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Magnetic helicity content in solar wind flux ropes

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Abstract. Magnetic helicity (H) is an ideal magnetohydrodynamical (MHD) invariant that quantifies the twist and linkage of magnetic field lines. In magnetofluids with low resistivity, H decays much less than the energy, and it is almost conserved during times shorter than the global diffusion timescale. The extended solar corona (i.e., the heliosphere) is one of the physical scenarios where H is expected to be conserved. The amount of H injected through the photospheric level can be reorganized in the corona, and finally ejected in flux ropes to the interplanetary medium. Thus, coronal mass ejections can appear as magnetic clouds (MCs), which are huge twisted flux tubes that transport large amounts of H through the solar wind. The content of H depends on the global configuration of the structure, then, one of the main difficulties to estimate it from single spacecraft *in situ* observations (one point - multiple times) is that a single spacecraft can only observe a linear (one dimensional) cut of the MC global structure. Another serious difficulty is the intrinsic mixing between its spatial shape and its time evolution that occurs during the observation period. However, using some simple assumptions supported by observations, the global shape of some MCs can be unveiled, and the associated H and magnetic fluxes (F) can be estimated. Different methods to quantify H and F from the analysis of *in situ* observations in MCs are presented in this review. Some of these methods consider a MC in expansion and going through possible magnetic reconnections with its environment. We conclude that H seems to be a 'robust' MHD quantity in MCs, in the sense that variations of H for a given MC deduced using different methods, are typically lower than changes of H when a different cloud is considered. Quantification of H and F lets us constrain models of coronal formation and ejection of flux ropes to the interplanetary medium, as well as of the dynamical evolution of MCs in the solar wind.

Keywords. Magnetohydrodynamics (MHD), Sun: solar wind, Sun: solar-terrestrial relations, Sun: magnetic fields

1. Introduction

Magnetic helicity (H) is a magnetohydrodynamical (MHD) quantity that quantifies the relative twist and linkage between magnetic field lines; H is a conserved quantity (with respect to the typical evolution times of the system) in many media with low dissipation, as the heliosphere.

Twisted magnetic flux tubes (i.e., flux ropes) are ubiquitous in space physics. They are key pieces of magnetic field ($\vec{B}$) configurations and are present in the photosphere of the Sun, in the solar corona, in the solar wind, in different locations of planetary magnetospheres and ionospheres, etc. Thus, magnetic flux ropes can store and transport magnetic energy (E) and, because their magnetic field lines are twisted, also important amounts of magnetic helicity.

1.1. *Coronal mass ejections and magnetic clouds*

Coronal Mass Ejections (CMEs) are massive expulsions of magnetized plasma from the solar atmosphere due to a destabilization of the coronal magnetic configuration that can form flux rope structures (e.g., Gosling *et al.*, 1995). Thus, CMEs remove plasma, energy, and magnetic helicity from the Sun and expel them into interplanetary space. As a consequence of this ejection, CMEs can form confined magnetic structures with both extremes of the magnetic field lines connected to the solar surface, extending far away from the Sun into the solar wind, while the coronal magnetic field is restructured in the low-corona. When they are detected in the interplanetary (IP) medium, they are called interplanetary coronal mass ejections (ICMEs), which are transient structures that perturb the stationary solar wind as they move away from the Sun.

A subset of ICMEs, called magnetic clouds (MCs), are characterized by *in situ* observations of low proton temperature, enhanced magnetic field strength (typically larger than ~ 10 nT), and smooth and large rotation ($\sim 180°$) of the magnetic field vector observed during several hours (Burlaga *et al.*, 1981). The two last characteristics observed in MCs are interpreted as single spacecraft observations of large scale flux ropes traveling in the solar wind (e.g., Burlaga *et al.*, 1981; Bothmer & Schwenn, 1998).

One of the main difficulties determining the global magnetic configuration of a MC from single spacecraft *in situ* observations (one point - multiple times) is that, due to the high speeds of the interplanetary plasma, a single spacecraft can only observe a linear (one dimensional) cut of the MC global structure. Another serious difficulty is the intrinsic mixing between its spatial shape and its time evolution, during the observing period. Despite these difficulties, from the analysis of the observed time profiles of the magnetic field ($\vec{B}$) components, it is possible to infer many of its main features.

