MAGNETIC FLUX CHANGE RATES AND NONTHERMAL FLARE EMISSION

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Abstract. We tested the standard flare model by measuring the magnetic flux change rate in five flares of different GOES classes and compared it to the observed nonthermal flare hard X-ray emission. In addition we calculated the cumulated positive and negative magnetic reconnection flux, as well as the total reconnection flux. We also investigated the relations between the total reconnection flux, the GOES importance of the events, and the linear velocity of the flare-associated CMEs. The required observables (newly brightened flare area and magnetic field strength inside this area) were measured using high-cadence Hα and TRACE 1600Å image time series along with MDI/SOHO magnetograms. RHESSI and INTEGRAL hard X-ray time profiles in nonthermal energy bands served as observable proxies for the flare energy release rate. We found good temporal correlations between the derived magnetic flux change rate and the observed nonthermal emission in all events. Cumulated positive and negative fluxes were roughly balanced. The amount of magnetic reconnection flux was larger in more energetic events than in weaker ones. Flares with more reconnection flux were associated with faster CMEs. The findings indicate that the standard flare model is applicable to the analysed events.

Key words: active Sun - flares - magnetic fields - chromosphere - corona

1. Introduction

In the CSHKP model (e.g., Carmichael, 1964; Sturrock, 1966; Hirayama, 1974; Kopp and Pneuman, 1976; Forbes and Priest, 1984; Forbes and Lin, 2000), which is commonly used to explain observed features in two-ribbon flares and CME events, a filament becomes unstable and erupts (cf. Figure 1). As a result, a coronal mass ejection (CME) is launched, stretching the underlying magnetic field and thus allowing the field lines that are
rooted in opposite magnetic polarity domains to come in close contact to each other, i.e., a tangential discontinuity arises. As a consequence, a current sheet (CS) is formed below the erupting structure.

As the structure rises, the CS elongates, involving magnetic reconnection for two reasons: (1) if the CS gets too long, tearing instability causes its disruption into many magnetic islands with O-points in their centre and X-points in between; (2) part of the mass that has been pushed upward in front of the CME can flow down again at its flanks. This mass then flows towards the CS, because of a horizontal pressure gradient caused by the erupting structure. Due to the frozen flux condition that is usually valid in the corona, the magnetic field is coupled with the plasma motion and thus forced to approach the CS as well. When two oppositely directed field lines ‘collide’ in the diffusion region (DR) – a tiny spot inside the CS with non-zero resistivity – reconnection sets in, and magnetic flux from formerly separated magnetic polarity domains is unified. During this process, magnetic excess energy that has been built up for many hours or
even days is released within seconds to minutes. Particles are accelerated to nonthermal energies, plasma and heat flows are initiated, and MHD shock waves are generated. A significant amount of the total energy goes into fast electrons (e.g., Hudson, 1991; Dennis et al., 2003).

The released energy and heat is transported to the chromosphere, where it is deposited, producing the bright flare kernels and ribbons observed in H\alpha and UV. In addition, the fast electrons hitting the thick-target chromosphere create nonthermal hard X-ray (HXR) emission via bremsstrahlung when scattered off ions. This emission acts as indicator for the rate of accelerated electrons, and therefore is considered as a proxy for the energy release rate in the flare.

As the chromospheric plasma is heated an overpressure arises and the hot material is tossed upward, filling the newly created flare-loops, which begin to emit soft X-ray (SXR) and extreme ultraviolet (EUV) radiation. The SXR peak flux allocates the flare in the GOES importance scheme and can be understood as a measure of the cumulated energy in the hot, thermal plasma, evaporated into the chromosphere (e.g., Veronig et al., 2002, 2005).

Since the erupting structure continuously rises to larger coronal heights, the reconnection also occurs at larger heights. Therefore, the bright footpoints of newly reconnected field lines lie further and further apart as the flare progresses, and an observer gets the impression of separating flare ribbons. As the corona and chromosphere are coupled via the reconnected field lines, the rate at which magnetic field lines are reconnected is associated with the separating flare ribbons, and the coronal magnetic flux change rate \( \dot{\phi} \)

\[
\dot{\phi} = \frac{\partial}{\partial t} \int B_n \, da
\]  

(1)

can be estimated by measuring the flux change rate from photospheric/ chromospheric observations (Forbes and Priest, 1984; Forbes and Lin, 2000). \( B_n \) in Equation (1) is the photospheric magnetic field strength component perpendicular to the solar surface inside the newly brightened area \( da \), which is swept by the flare ribbons.

