 L}{2\tau_0}\left[1 - J_0(2R\tau_0)\right]$$

Force Free Field with constant twist (Gold&Hoyle, R.Astron. Soc, 1960)

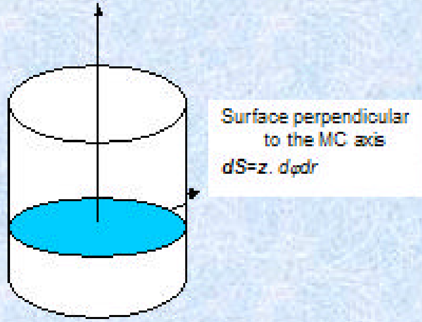
$\mathbf{B} = \frac{B_0}{1+\tau_0^2 r^2}\mathbf{z} + \frac{B_0 \tau_0 r}{1+\tau_0^2 r^2}\boldsymbol{\varphi}$ $\quad \tau(r) = \tau_0$ $(\tau_0 = cte)$

$$\mathbf{A} = -\frac{B_0}{2\tau_0}\ln(1+\tau_0^2 r^2)\mathbf{z} + \frac{B_0}{2\tau_0^2 r}\ln(1+\tau_0^2 r^2)\boldsymbol{\varphi}$$

$$\frac{H_r}{L} = \left(\frac{8\pi\left[\ln(1+(2R\tau_0)^2/4)\right]^2}{(2R\tau_0)^4}\right)B_0 R^4 \tau_0 = \frac{\pi B_0^2}{2\tau_0^3}\left[\ln(1+\tau_0^2 R^2)\right]^2$$

$$F_z = B_0 \pi \ln(1+\tau_0^2 R^2)/\tau_0^2$$

$$F_\varphi = \frac{LB_0}{2\tau_0}\ln(\tau_0^2 R^2 + 1)$$



Non Force Free Field with constant currents (Hidalgo et al., JGR, 2002)

$\mathbf{J} = j_\varphi \boldsymbol{\varphi} + j_z \mathbf{z}$ (j_φ y j_z constants) $\quad B_0 = \frac{j_\varphi R}{4\pi}$

$\mathbf{B} = B_0 \tau_0 r \boldsymbol{\varphi} + B_0(1 - r/R)\mathbf{z}$ $\quad \tau_0 = \frac{j_z}{2 j_\varphi R}$

$$\mathbf{A} = \frac{B_0 r}{R}(R/2 - r/3)\boldsymbol{\varphi} - \frac{B_0}{2}\tau_0 r^2 \mathbf{z}$$

$$\frac{H_r}{L} = \frac{7\pi}{30}B_0^2 R^4 \tau_0$$

$$F_z = B_0 \pi R^2/3 \qquad F_\varphi = \frac{LB_0 \tau_0 R^2}{2}$$

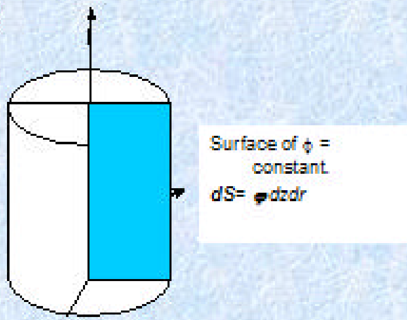
Non Force Free Field with poloidal current lineal with the radius and constant axial current (Cid et al., Solar Phys, 2002)

$$\mathbf{B} = J_z r \varphi + \gamma(R^2 - r^2)\mathbf{z} = B_0 \tau_0 r \varphi + B_0(1 - r^2/R^2)\mathbf{z}$$

$\mathbf{A} = (\frac{B_0 r}{2} - \frac{\pi\gamma r^3}{2c})\varphi - \frac{J_z \pi r^2}{c}\mathbf{z}$ $\quad B_0 = 2\pi\gamma R^2/c$

