The Depth and the Vertical Extent of the Energy Deposition Layer in a Medium-class Solar Flare

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Abstract

We analyze here variations of the position and the vertical extent of the energy deposition layer (EDL) in the C1.6 GOES-class solar flare observed at 10:20 UT on 2012 September 10. The variations of the EDL are contrasted with the variations of the spectra and emission intensities recorded in the Hα line with very high time resolution using the MSDP spectrograph at Białków Observatory. The flare radiated hard X-rays (HXR) detectable up to a energy of 70 keV. A numerical model of the flare used in the analysis assumes that the nonthermal electrons (NTEs) carried the external energy to the flare. The energy flux of the NTEs was derived from a nonthermal component seen in RHESSI spectra. The main geometrical parameters of the flare were derived using restored RHESSI imaging data. We found that the variations of the X-ray fluxes recorded in various energy bands and the variations of the Hα intensities were well-correlated in time during the pre-impulsive and impulsive phases of the flare, and they agreed with the variations of the calculated position and vertical extent of the EDL. The variations of the emission noticed in various parts of the Hα line profile were caused by individual episodes of energy deposition by the beams of NTEs of various energy spectra on various depths in the chromospheric plasma. These results supplement our previous findings for the solar flare on 2013 June 21, having nearly the same GOES class of C1.1 but HXR emission below 34 keV only.

Unified Astronomy Thesaurus concepts: The Sun (1693)

Supporting material: animation

1. Introduction

Solar flares are violent and powerful phenomena that alternate properties of the whole surrounding solar atmosphere, influence properties of the interplanetary environment via various direct and indirect mechanisms, and shape so-called space weather and numerous geophysical processes. For this reason, solar flares have been thoroughly observed and analyzed for many dozens of years. Very intensive and effective investigations started in the 1960s when space-based X-ray and EUV data became available.

Solar flares encompass a very complicated system of interrelated processes, taking place in a violently evolving environment of nonpotential magnetic fields in the active regions (Jain et al. 2011; Choudhary & Deng 2013; Kowalski et al. 2019; Toriumi & Wang 2019). Solar flare radiation ranges from X-rays to the radio band, covering almost the entire range of the electromagnetic spectrum (Fletcher et al. 2011). In the case of the most powerful flares, gamma emission is also recorded (Smith 2005). The time and spatial scales of the physical processes in solar flares are very small, still below the capabilities of present space- and ground-based instruments. New insight into solar flares will be provided by NASA Parker Solar Probe and ESA-NASA Solar Orbiter (Müller et al. 2013; Fox et al. 2016), as well as the ground-based 4 m class Daniel K. Inouye Solar Telescope (DKIST) in Hawaii and the European Solar Telescope (EST) due to be installed in the Canary Islands (Elmore et al. 2014; Jurčák et al. 2019). In the meantime, very small-scale processes can only be investigated indirectly, with state-of-the-art numerical models and refined theoretical studies.

The general 2D model of the physical mechanisms and energy release processes occurring in solar flares (so-called CSHKP model), was elaborated more than 50 yr ago by Carmichael (1964), Sturrock (1966), Hirayama (1974), and Kopp & Pneuman (1976). After numerous modifications over the years, it evolved into a commonly accepted standard model of the flares (Dennis & Schwartz 1989; Shibata 1999). The model assumes that energy accumulated already in nonpotential magnetic fields is released via avalanches of local reconnections and then is converted into the kinetic energy of the charged particles (in particular, nonthermal electrons) and the internal, kinetic, and potential energy of the plasma, in addition to causing various electromagnetic emissions. The beams of the nonthermal electrons are guided by loop-like magnetic structures rooted toward the chromosphere and even upper photosphere, where the energy is deposited, causing impulsive local heating and evaporation of chromospheric material.

Although the time and spatial scales cannot be observed, the general characteristics of the processes can be derived from their emissions recorded in hard X-ray (HXR via bremsstrahlung), soft X-ray (SXR; thermal), UV, and even visible domains. In the case of visible-domain emissions, the chromospheric emission in the hydrogen Hα line (λ = 6563 Å) is used as an effective diagnostic tool while its emission depends on the energy deposition in the chromosphere (Vernazza et al. 1973, 1981) and reveals the local configuration of the magnetic fields. Other spectral lines of the visible range—such as the Hβ line (λ = 4861 Å)—can also be used to study the energy deposition in the lower solar atmosphere (Kuridze et al. 2020).

High time-resolution spectral observations of the Hα line profile provide very valuable data (Zarro et al. 1988; Graeter & Kucera 1992; Heinzel et al. 1994; Radziszewski et al. 2007; Druett et al. 2017; Falewicz et al. 2017). Canfield et al. (1984) investigated the effect of a nonthermal electron beam and coronal pressure enhancement on synthesized Hα line profiles,
and suggested that increased pressure can cause line profile broadening and increase the total intensity of the Hα line. Theoretical analyses were also performed by Heinzel (1991). He estimated the cooling time of the chromosphere to be of the order of one second. Thus, structures seen in strong chromospheric lines should change their brightness within similarly short time intervals, clearly revealing a high correlation of the variable HXR and Hα emissions. Many observations in the Hα line and X-rays have been made. Starting in the early 1980s, Kurokawa and his coworkers observed solar flares through a narrow-band Hα filter (Kurokawa et al. 1986, 1988; Kitahara & Kurokawa 1990). They found that the time lags between Hα and either hard X-ray or microwave emission are shorter than 10 s. Wang et al. (2000) made Hα observations of solar flares with a time resolution of 0.033 s. They found that, during the seven-second-long period, the Hα emission of a flare kernel showed fast (0.3–0.7 s) fluctuations correlated with variations of the HXR flux. Trottet et al. (2000) found a strong time correlation between HXR and Hα emission from a GOES X1.3 class flare on 1991 March 13. Radziszewski and coworkers (Radziszewski et al. 2006, 2007, 2011) subsequently investigated time variations of the Hα and X-ray emissions observed during the pre-impulsive and impulsive phase of numerous solar flares. They showed that, in many cases, the variations of the X-ray light curves recorded in various energy bands and the variations of the Hα light curves and line profiles were highly correlated and the time delay between relevant individual local peaks of the HXR and Hα emissions is only on the order of 1–3 s.