The chirality associated with the magnetic configuration of the flux rope (i.e., the sign of H contained in the large scale flux rope) together with its relative orientation with respect to the heliosphere can be estimated in some MCs from the direct analysis of the magnetic field components (Bothmer & Schwenn, 1998).

Coronal mass ejections are frequently associated with filament eruptions. The direction of the MC axis is frequently found to be roughly aligned with that of the disappearing filament (Bothmer & Schwenn, 1994; Bothmer & Schwenn, 1998), preserving their chirality. This result has been also found in some detailed studies of individual cases by Marubashi (1997); Yurchyshyn *et al.* (2001); Ruzmaikin *et al.* (2003); Yurchyshyn *et al.* (2005). However, a few cases presenting a rotated MC axis with respect to its solar counterpart have also been found (e.g., Harra *et al.*, 2007; Foullon *et al.*, 2007).

1.2. *Aim and road map of the paper*

The main aim of this paper is to review the methods to estimate the amount of H contained in magnetic clouds, starting from elemental concepts/definitions and combining them with observations and modeling of flux ropes in the solar wind. We also mention the main difficulties and the main sources of uncertainty associated with these estimations and why these estimations are useful to gain insight in physical mechanisms of heliophysics (Section 1.3).

The definition of H, the reasons of its conservation in space physics, and theoretical expressions for cylindrical flux ropes are presented in Section 2. Then, we present a brief review of MCs (Section 3), different methods to analyze them and compute magnetic flux (Section 4, where an analysis of a case studied is also presented) and H (Section 5). Finally, in Section 6, the conclusions are given.

1.3. *Magnetic helicity in space physics*

When the complexity of a physical system is such that a detailed treatment (taking into account all its degrees of freedom) is not possible, the use of conserved quantities is one of the most useful ways to study it. Even when the system does not have exact conserved quantities, some 'almost' conserved quantities (as e.g., adiabatic invariants) are successfully used to describe its properties.

Magnetic helicity is approximately conserved in the solar atmosphere and the heliosphere (Berger, 1984). Thus, the study of conserved quantities such as magnetic flux (F) and H can help us to understand the physical mechanisms involved in the heliosphere.

Many recent combined quantitative studies of F and H in MCs and their solar sources have been successfully done and have been useful to put some constrains on coronal magnetic configurations and on flux rope formation/eruption models (e.g., Mandrini *et al.*, 2005; Luoni *et al.*, 2005; Attrill *et al.*, 2006; Longcope *et al.*, 2007; Qiu *et al.*, 2007; Harra *et al.*, 2007; Mandrini *et al.*, 2007; Rodriguez *et al.*, 2008; Mostl *et al.*, 2008). Extensions of this kind of analysis and further developments are needed to improve our understanding of this association (see, e.g., the review by Démoulin, 2008).

The solar differential rotation produces an excess of H and it has been suggested that this helicity excess is carried away from the Sun by CMEs (e.g., Ruzmaikin *et al.*, 2003). Thus, the quantification of F and H in MCs is also crucial to improve estimations of the global release of F and H during the solar cycle, putting constrains on solar dynamo models (e.g., Parker 1987; Bieber & Rust, 1995).

Larger amounts of H have been found in the pre-event phase of active regions (ARs) that later produced coronal mass ejections than in ARs having only confined flares (Nindos & Andrews, 2004). However, different models provide different and controversial results on the role of H in the launch of CMEs (e.g., see Démoulin, 2007).

Conservation of H (together with other properties of the plasma) can determine the evolution of a turbulent flow and the best-known consequence of this dynamical evolution is the inverse cascade in 3D-MHD and the evolution toward a force free state (see e.g., Smith, 2003 and references there in). In particular, for spatial scales smaller than the integral/correlation scale of magnetic field fluctuations, which for a heliodistance of one astronomical unit (AU) is $\sim 10^{-2}$ AU (e.g., Matthaeus *et al.*, 2005), the content of H in the interplanetary plasma can be computed from observations of the correlation tensor of magnetic field fluctuations using similar techniques to the ones used by Dasso *et al.* (2005b). The importance of quantifying the content of H in the interplanetary fluctuations is also linked with its influence on the propagation of cosmic rays, for instance modifying the pitch angle scattering coefficient (Bieber *et al.*, 1987).

