Flare Energy Release at the Magnetic Field Polarity Inversion Line during the M1.2 Solar Flare of 2015 March 15. I. Onset of Plasma Heating and Electron Acceleration

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Abstract

We present the study of the SOL2015-03-15 M1.2 flare, revealing acceleration of electrons and plasma heating in the sheared twisted magnetic structure at the polarity inversion line (PIL). The purpose is to make an analysis of nonthermal electron dynamics and plasma heating in the highly stressed magnetic loops interacting at the PIL by using X-ray, microwave, ultraviolet, and optical observations. It is found that the most probable scenario for the energy release at the PIL is the tether-cutting magnetic reconnection between the low-lying (3 Mm above the photosphere) magnetic loops within a twisted magnetic flux rope. Energetic electrons with the hardest spectrum appeared at the onset of plasma heating up to the superhot temperature of 40 MK. These electrons are localized in a thin magnetic channel with a width of around 0.5 Mm and a high average magnetic field of about 1200 G. The plasma beta in the superhot region is less than 0.01. The estimated density of accelerated electrons is about \(10^9\) cm\(^{-3}\), which is much less than the superhot plasma density. The energy density flux of nonthermal electrons is estimated up to \(3 \times 10^{12}\) erg cm\(^{-2}\) s\(^{-1}\), which is much higher than in the currently available radiative hydrodynamic models. These results revealed that one needs to develop new self-consistent flare models reproducing 3D magnetic reconnection at the PIL with strong magnetic field, spatial filamentation of energy release, formation of high-energy density populations of nonthermal electrons, and the appearance of the superhot plasma.

Key words: Sun: chromosphere – Sun: corona – Sun: flares – Sun: magnetic fields – Sun: particle emission – Sun: photosphere

1. Introduction

In the standard model of an eruptive two-ribbon solar flare (e.g., Hirayama 1974; Magara et al. 1996; Tsuneta 1997; Shibata & Magara 2011), nonthermal electrons are produced owing to the magnetic reconnection in the cusp below an erupting plasmoid, causing a coronal mass ejection (CME). Hard X-ray (HXR) emission is generated by nonthermal electrons precipitated into the chromosphere in two sources located in opposite footpoints of magnetic loops under an erupting plasmoid. Soft X-ray (SXR) emission is generated in flare magnetic loops filled with hot plasma. In the case of disk observations the magnetic field polarity inversion line (PIL) intersects the SXR source and is located between two HXR sources. The specific flares were found with RH ESSI (Lin et al. 2002) observations, where HXR emission from coronal parts of the flare loop dominates HXR emission from the loop footpoints. In such events the loop-shaped X-ray sources were observed (e.g., Battaglia et al. 2005; Veronig et al. 2005; Jiang et al. 2006; Guo et al. 2012). Nobeyama Radioheliograph (NORH; Nakajima et al. 1995) observations also often show loop structures in the microwave range (e.g., Kupriyanova et al. 2010; Morgachev et al. 2014), although there is an opinion that the real structure can be more complicated (e.g., Warren et al. 2002; Zimovets et al. 2013; Grechnev et al. 2017).

A classical 2D model of magnetic reconnection assumes the interaction of the opposite-polarity magnetic flux tubes at a null point. At the reconnection site, plasma is heated and thermal electrons are accelerated, forming a nonthermal power-law energetic spectrum. Loop-like geometry of X-ray and microwave sources can be easily explained within the standard flare model; however, alternative interpretations are possible. Magnetic reconnection can occur in a magnetic configuration without null points as well (for a review, see, e.g., Priest & Forbes 2002). For example, twisted magnetic flux ropes (MFRs) elongated along the PIL can experience internal magnetic reconnection (Démoulin et al. 1996; Gordovskyy & Browning 2011; Pinto et al. 2016). In such a case, charged particles will be directly accelerated and injected into the reconnect flux tubes (Gordovskyy & Browning 2011, 2012; Gordovskyy et al. 2013, 2014).

Another scenario of 3D magnetic reconnection in the vicinity of the PIL is the tether-cutting magnetic reconnection (TCMR). For example, this model was discussed by Moore et al. (2001), where two crossed MFRs interact at the PIL-forming small-scale sheared arcade below the reconnection site. Large-scale erupting magnetic structure above the reconnection site can also be formed. Liu et al. (2013) demonstrated the possibility of the TCMR in a solar flare using multiwavelength observations and nonlinear force-free extrapolation of the magnetic field. The possibility of a CME triggering by a TCMR process was presented in the work of Aulanier et al. (2010), where numerical MHD modeling was performed.

Another way to trigger energy release at the PIL is to stimulate magnetic reconnection by a small-scale flux emergence at the PIL. Interaction of the upward-moving magnetic flux with the overlying magnetic field will lead to the current sheet formation with subsequent plasma heating and electron acceleration at the PIL. The numerical MHD simulations of a flare process in the frame of this scenario were demonstrated in

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the work of Kusano et al. (2012). There were also some flare observations confirming results of numerical modeling (e.g., Bamba et al. 2017a; Muhamad et al. 2017).

In the work of Sharykin et al. (2017b) flare energy release at the PIL was studied for an M1.2-class solar flare that occurred on 2014 June 12. The nonlinear-force-free field (NLFFF) modeling reveals TCMR-like interaction of two MFRs with oppositely directed magnetic field at the PIL. These observations indicate that the energy release in that flare could happen in the dense chromosphere plasma in the regions with strong electric currents near the PIL. Magnetic reconnection was possibly triggered by the interaction of the MFRs forming a current sheet elongated along the PIL. However, there was no strong HXR emission to study the population of accelerated electrons in that flare.

Magnetic reconnection at the PIL can be stimulated in the very initial phase of a flare. For example, there were a lot of observations (e.g., Severnyi 1958; Chifor et al. 2007; Zimovets et al. 2009; Bamba et al. 2017b; Wang et al. 2017) reporting preflare activity around the PIL in different ranges of the electromagnetic spectrum. After the initial phase, a flare can develop following the standard model. Such a scenario was discussed recently in the theoretical work of Priest & Longcope (2017). According to this work, a flare can start with or without a preexisting flux rope under a sheared arcade of magnetic loops along the PIL; the so-called zipper phase (elongation of flare ribbons along the PIL) is associated with a reconnecting twisted magnetic structure at the PIL. In particular, evidences of the zipper effect, indicating 3D magnetic reconnection along the PIL, were observed in many events (e.g., Bogachev et al. 2005; Grigis & Benz 2005; Liu et al. 2009, 2010; Qi 2009; Qi et al. 2010, 2017; Kuznetsov et al. 2016). The zipping-like reconnection can happen in both the eruptive and noneruptive flares (Zimovets et al. 2018).

Summing up, it is clear that energy release in the vicinity of the PIL is connected with 3D restructuring of the magnetic field. To our mind there were no detailed quantitative studies of nonthermal electrons in the low-lying magnetic structures elongated along the PIL. The majority of the works devoted to the study of nonthermal electrons considered simple magnetic loop-like geometry in the frame of the standard model to interpret multiwavelength observations of solar flares. Our special interest is to consider a case with the highly sheared low-lying magnetic loops interacting with each other in the vicinity of the PIL (i.e., a pronounced TCMR case). In this geometry a strong magnetic field component originates along the possible current sheet. The motivation to study the energy release in such a magnetic configuration is to understand the peculiarities of a population of nonthermal electrons that originated during 3D magnetic reconnection and how they are related to plasma heating.

