Quantitative link between solar ejecta and interplanetary magnetic clouds: magnetic helicity

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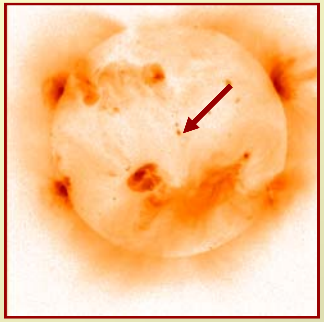
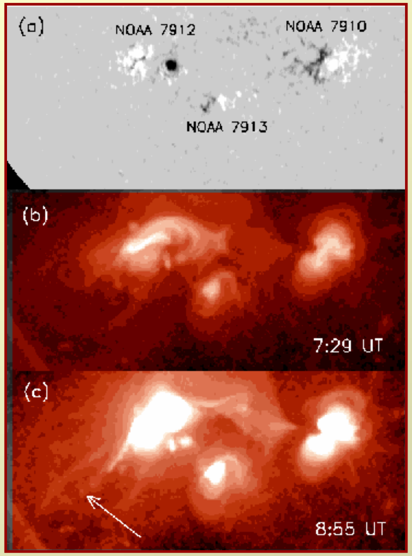
5 Konkoly Observatory, Hungary





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Summary

Analyze two ejective solar events:

14 October, 1995

11 May, 1998

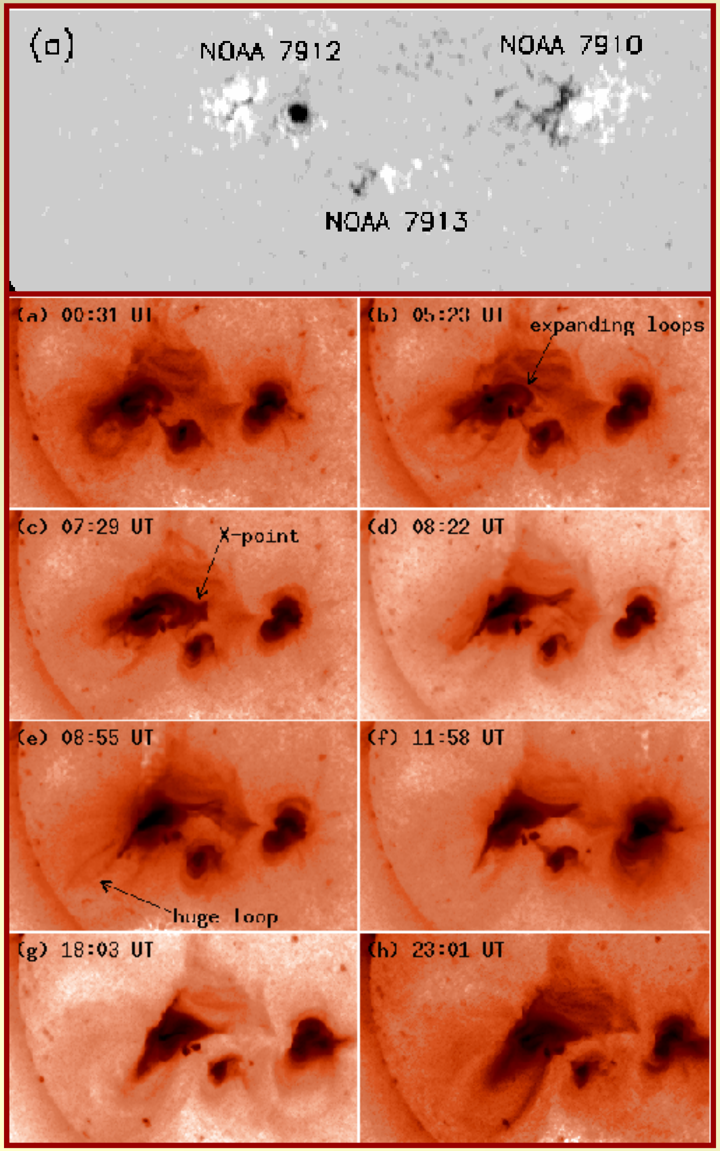
Compute global quantities in the Sun: flux and magnetic helicity.

Identify and model in situ data of the associated interplanetary Magnetic Clouds.

Compute global quantities in the interplanetary medium: flux and magnetic helicity.

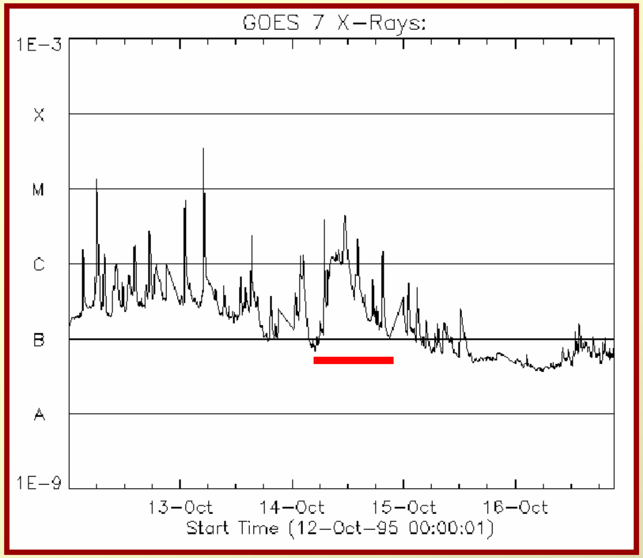
Show the quantitative link between the eruptions and the MCs.

The coronal event on 14 October, 1995



C1.6 LDE starting on 14 October, 1995 at 5:00 UT and lasting 15 hours.

