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Optimized Grad – Shafranov Reconstruction of a Magnetic Cloud Using STEREO-*Wind* Observations

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Abstract We present results on the geometry of a magnetic cloud (MC) on 23 May 2007 from a comprehensive analysis of *Wind* and STEREO observations. We first apply a Grad – Shafranov reconstruction to the STEREO-A plasma and magnetic field data, delivered by the PLASTIC and IMPACT instruments. We then optimize the resulting field map with the aid of observations by *Wind*, which were made at the very outer boundary of the cloud, at a spacecraft angular separation of 6°. For the correct choice of reconstruction parameters such as axis orientation, interval and grid size, we find both a very good match between the predicted magnetic field at the position of *Wind* and the actual observations as well as consistent timing. We argue that the reconstruction captures almost the full extent of the cross-section of the cloud. The resulting shape transverse to the invariant axis consists of distorted ellipses and is slightly flattened in the direction of motion. The MC axis is inclined at $-58°$ to the ecliptic with an axial field strength of 12 nT. We derive integrated axial fluxes and currents with increased precision, which we contrast with the results from linear force-

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free fitting. The helical geometry of the MC with almost constant twist (≈1.5 turns AU^{-1}) is not consistent with the linear force-free Lundquist model. We also find that the cloud is non-force-free ($|\boldsymbol{J}_\perp|/|\boldsymbol{J}_\parallel| > 0.3$) in about a quarter of the cloud cross sectional area, particularly in the back part which is interacting with the trailing high speed stream. Based on the optimized reconstruction we put forward preliminary guidelines for the improved use of single-spacecraft Grad – Shafranov reconstruction. The results also give us the opportunity to compare the CME direction inferred from STEREO/SECCHI observations by Mierla *et al.* (*Solar Phys.* **252**, 385, 2008) with the three-dimensional configuration of the MC at 1 AU. This yields an almost radial CME propagation from the Sun to the Earth.

1. Introduction

Interplanetary coronal mass ejections (ICMEs) are the *in situ*-observed counterparts of coronal mass ejections (CMEs) as imaged by solar coronagraphs. Magnetic clouds are a subset of ICMEs characterized by a smooth rotation of the magnetic field vector with a stronger-than-average total field, low proton temperatures, and a low ratio of the plasma-to-magnetic pressure (Burlaga *et al.*, 1981). It has been suggested that magnetic clouds may form the central flux ropes of ICMEs, with the classification of the observed signatures depending on the trajectory of the spacecraft (Cane and Richardson, 2003; Jian *et al.*, 2006; Gopalswamy, 2006; Reinard, 2008). However, it seems unlikely that every ICME has an MC core (Riley *et al.*, 2006). Aside from this, many other unsolved questions regarding the three-dimensional shape of MCs in the heliosphere remain. It has been shown from a variety of independent studies that MCs are magnetic flux ropes of locally straight cylindrical geometry (Burlaga, 1988; Farrugia, Osherovich, and Burlaga, 1995; Shodhan *et al.*, 2000; Liu *et al.*, 2008). On the large-scale an MC is thought to form a bent flux rope extending from the Sun into interplanetary space (Burlaga, Lepping, and Jones, 1990; Marubashi, 1997; Bothmer and Schwenn, 1998) with its feet possibly still connected to the Sun (*e.g.*, Farrugia *et al.*, 1993b, and references therein). Also the possibility that the forward regions of MCs are peeled off by reconnection with the interplanetary magnetic field during their propagation from Sun to Earth has been recently put forward (Dasso *et al.*, 2006, 2007; Gosling *et al.*, 2007; Möstl *et al.*, 2008). Previously, Farrugia *et al.* (2001) had studied a reconnection layer at the leading edge of a magnetic cloud separating the cloud from the ejected material ahead of it. This possibility should be borne in mind as it influences the MC magnetic flux budget, which is important for establishing the Sun – Earth link (*e.g.* Longcope *et al.*, 2007; Qiu *et al.*, 2007; Démoulin, 2008; Möstl *et al.*, 2009). However, aside from very few events (Mulligan *et al.*, 1999; Mulligan and Russell, 2001), the shape of the MC cross-section and its longitudinal extent are not well known due to a lack of suitable multi-spacecraft observations.

In addition to their unique stereoscopic imaging capabilities, the two *Solar TErrestrial Relations Observatory* (STEREO) spacecraft drifting away from Earth in the ecliptic at the rate of 22° yr^{-1} also provide unprecedented two-point *in situ* measurements of the local interplanetary magnetic field, the solar wind plasma flow parameters and composition. Mission phase 1, from January 2007, when the STEREO separation was 0.05°, to April 2008 (separation 50°), is the most promising for observing MCs at more than one spacecraft (Kaiser *et al.*, 2008). Multi-spacecraft analyses have been conducted for two magnetic cloud events, those on 22 May 2007 (Liu *et al.*, 2008; Kilpua *et al.*, 2009; Möstl *et al.*, 2009) and on 23 May 2007 (Kilpua *et al.*, 2009). Both MCs were strongly inclined (≈50° and ≈−60°, respectively) to the ecliptic and thus the STEREO spacecraft, separated by 9°, crossed the MC approximately *perpendicular* to its axis. These efforts have shown that the cross-section of these two MCs is indeed "flattened", *i.e.* elongated in the plane transverse to the MC axis and its direction of motion, but to a lesser extent than what has previously been thought (Riley and Crooker, 2004; Liu *et al.*, 2006). This discrepancy might be caused by their highly inclined axes as well as their interaction with high-speed solar wind streams during solar minimum.

It is the aim of this paper to demonstrate quantitatively the ability of the method of Grad – Shafranov (GS) reconstruction (Hau and Sonnerup, 1999; Hu and Sonnerup, 2002; Sonnerup *et al.*, 2006) to retrieve an approximately correct cross-section of a magnetic cloud. To this end, we revisit the magnetic cloud event on 23 May 2007 and add new elements to previous analysis. Basic GS-reconstruction of the 23 May 2007 event has already been discussed by Kilpua *et al.* (2009). Here, we extend this analysis to demonstrate further that this MC is non-force free and its twisted field lines have an unexpected property, and to provide a set of guidelines for future use of the GS method. It has also been claimed that the GS method has a limited spatial domain which does not allow the full cross-section to be recovered (Riley *et al.*, 2004). Contrary to this, we will show that for this average-sized magnetic cloud (scale size in the radial direction = 0.12 AU) the reconstruction from STEREO-A data, constrained by *Wind* observations, covers almost the complete cloud cross-section. We also consider that GS is a static method which does not include the often reported expansion of the MCs (*e.g.* Farrugia *et al.*, 1992, 1993a, 1997; Dasso *et al.*, 2007; Démoulin *et al.*, 2008; Lepping *et al.*, 2008).

Very few MCs have been observed during the present solar minimum up to now and we selected this event because it is uniquely suited to an in-depth analysis, particularly since the spacecraft are separated by a distance of order the scale size of the ejecta. The event is connected to a GOES-class B6 flare and partial halo coronal mass ejection (CME) event in active region 10956 on 20 May 2007 (Mierla *et al.*, 2008; Kilpua *et al.*, 2009). Thus, our event is at the lower end of the importance classification of solar eruptions as observed during solar minimum.

