QUANTITATIVE LINK BETWEEN SOLAR EJECTA AND INTERPLANETARY MAGNETIC CLOUDS: MAGNETIC HELICITY

C.H. Mandrini¹, S. Dasso¹,², M.L. Luoni¹, S. Pohjolainen³, P. Démoulin², and L. van Driel-Gesztelyi⁴,⁵,⁶

¹Instituto de Astronomía y Física del Espacio, IAFE, CONICET-UBA, CC. 67, Suc. 28, 1428, Buenos Aires, Argentina
²Departamento de Física, Facultad de Ciencias Exactas y Naturales, UBA, PBI, 1428 Buenos Aires, Argentina
³Taurlo Observatory/VISPA, University of Turku, FIN-21500 Piikkiö, Finland
⁴Observatoire de Paris, LESIA, UMR 8109 (CNRS), F-92195, Meudon, France
⁵Mullard Space Science Laboratory, Univ. College London, Holmbery St. Mary, Dorking, Surrey, RH5 6NT, UK
⁶Konkoly Observatory, H-1525 Budapest, P.O. Box 67, Hungary

ABSTRACT

We provide evidence for the link between coronal ejective events and their interplanetary manifestations. We combine multi-wavelength remote sensing and in situ observations with the computation of the coronal and interplanetary magnetic fields using a standard linear force-free approach. The analysis and computations are applied to one of the smallest (on 11 May, 1998) and to a large ejection (on 14 October, 1995), as well as to their related magnetic clouds. The connection between the coronal and interplanetary events is shown by comparing the magnetic helicity variation (pre- to post-eruption) in the corona to the helicity content in the associated magnetic clouds, and through the compatibility of other observational characteristics and computed quantities (e.g. magnetic flux) in both environments. Our results show that, within the uncertainties, the computed helicities are in good agreement. For the event on 11 May, 1998, the ejected magnetic flux and the flux in the associated interplanetary cloud also agree. Such quantitative analyses help to unambiguously identify the solar source region of magnetic clouds, and allow us to constrain theoretical models in both environments.

In this work we show the direct link between measurements of global MHD quantities in the Sun and the interplanetary medium. We evaluate the magnetic helicity and flux loss during ejective events, and compare them to the magnetic helicity and flux in their resulting MCs at 1 AU. This work summarizes the results of the studies by Mandrini et al. (2005) and Luoni et al. (2005). The first paper shows a study of an eruptive coronal bright point, which appeared at Sun centre on 11 May, 1998, and identified the corresponding MC ~ 4.5 days later using in situ data obtained with the Magnetic Field Instrument (MFI) on board the spacecraft Wind. The second paper presents a similar study of the 18-19 October, 1995, MC that reached the Earth producing the largest geomagnetic storm observed in the period of 1994-1997 (Dst = −120 nT). This MC was reportedly linked to a long-duration event (LDE) (van Driel-Gesztelyi et al. 2000). We revisit the results of both papers and put them within the same context, showing that the one-to-one quantitative relation between coronal and interplanetary events occurs for a wide range of parameters (e.g. size, magnetic flux and helicity). In Section 2, we briefly review the two coronal events, their magnetic modelling and computation of global MHD quantities. We summarize the interplanetary observations and magnetic helicity and flux computations using a standard linear force-free model for both associated clouds in Section 3. Finally, we compare our results and conclude in Section 4.
2. THE EVENTS IN THE CORONA AND THEIR MAGNETIC FIELD MODEL

2.1. The long duration event on 14 October 1995

Figure 1 (lower colour panels) shows the evolution of the C1.6 (GOES class) LDE on 14 October, 1995. The top image in this figure is a Kitt Peak magnetogram, where three nearby ARs can be seen. The 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 event began by loop brightenings in the central part of the AR during which some sigmoidal loops became visible (Fig. 1). By 07:29 UT the expanding loops encountered the magnetic fields of a neighbouring region (AR 7910) and an "X-like" coronal structure appeared, presumably the result of reconnections between loops belonging to AR 7912 and AR 7910. The expansion of AR 7912 continued, and by 08:55 UT the span of the fading loops, in projection, became comparable to the solar radius. We do not have direct observation of the ejected CME, since in October 1995 space-borne coronagraph observations were not available. However, a strong statistical link between LDE and CME occurrences and the observation of the actually expanding sigmoidal structures provide evidence of a CME in this event (Webb 1992).