non-Hale AR7912

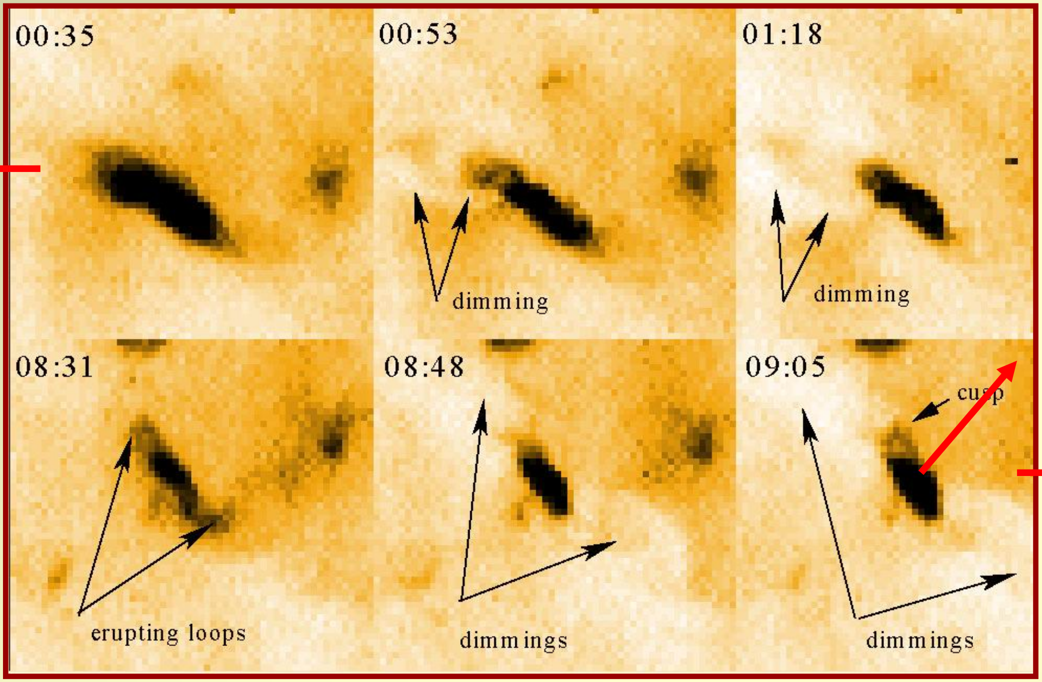


SXT - full disk images

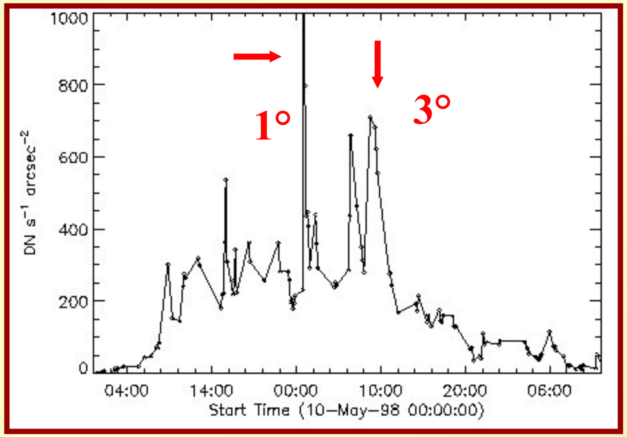
Kitt Peak magnetogram

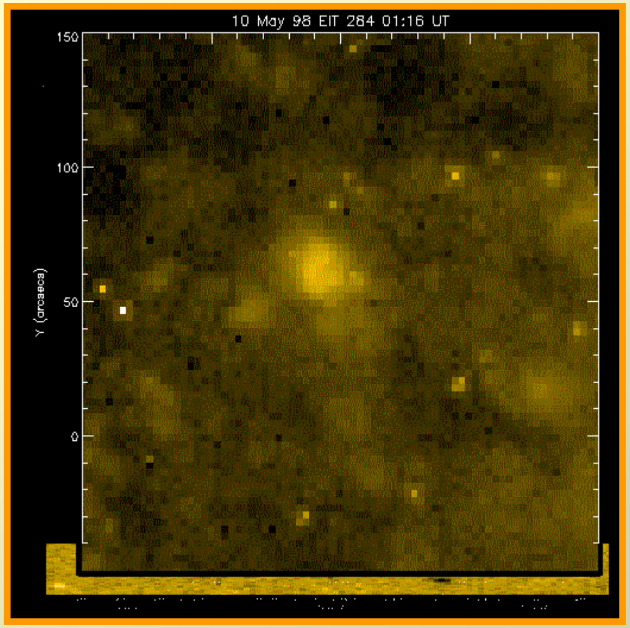
van Driel-Gesztelyi et al. 2000

The small eruptive events on 11 May 1998



EIT 195 images in reversed contrast, events at 00:50 UT and 08:45 UT.





EIT 284, 10 – 12 May 1998

1° event → elongated loops → burst → compact core → NE dimming

3° event → elongated loops → burst → compact core → NE + SW dimmings and cusp

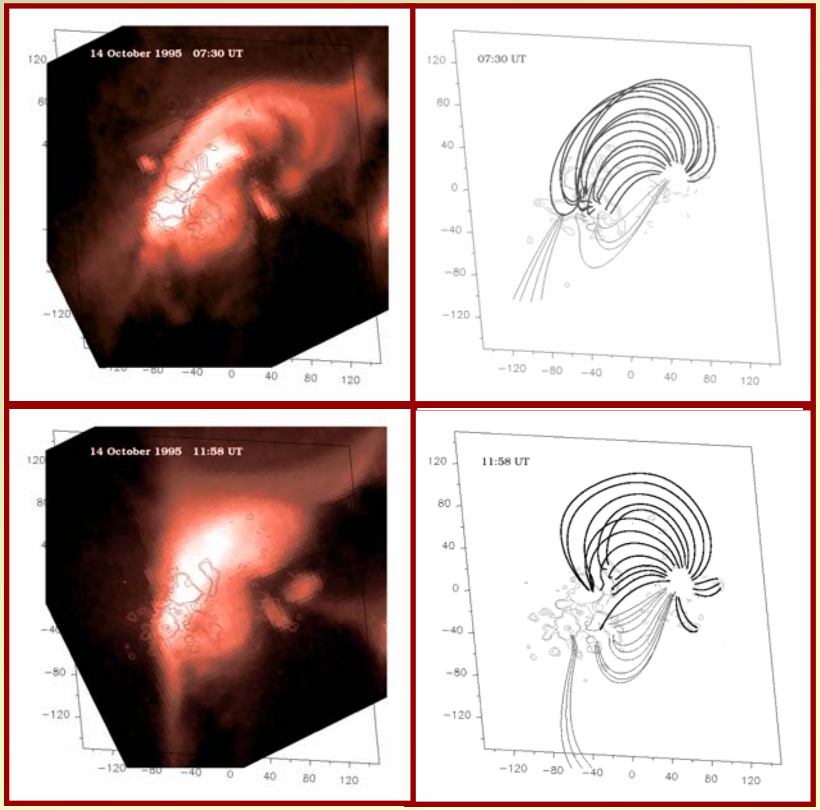
Dimmings -- loss or depletion of mass or cooling
Cusp-shaped loops -- reclosing of loops after opening

→ **signatures of eruption**

"Shortening" of coronal loops → **relaxation** (lower energy state).

Mandrini et al. 2005

AR7912 - Coronal magnetic helicity



SXT full disk at 07:30 UT and 11:58 UT

Magnetic maps - thick (thin) lines higher (lower) α.
Isocont. = ± 70., 140. G.

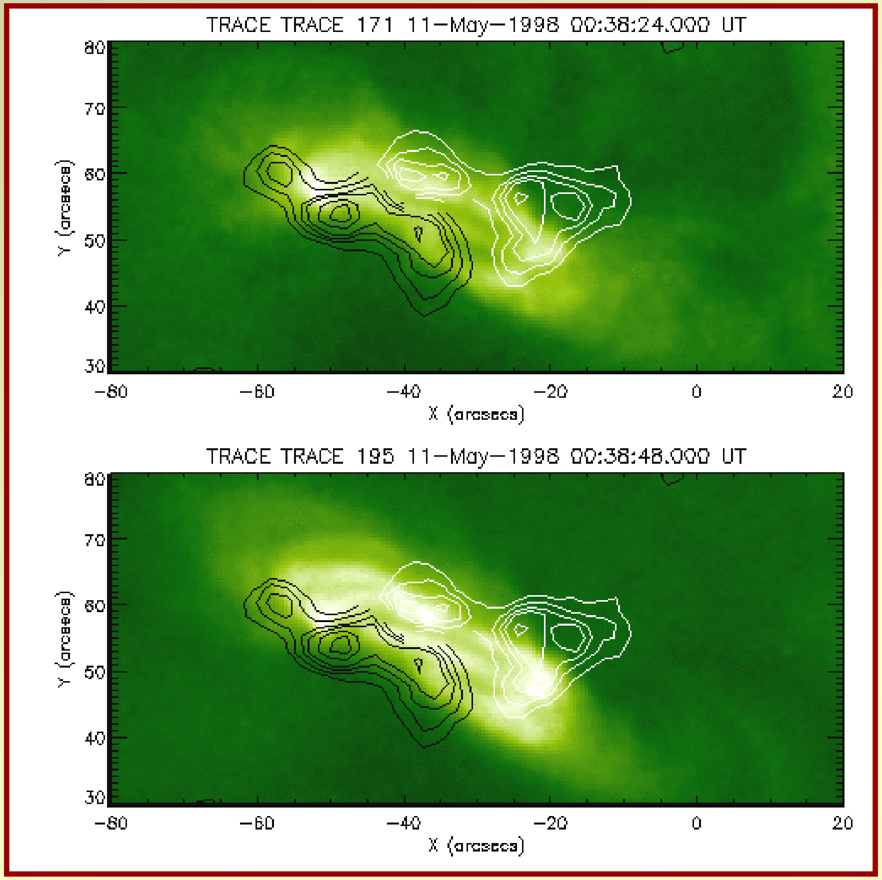
We compute the (linearized) relative coronal magnetic helicity using a lfff model - $\nabla \times B = \alpha B$ - and an FFT method.

Time UT	α (10^{-2} Mm^{-1})	H_{cor} (10^{42} Mx^2)	F_{AR} (10^{21} Mx)
07:30	0.94-2.07	7.-15.	8.0
11:58	0.12-1.50	1.-12.	8.4

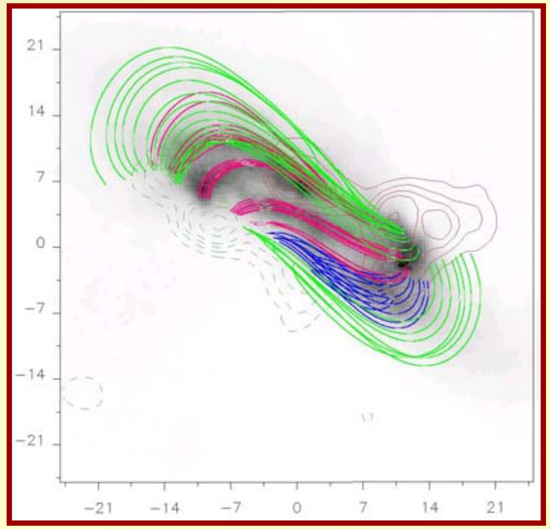
Luoni et al. 2005

Small AR - Coronal magnetic helicity

Mandrini et al. 2005



TRACE 195, 00:38 UT on May 11 - MDI isocontours, 00:03 UT



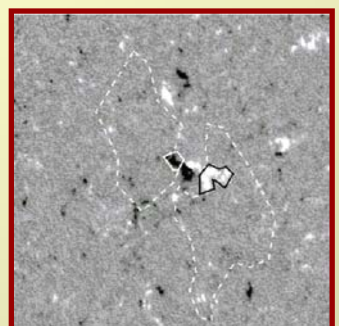
red, α = -0.11 Mm^{-1}

green+blue, α = -0.08 Mm^{-1}

Isocont. = ± 25., 50., 75., 100. 150., 200. G.