Several investigations have also shown the blue asymmetry of the Hα line profile during the early rise phase of the flare (see Heinzel et al. 1994 and references therein). However, the underlying physical processes remain elusive. In particular, although Heinzel et al. (1994) proposed that the early blueshift in the Hα line to be due to electron beams with return current, Kuridze et al. (2015) emphasized the role of steep gradient in the velocity of emitting plasma in shifting the wavelength of maximum opacity, thus adding another dimension of complexity to the implications obtained merely by the shift in the Hα line profile. A direct comparison of the observed and modeled properties of the time variations of the Hα and X-ray emissions can also give new clues with regard to physical processes acting at the flaring loop footpoints. Falewicz and coworkers (Falewicz et al. 2017) compared time variations of the Hα and X-ray emissions observed during the pre-impulsive and impulsive phases of the C-class solar flare with those of plasma parameters and synthesized X-ray emission from a hydrodynamic numerical model of the flare. The time variations of the X-ray fluxes in various energy bands, Hα intensities, and Hα line profiles were well-correlated, and the timescales of the observed variations agreed with the calculated variations of the plasma parameters at the flaring loop footpoint, reflecting the time variations of the vertical extent of the energy deposition layer (EDL).

The high time-resolution observations of Hα line profiles and light curves provide comprehensive information on the dynamical processes during the various stages of the flare evolution, which can be compared with numerical models of the flares based on multiband (X-rays, UV, visual) data and state-of-the-art numerical codes. In this paper, we investigate and discuss the evolution of a so-called EDL of a medium-class C1.6 solar flare observed at 10:20 UT, 2012 September 10, in active region NOAA 11564. In Section 2, we present the basic properties of this flare and the data used in this study. In Section 3, we describe an analysis of the data. In Section 4, we present an extended analysis of fast reactions of the Hα emission and the shape of the line profile of the impulsive heating of the plasma by the NTEs. Section 5 presents the numerical model of the flare. Section 6 provides the outcomes of a single-loop one-dimensional hydrodynamic (1D-DH) model of the flare in the context of the evolution of the EDL during the various phases of the flare, compared with a detailed analysis of variations of the HXR and Hα emissions. In Section 7, we present a discussion and conclusions from this analysis.

2. C1.6 Solar Flare on 2012 September 10

The C1.6 GOES-class solar flare occurred in the $\beta\gamma$-type active region NOAA 11564 (S13W8, $x = 850^\circ$, $y = -225^\circ$) at about 10:20 UT on 2012 September 10 (Figure 1). A very faint pre-flare increase of the soft X-ray emission was recorded by GOES-15 satellite at about 10:19 UT. The initial increase of the X-ray emission started at 10:19:30 UT; the impulsive phase of the flare started at 10:21:15 UT and ended at 10:21:52 UT (Figure 2). Maximum emission in GOES was C1.6 at 10:24:00 UT (Figure 2). Between 10:21:25 UT and 10:21:52 UT, the RHESSI satellite (Lin et al. 2002) recorded a strong hard X-ray emission in the 20–70 keV energy range (Figure 3). The X-ray flux was low enough that the attenuators were activated only after 10:22:40 UT (before this time, they remained in A0 state).

Between 10:20 UT and 10:43 UT, the flare was also observed in the hydrogen Hα line ($\lambda = 6563$ Å) with the Horizontal Telescope (HT) and Multi-channel Subtractive Double Pass imaging spectograph (MSDP) installed at the Białków Observatory of the University of Wrocław (Mein 1991; Rompolt et al. 1993). The field of view (FOV) of the HT-MSDP compound system covered an area of 942 × 119 arcsec$^2$ on the Sun, centered on Hα brightenings seen in the NOAA 11564. Two-dimensional spectra images formed by the nine-channel prism box covered a 2.4 Å wide wavelength band around the Hα line and were recorded with the fast Andor iXon3 885 camera (1002 × 1004 px$^2$) with a spatial resolution of 1.6 s of arc per hardware pixel and spectral resolution of 0.4 Å. The cadence of the exposures was equal to 0.05 s (equal to 20 spectra images per second). The time variations of the Hα line profiles averaged over the brightest part of the Hα structure delimited with an isoncontour of 90% of the highest signal are shown in Figure 4.

The Hα emission of the flare was correlated in space and in time with the impulsive brightenings recorded in the hard X-ray and UV bands by the RHESSI and the SDO satellites (Lin et al. 2002; Pesnell et al. 2012), and it reached a maximum during the impulsive phase of the flare. The four intermediate emission peaks H1–H4 in the hard X-rays at 10:21:28 UT, 10:21:33 UT, 10:21:41 UT, and 10:21:47 UT, respectively, coincided with the intermediate maxima of the emission in the Hα line (Figure 5). Two intermediate X-ray peaks, labeled H1 and H2, marked with two green vertical lines, coincide with the pronounced Hα peak observed at about 10:21:30 UT. The next two X-ray peaks, labeled H3 and H4, coincided with the second, longer-lasting and substructured peak of the Hα emission observed between 10:21:35 UT and 10:22:05 UT. All intermediate increases of the Hα emission were recorded in various parts of the Hα line profile occurred immediately after
or nearly simultaneously with the hard X-ray pulses. Some differences in variations recorded in various parts of the Hα line profile reflect differences in penetration depths of the individual NTEs beams. The time derivatives of the GOES light curves show three unambiguous local maxima coinciding with the H1, H3, and H4 peaks seen in the RHESSI data. The H2 peak seen in the RHESSI data does not have a clear counterpart in the derivatives of the GOES light curves, but a small increase of the derivative of the 0.5–4 Å GOES light curve can be discerned. A long and dense Hα surge was ejected along an arcade of the magnetic loops anchored in the NOAA 11564 active region just at the beginning of the impulsive phase of the flare. However, its optically dense plasma did not obscure any Hα flaring kernel up to 10:22:40 UT.

3. Data Processing

Data collected by the RHESSI with its 3F, 5F, 6F, and 8F detectors allowed the restoration of images of the flaring structures seen in X-rays. The PIXON image restoration algorithm was applied, with effective pixel size equal to one second of arc. A 20 s long signal accumulation time was selected to obtain a sufficient signal-to-noise ratio (Metcalfe et al. 1996; Hurford et al. 2002). X-ray data from RHESSI were applied also for the reconstruction of light curves and X-ray energy spectra (Figure 6). X-ray fluxes recorded in the 6–10 keV energy range were summed over the front segments of six detectors: 1F, 3F, 5F, 6F, 8F, and 9F. The fluxes recorded in the energy range 10–70 keV were summed over the seven detectors: 1F, 3F, 5F, 6F, 7F, 8F, and 9F. The 2F and 4F detectors were excluded due to their excessively enhanced backgrounds. All details concerning the processing of the RHESSI data with the use of the OSPEX package of the SolarSoftWare (SSW) as the subtraction of the background from RHESSI and GOES data are described in detail in Paper I. For consistency with the results presented in Paper I, the whole X-ray flux was divided into four energy subranges: 6–10, 10–20, 20–34, and 34–70 keV.