$\frac{H_r}{L} = \frac{\pi}{3}B_0^2 \tau_0 R^4$ $\quad \tau_0 = J_z/\gamma R^2 = J_z/B_0$

$$F_z = \frac{B_0 \pi R^2}{2} \qquad F_\varphi = \frac{LB_0 \tau_0 R^2}{2}$$



Once determined the boundaries and the orientation of the MC, the observations are compared with the models (non-linear least square method)

Orientation of the tube (S/C trajectory in the flux tube coordinates) from MV → $\mathbf{r}_{S/C}(t)$ → Mínimize χ^2 giving freedom only to the physical parameters

↓

$$c^{2}_{B_0, t_0} = \sum_i [\mathbf{B}^i{}_{obs}(\mathbf{r}_{S/C}(t)) - \mathbf{B}^i{}_{model}(\mathbf{r}_{S/C}(t), B_0, t_0)]^2$$

•Minimum Variance Method (geometry)

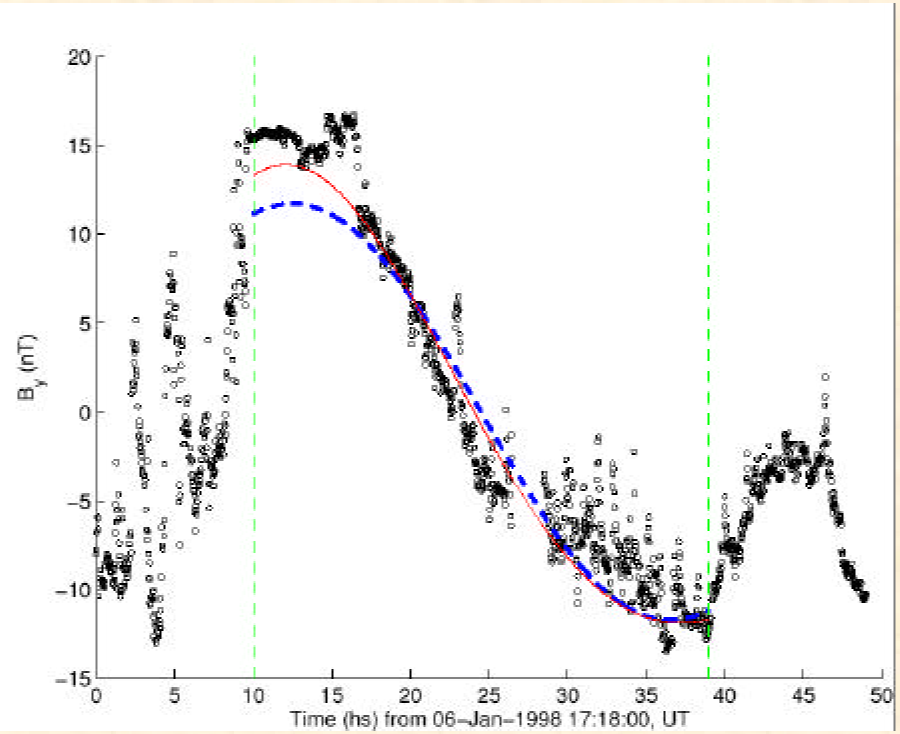
•Least Square Method Fit (Physical Parameters)

