LINKING CORONAL TO HELIOSPHERIC MAGNETIC HELICITY: A NEW MODEL-INDEPENDENT TECHNIQUE TO COMPUTE HELICITY IN MAGNETIC CLOUDS

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ABSTRACT

Magnetic clouds (MCs) are a subset of interplanetary coronal mass ejections (ICMEs), which carry a significant amount of large scale magnetic helicity (MH) away from the solar corona as they travel to the external heliosphere. From a theoretical point of view, it is expected that MH be preserved in the solar corona and the heliosphere. In particular, it will be preserved in MCs during their evolution through the interplanetary medium. Thus, MH plays a key role to link the magnetic properties of MCs with their solar active region (AR) sources, helping us to improve the knowledge of the ejection mechanisms in the corona. MH studies permit also to restrict the various models proposed to represent the structure of clouds. We present here a new method to compute the MH in clouds, which provides values for the helicity per unit length along the flux tube axis using the observed interplanetary magnetic field. The method only assumes that the cloud section is circular. We apply this method to two MCs, one of the biggest and one of the smallest ever observed, and compare our results with the helicity ejected from their respective solar sources.

Key words: Solar ejections, Magnetic clouds, Magnetic helicity.

1. INTRODUCTION

CMEs are expulsions of mass and magnetic field from the Sun. Low (1996) pointed out that one of the most important roles of CMEs is to carry away magnetic helicity (MH) from the Sun. Since MH is well preserved even in non-ideal MHD (Berger 1984), the helicity is expected to be conserved during the ejection of a CME into the interplanetary space. Part of these ejections are detected in situ as MCs. An MC is characterized by lower proton temperature and higher magnetic field strength than the surrounding solar wind. Typically, the magnetic field vector shows a smooth significant rotation across the cloud (Burlaga et al. 1981) indicating a helical (flux rope) magnetic structure.

How much helicity is carried away from the Sun by a CME is still a question that may be answered by measuring the decrease of helicity in the corona due to a CME, or measuring the helicity content of the resulting MC. Several attempts have been done to quantify the MH and/or its variation in the corona and the interplanetary medium (see Luoni et al. 2005, for a review). The first direct link between the measurement of MH loss in the solar corona due to a CME and MH computed in its resulting MC at 1 AU, was done by Mandrini et al. (2005) for one of the smallest events ever observed both in the corona and in the interplanetary medium. A similar study was then done by Luoni et al. (2005) for a typical coronal long duration event (LDE) and associated MC. For both cases the authors reached the same conclusion, the MH variation from before to after the coronal ejection matched the MH content of the associated MC. In this paper we briefly review the two coronal events and the coronal MH computation (Section 2). We summarize the interplanetary medium observations and helicity computation using a standard linear force-free model for its magnetic field and, then, we compute the MH using a model-independent technique (Section 3). Finally, we discuss and conclude (Section 4).

2. THE CORONAL EVENTS

On 14 Oct. 1995 a C1.6 (GOES class) LDE started in AR 7912 (NOAA number) after ≈ 05:00 UT, reached...
maximum X-ray flux at 09:21 UT and lasted for at least 15 hours. The LDE started by loop brightenings in the central part of the AR, during which some of the sigmoidal loops became visible. By 07:29 UT the expanding loops encountered the magnetic fields of a neighbouring region (AR 7910) and an "X-point" coronal structure appeared, presumably the result of inter-active-region reconnections. The expansion of AR 7912 continued, and by 08:55 UT the span of the fadng loops, in projection, became comparable to the solar radius. For a more detailed description of the LDE we refer to Van Driel-Gesztelyi et al. (2000). Since in Oct. 1995 space-born coronagraph observations were not yet available, we do not have direct observation of the CME.