The reconstructed RHESSI X-ray light curves have a native four-second-long time resolution determined by the rotation period of the spacecraft. To facilitate a qualitative comparison of concurrent variations of the emissions observed in the X-rays and the Hα line, to obtain a much higher time resolution of 0.05 s, the X-ray light curves were demodulated to a time resolution of 0.25 s using the SSW demodulation procedure of G. Hurford (2004, private communication). All demodulated X-ray light curves were smoothed by a one-second-wide boxcar filter to suppress noises.

The X-ray spectra recorded by RHESSI during the impulsive phase of the flare revealed thermal and nonthermal components. The spectra were therefore fitted with a single-temperature thermal plus thick-target (version 2) model (vth + thick2) available in the RHESSI SSW software. The thick-target model was defined by the total integrated electron flux \( N_{\text{th}} \), the power-law index of the electron energy distribution \( \delta \), and the low-energy cutoff of the electron distribution \( E_c \). The actual values of the \( E_c \) and \( \delta \) were controlled and rectified in
The spectra collected during the pre-impulsive phase, the impulsive phase, when the nonthermal component was in forward and backward directions, starting from a maximum range: 6–10 keV, 10–20 keV, 20–34 keV, and 34–70 keV during the impulsive phase of Cl.6 GOES-class solar flare on 2012 September 10. Light curves were recorded without the attenuators (A1 was activated at 10:22:44 UT), demodulated to a time resolution of 250 ms, and smoothed with a one-second-wide boxcar filter. Vertical green lines (marked H1, H2) and purple lines (marked H3, H4) indicate four intermediate maxima of the hard X-ray emission observed in the 20–34 keV energy range (see main text for discussion).

Figure 3. X-ray light curves recorded by RHESSI satellite in four energy ranges: 6–10 keV, 10–20 keV, 20–34 keV, and 34–70 keV during the impulsive phase of Cl.6 GOES-class solar flare on 2012 September 10. Light curves were recorded without the attenuators (A1 was activated at 10:22:44 UT), demodulated to a time resolution of 250 ms, and smoothed with a one-second-wide boxcar filter. Vertical green lines (marked H1, H2) and purple lines (marked H3, H4) indicate four intermediate maxima of the hard X-ray emission observed in the 20–34 keV energy range (see main text for discussion).

case of excessively abrupt variations. The fits were calculated in forward and backward directions, starting from a maximum of the impulsive phase, when the nonthermal component was strong and distinct. Figure 6 shows three examples of the spectra collected during the pre-impulsive phase, the impulsive phase, and just after the impulsive phase of the flare.

The spectra images collected with the MSDP spectrograph were processed in a standard way, discussed in detail in previous publications by Radziszewski et al. (2006) and Radziszewski & Rudawy (2013). For all spectra images, the Hα line profiles were reconstructed for all pixels of the FOV in the spectral range of $\Delta \lambda = \pm 1.2$ Å from the Hα line center. Furthermore, quasimonochromatic images of the entire FOV were reconstructed in 13 wavelengths separated by 0.2 Å (an effective wave band of the images was equal to 0.06 Å). Due to some instabilities of the telescope pointing and a variable atmospheric seeing causing deformations and shifts of the observed structures, a special customized procedure was applied to correct displacements of Hα images; see Radziszewski et al. (2007) for details. The SDO/HMI continuum images were used for precise co-alignment of the Hα images with the coordinate system of the satellite data. Using these data, the light curves of the flaring kernel were evaluated in freely selected wavelengths over the range $\Delta \lambda = \pm 1.2$ Å from the line center for the whole period of the MSDP observations (Figure 7).

4. Impulsive Phase of the Flare

In this section, we present a detailed analysis of changes of Hα hydrogen spectral line profiles ($\lambda_0 = 6562.8$ Å) during the impulsive phase of the 2012 September 10 flare, in order to relate fast changes of Hα emission to energy conveyed to the chromosphere by NTEs. In general, variations of the integrated emission of the whole flare kernel, which can be delimited by an arbitrarily selected isophote, have time histories that differ significantly from the variations of the emission of selected, brightest nuclei of the kernel, limited also by another arbitrarily selected and substantially higher isophote. For the purposes of this analysis, measurements of the integrated emissions of the flaring kernels and local nuclei of the kernel were performed applying isophotes of 90% and 98% of the highest signal, respectively. Here and everywhere further in this work, the emission level is referred to as a measured emission with subtracted emission of the quiet chromosphere.

Panels (a) and (b) of Figure 4 show variations of the mean profiles of the Hα line emitted by the flaring kernel delimited by 90% isophote of the maximal emission, while Figure 5 shows variations of the integrated emission of the kernel delimited by the same isophote.

The MSDP spectrograph provides spectral observations with a high time resolution (0.05 s), collected simultaneously for the entire observed region of the solar disk while maintaining two-dimensional spatial resolution (limited by seeing only). Thanks to this, it was possible to determine a course of fast local variations of the Hα line intensities and line profiles emitted by spatially limited, bright subnuclei of the flaring kernel. Due to the high time correlation of variations of the emission observed in HXRs and the emission of the selected small nuclei of the flaring kernel in the Hα line, these nuclei were considered to be spatially limited and in time-limited regions of energy deposition by beams of the nonthermal electrons. The conductive transport of the energy along the flaring loops has not been considered, because transport through conductivity is much slower, being typically 10 s (Radziszewski et al. 2007, 2011), and so cannot be responsible for the fast changes seen.

During the impulsive phase of the investigated flare, four separate maxima (pulses) of the HXR emission were recorded at $T_{\alpha} = 10:21:28$ UT, $T_{\beta} = 10:21:33$ UT, $T_{\gamma} = 10:21:41$ UT, and $T_{\delta} = 10:21:47$ UT, and were marked as H1, H2, H3, and H4, respectively (see Section 2 for details). For each of these pulses, the time evolution of the Hα line profiles emitted from the lightest area in a frame of a whole Hα flaring kernel was analyzed within a period DTi lasting from $T_{\alpha} - 2$ s to $T_{\delta} + 2$ s, respectively. Due to the short duration of the nonthermal electron beams and the short reaction time of the chromosphere to the local deposition of the energy, the selected length of the time intervals is sufficient for this analysis (Figure 8).