From our point of view there was only one detailed quantitative study confirming localization of nonthermal electrons in the low-lying magnetic loops at the PIL. The work of Altyntsev et al. (2017) presents a detailed analysis of a solar flare revealing unusual reversal of microwave emission polarization at high frequencies between 17 and 35 GHz. The authors of that work used multiwavelength observations, including microwave data from the Nobeyama Solar Radio Observatory. The reported behavior of the polarization spectrum was explained by nonthermal electrons with a beam-like pitch-angle distribution localized very low in the dense corona and a magnetic field value of more than 500 G. Despite this important result, there was no detailed investigation of magnetic field topology or fine spatial structure of the flare energy release site in that paper.

The scope of the present work is to make a quantitative multiwavelength analysis of nonthermal electrons and plasma heating in the highly stressed magnetic loops interacting with each other in the close vicinity of the PIL. This aim assumes the solution of two main tasks. The first task is to estimate the density of electrons accelerated at the PIL and to compare it with density of the heated plasma. It helps to understand how many (in other words, what percentage) electrons were accelerated from the background thermal plasma confined in the magnetic structure near the PIL. To solve this task, we made detailed spectral analysis of both X-ray and microwave emissions of the flare. The RHESSI, Nobeyama Radio Polarimeter (NoRP), and NoRH data are used for this purpose. The second task is to investigate the topology of the magnetic field and its distribution at the PIL, where nonthermal electrons appear and plasma was heated. For this reason, we reconstructed the magnetic field in the NLFFF approximation near the PIL region using the photospheric vector magnetograms obtained with the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). We also analyzed optical and extreme-ultraviolet (EUV) images obtained with the Solar Optical Telescope (SOT; Tsuneta et al. 2008) on board Hinode (Kosugi et al. 2007) and the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO with high spatial resolution to determine the fine structure of the flare energy release site needed to identify the flare magnetic structure at the PIL and estimate its size. This helps us to compare the magnetic energy released in the flare site with the energy contents of accelerated electrons and heated plasma.

The paper is divided into four sections. Section 2 describes observations (time profiles and images of the flare region selected) made in different parts of the electromagnetic spectrum. Section 3 is devoted to the detailed analysis of X-ray spectra from the RHESSI observations. Flare energetics and estimations of plasma and nonthermal electrons densities are also summarized here. Analysis of magnetic field topology and microwave emission from the observations by the Nobeyama Solar Radio Observatory is described in Section 4. Discussion and conclusions are drawn in Section 5.

2. Observations

2.1. Event Selection

In this section we describe observations of the solar flare selected for the analysis. There were several criteria of the event selection:

1. Availability of the RHESSI HXR observations at least up to 50 keV with a sufficient count rate needed for spectroscopy and imaging analysis. X-ray emission sources have to be located close to the PIL in the regions of strong vertical electric currents determined from vector magnetograms. This allows us to find the events where nonthermal electrons were transported in the sheared twisted magnetic structures elongated along the PIL.

2. Availability of the NoRH and NoRP observations of the nonthermal microwave emission. Microwave emission sources also have to be located close to the PIL. Joint
HXR and microwave observations will allow us to make detailed quantitative analysis of nonthermal electrons parameters.

3. Initial flare EUV emission sources from AIA/SDO have to be located close to the PIL. AIA images in the 94 and 335 Å (the less sensitive) channels should not be saturated during the impulsive phase.

4. Flare location is in the central part of the solar disk ($\lesssim 500''$ from the center). Such a location is preferable for analysis of HMI vector magnetograms and to minimize the projection effects.

Using these criteria, we have found that a solar flare of GOES M1.2 class occurred on 2015 March 15, starting at 22:42 UT and peaking at 23:22 UT (according to the GOES data). The flare occurred in the NOAA active region 12297 with the heliographic coordinates S17W38. The flare time profile was composed from three successive subflares. Our study will be devoted to the first one, as it satisfies all criteria listed above and reveals the most intensive HXR and microwave emissions in the vicinity of the PIL, which allows us to investigate accelerated electrons and plasma heating at the PIL. Accordance of the selected flare to the aforementioned criteria will be illustrated in the subsequent subsections.

The available observational data from HMI/SDO allow us to make a detailed investigation of the magnetic field dynamics in the flare region of the selected event. However, it is beyond the scope of this work. The subsequent paper (Paper II) will describe magnetic data and electric currents in details. This work (Paper I) is mostly concentrated around X-ray and microwave emissions generated from the PIL region.

2.2. Flare X-Ray Emission Detected by RHESSI

Figure 1(a) shows temporal profiles of the RHESSI X-ray count rates in the 6–12 keV, 12–25 keV, 25–50 keV, and 50–100 keV energy bands. HXR peaked at around 22:45:46 UT, and the total duration of the impulsive phase (according to the 25–50 keV data) was about 100 s. A secondary softer HXR peak was around 22:46:27 UT. Time profiles of HXR emission are very similar to the microwave emission from NoRH and NoRP. One can see that the 12–25 keV time profile is similar to the count rate in the energy band of 25–50 keV. The nonthermal component in these energy bands is possibly stronger than the thermal one, or plasma heating and nonthermal electron precipitation to the dense solar atmosphere were simultaneous. However, one needs to make a spectral analysis of X-ray spectra (see Section 3) to make a proper investigation of heating and acceleration rates in the flare region.

RHESSI images were reconstructed with the CLEAN algorithm (Hurford et al. 2002) using detectors 1, 3, 5, 7, and 8. Detector 1 reveals sufficient count rate modulation to achieve spatial resolution around 2$''$–3$''$. The left panel in Figure 2 shows positions of the HXR 25–50 keV (at the level of 70% from the maximum brightness) contours relative to the PIL and vertical electric currents for the three different subsequent time intervals. The PIL and electric currents were calculated from the HMI vector magnetogram reprojected onto the heliographic grid. One can see that the projection of the HXR sources on the photosphere coincides with the regions of the strong vertical electric currents. We assume that the 25–50 keV HXR sources are in the chromosphere at the height below around 1–2 Mm. The projection effect is small for this flare. Thus, nonthermal electrons are probably localized in the twisted sheared magnetic structure near the PIL, if one assumes that the strong electric currents observed on the photosphere can ascend to the chromosphere and low corona.

Furthermore, the left panel of Figure 2 indicates that the correlation between the HXR emission sources and strong vertical currents is not equally strong on both HXR emission sites, with the northern emission source showing a more evident correlation with the strongest currents. Apparently, the magnetocurrent structure where the flare occurred and the electron acceleration/precipitation happened is not symmetric. This is quite natural for a real active region. Here we also need to note that the times and durations of data used, i.e., the HXR images from RHESSI and the vector magnetograms from HMI/SDO, are different. The time cadence of the HMI/SDO vector magnetograms is 720 s, which is more than the duration of the entire flare impulsive phase (see Figure 1). This could be the reason for the incomplete spatial correlation observed between the HXR sources and the vertical electric currents.

In Figures 3 and 4 the RHESSI contour maps are compared with the EUV images from AIA/SDO and Ca II images from SOT/Hinode, respectively (Sections 2.4 and 2.5). X-ray maps...
are plotted for two energy bands: 6–12 keV and 25–50 keV. The first energy range mostly corresponds to thermal emission and the second one to nonthermal emission. All X-ray emission sources were located very close to the PIL in the image plane. The SXR emission source in the beginning of the impulsive phase had a worm-like shape, elongated along the PIL. It seems that a hot plasma channel was formed. SXR maps in the subsequent two time intervals show the rather compact SXR source located between double HXR sources. In these cases we probably observe a highly sheared source located between double HXR sources. In Figures 4(a), (c), and (d)) loop-like magnetic structure. Detailed investigation of the spatial structure of the flare region will be made using observations in other ranges of the electromagnetic spectrum (see the next sections) and analysis of the magnetic field extrapolation results (Section 4.1).

