

Non-axisymmetric and Multi-tube Magnetic Flux Ropes in the Solar Wind

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Acknowledgement

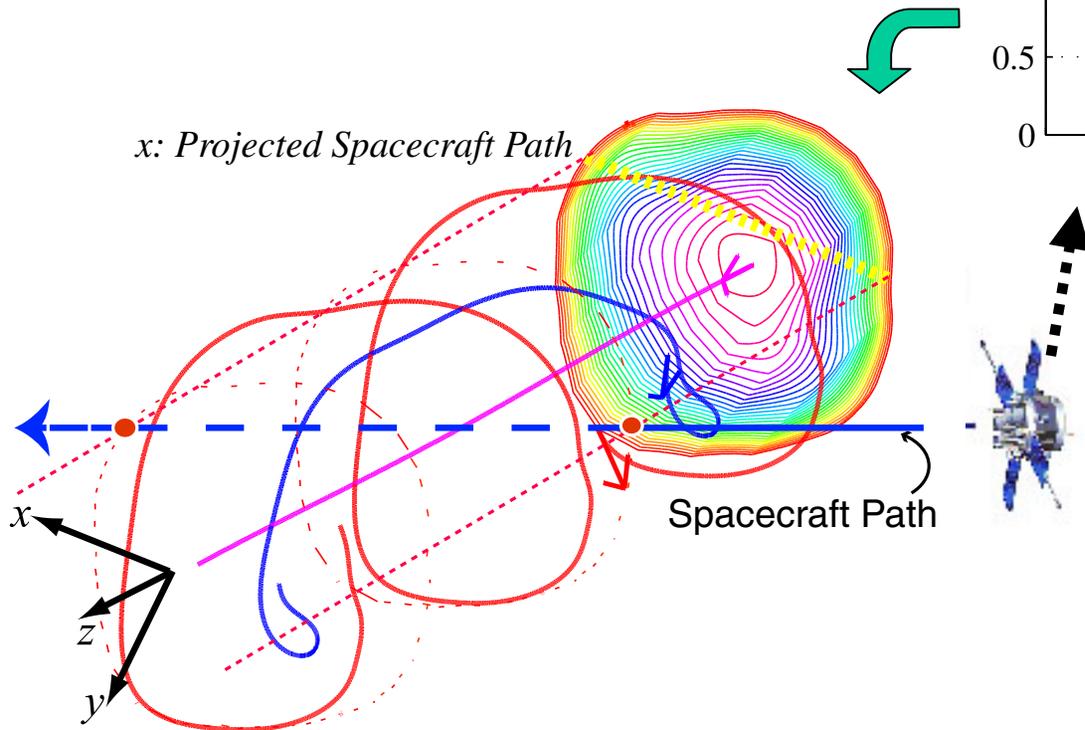
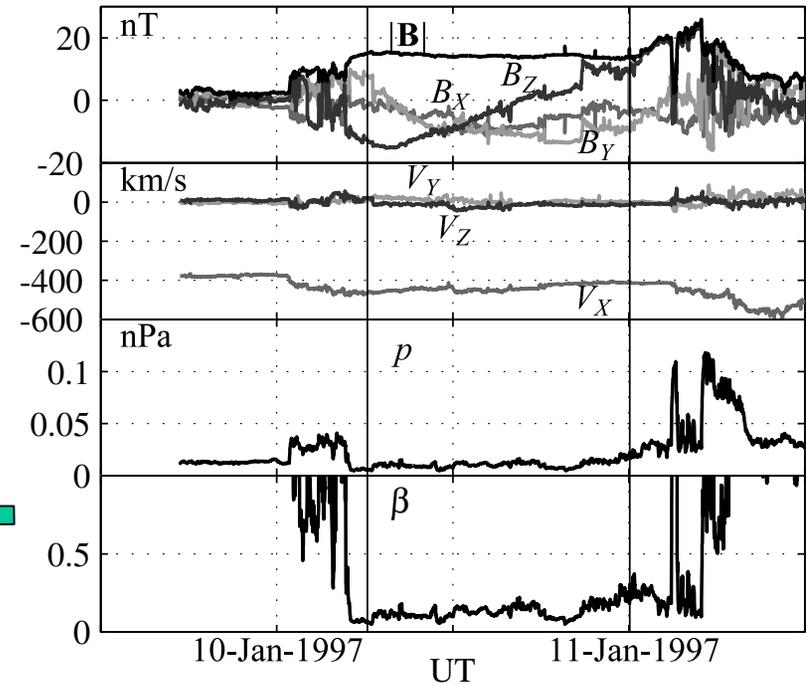
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Grad-Shafranov (GS)

Reconstruction: A novel technique to derive the cross-sections of magnetic structures in space plasmas from limited spacecraft measurements along a single line.



Overview

- Grad-Shafranov (GS) equation, the GS reconstruction technique, and diagnostic measures.
- Advantages and limitations.
- Applications to magnetic clouds/ejecta observations.
 - Single flux-rope topology
 - Multiple flux-rope topology
- Solar connections – SHINE theme.
- Summary and Goals

Theory and Technique

- One-fluid Magnetohydrostatic Theory
 - 2 1/2 D: $\partial/\partial z \approx 0$ $B_z \neq 0$
 - Co-moving frame: DeHoffmann-Teller (HT) frame
 - No inertia force


$$\nabla p = \mathbf{j} \times \mathbf{B}, \quad \mu_0 \mathbf{j} = \nabla \times \mathbf{B}, \quad \nabla \cdot \mathbf{B} = 0.$$

Grad-Shafranov (GS) Equation:

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} = -\mu_0 \frac{d}{dA} \left(p + \frac{B_z^2}{2\mu_0} \right) = -\mu_0 \frac{dP_t}{dA}$$

$$\mathbf{B} = (\partial A / \partial y, -\partial A / \partial x, B_z(A)). \quad \nabla A \cdot \mathbf{B}_t = 0$$

$$P_t(A) = p(A) + B_z^2(A) / 2\mu_0$$

- GS Reconstruction Technique

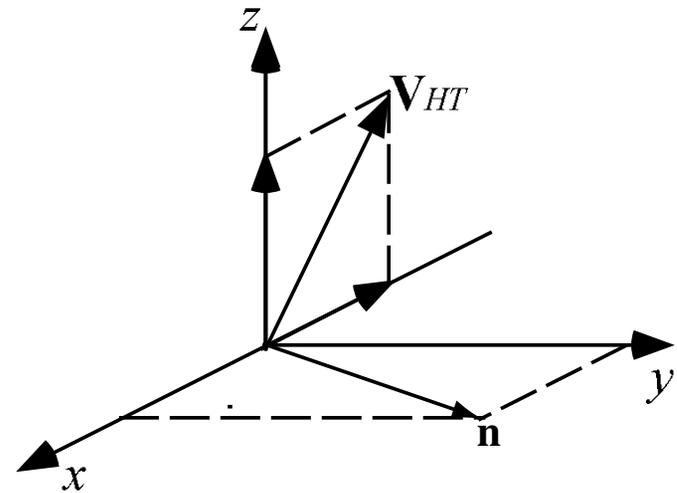
- Determine the z axis by optimizing $P_t(A)$ being single-valued
- Transform time to spatial dimensions via deHoffmann-Teller frame velocity, \mathbf{V}_{HT} , and calculate $A(x,0)$,

$$A(x,0) = -\int_0^x B_y(\xi,0) d\xi$$

$$d\xi = -\mathbf{V}_{HT} \cdot \hat{\mathbf{x}} dt$$

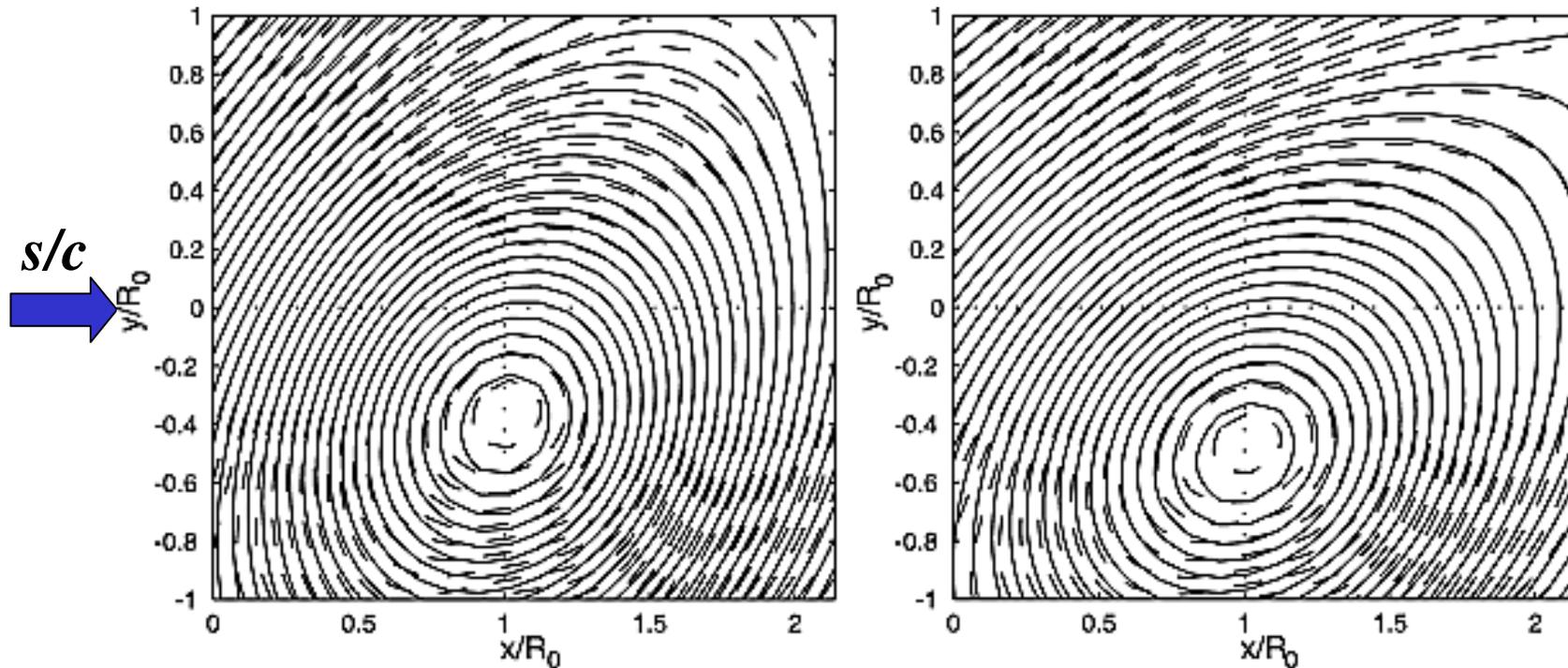
- Calculate $P_t(x,0)$ directly from measurements.
- Fit $P_t(x,0)/B_z(x,0)$ vs. $A(x,0)$ by a function, $P_t(A)/B_z(A)$.

- Obtain $A(x,y)$ by Taylor expansions, stepping away from $y=0$, utilizing $A(x,0)$, $B_x(x,0)$, and GS equation.

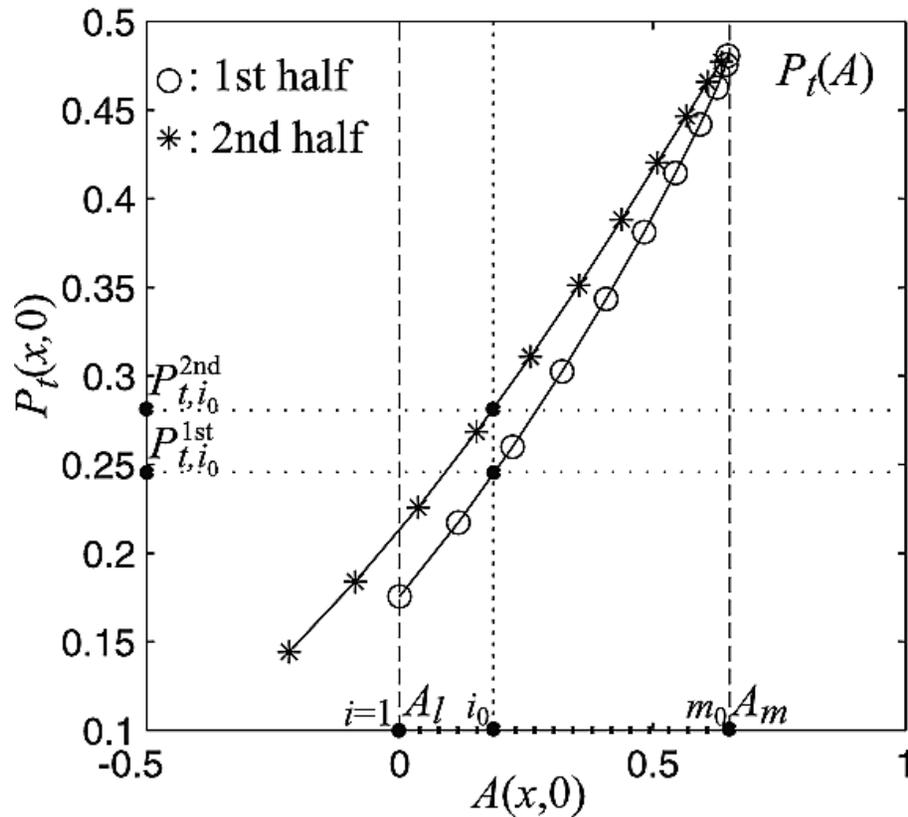


x: projected s/c path

- Benchmark: non-symmetric single flux-rope model: (no geometrical constraint on the cross-section)



Solid lines are analytic solutions (contours of A) and dashed lines are numerical solutions obtained by GS technique using data along $y=0$.



