

Model-independent large-scale magnetohydrodynamic quantities in magnetic clouds

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Received 1 November 2004; received in revised form 21 February 2005; accepted 11 March 2005

Abstract

Magnetic clouds are the interplanetary manifestation of coronal mass ejections, which are transient expulsions of major quantities of magnetized plasma, from the Sun toward the heliosphere. The magnetic flux and helicity are two key physical magnitudes to track solar structures from the photosphere-corona to the interplanetary medium. To determine the content of flux and helicity in magnetic clouds, we have to know their 3D structure. However, since spacecrafts register data along a unique direction, several aspects of their global configuration cannot be observed. We present a method to estimate the magnetic flux and the magnetic helicity per unit length in magnetic clouds, directly from in situ magnetic observations, assuming only a cylindrical symmetry for the magnetic field configuration in the observed cross-section of the cloud. We select a set of 20 magnetic clouds observed by the spacecraft Wind and estimate their magnetic flux and their helicity per unit length. We compare the results obtained from our direct method with those obtained under the assumption of a helical linear force-free field. This direct method improves previous estimations of helicity in clouds.

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Keywords: Magnetic clouds; Magnetic helicity; Interplanetary medium; Magnetohydrodynamics; Solar wind; Astrophysical plasmas

1. Introduction

Coronal mass ejections (CMEs) are huge expulsions of mass and magnetic field from the Sun. Magnetic helicity measures several aspects of a given magnetic structure, and it is practically conserved in the solar atmosphere and the heliosphere (Berger, 1984). One of the most important roles of CMEs is to carry away magnetic helicity (MH) from the Sun (Low, 1996), that would accumulate incessantly in the active region corona, since it is generated by the solar dynamo (helical turbulence and differential rotation) without changing sign with the cycle. On the northern hemisphere, magnetic

features have preferentially negative (left-handed) helicity, while on the southern hemisphere features show preference for the opposite sign (positive, right-handed helicity), for a recent review about chirality of magnetic features see Pevtsov and Balasubramaniam (2003).

A magnetic cloud at 1 AU can be identified (see, e.g. Burlaga, 1995), from in situ observations in the interplanetary space, by a low proton temperature, an enhanced magnetic field strength with respect to ambient values, and a large rotation of the magnetic field vector, consistent with a helical (flux rope) magnetic structure, which clearly has non-zero helicity.

To determine the amount of magnetic helicity contained in (and transported by) a magnetic cloud, we need to know its 3D magnetic configuration. Despite these astrophysical objects have been observed for more

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than 20 years, their global magnetic structure when they reach heliodistances of ~ 1 AU is not yet properly known. The first attempt to estimate the magnetic helicity in MCs was made by DeVore (2000), who used a sample of 18 MCs analyzed by Lepping et al. (1990) using the classical Lundquist (1950) model. He obtained a mean helicity value of 2×10^{42} Mx² (for a flux rope length of 0.5 AU) and a mean magnetic flux of 1×10^{21} Mx for these MCs. Démoulin et al. (2002) and Green et al. (2002) developed a method to measure the helicity content of active regions in the corona obtaining a typical value of $4\text{--}23 \times 10^{42}$ Mx². These authors computed the helicity budget for two active regions (ARs) and compared it with the amount of helicity carried away by the CMEs ejected from those ARs. They considered that each CME transported an amount of helicity equal to the mean helicity content in magnetic clouds. To estimate this mean helicity, they assumed an MC as a cylindrical flux rope and they computed the helicity per unit length (as DeVore (2000)) under a Lundquist's model for the field distribution in the plane (section) perpendicular to the tube axis. Thus, assuming the same helicity per unit length for the different sections along the flux tube axis and a non-curved axis, they computed the helicity content from a direct multiplication of the helicity per unit length by the length of the tube. This length, which is one of the less known parameters of MCs, was varied between $L_1 = 0.5$ and $L_2 = 2$ AU. However, they did not link the CMEs to any MC observation (see also Mandrini et al., 2004).