A model of the coronal field was done using magnetograms provided by the Imaging Vector Magnetograph (IVM, LaBonte et al. 1999) at Mees Solar Observatory. We extrapolated the observed photospheric line of sight component of the field to the corona under the linear (or constant $\alpha$) force-free field assumption: $\nabla \times \mathbf{B} = \alpha \mathbf{B}$. Two different magnetograms from IVM were used, one at 00:20 UT and another at 17:55 UT, on 14 October. To determine $\alpha$, we use two Yohkoh/SXT full disc 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 (when the SXT loops were more relaxed). In general,
α is not constant along an AR. In this particular case, α was higher in the northern part and lower in the southern part of the region. This is illustrated in Figure 2, where field lines with the lower and higher α values are shown with thin and thick lines, respectively. The values of α are (0.94-2.07) × 10^{-4} Mm^{-1} for the model depicted in panel (b), and (0.12-1.50) × 10^{-3} Mm^{-1} for the model in panel (d). We compute the relative coronal magnetic helicity, $H_{cor}$, as done in Mandrini et al. (2005). The values of $H_{cor}$ are in the range (0.94-2.07) × 10^{44} Mx^2 and (0.12-1.50) × 10^{44} Mx^2 for the earlier and later IVM maps, respectively. We also determined the unsigned photospheric magnetic flux (average between positive and absolute value of the negative fluxes) from the two IVM magnetograms, the values are 7.8–8.4 × 10^{21} Mx for the earlier and later maps, respectively.

2.2. An X-ray bright point on 11 May 1998

During a survey of X-ray bright points that showed enhanced emission at cm- and mm-wavelengths, we observed an isolated radio bright point on 11 May, 1998. We found multi-wavelength evidence of its eruptive nature in soft X-ray and EUV observations. The bright point was well isolated from ARs present on the Sun and 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 the SXT light curve (see Fig. 3 top right). The first event started between the images taken at 00:42 UT and 00:51 UT, it 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 08:03 UT and 08:44 UT and ended at 11:00 UT. Then, its duration was of about 3 hours. In EUV images (from the Extreme Ultraviolet Imaging Telescope, SoHO/EIT, see Fig. 3 left), the first X-ray event was accompanied by formation of dimmings. The second X-ray burst was the 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 helicity, we modelled the magnetic field using a Michelson Doppler Imager (SoHO/MDI) magnetogram at 00:03 UT, 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. As usually found in other ARs, α is higher in the core of the region than in the peripheries. We point out that the values of α (-0.08 Mm^{-1} for the green and blue and -0.11 Mm^{-1} for pink field lines in Fig. 4, respectively) used to model TRACE loops imply that the coronal field is strongly non-potential. To compute the variation of the coronal helicity, we need observations after the SXT 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 helicity, we select the closest in time (at 11:11 UT) MDI magnetogram after the third X-ray burst (starting at ∼ 8:03 UT) and, using the previously determined values for α, we computed \( H_{\text{corr}} \). The values of |\( H_{\text{corr}} \)| are in the range \((5.2 - 7.5) \times 10^{39} \) Mx and \((2.9 - 4.2) \times 10^{39} \) Mx for the MDI maps at 00:03 UT and 11:11 UT, respectively.

The magnetic flux contained in a solar ejecta is another global quantity that can be used to link the coronal to interplanetary observations. An upper limit to this quantity can be estimated considering the magnetic flux contained in the dimmings. The dimmings for the first and third bursts cover parts of the small AR polarities and the surrounding quiet Sun regions. By performing careful measurements with different threshold values for the line of sight magnetic field, Mandrini et al. (2005) found that the flux in the dimmings that could be involved in the explosion was \( F_{\text{dimm}} = 13 \pm 2 \times 10^{18} \) Mx (see Fig. 3) for the third burst (the largest event in terms of integrated X-ray flux and EIT dimming extension). The peak unsigned flux value in the AR was \( 32 \times 10^{18} \) Mx.

