Reconstruction of magnetic clouds with two spacecraft: Examples from WIND-ACE and STEREO-WIND

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ABSTRACT

- We reconstruct **magnetic clouds** (MCs, the core flux rope of ***Coronal Mass Ejections***) at 1 AU, focusing on **combining measurements from two spacecraft** to optimize the magnetic field map, thus doing in the interplanetary medium what other authors have done in the context of flux transfer events at the magnetopause.
- **Three magnetic clouds** are selected, of different sizes, seen by both **WIND** and **ACE**, when their separations where largest (1998, 2001). We undertake a **quantitative comparison** with results from with minimum variance (MV) analysis and linear force-free fitting (FF).
- We also take a first look at the **magnetic cloud on May 22, 2007**, seen by **WIND and STEREO-B**. A magnetic field map is obtained from STEREO-B plasma and magnetic field observations, delivered by the **PLASTIC** and **IMPACT** instruments. We then optimize this field map by checking for consistency with observations by WIND. We find a **shape** of the magnetic cloud's cross-section slightly **elongated perpendicular to the direction of motion** ("flattening").

METHOD

We numerically solve the **Grad-Shafranov equation**, based on MHD theory:

(e.g. *Hau and Sonnerup, 1999; Hu and Sonnerup, 2002; Sonnerup et al. 2006*)

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

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

A(x,y) is the *z* - component of the vector potential, *p* is the plasma pressure, and *$P_t(A)$* is the transverse pressure, a function of *A* alone.

Features:

- 2½ -dimensional (invariant but not cylindrical). Magnetic field maps are generated, with spacecraft observations as initial values; thus no preconceptions on geometry,
- Structure moves with time-independent deHoffmann–Teller velocity (**V_{HT}**),
- Self-consistent, non force-free, number of flux tubes not prescribed,
- Invariant axis: where *$P_t(A)$* displays minimal scatter (i.e. *$P_t(A)$* is single-valued).

Multi-spacecraft extension: *Sonnerup et al. (2004)*, *Hasegawa et al. (2005, 2006, 2007)* for magnetopause transects, flux transfer events and flux ropes in the magnetotail. *Möstl et al. (2008)* for the 20 November, 2003 MC (Wind/ACE).

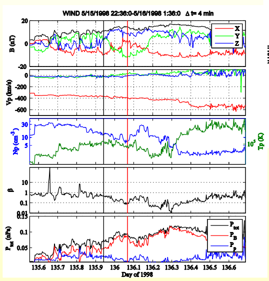
- Merging of individual magnetic field maps into one combined map.
- Invariant axis found by correlation coefficients between predicted and observed magnetic field components (consistency check).

Advantages:

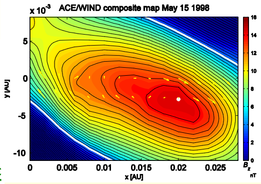
- **Independent test** of magnetic flux rope topology, flexibility.
- **Optimization of the invariant axis and shape** of the structure through correlation coefficients, not only from constraint that *$P_t(A)$* is single-valued.
- **Magnetic fluxes, orientations** etc. are more robust, important in relating magnetic clouds to their associated **flares and CMEs** (e.g. *Leamon et al. 2004; Qiu et al., 2007; Longcope et al., 2007; Möstl et al., 2008*).

(1) May 15 1998 event

- Smallest MC (D ~ 0.025 AU) which was related to its solar source active region (*Mandrini et al., 2005*). Fig. 1: WIND observations, Fig. 2: combined *$P_t(A)$* function.
- MC appears **elongated** approximately **in the direction of motion** *x* (Fig. 3), *y* separation ACE-Wind 1/10 of its radial size.
- Correlation coefficient cc=0.96 maximized at orientation θ=52°, φ=229° (latitude θ measured from ecliptic, longitude φ from sunward (0°) towards east (90°) in GSE.



(1) WIND: SWE, MFI; Magnetic field and plasma data (protons) (format as Fig. 4)

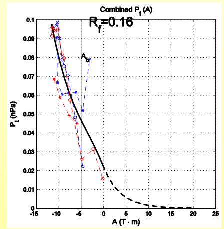


(3) Combined magnetic field map: B_z is color coded, pointing out of the paper; black contours are magnetic field lines in the paper plane. Arrows are observations (upper Wind, lower ACE)

	May 15 1998	Apr 22 2001	Mar 19 2001
$\mathbf{V}_{HT}$, km/s	(-394.4,-11.5, 7.0)	(-365.6 3.5 -4.7)	(-375.3, 4.4, 7.0)
cc_{HT}	0.9990	0.9993	0.9946
Walén slope	-0.3372	0.0182	0.0383
θ, deg (FF, MV)	52 (?,59)	-40 (-50, -30)	-53 (-66, -62)
ϕ, deg (FF, MV)	229 (?,172)	300 (327, 287)	125 (125, 141)
handedness	LH	LH	LH
D, AU	0.028	0.147	0.331
B_{max}, nT	14.6	15.2	18.1
Φ_t, 10^{20} Mx	0.1 (0.09-1.4)	3.2	10.4
Φ_p, 10^{20} Mx/AU	1.6 (1.9-2.3)	12.1	17.3
$cc_{combi}(Wind, ACE)$	0.96 (0.88,0.90)	0.985 (0.976, 0.971)	0.98 (0.979, 0.968)
$\vec{s}$ (x,y,z), AU	(0.0003, -0.0026, -0.0012)	(0.0113, -0.0087, -0.0035)	(0.0111, -0.0060, 0.0002)

Event 1: fluxes in (…) from *Mandrini et al., 2005*; events 2, 3: FF from *Lynch et al., 2005.*

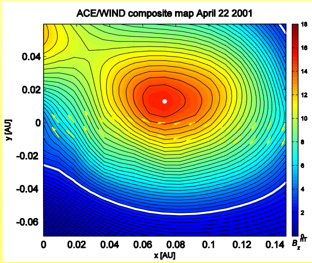
⇦ Table 1: Results for all 3 events, including axial and poloidal magnetic fluxes



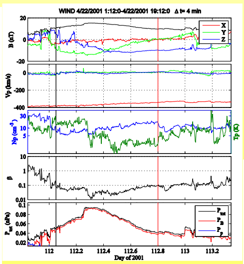
(2) Combined $P_t(A)$ plot (red ACE, blue WIND); fitting function (solid black); residue R_f=0.16.

