Time Variations of Observed Hα Line Profiles and Precipitation Depths of Nonthermal Electrons in a Solar Flare

Robert Falewicz1, Krzysztof Radziszewski1, Paweł Rudawy1, and Arkadiusz Berlicki1,2

1 Astronomical Institute, University of Wrocław, 51-622 Wrocław, ul. Kopernika 11, Poland
falewicz@astro.uni.wroc.pl, radziszewski@astro.uni.wroc.pl, rudawy@astro.uni.wroc.pl
2 Astronomical Institute, Academy of Sciences of the Czech Republic, Ondřejov, Czech Republic; berlicki@astro.uni.wroc.pl

Received 2016 May 31; revised 2017 August 1; accepted 2017 August 30; published 2017 September 25

Abstract

We compare time variations of the Hα and X-ray emissions observed during the pre-impulsive and impulsive phases of the C1.1-class solar flare on 2013 June 21 with those of plasma parameters and synthesized X-ray emission from a 1D hydrodynamic numerical model of the flare. The numerical model was calculated assuming that the external energy is delivered to the flaring loop by nonthermal electrons (NTEs). The Hα spectra and images were obtained using the Multi-channel Subtractive Double Pass spectrograph with a time resolution of 50 ms. The X-ray fluxes and spectra were recorded by RHESSI. Pre-flare geometric and thermodynamic parameters of the model and the delivered energy were estimated using RHESSI data. The time variations of the X-ray light curves in various energy bands and those of the Hα intensities and line profiles were well correlated. The timescales of the observed variations agree with the calculated variations of the plasma parameters in the flaring loop footpoints, reflecting the time variations of the vertical extent of the energy deposition layer. Our result shows that the fast time variations of the Hα emission of the flaring kernels can be explained by momentary changes of the deposited energy flux and the variations of the penetration depths of the NTEs.

Key words: Sun: chromosphere – Sun: corona – Sun: flares – Sun: X-rays, gamma rays

1. Introduction

Observations of solar flares in hard X-rays (HXR) reveal bright, compact emission sources at flaring loop footpoints, where dense and cold chromospheric plasma is heated by beams of nonthermal electrons (NTEs). In the light of strong chromospheric lines such as the hydrogen Hα line (λ = 6562.8 Å), the flare emission sources are in the form of bright localized kernels and ribbons. The light curves of the HXR and Hα sources are strikingly similar (Radziszewski et al. 2007, 2011; Radziszewski & Rudawy 2013). The NTEs are accelerated in so-called primary energy release sources, located close to the tops of flaring loops. During the precipitation along the magnetic loops, the NTEs are slowed down and thermalized by Coulomb collisions with ambient ions, mostly in the relatively dense plasma near the loop footpoints, but a small part of their kinetic energy is radiated as HXR bremsstrahlung. The energy delivered by the NTEs also powers heating and macroscopic motions of the upward-moving, “evaporated” plasma and emission in soft X-rays (SXR) and chromospheric lines (Brown 1971; Antonucci et al. 1984, 1999; Fisher et al. 1985a; Fletcher et al. 2011; Holman et al. 2011). The parameters of the NTE beams, such as the distribution, total energy, and precipitation depths, vary rapidly, with timescales of seconds. The time variations of the HXR emission are also a function of the temporal and spatial variations of the plasma properties along the flaring loop (mostly the density and the temperature of the plasma near the loop footpoints; see Battaglia et al. 2012).

Strong chromospheric emission lines in flares, particularly the Hα line, are formed at heights extending from the upper photosphere to the upper chromosphere (Vernazza et al. 1973, 1971; Kasparova & Heinzel 2002; Berlicki & Heinzel 2004). The intensities and line profiles of the Hα emission depend on many factors, e.g., the vertical and horizontal stratification of plasma characteristics inside the loop (Fisher et al. 1985a; HeiŽel et al. 1994; Allred et al. 2005; Berlicki 2007; Falewicz et al. 2015), the bulk and turbulent plasma motions (Abbett & Hawley 1999; Berlicki et al. 2005), the precipitation time of the NTEs (Kasparova & Heinzel 2002), the propagation velocities of the conduction fronts (Reep et al. 2016), and the properties and variations of the NTE beams penetrating the plasma at the loop footpoints (Kasparova et al. 2009).