During the DT1 interval (H1 pulse), the mean Hα line profile of the nucleus of the flaring kernel delimited by the 98% isophote was continually asymmetrical, having emission in the red wing higher than in the blue wing. During the whole time
Figure 4. Left panel: variations of the mean Hα line profile of the flaring kernel delimited with an isocontour of 90% of the highest intensity in the Hα line center. Mean Hα line profile of the nearby region of the quiet solar chromosphere (QCh) is shown as the dotted black line. Profiles drawn in orange, green, blue, and purple correspond to the H1, H2, H3, and H4 peaks of the HXR recorded at 10:21:28 UT, 10:21:33 UT, 10:21:41 UT, and 10:21:47 UT, respectively. Red profile was taken during the impulsive phase of the flare at 10:21:20 UT (before the H1 peak). Middle panel: full time-cadence series of the mean Hα line profiles of a part of the flaring kernel delimited with an isocontour of 90% (as in the left panel). Time is given in seconds after 10:21:20 UT. Right panel: variations of the mean Hα line profile of the brightest fragment of the flaring kernel delimited with an isocontour of 98% of the largest intensity in the Hα line center. All profiles are normalized to unity from line-center intensity of QCh to blue wing at −1.0 Å.

Figure 5. Hα line light curves recorded in $\lambda = \lambda_{00} - 1.0 \, \AA$, $\lambda = \lambda_{00}$, and $\lambda = \lambda_{00} + 1.0 \, \AA$ with the HT-MSDP system during the C1.6 GOES-class solar flare on 2012 September 10. Double green and purple vertical lines indicate four intermediate maxima (H1–H4) of the hard X-ray emission recorded by the RHESSI satellite above 20 keV.

interval, a systematic but gradual increase of the Hα line emission was observed, each step lasting about a second. The observed variations of the Hα emission may indicate that the stream of the nonthermal electrons inducing the H1 pulse of HXR radiation was varied in time, showing subsecond-long changes in the efficiency of the magnetic reconnection and/or acceleration of electrons.

During the DT2 interval (which included the H2 pulse), very abrupt changes of the mean Hα line profile of the nucleus of the flaring kernel delimited by 98% isophote were observed. In just half a second, from 10:21:32.75 UT to 10:21:33.25 UT, the emission in the blue wing of the profile at the wavelength $\lambda = \lambda_0 - 0.4 \, \AA$ dropped sharply, but increased in the red wing of the line at the wavelength $\lambda = \lambda_0 + 0.4 \, \AA$. The strong asymmetry of the profile persisted until just over a second after $t_{02}$ (after the maximum of H2), and then it decreased, but the profile remained asymmetrical all the time. The strong asymmetry of the profile lasted less than 2 s and it was well-correlated in time with the HXR pulse marked H2. Sudden changes of asymmetry of the profiles measured for the wavelengths $\lambda = \lambda_0 \pm 0.4 \, \AA$ can be attributed to short-lasting plasma motions with a velocity amplitude of $\pm 20 \, \text{km s}^{-1}$.

In a case of the H3 pulse, the emission of the subnucleus of the flaring kernel, delimited by the 98% isophote measured at the Hα line, reached a maximum one second after the maximum of the H3 pulse in HXR (at 10:21:42 UT) and then began to decrease, so as little as two seconds after the impulse (at 10:21:43 UT), the emission measured in the center of the Hα line returned to the prepulse level. In total, the impulsive enhancement of the Hα emission lasted only three seconds, while the emission profile remained asymmetrical throughout.

In the case of the H4 pulse, during the DT4 period, the Hα emission of the nucleus of the flaring kernel delimited by the 98% isophote reached a maximum in less than one second after the maximum emission recorded in HXR (at 10:21:47.60 UT), and then began to decrease, reaching 1.5 s after the maximum of the HXR pulse (at 10:21:48.50 UT), i.e., a lower level than before the pulse. Such a fast decrease of the emissions in the Hα line agrees with the assumption of a very fast relaxation of the chromosphere after a rapid heating by NTEs.

Figure 8 shows variations of the mean Hα profiles emitted by the relevant subnuclei of the flaring kernel delimited by 98% isophote during the four-second time intervals encompassing H1, H2, H3, and H4 HXR pulses, respectively. Figure 8 (left column) shows three representative Hα profiles selected from...
the profiles shown in Figure 8 (right column): the Hα line profile at the moment of the HXR pulse maximum, as well as profiles measured 2 s before and 2 s after the maximum of the HXR pulse. Four examples of Hα line profiles evolution for various nuclei (98% isophote) of the flaring kernel are given in online material.

5. Numerical Model of the Flare

The 1D–HD numerical model of the flare was calculated using the modified hydrodynamic one-dimensional Solar Flux Tube Model; see Mariska et al. (1982, 1989) and Falewicz et al. (2009) for details. A discussion of the use and accuracy of the 1D–HD numerical models of the solar flares was given in Paper I (Falewicz et al. 2017 and references therein), where we showed that 1D–HD numerical models remain a valuable tool in investigations of the solar flares thanks to their moderate complexity and moderate volume of the necessary calculations.

The model was calculated under the basic assumption that plasma confined in the flaring loop was heated only by variable NTE beams. This assumption is supported by the results of Falewicz et al. (2011) and Falewicz (2014) demonstrating that, in some flares, the energy delivered by NTEs fulfills the energy budgets during the pre-impulsive and impulsive phases of the flare. However, in many other flares, the energy carried by NTEs is not large enough to balance the budget, thus some auxiliary energy sources and transfer mechanisms are active (Liu et al. 2013; Aschwanden et al. 2016).

The restored RHESSI X-ray images were used for the evaluation of the main geometric characteristics of the flaring loop. Following Paper I, the area and positions of the flare footpoints were evaluated using the SSW CENTROID procedure, the 30% intensity contour was selected as the delimiter of the footpoints, and the perspective foreshortening was reduced using the method proposed by Aschwanden et al. (1999). To obtain a reasonable agreement between synthetic and observed X-ray light curves, the cross section and the length of the loop were arbitrarily adjusted in their error ranges.