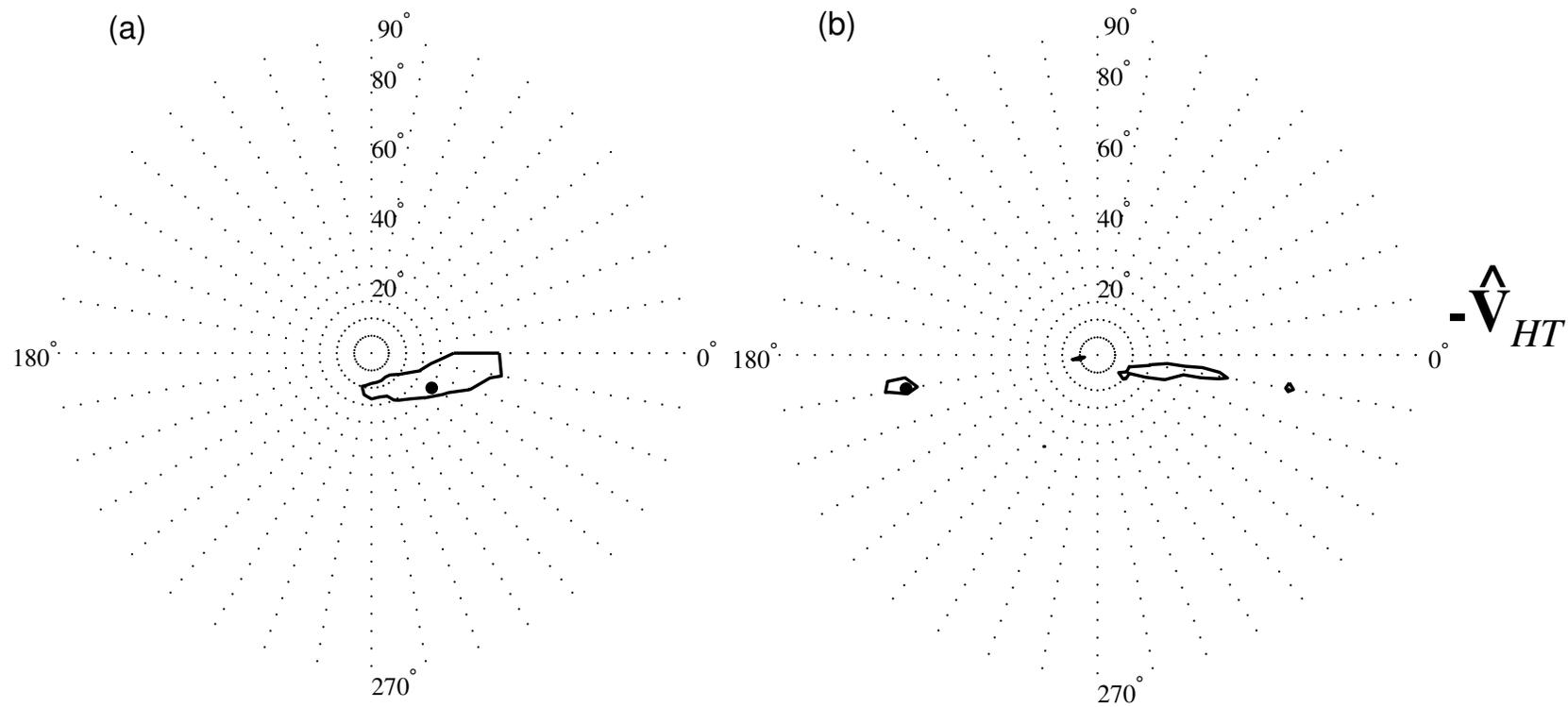
- Finding z axis by minimizing residue of $P_t(A)$:

$$Residue = \left[\sum_i (P_{t,i}^{1st} - P_{t,i}^{2nd})^2 \right]^{\frac{1}{2}}$$

$$/ |\max(P_t) - \min(P_t)|$$

*Enumerating all possible directions in space to find the optimal z axis for which the associated Residue is a minimum. A **residue map** is constructed to show the uniqueness of the solution with uncertainty estimate.*

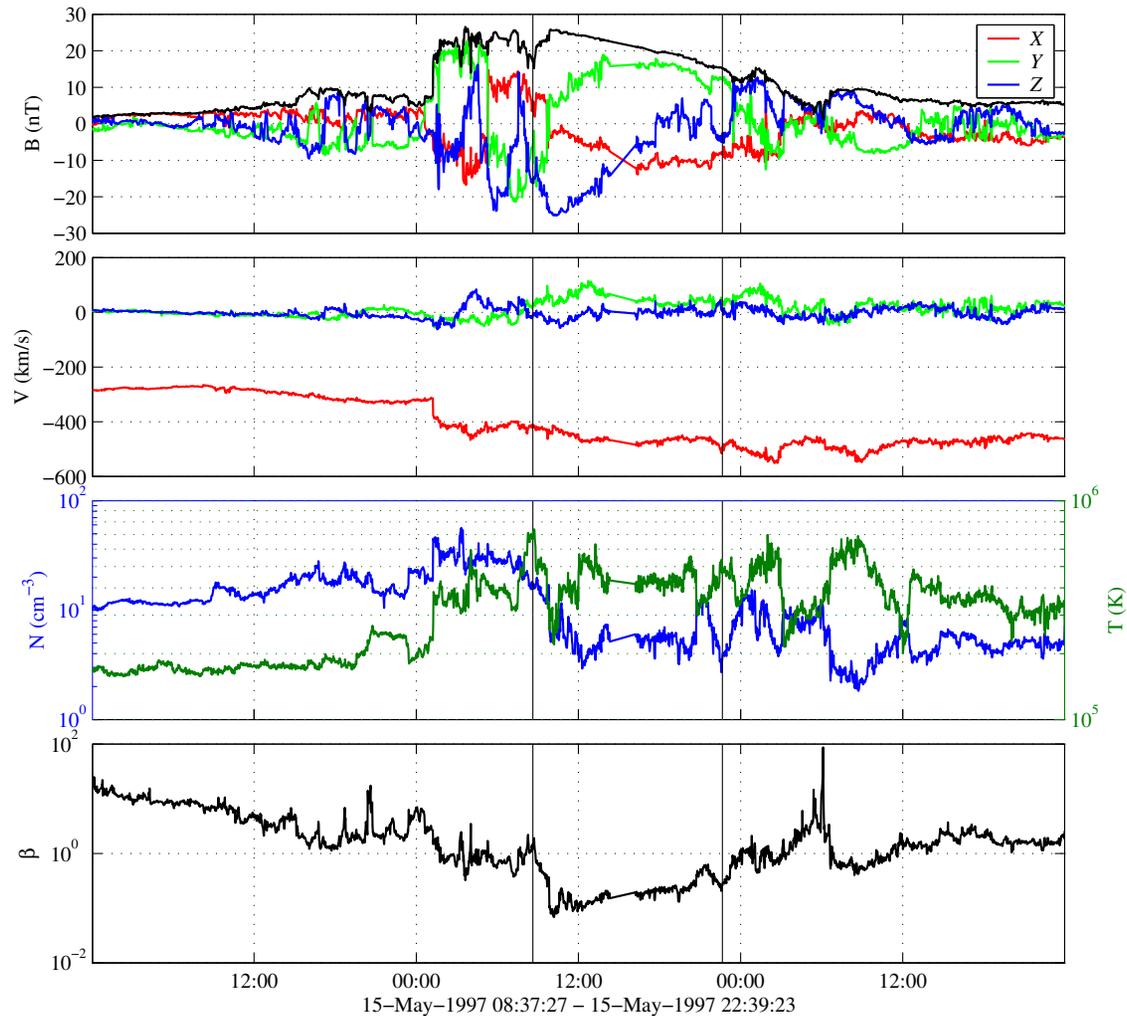
Residue map:



- Features of the GS Reconstruction Technique:
 - Fully 2 ½ D solution (less fitting)
 - Self-consistent theoretical modeling (less subjective)
 - Utilization of simultaneous magnetic and plasma measurements
 - Non-force free
- Limitations:
 - 2D, uncertainty in \mathbf{z} (the quality of $P_t(A)$ fitting, R_f)
 - $2D \Rightarrow P_t(A), P_t(A) \not\Rightarrow 2D$
 - Time stationary (quality of the HT frame)
 - Static (evaluating the residual plasma flow)
 - Numerical errors limit the extent in y direction (rule of thumb: $|y| \leq |x|, \Delta y \ll \Delta x$)

Single Flux-rope Magnetic Cloud

- SHINE Campaign Event: *May 12, 1997* (Wind)



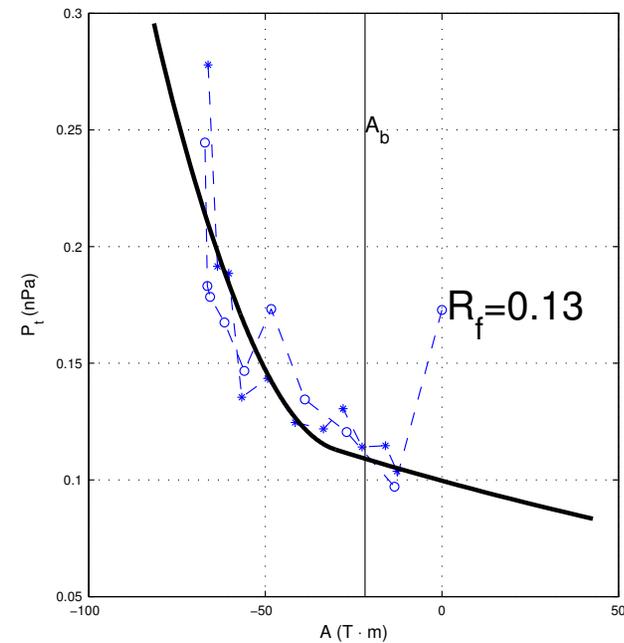
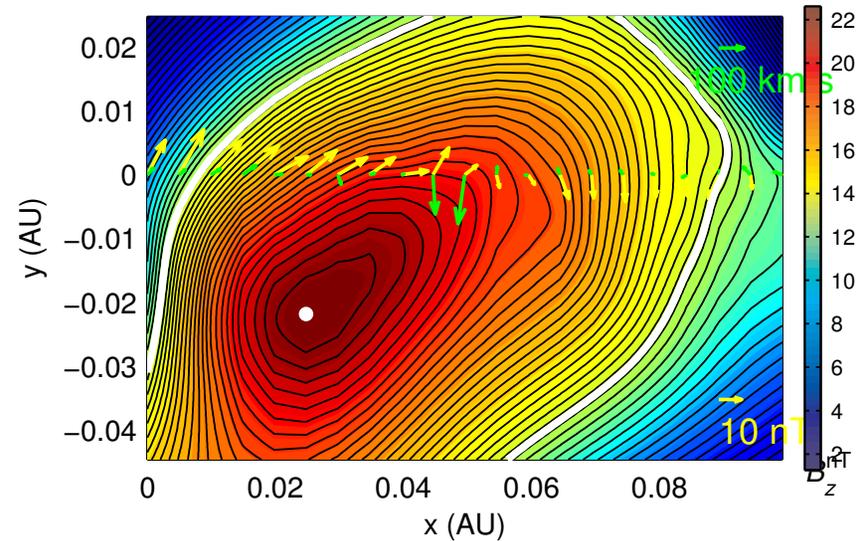
- Cross-section (top)
(transverse field lines and $B_z(x,y)$ in color; yellow arrows are measured transverse magnetic vectors)

- Boundary definition: the cylindrical surface having $A=A_b$ (highlighted by the white contour line) beyond which data (circles and stars) no longer appear following the black curve, $P_t(A)/B_z(A)$.