Thus, H is one of the most (if not the most) important MHD quantity in space physics which quantifies characteristics of magnetic field structures and their consequence for another constituents of the system.

2. Magnetic helicity

For a closed magnetic field configuration inside a volume (Vol), H is defined from the magnetic field and its vector potential ($\vec{A}$, such that $\vec{B} = \vec{\nabla} \times \vec{A}$):

$$H = \int_{Vol} \vec{A} \bullet \vec{B} \; dV \tag{2.1}$$

Elsasser (1956) noticed that for an ideal MHD system, H is a conserved quantity; Moffat (1969) related H with the linking number between two curves, which can be

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quantified using an integral formula derived by Carl Friedrich Gauss in 1833 (see, e.g., Hirshfeld, 1998), and shown that H can be constructed from the sum of the Gauss linking numbers over every pair of field lines within a volume.

For a non-ideal MHD system (i.e., non-null resistivity, $\eta \neq 0$), magnetic reconnection processes are allowed even for systems with very low η. On the other hand, the dissipation of H is associated with the intensity and the relative alignment between the electric current ($\vec{J}$) and $\vec{B}$: $d_t H \sim -\eta \int \vec{J} \bullet \vec{B} \; dv$.

Thus, and because (i) $\vec{J}$ can increase in current sheets associated with reconnection and (ii) the relative connectivity of magnetic field lines is altered during reconnection processes, in principle it is a valid question 'Is H conserved during reconnection?'.

The answer was given by Berger (1984), who showed that the amount of dissipated H is negligible for transient fast reconnection, as happens in many physical systems in space physics (e.g., the solar corona, the solar wind, planetary magnetospheres).

Part of the answer is based on (i) current sheets associated with reconnection are very small with respect to the bulk of the volume occupied by the fluid (e.g., Morales *et al.*, 2005), (ii) field lines in a plasma form in fact thin flux tubes with internal structure (the twist, which also can add H), and (iii) reconnection between two thin flux tubes is progressive, transforming step by step part of the initial helicity associated with the removed linkage into helicity associated with new additional twist (see, e.g., Section 2.4 of Biskamp, 2000, in particular Figures 2.10 and 2.11). Thus, plasma field lines are not 'naked' but 'dressed with twist' (Biskamp, 2000).

In a turbulent 3D-MHD system there is a net flux of H to larger spatial scales (Frisch *et al.*, 1975; Alexakis *et al.*, 2006) and consequently its dissipation is also inhibited.

The Hall effect can be relevant in space physics, mainly during physical processes occurring at small scales. In particular, it can change the turbulent properties and increase the reconnection rate of a dissipative magnetofluid. However, for a Hall MHD sytem (HMHD) H is also an ideal invariant (Turner, 1986), and the presence of relaxed states with H almost condensed in longest wavelength modes have been also found for weakly dissipative systems (e.g., Servidio *et al.*, 2008).

Because of the gauge freedom of $\vec{A}$, the definition of H given in Eq. (2.1) is physically meaningful only when the magnetic field is fully contained inside the volume V (i.e., the normal component $B_n = \vec{\mathbf{B}} \cdot \widehat{\mathbf{n}}$ vanishes at any point of the surface S surrounding V).

A gauge-independent relative magnetic helicity can be defined even when B_n is different to zero at S (Berger & Field, 1984). The meaning of this relative helicity (H_r) is such that it measures the helicity with respect to the value of H for a given reference field ($\vec{B}_{\text{ref}}$), which has the same distribution of B_n on S:

$$H_r(\vec{B}) = H(\vec{B}) - H(\vec{B}_{\text{ref}}) = \int_V [\vec{\mathbf{A}} \cdot \vec{\mathbf{B}} - \vec{\mathbf{A}}_{\text{ref}} \cdot \vec{\mathbf{B}}_{\text{ref}}] \, dV \, . \tag{2.2}$$

If we choose a different gauge to define the vector potential (i.e., we define $\vec{\mathbf{A}}' = \vec{A} + \vec{\nabla}\psi$, where ψ is any scalar function), the new relative helicity H_r' is given by:

$$H_r' = H_r + \int\int_{S(V)} \psi(\vec{\mathbf{B}} - \vec{\mathbf{B}}_{\text{ref}}) \cdot \vec{\mathbf{ds}} = H_r \, . \tag{2.3}$$