Magnetic clouds can be modeled locally using a helical cylindrical geometry as a first approximation (Farrugia et al., 1995). One of the most commonly used models to describe their magnetic configuration is the linear force-free field (see, e.g. Lepping et al., 1990). However, several modeling and fitting methods have been used to reproduce the magnetic structure of MCs (see, e.g., Dasso et al., 2005).

In this paper, we present a new method to estimate the magnetic helicity of interplanetary cylindrical flux ropes. We apply it to a set of 20 magnetic clouds and we compare our results with the values of the helicity obtained under the assumption of a linear force-free cylindrical model (Lundquist, 1950) for the magnetic configuration of the cloud. In Section 2, we describe the analysis of the data and our results, while in Section 3, we present a discussion and our conclusions.

2. Data analysis and modelling

We select all the MCs observed by the spacecraft Wind from 22 August 1995 to 07 November 1997, taking the start and the end times given in <http://lepmfi.gsfc.nasa.gov/mfi/mag.cloud-publ.html>. We analyze the magnetic data measured by the Magnetic Field Instru-

ment, MFI, aboard Wind (Lepping et al., 1995) in GSE (Geocentric Solar Ecliptic) coordinates. These observations have been downloaded with a temporal cadence of 3 s from <http://cdaweb.gsfc.nasa.gov/cdaweb/istp-public/>. Because we are only interested in the large-scale magnetic structure of the clouds and not in the magnetic fluctuations, we analyzed smoothed data using 100 averaged points per cloud, which for a cloud observed during ~ 1 day corresponds to a time cadence of ~ 15 min.

The orientation of the axis of every cloud is obtained using a minimum variance (MV) analysis, as discussed in Bothmer and Schwenn (1998). From this analysis, we define a system of reference fixed to the cloud and we rotate the observed GSE components of the field to this frame. The cloud frame is defined such that \hat{x}_{cloud} corresponds to the cylindrical radial direction (\hat{r}) in the ideal case of the spacecraft crossing the axis of the cloud (i.e. $p = 0$, being the impact parameter, p , the minimum distance between the cloud axis and the spacecraft) as it leaves the structure, \hat{z}_{cloud} is parallel to the axis of the cylinder (sign such that $B_{z,\text{cloud}}$ is positive at the cloud axis), and \hat{y}_{cloud} completes a right handed reference system. We determine the sign of the flux rope helicity from the global behavior of the field components. The radius (R) of the cloud is estimated from the duration of the MC and the observed solar wind speed. The list of the start and end times, radius (R), and the helicity sign, are given in Table 1 for the analyzed clouds.

We model the magnetic field configuration of every cloud using the Lundquist's model in the MV coordinates. The physical parameters that fit best the

Table 1
List of the studied magnetic clouds

#	Start	End	R	H
1	22-Aug-1995 22UT	23-Aug-1995 19UT	9.1	+
2	18-Oct-1995 19UT	20-Oct-1995 00UT	13.7	+
3	16-Dec-1995 05UT	16-Dec-1995 22UT	6.5	–
4	27-May-1996 15UT	29-May-1996 07UT	13.2	–
5	01-Jul-1996 17UT	02-Jul-1996 09UT	6.5	–
6	07-Aug-1996 13UT	08-Aug-1996 10UT	8.6	+
7	24-Dec-1996 03UT	25-Dec-1996 10UT	13.0	+
8	10-Jan-1997 05UT	11-Jan-1997 02UT	10.1	+
9	21-Apr-1997 15UT	23-Apr-1997 07UT	8.9	+
10	15-May-1997 09UT	16-May-1997 01UT	8.4	–
11	16-May-1997 07UT	16-May-1997 14UT	3.6	–
12	09-Jun-1997 02UT	09-Jun-1997 23UT	8.2	+
13	19-Jun-1997 05UT	19-Jun-1997 18UT	4.7	+
14	15-Jul-1997 06UT	16-Jul-1997 01UT	8.2	–
15	03-Aug-1997 14UT	04-Aug-1997 01UT	3.2	–
16	18-Sep-1997 00UT	20-Sep-1997 12UT	20.5	+
17	21-Sep-1997 22UT	22-Sep-1997 18UT	9.9	–
18	01-Oct-1997 16UT	02-Oct-1997 23UT	14.8	–
19	10-Oct-1997 23UT	12-Oct-1997 00UT	12.0	+
20	07-Nov-1997 05UT	08-Nov-1997 04UT	8.4	+