The initial pressure in the transition region in the loop and the spatial distribution of temperature along the loop were selected to obtain a steady state of the plasma inside the loop before the flare. The derived constant cross section of the loop was equal to $S = (1.14 \pm 0.93) \times 10^{16} \text{ cm}^2$, and the half-length was...
Figure 8. Left column: \(H\alpha\) line profiles of the brightest part of the flaring kernel delimited with an isocontour of 98% of the highest intensity in the \(H\alpha\) line center recorded two seconds before, at the moment of, and two seconds after the H1, H2, H3, and H4 peaks of the HXR recorded at 10:21:28 UT, 10:21:33 UT, 10:21:41 UT, and 10:21:47 UT, respectively. Right column: four-second-long series of the mean \(H\alpha\) line profiles of the same part of the flaring kernel (98%—like in the left column), and the same time intervals for H1–H4 peaks. Individual time series of profiles in the right column are displayed at a right angle to highlight the individual character of each profile’s changes. All profiles are normalized as in Figure 4. An animation of the right column panels is available. In the video, the \(H\alpha\) line profiles are rotated about the intensity axis to give views of the time and wavelength axes. The video makes one rotation in its 9 s duration. (An animation of this figure is available.)
were adjusted. The slight differences between the observed and synthetic GOES 1–8 Å fluxes by modification of an amount of the absorbed energy. Steady-state spatial and spectral distributions of the NTEs along the flaring loop were calculated for each time step of the model using the Fokker–Planck formalism (McTiernan & Petrosian 1990). Using these data, spatial distributions of the thermodynamic parameters of the plasma—X-ray thermal and nonthermal emissions, and the integral fluxes in the selected energy ranges—were calculated for each time step. The thermal emission of the optically thin plasma was based on the X-ray continuum and line emissions calculated using the CHIANTI (version 7.1) atomic code (Dere et al. 1997; Landi et al. 2006). For plasma temperatures above \(10^5\) K, the element abundances are based on the coronal abundances (Feldman & Laming 2000), while below \(10^5\) K, photospheric abundances were applied.

Emitted X-ray fluxes, plasma temperatures, and emission measures, derived from GOES-15 fluxes before and during the impulsive phase of the flare, compared with the same quantities calculated using the numerical model of the flare, are shown in Figure 9. The computed GOES temperatures are representative of the plasma with the highest differential emission measure in the flare. The emission measures were calculated as integrals of the computed differential emission measures for plasma hotter than 1 MK only. The synthetic GOES 0.5–4 Å flux calculated at various stages of the plasma in the numerical model qualitatively followed the observed one. The fluxes were nearly equal at the beginning of the flare only, between 10:21:30 UT and 10:22:00 UT, but after 10:22 UT up to 10:26 UT, the modeled flux was always lower than the observed one. The synthetic GOES 1–8 Å flux equaled the observed flux if the \(E_e\) were adjusted. The slight differences between the observed and modeled GOES 0.5–4 Å fluxes (Figure 9, upper panel) are reflected in temperature variations of the plasma temperatures and emission measures (Figure 9, central and lower panels) because any variation of the 0.5–4 Å flux ratio causes proportional differences in the estimated temperatures and emission measures of the plasma (White et al. 2005). As a result, between 10:22 UT and 10:26 UT, the calculated temperatures were always lower and the calculated emission measures were always higher than the respective observed quantities.

6. Results

The MSDP spectrograph provides spectra with a high time resolution (0.05 s), simultaneously for the entire observed region of the solar disk while maintaining two-dimensional spatial resolution (limited by seeing). It was thus possible to determine variations of the chromospheric flaring emission in the \(H\alpha\) hydrogen line, resulting from short-lasting and spatially limited energy supplied by the beams of the nonthermal electrons. Local variations of the chromospheric emission in the \(H\alpha\) hydrogen line during the impulsive phase of the compact solar flare of the September 10 flare were analyzed. The results of the observations collected in the \(H\alpha\) line were compared with the measured HXR emission, while by demodulating the data, the time resolution was improved to 250 ms (G. Hurford 2004, private communication).

It has been found that the local changes of the \(H\alpha\) emission, measured for the subnuclei of the flaring kernel delimitied by 98% isophote, are closely correlated in time with the variations of the HXR emissions. These variations occur significantly more dynamically than variations of the emission of the entire flaring kernels, limited by any significantly lower isophote, e.g., 90% of maximum emission. Thus, these areas can be considered as local and short-lasting areas of the energy deposition by the nonthermal electron beams.

The variations of the emission of the individual subnuclei of the flaring kernel occur on subsecond timescales, showing various forms of variability: (a) pulsating increases in brightness (H1 pulse); (b) sudden asymmetries of the \(H\alpha\) profile if measured for \(\lambda = \lambda_0 \pm 0.4\) Å (H2 pulse); (c) impulsive increases of the emission (H3 pulse); (d) abrupt but short-lasting increase of the emission while maintaining the asymmetry of the profile (H4 pulse).

Measurements of variations of the mean \(H\alpha\) emissions of entire flaring kernels are useful for analyzing the global features of the phenomenon (e.g., flash curve analysis) only. However, the analysis of individual episodes of local interactions between
nonthermal electron beams and a chromosphere is possible only with the use of spectral observations made with high temporal and spatial resolution, and should be carried out using data collected for selected, small areas only, with the highest emission within the whole Hα flaring kernel.

The observed rapid local variations of the profiles and emission intensities of the Hα line testify to very fast changes in the parameters of the chromospheric plasma as a result of rapid changes of the energy flux supplied locally by the beams of the nonthermal electrons during subsequent episodes of the impulsive phase. The course of variations of the emissions profiles of the Hα line compared with the variations of the HXR emissions indicates that the reaction time of the chromosphere to changes in the supplied energy flux manifested through the changes in the profiles of the emitted Hα line is only a few tens of a second.

To compare the X-ray light curves observed by the RHESSI and synthesized X-ray light curves calculated with the model, the calculated thermal and nonthermal emissions and the estimated observed background emission were summarized. For the most rapidly varying part of the impulsive phase, between 10:21:30 UT and 10:23:00 UT, four light curves summarized over the 6–10 keV, 10–20 keV, 20–34 keV, and 34–70 keV energy bands are presented in Figure 10. While the calculated X-ray fluxes were expressed in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\), the observed X-ray fluxes were converted to the same units using two standard methods. In the first method, the RHESSI instrumental response matrix with diagonal coefficients only was applied and the time resolution was equal to four s. In the second method, the full RHESSI instrumental response matrix was used, but the time resolution was much worse, due to the necessary accumulation time being much longer.

In the 34–70 keV and 20–34 keV energy bands, the X-ray emissions of the flare were dominated by nonthermal processes, and thus the variations of the nonthermal component define the total emission. Due to obvious differences in the applied conversion methods, the converted observed fluxes in this energy range differ by a factor up to five, but the calculated variations of the X-ray flux are within the statistical ranges of the observed flux count rates. The relative contribution of the nonthermal component decreases in the lower energy bands, where in the 6–10 keV band, the thermal component plays a dominant role. The agreement of the observed and synthesized light curves in both energy bands (6–10 keV and 10–20 keV) was good (to a factor of two) only during the short period (10:21:30 UT and 10:21:50 UT) when the NTE beams precipitated along the loop and the plasma had just begun its sudden evaporation. The total emission was dominated by nonthermal flux in the 10–20 keV energy band, but by thermal flux in the 6–10 keV band. Nonetheless, in both cases, the modeled fluxes have correct proportions and total amounts. However, after this period, the observed emission was dominated by thermal emission and the observed flux became one order larger than the calculated one, apparently due to the errors of the modeled densities and temperatures of the plasma along the loop.