(2) April 22 2001 event

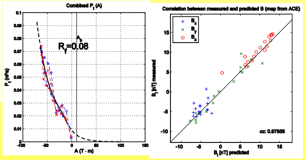
- Medium-sized MC (D~0.14 AU)
- Impact parameter higher, shape quite circular
- Separation in map almost 0.01 AU



(5) Combined magnetic field map: upper WIND, lower ACE , same format as Fig. 3



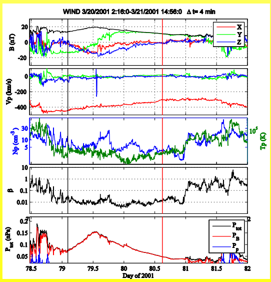
(4) WIND: Magnetic field components, proton bulk velocity, proton number density (blue), proton temperature (green), proton beta, magnetic and plasma pressure.



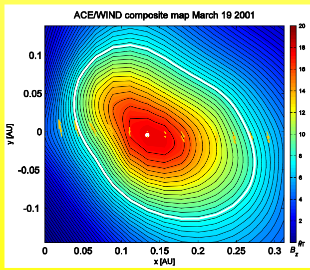
(2) Left: Combined *$P_t(A)$* (same format as Fig.2) Right: Observations (WIND) vs. predictions from the field map from ACE

(3) March 19 2001 event

- Large MC (diameter ~0.3 AU), Near- Earth s/c separation very small compared to the size of the structure.
- Shape seems flattened perpendicular to its direction of motion – expected from numerical simulations and theory (Riley & Crooker, 2004).



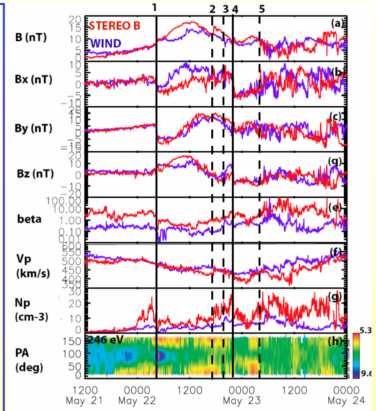
(6) WIND: Magnetic field and plasma data



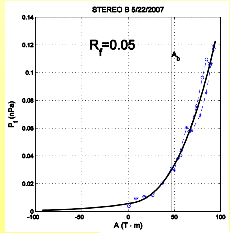
(7) Magnetic field map arrows are s/c trajectories (upper WIND, lower ACE)

(4) STEREO-WIND event May 22, 2007

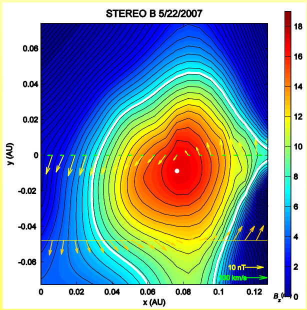
- **Figure 8** (from *Huttunen et al.*, GRL, submitted, 2008): Plasma-data from **PLASTIC** (*Galvin et al., 2008*); magnetic field components (GSE) from **IMPACT** (*Luhmann et al. 2007);* Independent test of flux rope topology (*Liu et al., 2008*). Interval used for GS: vertical lines 1-2.
- Shock penetrates into back of MC at STEREO-B (vertical line 2; prevents modelling of MC field lines behind the shock).
- Spacecraft-separation: **0.048 AU** along *y* in the map, Fig. 10: **true shape of the magnetic cloud cross-section can be recovered for the first time!**
- **Fig. 10: GS-map from STEREO-B, optimized by WIND observations**: Correlation coefficient *cc*=0.93 maximized at orientation 55° / 70° (lat., long. GSE). MV: 53° / 77° (*Huttunen et al., 2008)*
- STEREO A: at *y*= - 0.12 AU in Figure 10. No clear signature, unlikely that MC is observed.



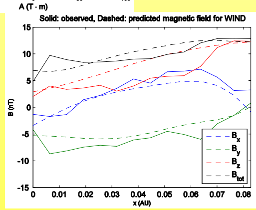
(8) STEREO-B (red), WIND (blue).



⇦ **(9)** STEREO-B *$P_t(A)$* relation with fitting function (black). Circles inbound, stars outbound. A_b = white contour in Fig. 10.



(10) STEREO-B magnetic field map: B_z (color coded) points out of the paper; Black contours are field lines in the plane of the paper; upper trajectory STEREO B, lower WIND; arrows are observations.



(11) Predicted magnetic field components from the STEREO-B map (dashed) vs. WIND observations (solid) for field lines crossed by both s/c.

Conclusions

- New method based on multi-spacecraft information is capable of retrieving robust orientations, shapes and magnetic fluxes for large spacecraft separation; results comparable to other methods.
- Variety of shapes of cross-sections possible, depending on size? small MCs circular, large flat?
- First step to infer full 3D-structure of magnetic clouds (future *HELEX* and *Solar Orbiter* observations).

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