The event number (#), the start and the end times, the radius (R , in 10^{-2} AU) of the cloud, and the helicity sign (H) are given.

observations ($B_{y,\text{cloud}}$ and $B_{z,\text{cloud}}$), and the flux and helicity, are computed following the method described in Dasso et al. (2003). Fig. 1 shows the observed and modeled curves for $B_{y,\text{cloud}}$ and $B_{z,\text{cloud}}$, for the magnetic cloud observed during 18–20 of October, 1995 (event #2 in Table 1). Dashed lines show the observed field, thick line corresponds to the period of time when the spacecraft is going into the cloud, until it reaches the minimum distance to the cloud axis (in-bound), and thin line corresponds to the outgoing travel (out-bound). The continuous curve corresponds to the fitted Lundquist's model. Vertical dashed lines mark the boundaries of the cloud. As seen in this figure, this model overestimates the observations of $B_{z,\text{cloud}}$ near the cloud axis, and underestimates the observed $|B_{y,\text{cloud}}|$ in the external part of the cloud.

Following Berger (1984), a gauge-independent relative helicity per unit length L along the tube axis, H_r/L , can be defined for cylindrical flux ropes, independently from the reference field, as:

$$H_r/L = 4\pi \int_0^R A_\phi B_\phi r dr. \quad (1)$$

The azimuthal component of the vector potential, $A_\phi(r)$, can be written in function of the partial magnetic flux, $\Phi_z(r)$, across a surface perpendicular to the cloud axis as:

$$A_\phi(r) = \frac{1}{r} \int_0^r r' B_z(r') dr' = \frac{\Phi_z(r)}{2\pi r}, \quad (2)$$

and thus, the relative helicity can be computed as an integral of B_ϕ weighted with the accumulative flux:

$$H_r/L = 2 \int_0^R B_\phi(r) \Phi_z(r) dr. \quad (3)$$

This expression allows us to estimate H_r/L directly from the observed field. For every cloud, we construct two subseries for $B_{y,\text{cloud}}$ and $B_{z,\text{cloud}}$. The first subseries corresponds to the in-bound data and the second one to the out-bound.