2.3. Flare Microwave Emission Detected by the Nobeyama Solar Radio Observatory

Figure 1 shows the temporal evolution of the selected flare (around the impulsive phase) at different wavelengths. Figures 1(b)–(d) show the NoRH and NoRP radio data. NoRP measures both the emission intensity (Stokes I) and circular polarization (Stokes V) at five frequencies of 2, 3.75, 9.4, 17, and 34 GHz. Radio emission peaked at the same time as the HXR (Figure 1(a)), e.g., around 22:45:46 UT. NoRP time profiles also have a secondary peak as for HXR data. Most likely, both radio and HXR emissions were produced by the same population of nonthermal electrons (but in different range of the spectrum). The maximum radio flux (at frequency $f_{p}$) was observed around 35 GHz and was about 350 sfu. Maximal radio fluxes at 9.4 and 17 GHz were a bit earlier. The time delay was about 7 s. Radio fluxes at low frequencies were quasi-constant during 25 s of the impulsive phase. Peak frequency cannot be exactly defined owing to low NoRP frequency resolution. However, we can state that $f_{p}$ was higher than 17 GHz during the HXR and microwave maximum. Such a large peak frequency can be explained by the fact that nonthermal electrons with a hard spectrum produce gyrosynchrotron emission from the region of strong magnetic field (Dulk 1985). In Section 4 we will describe analysis of the microwave spectrum in detail. The circular polarization was detected only for two frequencies of 3.75 and 17 GHz, and the polarization degree was about 25% and 10%, respectively. We conclude that the observed microwave radio emission was generated via the gyrosynchrotron mechanism.

Figure 5 shows the NoRH microwave images of the flare at nine different subsequent times. NoRH radio flux is presented in Figure 1(b) by thick lines. One can see that NoRH data points are very close to NoRP measurements. NoRP produces microwave maps of the Sun at frequencies of 17 GHz (Stokes I and V) and 34 GHz (Stokes I only) with spatial resolution of up to 10″ and 5″, respectively. The images were synthesized using the CLEAN algorithm. Due to the small elevation of the Sun under the horizon, the resulting NoRH beam was elongated, and spatial resolution was reduced up to 15″ along the large axis of the NoRH beam ellipse. One can see that there was only one radio emission source located close to the PIL.
during the entire flare time. In Figure 1(b) thin lines mark the time profiles of ratio $S/S_0$ at 17 and 34 GHz, where $S$ is the FWHM area of the apparent source and $S_0$ is the FWHM area of the NoRH beam. During maximal radio flux, the source size was comparable to the beam size. This means that the real emission source was compact. The ratio between source and beam sizes began to increase after 22:47:00 UT and was about 3 for 17 GHz and 2 for 34 GHz at 22:50:00 UT. Thus, the emission region experienced expansion during the impulsive phase. This expansion probably reflects a volume increase of the flare magnetic structures where nonthermal electrons were accelerated and transported.

2.4. Comparison of X-Ray Maps with EUV Images

We consider the EUV images from two AIA channels of 94 (top panels of Figure 3) and 304 Å (bottom panels of Figure 3), corresponding mainly to the hot ($\sim$10$^7$ K) and warm ($\sim$10$^5$ K) plasmas. Figure 3 compares the EUV images with the RHESSI X-ray contour maps (6–12 keV and 25–50 keV) for three time moments. One can notice that all EUV emission sources seen in both channels were very close to the PIL and had a complex spatial structure. The strongest HXR emission was generated in the two HXR sources shown by blue contours in the central part of the image.

During the first considered moment, the SXR source had an elongated shape with a length of $\approx$40″ along the PIL. The brightest 94 Å emission was generated from the thin filiform source between the two HXR sources and covered by the SXR contour. The width of the observed hot structure is about 2 Mm and was estimated from the image slice shown in the panel. The estimated volume of the hot cylindrical channel is about $9 \times 10^{25}$ cm$^3$. One also can see the distant compact 94 Å emission source coinciding with the 304 Å source around the point with the coordinates of ($-242″$, $478″$), where we also observed the weak HXR source. We likely observe a distant footpoint of the flaring magnetic loop inside the MFR.

At the second time interval there were four bright 304 Å emission sources. Two of them are located in the central part of the image and correspond to the HXR sources. SXR emission was generated from the compact source located between the two HXR sources. The AIA 94 Å image shows an emission distribution similar to the 304 Å channel. We likely observe the interaction of two sheared magnetic loops at the PIL similar to the TCMR interaction (Liu et al. 2013). Four EUV sources could correspond to the footpoints of these loops. In
Section 4.1 we will confirm this magnetic geometry by magnetic field extrapolation in the region around the PIL.

One can also note that the brightest EUV emission at the time of the HXR peak (94 Å image at 22:45:51 UT) did not coincide with the location of the SXR (6–12 keV) centroid. The EUV sources on different sides of the PIL are likely hot footpoints of the flare magnetic structures. To explain differences between SXR contours and the distribution of the EUV sources from the AIA 94 Å channel, one can suppose that RHESSI measures emission from hotter plasma. The maximum of the AIA 94 Å response function is about 7 MK. Temperature in the SXR-emitting plasma can be significantly higher.

Thus, we have a very hot coronal magnetic structure observed by RHESSI with “cooler” footpoints detected by AIA in the 94 Å channel. However, one needs to estimate the temperature of the SXR-emitting plasma to confirm this. This will be done in Section 3.1, where the spectral analysis of X-ray spectra from the RHESSI spacecraft is presented.

### 2.5. Comparison of the X-Ray Maps with SOT/Hinode Ca II Images

To resolve the fine spatial structure of the flare energy release in the lower solar atmosphere, we used Ca II (6684 Å) images from SOT/Hinode. We have two sets of Ca II images with different temporal and spatial resolutions covering the flare time period. SOT Ca II diffraction-limited images have a spatial resolution of 0.28. The first available set of images has a time cadence of 1 minute and a pixel size of 0.2. The last image of this set at 22:45:36 UT (Figures 4(a) and (c)) was made in the rise phase of the HXR and microwave emission. The subsequent array of images has a temporal resolution of 20 s and a pixel size of 0.1. The first image of this set was made at 22:46:24 UT (Figure 4(d)) and corresponds to the decay phase of the HXR and microwave emissions. In Figures 4(a)–(d) we presented thresholded images to enhance contrast and to demonstrate size and shape of the flare ribbons. Ribbons are thin and intersect sunspot penumbrae. One can also see that the flare ribbons were very close to the PIL during the impulsive phase of the flare.

We compared the emission sources seen in these two images with the RHESSI X-ray images made in the energy bands of 6–12 keV and 25–50 keV. The strongest HXR sources coincide with the ribbons seen in the Ca II images. We see that only part of the ribbon area is covered by the HXR sources. HXR emission is likely to be generated from some particular magnetic loops, whereas the total flare energy release involved larger magnetic structures traced by the optical ribbons.
To estimate the width of the observed Ca II ribbons, we plotted the intensity profiles (Figures 4(b) and (e)) along the observational slits marked by short white horizontal lines in Figures 4(a) and (d). There are three positions for observational slits. Slits 1 and 3 intersect only ribbons corresponding to the southern and northern HXR sources, respectively. Slit 2 intersects the region of the SXR maximal intensity. From these plots it was found that the ribbon FWHM is about 1 Mm. This value is comparable to those obtained in the work of Krucker et al. (2011).