The NTEs deposit the energy along the whole flaring loops, but a vast majority of the energy is deposited inside limited plasma volumes called the EDL, located chiefly in the chromospheric parts of the loops. The upper and lower boundaries of the EDL can be defined arbitrarily (following the Paper I) as altitudes where the deposited energy fluxes start to increase rapidly near the chromosphere and where they drop below 0.01 erg s\(^{-1}\) cm\(^{-3}\) inside the chromosphere, respectively.

The GOES and the RHESSI satellites recorded the first noticeable increase of the X-ray emission at 10:18:30 UT. The pre-flare gradual increase of the emission ended at about 10:21:12. An impulsive increase of the X-ray emission started at 10:21:12 UT in all applied RHESSI energy channels. During the impulsive phase, the RHESSI also recorded four individual intermediate peaks of the hard X-ray emission, easily visible in energies above 10 keV. The first two pulses peaked in the energy range 20–34 keV at 10:21:28 UT and 10:21:33 UT, respectively. The two much stronger pulses peaked at 10:21:41 UT and 10:21:47 UT, respectively. Due to variances of the thermal emission, the hard X-ray emission above 20 keV returned to the pre-flare background level at about 10:21:53 UT, while in the 6–10 keV and 10–20 keV bands, the fluxes persistently increased beyond the end of the impulsive phase of the flare. During the early phase of the flare, the maximal flux of the deposited energy was on the order of 2839 erg s\(^{-1}\) cm\(^{-3}\), causing gradual heating of...
the local plasma. The GOES class of the flare peaked at C1.6 only, but the flare emitted X-rays having energies up to 70 keV.

Up to 10:21:32 UT, the calculated vertical extent of the EDL equal to $D = 500$ km remained constant due to the slow evaporation of the plasma (Figure 7). The upper boundary of the EDL has an initial altitude of $H_u = 1400$ km above the temperature minimum. It started a slow, continual decline concurrently with the H2 intermediate peak of the X-ray emission at about 10:21:33 UT. As a result, up to 10:21:35 UT, the thickness of the EDL was gradually reduced to $D = 450$ km and the altitude of its upper boundary dropped to $H_u = 1350$ km. Just after the end of H2, the thickness of the EDL abruptly increased to $D = 1150$ km as a result of a sudden reduction of the lower boundary in response to a greatly increased flux of the deposited energy. At 10:21:40 UT and 10:21:44 UT, the EDL expanded again to $D = 1450$ km and $D = 1625$ km, respectively, corresponding to the energy deposited by the NTE beams manifested by the H3 and H4 peaks. At the moment of the maximum vertical extent, the upper boundary of the EDL was at an altitude of $H_u = 1325$ km while the lower boundary was at an altitude of $H_D = -300$ km, i.e., below the temperature minimum level. Just after the maximum of the H4 intermediate peak, the lower boundary of the EDL returned instantly to the temperature minimum ($H_D = 0$ km), and just after the end of the H4 intermediate peak at 10:21:52 UT, it returned instantly to the altitude of about $H_D = 1000$ km, a little above the altitude at the pre-impulsive phase of the flare. At the same time, the upper boundary of the EDL lowered gradually to $H_u = 1250$ km, thus the resulting vertical extent of the EDL shrank to only $D = 250$ km. The minimal vertical extent of the EDL equal to $D = 175$ km was achieved at 10:22:12 UT due to a persistent reduction of the altitude of the upper boundary and a small increase of the altitude of the lower boundary. At the same time, the impulsive enhancement of the Hα emission ended as well. The EDL widened again to $D = 420$ km starting from 10:22:28 UT, concurrent with the subsequent increase of the hard X-ray flux best seen in the 20–34 keV but noticeable also in remaining X-ray energy bands.

Due to the effects of perspective, the Hα brightening was located near the central part of the extended loop-shaped structure visible in the X-rays images (see Figure 1). The increased Hα emission was recorded from the very beginning of the observations at 10:20:00 UT in the red wing of the Hα line (see Figure 5) and at about 10:20:50 UT in the Hα line center. In the blue wing of the line profile, the emission dropped a little up to 10:21:10 UT but sharply increased afterward. The light curves presented in Figure 5 are scaled to the signal of the quiet Sun (QS), and the wavelengths of the emission are measured in the reference systems of the emitting plasma, i.e., correcting for solar rotation and proper motions along the flaring loop.

An intermediate peak of the Hα emission, recorded between 10:21:30 and 10:21:33 UT in the blue wing of the line, at 10:21:30 UT in the line center, and at 10:21:33 UT in the red wing, occurred concurrently with the H1 and H2 peaks of the X-ray emission recorded by the RHESSI satellite. The H1 and H2 peaks had similar fluxes in the 10–20 keV and 20–34 keV energy bands, but in the 34–70 keV energy band, the H1 peak was much fainter than the H2 peak. Thus, the NTE beams related to H1 and H2 peaks had various energies, and the NTEs related to the H1 peak precipitated a little more shallowly than the NTEs related to the H2 peak, and they deposited their energy in various altitude ranges of the chromosphere. The maximum of the Hα emission was recorded between 10:21:40 UT and 10:21:53 UT. The emission in the line center and the blue wing of the profile ($-1.0$ Å) peaked almost simultaneously at 10:21:45 UT, while the maximum in the red wing ($+1.0$ Å) peaked about 10:21:53 UT. The maximum occurred concurrently with the H3 and H4 peaks of the X-ray emission recorded by the RHESSI satellite. The H3 peak of the HXRs had a substantially lower flux than the H4 peak in all energy bands, but their energy spectra were similar. Thus, in both cases, the NTE beams deposited energy in the same range of altitudes and caused nearly simultaneous increases of the emission in the whole profile.

The variations of the Hα emission in various parts of the line profile are shown in Figure 11 by the variations of the wing-to-line-center intensity ratios (IRs). The IRs measured at $\Delta \lambda = \pm 0.5$ Å, $\Delta \lambda = \pm 0.7$ Å, and $\Delta \lambda = \pm 1.0$ Å respectively during the impulsive phase of the C1.6 GOES-class solar flare on 2012 September 10. Vertical green and purple lines indicate four intermediate maxima of the hard X-ray emission recorded by RHESSI in the 20–34 keV energy range.
wavelength ranges, most noticeably in the far wings of the line (±1.0 Å). Concurrently with the first intermediate X-ray peak H1, the IRs peaked briefly at 10:21:28 UT. Following this, the IRs increased much more between 10:21:30 UT and 10:21:46 UT. During this increase, the relatively faint H2 intermediate X-ray peak occurred over the course of an ascent stage while a much stronger H3 peak occurred during a descending phase. Despite relatively high emission of the H3 peak, it was barely marked with a tiny intermediate increase of the IRs only.