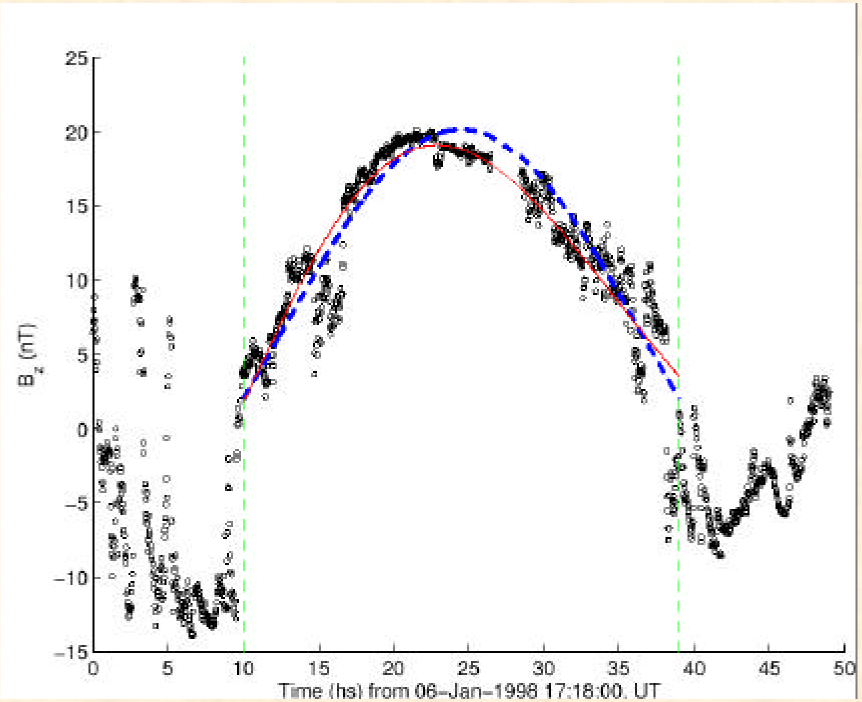
•We make also a Simultaneous fit (geometrical plus physical parameters)

Expansion Effect

(self similar radial expansion model)

From Nakwacki et al., SW11 2005





$$B_\phi = \frac{B_{0\phi}}{(t+T_0)} J_1\left(\frac{\alpha_t}{(t+T_0)}\bar{R}\right)$$

$$B_z = \frac{B_{0z}}{(t+T_0)^2} J_0\left(\frac{\alpha_t}{(t+T_0)}\bar{R}\right)$$

$$\Phi_z(t) = \Phi_z(0) = \frac{2\pi \bar{R} B_{0z}}{(t+T_0)\alpha_0} J_1(\bar{\alpha}_t \bar{R})$$

$$H_r(t) = H_r(0) = \frac{2\pi \bar{B}_{0z} B_{o\phi} \bar{R}^2}{\alpha_0}\left[J_1^2(\bar{\alpha}_t \bar{R}) + J_0^2(\bar{\alpha}_t \bar{R}) - \frac{2 J_1(\bar{\alpha}_t \bar{R}) J_0(\bar{\alpha}_t \bar{R})}{\bar{\alpha}_t \bar{R}}\right]L$$

$$E_m(t) = \frac{\bar{R}^2}{8}\left[[J_1^2(\bar{\alpha}_t \bar{R}) + J_0^2(\bar{\alpha}_t \bar{R}][\bar{B}_{0\phi}^2 + \bar{B}_{0z}^2] - \frac{2\bar{B}_{0\phi}^2 J_1(\bar{\alpha}_t \bar{R}) J_0(\bar{\alpha}_t \bar{R})}{\bar{\alpha}_t \bar{R}}\right]L$$

$\bar{B}_{0z} = \frac{B_{0z}}{(t+T_0)^2}$, $\bar{B}_{0\phi} = \frac{B_{0\phi}}{(t+T_0)}$, $\bar{\alpha}_t = \frac{\alpha_0}{(t+T_0)}$, $\bar{R} = R_0 \frac{(t+T_0)}{T_0}$ and B_{0z}, $B_{0\phi}$, α_0 constant

Model	$\frac{H_r}{L}$ $(nT^2 AU^3)$	$\frac{E_m}{L}$ $(nT^2 AU^2)$	Φ_z $(nT AU^2)$
Static	-0.442	0.382	0.414
Initial	-0.534	0.471	0.413
Final	-0.534	0.398	0.413

[Dasso et al., Adv Space Res 2005]