α Mm^{-1}	H_{cor} (10^{39} Mx^2) 00:03 UT	H_{cor} (10^{39} Mx^2) 11:11 UT	ΔH_{cor} (10^{39} Mx^2)
-0.08	-5.2	-2.9	-2.3
-0.11	-7.3	-4.2	-3.1

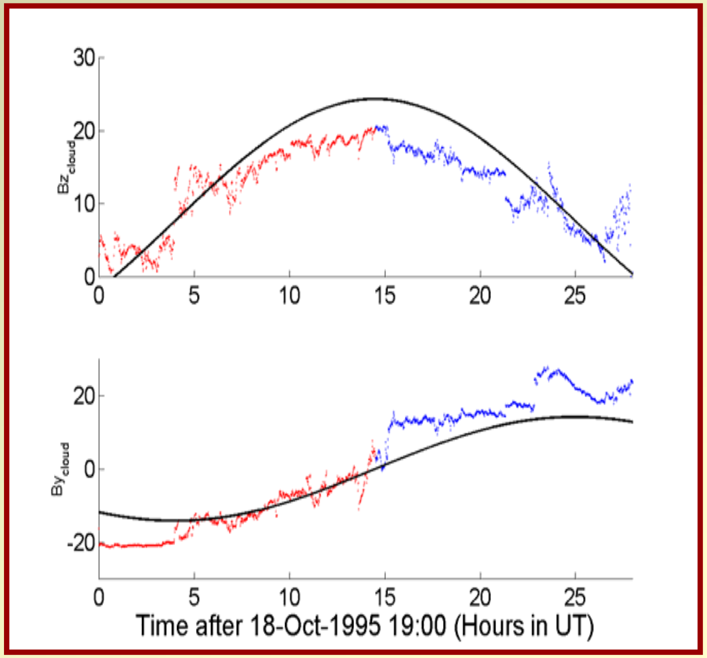
Magnetic flux in an ejection -- important global quantity to link coronal to interplanetary observations.
Upper limit → magnetic flux contained in the dimmings



$F_{dimming}$~13. ± 2. x 10^{19} Mx

<F_{AR}>~32 x 10^{19} Mx, max.

Interplanetary event on 18-19 October, 1995



Observed (red-blue) and fitted (black) components of the magnetic field (nT) in the cloud frame

Lepping et al. 1997, Larson et al. 1997, Janoo et al. 1998, Collier et al. 2001,

Hidalgo et al. 2002

An interplanetary flux tube can be modelled locally as a straight cylindrical structure.

Using the lfff model $\mathbf{B} = B_0 J_0(\alpha r)\mathbf{z} + B_0 J_1(\alpha r)\boldsymbol{\varphi}$

(Lundquist's model).

Taking an appropriate reference field:

$$\tau(r) = \frac{J_1(\alpha r)}{r J_0(\alpha r)} \ , \ \tau_0 = \alpha / 2$$

$$\frac{H_r^{LFFF}}{4\pi L} = \frac{B_0^{\ 2}}{2\tau_0} \int_0^R dr \ r J_1^{\ 2}(2\tau_0 r)$$

$$F_z = \frac{2\pi B_0}{4\tau_0^2} \int_0^{2\tau_0 R} dx \ x J_1(x)$$

$$\frac{F_\varphi}{L} = \frac{B_0}{2\tau_0} \int_0^{2\tau_0 R} dx \ J_1(x)$$

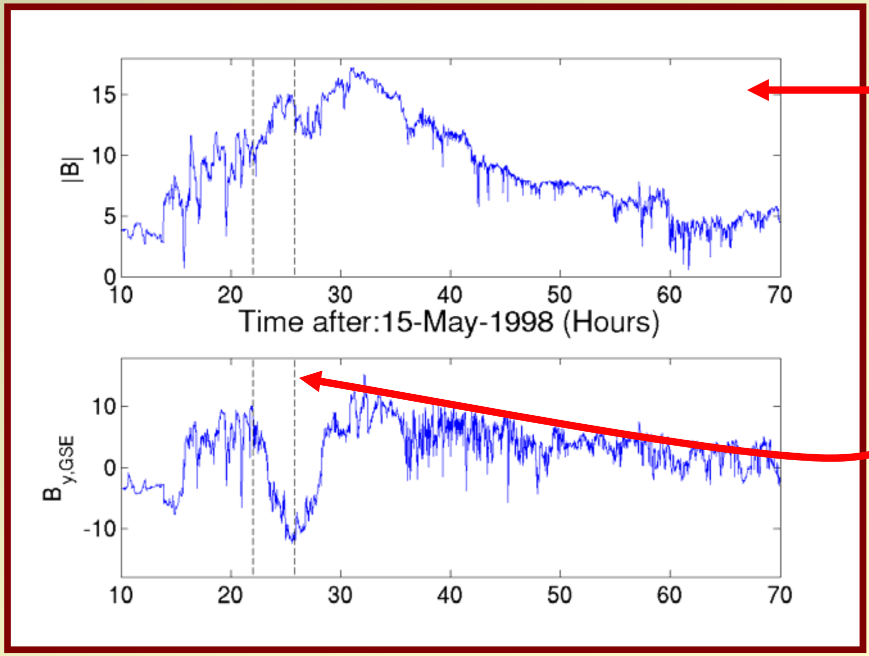
Model	R	τ_0	B_0	F_z	H_r/L
	AU	AU^{-1}	nT	Mx	Mx^2/AU
Lund.	0.12	10	24.3	$1.1x10^{21}$	$3.0x10^{42}$

Luoni et al. 2005

θ = -5° φ = 203°

from a MV method

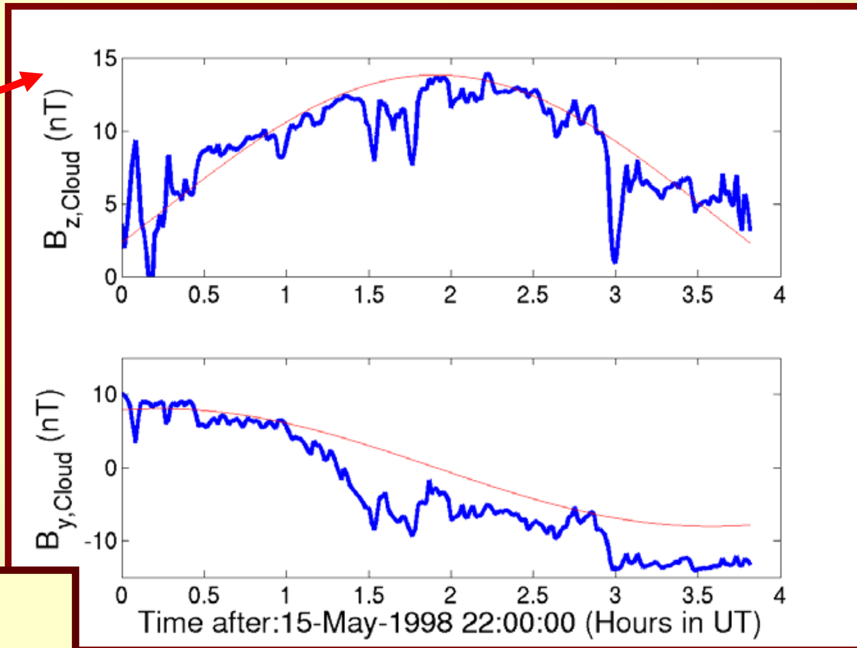
Small MC on 15-16 May, 1998



Scanning WIND data 2-5 days after the solar events:

- **300 km/s ≤ |Vr| ≤ 400 km/s from May 13 – 16.**
- **between May 15 –17 extended region with high and disordered field, low proton β → complex interplanetary ejecta.**

Isolate a small MC from 22:00 UT on May 15 to 01:50 UT on May 16 → with a solar wind speed ~350±50 km/s the travel time is ~119±17 hs → good candidate to be the interplanetary manifestation of the solar event.