-Typical parameters obtained:

y_0	$B_{z\max}$	$j_{z\max}$	Φ_z	I_z
AU	nT	10^{-12}A/m^2	10^{12}Wb	10^8 A
-0.02	23	-6.7	1.9	3.3

and $\mathbf{z}=(136, 326)\pm (3,6)^\circ$ GSE

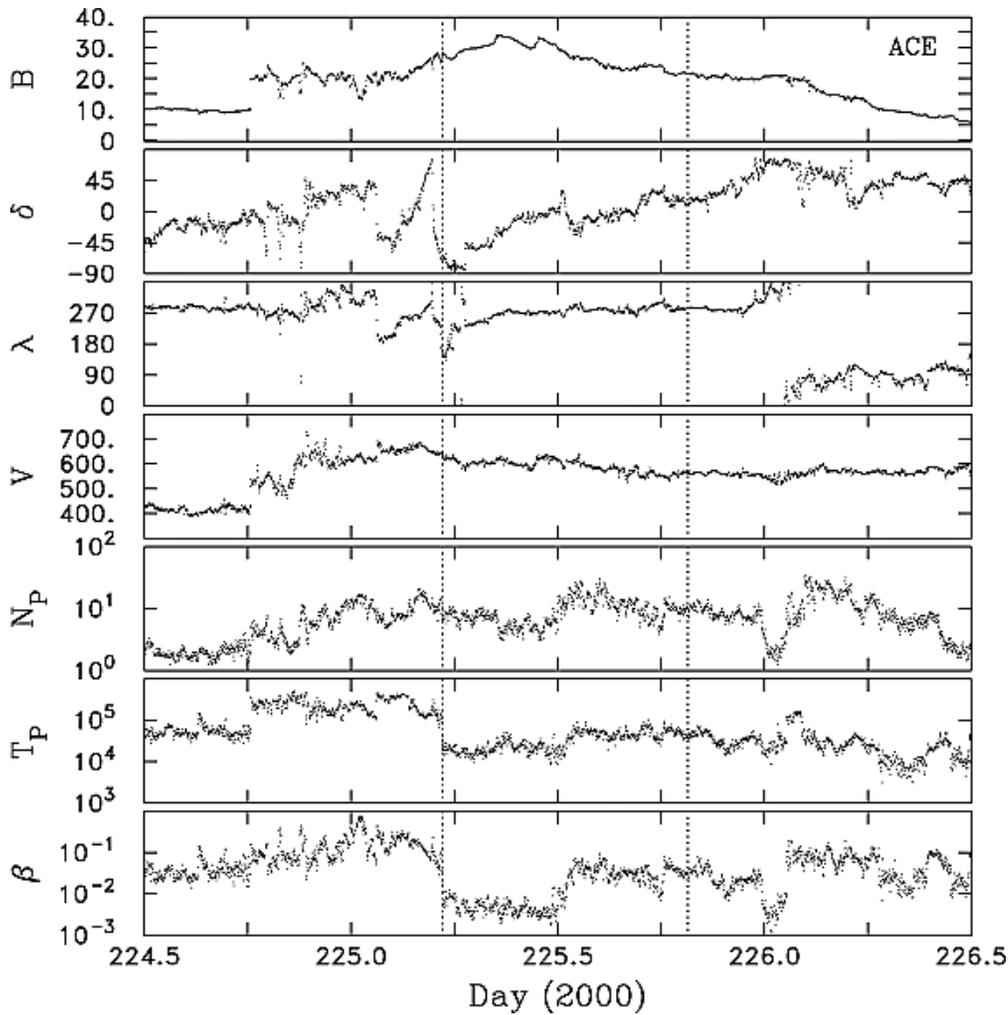


Multi-tube Flux-rope Ejecta

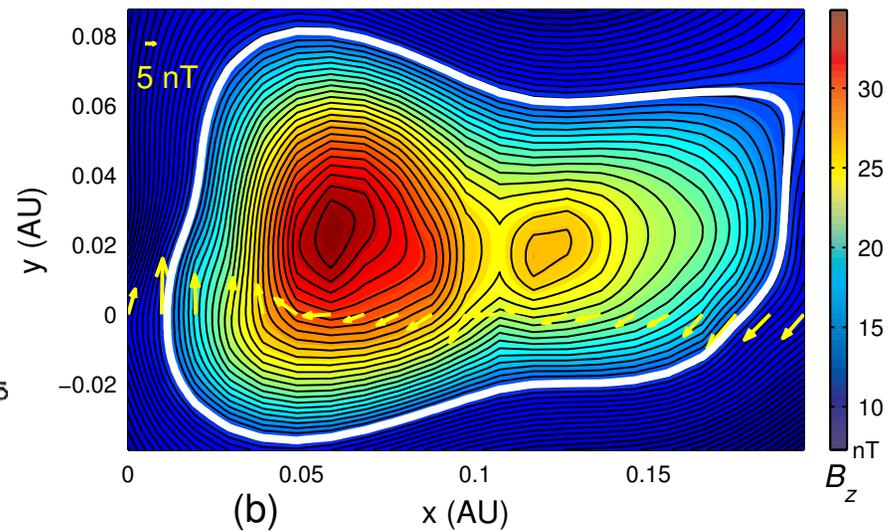
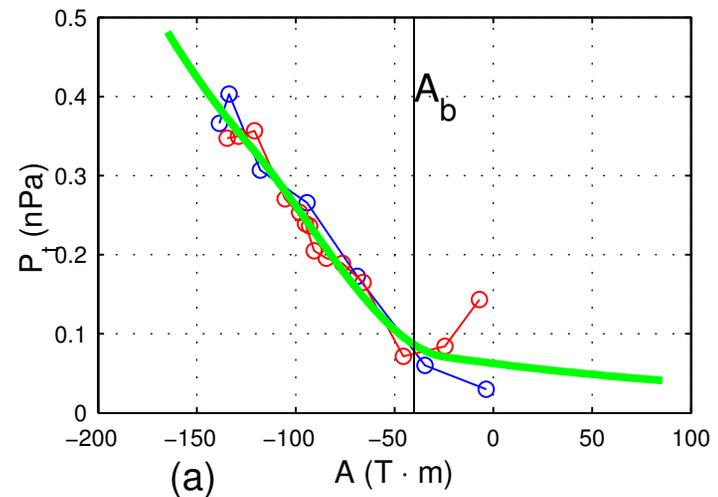
- Six multiple flux-rope clouds/ejecta out of 53 ACE events during year 1998 – 2002 (~20 single flux-rope)

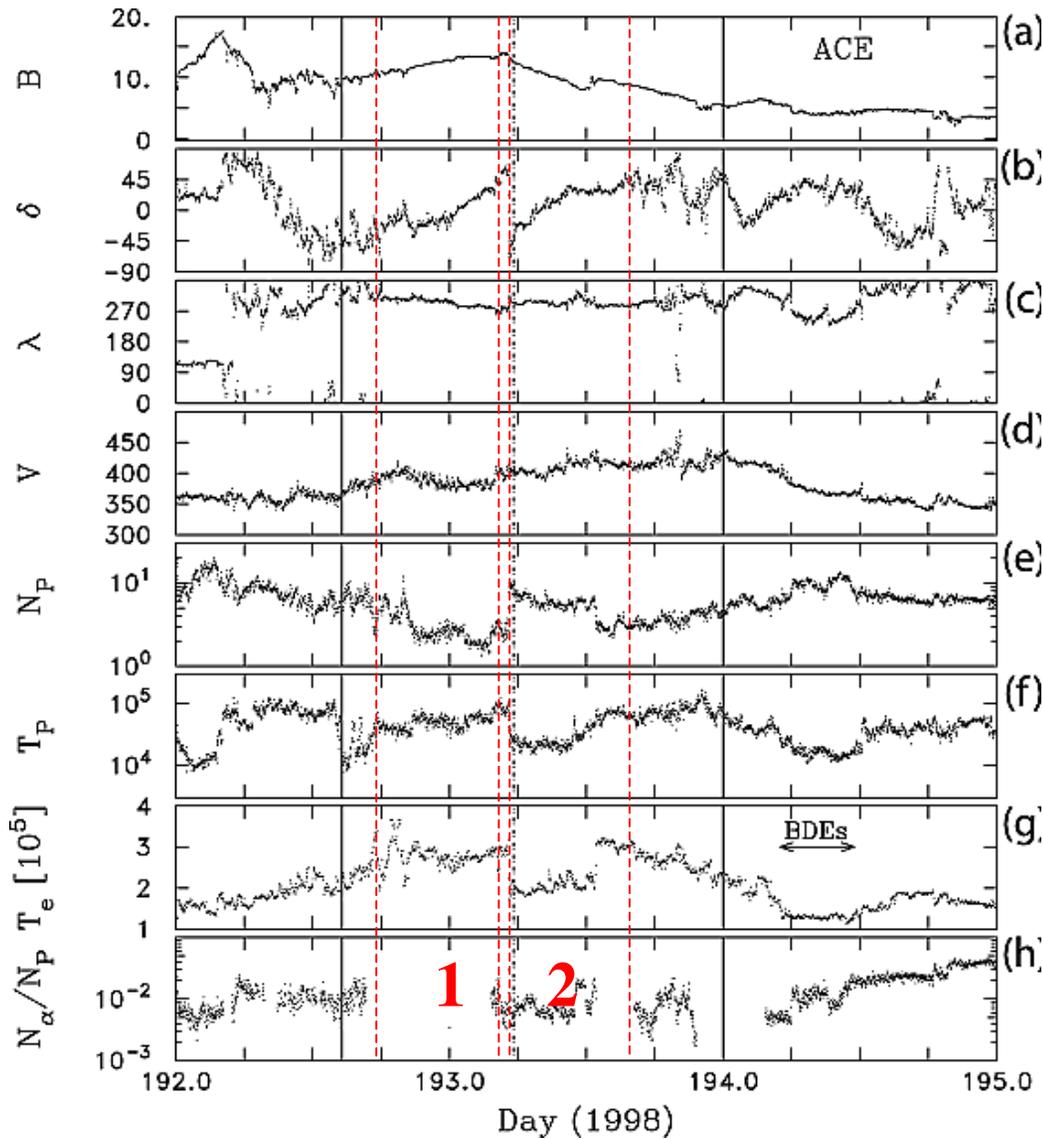
<u>Event</u>	<u>DOY</u>	<u>Characteristics</u>
03/25/1998	84.704 – 85.422	double flux ropes
06/24/1998	175.852 – 176.444	double
07/11/1998	192.607 – 194.000	double
09/15/1999	258.355 – 258.777	possible triplet
08/12/2000	225.222 – 225.815	double
10/03/2002	276.296 – 277.431	multiple

• ACE August 12, 2000 Event (*Hu et al.*, [2003])



$\mathbf{z}=(-0.34, -0.90, -0.28) \pm (0.06, 0.04, 0.07)$ RTN



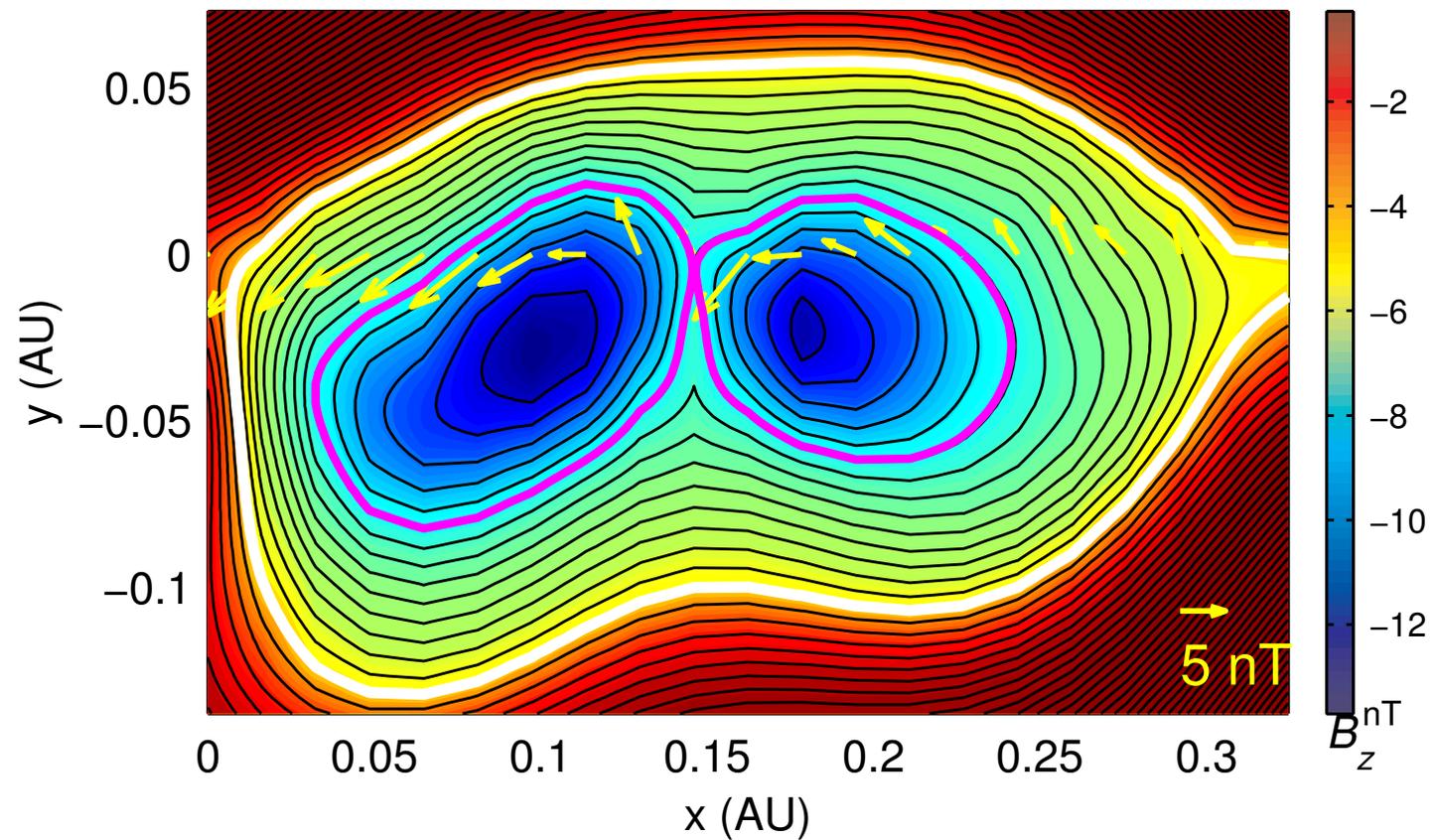


- July 11 1998 event

- Apparent magnetic signatures of multiple structures denoted by **1**, and **2**.