Under the assumption of cylindrical symmetry
(without assumptions of any model to magnetic configuration)
it is possible to estimate fluxes and H_r/L from observations, as:

$$\Phi_z(r) = 2p \int_0^r dr' \, r' B_z(r') \qquad \Phi_f(r) = L \int_0^r dr' B_f(r')$$

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

- H can be expressed as the contribution of azimuthal field weighted by accumulated axial Flux (a geometrical interpretation of helicity)

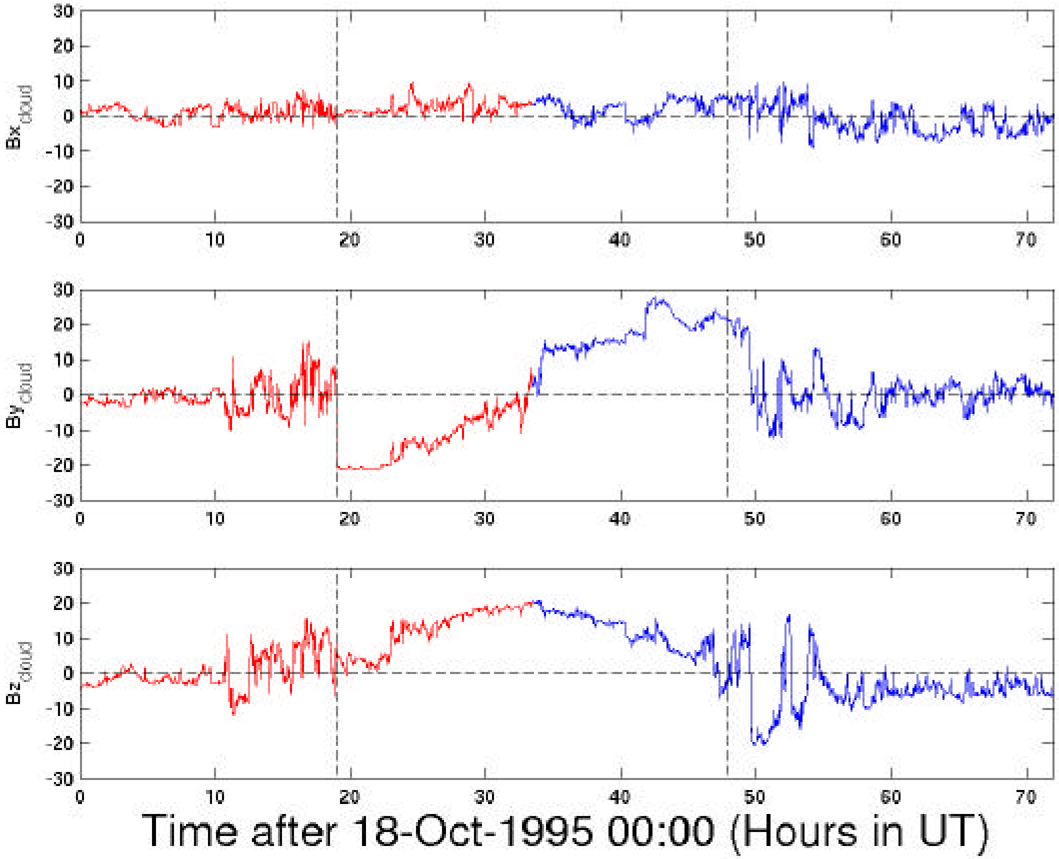
- The field inside the unobserved core (if p≠0) can be modeled; but correction for fluxes and H are low: D ~ $(p/R)^2$

