OBSERVATIONAL CHARACTERISTICS OF MAGNETIC RECONNECTION IN A TWO-RIBBON FLARE

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Abstract. A well-observed GOES M3.9 two-ribbon flare was analysed in order to derive the local reconnection rate (coronal electric field) and the global reconnection rate (magnetic flux change rate), as well as the energy release rate (Poynting flux) in a two-ribbon flare from chromospheric/photospheric observations, using TRACE 1600 Å, Kanzelhöhe Hα, SOHO/MDI, and RHESSI hard X-ray (HXR) data. We found good temporal correlations between the derived time profiles and observed HXR flux. Furthermore, it was confirmed that equal shares of positive and negative magnetic flux participated in the reconnection process. The findings indicate that the 2D reconnection model is applicable to the analysed flare.

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

1. Introduction

Magnetic reconnection is now generally accepted as the mechanism of energy release in solar flares, but we do not know how the magnetic excess energy, which is stored in a sheared or twisted field configuration, is converted to plasma energy on a time scale of minutes. The reconnection rate is one of the most important quantities in reconnection physics, but at the present time there is no established theory of the physics that determines this rate. Until now only a few observations of a plasma inflow into the reconnection region have been made (e.g., Yokoyama et al., 2001; Lin et al., 2005; Narukage and Shibata, 2006), however, the reconnection region itself is far too small to be observed directly. Therefore, indirect methods are needed to determine the reconnection rate from observations. In this context we can exploit the observed Hα/UV flare ribbon expansion away
from the magnetic inversion line, which is the chromospheric signature of the progressive magnetic reconnection in the corona in which field lines are reconnected at successively higher altitudes. In the following, the relations that were used in this study to connect the observed flare characteristics with the reconnection physics are listed (for further discussion see Miklenic et al., 2007).

(1) Coronal electric field $E = v B$ (local reconnection rate; Forbes and Priest, 1984; Forbes and Lin, 2000), where $v$ is the apparent chromospheric ribbon velocity, and $B$ is the normal component of the photospheric magnetic field strength at the ribbon front. $E$ describes the rate at which magnetic field lines are carried into the reconnection site, then break and reconnect.

(2) Poynting flux $S \propto v B^2 / \mu$, where $\mu$ is the magnetic permeability (Asai et al., 2004; Isobe et al., 2002). $S$ is proportional to the energy release rate in a solar flare.

(3) Magnetic flux change rate $\dot{\varphi}$ (global reconnection rate; Forbes and Priest, 1984; Forbes and Lin, 2000)

$$\dot{\varphi} = \frac{\partial}{\partial t} \int B_n \, da,$$

where $B_n$ is the photospheric magnetic field strength component perpendicular to the solar surface in the newly brightened area $da$ that is swept by the flare ribbons. $\dot{\varphi}$ describes the rate at which the net open magnetic flux is converted to closed flux. Equation (1) has to be applied separately to both polarity domains, which gives $\varphi_-$ and $\varphi_+$, and the mean of both domains gives $\dot{\varphi}$. Afterwards, the ratio $R = |\varphi_-| / \varphi_+$ of positive and negative magnetic flux that participates in the reconnection process can be calculated ($\varphi_+ = \int \dot{\varphi}_+ \, dt$ and $\varphi_- = \int \dot{\varphi}_- \, dt$; Qiu and Yurchyshyn, 2005).

The first aim of our study was to derive $E$, $S$, and $\dot{\varphi}$ from chromospheric and photospheric observations. It is expected that peaks in the temporal evolution of the derived profiles and peaks in the observed HXR flux, which can be used as a proxy for reconnection and energy release rates (e.g., Hudson, 1991), should occur simultaneously. Secondly, we wanted to verify whether equal shares of positive and negative magnetic flux participated in the reconnection process, i.e., $R$ is expected to be 1.
2. Data, observations and analysis

We analysed a comparatively simple two-ribbon flare (GOES-class M3.9, Hα importance 2N, position S02°, E37°) in the NOAA Active Region 501, which occurred on November 18, 2003. The required observables (ribbon velocity, newly brightened area, and magnetic field strength component normal to the solar surface at the ribbon front location and within the newly brightened area, respectively) were determined using the following data sets: (1) a full-disc Hα image time series (pixel size 2.2″, cadence ~ 11 s) provided by the Kanzelhöhe Solar Observatory (KSO), Austria; (2) a TRACE 1600 Å image sequence (pixel size 0.5″, cadence ~ 23 s) derived from the Transition Region and Coronal Explorer (TRACE); (3) a full-disc magnetogram before flare onset (pixel size ~ 2.0″) provided by the MDI/SOI instrument on board the Solar and Heliospheric Observatory (SOHO).