The standard model predicts co-temporal evolution of the derived flux change rate and the observed HXR flux, i.e., peaks in both profiles are expected to occur roughly at the same time. It also predicts equal amounts of positive and negative magnetic flux participating in the reconnection process.
at each moment. This should be reflected in identical cumulated positive and negative flux profiles in the ideal case. Furthermore, the model suggests that flares with more reconnection flux should be more energetic (higher GOES importance), because more reconnection flux also means more released energy available to heat the chromospheric plasma, which then evaporates and fills the flare loops. In addition, the model allows the initiation of a feedback-relationship (Vršnak et al., 2005) between the reconnection in the flare and the CME kinematics after the initial state of the eruption, because: (1) the reconnection reduces the net tension of the overlying field and enhances the magnetic pressure below the flux-rope; (2) the upward-directed reconnection jet carries the newly reconnected field lines to the erupting flux-rope and supplies it with additional poloidal flux (cf. \( B_\phi \) in Figure 1). This results in an increase of the hoop force and facilitates the upward motion (e.g., Vršnak, 1990; Maričić et al., 2007; Temmer et al., 2008). Both effects lead to an enhanced and extended acceleration phase of the erupting structure. As a consequence, CMEs associated with flares are supposed to be faster than CMEs without flares. Moreover, there is a statistical tendency of larger CME accelerations, i.e., faster CMEs, being associated with more powerful flares (Maričić et al., 2007).

2. Data and Methods

To test the model predictions we selected five dynamical (tworibbon) flares of different GOES importance that were associated with CMEs. Table I lists information on the events. The flare position on the solar disc (not more than \( \pm 40^\circ \) away from disc centre), the availability of high-cadence image time series in \( \text{H}_\alpha \) or UV, and complete coverage of the impulsive phase in HXRs served as selection criteria. All flares were located near active regions.

To detect the newly brightened area in an event we used \( \text{H}_\alpha \) images provided by various ground-based observatories (Kanzelhöhe, Hvar, Meudon, and Big Bear), and UV images in the 1600 Å passband from TRACE. The cadence of the time series ranged between 4 and 60 s, the pixel scales between 0.3 and 2.2"/pixel. The normal component of the magnetic field inside the newly brightened area was derived from full-disc line-of-sight magnetograms (SOI/MDI instrument on board SOHO).

Full-disc nonthermal HXR-intensity time profiles from RHESSI and INTEGRAL were used as observable proxy for the flare energy release rate.
Table I: Event Information. For each event we list the date, heliographic position, GOES importance, time of GOES maximum of the flare, time of first LASCO C2 appearance, and the linear velocity of the associated CME, i.e., the speed obtained by fitting a straight line to the CME-height-time measurements. Details on the CMEs were obtained from the SOHO LASCO CME CATALOG (Yashiro et al., 2004, http://cdaw.gsfc.nasa.gov/CME_list/).

<table>
<thead>
<tr>
<th>Date</th>
<th>Position</th>
<th>GOES Class</th>
<th>Max. [UT]</th>
<th>LASCO C2 [UT]</th>
<th>$v_{\text{lin}}$ [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 May 19</td>
<td>N01 W05</td>
<td>B9.5</td>
<td>13:02</td>
<td>13:24</td>
<td>960</td>
</tr>
<tr>
<td>2006 Jul 06</td>
<td>S10 W30</td>
<td>M2.5</td>
<td>08:35</td>
<td>08:54</td>
<td>910</td>
</tr>
<tr>
<td>2003 Nov 18</td>
<td>S02 E37</td>
<td>M3.9</td>
<td>08:31</td>
<td>08:50</td>
<td>1660</td>
</tr>
<tr>
<td>2005 Jan 15</td>
<td>N13 W04</td>
<td>X2.6</td>
<td>23:02</td>
<td>23:06</td>
<td>2860</td>
</tr>
<tr>
<td>2003 Oct 28</td>
<td>S16 E08</td>
<td>X17.2</td>
<td>11:10</td>
<td>10:54</td>
<td>2460</td>
</tr>
</tbody>
</table>

The RHESSI energy bands were chosen in such a way that: (1) the emission was nonthermal; (2) the photon energies were low enough to produce reasonable count statistics. To satisfy these demands, different energy bands were required in each event (cf. Figure 3b – 3f) since the GOES importance ranged between B and X.

The following data reduction procedures were accomplished: (1) differential rotation of the images to the same reference time; (2) cross-correlation of Hα image time series to account for seeing effects; (3) adjustment of the different pointings of TRACE WL and 1600 Å; (4) MDI image conversion from SOHO-view to Earth-view; (5) removal of transient bright non-flare features such as cosmic rays; (6) co-alignment of the different data sets using MDI continuum, Hα blue wing, and TRACE WL images, and utilizing sunspots near the flare sites as a reference.