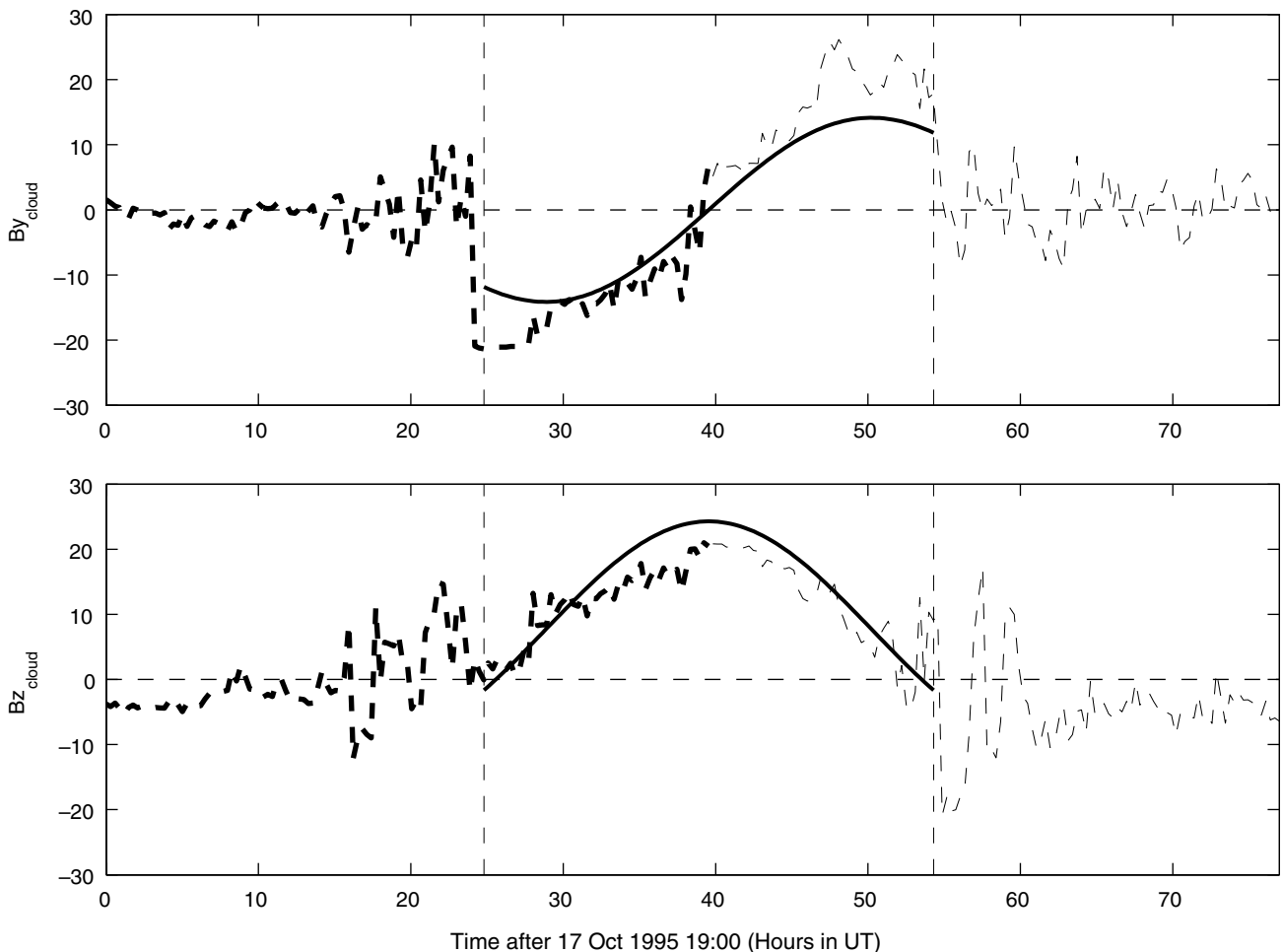


Fig. 1. Magnetic field (nT) in the local coordinate system (see main text).

Thus, under the assumption of a cylindrical geometry for the cloud and $p \sim 0$, we calculate $\Phi_z(r)$ and then, using Eq. (3), we compute H_r/L for the set of analyzed clouds. Fig. 2 shows the accumulative flux (upper panel) and helicity per unit length (lower panel) for the magnetic cloud labeled as #2 in Table 1, thick and thin lines correspond to in-bound and out-bound, respectively. There is a clear change of the slope in both quantities near both boundaries. Also both curves show that near the axis of the cloud (and up to $\sim R/3$) they are more in-bound/out-bound symmetric than in the external region. This general feature is roughly present in most of the analyzed clouds (15/20) (not shown).

The obtained values for the total flux (Φ_z) and H_r/L , from the direct method (in-bound and out-bound) and from the Lundquist's model (L), are shown in Fig. 3. The left panel shows that the values of $\Phi_{z,L}$ are between the two values computed for each of the two branches (in-bound and out-bound) in 14/20 cases. When $\Phi_{z,L}$ is not between the two branches, it is always the largest value. The right panel shows the absolute value of the relative magnetic helicity per unit length ($|H_r/L|$). The

values of $|H_{r,L}/L|$ are between those obtained from the two branches in 18/20 clouds.

In order to estimate the in-bound/out-bound asymmetry of the clouds, we define $\Delta\Phi_z = |\Phi_{z,out} - \Phi_{z,in}|$, $\langle\Phi_z\rangle = (\Phi_{z,out} + \Phi_{z,in})/2$, $\Delta H = |H_{r,out} - H_{r,in}|$, and $\langle H\rangle = (H_{r,out} + H_{r,in})/2$, resulting $\Delta\Phi_z/\langle\Phi_z\rangle$ lower than 0.45 for 17/20 clouds and $\Delta H/\langle H\rangle$ lower than 0.55 for 12/20 clouds.