2. Magnetic Cloud Event on 23 May 2007

For data plots and a basic GS reconstruction of this event we refer the reader to Kilpua *et al.* (2009). The reconstructed and optimized (to be discussed later) magnetic field map from STEREO-A is shown in Figure 1(b). A 3D view of its local orientation in the heliosphere is shown in Figure 2. In this paper we do not use a genuine multi-spacecraft GS method (Sonnerup, Hasegawa, and Paschmann, 2004; Hasegawa *et al.*, 2005, 2006; Möstl *et al.*, 2008, 2009), *i.e.* we do not create combined magnetic field maps, but use GS reconstruction at one spacecraft to correlate model predictions with observations at another spacecraft (Hasegawa *et al.*, 2004).

Because this event presents a unique opportunity to model a MC cross-section with two spacecraft separated by a distance of the same order as the linear scale size of the MC, we discuss four additional aspects not described in Kilpua *et al.* (2009): (1) The correlation between the predicted magnetic field map reconstructed from STEREO-A and the observations by *Wind* is quantified and discussed for all magnetic field components. (2) The *Wind* observations are used to optimize this correlation and clues are presented on how to handle the GS method when applied to single-spacecraft measurements. In this way an improvement on the use of GS reconstruction is suggested. (3) From the optimized magnetic field map, currents are calculated to show *where* the force-free condition in the MC breaks down, and (4) the number of field line turns per unit length (*i.e.* the twist of the field lines or equivalently how often a field line winds around the MC axis per AU) is calculated for different

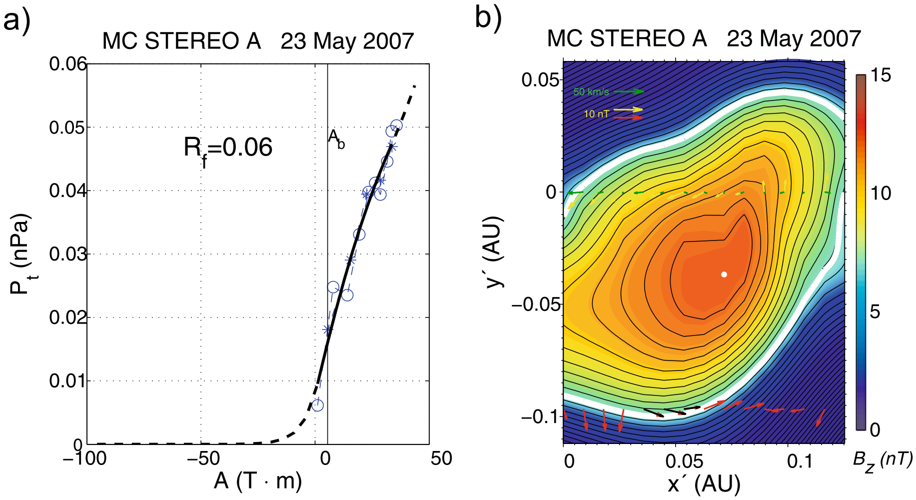

Figure 1 23 May 2007 MC: (a) $P_t(A)$ plot with polynomial fitting function of order $f_\mathrm{p} = 2$ (solid black) and exponential tails (dashed black). Circles denote inbound, stars outbound measurements. The vertical line A_b delimits the interval where $P_t(A)$ is single-valued, corresponding to the thick white contour line in the map (right panel). (b) Reconstructed magnetic field map from STEREO-A measurements optimized using *Wind* observations (see text). Black contours represent transverse magnetic field lines in the paper plane, and color-coded is the B_z component pointing out of the paper. The MC axis is at the white dot. Upper (lower) yellow (red, black) arrows are STEREO-A (*Wind*) observations of transverse magnetic field components, green arrows are residual velocities in the deHoffmann – Teller frame at STEREO-A. The solid white contour is the MC boundary.

distances to the axis, exhibiting an unexpected behavior, not consistent with the often used linear force-free constant-α Lundquist model (*e.g.* Goldstein, 1983; Burlaga, 1988; Lepping, Burlaga, and Jones, 1990; Leitner *et al.*, 2007).

2.1. Optimized Reconstruction and GS Guideline

The GS method was originally developed for magnetopause applications (Hau and Sonnerup, 1999) and its validity has been shown by multi-spacecraft observations, *e.g.* flux transfer events modeled as magnetic flux ropes (Hasegawa *et al.*, 2006) and one magnetic cloud (Liu *et al.*, 2008). For an in-depth description of the method we refer the reader to Hu and Sonnerup (2002) and Sonnerup *et al.* (2006), but for better understanding of what follows we describe some elements necessary for the following discussion. The STEREO magnetic field data from the *In situ* Measurements of PArticle and CME Transients experiment (IMPACT, Luhmann *et al.*, 2008) are rotated (implemented in *SolarSoft*) from the RTN coordinate system to a GSE system to facilitate the analysis using the *Wind* magnetic field data (also in GSE; Lepping *et al.*, 1995). We also use plasma bulk parameters from the PLAsma and Supra-Thermal Ion Composition experiment (PLASTIC) on board STEREO (Galvin *et al.*, 2008) and the Solar Wind Experiment (SWE) on board *Wind* (Ogilvie *et al.*, 1995). The reference frame is the so-called the deHoffmann – Teller frame, moving with a velocity $\mathbf{V}_{\mathrm{HT}}$ (*e.g.* Khrabrov and Sonnerup (1998), see *e.g.* Sonnerup *et al.* (2006) for notes on proper use), where the flow is aligned with the magnetic field. An invariant axis $\hat{\mathbf{z}}'$ is derived through the condition that the transverse pressure,