The H4 intermediate peak of the X-ray emission, having the highest emission X-ray flux, occurred just at the beginning of a new strong increase of the IRs at 10:21:48 UT. The increase of the IRs was best seen in the red wing of the Hα line, but it was also recognizable in the blue one. The IRs increased first to a level similar to the previous one, then after a decrease it remained constant or slightly increased at all wavelengths. The IR variations were synchronized with the relevant peaks of the X-rays, and the time delays between X-ray impulses and abrupt variations of the Hα profiles were virtually equal to zero.

7. Discussion and Conclusions

The 1D hydrodynamic numerical model of the 2012 September 10 flare was calculated under the assumption that the NTEs carried the entire flare energy. The flare emitted hard X-ray flux detected by the RHESSI up to an energy of 70 keV, thus the clear nonthermal component of the RHESSI spectra was easily distinguished and the NTE energy derived. The model was optimized by an automatic fit of an actual value of the cutoff energy parameter $E_c$ to obtain a good match between observed and calculated GOES-15 soft X-ray fluxes measured in the 1–8 Å wave band. The chief geometrical parameters of the flare, like loop length and diameter, were derived using derived imaging RHESSI data. The modeled variations of the vertical extent and the altitude of the EDL were compared with variations of the high time-resolution spectra and emission intensities observed in the Hα line.

To compare the X-ray light curves observed by the RHESSI and synthesized X-ray light curves calculated with the numerical model of the flare, the emitted X-ray fluxes and the estimated backgrounds were calculated for the impulsive phase of the flare in 6–10 keV, 10–20 keV, 20–34 keV, and 34–70 keV energy bands (selected to be consistent with the energy bands applied in Paper I). The relevant observed X-ray fluxes were converted to photon $cm^{-2}s^{-1}keV^{-1}$ units twice, first using the RHESSI instrumental response matrix with diagonal coefficients for data with four-second time resolution, and then using the full RHESSI instrumental response matrix for data with longer accumulation times.

The X-ray emission of the flare above 20 keV was dominated by the nonthermal processes, and the calculated X-ray fluxes in the 20–34 keV and 34–70 keV energy bands are within the limits of the observed fluxes restored by both methods (Figure 9). Below 20 keV, the relative contribution of the nonthermal component decreases substantially, and in the 6–10 keV band, the thermal component plays a dominant role. The agreement of the observed and synthesized light curves in 6–10 keV and 10–20 keV energy bands was good only during the short period when the NTE beams precipitated along the loop and the plasma just started the violent evaporation. During this period, in the 10–20 keV energy band, the emission was dominated by the nonthermal flux, while in the 6–10 keV band, it was dominated by the thermal emission. In both cases, the modeled fluxes have correct contributions and total amounts. Four intermediate peaks (H1–H4) of the hard X-ray emission occurred at nearly even intervals in time. Such quasi-periodicity of the peaks could reflect a quasi-periodic variation of efficiency of an involved acceleration process of the nonthermal electron beams (Aschwanden et al. 1994; Wang et al. 2002; Srivastava et al. 2008; Zimovets & Struminsky 2010; Hayes et al. 2019).

After the impulsive phase, the total observed emission of the flare was dominated by a thermal component. The observed flux was one order larger than the calculated one. As was discussed in Paper I, the abovementioned differences between the modeled and the observed fluxes were caused by the inevitable discrepancies between the spatial distribution of the local thermodynamic and kinematic parameters of the plasma in the numerical model and inside the real flaring loop as well as by differences in precipitation depths of the NTEs of various energies. The NTE beams containing large populations of high-energy electrons (i.e., with a hard spectrum) effectively precipitate down to relatively low altitudes into the chromosphere because they weakly interact with the plasma confined in the upper part of the loop. As a result, the relatively small portion of the transmitted energy is deposited in the upper part of the chromosphere and/or transition region, causing moderate “gentle evaporation.” In contrast to them, the low-energy NTEs efficiently deposit their energy in the upper part of the chromosphere, where the densities are relatively low, giving rise to “explosive evaporation” (for further details, see Falewicz et al. 2009). Thus, the HXR nonthermal emission is directly related to the total flux of the accelerated NTEs, whereas the XRR and HXR thermal emissions are related to the energy effectively deposited by the NTEs. As was discussed in Paper I, the assumed power-law energy spectrum of the injected NTEs also caused some differences between the modeled and the observed X-ray fluxes in the low-energy X-ray bands.

The variations of altitude and the vertical extent of the EDL are compared with the variations of the spectra and emission intensities recorded in the Hα line using the Multi-channel Subtractive Double Pass imaging spectrograph in the Białków Observatory. The spectra images were recorded with a time cadence of 0.05 s in an effective wave band of 2.4 Å. High-cadence series of the quasi-monochromatic images of the whole FOV and the light curves of the selected flaring kernels at various wavelengths were derived.

In the September 10 flare, the Hα emission of the flare was well-correlated spatially and in time with the impulse brightenings recorded in the hard X-rays by RHESSI. The Hα emission reached a maximum during the impulsive phase of the flare, while the noticeable intermediate maxima of the Hα emission coincided with intermediate emission peaks detected in the hard X-rays during the impulsive stage. Agreement of the spatial and time variations of X-ray fluxes at all energies with the H-alpha variations validate our previous results (Radziszewski et al. 2007, 2011; Falewicz et al. 2017).

The NTEs deposited energy along the whole flaring loop, but a vast majority of the energy was deposited inside limited plasma volumes called the EDLs, located in the chromospheric sections of the loops. The upper and lower boundaries of the EDL can be defined arbitrarily (following Paper I) as altitudes where the deposited energy fluxes start to increase rapidly nearby the chromosphere (the upper limit) and where they drop.
below 0.01 erg s\(^{-1}\) cm\(^{-3}\) inside the chromosphere (the lower limit), respectively. The vertical extent and the altitude of the EDL can be modeled numerically but cannot be observed directly in any spectral range. However, the spatial and time variations of the modeled emissions can be compared with the observed ones, indirectly confirming the correctness of the model—and thus the correctness of the reconstructed parameters of the EDL and their changes.