The magnetic flux change rate was determined applying Equation (1). Difference images and intensity thresholds were used to discern flare pixels and non-flare pixels. To be counted as a newly brightened pixel a particular pixel has to: (1) exceed the threshold; (2) be a non-flare pixel in all preceding images; (3) be located inside the currently analysed magnetic polarity domain, since the analysis has to be carried out separately for each polarity; (4) exceed the MDI noise level of 20 G (for further details see Miklenic et al.,
2007). After the detection of the newly brightened area $da$, which consists of all pixels meeting the aforementioned criteria, we take the products $\text{pixel area} \times B_n$ for each pixel inside $da$, with $B_n = (1.56 B) / \cos(\phi)$. The sum of all products gives the newly reconnected flux at time $t$. Adding this flux to the flux that has been reconnected up to time $t$ yields the cumulated flux. Division of the newly reconnected flux by the time interval between two consecutively taken frames gives the flux change rate for each polarity domain, and the mean of both domains gives the magnetic flux change rate $\dot{\varphi}$. For further details on the measurement of the observed quantities and the used data sets see Miklenic et al. (2008).

3. Results and Discussion

In the following the results are presented in a highly abridged form. The selected examples are supposed to provide an insight into studies on magnetic reconnection rates and fluxes. For a detailed report we refer to Miklenic et al. (2008).

Figure 2a – 2d shows the ribbon separation of the 2006 July 06 flare observed in Hα filtergrams of Hvar Observatory (Croatia). Panel 2e displays the calculated total flare area, i.e., the sum of the newly brightened areas in all images, superposed on a decay phase image, and in 2f the contours of this area are plotted on the MDI magnetogram of the flaring region. The magnetic field topology affects both the shape of the flare ribbons and the size of the total flare area, as strong magnetic fields prevent the flare ribbons from spreading easily. Instead, strong fields slow down or even stop the ribbons, and therefore diminish the brightened area in a flare. In the example shown here, the northern (upper) ribbon entered the umbra of the nearby sunspot with its strong magnetic fields. Therefore, its area remained small compared to the southern (lower) ribbon, and it was stopped at the border between umbra and penumbra.

In Figure 3a an example of the progression of cumulated reconnection-flux profiles is presented. The positive and negative flux profiles look similar over the entire time range. This indicates that almost equal shares of positive and negative magnetic flux participate in the reconnection process at

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$B$: reported photospheric line-of-sight magnetic field at location of flare pixel; 1.56: correction factor to account for MDI underestimation of strong fields (Berger and Lites, 2003); $\phi$: heliographic flare position. Division by $\cos(\phi)$ derives a radial field at each pixel.
each time, as it is theoretically expected. During the impulsive phase, when more and more flux is reconnected, the cumulated flux profiles steeply rise. In the decay phase, i.e., after the GOES flux reaches its maximum, the reconnection process slows down and ceases, and the amount of newly re-connected flux decreases. This results in nearly constant cumulated flux profiles during this phase of a flare. At the end of the analysed time interval the ratio of cumulated positive vs. negative reconnection flux is 1.02 in this event, and the total flux $\varphi_{\text{tot}}$ adds up to $\sim 15.5 \times 10^{21}$ Mx.

Figure 2: 2006 July 06, M2.5 flare – Panels a) – d): Temporal evolution of the flare ribbons in Hα. a): impulsive phase image, b): time of RHESSI maximum, c): time of GOES maximum, d): decay phase image. e): calculated total flare area on decay phase image (black with white contours: negative polarity, white with black contours: positive polarity), f): total flare area on MDI magnetogram. Contours are the same as in e).

In Figure 3b – 3f, the derived magnetic flux change rate $\dot{\varphi}$ is compared to the observed nonthermal HXR emission. We found good temporal correlations in all events, i.e., HXR-peaks were clearly reflected in the magnetic flux change-rate profiles, as it is expected from the standard model. However, taking a closer look at each individual event, it is obvious that the two weaker HXR peaks in Figure 3b, or the two distinct peaks in Figure 3d are not resolved in the $\dot{\varphi}$-profiles. Also the relative height of the nonthermal emission-peaks is not always reproduced in the $\dot{\varphi}$-profiles (cf. Figure 3e)
Figure 3: a): GOES 12 1 – 8 Å soft X-ray (SXR) profile (right y-axis), cumulated positive and negative reconnection flux ($\varphi_+ + \varphi_-$), and cumulated total magnetic reconnection flux ($\varphi_{\text{tot}}$) plus error estimate for the 2003 Oct 28 X17.2 flare. For the sake of clarity we plot $2\varphi_{\text{tot}} = \varphi_+ + \varphi_-$. The error estimates were obtained using an upper and lower intensity threshold in the detection of the newly brightened area. Fluxes are given in units of $10^{21}$ Mx, b) – f): Temporal comparison of derived magnetic flux change rate and nonthermal emission for the five analysed events. Gray vertical bars in (e) and (f) mark time delays of RHESSI peaks compared to $\varphi$-peaks. The amount of delay is given in seconds on the left of each bar. Left y-axis: magnetic flux change rate in units of $10^{18}$ Mx/s, right y-axis: nonthermal emission count rate.