- Thus, 10% in p/R will introduce an error of 1% in fluxes and H

MC of Oct 18-19, 1995 Wind
A Large Cloud

θ	φ
[-2,5]	[285,295]

	a, AU^{-1}	B_0, nT
LFFF	20	24

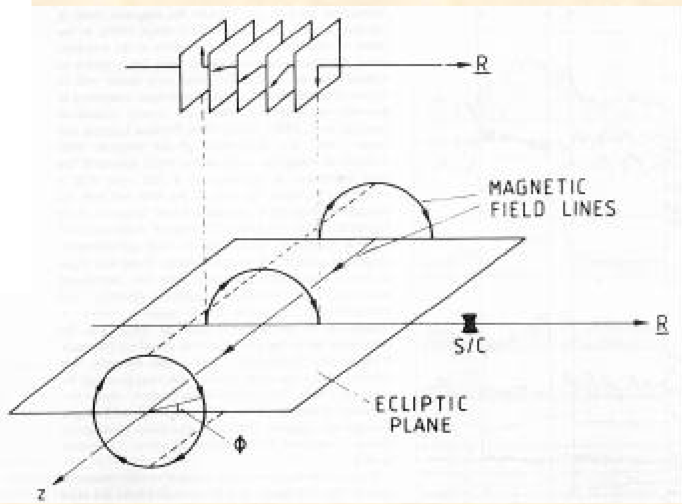


Different authors choose different end times (between Oct 19 22:54UT and Oct 20 01:38UT), e.g.,:

[Lepping et al., JGR 1997]

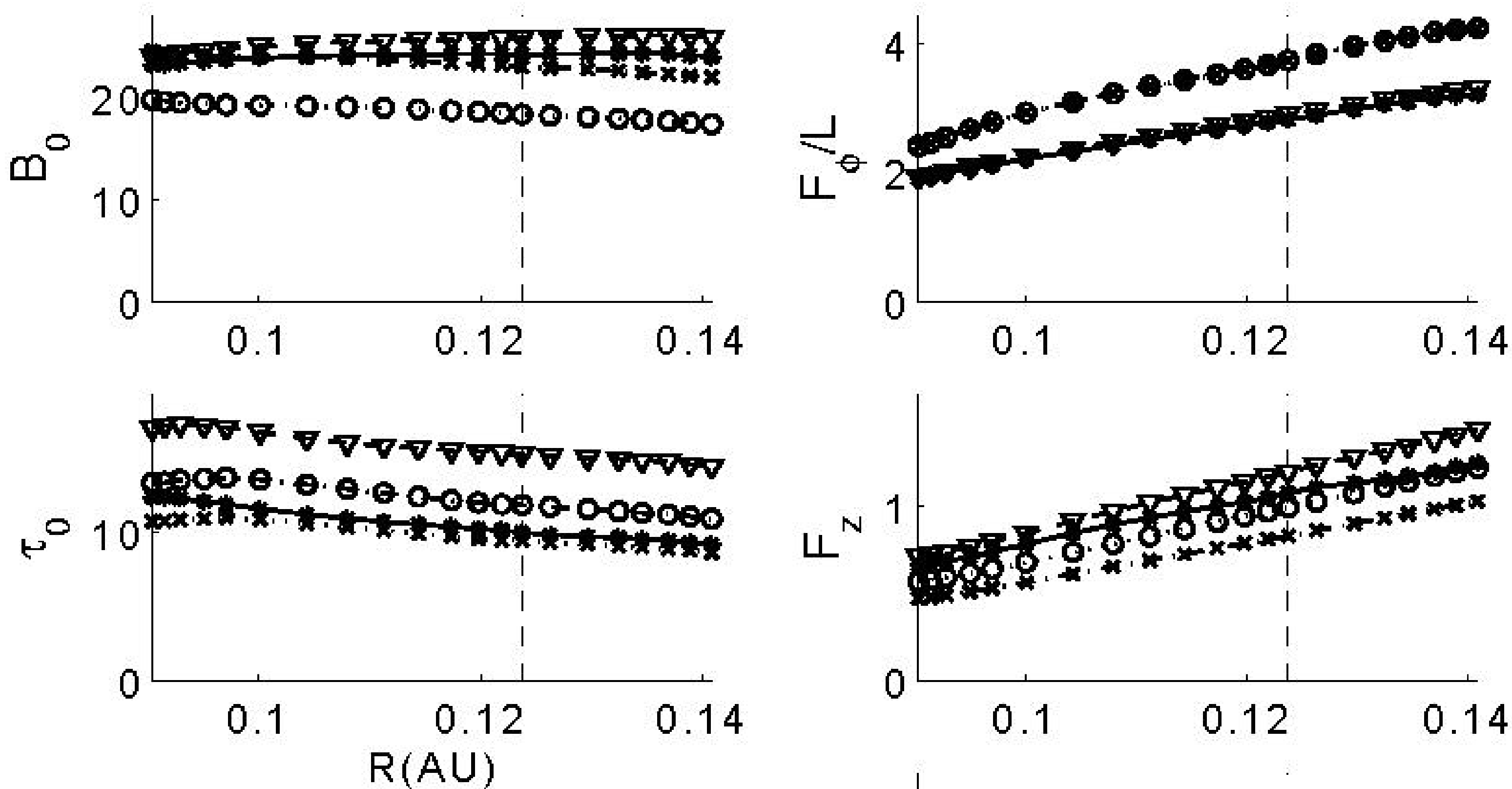
[Larson et al., GRL 1997]