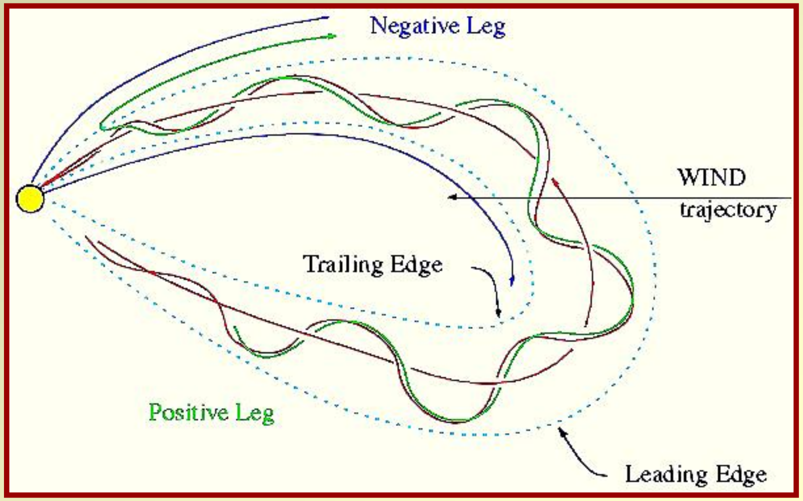
θ = 59° φ = 172°

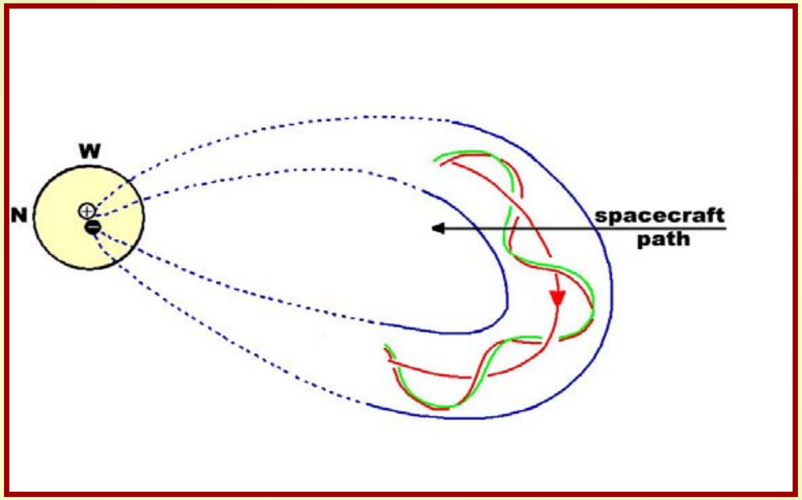
from a MV method

Model	R	τ_0	B_0	F_φ/L	F_z	H_r/L
	AU	AU^{-1}	nT	Mx/AU	Mx	Mx^2/AU
Lund.	1.6×10^{-2}	-66	13.8	20×10^{19}	1.3×10^{19}	-3.0×10^{39}

Mandrini et al. 2005

Linking coronal eruptions to interplanetary MCs





Schematic global views of the MCs
Top 18-19 October, 1995 (Larson et al.1997) – bottom 15-16 May, 1998 (Mandrini et al. 2005)

Quantitative link:

October event

$\langle F_{AR} \rangle \sim 8.2 \times 10^{21}$ Mx $F_{cloud} = 1.1 \times 10^{21}$ Mx

$F_{cloud} \sim 10\% \, F_{AR}$ (as in statistical studies by Lepping et al. (1991), Zhao et al. (2001), Watari et (2001))

$$3 \times 10^{42}\ Mx^2 \leq \Delta H_{cor} \leq 6 \times 10^{42}\ Mx^2$$

$$H_{cloud} = 7 \times 10^{42}\ Mx^2 \ \text{(maximum)}.$$

L ~ 2.4 AU → estimated from in situ observations of impulsive electrons, flux tube connected to the Sun (Larson et al. 1997).

May event

$F_{dimmings} \sim 13 \pm 2 \times 10^{19}$ Mx $F_{cloud} = 10 - 20 \times 10^{19}$ Mx

$$2.3 \times 10^{39}\ Mx^2 \leq |\Delta H_{cor}| \leq 3.1 \times 10^{39}\ Mx^2$$

$$1.5 \times 10^{39}\ Mx^2 \leq |H_{cloud}| \leq 3.0 \times 10^{39}\ Mx^2$$

L ~ 0.5 – 1 AU → estimated considering that the small MC was detached from the Sun ~1 day after ejection + distance travelled by Alfvèn waves (~100 km/s) in 3.5 days (~0.2 AU).

Conclusions

We have shown, based on the computation of global MHD quantities, the link between solar ejections and magnetic clouds.

This happens for events with a very different range of sizes, fluxes and helicities:

-a factor 6 in size

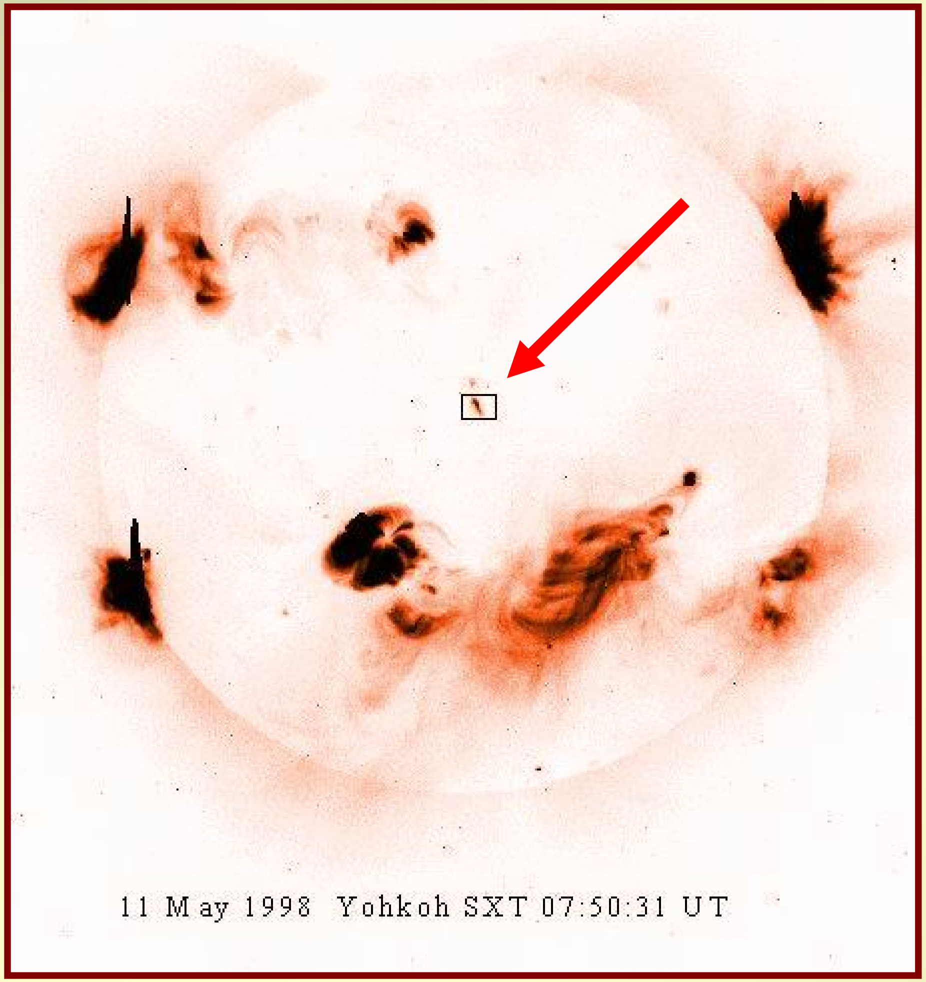
-a factor 20 in flux

-a factor 10^3 in magnetic helicity

More examples are needed to confirm this link. Then, the different nature of coronal (remote sensing) and interplanetary (in situ) data could be combined to constrain models in both domains.