3. THE INTERPLANETARY EVENTS AND THEIR MAGNETIC FIELD MODEL

3.1. The magnetic cloud on 18-19 October 1995

On October 18-19, 1995, an MC presenting a strong southward component for about 15 hours was observed by the Wind spacecraft. This MC was linked to the LDE in AR 7912 and was studied by several authors (see references in Luoni et al. 2005). The in situ plasma and magnetic data indicate that the cloud reached the spacecraft at ∼ 19:00 UT, on 18 October. The beginning of the cloud is very clear; however, its end time cannot be well determined and different authors take different values. An end time at ∼ 23:00 UT on 19 October has been taken by several authors (e.g., Lepping et al. 1997), which is the one we will use here. Information on the length of the flux tube in MCs can be obtained by studying the electron distribution function. Based on such data combined with observations of Type III bursts, Larson et al. (1997) concluded that this MC was connected to the Sun at least at one end. They estimated the semi-length for 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 & Schwenn 1998). We downloaded the MFI data from [http](http://cdaweb.gsfc.nasa.gov/cdaweb/istp-public/). From this analysis we obtained the components of the field in a cartesian system attached to the cloud (local components), such that: (a) \( B_{z,\text{Cloud}} \) is the axial component, being its value positive at the cloud centre, (b) \( B_{\phi,\text{Cloud}} \) is the azimuthal component (\( B_{\phi,\text{Cloud}} \)) once the spacecraft crossed its axis, and (c) \( B_{r,\text{Cloud}} \) is the radial component, also after leaving the MC centre. Figure 5 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 per unit length contained in the cloud (\( H_{\text{Cloud}}/L \)), the magnetic flux in the \( B_{z,\text{Cloud}} \) component (\( F_{z,\text{Cloud}} \)), and in the \( B_{\phi,\text{Cloud}} \) component per unit length (\( F_{\phi,\text{Cloud}}/L \)) (Mandrini et al. 2005). The corresponding values are: \( H_{\text{Cloud}}/L = 3.7 \times 10^{42} \) Mx AU\(^{-1} \), \( F_{z,\text{Cloud}} = 1.1 \times 10^{41} \) Mx and \( F_{\phi,\text{Cloud}}/L = 3.0 \times 10^{31} \) Mx AU\(^{-1} \) (Luoni et al. 2005).

3.2. The small cloud on 15-16 May 1998

To identify the MC linked to the ejective event on 11 May, 1998, we scan Wind data from ∼ 10:00 UT on 13 May to ∼ 04:00 UT on 16 May, 1998, around the expected time of arrival if a cloud would have been ejected towards Earth. A very extended complex ejecta, containing plasma with a high intensity and disorderly magnetic field, and low proton β (β, ratio of the plasma to the magnetic pressure), was observed by Wind between 15-17 May, 1998. We identified a small event inside the complex ejecta, lasting from 22:00 UT on 15 May to 01:50 UT on 16 May, arriving about 4 days and 14 hours (110
hours) after the coronal eruption. This small cloud was a good candidate to be the interplanetary manifestation of the solar eruption because, considering an average speed of $\sim 350\pm50$ km/s as measured for the solar wind, we expected a travel time of $\sim 119 \pm 17$ hours from the corona to 1 AU, in very good agreement with the observed arrival time. The identified interplanetary event showed a large and coherent rotation of the $y$ component of the magnetic field in the GSE (Geocentric Solar Ecliptic) system. Figure 6 shows the observed components of the field in the local frame and Lundquist’s model fitted to the observations. As in the previous case, we compute $H_{\text{Cloud}}/L$, $F_{x,\text{Cloud}}$, and $F_{\varphi,\text{Cloud}}/L$. Our results are: $H_{\text{Cloud}}/L = -3.3 \times 10^{39}$ Mx AU$^{-1}$, $F_{x,\text{Cloud}} = 1.3 \times 10^{19}$ Mx and $F_{\varphi,\text{Cloud}}/L = 20.0 \times 10^{19}$ Mx AU$^{-1}$ (Mandrini et al. 2005). 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 by the time it was observed in situ. A simple proportionality gives a length of $\sim 0.5$ AU, but considering reconnection with neighbouring magnetic structures, a length of 1 AU is also probable.