[Janoo et al., JGR 1998]



Fitted and derived magnitudes for different choosen boundaries

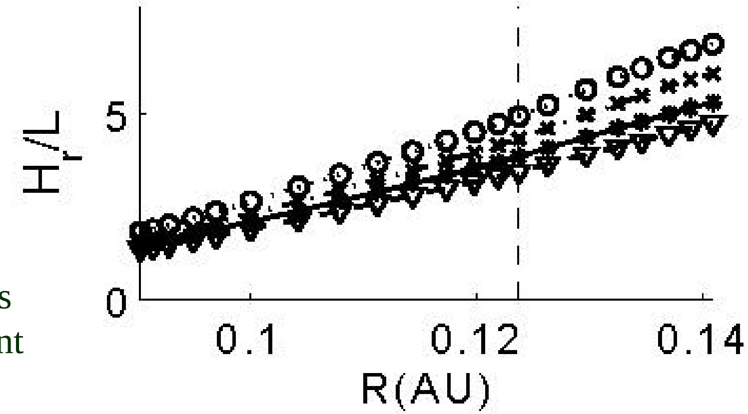
*: L
∇: GH
X: H
o: C



Full shown radius range corresponds to the end time choosen between:
Oct 19, 17:31UT and
Oct 20, 01:38UT

Vertical dashed line:
Oct 19, 22:54UT

D**F**$_f$**~20%,**
D**F**$_z$**~25%,**
D**H~35%**
For end boundaries choosen as different previous authors



Accumulative flux F_y/L

[from Dasso et al., A&A 2006, in press]