Dynamics of the area of the flare ribbons is shown in Figure 4(f). To estimate the area of the ribbons, we considered only the region limited by the rectangular box plotted in Figure 4(c). This box includes the strongest X-ray emission sources. The area was calculated as the number of pixels with intensity higher than a threshold limit. There are three threshold values of 1000, 1500, and 2000 DN. All time profiles revealed that the maximal ribbon area was during the second HXR pulse and does not exceed a value of $6 \times 10^{17}$ cm$^2$. During the HXR and microwave peaks, the area was $2 \times 10^{17}$ cm$^2$ for a threshold of 1000 DN and $0.6 \times 10^{17}$ cm$^2$ for a threshold of 2000 DN.

The obtained values of the ribbon area around HXR sources can be used to estimate the lower limit on the density of the nonthermal electrons. To do this, one can consider nonthermal electrons to be distributed uniformly through all ribbon areas. However, it was shown that nonthermal electrons are likely to be injected into local regions of the ribbons. The HXR sources had an approximately symmetric shape (let us say a circular shape). Assuming the area of nonthermal electron precipitation to be circular in shape with a radius equal to 0.5 Mm (half of the ribbon width), one can also estimate the upper limit for the density of the nonthermal electrons. Estimations of nonthermal electron density will be presented in Section 3.1.
3. Parameters of Nonthermal Electrons and Hot Plasma Deduced from the X-Ray Spectra

3.1. Spectral Analysis of the X-Ray Emission

In this section we describe the analysis of the X-ray spectra measured with RHESSI to determine parameters of hot flare plasma and accelerated electrons in the flare region. Figure 6 shows the examples of RHESSI X-ray and NoRP radio spectra at three time ranges of the flare considered. The X-ray spectrum (top panels of Figure 6) was fitted with a superposition of a single-temperature bremsstrahlung radiation function and a double power-law function to account for the thermal and nonthermal components, respectively. Fitting results are summarized in Figure 7. Temporal resolution is 8 s. A gap in data is due to a change of the RHESSI attenuator state.

There are two free fitting parameters for the single-temperature model of the SXR spectra: temperature \( T \) and emission measure \( \text{EM} \) of the SXR-emitting plasma. The contribution of the line emission and free-bound continuum is calculated in OSPEX using the CHIANTI package. Fitting values of \( T \) and \( \text{EM} \) are presented in Figures 7(b) and (c). One can see that there was very strong plasma heating up to 40 MK preceding the HXR peak. Such a high temperature is referred to as superhot (see Caspi & Lin 2010). The appearance of superhot plasma can be connected with direct plasma heating in the region close to the magnetic reconnection site. The emission measure in the beginning of the impulsive phase was about \( 10^{46} \text{cm}^{-3} \) and increased up to \( 3 \times 10^{47} \text{cm}^{-3} \), while the plasma temperature decreased to a “normal” value of 22 MK.

To estimate thermal plasma density, we use the formula \( n_{th} = \sqrt{\text{EM}/V} \), where \( V \) is volume occupied by thermal plasma. In Figure 3 it can be seen that the approximate distance between the two strongest HXR emission sources did not significantly change during the flare impulsive phase. One can assume a quasi-constant volume of the magnetic loops, where nonthermal electrons were transported and plasma was heated up to superhot temperatures. Moreover, from the NoRH images we know that the microwave sources at 17 and 34 GHz also had a quasi-constant area (see Figures 1(b) and 5) during the impulsive phase. That is why, to estimate temporal dynamics of the plasma density, we will assume a constant volume of the flare magnetic structure. To estimate the volume value, we consider the loop length to be 14 Mm, which corresponds to the distance between the HXR sources. The loop cross-section radius is considered to be 1 Mm; this value was estimated from the AIA 94 Å image (see Section 2.4 and bottom left panel of Figure 3). The time profile of \( n_{th} \) is shown in Figure 8(b) by the

Figure 6. RHESSI X-ray (top) and NoRP (bottom) spectra made for the flare impulsive phase. In the top panels, the thermal and nonthermal (double power-law) components of the model fitting function are shown by the red and blue lines, respectively. Parameters of the fittings are written in the plots.
Figure 7. Spectral parameters of the X-ray emissions during the flare impulsive phase. (a) Photon flux at 10 (red) and 50 keV (black). (b) Emission measure EM of thermal plasma. (c) Temperature $T$ of thermal plasma. (d) Normalization $A_{30}$ of the HXR spectrum at 30 keV. (e) Break energy $E_{\text{low}}$ in the HXR photon spectrum simulating the presence of the low-energy cutoff in the spectrum of nonthermal electrons. (f) Power-law spectral indices $\gamma$ of the HXR spectra. (g) Normalized $\chi^2$ of the fittings.
thin line. Thermal plasma density is also calculated for the case of a very thin magnetic loop with a cross-section radius of 0.25 Mm and shown by the thick line in Figure 8(b).

The nonthermal component of the X-ray spectrum ($\lesssim 20$ keV) was approximated by a double power law. The first free fitting parameter is normalization $A_{30}$ (Figure 7(d)) of the power-law function at an energy of 30 keV. The break energy $E_{\text{low}}$ in the HXR spectrum (Figure 7(e)) is also a free fitting parameter and simulates the presence of the low-energy cutoff in the nonthermal electron spectrum. The first three time intervals are characterized by $E_{\text{low}} = 20$–24 keV. Then its value was reduced to $\approx 18$ keV. The low-energy spectral index (at $E < E_{\text{low}}$) of the nonthermal component was fixed at a value of 1.5. The third free fitting parameter shown in Figure 7(f) is power-law index $\gamma$. Dynamics of the power-law index show soft-hard-soft behavior with a minimal value of 3 during the HXR maximum. At the end of the impulsive phase the spectrum became the softest, with $\gamma$ up to 7.

The obtained fitting parameters allow us to estimate the total nonthermal X-ray photon flux above $E_{\text{low}}$ as $I_{\text{ph}}(E > E_{\text{low}}) = AE_{\text{low}}/(\gamma - 1)$ and then determine the flux of the nonthermal electrons using the formula from the work of Syrovatskii & Shmeleva (1972). In Figure 8(a) there are values of the integrated nonthermal electron flux above $E_{\text{low}}$ of 30, 50, and 100 keV. One can see that the maximal total flux of nonthermal electrons was after the HXR maximum. It can be explained by those facts that at the time of peak flux of the nonthermal electrons the spectrum was softer, $\gamma \approx 6$, compared to the time moment of the HXR peak, where $\gamma \approx 3$. The maximal flux of the energetic electrons with energies higher than 30 keV coincided with the HXR and microwave peaks. The flux of accelerated electrons at the HXR peak was $\approx 10^{35}$ electrons s$^{-1}$, whereas its largest value was $5 \times 10^{35}$ electrons s$^{-1}$.