3. Discussion and conclusions

We have shown a method to compute the magnetic flux and magnetic helicity content for cylindrical flux ropes, and we have applied it to a set of 20 magnetic clouds. We compare the results obtained using the direct method with those derived from the Lundquist's model. Our results indicate that there is a relatively good agreement between the two ways to compute these quantities. We find that the Lundquist's model is a good proxy to estimate $H_{r,L}/L$, while it has a slight tendency to overestimate Φ_z .

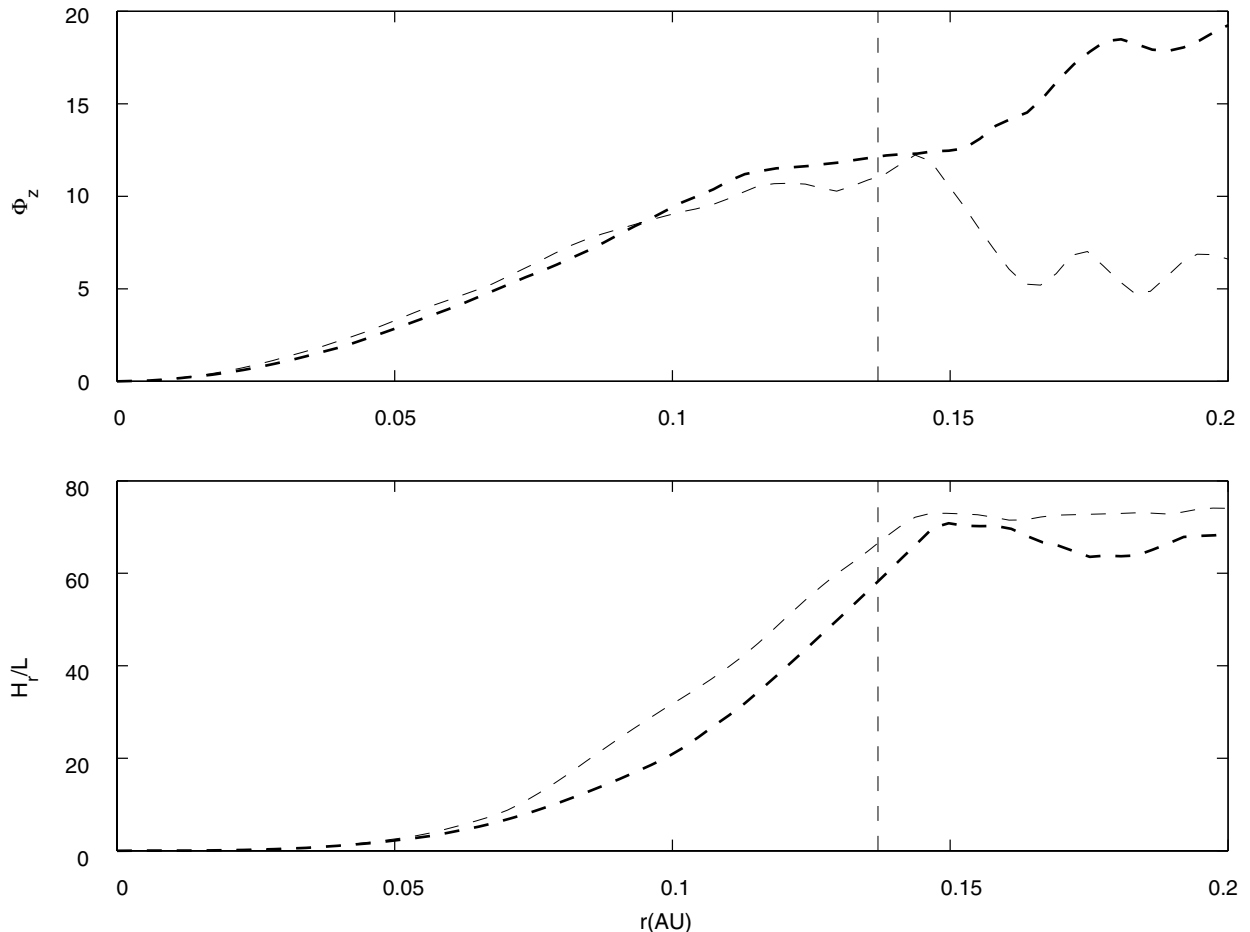


Fig. 2. Magnetic flux, Φ_z in units of 10^{20} Mx, and helicity per unit length, H_r/L in units of 10^{41} Mx²/AU.