$$P_t(A) = p + B_z'^2/2\mu_0, \tag{1}$$

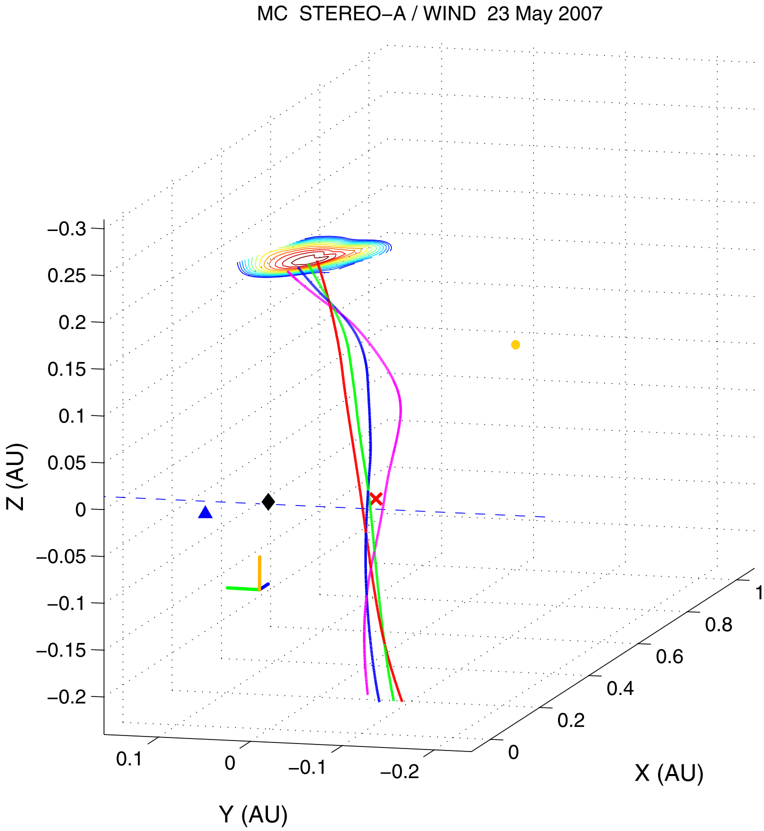

Figure 2 23 May 2007 MC: 3-D plot of the optimized reconstruction in the heliosphere. The positions of STEREO-A (red X), *Wind* (black diamond) and STEREO-B (blue triangle) are indicated. Invariance along the axis for 0.3 AU was assumed. The coordinate system is GSE (unit vectors indicated: blue X, green Y, orange Z). The Sun is the small yellow sphere (to scale).

with p being the plasma pressure and B'_z the observed magnetic field component along $\hat{\mathbf{z}}'$, must be as close as possible to a single-valued function (Hu and Sonnerup, 2002). A reconstruction coordinate system ($\hat{\mathbf{x}}'$,$\hat{\mathbf{y}}'$,$\hat{\mathbf{z}}'$) is established (these are the coordinates in Figure 1(b), with $\hat{\mathbf{z}}'$ pointing out of the paper). The magnetic field observations are resampled to a number of n_x points with a anti-aliasing low-pass filter (function "resample" in MATLAB). To numerically integrate the Grad – Shafranov equation, *i.e.*,

$$\frac{\partial^2 A}{\partial x'^2} + \frac{\partial^2 A}{\partial y'^2} = -\mu_0 \frac{\mathrm{d}P_t(A)}{\mathrm{d}A} = -\mu_0 \frac{\mathrm{d}(p + B_z'^2/2\mu_0)}{\mathrm{d}A} = -\mu_0 j_z(A), \qquad (2)$$

where A is the vector potential and $j_z(A)$ the axial current density, the right-hand side, *i.e.* the derivative $P_t(A)$, has to be known. To this end the measurements of $P_t(A)$ are fitted to a polynomial function, and exponential tails are used for those values of the vector potential A which are not covered by observations (Figure 1(a)).

With the help of multi-spacecraft observations it is then possible to test the validity of two main method assumptions, namely, (1) time-independency, and (2) invariance along a particular direction. Further they show how to choose several parameters of the reconstruction which are not clear a priori and which have been thus far inferred from reconstruction of analytical data (Hu and Sonnerup, 2002). The parameters which influence the shape of the resulting magnetic field map (Figure 1(b)) are: the number of grid points n_x along $\hat{\mathbf{x}}'$, usually $n_x = 15-21$ (Hu and Sonnerup, 2002; Hu *et al.*, 2004); the order of the polynomial f_p for fitting the function $P_t(A)$ (often $f_\mathrm{p} = 2-4$); the chosen data time interval (Hu *et al.*, 2004), and the orientation of the invariant axis $\hat{\mathbf{z}}'$.

An expanding MC would also influence the resulting magnetic field map. The expansion effect can be estimated using the expansion velocity $V_{\mathrm{exp}} = (V_l - V_t)/2$ with the leading edge (front boundary) velocity $V_l = 535\ \mathrm{km\,s^{-1}}$ and the trailing edge (back boundary) velocity $V_t = 453\ \mathrm{km\,s^{-1}}$. The deHoffmann – Teller velocity is $V_{\mathrm{HT}} = 493\ \mathrm{km\,s^{-1}}$ and the ratio $V_{\mathrm{exp}}/V_{\mathrm{HT}} = 0.083 \ll 1$ (Möstl *et al.*, 2009), so the expansion effect, while clearly observed, may not be particularly significant here.

The separation vector from STEREO-A to *Wind* in cloud–centered coordinates is $\mathbf{s}' = [-0.0589; -0.0967; -0.0155]$ AU. Thus the probes are separated mainly along $-\hat{\mathbf{y}}'$, making the event ideally suited to determine the cross-section of the cloud.

The *Wind* data have been time-shifted according to the assumption that the cloud, and thus the integration domain box, moves with constant $\mathbf{V}_{\mathrm{HT}}$ velocity (Möstl *et al.*, 2009):

$$t_W = s'_x/(\hat{\mathbf{x}} \cdot \mathbf{V}_{\mathrm{HT}}), \tag{3}$$

i.e. the separation vector component s'_x divided by the deHoffmann – Teller velocity along $\hat{\mathbf{x}}$. The result is $t_W = +5.38$ h. The full time interval at *Wind* is therefore 23 May 2007 06:20 – 17:48 UT; the *Wind* magnetic field data have been resampled also to a number of n_x points and plotted as arrows in the $\hat{\mathbf{x}}' - \hat{\mathbf{y}}'$ plane in Figure 1(b) (lower trajectory). From this full interval we pick out the time range 9:36 – 11:12 UT corresponding to three clearly rotating arrows in Figure 1(b) between 0.036 and 0.054 AU along $\hat{\mathbf{x}}'$ highlighted in black color (this choice will become more clear a posteriori). For every trial reconstruction a correlation coefficient is calculated between the predictions from the map (linearly interpolated between grid points) and the observed magnetic field components underlying these three arrows. Figure 3 shows this comparison (already optimized, see below), with the predicted field components at *Wind* position plotted as circles. From our study of this event, we draw some conclusions on how to choose the parameters quoted above correctly, as gauged by the value of *cc*:

- n_x: for a choice of $n_x = 11-17$, the field map is about the same as in Figure 1(b) and $cc > 0.8$. The best match was found for $n_x = 15$ ($cc = 0.94$).
- f_p: a polynomial of order 2 is much better than orders 3 or 4; for $f_\mathrm{p} > 2$ the right hand side of Equation (2), $\mathrm{d}P_t(A)/\mathrm{d}A = j_z$, becomes larger, assuming stronger axial currents j_z which shrinks the cross-section in the $\hat{\mathbf{y}}'$ direction to an unreasonable small extent placing *Wind* completely outside the MC, contrary to what is observed (and also lowering the *cc*).
- Interval: the time interval (Table 1) was chosen following Hu *et al.* (2004), who claimed that the interval should be determined as such that $P_t(A)$ begins and ends at about the same A value. We can completely confirm this statement, as a much longer or much shorter time interval than the one corresponding to this rule also leads to unreasonable magnetic field maps. The final STEREO-A data time interval used for the reconstruction (Figure 1(b)) is 23 May 2007 00:56 – 12:24 UT.
- Axis orientation ($\theta = 58°$, $\phi = 220°$): keeping the other parameters fixed and changing the orientation in only a few degrees ($\theta \pm 2°$, in $\phi \pm 5°$) the *cc* quickly decreases, which tells us that the invariant axis, as determined by single-spacecraft GS, is the correct one.