The spectral index of accelerated electrons in the HXR source region is related to the emission spectral index as $\delta = \gamma + 1$ using the thick target approximation (Brown 1971; Syrovatskii & Shmeleva 1972). The nonthermal electron number density $n_{\text{nth}}$ (for a power-law spectrum, in the nonrelativistic approximation) is estimated using the formula (with all parameters in CGS units)

$$n_{\text{nth}}(E > E_{\text{low}}) = \frac{F(E > E_{\text{low}})}{S} \sqrt{\frac{m_e}{2E_{\text{low}}} \frac{\delta - 3/2}{\delta - 1}},$$

where $F(E > E_{\text{low}})$ is the integrated nonthermal electron flux above $E_{\text{low}}$, $m_e$ is the electron mass, and $S$ is the precipitation area of the nonthermal electrons. We estimate the concentration of nonthermal electrons in the case of thin and thick magnetic loops with radii of 1 and 0.25 Mm, respectively. Values of $n_{\text{nth}}$ are shown in Figure 8(b) and compared with thermal plasma density $n_{\text{th}}$. The ratio $n_{\text{nth}}/n_{\text{th}}$ is in the range of 1%–2% for the thick magnetic loop and $n_{\text{nth}}/n_{\text{th}} = 3\%$–9% for the thin loop. Thus, our estimations show that less than 10% of electrons are accelerated from the thermal hot and superhot plasma population contained in the flare region.

### 3.2. Flare Energetics

In this subsection we will discuss energetics (i.e., the main different energy channels) in the flare region using fitting results from the previous subsection. Internal plasma energy can be calculated following the expression $U_0 = 3k_B T\sqrt{E\cdot V}$, where $k_B$ is the Boltzmann constant. In Figures 8(c) and (d) we
present the time derivative of the thermal energy \(dU_{th}/dt\) for two cases of magnetic loops of different cross-section radii: 0.25 and 1 Mm (panels (c) and (d), respectively). Cooling (orange line and circles) of the flare region began approximately after 22:46:35 UT.

Kinetic power of the nonthermal electrons is calculated as

\[
P_{\text{nonth}}(E > E_{\text{low}}) = \frac{F(E > E_{\text{low}})E_{\text{low}}^\delta - 1}{\delta - 2}.
\]  

(2)

The peak value of \(P_{\text{nonth}}\) is about \(2 \times 10^{28}\) erg and was achieved at about 22:46:35 UT. This time does not correspond to the HXR maximum, as maximal flux of nonthermal electrons was achieved at this time moment. During all flares, kinetic power of the nonthermal electrons dominated over the time derivative of the internal energy. In the case of a thick magnetic loop with radii of 0.25 Mm, \(P_{\text{nonth}}/(dU_{th}/dt) \approx 4.5\) in the beginning of the impulsive phase, and this value was increased up to 35 in the peak of \(dU_{th}/dt\).

In addition to calculating the time derivative of the plasma internal energy and the kinetic power of the accelerated electrons, it is also necessary to take into account the radiative heat losses from the entire superhot region. For an X-ray-emitting plasma, the heat losses are estimated as \(L_{\text{rad}} = EM \times 10^{-17.73}T^{-2.73}\) for flare temperatures (Rosner et al. 1978). One can see that cooling appeared at the time moment when \(L_{\text{rad}} \approx dU_{th}/dt\), taking into account errors of \(U_{th}\). Close equality of these two energies was achieved in the case of a thin magnetic loop with radii of 0.25 Mm.

To estimate heat transfer from the superhot region to cooler footpoints, one can use the assumption of classical (Spitzer) thermal conduction: \(L_{\text{cond}} \approx 4 \times 10^{-6}T^{1/3}/L\), where \(L\) characterizes the linear length scale of the temperature gradient that is taken to be equal to the flare loop length. The maximal possible value of the heat flux is estimated as saturated heat flux, which is determined by the expression \(L_{\text{sat}} = \nu_e n_{th} T_e S\), where \(\nu_e\) and \(T_e\) are thermal electron velocity and temperature, respectively. This formula means that heat is transported along the magnetic loop by thermal electrons spreading with thermal velocity in the same direction. Heat conduction cannot exceed saturated flux. The classical and saturated heat fluxes are presented in Figures 8(c) and (d) by gray lines. Generally, kinetic power of nonthermal electrons also dominates over heat conduction losses. However, in the case of a thick loop \(L_{\text{cond}} \geq P_{\text{nonth}}\) during the first 30 s. But taking into account the fact that heat conduction flux cannot be higher than \(L_{\text{sat}}\), we see that \(P_{\text{nonth}} \lesssim L_{\text{sat}}\) during the entire impulsive phase and both cases of thin and thick loops considered.

It is worth noting that the maximal thermal energy is usually comparable to the nonthermal energy of accelerated electrons (e.g., Emslie et al. 2012; Aschwanden et al. 2016). In the case of the studied flare the total kinetic energy of nonthermal electrons in the analyzed time range is about \(10^{39}\) erg. The maximal plasma internal energy for the case of a thick magnetic loop did not exceed \(3 \times 10^{38}\) erg. We can see a two-order-of-magnitude difference between total energies of thermal and nonthermal electrons. This indicates that the bulk of the released energy is transferred from the superhot region by nonthermal electrons, not by thermal conductivity.

As magnetic free energy (we estimate its value by subtracting potential field energy from NLFFF energy) is believed to be the main source of flare energy, one should estimate it as well. The value of the free magnetic energy change during the flare was calculated for the NLFFF extrapolations using two subsequent HMI vector magnetograms (made before and after the flare) as boundary conditions. For extrapolation, we first used the optimization method (Wheatland et al. 2004) implemented by Rudenko & Myshyakov (2009; see Section 4). The resulting value is about \(4.6 \times 10^{31}\) erg, which is much larger than that obtained at other flare energy channels discussed above. We also estimated the uncertainty of the magnetic free energy calculation related to the Gaussian noise with \(\sigma = 30\) G (for each magnetic field component) added to the magnetogram. We found this error to be about 1%, which is negligible.

It is known that different methods of magnetic field extrapolation give different estimates of free energy in active regions (e.g., DeRosa et al. 2015). Thus, we also decided to make an additional calculation of the free magnetic energy change using another implementation of the optimization method by Wiegelmann (2004). A preprocessing 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 estimated value of the free magnetic energy change during the flare is about \(2.9 \times 10^{31}\) erg. The difference between the results of the two methods is about \(1.7 \times 10^{31}\) erg, or 37%. The difference is substantially larger than the difference due to the addition of the Gaussian noise to the used magnetograms. This indicates that the main error is related to the field extrapolation methodology, rather than to the uncertainties of the boundary data. Nevertheless, both estimates of the free magnetic energy released are significantly higher than other flare energy channels discussed (related to the heated plasma and accelerated electrons). Free energy can be lost in many other energy ranges and by other processes, and one can only expect the estimated variation of the magnetic free energy to be much above the values examined in this paper. From this point of view, our calculations are consistent, which gives us grounds to believe that they are sufficiently correct.

It is also worth estimating the energy flux density of nonthermal electrons \(P_{\text{nonth}} = P_{\text{nonth}}/S\). For the case of thick and thin loops we found maximum values of \(1.7 \times 10^{11}\) erg \(s^{-1} \text{ cm}^{-2}\) and \(2.5 \times 10^{12}\) erg \(s^{-1} \text{ cm}^{-2}\), respectively. These values are consistent with similar estimates made for the much stronger X-class helioseismic solar flare of 2012 October 23, described in the work of Sharykin et al. (2017a), indicating highly efficient acceleration of electrons in the flare studied here (see Section 5).

4. Analysis of Radio Emission

4.1. Magnetic Field Extrapolation for Gyrosynchrotron Radio Emission Modeling

To study the magnetic field structure in the flare region, we use HMI observations, which provides vector magnetograms with 720 s cadence. We have selected the magnetogram closest to the flare impulsive phase (i.e., at 22:46:00 UT) and recalculated all of the magnetic field \(B\) components from the local helioprojective Cartesian system to the Heliocentric Spherical coordinate system.

