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Investigation of magnetic free energy dynamics in the M1.2-class complex solar flare of March 15, 2015 using the 135-second HMI vector magnetograms

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Abstract. We investigate magnetic free energy (MFE) dynamics in the M1.2 solar flare occurred on March 15, 2015, 22:45 UT. We use the nonlinear force-free field (NLFFF) model of the coronal magnetic field on the basis of 135-second HMI vector magnetograms (standard magnetograms have a temporal resolution of 720 s) from the Heliosesmic and Magnetic Imager (HMI). Since we consider a rather long event (about 100 minutes) with several episodes of energy release of different temporal dynamics (pulsed or more gradual), we can find features of the MFE dynamics relative to the flare energy release stages using 135-second vector magnetograms. It is shown that the main MFE dissipation (approximately 30 % of the initial level) occurred during the two first subflare bursts seen in microwave hard X-ray ranges. These two bursts developed at low (less than 5 Mm) magnetic structures extremely elongated along the magnetic field polarity inversion line (PIL), while the other long-lasting bursts without appreciable MFE dissipation occurred in a growing flare arcade of magnetic loops. The obtained results are in favor of the fact that most of the MFE is localized in magnetic structures with a strong electric current at the PIL. It is possible that local monitoring of the preflare state around the PIL based on magnetic extrapolations with high temporal and spatial resolution will allow further improvement of methods for predicting solar flares. The dynamics of relative helicity are also studied in relation to the dynamics of the eruptions, and we found that the first impulsive subflares were accompanied by the most significant drop in helicity.

Keywords: Sun: solar flares, magnetic fields; electric currents; eruption; hard X-ray emission

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1 Introduction

Magnetic field energy in the solar corona is believed to be the main reservoir for solar flares. The most variable part of the magnetic energy, known as “magnetic free eneregy” (MFE), can be estimated as a difference between energies of the non-linear force-free and potential magnetic fields over a parental active region. There are a lot of works showing significant changes of the MFE during the flares (e.g., Sun et al. 2012; Liu et al. 2023).

A solar flare is highly dynamic non-staionary process on time scales from subsecond time intervals to hours. The standard HMI (Scherrer et al. 2012) vector magnetograms onboard the Solar Dynamics Observatory have a 12-minute time cadence, which is insufficient to capture the features of magnetic field changes during the impulsive phases of flares. To study the dynamics of the magnetic fields and associated MFE we need special flares with long impulsive phase or with a few separated HXR bursts. A more realistic option for this study is to use the better time resolution of vector magnetograms.

Today 135-second HMI vector magnetograms are available and successfully used to study flare energy release (e.g., Sun et al. 2017; Sharykin et al. 2020). In this paper, we study the dynamics of the MFE using high-cadence HMI vector magnetograms for a specific flare consisting of several subflares with their own impulsive phases. The main aim is to determine the stage of the flare when most of the MFE disappears during the complex flare chosen for this study.

2 Analyzed dynamics of the solar flare and MFE

This work continues our previous works (Sharykin et al. 2018, 2020, we do not discuss their results here), which were devoted to the detailed quantitative multiwavelength analysis of electrodynamics, nonthermal electron dynamics and plasma heating in the system of highly sheared magnetic loops interacting at the PIL during the confined (non-eruptive) M1.2 solar flare SOL2015-03-15T22:43.

Figure 1 shows flare time profiles (a, b) presenting multistage nature (three subflares) of the entire flare event, and position of the flare emission sources (in different wave ranges) relative to the magnetic field and electric current structure in the photosphere (d–f); 135-second HMI vector magnetograms). One can see that the different flare emission sources were located very close to the PIL. They partially coincided with areas of increased vertical electric currents (e) and horizontal gradient of the vertical magnetic field (f), which is a sign of a large local amount of the MFE in the corresponding areas.