To compute MH in the corona, we first model the coronal field. Using magnetograms provided by the Imaging Vector Magnetograph (IVM) (LaBonte et al. 1999), at Mees Solar Observatory, we have extrapolated the observed photospheric line of sight component of the field to the corona under the linear (or constant $\alpha$) force-free field assumption: $\vec{\nabla} \times \vec{B} = \alpha \vec{B}$. Two different magnetograms from IVM were used to compute the coronal field, one at 00:20 UT and another at 17:55 UT, on Oct. 14, 1995. To determine $\alpha$, we use two Soft X-ray Telescope (Yohkoh/SXT) full disk images, one at 07:30 UT (the time at which the SXT loops appeared to be most sheared) and the other at 11:58 UT (by this time the SXT loops became more relaxed). These times are well before the maximum of the LDE at 09:21 UT in GOES data and well after the largest observable expansion of the SXT loops (and maximum of the LDE), respectively. In general, $\alpha$ is not constant along the AR. In this particular case, $\alpha$ was higher in the northern part of the AR and lower in its southern part. This is illustrated in Figure 1, where field lines with the lower and higher $\alpha$-values are shown with thin and thick lines, respectively. The values of $\alpha$ are shown in Table 1. Once the coronal model is determined, we compute the relative coronal magnetic helicity, $H_{\text{cor}}$, as done in Mandrini et al. (2005). Table 1 lists the values for $H_{\text{cor}}$.

During a survey of X-ray bright points that showed enhanced emission at cm- and mm-wavelengths, we observed an isolated radio bright point near the center of the disc on May 11, 1998. We found multi-wavelength evidence of its eruptive nature (see, Mandrini et al. 2005, for a full description of soft X-ray and EUV observations). The bright point location is shown in soft X-rays just before its largest eruption, in Figure 2. It was well isolated from ARs present on the Sun and located almost at the disc centre in an ideal position for any ejecta to reach the Earth.

We refer here to the ejective events as seen in SXT light curve. The first event started between the images taken at 00:42 UT and 00:51 UT and had a duration of 26 minutes. Two close in time X-ray bursts followed the first one. The second event occurred between 06:00 UT and 08:00 UT, while the third one started between SXT full-disc images at 08:03 UT and 08:44 UT and ended at 11:00 UT. Then, its duration was of about 3 hours. In EUV images (as seen by the Extreme Ultraviolet Imaging Telescope, EIT), the first X-ray event was accompanied by formation of dim-
The second X-ray burst was weakest of the three events. During the third SXT burst, the EUV emission showed elongated sigmoidal loops, followed by shortening of the emitting region and appearance of a cusp and extended dimmings.

To compute the coronal MH, we modelled the coronal magnetic field using an MDI magnetogram previous to the soft X-ray bursts and an EUV image taken by the Transition Region and Coronal Explorer (TRACE) at 00:38 UT on 11 May, 1998. As usually found before in other ARs, α is higher in the core of the region than in the peripheries. We point out that the values of α (shown in Table 1), used to model TRACE loops imply that the coronal field is strongly non-potential. To compute the variation of the coronal MH, we need observations after the X-ray bursts. Unluckily, TRACE images are only available before the first X-ray burst; on the other hand, individual loops are not distinguishable in EIT or SXT images. Taking a conservative approach to determine a lower bound for the variation of the coronal magnetic helicity, we select the closest in time MDI magnetogram after the third X-ray burst (starting at ≈ 8:03 UT) and, using the previously determined values for α, we computed $H_{corr}$. The results are shown in Table 1.

3. THE INTERPLANETARY EVENTS

On Oct. 18-19, 1995, a magnetic cloud presenting a strong southward component for about 15 hours was observed by the Wind spacecraft. This MC was reported linked to the LDE at AR 7912 (van Driel-Gesztelyi et al. 2000) and it has been studied by several authors. The in situ plasma and magnetic data indicate that the cloud reached the spacecraft at ~ 19:00 UT, on Oct. 18, 1995. While the entry of the cloud is very clear, its exit time cannot be well determined and different authors take different values. An end time at ~ 23:00 UT, on Oct. 19, 1995 has been taken by several authors (e.g., Lepping et al. 1997), which is the one we will use in this paper.

Information on the length of the flux tube in MCs can be obtained by studying the electron distribution function. Counter-streaming electrons are considered to indicate magnetic connection to the Sun. The absence of electron streams is interpreted as a full disconnection. Based on such data, Larson et al. (1997) concluded that the Oct. 18-19 MC was connected to the Sun at least one end. They estimated the semi-length of the field lines near the centre of the cloud as ~ 1.2 AU.