4. QUANTITATIVE LINK BETWEEN CORONAL AND INTERPLANETARY EVENTS

Magnetic flux and magnetic helicity are two important global physical quantities that characterize a magnetic field configuration. Computing these quantities at the coronal level and in the interplanetary space links the interplanetary events to their coronal source region, in the following way:

-Magnetic helicity. For both ejective events and associated MCs the magnetic helicity sign and magnitude agrees. The decrease of the coronal magnetic helicity (before and after the ejection) for the 14 October event is in the range of $3\times10^{42}$ Mx$^2 \leq \Delta H_{\text{cor}} \leq 6 \times 10^{42}$ Mx$^2$; while taking a length of 2.4 AU, we find that $H_{\text{Cloud}} = 9.0 \times 10^{42}$ Mx$^2$, which is an upper limit for the helicity since we assume the same length for both legs of the cloud (see the discussion in Section 3). For the small AR, the coronal helicity variation is $2.3 \times 10^{39}$ Mx$^2 \leq \Delta|H_{\text{cor}}| \leq 3.1 \times 10^{39}$ Mx$^2$; meanwhile for the cloud we estimate that $|H_{\text{Cloud}}| \sim 1.5 \times 10^{39}$ Mx, considering both probable lengths (0.5 and 1.0 AU, Section 3). In both examples the agreement is quite good (remarkable in the case of the small AR), considering the large errors that could be involved in these computations. We emphasize that this happens for events for which the magnetic helicity differs in 3 orders of magnitude!

-Magnetic flux. For this quantity, we can compare the photospheric flux at the solar level to the flux in the axial ($B_{z,\text{Cloud}}$) and azimuthal ($B_{\varphi,\text{Cloud}}$) components of the MC. For the event on 14 October, we have no proxy for the ejected flux (e.g. we observe no dimmings in soft X-rays); then, we can only compare $F_{\text{AR}} \sim 8.1 \times 10^{21}$ Mx to $F_{z,\text{Cloud}} = 1.1 \times 10^{21}$ Mx and $F_{\varphi,\text{Cloud}}/L = 3.0 \times 10^{21}$ Mx AU$^{-1}$. The flux in the axial component of the cloud is $\sim 0.1$ of the AR flux. This result agrees with several statistical studies of MCs (see the discussion in Luoni et al. 2005). However, when we compare $F_{\text{AR}}$ to $F_{\varphi,\text{Cloud}}$ taking a maximum length of 2.4 AU, we find a much closer agreement ($F_{\varphi,\text{Cloud}} \sim 90\% F_{\text{AR}}$). What can we infer about the origin of the ejected flux tube from this result? Let us do the same comparison for the small
$10 \times 10^{19} \text{ Mx} \leq F_{\phi \text{, Cloud}} \leq 20 \times 10^{19} \text{ Mx}$ in very good agreement with $F_{\text{dimming}}$.

We have shown the link between coronal and interplanetary events using the computation of global MHD quantities. This happens for events with very different characteristics, i.e. with sizes differing in a factor 6, magnetic fluxes in a factor 25 and magnetic helicities in a factor $10^3$. We can also infer from our comparison what the most probable origin of an ejected flux rope is. If this quantitative link could be confirmed for more cases; then, observations of a very different nature, like coronal (remote sensing) and interplanetary (in situ) ones, could be combined to constrain models in both environments.

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Figure 7. A sketch showing the way a magnetic flux tube can be formed by magnetic reconnection in an expanding sheared arcade. The upper and lower panels show two field lines belonging to the expanding arcade (top), and a small arcade and flux tube (bottom), before and after reconnection respectively. Further reconnection (not shown) between the flux tube and the large scale arcade above will increase the number of turns in the flux tube. Coronal dimmings are expected to form in all the expanding arcade. However, only a fraction of the photospheric flux of the dimmings contributes to the longitudinal flux of the twisted flux tube; the remaining part is transferred (through reconnection) to the magnetic flux in the azimuthal component.