ON THE IMPORTANCE OF MAGNETIC HELICITY IN THE CME INITIATION PROCESS

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ABSTRACT

An important role of CMEs is that they carry away magnetic helicity, which would otherwise accumulate incessantly in the Sun. Some active regions produce many CMEs, and others far less during their entire existence. Searching for the underlying cause of the differences in CME productivity, we find strong indications that magnetic helicity levels play a very important role in this. Based on observations and model calculations of two well-studied CME prolific active regions (NOAA 7978 in July-November 1996 and NOAA 8100 in November 1997-March 1998) we evaluate the relative importance of different mechanisms for helicity input in these active regions. The latter can provide clues to the understanding of the differences in their helicity output, i.e. in the number of CMEs they produce. Such studies are aimed at improving our forecasting ability of CMEs.

1. INTRODUCTION

The best known magnetic pattern in solar activity is described by Hale's law [15], i.e. the magnetic polarity of bipolar sunspot groups (i.e. the polarity of the spot, which "leads" in the sense of solar rotation) is the opposite on the northern and the southern hemispheres. The polarity of spot groups change from cycle to cycle, thus a full magnetic cycle lasts for 22 years.

A more recently recognized rule is the hemispheric pattern of the helicity in solar activity phenomena [31,23]. Magnetic helicity is a measure of the linkage of the magnetic field lines within a volume. It can be expressed as the sum of twist and the writhe of a magnetic configuration. In the majority (70-80 %) of solar active regions, helicity was found to be positive on the southern and negative on the northern hemisphere [23]. This hemispheric helicity rule is cycle-invariant, unlike the polarities of the spot groups. Other solar activity features, which represent different signatures of helicity e.g. filaments, coronal arcades, sigmoidal coronal loops, sunspot whorls follow this hemispheric pattern as well [20, 21, 7, 29, 26].

Helicity is one of the few global quantities, which is conserved even in resistive MHD on a timescale less than the global diffusion timescale [1]. Since the solar helicity pattern is cycle-invariant, helicity would incessantly accumulate, unless the Sun finds a way to get rid of it. Helicity is continuously generated in the toroidal flux layer (see e.g. [31]) and tachocline by differential rotation and helical motions, brought up by the emergence of buoyant twisted flux tubes [16, 18, 10], furthermore, increased by surface differential rotation [12, 10, 11, 13, 14] and localized shearing foot-point motions [11, 8, 9].

CMEs liberate stored magnetic energy over a large volume, lead to the partial opening of the magnetic field and, as a result, helicity does not remain conserved in a volume on the active region scale. Thus CMEs are prime candidates for carrying away accumulated helicity [28, 19]. The twisted flux tube ejected in a CME appears in the interplanetary space as a magnetic cloud in which, in many cases, the twisted nature remains well observable. Like this, helicity can be traced from the solar corona as far as to the Earth and beyond.

2. TWO CASE-STUDIES

Collecting clues to find the underlying cause of CMEs Démoulin, Green and co-workers [10, 13, 14] studied the dominant source of the magnetic helicity shed by CMEs. They analyzed the long-term magnetic helicity budget of two solar active regions: of AR 7978 between July-November 1996 [10] and of AR 8100 in the period of November 1997 and February 1998 [13, 14].

These authors [10, 13, 14]

- carried out linear force-free field (lfff) extrapolations using MDI magnetic data and computed the relative coronal magnetic helicity from their models,
- calculated magnetic helicity generated by the differential rotation from observed magnetic field distributions of the ARs (SOHO/MDI),
- identified all the CMEs which originated from AR 7978 and AR 8100, then using physical quantities derived from IP magnetic cloud measurements, estimated the magnetic helicity shed by CMEs.

Table 1. CME number per rotation and the linear force-free parameter α at CMP in AR 7978. The 4th column gives CME numbers corrected for LASCO data gaps.

Rot. No. No.	Date 1996	No. of CMEs Obs.	Corr.	α $10^{-2}Mm^{-1}$
1st	07 July	8	11	1.0
2nd	03 Aug.	5	5	0.3-0.75
3rd	30 Aug.	2	3	0.9-1.0
4th	25 Sept.	5	5	1.0-1.4
5th	23 Oct.	3	4	0.9-1.4
6th	18 Nov.	3	3	0.9-0.9
Total		26	31	

Table 2. CME number per rotation and the linear force-free parameter α at CMP in AR 8100. The 4th column gives CME numbers corrected for LASCO data gaps and for CMEs missed when the AR was on the far side of the Sun.