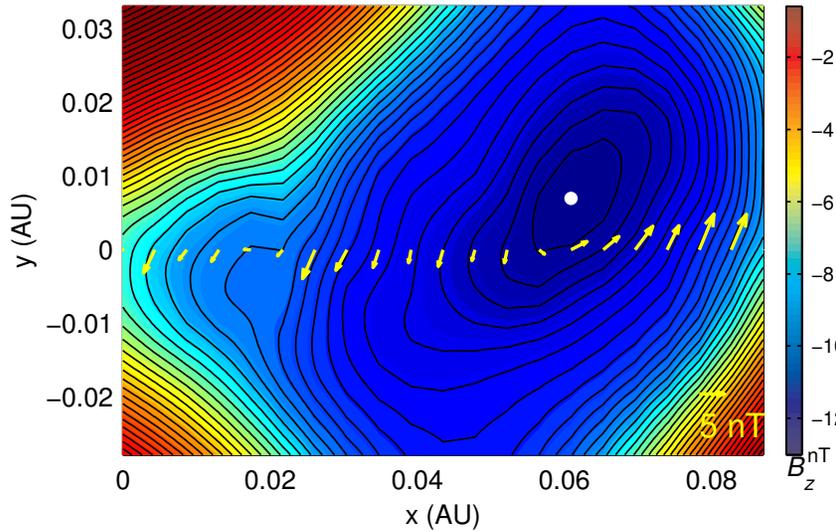
- GS reconstruction is applied to the larger interval (solid vertical lines) and subintervals **1**, and **2**.

July 11, 1998 [Hu et al, 2004]

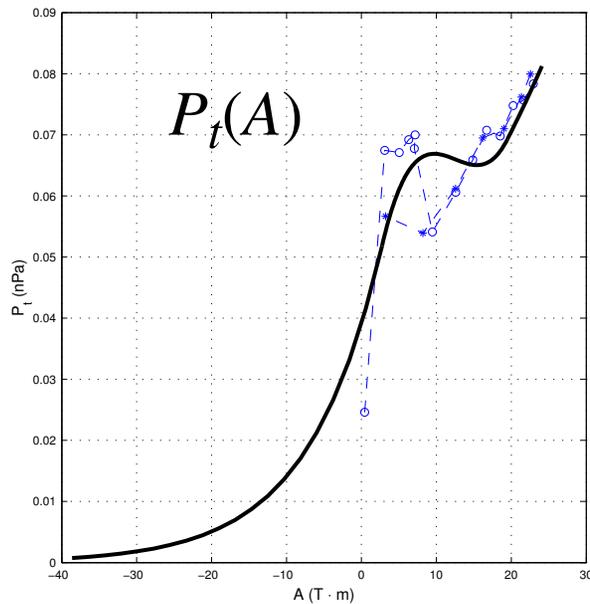
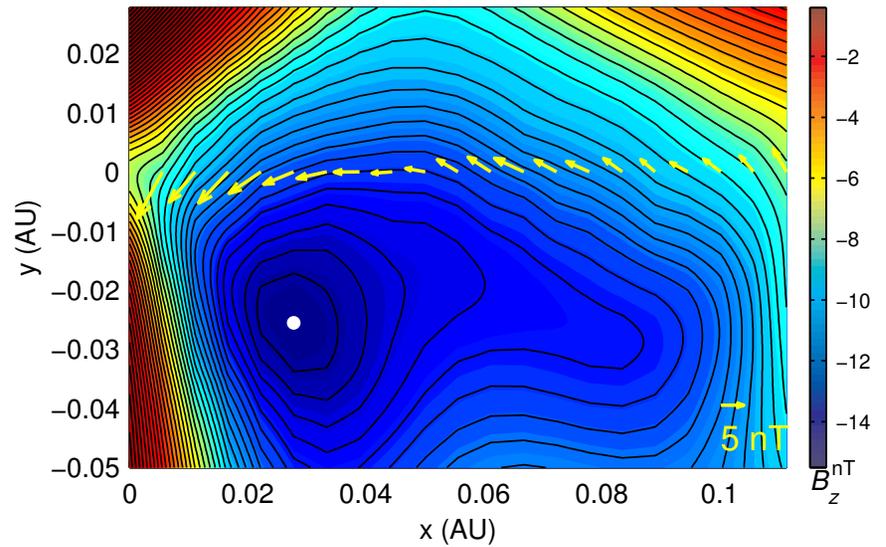


$\mathbf{z}=(0.057, 0.98, -0.18) \pm (0.08, 0.01, 0.03)$ RTN

• Flux rope 1



• Flux rope 2



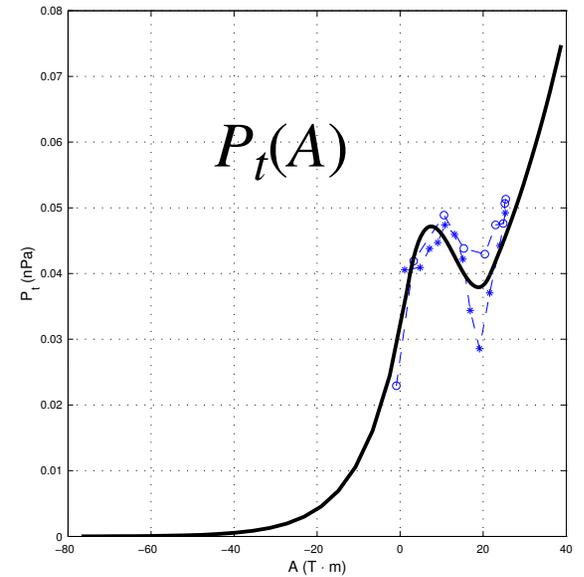
$$\mathbf{z}_1 = (116^\circ, 4^\circ) \pm (5^\circ, 6^\circ)$$

$$|\mathbf{V}_{HT1}| = 389 \text{ km/s}$$

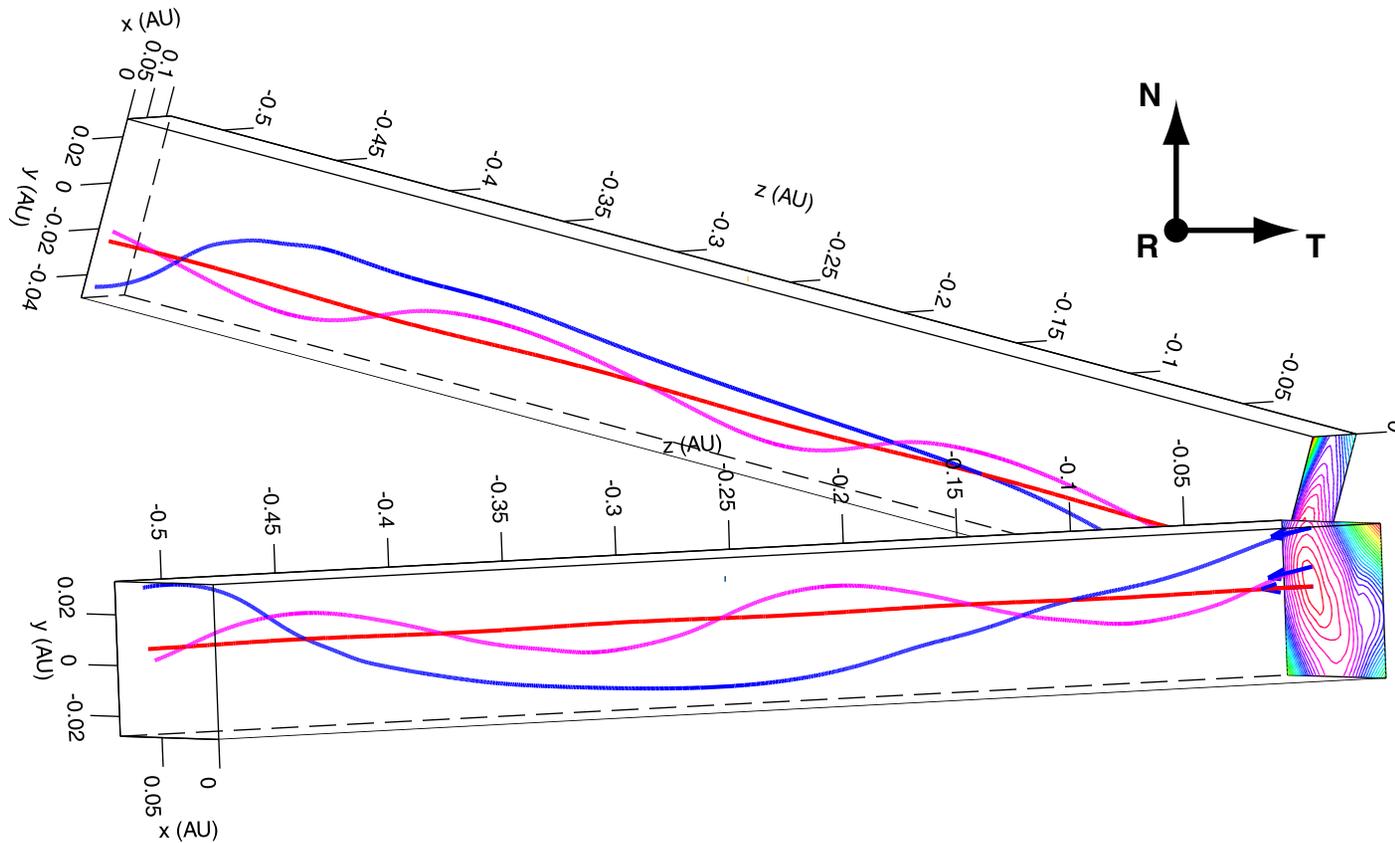
$$\mathbf{z}_2 = (81^\circ, 345^\circ) \pm (7^\circ, 2^\circ)$$

$$|\mathbf{V}_{HT2}| = 422 \text{ km/s}$$

(both left-handed)



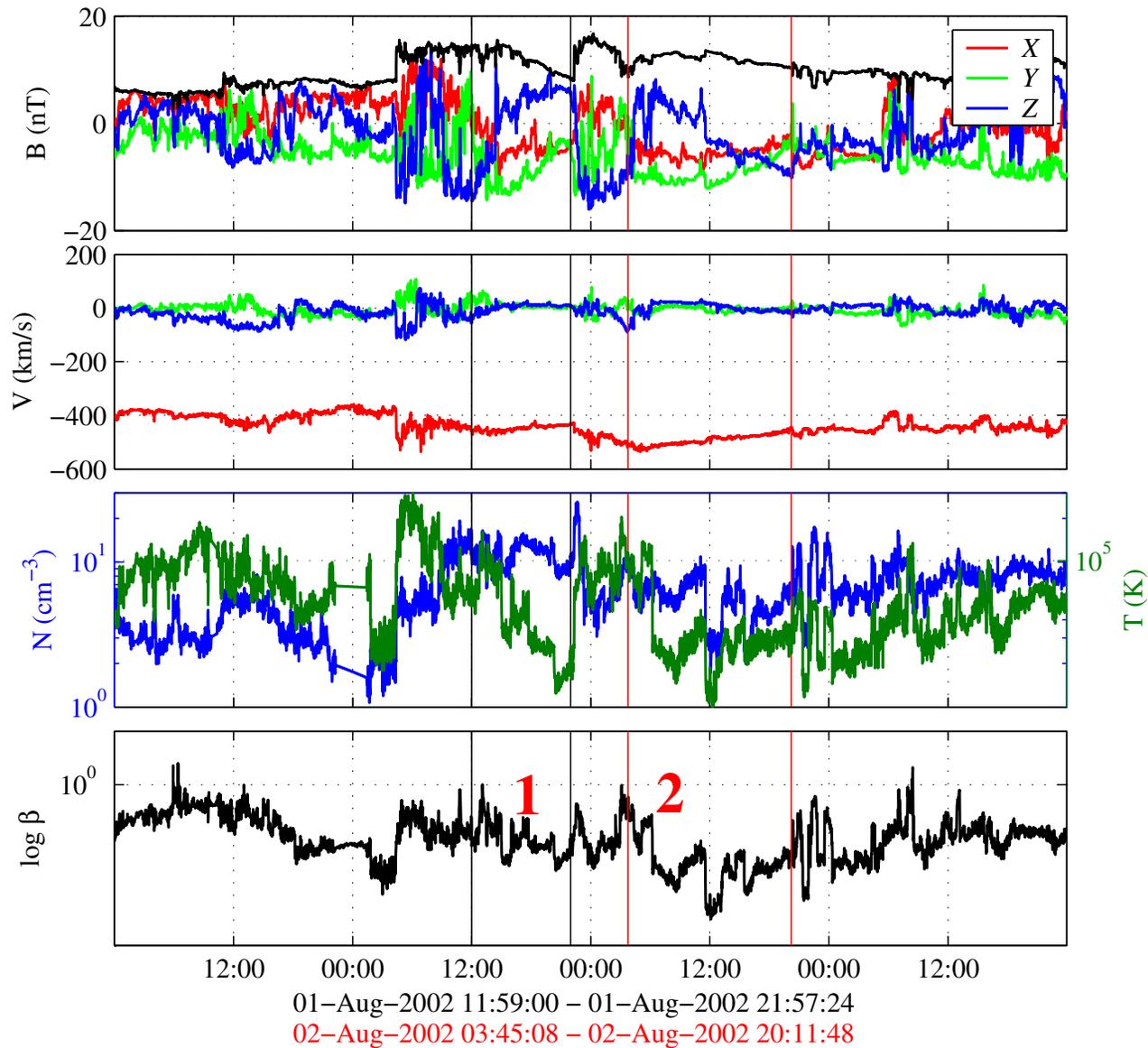
View towards Sun:



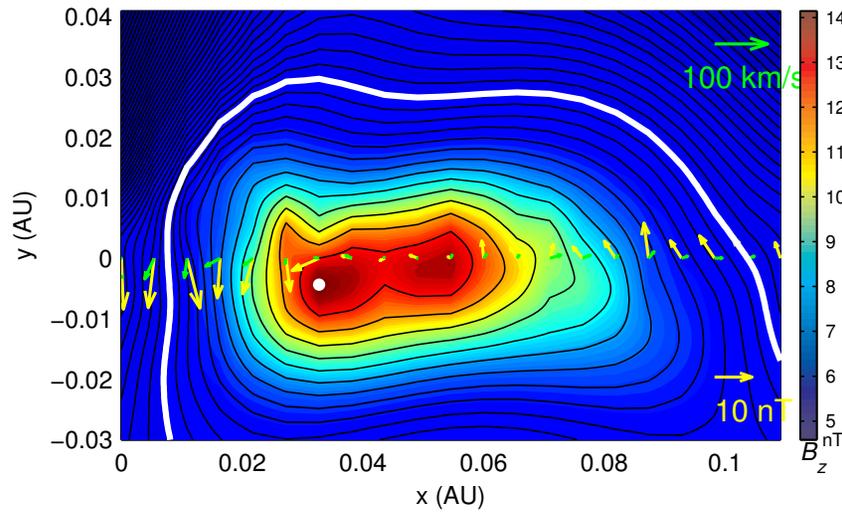
Field line twist, τ	Flux rope 1	Flux rope 2
Pink	$4.2 \times 2\pi/\text{AU}$	$4.7 \times 2\pi/\text{AU}$
Blue	$1.9 \times 2\pi/\text{AU}$	$1.9 \times 2\pi/\text{AU}$

$$\tau \Phi_z^2 \sim 10^{25} - 10^{26} \text{ Wb}^2$$

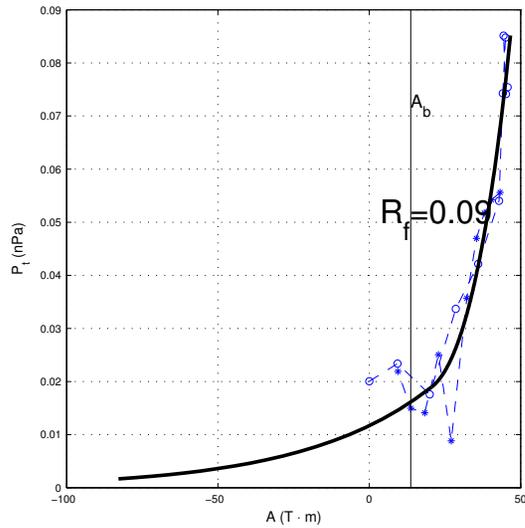
• August 1st and 2nd 2002 event



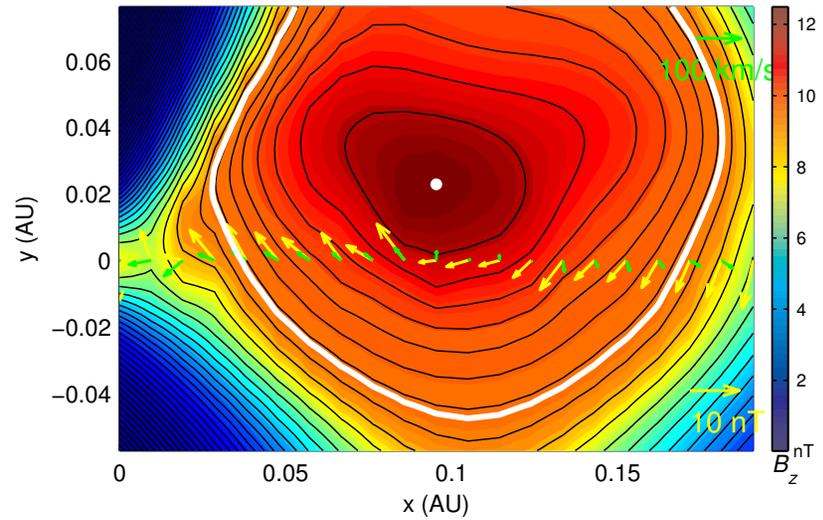
1: Right-handed



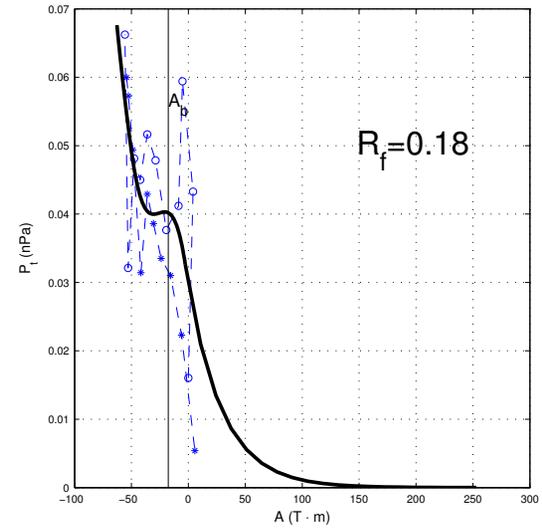
$$\mathbf{z}_1 = (105, 168) \pm (4, 4)^\circ$$



2: Left-handed

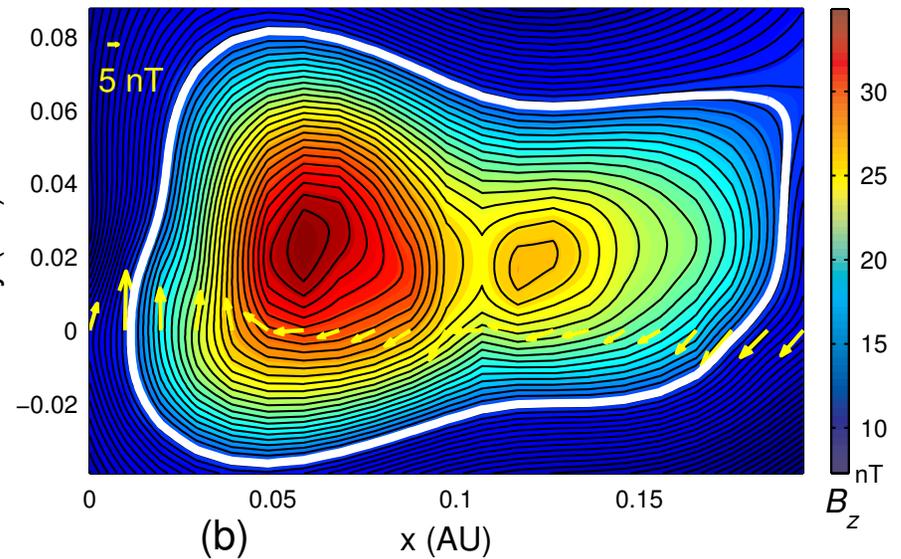
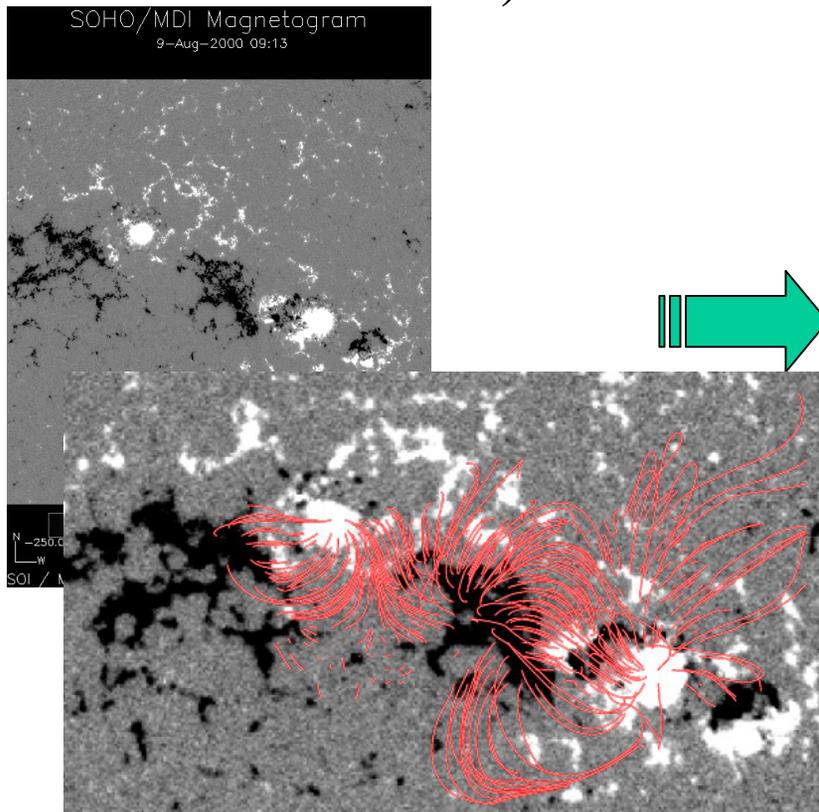


$$\mathbf{z}_2 = (97, 193) \pm (1, 1)^\circ$$



Solar Sources*

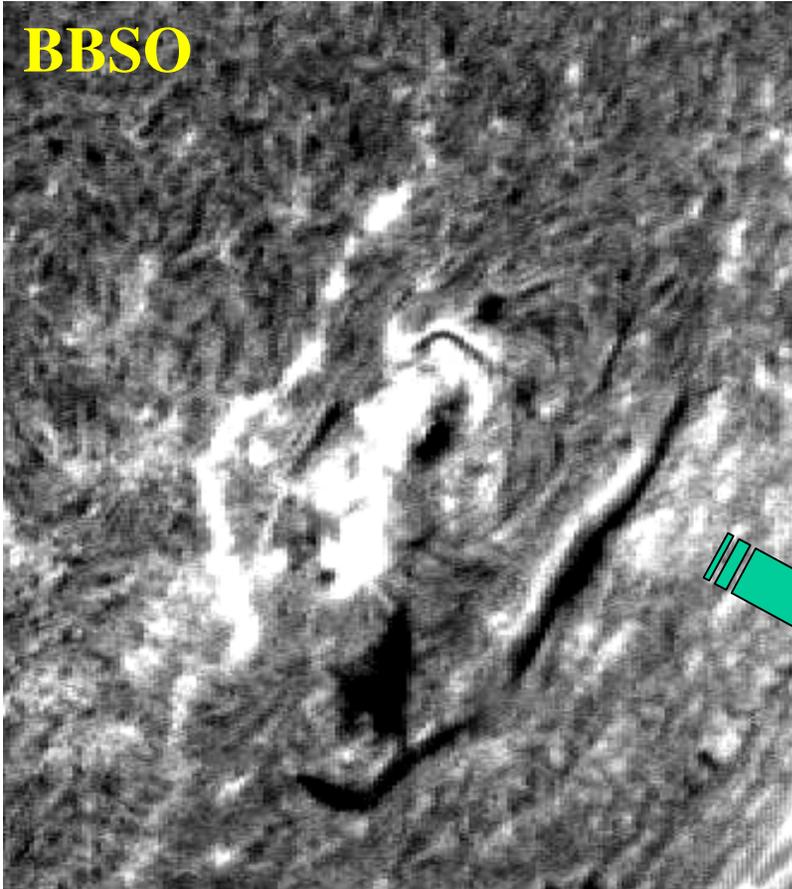
- 08/09/2000 1630 UT Full Halo CME (partial halos on 08/08 and 08/10)*



negative helicity (left-handed)