The emission of the flare in the H\(_\alpha\) line started to brighten exactly at the beginning of the impulsive phase, at 10:20:00 UT in the red wing of the H\(_\alpha\) line (see Figure 4), at about 10:20:50 UT in the H\(_\alpha\) line center, and at 10:21:10 UT in the blue wing of the line profile (after a short but noticeable drop of the intensity; see Section 6).

The vertical extent of the EDL during the initial stage of the impulsive phase was 500 km, and it remained constant up to 10:21:32 UT due to the slowly evaporation of a gently heated plasma. An intermediate peak of the H\(_\alpha\) emission was recorded between 10:21:30 UT and 10:21:33 UT, concurrent with the H1 and H2 peaks of the X-ray emission recorded by the RHESSI satellite. The NTE beams related to the H1 and H2 peaks had various energies, and they deposited energy at various altitudes in the chromosphere. At 10:21:44 UT, the EDL expanded to \(D = 1625\) km, due to a sudden decrease in height of its lower boundary caused by substantially increased energy deposition at low altitudes in the chromosphere by the high-energy and deeply penetrating NTEs. These NTEs were manifested by the intermediate H3 and H4 XHR peaks seen in the 34–70 keV energy bands. Just after the H4 peak, at about 10:21:53 UT, the vertical extent of the EDL shrank to \(D = 250\) km, because the energy flux deposited at low altitudes nearly vanished. The maximum of the H\(_\alpha\) emission was recorded at the same time, between 10:21:40 UT and 10:21:53 UT. The emissions in the H\(_\alpha\) line center and the blue wing of the profile (\(\sim 1.0\) Å) peaked almost simultaneously at 10:21:45 UT, while the emission in the red wing (\(\sim 1.0\) Å) peaked at about 10:21:53 UT. The H3 and H4 peaks of the HXRs had similar energy spectra, so the related NTEs electron beams deposited energy inside the same range of altitudes, down to an altitude of \(H_0 = 200\) km below the pre-flare altitude of the temperature minimum, and caused nearly simultaneous increases of the whole line profile.

The upper boundary of the EDL had an initial altitude of \(H_u = 1400\) km above the temperature minimum, but due to the plasma evaporation, it gradually reduced to \(H_u = 1250\) km at the end of the HXR emission at 10:21:53 UT. Eventually, it reduced to an altitude of \(H_u = 1175\) km at the end of the modeled period as a result of an ongoing gentle plasma heating and evaporation by low-energy NTEs. The lower boundary of the EDL had an initial altitude of \(H_b = 900\) km above the temperature minimum, but due to three consecutive episodes of intense heating by the high-energy NTEs, it suddenly decreased to an altitude of \(H_b = -300\) km at the maximum of the HXR emission at 10:21:44 UT, below the initial altitude of the temperature minimum. Just after the end of the HXR emission, the lower boundary of the EDL returned instantly to the altitude of about \(H_b = 1000\) km, a little above the altitude noticed during the pre-impulsive phase of the flare.

The differences between variations of the emissions recorded in various parts of the H\(_\alpha\) line profile are well-illustrated by the variations of the wing-to-line-center intensity ratios (IRs). A slow, gradual decrease of the IRs occurred in all discussed wavelength ranges during the pre-impulsive phase of the flare. Next, the IRs increased noticeably between 10:21:30 UT and 10:21:46 UT, concurrently with the H2 intermediate HXR peak. However, the much stronger H3 intermediate X-ray peak was barely marked with a tiny intermediate increase of the IRs only. The H4 intermediate HXR peak, having the highest X-ray flux, occurred simultaneously with a new and strong increase of the IRs at 10:21:48 UT. The increases of the IRs were best seen in the red wing of the H\(_\alpha\) line, but they were also recognizable in the blue one. The variations of the IRs were synchronized with the relevant peaks of the X-rays, and the time delays between X-ray impulses and abrupt variations of the H\(_\alpha\) profiles were virtually equal to zero.

As a result, we found that the variations of the X-ray fluxes recorded in various energy bands and the variations of the H\(_\alpha\) intensities measured in various parts of the line profile were well-correlated in time during the pre-impulsive and impulsive phases of the flare, and they agreed well with the variations of the calculated position and variations of the vertical extent of the EDL. The variations of the emission noticed in various parts of the H\(_\alpha\) line profile were caused by individual episodes of the energy deposition by the NTEs of various energy spectra on various depths in the chromospheric plasma. Namely, the NTE beams manifested by hard X-ray emission up to 70 keV deposited their energy at low altitudes in the chromosphere, where the wings of the H\(_\alpha\) line are formed, and varied concurrently with the increases of the wing-to-line center intensity ratio (IRs). The NTE beams manifested by relatively soft X-ray emission deposited their energy at much higher altitudes in the chromosphere, concurrently with the increases of the emission in the center of the H\(_\alpha\) line. These conclusions can be compared with our results for the solar flare on 2013 June 21, presented in detail in Paper I. That flare had nearly the same GOES class of C1.1 as the flare on 2012 September 10, but the RHESSI detected HXR emission only below 34 keV. Both flares were investigated by us using the same methodology and similar observational data, and they were modeled with the same numerical code. The variations of the IRs ratios in a course of the impulsive phase of a solar flare indicate not only a relative variation of the intensities recorded in various parts of the line profile, but also variations of an actual effective altitude of the EDL.

In the case of the 2013 June 21 flare, the time variations of the H\(_\alpha\) line profiles emitted by flaring kernels were also caused by temporal variations of penetration depths of NTE beams along the flaring loops. However, due to the much lower energies and penetration depths of the NTEs manifested by HXR\(_s\) below 34 keV, the energy delivered to low altitudes in the chromosphere was low and the deposition period was short. As a result, IRs decreased abruptly just after the first impulse seen in the 20–34 keV energy band (see Figure 13 in Paper I). Some short-lasting secondary increases of the IRs were correlated in time with the subsequent X-ray impulses recorded in both HXR and SXR ranges, related to secondary minor episodes of the energy deposition. Most of the energy carried by low-energy NTEs was deposited at relatively high altitudes of the chromosphere. In the case of the flare on 2012 September 10, a substantial amount of the energy was deposited by the high-energy NTEs at low altitudes.

In the case of both flares, the very fast variations of plasma properties in the lower parts of flaring loops are revealed well by the numerical models. The timescales of variations of the plasma parameters are compatible with the timescales of the variations of the chromospheric emission. A cross-comparison...
of the variations of the emissions recorded in various ranges of the spectrum (like X-rays and visual domain) validates the results of the numerical models, and it allows estimations of properties of the flaring plasma that are not directly observable—for example, the altitude, the vertical extent, and the time variations of the EDL in the feet of the flaring loop.

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