To make quantitative analysis of flare microwave emission, one needs to determine the distribution of the magnetic field in the flare region. To reconstruct the 3D structure of the coronal magnetic field, we use the NLFFF magnetic field extrapolation with the HMI/SDO vector magnetogram used as a boundary condition.
The extrapolation is made using the optimization method (Wheatland et al. 2000) implemented by Rudenko & Myshyakov (2009). The extrapolation results are shown in Figure 9, where the field lines of the selected magnetic loop are plotted. The side view of these structures is shown in panel (b). It is shown that the height of a bunch of these magnetic field lines did not exceed 3 Mm. Two cases of the magnetic structures are considered. Generally, the magnetic field lines were chosen to reproduce the observed locations of the HXR footpoints and microwave source. The twisted magnetic structure is elongated along the PIL. The distribution of the magnetic field is not significantly changed along the central line of the magnetic structure. The maximal value is about 1400 G, whereas the minimal one is about 850 G. The resulted magnetic field lines have footpoints located very close to the PIL. This is also in accordance with the observed optical and EUV emission sources at the PIL. Finally, NLFFF modeling reveals the closed low-lying twisted magnetic structure at the PIL, where flare energy release occurred. Thus, plasma heating and acceleration of electrons were stimulated in the found magnetic structure.

The distribution of the magnetic field strength is presented in Figure 10. We selected two regions of interest (ROIs) at the PIL to find the histogram of magnetic field distribution. The first ROI with a length of 28 Mm along the PIL, marked by red color in the left panel of Figure 10, covers a larger area than the other one (blue color), with a length of 12 Mm. The width of both ROIs is about 6 Mm across the PIL. Distributions of the magnetic field are shown in the right panel of Figure 10. One can see that the maximal probable values of these two distributions are approximately the same and equal to 1180 G. FWHM (marked by vertical dotted lines) is about 200 G for both distributions. That is why a large number of the volume cells in the vicinity of the PIL have values of the magnetic field in the range from 1100 to 1300 G. The smaller ROI has a minimal value of the magnetic field of around 1000 G, whereas the larger one reveals magnetic field values in the range of 300–1000 G.

4.2 Gyrosynchrotron Radio Emission Modeling for a Uniform Source

In the previous sections it was shown that the accelerated electrons were injected into the compact magnetic structure elongated along the PIL (or they were directly accelerated...
there), NLFFF extrapolation of the magnetic field in the flare region reveals that the magnetic field at the PIL does not significantly vary in space. As a first step, we have decided to make a simple quantitative analysis of the flake microwave gyrosynchrotron spectrum assuming a uniform source. The Stokes $I$ radio spectrum is calculated using the Fast Gyrosynchrotron Codes by Fleishman & Kuznetsov (2010), where the authors used some analytical approaches and numerical methods to calculate the microwave emission with high speed and good accuracy for different energy and pitch-angle distributions of nonthermal particles. For simplicity, the uniform pitch-angle distribution is considered. The reason for doing this can be, for example, high background thermal plasma density or MHD turbulence leading to fast (compared with the observational time) isotropization of pitch-angle distribution of nonthermal electrons. Angle $\Theta$ between the line of sight and the magnetic field is taken as 80°. Parameters of the thermal plasma and the spectrum of nonthermal electrons (at the HXR and microwave peak) were taken from the X-ray spectral fitting described in Section 3.1.

Four geometrical cases with different sizes of the region with nonthermal electrons are considered. The emitting region is assumed to be rectangular, with the length $L$ comparable to the linear size of the observed magnetic structure parallel to the PIL, where nonthermal electrons were transported. The width is equal to the line-of-sight depth $2R_{MW}$. We consider models with different $R_{MW}$ (0.15, 0.25, 0.5, and 1 Mm) and $L$ (13.3, 8, 10, and 10 Mm) presented in Table 1. These values of $R_{MW}$ give different areas $2R_{MW}L$ of the emitting region in the plane of sky and cross-section area $4R_{MW}^2$ (see Table 1).

Such linear sizes of the emitting region in the four models were selected for the following reason. The scope is to obtain gyrosynchrotron spectrum peak frequency higher than 17 GHz and maximal observed radio flux. Figure 11 demonstrates how the peak intensity and frequency of the gyrosynchrotron spectrum depend on the density of nonthermal electrons and magnetic field strength in the source. The levels of constant peak frequency are marked by solid lines. The dotted line corresponds to the constant peak intensity with a value of 350 sfu, which is the maximal observed radio flux at a frequency of 35 GHz during the studied flare (Figures 1(b) and (c)). The gray stripe marks the range of the magnetic field values in the microwave source determined from the magnetic field distribution histogram (Figure 10) obtained from the NLFFF extrapolation.

Considering the intersection of the dotted and solid lines with the gray stripe, one can deduce the approximate density of nonthermal electrons $n_{MW}$ in the radio source and peak frequency $f_p$ of the resulting gyrosynchrotron radio spectrum (see corresponding lines in Table 1). In the case of $f_p = 35$ GHz we have $n_{MW} \sim 10^9$ cm$^{-3}$. Assuming a cross section of the magnetic loop in the footpoints equal to $4R_{MW}^2$, one can deduce the density of the precipitated nonthermal electrons producing HXR emission. From Equation (1), taking $F(E > E_{th}) = 10^{35}$ electrons s$^{-1}$, we have estimated the values of $n_{HXR}$ and compared them with $n_{MW}$ in Table 1. In the case of $R_{MW} = 0.25$ Mm the value of $n_{HXR} = 4.6 \times 10^8$ cm$^{-3}$ is the closest to the $n_{MW} = 2 \times 10^9$ cm$^{-3}$.

Using the volume of the radio-emitting region $V = 4R_{MW}^2L$, we have estimated corresponding plasma density $n_{th} = \sqrt{EM/V}$ for EM $= 2.2 \times 10^{30}$ cm$^{-3}$. For model 2 $n_{th} = 1.2 \times 10^{11}$ cm$^{-3}$ and $n_{MW}/n_{th} \approx 0.017$. In other words, only 1.7% of electrons are accelerated from thermal plasma.

4.3. Gyrosynchrotron Radio Emission Modeling in the GX Simulator

3D modeling of the microwave radio emission is made using the GX Simulator package (Nita et al. 2015) with the Fast Gyrosynchrotron Codes (Fleishman & Kuznetsov 2010). In
our modeling, the main task is to explain the emission at 17 and 34 GHz, as we have imaging data for these frequencies and know exactly where this emission comes from. However, despite the absence of observations at lower frequencies, we will also discuss the emission at frequencies below 17 GHz and will select the appropriate model to explain the whole microwave spectrum from 2 to 35 GHz observed by NoRP.

To explain the dominating emission at 35 GHz, one should suspect peak frequency in the range of 17–35 GHz. In the previous section it was shown that to explain the observed $f_p$ and the maximal radio flux of 350 sfu, one needs to assume a population of nonthermal electrons with a density of around $2 \times 10^9$ cm$^{-3}$ uniformly distributed in the thin horn-like radio emission source with a width of 0.5 Mm and a length of 10 Mm. The magnetic field in the source is 1180 G. Such a simple analysis allowed us to find the appropriate real magnetic structure from NLFFF extrapolation and the distribution of nonthermal electrons within the found structure to reproduce the observed microwave spectrum.