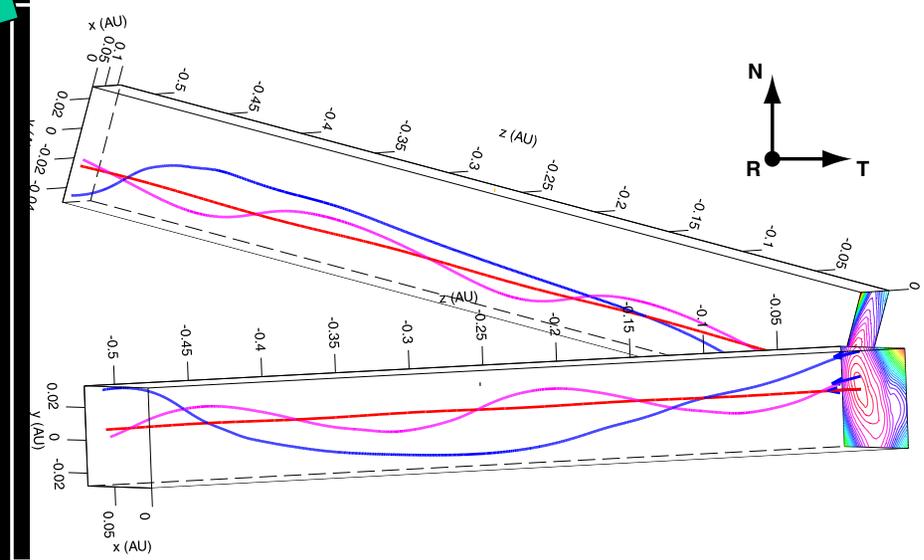
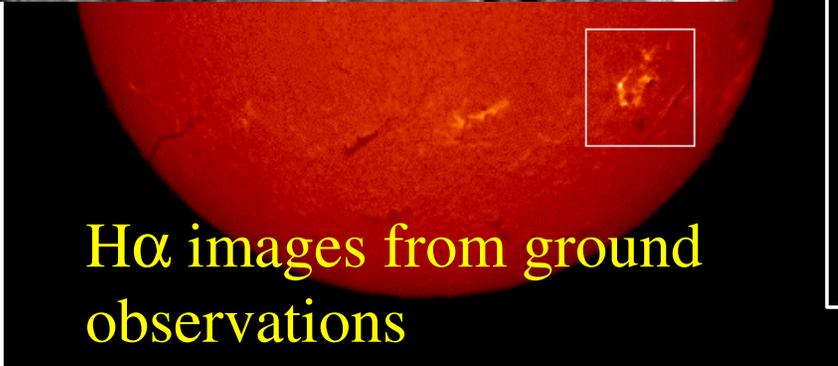
* SOHO LASCO CME Catalog (http://cdaw.gsfc.nasa.gov/CME_list/). This CME catalog is generated and maintained by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA.

BBSO

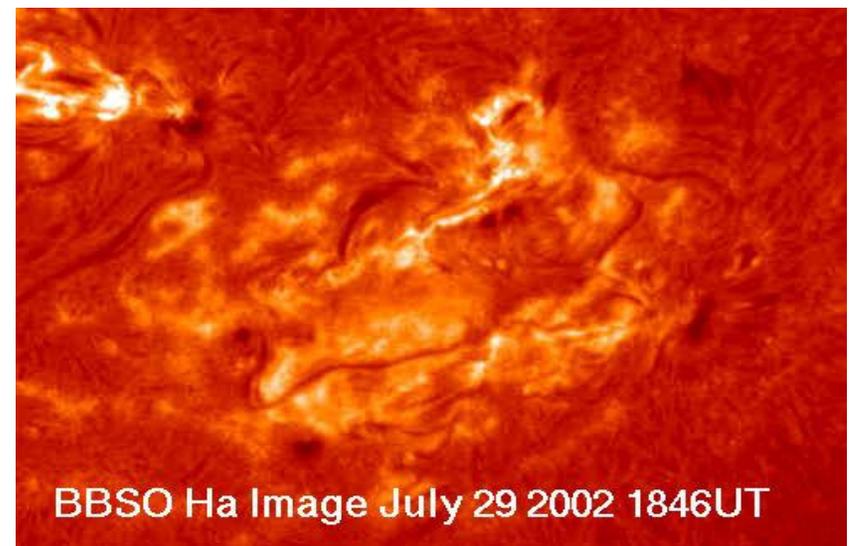
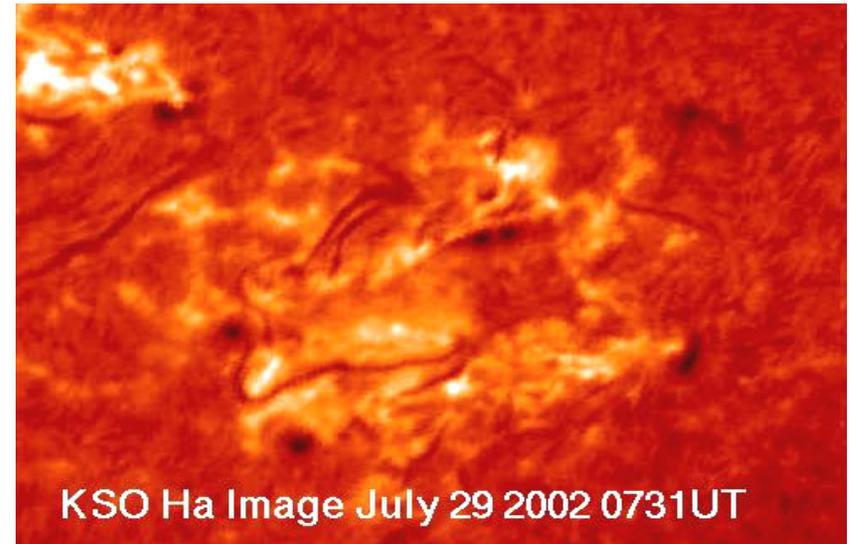
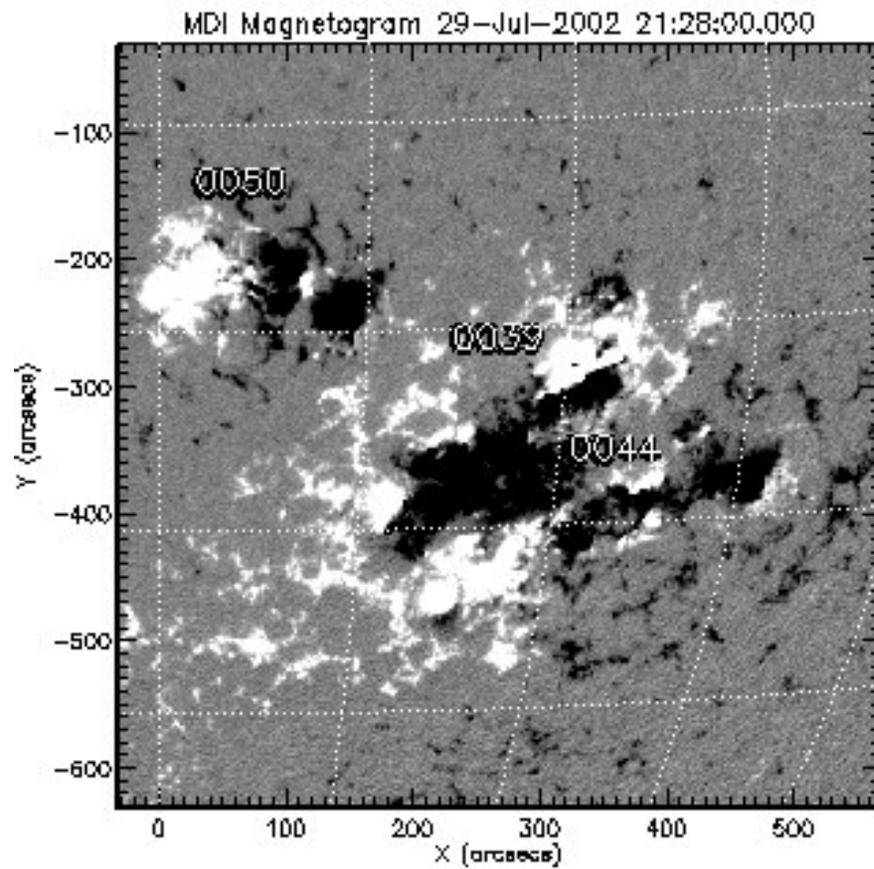


- July 9, 1998 Solar Flare (SOHO was out)

H α images from ground observations



- July 29, 2002 Halo and partial halo CMEs*



Summary and Goals

- Flux-rope interpretation is confirmed: substantial deviations from axial symmetry.
- Complexity in magnetic ejecta topology: more than one confined flux ropes; varied handedness/polarity.
- Validity to be assessed case by case; multi-spacecraft test is essential.
- Mechanisms for multi-tube formation: eruption of multiple ropes at the source; or interaction of consecutive eruptions.
- Answers may be sought in connection with solar observations and numerical modeling.

Supplements

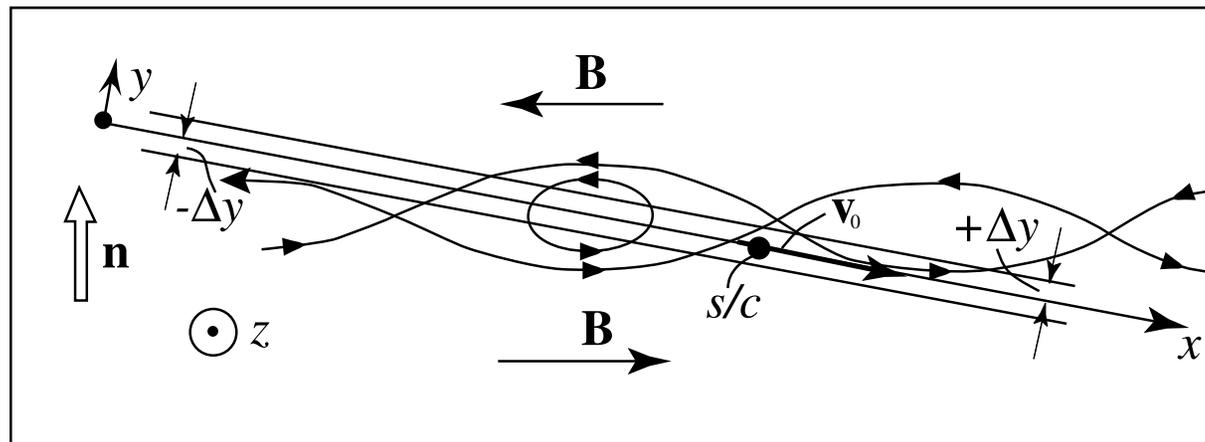
- GS Solver:

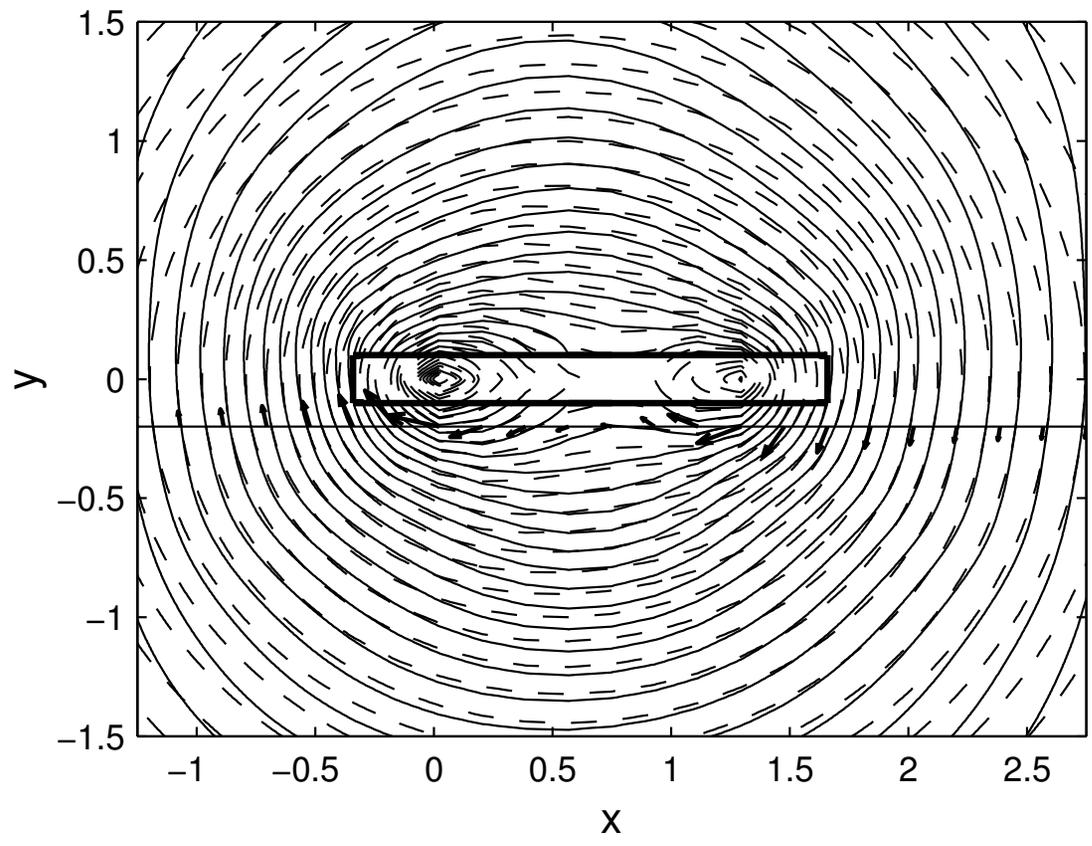
$$A(x, y \pm \Delta y) \cong A(x, y) + \left(\frac{\partial A}{\partial y}\right)_{x,y} (\pm \Delta y) + \frac{1}{2} \left(\frac{\partial^2 A}{\partial y^2}\right)_{x,y} (\pm \Delta y)^2,$$

$$B_x(x, y \pm \Delta y) \cong B_x(x, y) + \left(\frac{\partial^2 A}{\partial y^2}\right)_{x,y} (\pm \Delta y),$$