Rot.	Date 1997/98	No. of CMEs Obs.	Corr.	α $10^{-2}Mm^{-1}$
1st	02 Nov.	16	24.1	-1.30
2nd	29 Nov.	0	2.5	0.94
3rd	27 Dec.	6	11.7	0.82
4th	23 Jan.	9	16.8	0.94
5th	20 Feb.	4	9.6	1.00
Total		35	64.7	

2.1. Magnetic helicity

Magnetic helicity is defined by a volume integral: $H_m = \int_V \vec{A}.\vec{B}dV$, where $\vec{A}$ is the magnetic vector potential, and $\vec{B} = \vec{\nabla} \times \vec{A}$ is the magnetic field. It is physically meaningful only when $\vec{B}$ is fully contained inside the volume V. However, when this is not so ($B_n \neq 0$ along the boundary S), following [6], a relative magnetic helicity can be computed by subtracting the helicity of a reference field $\vec{B_0}$, which has the same B_n distribution on S as $\vec{B}$:

$$H_r = \int_V \vec{A}.\vec{B}dV - \int_V \vec{A_0}.\vec{B_0}dV. \qquad (1)$$

Since H_r is well conserved under solar conditions the only way helicity can be modified inside V is by helicity flux crossing the boundary S [6]:

$$\frac{dH_r}{dt} = -2\int_S [(\vec{A_0}.\vec{v})\vec{B} - (\vec{A_0}.\vec{B})\vec{v}].\vec{dS}, \qquad (2)$$

where $\vec{v}$ is the velocity of the plasma. The 1st term corresponds to helicity generation by plasma motion parallel to S, while the 2nd term denotes inflow and outflow of helicity through the boundary S.

2.2. Coronal relative magnetic helicity

SOHO/MDI magnetograms taken close to the central meridian passages of the studied ARs were used as boundary conditions for lfff magnetic extrapolations ($\vec{\nabla} \times \vec{B} = \alpha\vec{B}$; α=const). The extrapolated field lines were co-aligned with coronal loops observed with Yohkoh/SXT. Parameters of the best general fit between the models and observations were adopted for further computations(Tables 1 and 2). Using the best-fitting lfff models of the coronal field for each of the rotations [10 & 14] computed relative coronal helicity following [2]:

$$H_r = 2\alpha \sum_{n_x=1}^{N_x} \sum_{n_y=1}^{N_y} \frac{|\widetilde{B}^2_{n_x,n_y}|}{l(k_x^2+k_y^2)}, \qquad (3)$$

where $\widetilde{B}_{n_x,n_y}$ is the Fourier amplitude of the field component B_n, $l = \sqrt{k_x^2 + k_y^2 - \alpha^2}$, $k_x = 2\pi n_x/L$, $k_y = 2\pi n_y/L$ with L being the horizontal extension of the computational box.

2.3. Helicity generated by differential rotation

For a computation of magnetic helicity generated by photospheric plasma motions [1, 4] derived an expression for dH_r/dt which depends only on observable photospheric quantities (B_n and $\vec{v}$). Berger [3] showed that the helicity generation rate can be understood as the summation of the rotation rate of all the individual elementary flux pairs weighted by their magnetic flux. The latter method was applied by [10] to observations. It was noticed by [11] that photospheric plasma motions generate two different helicity terms: the rotation of each polarity introduces twist helicity while the relative rotation of opposite polarity flux concentrations injects writhe helicity. In the case of the differential rotation the generated twist and writhe helicities always have opposite signs, while their magnitudes are similar, thus they partially cancel. The amount of helicity injected by the differential rotation as computed by [10 & 14] using SOHO/MDI data for each rotation of ARs 7978 and 8100 is shown in Table 3.

2.4. Helicity ejected via CMEs

All the CMEs were identified which originated from ARs 7978 (26)[10] and 8100 (35) [14] during their long-term evolution using SOHO/LASCO & EIT, Yohkoh/SXT and Hα observations. Then these numbers were corrected for LASCO data gaps (mainly for AR 7978) and for the unidentified CMEs during the periods when AR 8100 was on the far side of the Sun. Due to a very low activity level in 1996 CMEs could be linked to AR 7978 even during its far-side locations, so there was no need for the latter correction. The results are shown in Tables 1 and 2, respectively.