We have imported results of NLFFF extrapolation into GX Simulator. We have selected the magnetic structure using the selection tool in GX Simulator in the following way. First, we defined the central line of the loop to achieve the closest correspondence between the central line location and HXR footpoints and microwave sources at available NoRH working frequencies of 17 and 34 GHz. Then, we defined the circular cross section of the magnetic structure at the top of the central line. The cross-section radius $R$ of the loop is 0.72 Mm, and the length of the central line $L = 12.6$ Mm. To visualize magnetic structure, 12 lines were drawn from the points distributed along the circle around the top point of the central line. The magnetic structure is presented in Figures 9(a1) and (b1) in two projections: on-disk view and side view. This structure is elongated along the PIL, which is in accordance with the observations made in different available ranges of the electromagnetic spectrum. The top point of the central line has a height of $\approx 1.5$ Mm. Thus, the flare magnetic structure is low-lying and located in the chromosphere or just slightly above it.

Nonthermal electrons are nonuniformly distributed inside the magnetic structure. We consider a Gaussian shape of the distributions of the nonthermal electrons along and across the magnetic structure. The distributions are determined by the expressions $n(r, l) = n_0 \exp\left(-3r/R\right)^2 \exp\left(-3l/L\right)^2$, where $R$ is the loop radius, $r$ is the coordinate along the loop, $L$ is the loop length, and $l$ is the coordinate along the loop from its top point. The peak number density is chosen to be $n_0 = 5 \times 10^8$ cm$^{-3}$ at the loop top. The efficient length of the radio source $L_{MW} = L/3 = 4.2$ Mm when $R_{MW} = R/3 = 0.24$ Mm.

Distribution and density of nonthermal electrons in the loop were chosen to reproduce the observed radio source and obtain a sufficient radio flux at 17 and 34 GHz to fit the radio spectrum measured by NoRP. The energy spectrum of nonthermal electrons obtained from the analysis of the X-ray spectrum is described by a power-law function with spectral index $\delta = 3.5$, low-energy cutoff $E_{low} = 20$ keV, and high-energy cutoff $E_{high} = 10$ MeV. For simplicity, we consider an isotropic pitch-angle distribution of the nonthermal electrons. The background thermal plasma is uniformly distributed in the loop and has number density $n_{th} = 10^{11}$ cm$^{-3}$ and temperature $T = 30$ MK. Previous analysis assuming a uniform source reveals that a nonthermal electron density of $2 \times 10^9$ cm$^{-3}$ is enough to explain the radio spectrum. Using GX Simulator, we found lower density (by a factor of 4), as we considered magnetic structure obtained from the NLFFF extrapolations with the nonuniform magnetic field and changing orientation (inclination to the line of sight) in space.

We have just described the model of the high-frequency part of the microwave spectrum. However, one can see (Figure 12) that this model fails to explain the whole wide radio spectrum. Below, we will describe a way to explain the emission at frequencies of 2, 3.75, and 9.4 GHz. Thus, we will discuss the low-frequency model (hereinafter the LF model). For construction of the LF model we selected a bit higher and wider magnetic structure in the vicinity of the PIL. It is shown in Figures 9(a2) and (b2). Distribution of the magnetic field along the loop is presented in panel (c2). The radius of the magnetic structure is 1.44 Mm, and the length of the central line is 17.6 Mm. This magnetic structure is filled by nonthermal electrons distributed along and across the central line according to the formula $n(r, l) = n_0 \exp\left[-1.6r/R\right]^2 \exp\left[-2.2l/L\right]^2$. The efficient length of the radio source $L_{MW} = L/7.2 = 8$ Mm when $R_{MW} = R/4.8 = 0.9$ Mm. The density at the loop top was taken as $n_0 = 10^7$ cm$^{-3}$. Such a density distribution was selected to achieve sufficient radio flux to explain the low-frequency (below 17 GHz) part of the microwave spectrum. The power-law index and low- and high-energy cutoffs were selected to be the same as in the case of the HF model, suggesting the same accelerator of electrons. The model spectrum is shown by the red solid line in Figure 12. The peak frequency of the LF spectrum is about 13 GHz.

Geometrically the constructed model can be described in the following way. There is a thick (large width) magnetic loop with a low-density population of nonthermal electrons with a high-density beam of nonthermal electrons spreading in a thin

| Model No. | 1 | 2 | 3 | 4 |
|-----------|---|---|---|---|
| $R_{MW}$ (Mm) | 0.15 | 0.25 | 0.5 | 1 |
| $L_{MW}$ (Mm) | 13.3 | 8 | 10 | 10 |
| $\pi R_{WW}^2$ (cm$^2$) | $7.1 \times 10^{14}$ | $2 \times 10^{15}$ | $7.9 \times 10^{15}$ | $3.1 \times 10^{16}$ |
| $S_{MW} = 2L_{MW}L$ (cm$^2$) | $4 \times 10^{16}$ | $4 \times 10^{16}$ | $1.9 \times 10^{17}$ | $1.9 \times 10^{17}$ |
| $V_{MW} = S_{MW}L$ (cm$^3$) | $9.4 \times 10^{23}$ | $1.6 \times 10^{24}$ | $7.9 \times 10^{25}$ | $3.1 \times 10^{25}$ |
| $f_p (\text{max}) = 350$ sfu (GHz) | 35 | 35 | 25 | 30 |
| $n_{MW} (\text{cm}^{-3})$ | $2 \times 10^9$ | $2 \times 10^9$ | $10^8$ | $1.3 \times 10^7$ |
| $n_{HXR} (S_{HXR} = S_{MW})$ (cm$^{-3}$) | $1.3 \times 10^{10}$ | $4.6 \times 10^9$ | $1.2 \times 10^9$ | $3 \times 10^8$ |
| $n_{th} (V_{SXR} = V_{MW})$ (cm$^{-3}$) | $1.5 \times 10^{11}$ | $1.2 \times 10^{11}$ | $1.7 \times 10^{10}$ | $2.7 \times 10^{10}$ |

Table 1

Summary of Four Models Describing Gyrosynchrotron Microwave Emission from the Uniform Source with Different Geometrical Parameters and Density of Nonthermal Electrons
channel inside a thicker one. The low- and high-density populations of nonthermal electrons produce low- and high-frequency radio emissions, respectively. As a result, one can see that the whole spectrum is nicely fitted by the combination of LF and HF models. However, the constructed LF model is rather speculative because there are no images at frequencies below 17 GHz. Thus, we cannot localize magnetic structure from where radio emission at lower frequencies is emitted. Here we assume that radio emission at low frequencies is also emitted from the PIL region, as all strongest emission sources

Figure 11. Plots where solid lines mark levels of constant peak frequency of the gyrosynchrotron radio spectrum. The dashed line corresponds to the level of constant radio flux of 350 sfu, which was maximal during the studied flare. Values of magnetic field and density of nonthermal electrons are written in the X- and Y-axes. The gray stripe shows FWHM of magnetic field distribution at the PIL obtained from the histograms shown in the right panel of Figure 10. Four panels correspond to different sizes of the region emitting gyrosynchrotron microwave emission (see Table 1).
were close to the PIL. However, we think that it is possible to create another LF model by playing with the geometry of the magnetic structure and the distribution of the nonthermal electrons inside it. Anyway, we have demonstrated that electrons in the closed twisted magnetic structure at the PIL can produce broadband gyrosynchrotron microwave emission. Emission at 17 and 34 GHz is definitely generated by the high-density beam of the nonthermal electrons transported in the very thin low-lying magnetic channel at the PIL.