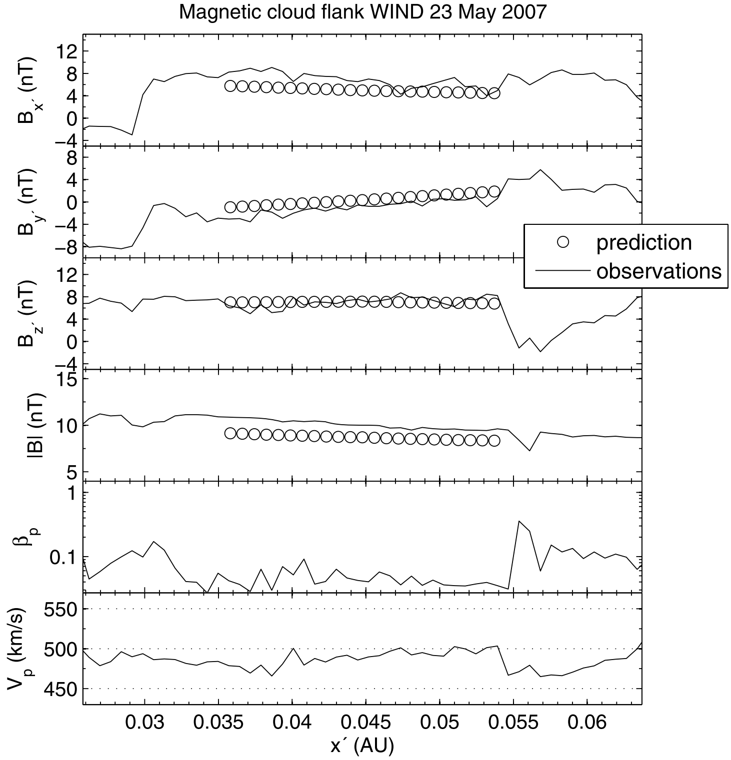

Figure 3 Comparison between the predicted magnetic field components (circles) and total field magnitude at the trajectory of *Wind* from the optimized STEREO-A magnetic field map (Figure 1(b)) with observations by *Wind* (solid lines), in reconstruction (MC) coordinates. Also shown is the proton β (the ratio of the proton-to-magnetic pressure) and the proton bulk velocity V_{p} for *Wind*. The full x-axis corresponds to the *Wind* time interval 23 May 2007 8:40 – 12:08 UT. The interval for which the predictions are plotted over the observations is 23 May 2007 9:36–11:12 UT.

The time shift t_W also depends on the orientation and only for the above given error bars there is a reasonable match between the relative timing of the predictions and observations in Figure 3.

Even though inferred from a single event, the presented results can also be considered as a guideline for the correct use of the single-spacecraft GS method for MCs. The best correlation coefficient between the filtered observations and predicted components at *Wind* is $cc = 0.94$, for a choice of n_x=15, $f_{\mathrm{p}} = 2$, the axis from single-spacecraft GS, and the time interval as described. One can see from Figure 3 that the decrease in B_x', the increase in B_y' and the almost constant value of B_z' are basically correctly modeled, although the total field strength is underestimated by 15% on average. There are also deviations between observed and predicted fields, especially in B_x', which stem from either the invariance or the time-independence assumption. Because the time-shift inferred from Equation (3) and the observations are consistent, we think that it is the invariance which fails and not the time-independence. This might be attributed to the fact that the flank region of the MC is already strongly distorted by the interaction with the surrounding solar wind.

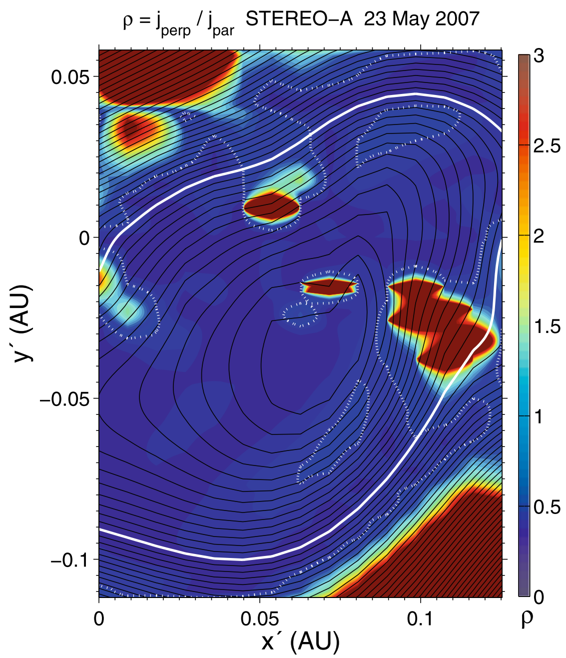

Figure 4 The ratio of the perpendicular to the parallel currents $\varrho = |\boldsymbol{J}_\perp|/|\boldsymbol{J}_\parallel|$ (color coded). The dotted white contour indicates the level where $\varrho = 0.3$, areas with $\varrho < 0.3$ are force-free by definition. Solid black contours are field lines in the $\hat{x}' - \hat{y}'$ plane. The solid white contour is again the MC boundary.

The derived axis orientation might be influenced by the minimum distance a spacecraft crosses to the MC axis (the impact parameter p). In this case p equals 30% of the MC radial scale size (see Table 1). From the optimized reconstruction we infer that the derived axis orientation remains practically the same for impact parameter values up to this value of p if the model assumptions are fulfilled; this has also been demonstrated for the GS method with analytic data by Hu and Sonnerup (2002), and for the minimum variance analysis method using unit vectors also with analytic data by Gulisano *et al.* (2007).

In summary, the separation distance between *Wind* and STEREO-A perpendicular to the MC axis is almost 0.1 AU, demonstrating the ability of the numerical GS solver, when used correctly, to return a reasonable magnetic field map up to this separation distance. We note that this separation is about twice that between STEREO-B and *Wind* for the 22 May 2007 MC event studied by Liu *et al.* (2008). Compared to the 22 May 2007 MC event the event we study here has the advantage that the full MC interval can be used as an input to the GS method.

2.2. Testing the Force-Free Assumption

From the optimized magnetic field map we calculated the currents from $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$. The parallel current follows from $\boldsymbol{J}_\parallel = \boldsymbol{J} \cdot \boldsymbol{B}/|\boldsymbol{B}|$, and the perpendicular current is given by $\boldsymbol{J}_\perp = \boldsymbol{J} - \boldsymbol{J}_\parallel$. The ratio $\varrho = |\boldsymbol{J}_\perp|/|\boldsymbol{J}_\parallel|$ is then calculated for every grid point, where we arbitrarily define a grid point to be force-free if $\varrho < 0.3$, because for this ratio $\boldsymbol{J}_\parallel$ still clearly dominates. Figure 4 shows the resulting map for ϱ. There are qualitative indications that about quarter of the cloud area is non-force-free, in particular the back part, where the MC is deformed (Figure 1(b)). Field lines which are approximately circular are force-free, as expected. We attribute this departure from the force-free state to an interaction with the trailing high-speed stream immediately following the MC interval at STEREO-A (Kilpua *et al.*, 2009).

