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Magnetic structure of solar flare regions producing hard X-ray pulsations

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ABSTRACT

We present analysis of the magnetic field in seven solar flare regions accompanied by the pulsations of hard X-ray (HXR) emission. These flares were studied by Kuznetsov et al. (2016) (Paper I), and chosen here because of the availability of the vector magnetograms for their parent active regions (ARs) obtained with the SDO/HMI data. In Paper I, based on the observations only, it was suggested that a magnetic flux rope (MFR) might play an important role in the process of generation of the HXR pulsations. The goal of the present paper is to test this hypothesis by using the extrapolation of magnetic field with the non-linear force-free field (NLFFF) method. Having done this, we found that before each flare indeed there was an MFR elongated along and above a magnetic polarity inversion line (MPIL) on the photosphere. In two flare regions the sources of the HXR pulsations were located at the footpoints of different magnetic field lines wrapping around the central axis, and constituting an MFR by themselves. In five other flares the parent field lines of the HXR pulsations were not a part of an MFR, but surrounded it in the form of an arcade of magnetic loops. These results show that, at least in the analyzed cases, the "single flare loop" models do not satisfy the observations and magnetic field modeling, while are consistent with the concept that the HXR pulsations are a consequence of successive episodes of energy release and electron acceleration in different magnetic flux tubes (loops) of a complex AR. An MFR could generate HXR pulsations by triggering episodes of magnetic reconnection in different loops in the course of its non-uniform evolution along an MPIL. However, since three events studied here were confined flares, actual eruptions may not be required to trigger sequential particle acceleration episodes in the magnetic systems containing an MFR.

1. Introduction

The processes of energy release in solar flares, especially in the impulsive phase, usually are intermittent and non-stationary. This is well evidenced by the presence of multiple peaks (bursts or pulsations) of different amplitudes and duration in the light curves of flare electromagnetic radiation in a broad range of wavelengths: from radio waves to hard X-rays (HXRs), and sometimes even up to gamma-rays (Dennis, 1988; Aschwanden, 2002; McAteer et al., 2007; Kupriyanova et al., 2010; Nakariakov et al., 2010a; Simões et al., 2015). Stellar flares often show similar properties (*e.g.*, see the discussion of "complex" flares in Davenport et al. (2014)).

Despite many years of studying of flare quasi-periodic pulsations (QPP), there is no full understanding of the underlying physical mechanisms yet (Nakariakov et al., 2010b, 2016; Van Doorsselaere et al., 2016; McLaughlin et al., 2018). In general, it is believed that the energy in solar flares is released by means of magnetic reconnection (Priest and Forbes, 2002; Shibata and Magara, 2011). Most probably, flare pulsations are also associated someway to magnetic reconnection. There are two main groups of possible models of long-period pulsations ($P \gtrsim 1$ s), which are the main subject of the present work: (1) based on MHD waves and oscillations, including the wave-driven reconnection; (2)

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based on the so-called "load/unload" mechanisms, *i.e.* spontaneous repetitive magnetic reconnection (Nakariakov and Melnikov, 2009).

The first group of models is more popular because of the direct link of the observed quasi-periodicity with the periodicity of the wave processes, ubiquity of MHD waves and oscillations in the solar atmosphere, and their potential ability to influence all main aspects of the generation of electromagnetic emission in flare regions. In particular, MHD oscillations and waves can be a quasi-periodic trigger/modulator of magnetic reconnection and can influence dynamics of non-thermal particles and plasma in flare loops. Moreover, the MHD oscillations based models are attractive since they could help to diagnose physical parameters of the flaring site (such as plasma density and magnetic field), if there is confidence in the correct choice of the model used (*e.g.*, Liu and Ofman, 2014; Nakariakov et al., 2016).

The "load/unload" mechanisms are mainly based on the possibility of the repetitive regimes of energy release in the flare sites through the "bursty" magnetic reconnection (Kliem et al., 2000), associated with successive generation of multiple magnetic islands and their subsequent coalescence in an extended quasi-vertical macroscopic current sheet generated in course of a flare development (Shibata and Tanuma, 2001; Drake et al., 2006a; Karlický et al., 2010). There are also several other models belonging to this group and based on different ideas (see, Nakariakov and Melnikov (2009); Nakariakov et al. (2016); Van Doorsselaere et al. (2016), as reviews on this issue).

Possibly, different mechanisms can operate in different flares, due to the wide variety of the physical processes included in the flare physics, or different mechanisms can accompany one another in the same flare region. Spatially-resolved observations of sources of the flare pulsations are important for understanding their mechanisms, and for reliable identification of the models used for their interpretation (*e.g.*, Grigis and Benz, 2005; Zimovets and Struminsky, 2009; Inglis and Dennis, 2012; Zimovets et al., 2013; Ning, 2014; Li and Zhang, 2015; Dennis et al., 2017).