5. Discussion and Conclusions

In this work we presented a detailed analysis of the spatially resolved observations of the M1.2 solar flare that occurred on 2015 March 15. This event was selected for the analysis owing to its strong emission sources at the PIL, suggesting interaction of stressed magnetic loops with high shear angle (up to 80°) that experience 3D magnetic reconnection. Another reason to select this event was the good association of the HXR sources with the regions of strong photospheric vertical electric currents. This indicates that accelerated electrons were accelerated/injected in the twisted magnetic structure. Our analysis allowed us to determine physical parameters of accelerated electrons, heated plasma, and magnetic field topology at the PIL where the observed emission sources were localized. The main results can be summarized in the following way:

1. Accelerated electrons and heated plasma were localized in the closed low-lying twisted magnetic structure at the PIL, with an average height of up to 3 Mm. The average magnetic field in this structure was about 1200 G.

2. The most energetic electrons with the hardest spectrum appeared at the onset of plasma heating up to a superhot temperature of 40 MK. Plasma beta in the superhot region was less than 0.01.

3. The density of the accelerated electrons at the PIL was about $10^9$ cm$^{-3}$. Estimations show that less than 10% of electrons are accelerated from the thermal superhot plasma assuming the same location of thermal and nonthermal populations.

4. The largest part of the total flare energy release during the impulsive phase was concentrated in the accelerated electrons. Total kinetic energy of the accelerated electrons was about $10^{30}$ erg when the thermal energy of the superhot plasma did not exceed $3 \times 10^{28}$ erg. Nonthermal electron energy flux is estimated up to $3 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$.

5. Joint analysis of the HXR, microwave, EUV, and optical data revealed that the accelerated electrons were transported in a thin magnetic channel within a twisted magnetic structure. The width of this channel was about 0.5 Mm when the total area of optical flare ribbons was up to $2 \times 10^{17}$ cm$^2$. Thus, only a part of the twisted magnetic structure was involved in the process of efficient (up to high energies) acceleration.

It was found that the flare energy release was developed in the low-lying twisted magnetic structure elongated along the PIL. The most likely mechanism for the initial flare energy release is the TCMR, where magnetic loops with high shear interact at the PIL and experience 3D magnetic reconnection with the strong guiding (along the electric current) magnetic field of $\sim 1$ kG. In the studied flare, these interacting magnetic structures are located in the twisted MFR found from the NLFFF extrapolation of the magnetic field. During the flare energy release, nonthermal electrons were injected into a very thin magnetic channel compared with the observed width of the flare ribbons. Thus, the acceleration process is connected with filamentation in the reconnecting sheared magnetic loops within the MFR. It should also be noticed that the previous works reported mainly the TCMR during solar flares in large-scale coronal magnetic structures (e.g., Liu et al. 2013). Possibly in such low-lying magnetic structures, as found in the investigated flare, the influence of partially ionized plasma and large gradients (chromosphere–corona interface) on magnetic reconnection may play a role. Future models should be able to reproduce complex physics of 3D magnetic reconnection at the PIL involving different atmospheric layers and producing accelerated electrons and superhot plasma.

The importance of fine spatial structuring of the flare energy release site was previously discussed in the works of Krucker et al. (2011), Zimovets et al. (2013), Sharykin & Kosovichev (2014), and Yurchyshyn et al. (2017), where authors used observations with high spatial resolution in different ranges of the electromagnetic spectrum. We think that the most important result of the present study is confirmation of the flare energy release filamentation with subsequent formation of high-energy density beams of nonthermal electrons.

It should also be noticed again that numerical modeling of gas dynamics response in flare regions previously did not consider such high-energy densities of $3 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$ as we found here. For example, in the most popular radiative hydrodynamics code RADYN (e.g., Allred et al. 2006) the maximal considered energy flux was $10^{11}$ erg s$^{-1}$ cm$^{-2}$. Numerical radiative gas dynamics models should be able to reconstruct the behavior of flare chromospheric plasma under such energy fluxes. This is important for explanation of the lower solar atmosphere response to injection of nonthermal
electrons. For example, in the work of Sharykin et al. (2017a) it was discussed that high-density beams of nonthermal electrons can be a reason for white-light emission and sunquake generation. Moreover, a dense population of nonthermal electrons will lead to very strong induced return currents and more efficient generation of plasma waves affecting on the particles kinetics of high-energy electrons. Despite the large energy density of nonthermal electrons, our analysis revealed that the superhot plasma has enough particles to be accelerated. Ideally, a self-consistent model of 3D magnetic reconnection at the PIL with particle acceleration and their kinetics should be constructed. Such a model has to reproduce the formation of a high-energy density nonthermal electron population in the contest of filamentation of the flare energy release site in the MFR located at the PIL.

One of the interesting findings in this work is the formation of the superhot plasma with temperature reaching a value of 40 MK during the rather weak M-class solar flare. Great interest in this phenomenon is connected with the fact that such a large temperature can result from direct plasma heating in the primary energy release site in the solar corona (Caspì & Lin 2010). In our case the superhot plasma was formed at the PIL during probable TCMR in the low-lying MFR. Thus, numerical models have to reconstruct such extreme heating and low plasma beta. According to the statistical work of Caspi et al. (2014), it was shown that the plasma beta in the superhot region cannot be much less than unity. However, in our work, the estimated average magnetic field is about 1200 G, which is very high, and the resulting plasma beta in the superhot region is less than 0.01. Thus, the superhot plasma is fully magnetized, in contrast with the results of Caspi & Lin (2010), Caspi et al. (2014), and Sharykin & Kosovichev (2015). The high value of the magnetic field found in the flare region can be explained by the fact that the flare energy release happened in the very low-lying (just up to 3 Mm) magnetic structure near the sunspot. This flare was not accompanied by an eruption and a CME, i.e., the flare was confined and did not develop into a normal eruptive event with formation of a quasi-vertical reconnecting current sheet according to the standard model (Hirayama 1974; Magara et al. 1996; Tsuneta 1997). Thus, the flare studied can be considered a good example of an event in which the effective acceleration of electrons occurred in a closed magnetic system, which could be caused by the TCMR.

Another peculiarity is that the total energy of nonthermal electrons is much larger than the internal energy of the superhot plasma. In the work of Sharykin & Kosovichev (2015) the kinetic power of nonthermal electrons was comparable to the time derivative of the superhot plasma internal energy. However, in the work of Sharykin et al. (2014), it was shown that the kinetic power of nonthermal electrons can dominate over thermal energy. The conclusion was that acceleration can result in effective cooling due to efficient escape of fast electrons from the Maxwellian tail of the superhot plasma. In this work we found a two-order-of-magnitude difference between thermal and nonthermal energies. It seems that magnetic reconnection in the low-lying magnetic loops is a very efficient accelerator but not an efficient heater from the energy point of view. However, our estimates show that the change of magnetic free energy at the PIL region is enough to explain the total flare energetics, which is consistent with previous studies (e.g., Emslie et al. 2012).

To sum up, the selected flare is a demonstrative example of the noneruptive (confined) event with the primary energy release site located within the low-lying twisted magnetic structure with high magnetic shear. The TCMR of the magnetic loops at the PIL was found to be the most favorable scenario explaining the energy release. To our knowledge, we performed the first detailed quantitative analysis of the accelerated electrons and plasma heating in the frame of the pure 3D magnetic reconnection in the low solar atmosphere resulting in the confined solar flare. The obtained results can be used for further observational studies of the confined flares associated with the 3D magnetic reconnection and for development of new models where the flare energy release is outside the framework of the standard model.

It is worth noting that this work (Paper I) was mostly devoted to investigation of plasma heating and nonthermal electrons at the PIL region. We ignored here the detailed investigation of magnetic field dynamics at the PIL. A subsequent work (Paper II) will present the detailed study of magnetic fields, electric currents, and their relation to emission sources at the PIL using the high-cadence HMI vector magnetograms (Sun et al. 2017) with a temporal resolution of 135 s.

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