For cylindrical twisted flux tubes, $\vec{\mathbf{B}}(\vec{\mathbf{r}}) = B_\varphi(r)\widehat{\varphi} + B_z(r)\widehat{\mathbf{z}}$, the reference field can be chosen as $\vec{\mathbf{B}}_{\text{ref}}(r) = B_z(r)\widehat{\mathbf{z}}$ with $\vec{\mathbf{A}}_{\text{ref}}(r) = A_z(R)\widehat{\mathbf{z}} + A_\varphi(r)\widehat{\varphi}$ (so the reference field is chosen with null magnetic helicity since field lines are straight, and $\vec{\mathbf{A}} \times \widehat{\mathbf{n}} = \vec{\mathbf{A}}_{\text{ref}} \times \widehat{\mathbf{n}}$ at the surface of the cylinder, [see Dasso *et al.*, 2003]).

Thus, H_r can be expressed independently of $\vec{\mathbf{A}}_{\rm ref}$ and $\vec{\mathbf{B}}_{\rm ref}$ as (Dasso *et al.*, 2005c)

$$H_r = 4\pi L \int_0^R A_\varphi(r) B_\varphi(r)\, r dr = 2L \int_0^R B_\varphi(r) F_z(r)\, dr\,, \tag{2.4}$$

where L is the length along the magnetic tube, R its radius, and $F_z(r)$ the cumulative axial magnetic flux ($F_z(r) = 2\pi \int_0^r B_z(r')\, r'\, dr'$). Thus, as expected, H can be expressed as the sum of the contribution of the azimuthal field 'twisting around' the cumulative axial flux. Because the relative helicity is the one having significant interest for space physics, herein we will refer to H_r just as H.

3. Magnetic clouds

The identification of the MCs/ICMEs boundaries can present some difficulties, and several proxies and techniques can be used (see, e.g., the review by Dasso *et al.*, 2005a and the review by Zurbuchen & Richardson, 2006). Different proxies frequently imply different boundaries, and thus the correct identification of some MCs/ICMEs boundaries is an open problem that needs to be considered (Russel & Shinde, 2005).

In particular, to improve the quantification of magnetic fluxes and helicity, the identification of MC boundaries needs to be made as accurate as possible because (i) these quantities are extensive and thus they critically depend on the size of the object and (ii) because incorrect identification of the boundaries can lead to a wrong interpretation of the real magnetic structure/orientation.

Magnetic clouds can be modeled locally using helical cylindrical geometry as a first approximation (Farrugia *et al.*, 1995). The magnetic field in MCs is relatively well modeled by the so-called Lundquist's model (Lundquist, 1950), which considers a static and axially-symmetric linear force-free magnetic configuration (e.g., Goldstein, 1983), being the cylindrical flux rope in a Taylor state. However, many other different models have been also used to describe MCs, including cylindrical and oblate cross sections, force free and non-force free field configurations, static and expanding magnetic structures, etc. For a review of different models used to describe MCs and comparison of H and F derived from different models see, e.g., Dasso *et al.* (2005a).

To facilitate the understanding of MC properties, we define a system of coordinates linked to the cloud in which $\hat{z}_{\rm cloud}$ is along the cloud axis (with $B_{z,{\rm cloud}} > 0$ at the MC axis). Since the MC moves nearly in the Sun-Earth direction and its speed is much larger than that of the spacecraft (which can be supposed to be at rest during the cloud observing period), we assume a rectilinear spacecraft trajectory in the cloud frame. The trajectory defines a direction $\hat{d}$ (pointing toward the Sun); then, we define $\hat{y}_{\rm cloud}$ in the direction $\hat{z}_{\rm cloud} \times \hat{d}$ and $\hat{x}_{\rm cloud}$ completes the right-handed orthonormal base ($\hat{x}_{\rm cloud}, \hat{y}_{\rm cloud}, \hat{z}_{\rm cloud}$). We also define the impact parameter, p, as the minimum distance from the spacecraft to the cloud axis.