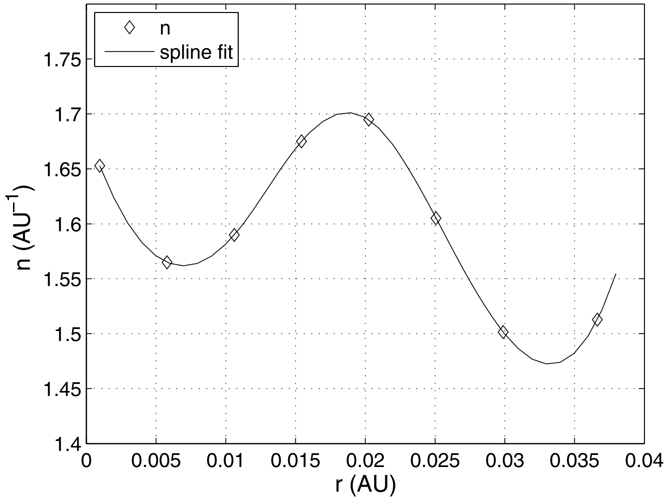

Figure 5 The number of turns n a field line makes around the MC axis per AU, plotted vs. distance from the axis r.

Table 1 Results for the 23 May 2007 MC at STEREO-A, for optimized GS reconstruction (middle column) and force-free fitting (right column). θ is the axis inclination to the ecliptic; ϕ is measured from GSE-X towards GSE-Y. The scale size in the radial direction, D, is calculated from GS in the $\hat{x}' - \hat{y}'$ plane perpendicular to the axis along the spacecraft trajectory, for FF this is twice the radius R_0 obtained from the fitting procedure. p is the closest distance a spacecraft passes to the MC axis (the impact parameter). For the poloidal flux Φ_p a range of flux tube lengths, to which Φ_p is proportional, of $L = 0.5 - 2$ AU was taken. The total axial current I is also given. The FF error bars are derived assuming a variation in $B_0 \pm 1$ nT and in $D \pm 0.01$ AU.

Parameter/method	GS	FF
start, UT (Δt)	00:56 (11 h 28 m)	01:02 (11 h 10 min)
V_{HT}, km s^{-1}	493	–
B_0, nT	11.8	16.1
θ, deg	−58	−68
ϕ, deg	220	281
H	R	R
D, AU	0.125	0.103
p, AU	0.037	0.023
Φ_t, 10^{21} Mx	0.30	0.13 ± 0.06
Φ_p, 10^{21} Mx	0.28 – 1.11	0.33 – 1.8
I, MA	323	322 ± 20

2.3. Field Line Turns

The number of turns n per AU for various distances from the MC axis r was calculated from the optimized map and the result is shown in Figure 5. For this we assumed invariance and followed magnetic field lines around the MC axis until they closed on themselves (similar to

Figure 2) to determine the so-called pitch. This is the axial length of a field line in AU that encircles the axis once, and n is the inverse of the pitch. For the linear force-free, constant-α Lundquist model, n is a monotonically increasing function of radial distance from the axis. For the MC under discussion, the behavior is not monotonic: a steady increase is only found between $r = 0.005 - 0.02$ AU (Figure 5), but then n declines. This means that the outer field lines are less twisted than the inner ones, which is at variance with the linear force-free model. Another event with a decrease in n has been reported by Hu and Sonnerup (2002). However, this is the first time that a magnetic cloud has been reconstructed which shows both first increasing and then decreasing n, and the optimization procedure gives us confidence in these results. Field lines for which $r > 0.037$ AU do not close on themselves in the magnetic field map so we cannot determine n. The number of turns $n = 1.5 - 1.7$ AU^{-1} does not vary much, for a length $L = 2.5$ AU the full number of turns is about four. An example of a small-scale flux rope with field line twist independent of r (a so-called " Gold-Hoyle" tube) was studied by Farrugia *et al.* (1999), and another MC event (18 October 1995) with almost constant n was discussed by Hu and Sonnerup (2002).

3. Summary and Conclusions

In this paper we demonstrated several issues related to the method of Grad – Shafranov reconstruction and its application to the 23 May 2007 magnetic cloud event, building on the work of Kilpua *et al.* (2009). We obtain the following new results. We used a novel technique for the first time in the interplanetary context in which a reconstructed magnetic field map is optimized through correlation techniques, and demonstrated the ability of the numerical solver used to return reliable results up to a spacecraft separation distance of $\approx$0.1 AU, which in this case corresponds to 80% of the clouds scale size in the radial direction. From this we answered some open questions on the correct use of the method and presented guidelines for its future use in magnetic clouds. From the optimized field map, currents were derived to show where in the magnetic cloud the force-free assumption breaks down. How the field lines are twisted in the non-force-free model was also discussed, exhibiting in this case an interesting behavior which is inconsistent with the popular force-free Lundquist model.

For comparison, the results of the optimized GS reconstruction and force-free fitting (FF, Lepping, Burlaga, and Jones, 1990) for global MC parameters are shown in Table 1. The good quality of the force-free fit is demonstrated in Figure 6. There is in general good agreement between the two methods, but there is a difference in the angle ϕ of 60 degrees (which could arise from the high inclination), the axial flux is underestimated by FF by about a factor of 2 and the axial field B_0 is also clearly higher for FF. But on the inclination, impact parameter, poloidal flux and axial current the agreement is very good. This is consistent with the work of Dasso *et al.* (2003) who found that various cylindrical models used for fitting the magnetic field profile of MCs also lead to similar magnetic fluxes. It could be that a systematic difference which arises from the deformed cross-section, the different twist of the field lines and the non-force-free treatment by GS affects some parameters more than others. We also note that the method without optimization, *i.e.* a "blind" reconstruction, gives quite similar results (see also Figure 6c in Kilpua *et al.*, 2009).

However, we think the confidence in the determination of the main cloud parameters, especially in the orientation, clearly increases with multi-spacecraft observations because for a good consistency between model predictions and observations there is not much variation possible in global parameters. The magnetic field map shows the main part of the cloud