The End

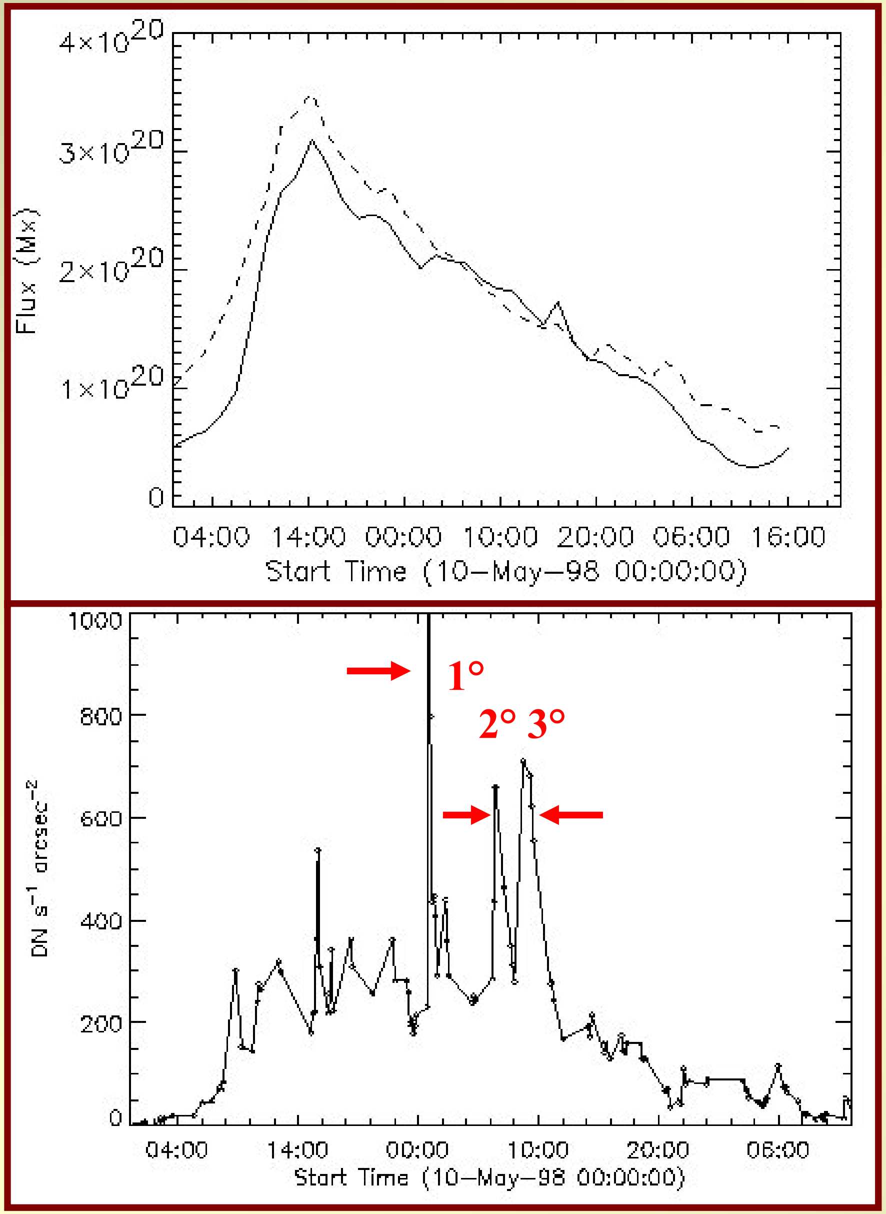
The small active region on the disk



The small AR was observed from May 10 to 12, 1998.

Its full evolution occurred close to disk center far from any other AR… and it was eruptive.

Evolution of the magnetic and soft X-ray flux



Outside flaring times (i.e. X-ray peaks) the X-ray flux (SXT) evolution agrees globally with the magnetic flux (MDI) evolution.

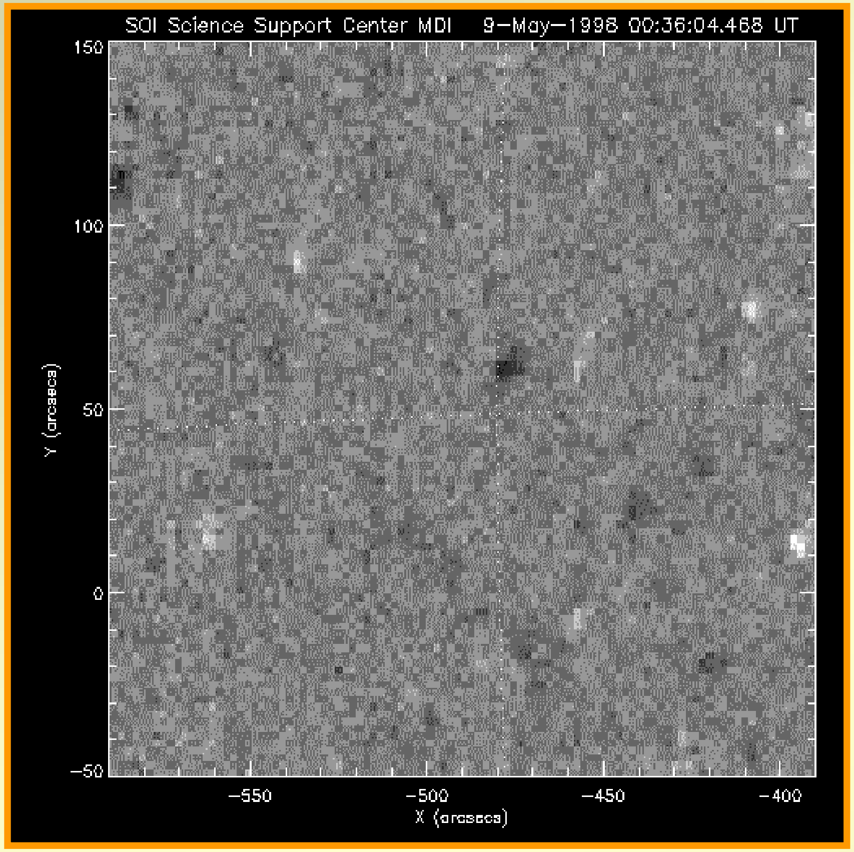
$\langle F_{AR} \rangle \sim 32 \times 10^{19}$ Mx at maximum

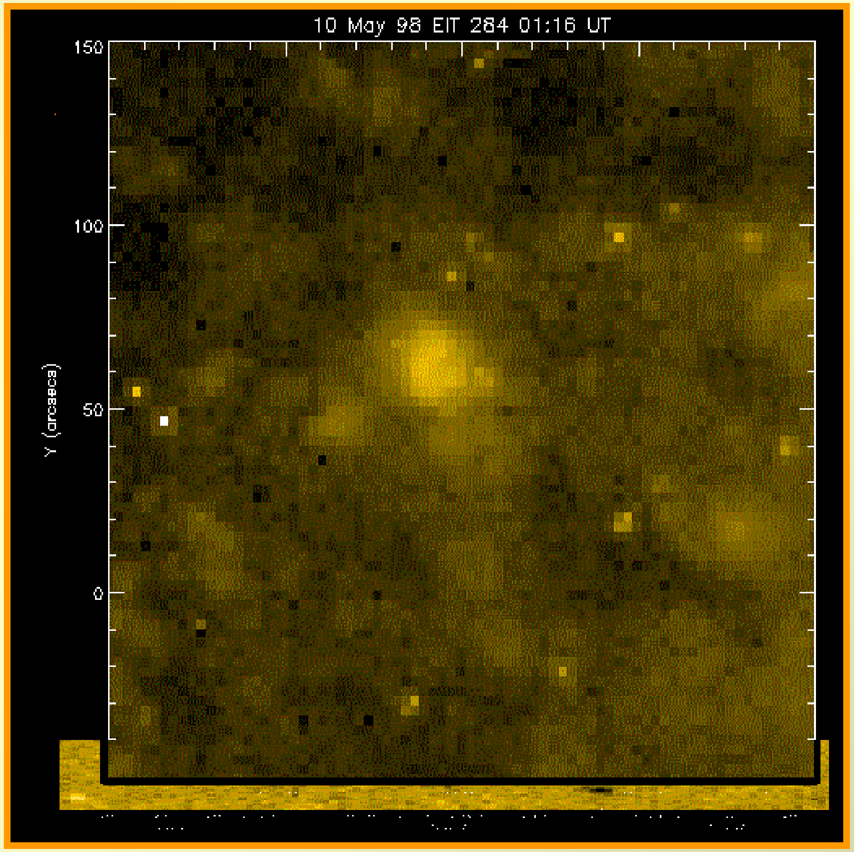
Most intense X-ray events on May 11:
1°) Max. ~ 00:50 UT, duration 26 min.
2°) Max. ~ 06:45 UT, duration 50 min.
3°) Max. ~ 08:45 UT, duration 3 hours

↓

The largest in time integrated X-ray flux

Photospheric and coronal evolution





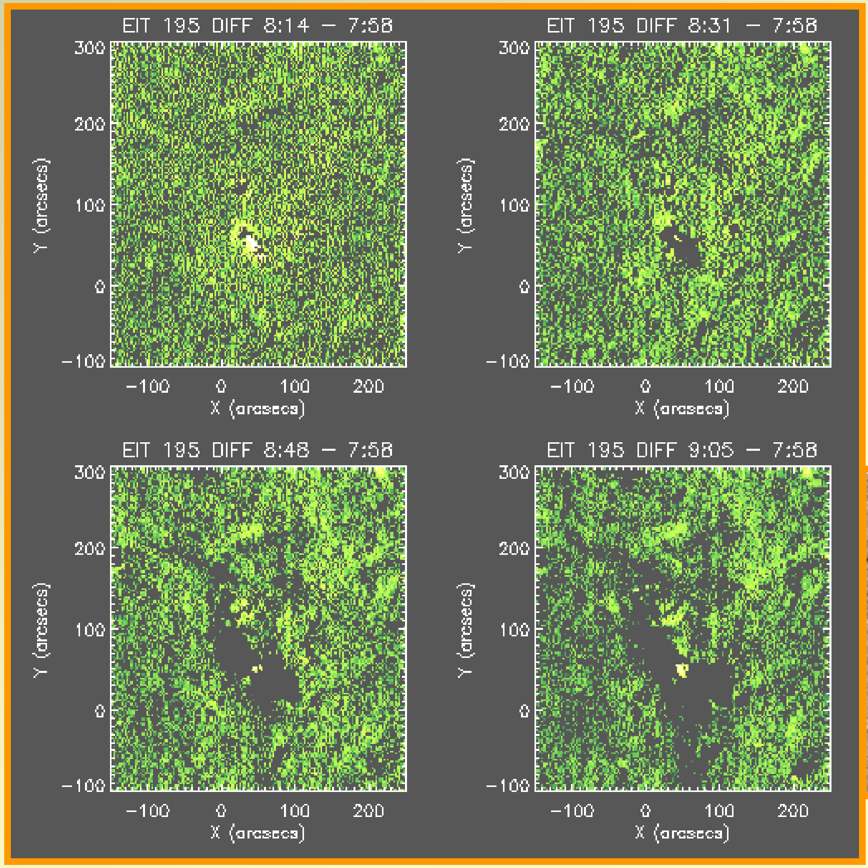
MDI from 9 May, 00:36 UT, to 12 May, 08:03 UT (AR decay).