The observed magnetic field in a MC can be expressed in this local frame transforming the observed components (B_x, B_y, B_z) with a rotation matrix to ($B_{x,{\rm cloud}}$, $B_{y,{\rm cloud}}$, $B_{z,{\rm cloud}}$). The local system of coordinates is especially useful when p is small compared to the MC radius (R) and for this case the rotation angles can be found using a fitting method (e.g., Dasso *et al.*, 2006) or applying the minimum variance (MV) technique to the normalized time series of the observed magnetic field (e.g., Gulisano *et al.*, 2007). In particular Gulisano *et al.* (2007), from the analysis of a set of cylindrical synthetic MCs, found that the normalized MV technique provides a deviation of the real main MC axis smaller than 10° even for p as large as 50% of the MC radius.

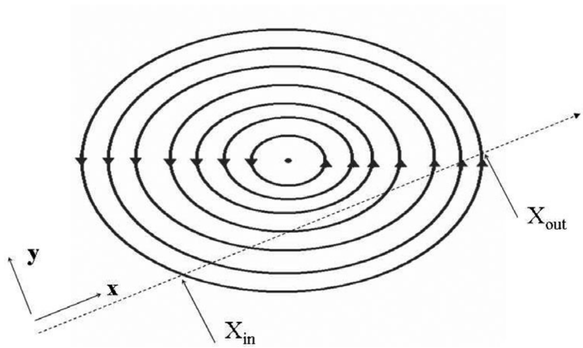

Figure 1. Scheme of the cancellation of F_y (see Eq. 4.3, 2D cut in the plane perpendicular to the axis of symmetry of the flux rope). The trajectory of the spacecraft (projected on this plane) is marked with dashed line, it enters to the flux rope at X_{in} and it exits at X_{out}. F_y will be canceled for a general shape of the flux rope cross section (translation symmetry along the MC axis is the only necessary condition for the cancellation).

4. Reconnection at the MC boundary: progressive pealing of a flux rope

Below we use $\nabla \cdot \vec{B} = 0$ and the local invariance of $\vec{B}$ along the MC axis to define the center and boundaries of twisted flux tubes in the solar wind.

Let us define a plane Π formed by points $\vec{r} = u\,\hat{x}_{\rm cloud} + p_0\,\hat{y}_{\rm cloud} + v\,\hat{z}_{\rm cloud}$, for u and v covering the real numbers and p_0 a fixed value corresponding to the impact parameter associated to the trajectory of the spacecraft that observes the MC. Thus, the magnetic flux of $\vec{B}$ across the plane Π, considering the closed flux rope, is:

$$\int_{flux\ rope} B_{y,cloud}\,dx\,dz = 0\,, \tag{4.1}$$

with x, z being the spatial coordinates in the $\hat{x}_{\rm cloud}$ and $\hat{z}_{\rm cloud}$ directions, respectively.

From the local invariance of $\vec{B}$ along the MC axis ($\hat{z}_{\rm cloud}$), Eq. (4.1) reduces to:

$$\int_{X_{in}}^{X_{out}} B_{y,cloud}\,dx = 0\,, \tag{4.2}$$

being valid for a general shape of the MC cross section, see Figure 1.

If one MC boundary is known, the above flux balance property can be used to find the MC center and the other boundary as follows. We define the cumulative flux

$$F_y(x) = L\int_{X_{in}}^{x} B_{y,cloud}(x')\,dx'\,, \tag{4.3}$$

where $X_{\rm in}$ is the position of the known boundary (e.g., the front of the MC). For $p = 0$ the position where $F_y(x)$ has its absolute extreme corresponds to the x position of the MC center (or to the position where the minimum approach is reached for $p \neq 0$). Then, when $F_y(x)$ goes back to zero at $x = X_{\rm out}$, we have the other boundary. The region from $x = X_{\rm in}$ to $x = X_{\rm out}$ defines the MC flux rope.

The time evolution of the magnetic field while the spacecraft is crossing the MC can affect the correct interpretation of the observations, mixing spatial variation and time evolution. For MCs in strong expansion during the observation time, this expansion effect can have consequences on the correct quantification of F and H using the direct method described above. Expressions to correct for this expansion effect have been presented by Dasso *et al.* (2007).