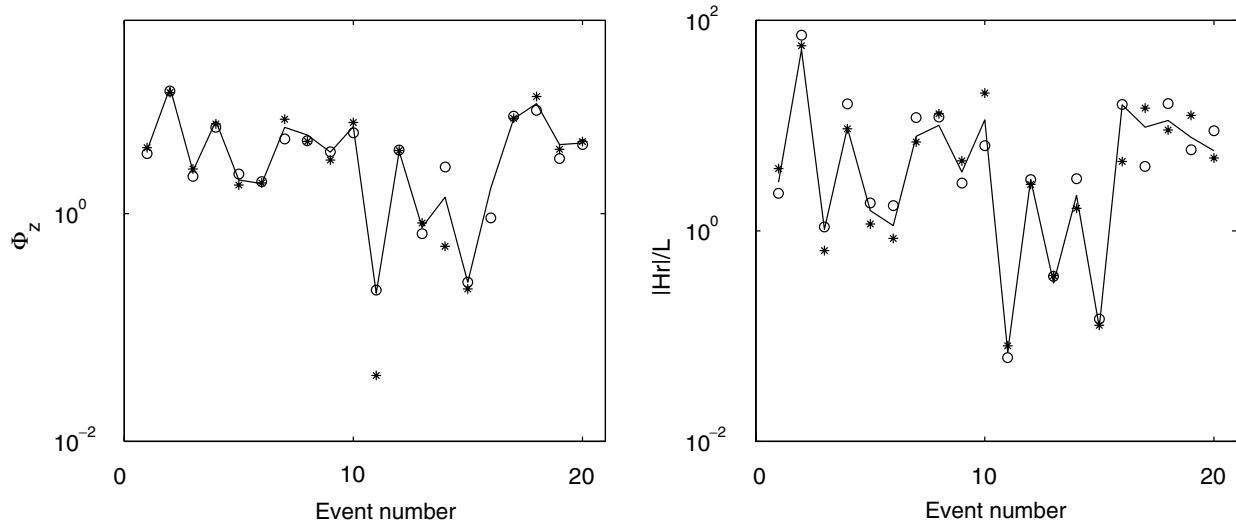


Fig. 3. Left panel: Φ_z in units of 10^{20} Mx, from Lundquist's model (continuous line) and from direct method (in-bound: *, out-bound: o). Right panel (same convention): $|H_r|/L$ in units of 10^{41} Mx²/AU.

The relative difference between the in-bound and out-bound estimations for both, total flux and total helicity, is lower than $\sim 1/2$ for more than half of the studied set of clouds.

If magnetic clouds were in-bound/out-bound symmetric when expelled from the Sun, our analysis shows that the level of in-bound/out-bound symmetry in their external part decreases as a consequence of the interaction with the surrounding solar wind. However, the inner part of the cloud (up to $r \sim R/3$) remains roughly symmetric for the majority of the analyzed clouds.

In our analysis, we assume that the spacecraft crosses a cylindrical flux rope going through the cloud axis. If p is not null and/or its shape is significantly oblate (with its major axis perpendicular to the Sun–Earth direction) instead of cylindrical (see, e.g., Vandas and Romashets, 2003; and references therein), the presented values would be lower bounds for Φ_z and $|H_r|/L$.

We have shown that global values of Φ_z and $|H_r|/L$ depend significantly on the chosen boundaries of the cloud (see Fig. 2), and also that there is a sudden change of the slope of $\Phi_z(r)$ and $|H_r(r)|/L$, at $r = R$. Thus, on one hand, improvements to the criteria (not well established yet) to determine the start and the end of the cloud will consequently improve the estimations of these global quantities. On the other hand, this discontinuity of the slope at the cloud edges can be considered an additional proxy to determine the borders of MCs.