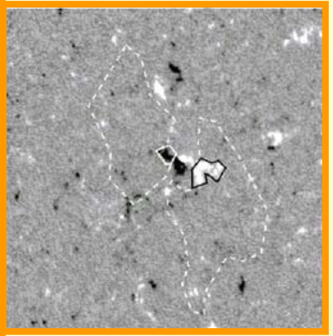
Rotation of polarities → evidence of the emergence of a highly twisted flux tube (López Fuentes et al. 2000, Mandrini et al. 2004).

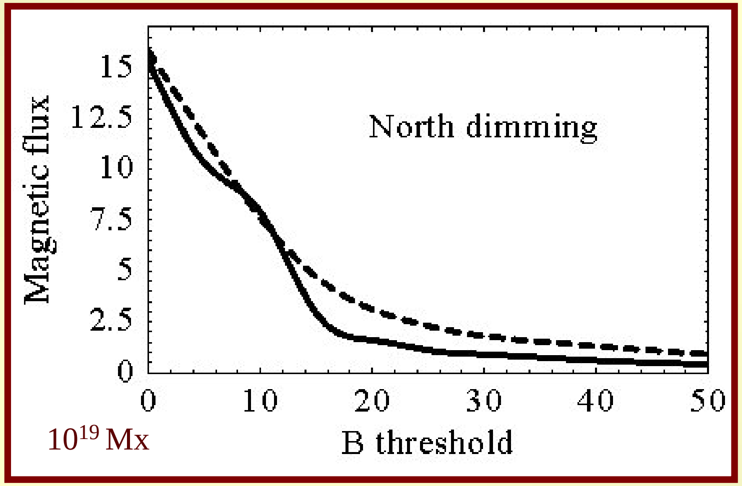
EIT 284 from 10 May, 01:16 UT, to 12 May, 07:05 UT.

Bright point followed by elongated sigmoidal appearance → evidence of high coronal twist → bright point again (AR decay).

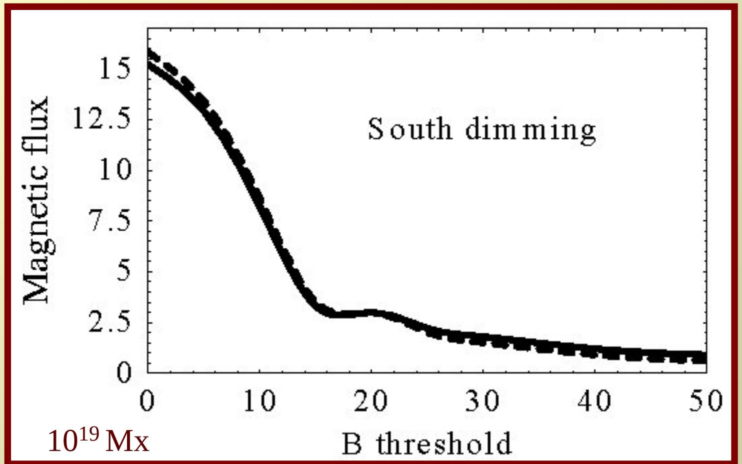
The flux in the dimmings







$F_{dimmings} \sim 13. \pm 2.\ x\ 10^{19}$ Mx



Difference images, EIT 195, showing the dimmings after 3° event - MDI high resolution magnetogram with contour of the dimmings.

Magnetic flux in an ejection -- important global quantity to link coronal to interplanetary observations.
Upper limit → magnetic flux contained in the dimmings

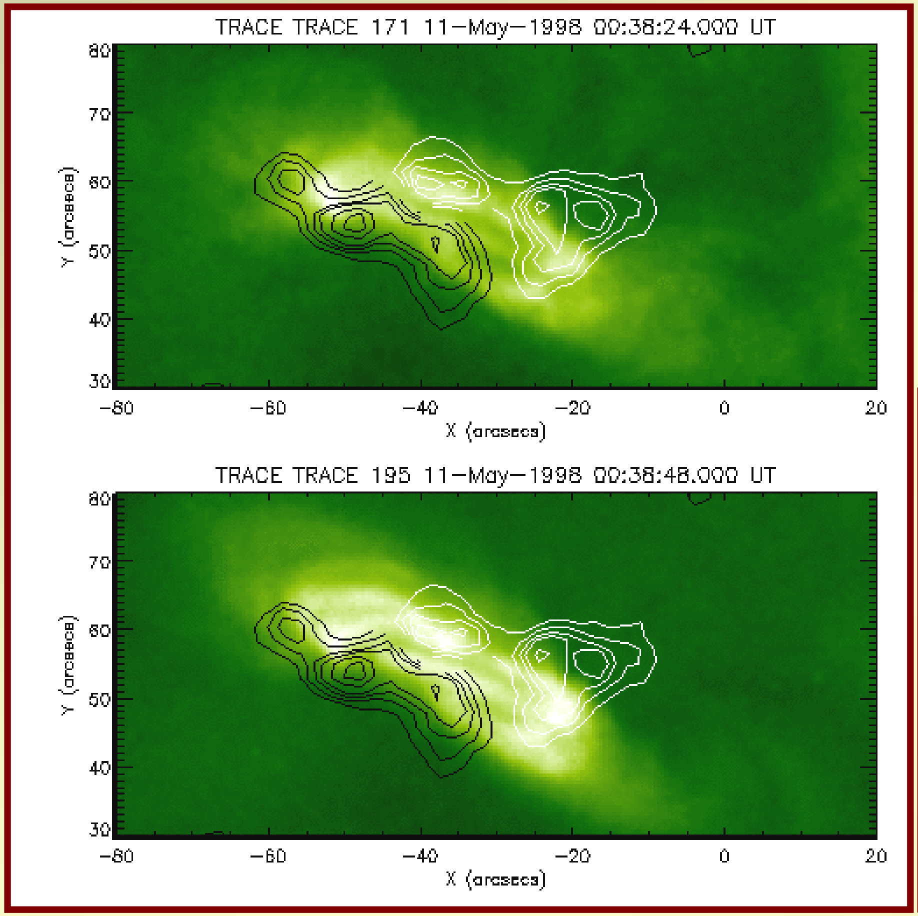
The coronal magnetic helicity

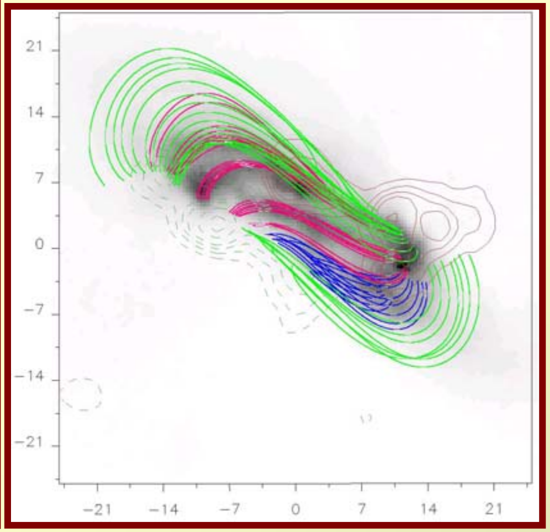
Using a lfff model - ∇xB=αB - of the coronal field and a FFT method, helicity is:

Berger (1985)

$$H_{Cor} = 2\alpha \sum_{n_x=1}^{N_x} \sum_{n_y=1}^{N_y} \frac{|B^2_{n_x,n_y}|}{l\,(k_x^2 + k_y^2)}$$

where $B_{nx,ny}$ are the Fourier amplitudes of the harmonics (n_x,n_y), $N_x = N_y$ the Fourier modes, $l = \sqrt{k^2_x + k^2_y - \alpha^2}$, $k_x = 2\pi n_x/L$, $k_y = 2\pi n_y/L$, and L is the size of the computational box.