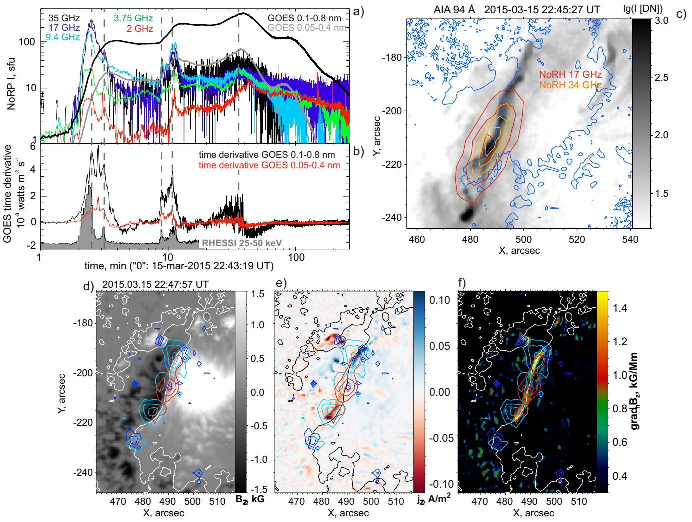

Fig. 1. Microwave time profiles (time is in log scale to show three subflares) at 5 frequencies from NoRP data are shown in panel (a) with overlayed GOES X-ray fluxes in two channels (thick grey and black curves). Panel (b) presents RHESSI 25-50 keV X-ray count rates compared with the time derivatives of GOES X-ray fluxes in 0.5–4 and 1–8 Å channels. The EUV 94 Å AIA image (background) is compared with the NoRH sources at 17 and 34 GHz (red and orange contours) in panel (c). RHESSI 6–12 and 25–50 keV X-ray sources in (d–f) are marked by red and cyan contours, respectively, and compared with: (d) B map, (e) j_z map, and (f) $\nabla_h(B_z)$ map. PIL is shown in panels (c–f) by blue, white, black and white colours, correspondingly.

Using nonlinear force-free model of the solar coronal magnetic field (NLFFF, approach of Rudenko & Myshyakov 2009) we calculated magnetic free energy with the 135-second temporal resolution and compared it with the GOES 1–8 Å lightcurve in Fig. 2(a). It is evident that the MFE experienced significant change during the first two subflares when we observe nonthermal emissions of the accelerated electrons around the PIL twisted magnetic structure. Th relative magnetic helicity (by Anfinogentov's method discussed in a review of Valori et al. 2016) also changed during an eruptive process associated with these two subflares (c–d). The dynamics of the eruption is shown by time-distance analysis performed for two observational slits crossing the bright PIL UV structure (b). Large helicity drops are usually interpreted as evacuation of helical magnetic structures due to the eruption.

3 Summary and concluding remarks

We found that the main dissipation of the MFE occurred during the first episodes of flare energy release associated with low-lying high-shear magnetic structures in

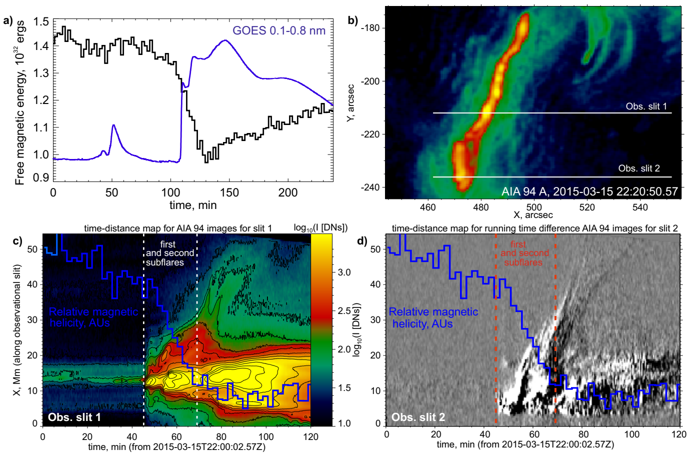

Fig. 2. The dynamics of the MFE and relative helicity in the flare region (roughly corresponding to the field of view in Fig. 1(d) and the X-ray flux of GOES 1–8 Å) is shown in panel (a). Panel (b) presents the AIA 94 Å flare image and positions of the horizontal observational slits, which were chosen to make time-distance diagram in (c) (94 Å) and (d) (running time differences of 94 Å images). The dynamics of the relative helicity is shown by the blue histogram-like curve in (c–d).

the PIL. These energy release episodes were characterized by the presence of the accelerated electrons and impulsive plasma motions (eruption). In other words, the release of MFE did not develop gradually throughout the flare event and throughout the entire volume of the AR, but was rather impulsive and concentrated in the vicinity of the PIL. Our findings suggest that processes in the PIL are critical for flaring energy releases and should be monitored to predict flares.

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