$$\frac{F_{y,cloud}(x)}{L} \doteq \int_{X_{in}}^{x} dx' \, B_{y,cloud}(x')$$

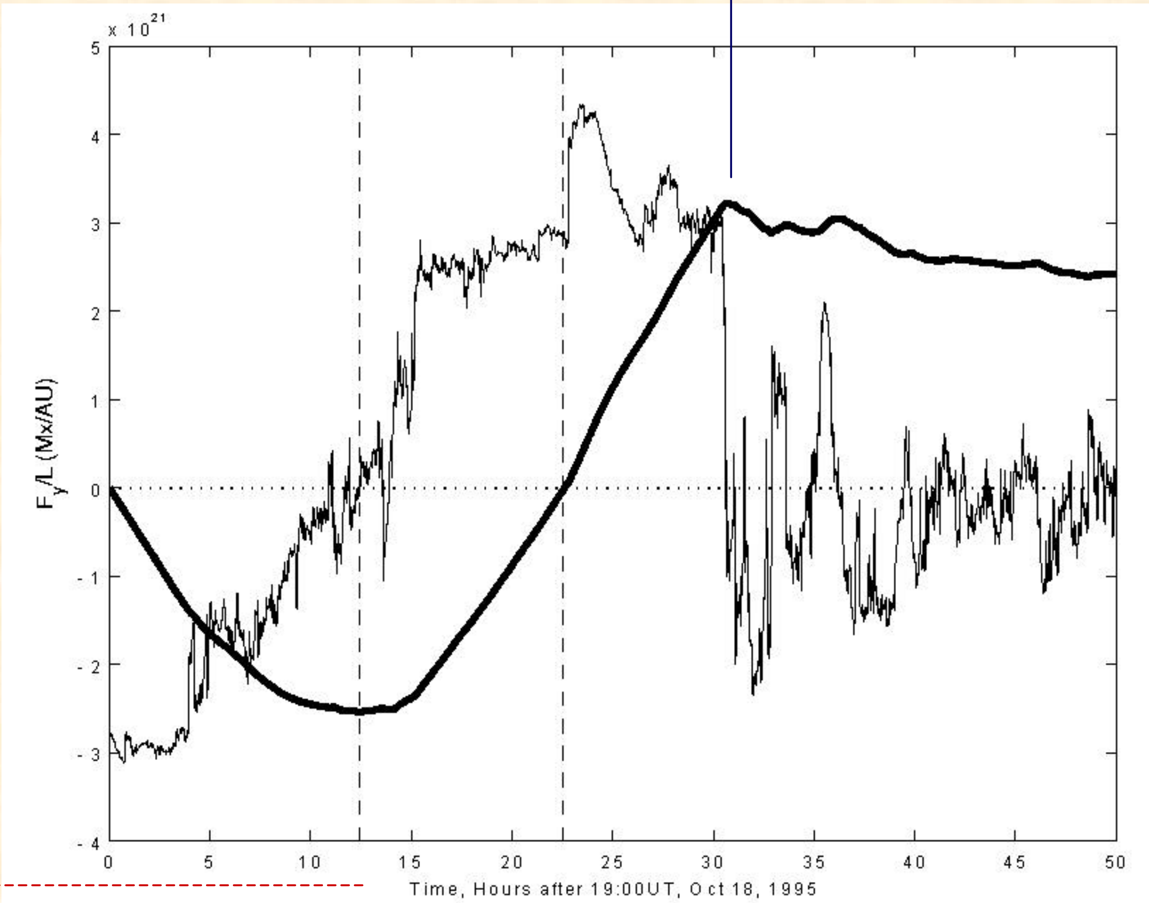
From Ñ•**B**=0 and local invariance of **B** along the cloud axis:

$$\int_{\substack{flux\\rope}} dx \, B_{y,cloud}(x) = 0$$

Oct 20, 01:36UT

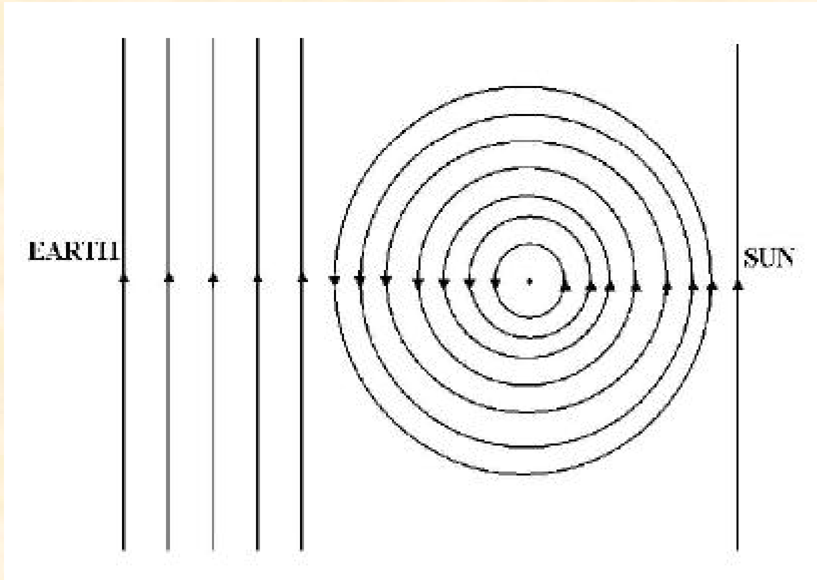
Oct 19, 07:26UT

Oct 19, 17:37UT

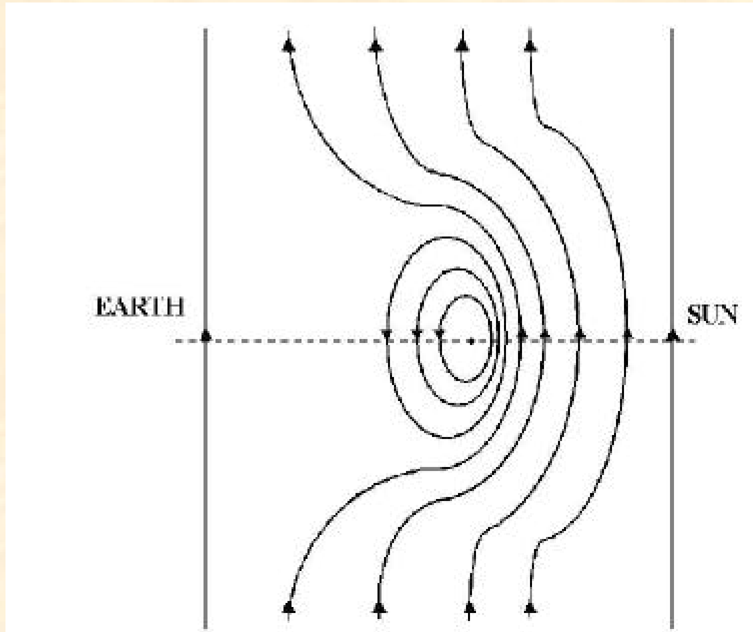


[from Dasso et al., A&A 2006, in press]

Schematic 2D view of the magnetic structure of the MC embedded in the SW



Because the MC is faster than the SW, anti-parallel field lines are forced to reconnection in the MC front



Part of the original flux in the front of the flux rope was removed, but the trail remains as ~ before reconnection

Solar Corona	Time (UT)	$\|a\|$ (10^{-2}Mm^{-1})	$\|\Delta H_{Cor}\|$ (Mx^2)	
14 Oct 1995	07:30 11:58	0.94-2.07 0.12-1.50	(7.-15.)x10^{42} (1.-12.)x10^{42}	Large MC
11 May 1998	00:03 11:11	0.08-0.11 0.08-0.11	(5.-7.)x10^{39} (3.-4.)x10^{39}	Small MC

Magnetic Cloud	Method	$\|H_{MC}\|$ (Mx^2)	
Oct 1995	LM DM$_{in}$ DM$_{out}$	10.x10^{42} 11.x10^{42} 11.x10^{42}	Large MC
May 1998	LM DM$_{in}$ DM$_{out}$	3.x10^{39} 3.x10^{39} 4.x10^{39}	Small MC

Conclusions and Remarks

- **Magnetic Helicity (H) and fluxes (F) are keys to gain insight about the physical processes during the ejection/travel of CMEs/MCs**

- **We show several techniques/methods to analyze F and H in MCs**

- **We compute the coronal H before and after two ejective events; this variation is consistent with the amount and sign of H found in MCs**

- **This happens even when the amounts of H vary in three orders of magnitude when the two events are compared**

- **We quantify typical variations for F and H, from uncertainties in MC boundaries; we find:** DF_f**~20%,** DF_z**~25%, and** DH**~35% (similar values to those obtained when different methods/models are used)**

- **From *in situ* 1AU observations of Oct 1995 MC, we deduce that the leading front of MC reconnected with overtaken SW B, and estimate H in the flux rope before and after this reconnection**

Thank you very much for your attention !!!