red, α = -0.08 Mm^{-1}

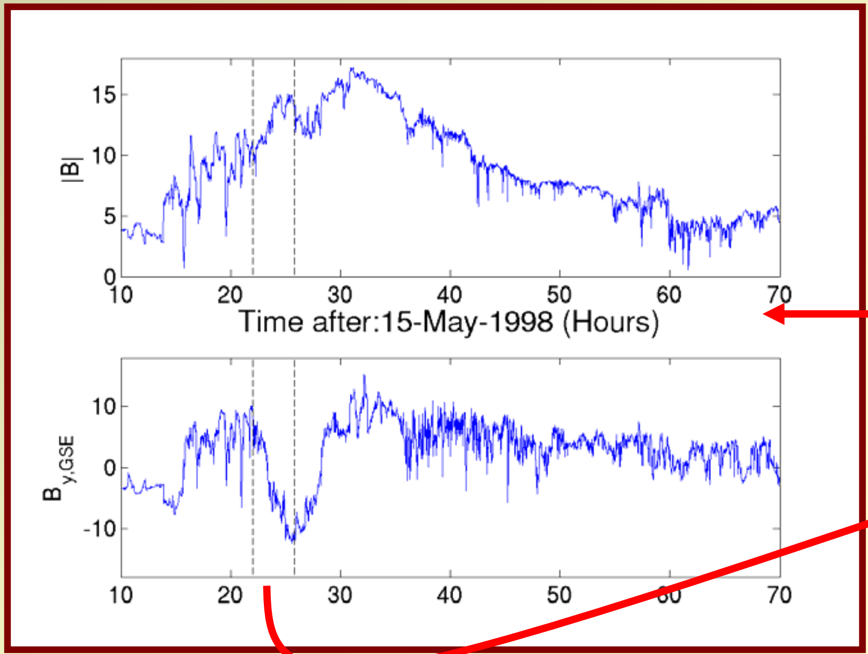
green+blue, α = -0.11 Mm^{-1}

Isocont. = ± 25., 50., 75., 100. 150., 200. G.

TRACE 195 (pixel size 1 arcsec) at 00:38 UT on May 11 with MDI isocontours of the field at 00:03 UT (positive: white, negative: black.

α Mm^{-1}	H_{cor} (10^{39} Mx^2) 00:03 UT	H_{cor} (10^{39} Mx^2) 11:11 UT	ΔH_{cor} (10^{39} Mx^2)
-0.08	-5.2	-2.9	-2.3
-0.11	-7.3	-4.2	-3.1

The associated interplanetary event - a small MC



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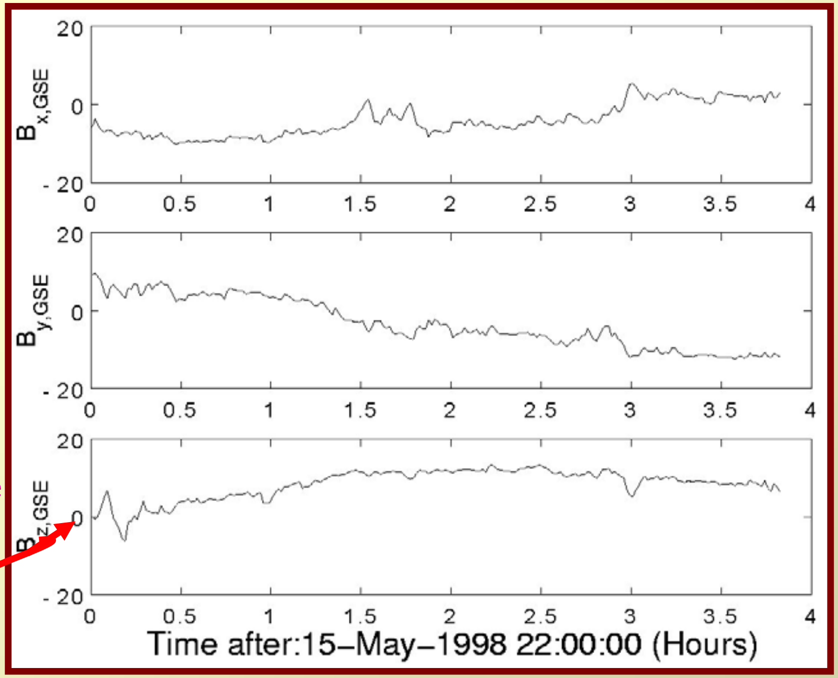
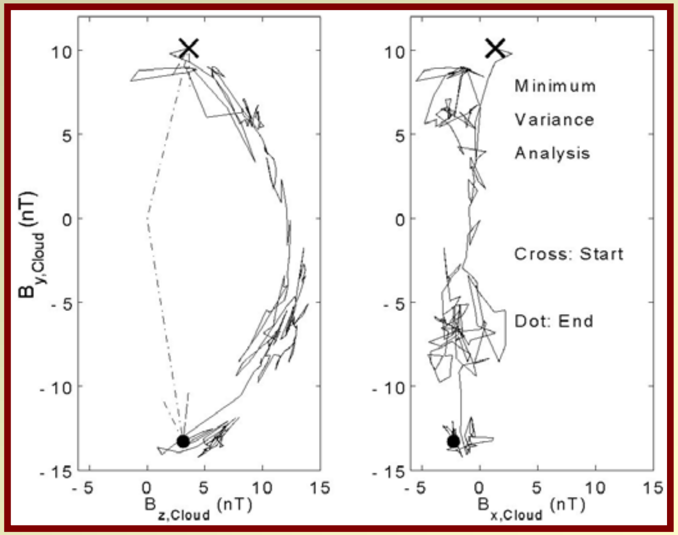


Isolate a small MC from 22:00 UT on May 15 to 01:50 UT on May 16 → with a solar wind speed ~350±50 km/s the travel time is ~119±17 hs → good candidate to be the interplanetary manifestation of the solar event.

Large coherent rotation of B_{yGSE} (~4 hours) → consistent with a cylindrical flux rope crossing the spacecraft; also high magnetic intensity and low proton T → MC.

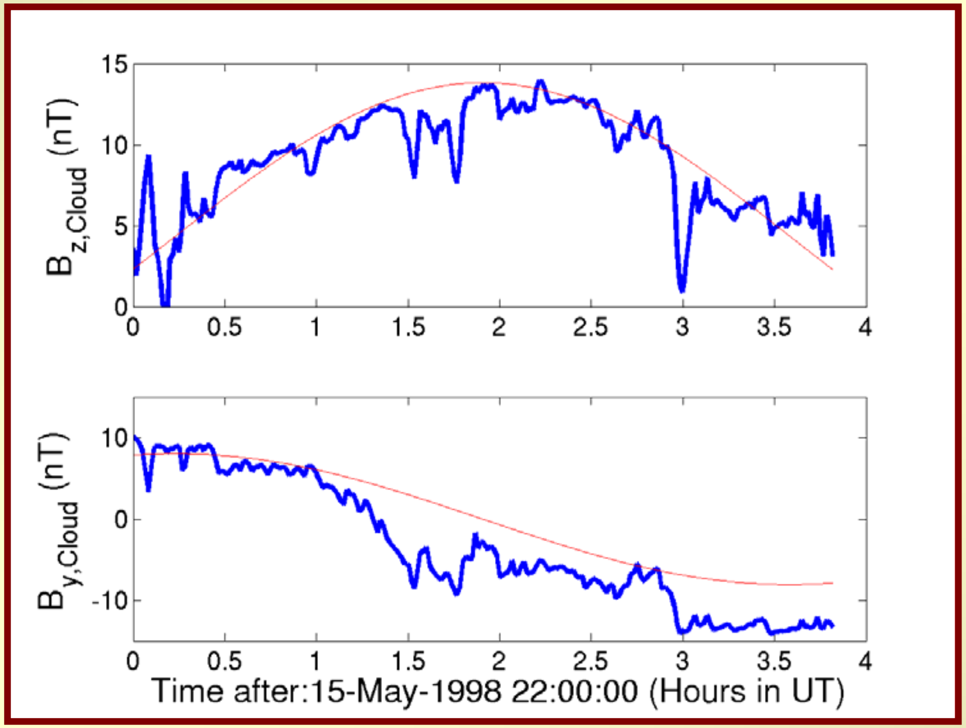
The global characteristics of the small MC



$\theta = 59°$ $\varphi = 172°$

from a MV method

Model	R AU	τ_0 AU^{-1}	B_0 nT	F_φ/L Mx/AU	F_z Mx	H_r/L Mx^2/AU
Lund.	1.6×10^{-2}	-66	13.8	20×10^{19}	1.3×10^{19}	-3.0×10^{39}



An interplanetary flux tube can be modelled locally as a straight cylindrical structure.