and 3f). In addition, in these two events the RHESSI peaks are delayed by $\sim 1$ min, indicated by the gray vertical bars, which highlight the time lag between the corresponding peak values. The numbers on the left of each bar give the time delay of the RHESSI peaks in seconds. The travel time of a reconnected field line from the diffusion region to the lower edge of the current sheet, or quasi-perpendicular regime of the lower termination shock, respectively, might explain this delay (Miklenic et al., 2007; Warmuth et al., 2008).

Table II lists the derived cumulated reconnection fluxes and flux ratios. Total fluxes ranged between $1.8 \times 10^{21}$ Mx for the weakest event and
15.5 × 10^{21} \text{ Mx} for the most energetic one. As predicted by the standard flare model, the cumulated positive and negative fluxes that we found were roughly balanced, with flux ratios ranging between 0.64 and 1.35. According to Qiu and Yurchyshyn (2005) flux ratios between 0.5 and 2 can be regarded as a good flux balance, given the numerous uncertainties involved in the measurements.

Table II: Cumulated reconnection fluxes and ratio of positive vs. negative flux at the end of the analysed time interval. Fluxes are given in units of 10^{21} \text{ Mx}. Fluxes in the flare on 2003 November 18, may be larger, since it was not possible to analyse the event up to the end of the impulsive phase due to gaps in the TRACE data after ∼ 08:24 UT. Error estimates in \( \varphi_{\text{tot}} \) are obtained from the lowest and highest of the appropriate intensity thresholds.

<table>
<thead>
<tr>
<th>Date</th>
<th>GOES class</th>
<th>( \varphi_{+} )</th>
<th>( \varphi_{-} )</th>
<th>( \varphi_{\text{tot}} )</th>
<th>( \frac{\varphi_{+}}{\varphi_{-}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 May 19</td>
<td>B9.5</td>
<td>1.4</td>
<td>-2.2</td>
<td>1.8 ±0.2</td>
<td>0.64</td>
</tr>
<tr>
<td>2006 Jul 06</td>
<td>M2.5</td>
<td>2.7</td>
<td>-2.5</td>
<td>2.6 ±0.4</td>
<td>1.06</td>
</tr>
<tr>
<td>2003 Nov 18</td>
<td>M3.9</td>
<td>&gt; 2.2</td>
<td>&gt; -2.4</td>
<td>&gt; 2.3 ±0.2</td>
<td>0.91</td>
</tr>
<tr>
<td>2005 Jan 15</td>
<td>X2.6</td>
<td>5.2</td>
<td>-3.9</td>
<td>4.5 ±0.4</td>
<td>1.35</td>
</tr>
<tr>
<td>2003 Oct 28</td>
<td>X17.2</td>
<td>15.6</td>
<td>-15.3</td>
<td>15.5 ±0.8</td>
<td>1.02</td>
</tr>
</tbody>
</table>

We also found a significant correlation between the total reconnection flux and the GOES importance of the events, a finding that is consistent with the flare model: The more magnetic flux is reconnected in a flare, the more energy is released into fast particles and can subsequently be deposited in the chromosphere. This energy heats the chromospheric plasma, which then evaporates, fills the flare loops and causes them to emit soft X-ray radiation, measured by the GOES satellites. The peak value of this radiation allocates the event in the GOES importance scheme. In addition, it turned out that flares with more reconnection flux were associated with faster CMEs. This correlation, which was also reported by Qiu and Yurchyshyn (2005), can be explained by a feedback-relationship between the CME kinematics and the reconnection process in the flare (Vršnak et al., 2005; Maričić et al., 2007; Temmer et al., 2008). The CME expansion determines the geometry of the system as well as the flows behind the flux-rope – both of which affect the reconnection process in the flare (Vršnak and Skender, 2005) – and the
reconnection in the flare additionally drives the CME by enhancing and prolonging the flux-rope acceleration (Vršnak, 1990).

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