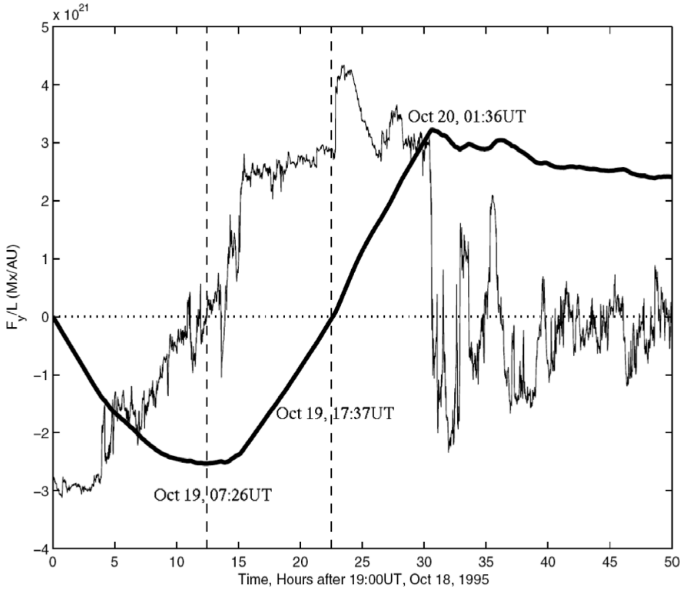

Figure 2. Cumulative flux of $B_{y,cloud}$ (thick solid line) starting from the leading boundary of the cloud. Thin solid line shows $B_{y,cloud}$ as a reference (in arbitrary units). The times of minimum and null flux accumulation are marked with vertical dashed lines. Adapted from Dasso *et al.* (2006)

The cumulative flux F_y for the MC observed on Oct 18, 1995, is shown in Figure 2 (thick solid line), together with the observed $B_{y,\rm cloud}$ component (thin solid line). Vertical dashed lines mark the time at which F_y/L reaches the minimum (Oct 19, 07:26 UT) and the time when the flux cancels (October 19, 17:37 UT). They correspond to the center and the rear boundary of the MC flux rope, respectively. However, different ends for this MC have been chosen in previous studies, e.g., Lepping *et al.* (1997) choose it at 00:00 UT on Oct 20, while Larson *et al.* (1997) choose it at 01:38UT on Oct 20. Other authors have chosen it at other different times. For details of the study of this event, see Dasso *et al.* (2006), and references therein.

We note that the flux balance determines the rear boundary of the flux rope where there is a discontinuity of $B_{y,\rm cloud}$. This is a confirmation of the correct rear boundary location since a current sheet, so a discontinuity of $\vec{B}$, is expected at the boundary of two different magnetic structures.

The analysis of F_y shows that this ICME is not simply formed by a closed flux rope. Some of the MC characteristics, such as the low magnetic variance and the low proton temperature, continue well behind the rear boundary of the flux rope (Lepping *et al.*, 1997). Indeed, the cumulative F_y shows a strong change in the slope at 01:36 UT on Oct 20, expected when the field of the solar wind starts to be integrated in Eq. (4.3). The most plausible physical scenario to create such 'back' magnetic structure is given by a previous (to the observation at 1AU) magnetic reconnection process between the (larger at that moment) original flux rope and the ambient magnetic field. We interpret the lack of flux cancellation in the 'back' as the evidence of a magnetic structure connected with solar wind field lines, which in the past formed the periphery of a larger flux rope (see Figure 6 in Dasso *et al.*, 2006). Thus, the flux rope was progressively peeled before its observation at 1AU.

This 'open' back (or not 'canceled flux') region at the ICME rear has been also recently found in several other events (Dasso *et al.*, 2007; Mostl *et al.*, 2008; Dasso *et al.*, 2008).

5. H in flux ropes

5.1. *H from MC models*

Theoretical expressions for H can be obtained for the models (see Section 3) used to represent the magnetic structure of MCs. In particular, for a given cylindrical model of the MC, H can be obtained replacing proper expressions for B_φ and A_φ in Eq. (2.4). The free parameters of the models can be obtained from fitting the models to *in situ* observations inside the MC (see, e.g., Dasso *et al.*, 2003).

From the analysis of 20 well determined MCs using different static models which consider very different distributions of the axial twist of the magnetic field, Gulisano *et al.* (2005) found that the dispersion of the obtained values of H varying the models considered for a given cloud, was one order of magnitude lower than the dispersion of H for different events. A similar conclusion was reached by Nakwacki *et al.* (2008a) using dynamical models that permit the radial expansion of the flux rope, and by Nakwacki *et al.* (2008b) using models that include radial and axial expansions.