Recently, based on the systematic analysis of spatially-resolved observations made by RHESSI (Lin et al., 2002) it was shown that footpoint (chromospheric) sources of HXR pulsations (with time differences between successive HXR peaks within the range $P \approx 8 - 270$ s) in all (29) flares studied are not stationary (anchored) in space — they demonstrate apparent displacement in the parent active regions (ARs) from pulsation to pulsation (Kuznetsov et al., 2016, hereafter referred to as Paper I). Based on these observations, it was concluded that the mechanism of flare HXR pulsations (at least with the characteristic time differences between the successive peaks P in the considered range) is related to successive triggering of the flare energy release in different magnetic loops of the parent ARs. The triggering mechanism was not directly identified in Paper I. Based on the fact that more than 85% of the analyzed flares were accompanied by coronal mass ejections (CMEs), *i.e.* were eruptive events, it was assumed that a non-uniformly erupting magnetic flux rope (MFR) could act as a trigger of the flare energy release. Successive interaction of different parts of the MFR with certain, spatially separated loops of the parent active region could initiate episodes of spatially-localized magnetic reconnection and acceleration of electrons, and, as a result, could lead to apparent motion of the HXR sources and to a series of the HXR pulsations. However, in Paper I the presence of an MFR in the parent ARs before the flares was just hypothesized, but it was not confirmed either by observations, or by extrapolation of the magnetic field.

The goal of the present paper is to investigate the geometry (structure) of the magnetic field in the flare regions studied in Paper I, based on the reconstruction (extrapolation) of the magnetic field in the non-linear force-free field (NLFFF) approximation (Wiegelmann and Sakurai, 2012). The first task is to verify whether MFRs were indeed presented in those ARs prior to the flare onset or not. It is known that an MFR can be present in an AR before its eruption and the subsequent flare, or an MFR can be formed from a sheared arcade due to the magnetic reconnection (Priest and Forbes, 2002; Schmieder et al., 2013; Cheng et al., 2017; Guo et al., 2017). We aim to check which of these two possibilities were realized in the ARs studied. To the best of our knowledge, such an analysis has not been performed systematically for flares with HXR pulsations. The second task is to analyze the spatial relation of MFRs (if present) and the parent magnetic field lines of the sources of the HXR pulsations. This will help to corroborate the aforementioned hypothesis on the important role of MFRs in generation of the flare HXR pulsations. Also, this will help to demonstrate explicitly that different HXR pulsations are emitted from different parts of an MFR rather than from a "single" oscillating loop as it is often assumed in some models of flare pulsations (*e.g.*, Zaitsev and Stepanov, 2008; Kupriyanova et al., 2010; Chen et al., 2016).

The paper is organized as follows. Selection and analysis (magnetic field extrapolation, visualization of the sources of HXR pulsations and magnetic field lines) of the flare regions is described in Section 2. The main results of the analysis are summarized and discussed in Section 3. Conclusions are given in Section 4.

2. Data analysis

2.1. Selection of events

For the analysis we took the last seven solar flares from the Paper I catalog (No 23–29): SOL2011-02-15, SOL2011-06-07, SOL2011-09-06, SOL2014-04-18, SOL2014-10-22, SOL2014-10-24, and SOL2014-11-09 (see Table 1). This choice is determined by the fact that the parent ARs of these events were observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al., 2012; Schou et al., 2012) instrument onboard the Solar Dynamics Observatory (SDO), and the vector magnetograms are available for these ARs, which is crucial for our study. We emphasize that this choice is determined only by the availability of these data, and by the events selection criteria in Paper I. No other additional (subjective) criteria are used. The light curves of solar HXR emission detected by RHESSI during these flares are shown in Fig. 1.

2.2. Extrapolation of magnetic field

For each of seven selected ARs we determined the pre-flare coronal magnetic field topology by adopting the non-linear force-free field (NLFFF) method developed by (Wheatland et al., 2000), and extended by (Wiegelmann, 2004) and (Wiegelmann and Inhester, 2010). A preprocessing procedure (Wiegelmann et al., 2006) was employed to remove most of the net force and torque from the data, so that the boundary can be more consistent with the force-free assumption. The NLFFF extrapolation used in our work adopts the same free parameters as Case-E in (Wiegelmann et al., 2012). As the boundary conditions, we used the Space-weather HMI Active Region Patches (SHARPs) data product described by Bobra et al. (2014). This data has a time step of 12 min, similar to the standard full-disk SDO/HMI vector magnetograms. We chose the data for the instants of time before the flares, within $2 - 31$ minutes prior to the flare onset times according to the

Table 1
The metrics of the magnetic fields reconstructed in the NLFF approximation for the investigated flares.

Flare id.	Flare no.	GOES class	L_1	L_2	($\mathbf{j}$, $\mathbf{B}$)-angle, deg	E_{nlff}/E_{pot}
SOL2011-02-15	23	X2.2	0.86	0.31	7.20	1.31
SOL2011-06-07	24	M2.5	1.65	1.15	6.22	1.36
SOL2011-09-06	25	X2.1	1.43	0.86	9.62	1.22
SOL2014-04-18	26	M7.3	1.75	1.15	7.29	1.39
SOL2014-10-22	27	X1.6	0.46	0.25	7.94	1.17
SOL2014-10-24	28	X3.1	0.42	0.23	7.38	1.20
SOL2014-11-09	29	M2.3	1.09	0.72	9.56	1.36