The following data sets were used as proxies for the reconnection and energy release rates: (1) a full-disc 20 – 60 keV HXR intensity time profile derived from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI); (2) a RHESSI 20 – 60 keV HXR image time series (CLEAN algorithm, front detector segments 3 to 8, natural weighting, spatial resolution ~ 8″, image integration times 30 s). The images were used: (a) to localize the sites where the bulk of the energy was deposited by fast electrons and then track the flare ribbons along paths that crossed these sites; (b) to construct individual imaging light curves in order to reconstruct the temporal evolution of the emission in particular subareas of the flaring region.

RHESSI observed 4 main HXR bursts in the course of the impulsive phase (see bottom rows of Figures 2 and 3), designated as bursts A, B, C, and D. In Figure 1 the HXR burst contours, along with the corresponding ribbon-tracking paths (A, BN, BS, CN, CS, and D), are superimposed on a TRACE image, which was taken during the rising phase of a previous flare event (M3.2, maximum at 07:52 UT).

* Determination of v and B:* A threshold technique was used to follow the expansion of the ribbon fronts (for further details see Miklenic et al., 2007). The ribbon front distance from the inversion line was measured, and the magnetic field strength at the ribbon-front location was registered and scaled (see Berger and Lites, 2003). In a next step, spline-smoothing was applied to the magnetic field and distance values in order to smooth out fluctuations due to measurement uncertainties. Finally, the ribbon velocity
Figure 1: HXR burst contours (solid) and ribbon-tracking paths (dotted) superimposed on a TRACE 1600 Å image. Thick-black: burst A, path A; thin-white: burst B, paths BN and BS (N stands for north, S for south of the inversion line); thin-black: burst C, paths CN and CS; and thick-white: burst D, path D. Gray line with filled dots at ends: magnetic inversion line. FOV: 120" x 190"
was calculated by taking the time derivative of the spline-smoothed distance profile.

*Newly brightened area:* To eliminate bright remnants from the previous flare event, the first TRACE image of the analysed time range was subtracted from each element of the image time series, and then, the newly brightened area in an image compared to the preceding images was determined by applying an intensity threshold to the difference-image time series. After detecting the newly brightened pixels in an image, the magnetic field strength values at these pixel locations were registered and summed up to give \( \dot{\phi}_+(t) \), \( \dot{\phi}_-(t) \), and the mean of both \( \dot{\phi}(t) \). Afterwards, the converted magnetic flux for each magnetic polarity domain was determined by taking the time integrals of \( \dot{\phi}_+ \) and \( \dot{\phi}_- \) to calculate the flux ratio \( R \).

3. Results

In Figures 2 and 3, the results for paths A, B, and C and for D, respectively, are presented. The grey vertical bars act as a visual accentuation of the peaks in the full-disc HXR 20–60 keV time profile that is presented in row 7 of Figures 2 and 3. For example, the dark-grey bar in the left column of Figure 2, designated as A, means that the derived time profiles that are presented in this column, were obtained by tracking the northern flare ribbon across path A, which crossed the location of HXR burst A in its centre, whereas the other bars highlight HXR bursts B, C, and D, which were not directly crossed by path A. However, since the locations of the HXR bursts were very close to one another, a particular ribbon tracking path could cross more than one HXR burst site. In these cases, however, it did not cross other burst sites at their centre, where the bulk of the energy is deposited, but instead traversed their periphery; e.g., ribbon-tracking path A also crossed the edge of HXR burst C, as well as the elongated region of HXR burst B (see Figure 1).

Figures 2 and 3 show that in 5 out of 6 tracking paths, the \( E \) and \( S \) profiles exhibit peaks that are roughly simultaneous with the particular HXR burst. Only the peak that appeared by tracking the southern ribbon along path CS was not closely associated with HXR burst C, but arose delayed by about \( 2-3 \) min. Despite this exception, we find that by tracking the flare ribbons along paths that cross the central region of a particular HXR burst site (main energy deposition site), these bursts can be repro-
Figure 2: Ribbon tracking results for paths A, BN, and BS. Dark-grey bars highlight the HXR burst that was directly crossed by the corresponding tracking path. Light-grey bars mark the other three HXR bursts. Row 1: Temporal evolution of the ribbon-front distance from the locally defined inversion line. Solid line: spline fit. Row 2: Apparent ribbon velocity. Row 3: Diamonds: absolute value of the MDI photospheric line-of-sight magnetic field strength at the ribbon front. Solid lines: spline fit. Row 4: Electric field or local reconnection rate. Row 5: Poynting flux or energy release rate, respectively. Row 6: 20 – 60 keV RHESSI HXR subregion light curves derived from the area where the HXR burst that was directly crossed by the associated ribbon tracking path was situated. Row 7: 20 – 60 keV RHESSI full-disc HXR time profile.
Figure 3: Same as in Figure 2 but for paths CN, CS, and D. Note that in path D (analysed in Hα) the diamonds are more noisy than in paths CN and CS (analysed in TRACE).