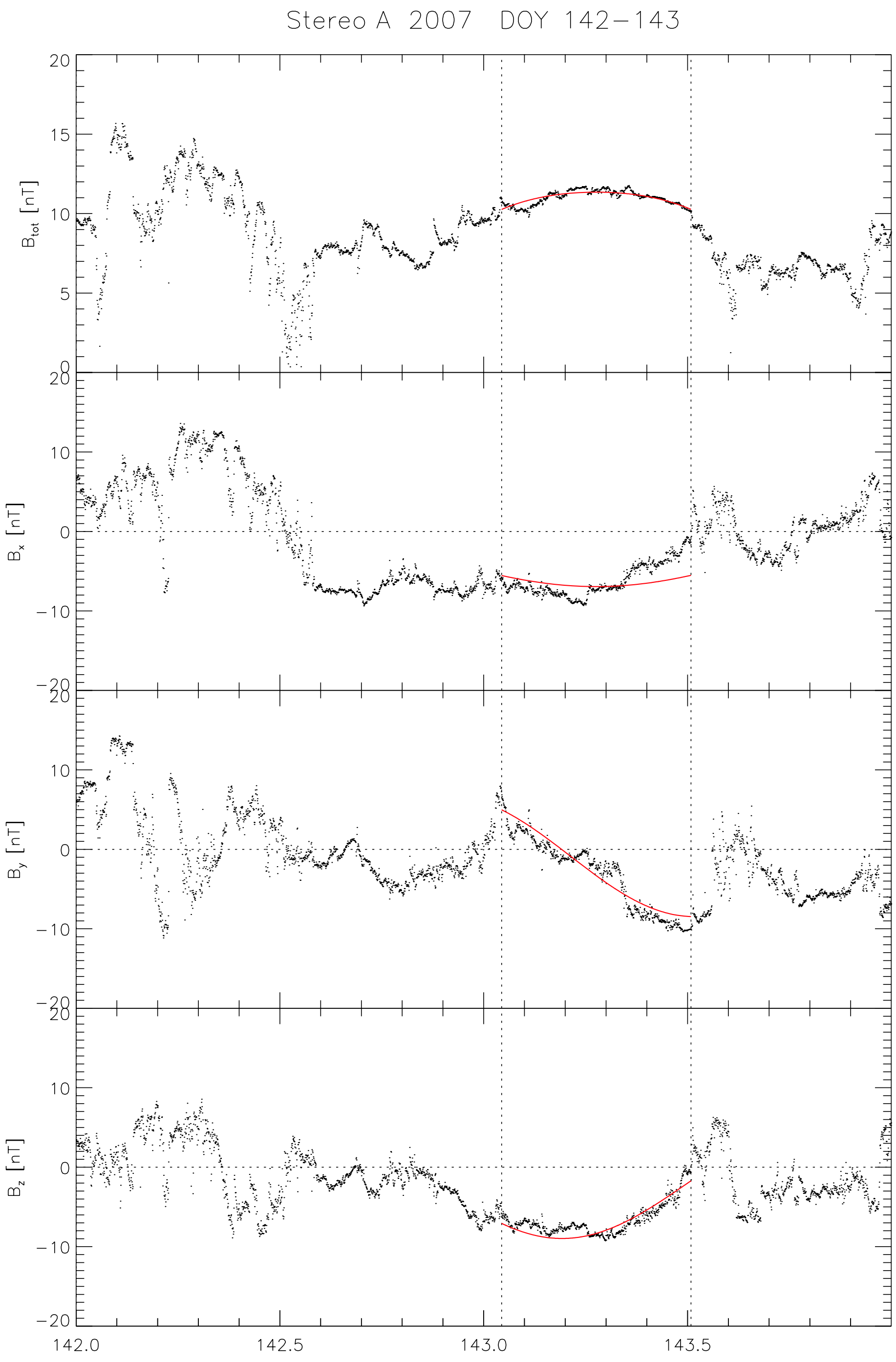

Figure 6 STEREO-A magnetic field components in GSE coordinates fitted by the linear force-free model (red solid line).

which seems to extend more in the $-\hat{\mathbf{x}}'$ and $+\hat{\mathbf{x}}'$ directions outside of the map (Figure 1(b)), and thus the fluxes and the total axial current in Table 1 are still underestimated. However, we think that the main spatial extent of the cloud is well covered and the results are quite close to reality (for further discussions see also Möstl *et al.*, 2009).

The often criticized circular, linear Lundquist model seems nevertheless to be a good description of the core region of at least some MCs, for which evidence has also been found by *e.g.* Dasso *et al.* (2005). The present method still assumes an invariant axis and time-independence. With multi-spacecraft observations, such as presented here, correlation techniques can be used to test these assumptions. These correlations showed that time-independence is quite valid for a time-lapse of about 5 hours from STEREO-A to *Wind*, and that there were some important departures from the assumption of invariance. This study was a first step to show that the method is indeed capable of returning an approximate shape of a magnetic cloud cross-section. In the future, it would be necessary to develop a complete 3D torus-shaped model of magnetic clouds which can then be constrained by multi-spacecraft observations of several events. In summary, the analysis shows the usefulness of widely separated multi-spacecraft observations in determining the three-dimensional shape of magnetic clouds (see also the suggestions by Marubashi and Lepping, 2007). Here, we found evidence that a magnetic cloud cross-section has the shape of a helical magnetic flux rope consisting of "distorted ellipses".

The optimized reconstruction method has given us a picture of the magnetic cloud 3D-configuration near Earth (Figure 2). The corresponding CME event on 20 May 2007 has been discussed by Mierla *et al.* (2008) using data from Inner Coronagraph (COR1) of the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) experiment from two view-points, inferring the CME direction and de-projected velocity. Kilpua *et al.* (2009) showed that this de-projected velocity matches much better the transit time of the MC than the projected velocity. Additionally, Mierla *et al.* (2008) were able to estimate the CME propagation direction as 2 degrees *east* of the Sun – Earth line between 2.4 to 6 $R_\odot$, and the latitude as -30 degree to the ecliptic. At Earth, the MC axis passes *west* of Earth by approximately 3 degrees (see Figure 2, and Figures 1 and 7 in Kilpua *et al.*, 2009) but seems to have its apex indeed below the ecliptic. Thus the longitude estimation was correct to within 5 degrees, indicating that the MC was not deflected much from the radial direction between 6 $R_\odot$ and 1 AU. However, this difference might already be decisive in forecasting the geo-effects of a highly inclined magnetic cloud from observations near the Sun.

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References

Bothmer, V., Schwenn, R.: 1998, The structure and origin of magnetic clouds in the solar wind. *Ann. Geophys.* **16**, 1.