Acknowledgments

We thank the NASA's Space Physics Data Facility (SPDF) for their data. This work was partially supported by the Argentinean grants: UBACyT X329,

PIP 2693 and PIP 2388 (CONICET), and PICT 12187 and PICT 14163 (ANPCyT). C.H.M. and P.D. thank ECOS (France) and SECyT (Argentina) for their cooperative science program (A01U04). C.H.M. and S.D. are members of the Carrera del Investigador Científico, CONICET.

References

- Berger, M.A. Rigorous new limits on magnetic helicity dissipation in the solar corona. *Geophys. Astro. Fluid* 30, 79–104, 1984.
- Bothmer, V., Schwenn, R. The structure and origin of magnetic clouds in the solar wind. *Ann. Geophys.* 16, 1–24, 1998.
- Burlaga, L.F. *Interplanetary Magnetohydrodynamics*. Oxford University Press, New York, 1995.
- Dasso, S., Mandrini, C.H., Démoulin, P., Farrugia, C.J. Magnetic helicity analysis of an interplanetary twisted flux tube. *J. Geophys. Res.* 108 (October), 1362, 2003.
- Dasso, S., Mandrini, C.H., Démoulin, P., Luoni, M.L., Gulisano, A.M. Large-scale MHD properties of interplanetary magnetic clouds. *Adv. Space Res.*, 2005 (in press).
- Démoulin, P., Mandrini, C.H., van Driel-Gesztelyi, L., Thompson, B.J., Plunkett, S., Kovári, Z., Aulanier, G., Young, A. What is the source of the magnetic helicity shed by CMEs. The long-term helicity budget of AR 7978. *Astron. Astrophys.* 382 (February), 650–665, 2002.
- DeVore, C.R. Magnetic helicity generation by solar differential rotation. *Astrophys. J.* 539 (August), 944–953, 2000.
- Farrugia, C.J., Osherovich, V.A., Burlaga, L.F. Magnetic flux rope versus the spherocak as models for interplanetary magnetic clouds. *J. Geophys. Res.* 100 (July), 12293–12306, 1995.
- Green, L.M., López fuentes, M.C., Mandrini, C.H., Démoulin, P., Van Driel-Gesztelyi, L., Culhane, J.L. The magnetic helicity budget of a cme-prolific active Region. *Sol. Phys.* 208 (July), 43–68, 2002.
- Lepping, R.P., Acuna, M.H., Burlaga, L.F., Farrell, W.M., Slavin, J.A., Schatten, K.H., Mariani, F., Ness, N.F., Neubauer, F.M., Whang, Y.C., Byrnes, J.B., Kennon, R.S., Panetta, P.V., Scheifele, J., Worley, E.M. The wind magnetic field investigation. *Space Sci. Rev.* 71 (February), 207–229, 1995.

- Lepping, R.P., Burlaga, L.F., Jones, J.A. Magnetic field structure of interplanetary magnetic clouds at 1 AU. *J. Geophys. Res.* 95, 11957–11965, 1990.
- Low, B.C. Solar Activity and the Corona. *Sol. Phys.* 167 (August), 217–265, 1996.
- Lundquist, S. Magnetohydrostatic fields. *Ark. Fys.* 2, 361–365, 1950.
- Mandrini, C.H., Démoulin, P., Van Driel-Gesztelyi, L., Green, L.M., Fuentes, M.C.L. Magnetic helicity budget of solar-active regions from the photosphere to magnetic clouds. *Astrophys. Space Sci.* 290, 319–344, 2004.
- Pevtsov, A.A., Balasubramaniam, K.S. Helicity patterns on the sun. *Adv. Space Res.* 32, 1867–1874, 2003.
- Vandas, M., Romashets, E.P. A force-free field with constant alpha in an oblate cylinder: a generalization of the Lundquist solution. *Astron. Astrophys.* 398 (February), 801–807, 2003.