Then, assuming one-to-one association between CMEs and magnetic clouds, i.e. interplanetary twisted flux tubes [33], and taking a mean magnetic field $B_0(2 \times 10^{-4}$ G) and radius R (2×10^{12} cm) of 18 magnetic clouds [17], furthermore, using a numerically integrated form of Bergers equation [5], the relative helicity per unit length in the twisted interplanetary flux tube was computed by [10]. For the length of the flux tube in the magnetic cloud two values were used: $L_1 = 0.5AU$ [12] which yielded $H_r \approx 2 \times 10^{42}Mx^2$ magnetic helicity in a magnetic cloud, and $L_2 = 2AU$ (the cloud is still connected to the Sun; e.g. [27]), which resulted in $H_r \approx 8 \times 10^{42}Mx^2$ for an average-sized magnetic cloud, i.e. CME. These mean helicity values have to be multiplied with the number of CMEs which originated from the analyzed AR to obtain the total magnetic helicity ejected from the ARs. Results are given in Table 3.

Table 3. The magnetic helicity budgets of AR 7978 (upper Table) and AR 8100 (lower Table) are listed per rotation. For AR 8100 the period of 2-5 Nov. is analyzed separately because of the change of sign of the helicity between the 1st and the 2nd rotations. The coronal helicity ($H_{\rm c.}$) and the change of coronal helicity ($\Delta H_{\rm c.}$) are computed from MDI magnetograms at successive CMPs. An interval of helicity is given for the corona and for the cloud estimations ($\Delta H_{\rm m.cl.}$) with both the observed and corrected numbers of CMEs (considering the two limits, 0.5 and 2 AU, for the length of the twisted flux tube in magnetic clouds). All values are in units of 10^{42} Mx^2.

No. of rot.	Date 1996	$H_{\rm c.}$	$\Delta H_{\rm c.}$	$\Delta H_{\rm d.r.}$	$\Delta H_{\rm m.cl.}$ obs.	$\Delta H_{\rm m.cl.}$ cor.	$\Delta H_{\rm c.} - \Delta H_{\rm d.r.}$
1st	07 Jul.			0.2	[16, 64]	[22, 88]	($\approx$ 7)
2nd	03 Aug.	[5, 11]	12	3.	[10, 40]	[10,40]	9
3rd	30 Aug.	[17, 23]	-9.5	3.	[4, 16]	[6, 24]	-13
4th	25 Sep.	[9, 12]	-5.5	1.	[10, 40]	[10, 40]	-7
5th	23 Oct.	[4, 6]	(-1)	0.8	[6, 24]	[8, 32]	-2
6th	19 Nov.	(4)	–	0.3	[6, 24]	[6, 24]	–
total		–		8.3	[52, 208]	[62, 248]	-6
	1997/98						
	2-5 Nov.	–		0.2, 0.8	[-20, -80]	[-20, -80]	-33.1
1st	02 Nov.	-11.0	33.5				30.2
2nd	29 Nov.	22.5	-2.9	[5.1,-4.6]	[0.0, 0.0]	[5.,20.]	-3.2
3rd	27 Dec.	19.6	-11.2	[-4.6,-2.8]	[12.,48.]	[24.,96.]	-7.5
4th	23 Jan.	8.4	-3.3	[-2.8,-1.6]	[18.,72.]	[34.,136]	-1.1
5th	20 Feb.	5.1	-2.0	-1.6	[8.,32.]	[19.,76]	-0.4
total 2-5			-19.4	-7.3	[38.,152.]	[82.,328.]	-12.2

3. DISCUSSION ON THE HELICITY BUDGETS

The two ARs studied by [10, 13 & 14] were quite different: AR 7978 was a classical bipolar AR oriented E-W, distorted only by the differential rotation, while AR 8100 was a complex AR in which the main magnetic polarities rotated around one another. The helicity generated by differential rotation had always the same sign though it decreased with time in AR 7978 (Table 3) while in AR 8100 after reaching a maximum it even changed sign (Table 3). The latter behavior was due to the changing relative importance of the twist and writhe helicities with the changing orientation of the bipole, while the profile of the differential rotation remained the same.