Burlaga, L.F.: 1988, Magnetic clouds and force-free fields with constant alpha. *J. Geophys. Res.* **93**, 7217.
Burlaga, L.F., Lepping, R.P., Jones, J.A.: 1990, Global configuration of a magnetic cloud. In: Russell, C.T., Priest, E.R., Lee, L.C. (eds.) *Physics of Magnetic Flux Ropes*, *Geophysical Monograph Ser.* **58**, AGU, Washington DC, 377.
Burlaga, L., Sittler, E., Mariani, F., Schwenn, R.: 1981, Magnetic loop behind an interplanetary shock – Voyager, Helios, and IMP 8 observations. *J. Geophys. Res.* **86**, 6673.
Cane, H.V., Richardson, I.G.: 2003, Interplanetary coronal mass ejections in the near-Earth solar wind during 1996 – 2002. *J. Geophys. Res. (Space Phys.)* **108**, 1156. doi:10.1029/2002JA009817.
Dasso, S., Mandrini, C.H., Démoulin, P., Farrugia, C.J.: 2003, Magnetic helicity analysis of an interplanetary twisted flux tube. *J. Geophys. Res. (Space Phys.)* **108**, 1362. doi:10.1029/2003JA009942.
Dasso, S., Gulisano, A.M., Mandrini, C.H., Démoulin, P.: 2005, Model-independent large-scale magnetohydrodynamic quantities in magnetic clouds. *Adv. Space Res.* **35**, 2172. doi:10.1016/j.asr.2005.03.054.
Dasso, S., Mandrini, C.H., Démoulin, P., Luoni, M.L.: 2006, A new model-independent method to compute magnetic helicity in magnetic clouds. *Astron. Astrophys.* **455**, 349. doi:10.1051/0004-6361:20064806.
Dasso, S., Nakwacki, M.S., Démoulin, P., Mandrini, C.H.: 2007, Progressive transformation of a flux rope to an ICME. Comparative analysis using the direct and fitted expansion methods. *Solar Phys.* **244**, 115. doi:10.1007/s11207-007-9034-2.
Démoulin, P.: 2008, A review of the quantitative links between CMEs and magnetic clouds. *Ann. Geophys.* **26**, 3113.
Démoulin, P., Nakwacki, M.S., Dasso, S., Mandrini, C.H.: 2008, Expected *in situ* velocities from a hierarchical model for expanding interplanetary coronal mass ejections. *Solar Phys.* **250**, 347. doi:10.1007/s11207-008-9221-9.
Farrugia, C.J.: 1997, Recent work on modelling the global field line topology of interplanetary magnetic clouds: A review. In: Crooker, N., Joselyn, J.A., Feynmann, J. (eds.) *Coronal Mass Ejections*, *Geophysical Monograph Ser.* **99**, AGU, Washington DC, 177.
Farrugia, C.J., Osherovich, V.A., Burlaga, L.F.: 1995, Magnetic flux rope versus the spheromak as models for interplanetary magnetic clouds. *J. Geophys. Res.* **100**, 12293.
Farrugia, C.J., Burlaga, L.F., Osherovich, V.A., Lepping, R.P.: 1992, A comparative study of dynamically expanding force-free, constant-alpha magnetic configurations with applications to magnetic clouds. In: Marsch, E., Schwenn, R. (eds.) *Solar Wind Seven, Proc. 3rd, COSPAR Colloq.*, 611.
Farrugia, C.J., Burlaga, L.F., Osherovich, V.A., Richardson, I.G., Freeman, M.P., Lepping, R.P., Lazarus, A.J.: 1993a, A study of an expanding interplanetary magnetic cloud and its interaction with the Earth's magnetosphere – The interplanetary aspect. *J. Geophys. Res.* **98**, 7621.
Farrugia, C.J., Richardson, I.G., Burlaga, L.F., Lepping, R.P., Osherovich, V.A.: 1993b, Simultaneous observations of solar MeV particles in a magnetic cloud and in the Earth's northern tail lobe – Implications for the global field line topology of magnetic clouds and for the entry of solar particles into the magnetosphere during cloud passage. *J. Geophys. Res.* **98**, 15497.
Farrugia, C.J., Janoo, L.A., Torbert, R.B., Quinn, J.M., Ogilvie, K.W., Lepping, R.P., Fitzenreiter, R.J., Steinberg, J.T., Lazarus, A.J., Lin, R.P., Larson, D., Dasso, S., Gratton, F.T., Lin, Y., Berdichevsky, D.: 1999, A uniform-twist magnetic flux rope in the solar wind. In: Suess, S.T., Gary, G.A., Nerney, S.F. (eds.) *Solar Wind Nine, AIP Conf. Ser.* **471**, 745.
Farrugia, C.J., Vasquez, B., Richardson, I.G., Torbert, R.B., Burlaga, L.F., Biernat, H.K., Mühlbachler, S., Ogilvie, K.W., Lepping, R.P., Scudder, J.D., *et al.*: 2001, A reconnection layer associated with a magnetic cloud. *Adv. Space Res.* **28**, 759.
Galvin, A.B., Kistler, L.M., Popecki, M.A., Farrugia, C.J., Simunac, K.D.C., Ellis, L., Möbius, E., Lee, M.A., Boehm, M., Carroll, J., *et al.*: 2008, The plasma and suprathermal ion composition (PLASTIC) investigation on the STEREO observatories. *Space Sci. Rev.*, **136**, 437.
Goldstein, H.: 1983, On the field configuration in magnetic clouds. In: Neugebauer, M. (ed.) *Solar Wind Five*, *NASA Conf. Publ.* **CP-2280**, 731.
Gopalswamy, N.: 2006, Properties of interplanetary coronal mass ejections. *Space Sci. Rev.* **124**, 145. doi:10.1007/s11214-006-9102-1.
Gosling, J.T., Eriksson, S., McComas, D.J., Phan, T.D., Skoug, R.M.: 2007, Multiple magnetic reconnection sites associated with a coronal mass ejection in the solar wind. *J. Geophys. Res. (Space Phys.)* **112**, A08106. doi:10.1029/2007JA012418.
Gulisano, A.M., Dasso, S., Mandrini, C.H., Démoulin, P.: 2007, Estimation of the bias of the minimum variance technique in the determination of magnetic clouds global quantities and orientation. *Adv. Space Res.* **40**, 1881. doi:10.1016/j.asr.2007.09.001.
Hasegawa, H., Sonnerup, B., Dunlop, M., Balogh, A., Haaland, S., Klecker, B., Paschmann, G., Lavraud, B., Dandouras, I., Rème, H.: 2004, Reconstruction of two-dimensional magnetopause structures from Cluster observations: Verification of method. *Ann. Geophys.* **22**, 1251.