Using the lfff model $\mathbf{B} = B_0 J_0(\alpha r)\mathbf{z} + B_0 J_1(\alpha r)\boldsymbol{\varphi}$

(Lundquist, 1950).

Taking an appropriate reference field:

$$\tau(r) = \frac{J_1(\alpha r)}{r J_0(\alpha r)} \ , \ \tau_0 = \alpha / 2$$

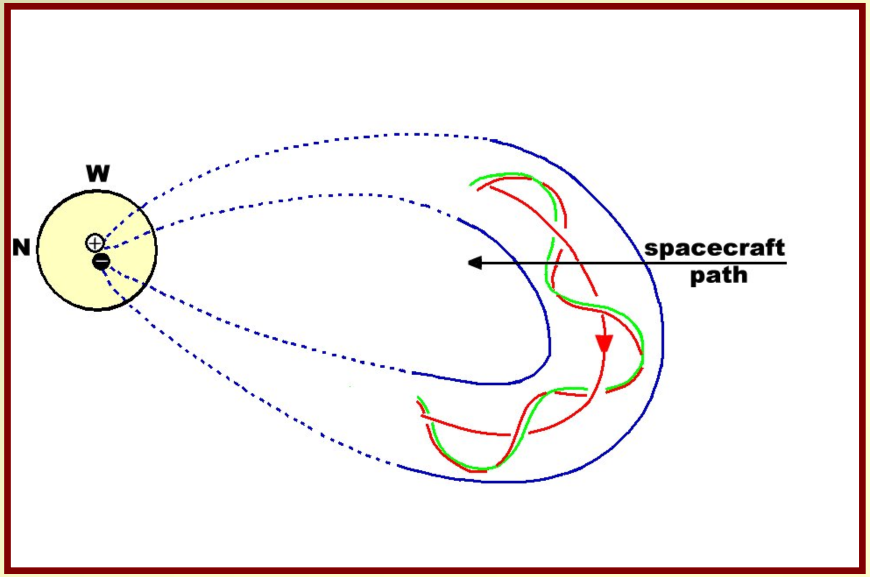
$$\frac{H_r^{LFFF}}{4\pi L} = \frac{B_0^{\ 2}}{2\tau_0} \int_0^R dr\ r J_1^{\ 2}(2\tau_0 r)$$

$$F_z = \frac{2\pi B_0}{4\tau_0^2} \int_0^{2\tau_0 R} dx\ x J_1(x)$$

$$\frac{F_\varphi}{L} = \frac{B_0}{2\tau_0} \int_0^{2\tau_0 R} dx\ J_1(x)$$

Linking the coronal eruption to the interplanetary MC

We propose that the 3° ejection, the one having the largest integrated X-ray flux, dimming extension and EIT core brightening shortening, is the source of the small MC.



Schematic global view of the small MC and its source region.

Clues:

- **location in the corona: disk center → travelling in the radial direction can be detected by WIND.**
- **timing: 4.5 days delay, expected for a slow CME at the slow solar wind speed.**
- **orientation of the MC axis the same as the direction of the coronal sigmoid.**
- **same sign of both magnetic fields and helicities.**

More clues:

$F_{dimmings} \sim 13 \pm 2 \times 10^{19}$ Mx $F_{cloud} = 10 - 20 \times 10^{19}$ Mx

$$2.3 \times 10^{39}\ Mx^2 \leq |\Delta H_{cor}| \leq 3.1 \times 10^{39}\ Mx^2$$

$$1.5 \times 10^{39}\ Mx^2 \leq |H_{cloud}| \leq 3.0 \times 10^{39}\ Mx^2$$

L ~ 0.5 – 1 AU → estimated considering that the small MC was detached from the Sun ~1 day after ejection + distance travelled by Alfvèn waves (~100 km/s) in 3.5 days (~0.2 AU).

Conclusion and remarks

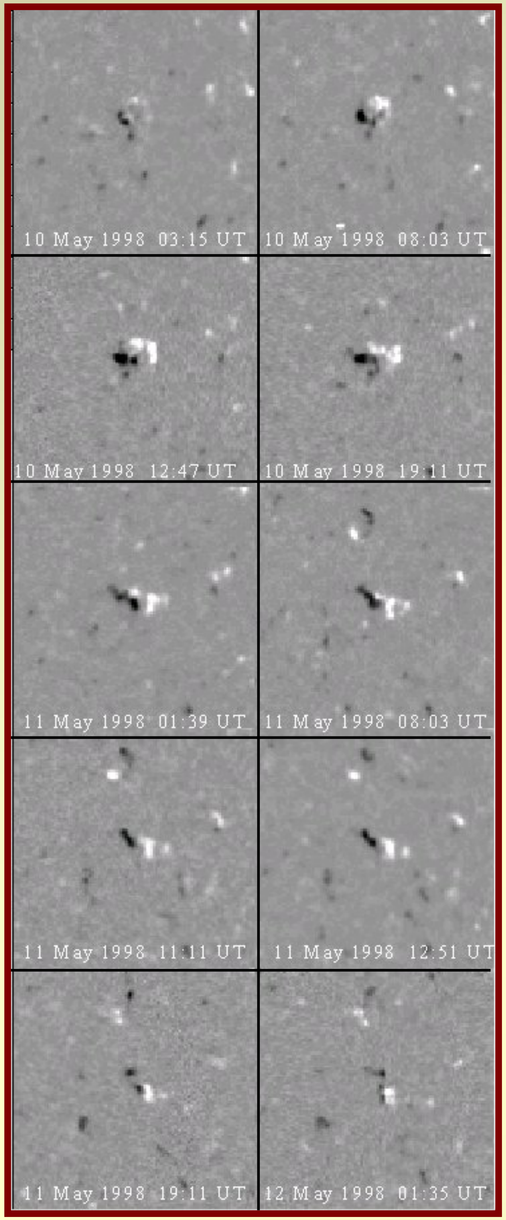
We have shown, based on several pieces of evidence, the link between a very small solar ejection and a very small magnetic cloud.

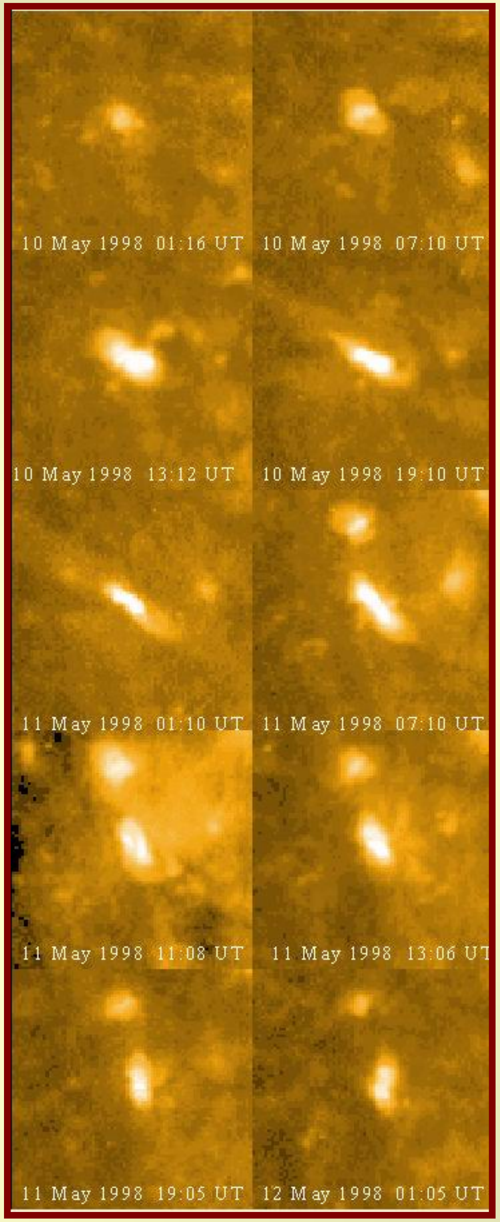
The relevance:

- **This example broadens our knowledge of solar eruptions: they can also be of small scale.**
- **These small events are a challenge for theoretical models** which are presently developed for large scale magnetic configurations. **How can such a small amount of flux lead to an eruption and send a magnetic flux rope into the interplanetary space?**

Next missions (Solar B and Stereo) may help us understand these small events $\rightarrow$ their relative importance in terms of magnetic flux, energy and helicity both in the corona and solar wind.

Photospheric and coronal evolution





The previous evolution image by image

May 10, 19:10 UT → elongated sigmoidal brightening.

May 11, 01:10 UT → "shortening" of the EUV core emission + elongated large scale loops (1° event).

May 11, 07:10 UT → again, elongated sigmoidal brightening (previous to 3° event).

The EUV emission extends and rotates in parallel to the photospheric changes