The local magnetic structure of MCs is usually modeled by a cylindrical helix. To determine its orientation, we apply the minimum variance (MV) method to the data (see e.g. Bothmer and Schwenn 1998). We analyze data from the Magnetic Field Instrument (MFI) aboard Wind, downloaded from http://cdaweb.gsfc.nasa.gov/cdaweb/stsp – pubtie/. From this analysis we obtain the components of the field in a cartesian system attached to the cloud (local components), such that: (a) $B_{z,cloud}$ is the axial component, being its value positive at the cloud centre, (b) $B_{y,cloud}$ is the poloidal component ($B_{y}$) once the spacecraft crossed its axis, and (c) $B_{z,cloud}$ is the radial component, also after leaving the MC centre. Figure 3 shows the observed component of the field and the classical model of Lundquist (the cylindrical linear force free field, Lundquist (1950)), fitted to the observations, following the method described in Dasso et al. (2003). From the fitted parameters and the radius, estimated from the duration of the MC and the observed solar wind speed, we compute the relative magnetic helicity contained in the cloud ($H_{MC}$) (Dasso et al. 2003).

The relative helicity can be computed also as an integral of $B_{y}$, weighted with the accumulative flux across a surface perpendicular to the cloud axis, $F_{z}(r)$, (Dasso et al. 2005):

$$H_{r}/L = 2 \int_{0}^{R} B_{y}(r) F_{z}(r) \, dr.$$  

Expression 1 can be used to estimate the helicity directly from the field observations, taking into account the two branches observed (the in-bound, when the craft is going to the center of the cloud, and the out-bound when it is escaping). Table 1 shows the values of $H_{MC}$ obtained from the Lundquist’s model and from the direct method.

We analyze also Wind data from ~ 10:00 UT on 13 May.
Table 1. Left block of columns shows the magnetogram time, the range of $\alpha$ and the range of $|H_{cor}|$. Right block shows the method (Lundquist’s Model and Direct Method) and $H_{MC}$, using lengths 2.4 AU and 1.0 AU for the October and May clouds, respectively.

<table>
<thead>
<tr>
<th>Coronal Event</th>
<th>Interplanetary event</th>
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<tr>
<td>Date</td>
<td>Time (UT)</td>
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<tr>
<td>14 October</td>
<td>07:30</td>
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<tr>
<td>1995</td>
<td>11:58</td>
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<td></td>
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<tr>
<td>11 May</td>
<td>00:03</td>
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<td>1998</td>
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to $\sim$ 04:00 UT on 16 May, 1998, around the expected time of arrival of the small coronal event on 11 May. A very extended complex ejeclcta, containing plasma with a high intensity and disordered magnetic field, and low proton $\beta$ (being $\beta$ the ratio of the plasma to the magnetic pressure), was observed by Wind between 15-17 May, 1998 (Fig. 4). We identified a small event inside the complex ejecta, lasting from 22:00 UT on 15 May to 01:50 UT on 16 May, around 4 days and 14 hours (110 hours) after the coronal eruption. This small cloud was a good candidate to be the interplanetary manifestation of this eruption because, considering an average speed of $\sim$ 350 $\pm$ 50 km/s, we expected a travel time of $\sim$ 119$\pm$17 hours from the corona to 1 AU, a very good agreement with the estimated delay. The identified interplanetary event showed a large and coherent rotation of the component $B_{GSE}$, for about 4 hours (beginning and end indicated by dashed vertical lines in Fig. 4). This is consistent with the observation of a cylindrical flux rope as it crosses the Wind spacecraft. From the coronal data, we know that the photospheric magnetic bipole disappeared about one day after the eruption (Mandrini et al. 2005), so the erupting flux rope was probably detached from its original solar source when it was observed in $\textit{situ}$. A simple proportionality gives a length of $\approx$ 0.5 AU, but considering reconnection with neighbouring magnetic field structures, the previous authors took a length of 1 AU as probable. We apply the same techniques discussed above to estimate the magnetic helicity and the results are shown in Table 1.

4. DISCUSSION AND CONCLUSIONS

We computed the coronal magnetic helicity before and after two ejective solar events. This variation is then compared to the helicity content in the associated magnetic cloud, obtained from the classical Lundquist’s model and from a new direct method. For the October 1995 event, both helicity signs are positive; while for the May 1998 event they are both negative. Furthermore, the helicity lost from the corona is consistent with the amount of helicity found in the interplanetary medium. This happens even when the amounts of MH vary in three orders of magnitude when the two events are compared !.

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