Hasegawa, H., Sonnerup, B.U.Ö., Klecker, B., Paschmann, G., Dunlop, M.W., Rème, H.: 2005, Optimal reconstruction of magnetopause structures from Cluster data. *Ann. Geophys.* **23**, 973.
Hasegawa, H., Sonnerup, B.U.Ö., Owen, C.J., Klecker, B., Paschmann, G., Balogh, A., Rème, H.: 2006, The structure of flux transfer events recovered from Cluster data. *Ann. Geophys.* **24**, 603.
Hau, L.N., Sonnerup, B.U.Ö.: 1999, Two-dimensional coherent structures in the magnetopause: Recovery of static equilibria from single-spacecraft data. *J. Geophys. Res.* **104**, 6899. doi:10.1029/1999JA900002.
Hu, Q., Sonnerup, B.U.Ö.: 2002, Reconstruction of magnetic clouds in the solar wind: Orientations and configurations. *J. Geophys. Res. (Space Phys.)* **107**, 1142. doi:10.1029/2001JA000293.
Hu, Q., Smith, C.W., Ness, N.F., Skoug, R.M.: 2004, Multiple flux rope magnetic ejecta in the solar wind. *J. Geophys. Res. (Space Phys.)* **109**, A03102. doi:10.1029/2003JA010101.
Jian, L., Russell, C.T., Luhmann, J.G., Skoug, R.M.: 2006, Properties of interplanetary coronal mass ejections at one AU during 1995 – 2004. *Solar Phys.* **239**, 393. doi:10.1007/s11207-006-0133-2.
Kaiser, M.L., Kucera, T.A., Davila, J.M., St. Cyr, O.C., Guhathakurta, M., Christian, E.: 2008, The STEREO mission: An introduction. *Space Sci. Rev.* **136**, 5. doi:10.1007/s11214-007-9277-0.
Khrabrov, A.V., Sonnerup, B.U.Ö.: 1998, deHoffmann – Teller analysis. In: Paschmann, G., Daly, P.W. (eds.) *Analysis Methods for Multi-Spacecraft Data*, *ISSI Sience Rep. Ser.* **1**, ESA, Noordwijk 221.
Kilpua, E.K.J., Liewer, P., Farrugia, C., Luhmann, J., Möstl, C., Li, Y., Liu, Y., Lynch, B., Vourlidas, A., Acuna, M., Galvin, A.B., Larson, D., Russell, C., Sauvaud, J.: 2009, Multispacecraft observations of magnetic clouds and their solar origins May 19 – 23, 2007. *Solar Phys.* **254**, 325. doi:10.1007/s11207-008-9300-y.
Leitner, M., Farrugia, C.J., Möstl, C., Ogilvie, K.W., Galvin, A.B., Schwenn, R., Biernat, H.K.: 2007, Consequences of the force-free model of magnetic clouds for their heliospheric evolution. *J. Geophys. Res. (Space Phys.)* **112**, A06113. doi:10.1029/2006JA011940.
Lepping, R.P., Burlaga, L.F., Jones, J.A.: 1990, Magnetic field structure of interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.* **95**, 11957.
Lepping, R.P., *et al.*: 1995, The wind magnetic field investigation, *Space Sci. Rev.*, **71**, 207.
Lepping, R.P., Wu, C.C., Berdichevsky, D.B., Ferguson, T.: 2008, Estimates of magnetic cloud expansion at 1 AU. *Ann. Geophys.* **26**, 1919.
Liu, Y., Richardson, J.D., Belcher, J.W., Wang, C., Hu, Q., Kasper, J.C.: 2006, Constraints on the global structure of magnetic clouds: Transverse size and curvature. *J. Geophys. Res. (Space Phys.)* **111**, A12S03. doi:10.1029/2006JA011890.
Liu, Y., Luhmann, J.G., Huttunen, K.E.J., Lin, R.P., Bale, S.D., Russell, C.T., Galvin, A.B.: 2008, Reconstruction of the 2007 May 22 magnetic cloud: How much can we trust the flux-rope geometry of CMEs? *Astrophys. J. Lett.* **677**, L133. doi:10.1086/587839.
Longcope, D., Beveridge, C., Qiu, J., Ravindra, B., Barnes, G., Dasso, S.: 2007, Modeling and measuring the flux reconnected and ejected by the two-ribbon flare/CME event on 7 November 2004. *Solar Phys.* **244**, 45. doi:10.1007/s11207-007-0330-7.
Luhmann, J. G., *et al.*: 2008, STEREO IMPACT investigation goals, measurements, and data products overview. *Space Sci. Rev.*, **136**, 117.
Marubashi, K.: 1997, Interplanetary flux ropes and solar filaments. In: Crooker, N., Joselyn, J.A., Feynman, J. (eds.) *Coronal Mass Ejections*, *Geophysical Monograph Ser.* **99**, AGU, Washigton DC, 147.
Marubashi, K., Lepping, R.P.: 2007, Long-duration magnetic clouds: a comparison of analyses using torus- and cylinder-shaped flux rope models. *Ann. Geophys.* **25**, 2453.
Mierla, M., Davila, J., Thompson, W., Inhester, B., Srivastava, N., Kramar, M., St. Cyr, O.C., Stenborg, G., Howard, R.A.: 2008, A quick method for estimating the propagation direction of coronal mass ejections using STEREO-COR1 images. *Solar Phys.* **252**, 385. doi:10.1007/s11207-008-9267-8.
Möstl, C., Miklenic, C., Farrugia, C.J., Temmer, M., Veronig, A., Galvin, A.B., Vršnak, B., Biernat, H.K.: 2008, Two-spacecraft reconstruction of a magnetic cloud and comparison to its solar source. *Ann. Geophys.* **26**, 3139.
Möstl, C., Farrugia, C.J., Miklenic, C., Temmer, M., Galvin, A.B., Luhmann, J.G., Huttunen, K.E.J., Leitner, M., Nieves-Chinchilla, T., Veronig, A., Biernat, H.K.: 2009, Multi-spacecraft recovery of a magnetic cloud and its origin from magnetic reconnection on the Sun. *J. Geophys. Res. (Space Phys.)* **114**, A04102. doi:10.1029/2008JA013657.
Mulligan, T., Russell, C.T.: 2001, Multispacecraft modeling of the flux rope structure of interplanetary coronal mass ejections: Cylindrically symmetric versus nonsymmetric topologies. *J. Geophys. Res.* **106**, 10581. doi:10.1029/2000JA900170.
Mulligan, T., Russell, C.T., Anderson, B.J., Lohr, D.A., Rust, D., Toth, B.A., Zanetti, L.J., Acuna, M.H., Lepping, R.P., Gosling, J.T.: 1999, Intercomparison of NEAR and Wind interplanetary coronal mass ejection observations. *J. Geophys. Res.* **104**, 28217.
Ogilvie, K.W., Chornay, D.J., Fritzenreiter, R.J., Hunsaker, F., Keller, J., Lobell, J., Miller, G., Scudder, J.D., Sittler, E.C. Jr., Torbert, R.B., *et al.*: 1995, SWE, A comprehensive plasma instrument for the wind spacecraft. *Space Sci. Rev.*, **71**, 55.

Qiu, J., Hu, Q., Howard, T.A., Yurchyshyn, V.B.: 2007, On the magnetic flux budget in low-corona magnetic reconnection and interplanetary coronal mass ejections. *Astrophys. J.* **659**, 758. doi:10.1086/512060.

Reinard, A.A.: 2008, Analysis of interplanetary coronal mass ejection parameters as a function of energetics, source location, and magnetic structure. *Astrophys. J.* **682**, 1289. doi:10.1086/589322.

Riley, P., Crooker, N.U.: 2004, Kinematic treatment of coronal mass ejection evolution in the solar wind. *Astrophys. J.* **600**, 1035. doi:10.1086/379974.

Riley, P., Linker, J.A., Lionello, R., Mikić, Z., Odstrcil, D., Hidalgo, M.A., Cid, C., Hu, Q., Lepping, R.P., Lynch, B.J., Rees, A.: 2004, Fitting flux ropes to a global MHD solution: A comparison of techniques. *J. Atmos. Solar-Terr. Phys.* **66**, 1321. doi:10.1016/j.jastp.2004.03.019.

Riley, P., Schatzman, C., Cane, H.V., Richardson, I.G., Gopalswamy, N.: 2006, On the rates of coronal mass ejections: Remote solar and *in situ* observations. *Astrophys. J.* **647**, 648. doi:10.1086/505383.

Shodhan, S., Crooker, N.U., Kahler, S.W., Fitzenreiter, R.J., Larson, D.E., Lepping, R.P., Siscoe, G.L., Gosling, J.T.: 2000, Counterstreaming electrons in magnetic clouds. *J. Geophys. Res.* **105**, 27261. doi:10.1029/2000JA000060.

Sonnerup, B.U.Ö., Hasegawa, H., Paschmann, G.: 2004, Anatomy of a flux transfer event seen by cluster. *Geophys. Res. Lett.* **31**, L11803. doi:10.1029/2004GL020134.

Sonnerup, B.U.Ö., Hasegawa, H., Teh, W.L., Hau, L.N.: 2006, Grad – Shafranov reconstruction: An overview. *J. Geophys. Res. (Space Phys.)* **111**, A09204. doi:10.1029/2006JA011717.