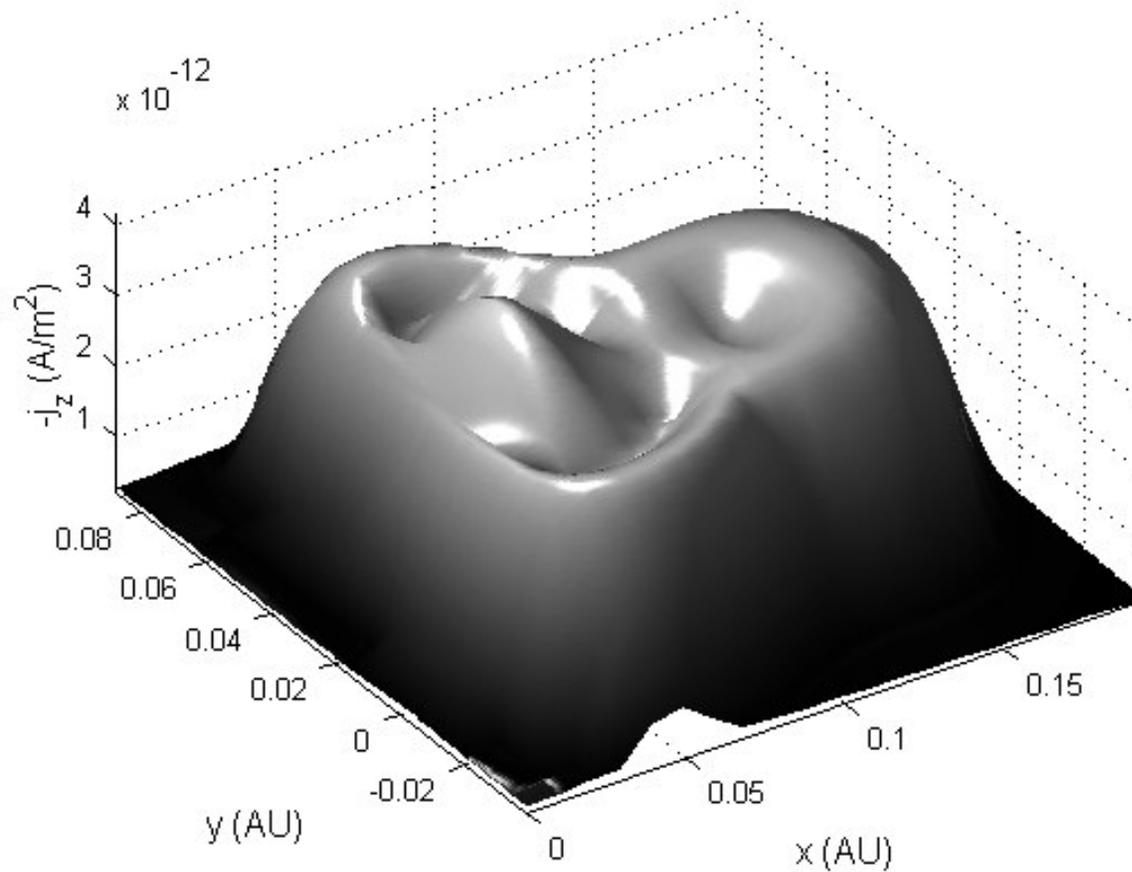
where $A(x, y)$, $(\partial A / \partial y)_{x,y} = B_x$ and

$$\frac{\partial^2 A}{\partial y^2} = -\frac{\partial^2 A}{\partial x^2} - \mu_0 \frac{dP_t}{dA} \text{ at } y=0 \text{ are initially known.}$$



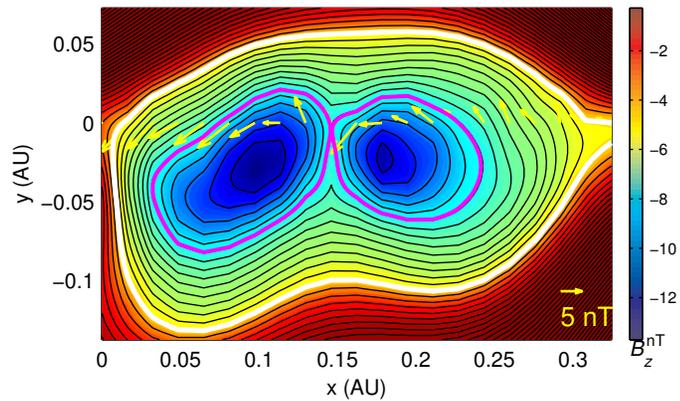


- Axial current density: $j_z = dP_t/dA$

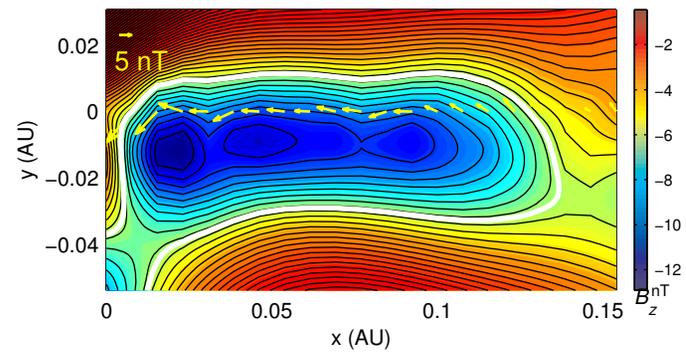


Total axial current $|I_z| \approx 1.1 \times 10^9$ A

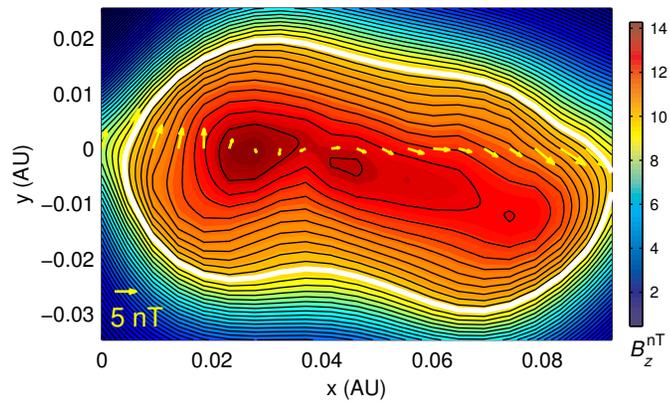
July 11, 1998



Sept. 15, 1999



June 24, 1998



March 25, 1998

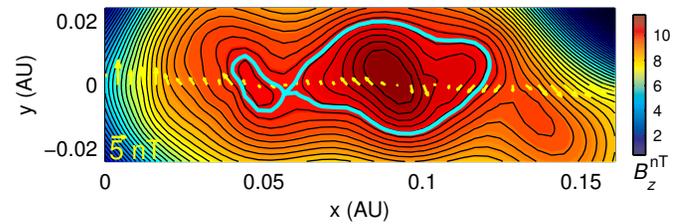
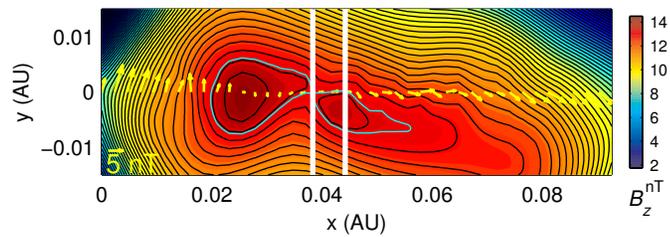
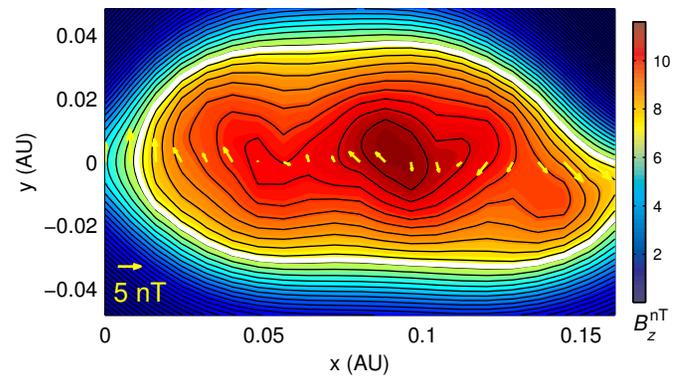


Table 1. Summary of Results

Event	Ejecta Interval	$\hat{\mathbf{z}}$ in angular RTN	B_{zmax}	j_{zmax}	Chirality ^a	Φ_z	I_z
	DOY	$(\delta, \lambda)^b$ in degrees	nT	$\times 10^{-12}$ A/m ²		$\times 10^{12}$ Wb	$\times 10^8$ A
03/25/1998	84.704 - 85.422	$(74, 162) \pm (9, 3)$	12	3.0	---	1.8	2.3
06/24/1998	175.852 - 176.444	$(36, 144) \pm (4, 6)$	14	6.9	---	0.81	1.4
07/11/1998	192.607 - 194.000	$(87, 350) \pm (5, 2)$	-14	1.7	---	7.5	5.9
09/15/1999	258.355 - 258.777	$(74, 324) \pm (2, 1)$	-13	6.6	---	1.1	3.1
08/12/2000 ^c	225.222 - 225.815	$(110, 197) \pm (4, 4)$	35	4.2	---	7.6	11

^a +, Right handedness; -, Left handedness.

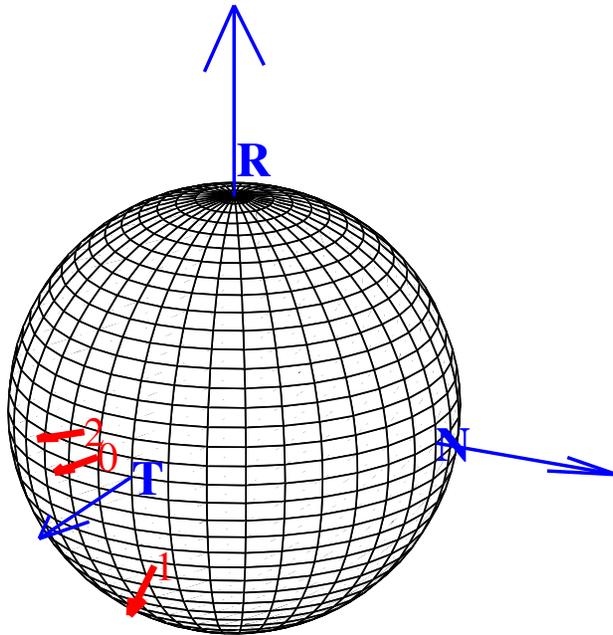
^b The polar angle, δ , of the unit vector, $\hat{\mathbf{z}}$, is measured from the positive R direction.

The azimuthal angle, λ , is measured from the positive T direction towards the positive N

direction.

^c After *Hu et al.* [2003].