5.2. *H from a direct method*

In this section we present a method to compute F and H directly from the observed magnetic field time series. It requires a transformation of the magnetic data to the cloud frame (Section 3). Three hypotheses are needed: local invariance along the cloud axis, cylindrical symmetry and a moderately low impact parameter.

The position at the minimum approach (similar to the the position of the center of the flux rope when the impact parameter is small) corresponds to the time when F_y is minimum (Section 4, Figs. 1 and 2), and we set the coordinate origin there ($x = 0$). Then, we split the time series of $\vec{B}$ in two subseries for $B_{y,\mathrm{cloud}}$ and $B_{z,\mathrm{cloud}}$. The first subseries corresponds to the in-bound path (the path when the spacecraft is going toward the center of the cloud, $x < 0$) and the second to the out-bound path (when the spacecraft has reached the minimum distance to the cloud axis and is going out the MC, $x > 0$). Differences in the results obtained with these two branches are mainly due to the non-cylindrical symmetry of the flux rope.

Thus, from Eq. (2.4) and for cases when p is small, the magnetic helicity can be estimated as:

$$H \approx 2L \int_0^{X_{out}} B_{y,\mathrm{cloud}}(x') F_z(x')\, dx' \,, \tag{5.1}$$

For the in-bound path the expressions are the same except that integral limits, $[0, X_{out}]$, are simply replaced by $[X_{in}, 0]$ (with $x < 0$).

If the impact parameter is not zero, the core of the flux rope is not present in the data; so, the fluxes and helicity will be underestimated. However, the relative underestimation for H and F is of the order of $(p/R)^2$ (see Section 5.3 of Dasso *et al.*, 2006).

Estimations of H from models and from this direct method (Dasso *et al.*, 2006), as well as from the in-bound and out-bound branches (Dasso *et al.*, 2005c) are in very good agreement.

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6. Conclusions

The quantification of the magnetic helicity (H) and the magnetic flux (F) in magnetic clouds helps us to constrain the formation, ejection, and dynamical evolution of flux ropes in the heliosphere.

We have presented different methods to estimate H and F in MCs which are robust in the sense that for well determined MCs, the obtained values are similar when different methods/techniques are used to compute them. Even more, a very good agreement has been found for the values of H obtained in magnetic clouds (H_{MC}) and the release of H (ΔH_{cor}) from their solar sources during the eruption (e.g., see Dasso *et al.*, 2005d and the review by Démoulin, 2008), a method completely independent and unbiased from the techniques used to estimate H in MCs. In particular a good agreement between H_{MC} and ΔH_{cor} was found from a comparative study of two magnetic clouds with very different sizes, having significantly different values of H: $H_{MC} \sim \Delta H_{cor} \sim 10^{43}$ Mx^2 (Luoni *et al.*, 2005; Dasso *et al.*, 2006) and $H_{MC} \sim \Delta H_{cor} \sim 10^{39}$ Mx^2 (Mandrini *et al.*, 2005).

From the discovery of magnetic clouds more than 25 years ago, very important progress has been made in the understanding of magnetic flux ropes in the solar wind. These astrophysical objects are in fact present in several systems of space physics, as much in our heliosphere as in the broader universe. Some of their main physical processes have been already unveiled; but of course many others are yet waiting to be revealed.

7. Acknowledgments

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Discussion

Girish: Potential field models have been successful in studying closed magnetic structures such as the heliospheric current sheet. But how can potential field models accommodate helicity calculations in the solar corona and solar wind? This is because these models use curl-free magnetic fields.

Dasso: We do not use potential field models to describe the magnetic configuration in the corona or solar wind (in the present work we used linear/non-linear force-free fields, or even non-force-free fields). Because the field configurations we are considering are not contained within closed volume (i.e., B_n can be different to zero at the boundary) we compute their magnetic helicity relative to a reference field configuration, which in the coronal case is generally a potential field.

Schmieder: Has STEREO already observed magnetic clouds?

Dasso: YES, one of the magnetic clouds observed by STEREO presents signatures of a flux rope in one of the spacecraft but not in the other one. This is a result consistent with the interpretation of some ICMEs as flux ropes being observed in their periphery.