Moreover, other HXR bursts, which are not centrally crossed but peripherally traversed by a particular ribbon-tracking path, also appeared in the E and S profiles, most prominently peak C in path A and peak A in path BN (left and middle columns of Figure 2, respectively), peak B in path CN and peak C in path D, (left and right columns of Figure 3, respectively). Again, peak C in the southern ribbon is an exception: By tracking this ribbon
Figure 4: Rows 1 and 2: Newly brightened area and magnetic-flux change rate in the positive (left panels) and negative (middle panels) polarity domains. Right panels: Mean of both polarity domains. The three peaks in the magnetic flux change rate appear around the HXR burst time intervals (grey vertical bars). Row 3: RHESSI 20–60 keV HXR full-disc time profile. In order to smooth out fluctuations due to measurement uncertainties, all profiles were slightly smoothed with a 3-point boxcar average.

along path BS, a second peak arises additionally to peak B (right column of Figure 2), but it is not closely associated with any of the HXR bursts. It is closest in time to burst C, but about 2–3 min delayed, similar to peak C (compare Figure 3, middle column).

A comparison of the $E$ peak values, which ranged from 2.7 to 11.8 V cm$^{-1}$, and the $S$ peak values with those of the HXR full-disc time profile shows that there is no clear correlation; e.g., peak A is distinctly highest in the HXR time profile but not highest in $E$ and $S$, whereas peak B is lowest in HXR, but BN is highest in both $E$ and $S$. The correlation gets better when comparing the $E$ and $S$ peak values with those of the HXR subregion imaging light curves, e.g., peaks CS and D show up much more clearly in those HXR subregion profiles that were derived from the HXR burst CS and D areas, as they do in the full-disc profile. However, we note that also in this case the correlation is still not unique; i.e., higher HXR subregion peak values are not necessarily associated with higher peaks in $E$ or $S$.

Rows 1 and 2 of Figure 4 show the temporal evolution of the newly brightened area (NBA) and the magnetic flux change rate $\dot{\varphi}$ for the positive and negative magnetic polarity domains (left and middle panels), as well
as the mean of both domains (right panels). The magnetic-flux change rate profiles reveal the decisive role of the magnetic field in the determination of the global reconnection rate. The three peaks that were observed in the HXR flux were reproduced much more clearly in the magnetic flux change rate than in the NBA. However, we note that in each case the peaks in the magnetic flux change rate occurred earlier by \( \sim 1 \, \text{min} \) than the associated HXR peaks.

Finally, the ratio \( R \) of converted positive \( \left( \varphi_+ = 1.33 \times 10^{21} \, \text{Mx} \right) \) vs. negative flux \( \left( \varphi_- = -1.39 \times 10^{21} \, \text{Mx} \right) \) was determined. \( R \) added up to 1.05. In the determination of \( R \), the intensity threshold value that was used to detect NBA proved not to be a crucial factor. Deviations from the theoretically expected flux ratio never exceeded 10\% with any of the tested thresholds.

4. Summary and conclusions

The peaks of the derived local reconnection rate \( E \) and energy release rate (Poynting flux \( S \)) correspond well to the peaks of the observed HXR flux (except for peak CS). Both \( v \) and \( B \) are essential in determining these rates, since both quantities act together. The peak values add up to \( E \approx 3 - 12 \, \text{V cm}^{-1} \). We conclude that the 2D reconnection model is applicable to the analysed flare, since in most cases the observed HXR peaks could be related to a corresponding peak in the \( E \) and \( S \) profiles. We note that although we found a good time correspondence between the HXR peaks and the reconnection parameters, the amplitude of the HXR peaks itself is not directly correlated with the peak value of the reconnection rate or the Poynting flux.

We find a good correlation between the magnetic flux change rate \( \dot{\varphi} \) (global reconnection rate) and observed HXR flux. However, we emphasize that the peaks in the \( \dot{\varphi} \)-profile occur earlier than the associated HXR peaks by \( \sim 1 \, \text{min} \). Based on the one event studied, it is not possible to draw conclusions on the statistical significance of this delay. However, since this delay could be related to the travel time of the reconnected field line from the diffusion region to the lower edge of the current sheet (for further discussion see Miklenic et al., 2007), we plan to extend this kind of study to a larger sample of flares.

The total magnetic flux that participates in the reconnection process is \( \approx 10^{21} \, \text{Mx} \) and is equal for positive and negative magnetic polarity domains.
within 5−10%. Bearing the measurement errors in mind, it can be concluded that the positive and negative fluxes involved are the same. This implies that basically all reconnected field lines were rooted in the flaring region.

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