- Comparison and composition:



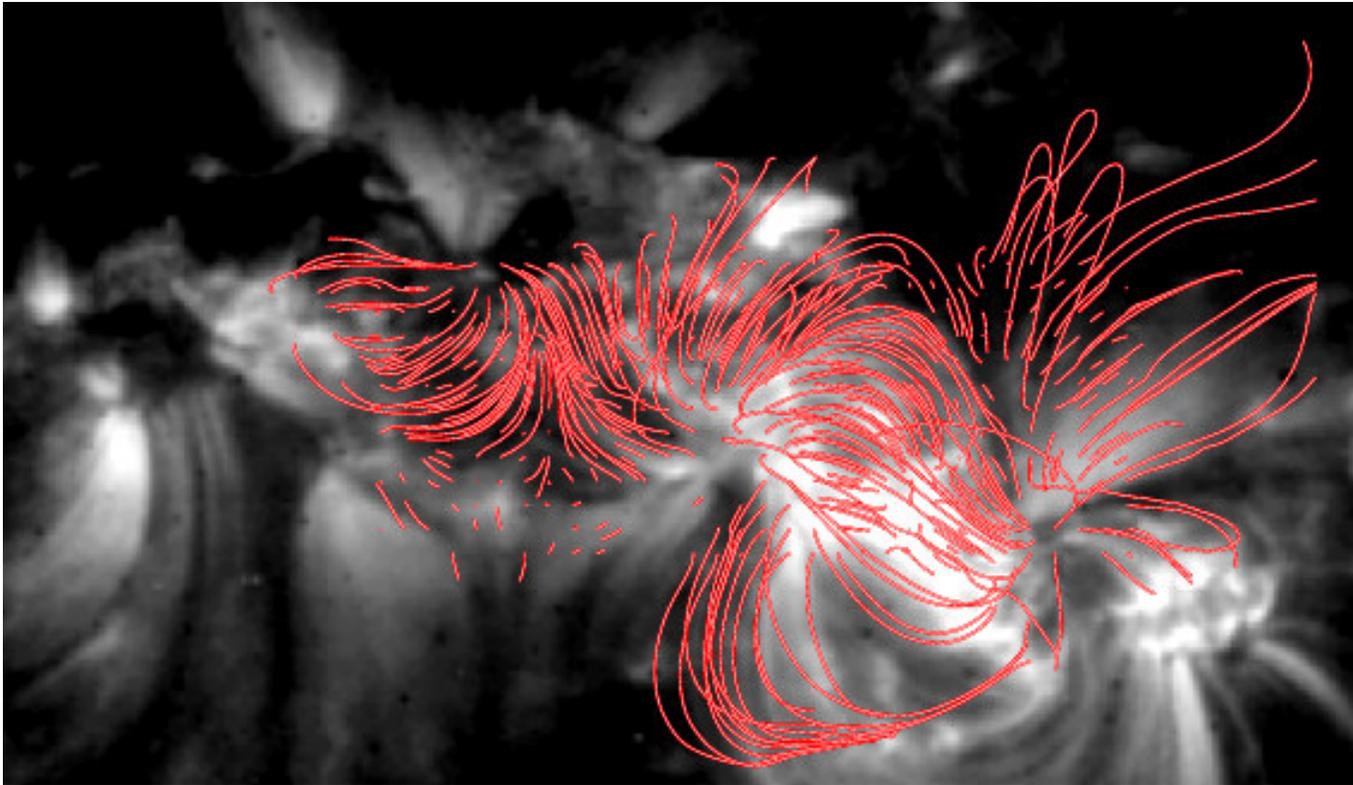
0: \mathbf{z} in Table 1

1: \mathbf{z}_1

2: \mathbf{z}_2

	Interval (DOY) 1998	B_{zmax} nT	j_{zmax} $10^{-12}A/m^2$	Chirality
0	192.607-194.000	-14	1.7	--
1	192.741-193.185	-13	2.8	-
2	193.210-193.667	-15	2.8	-

$$\angle(\mathbf{z}_1, \mathbf{z}_2) \approx 40^\circ$$



ACE/WIND Test

Top panel:

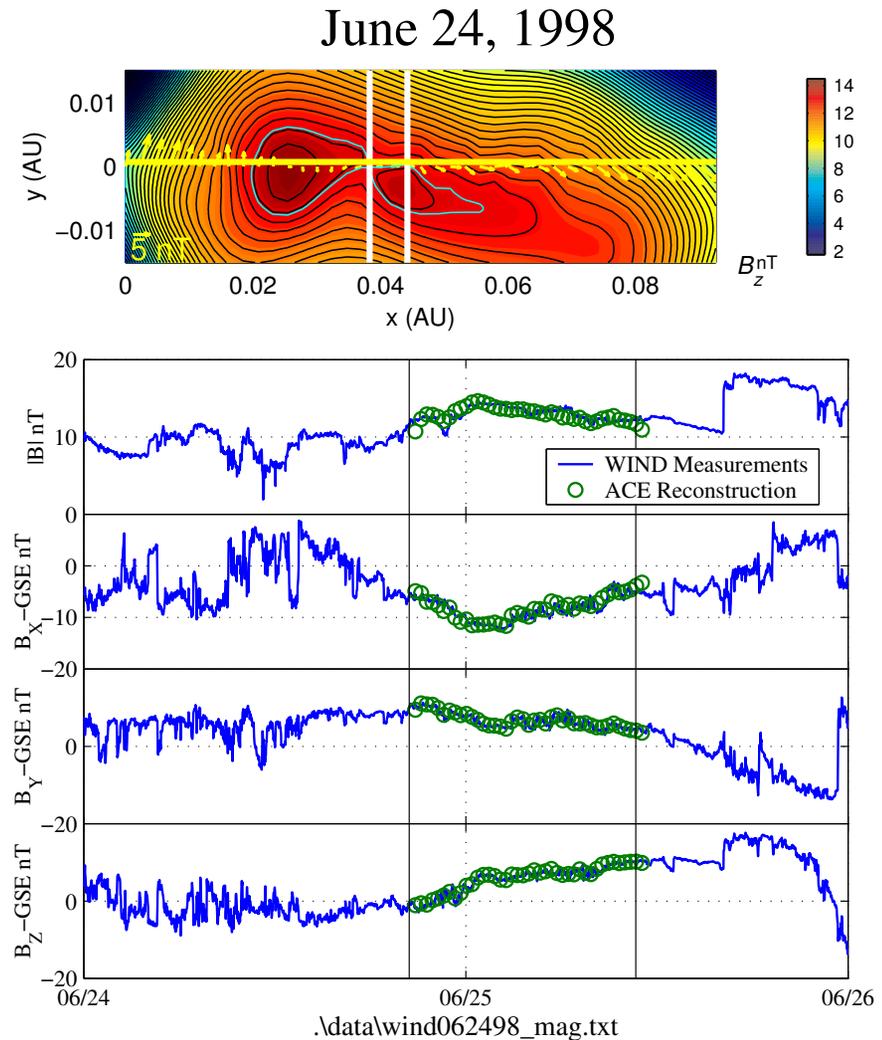
A cross-section is obtained by utilizing ACE data at $y=0$. The WIND path is projected onto the map as the yellow horizontal line.

Bottom panel:

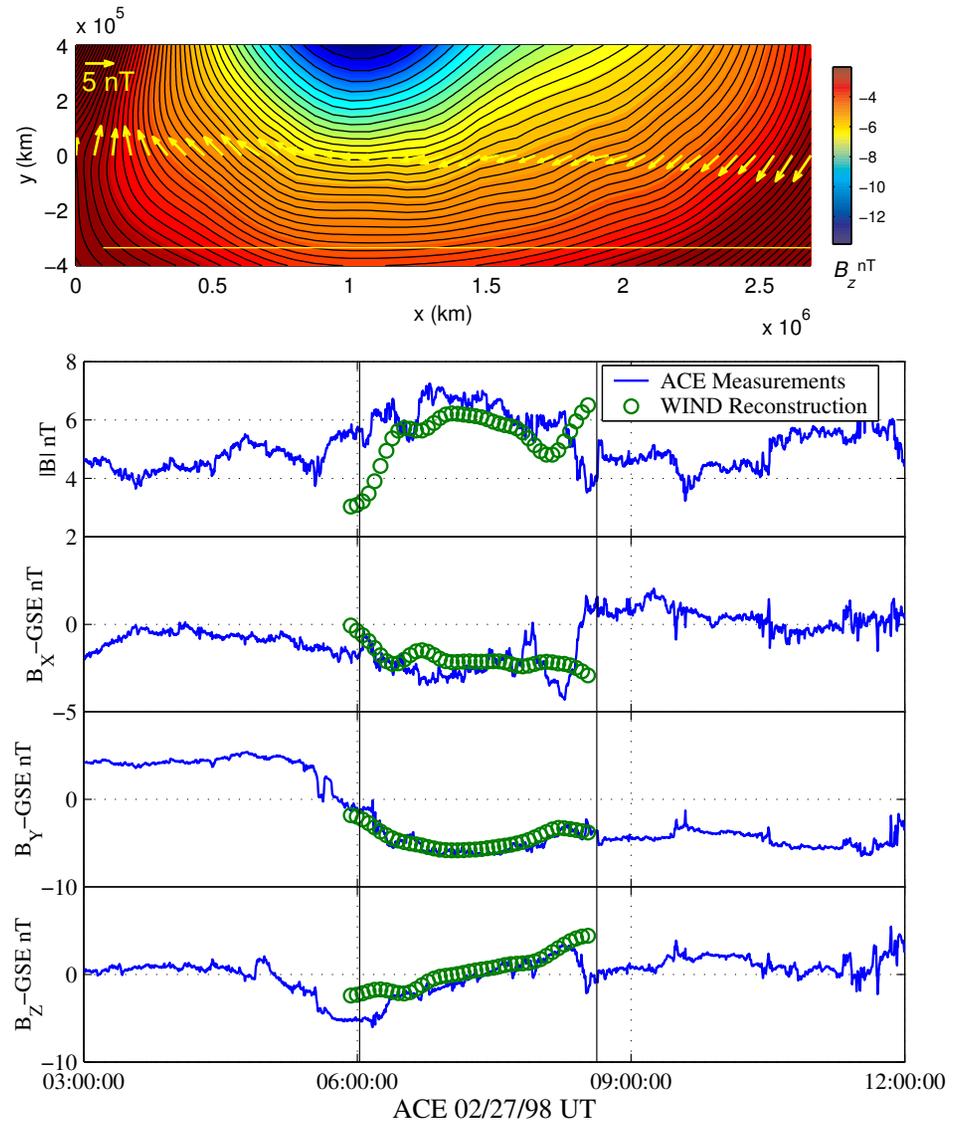
The numerical solutions along that line are compared with real WIND measurements.

WIND position relative to ACE:

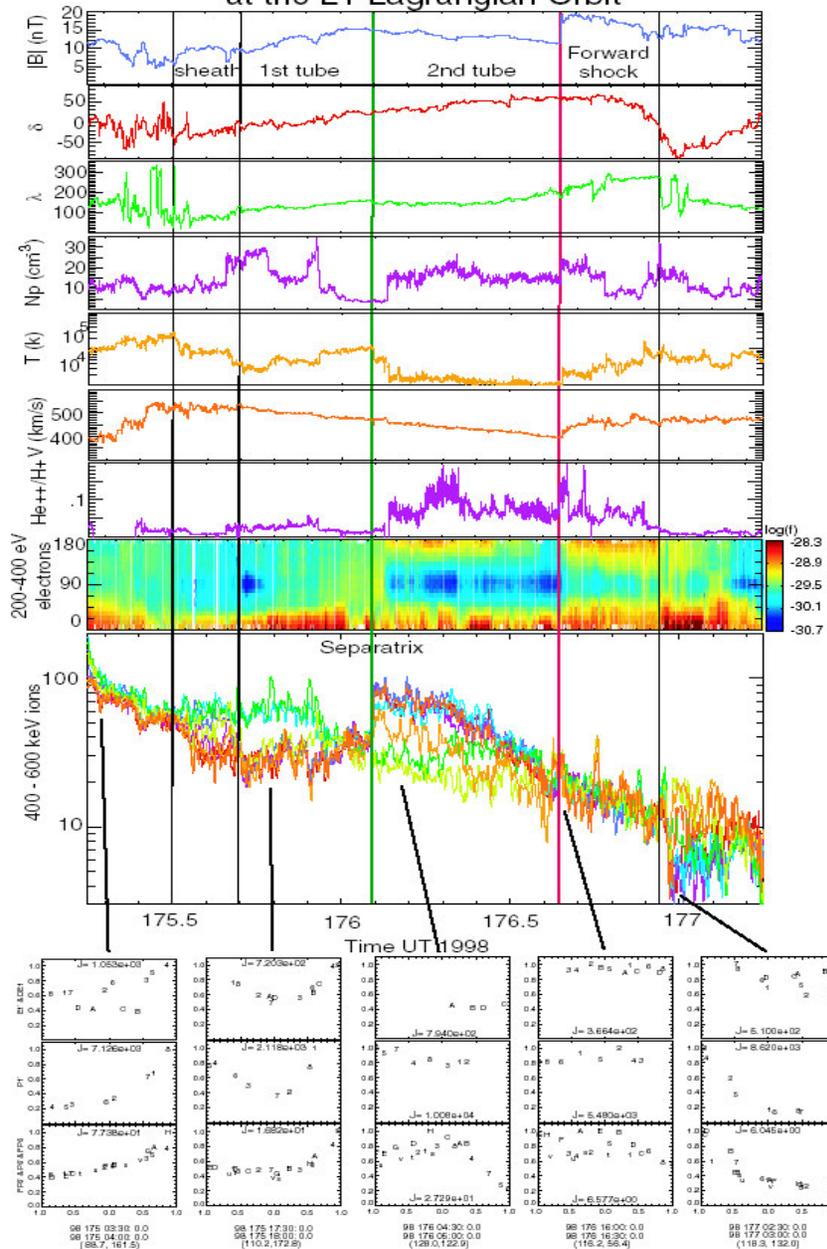
$$(\Delta x, \Delta y, \Delta z) = (-59, 17, 147) R_E$$



ACE position relative to WIND at (0,0,0) is (16, -53, 21) R_E .



June 24 Multi-tube Cloud Observation at the L1 Lagrangian Orbit



Haggerty et al. predicted twin
flux rope interpretation based
on energetic particles!

June 24, 1998