AR 7978 had positive relative coronal helicity (corresponding to the majority hemispheric helicity sign on the South), and the differential rotation injected positive helicity as well throughout the studied six solar rotations (Table 3). On the other hand, AR 8100, though it was also a South hemispheric AR, had *negative* coronal helicity during its first rotation, what was gradually decreasing between 2 and 5 November. The differential rotation and more localized shearing motions were found to generate positive helicity during this period, depleting the coronal helicity. The coronal helicity of AR 8100 changed sign and became positive by the second rotation, and remained positive after that (Table 3). During the second rotation the differential rotation generated positive helicity, however, by and after the third rotation it became negative and it was actually depleting again the coronal helicity of the AR.

When looking at the changes in coronal helicity from one rotation to the next, and comparing the changes with the amount of helicity generated by the differential rotation (4th and 5th columns in Table 3) it is obvious that the differential rotation is an inefficient generator of helicity and even in the more favorable case of AR 7978 it can not be the dominant source of magnetic helicity. This accentuates the importance of the second term in equation (2) representing helicity inflow and outflow through the boundaries of our coronal computational box. The total helicity budget of the ARs may be written:

$$\Delta H_{\rm emergence} = \Delta H_{\rm corona} - \Delta H_{\rm diff.rot.} + N.H_{\rm CME}, \quad (4)$$

where Δ denotes the variation of the helicity, N is the number of the CMEs and $H_{\rm CME}$ is the mean helicity carried away per CME event. $\Delta H_{\rm emergence}$ can be computed adding the last column to either the 6th or 7th column of Table 3 (considering either observed or corrected CME numbers).

In the helicity budget of AR 7978 the increase in coronal helicity during the first two rotations and the large amount of helicity carried away by CMEs during this period requires the largest input of helicity by the sub-photospheric layers. Indeed, major flux emergence episodes were observed then in the AR [10]. During later rotations the deficit in the helicity budget becomes smaller, but still not negligible. The total amount of helicity which we need to cover from twisted flux emergence (if we take the corrected CME numbers) can be estimated to be between $56 - 242 \times 10^{42} Mx^2$. For comparison, during the same period the differential rotation generated only $8.3 \times 10^{42} Mx^2$, so it clearly was a *minor contributor* to the magnetic helicity budget of AR 7978.

The flux emergence term appears to be even more important in the helicity budget of AR 8100, since the differential rotation and other shearing motions generated helicity of the opposite sign than that of the actual coronal helicity. Between the 2nd and the 5th rotations (taking the corrected CME numbers) $70 - 316 \times 10^{42} Mx^2$ helicity had to emerge to cover the budget deficit.

4. CONCLUSIONS

CMEs are preceded by a long-term build-up process, along which flux emergence, shearing and twisting footpoint motions are seen [32, 30]. All these processes are actually *increasing the magnetic helicity*.

However, the above mechanisms have very different efficiencies in injecting helicity into the corona. It was shown by [10,11,13,14] that the differential rotation is a very inefficient generator of helicity, due to a partial cancellation of twist and writhe helicities, which have opposite signs [11]. On the other hand, shearing motions localized between two polarities create twist and writhe helicities that have the same sign and add up. However, localized shearing motions involve only a fraction of the AR flux, thus the helicity generated by them, in most of the cases, is relatively small compared to the helicity needed for a CME (c.f. [8, 9, 10, 14]). Analyzing the long-term helicity budget of two CME prolific active regions (AR 7978 and AR 8100) [10 & 14] concluded that the main source of coronal magnetic helicity must be the inherent twist of the emerging flux tubes.

It was proposed by [18] that for the steady state the coronal helicity is determined by the amount of twist present in the sub-photospheric part of the flux tube forming the AR. Extending their model qualitatively to include CMEs one can say that when the coronal helicity of the steady state is above the threshold of the global instability for the coronal field, a CME will occur, removing part of the helicity. Next, an imbalance of the torque will charge the coronal field with helicity typically in a day, and the process can start again until the flux tube twist is exhausted or the flux tube is destroyed by convective motions. Computing the magnetic helicity in the context of CME occurrence for a large number of ARs may enable us to derive characteristic threshold values, which could lead to an improved short-term (days or hours) CME forecast.

The above statements also imply that the more helicity the flux tube forming the AR tube possesses, the more CMEs the active region will produce. Thus helicity studies can also lead to a better understanding of the CME productivity of ARs which can, in turn, lead to a better longer-term (weeks, months) CME forecast in the future.

This work provides one of the starting points of an ambitious project on CME initiation, propagation and interaction in which we combine multi-wavelength observations with modelling and MHD simulations of such events following them from the Sun to the Earth (see also [24, 25, 32, & 30]).

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