Physical processes causing the abrupt heating of plasma during solar flares and the subsequent evolution of the hot plasma within flaring loops are not fully understood. A comparison of the observed features of the flaring plasma with results from numerical models should help lead to a better understanding of the physics of the flaring plasma. Considering all the factors discussed above, the analysis of the time variations of the observed X-ray and Hα emissions could deliver irreplaceable data about the time variations of the spatial distributions of plasma parameters and processes in the flaring loops. However, due to very short timescales of the variations of the NTE beams, the X-ray bremsstrahlung emission, and the Hα line emission, the applied observational data should be collected with a sufficiently high time resolution.

In this paper we compare time variations of the Hα and X-ray emissions observed during the pre-impulsive and impulsive phases of a C1.1-class solar flare in the NOAA 11772 active region on 2013 June 21 with the variations of plasma parameters in the one-dimensional hydrodynamic (1D–HD) numerical model of the flare and with the variations of synthesized X-ray emission. The 1D–HD model was calculated using a modified hydrodynamic 1D Solar Flux Tube Model developed at the Naval Research Laboratory (see Mariska et al. 1982; Mariska & Poland 1985; Falewicz et al. 2009a, for details), under the assumption that energy is delivered to the flaring loop by the NTEs. Pre-flare parameters of the model and energy fluxes
delivered to the plasma during the flare were estimated using data from \textit{RHESSI} (Lin et al. 2002). The Hα line profiles and light curves, measured at several wavelengths over the Hα line profile, were recorded with high time resolution (0.05 s) using the Multi-channel Subtractive Double Pass spectrograph (MSDP), which was installed at the focus of the Horizontal Telescope (HT) at the Bialkow Observatory of the University of Wroclaw, Poland (Mein 1991; Rompolt et al. 1994).

In the following, Section 2 describes the flare observations and data reduction, Section 3 the numerical model of the flare, and Section 4 the flare’s Hα emission. The conclusions and discussion are given in Section 5.

2. C1.1 Solar Flare on 2013 June 21

The C1.1 \textit{GOES}-class solar flare occurred in a complex, β8 magnetic-type active region, NOAA 11772 (coordinates \(x = 457\°, y = -368\°; S15W31\)), on 2013 June 21 at 12:20 UT (Figure 1). The 1–8 Å X-ray emission of the flare recorded by \textit{GOES}-15 reached maximum at 12:22 UT, returning to the pre-flare background level at about 12:27 UT (Figure 2, upper panel). The impulsive phase of the flare started at 12:21:00 UT, reaching maximum 12–14 s later (Figure 2, lower panel). The increase in the SXR emission (<12 keV) recorded by \textit{RHESSI} was simultaneous with that in \textit{GOES}-15 0.5–4 Å emission.

Significant HXR emission was recorded by \textit{RHESSI} up to 34 keV only. The X-ray fluxes emitted by the flare were so low that the \textit{RHESSI} attenuators were not activated during the flare (i.e., they remained in the “A0” state). The signals were summed over the front segments of seven of the nine detectors: 1F, 3F, 4F, 5F, 6F, 8F, and 9F. The recorded data were analyzed using the OSPEX software of the SolarSoftWare (SSW) package. X-ray spectra were obtained with time resolution of 4 s and binned in the energy bands \(dE = 0.3\) keV in the 4–15 keV energy range and \(dE = 1.0\) keV in the 15–100 keV energy range. The pulse pileup, decimation, and albedo effects (due to Compton backscattering from the photosphere; Bai & Ramaty 1978; Kontar & Jeffrey 2010) were corrected using the \textit{RHESSI} standard analysis tool. The full 2D detector response matrix was applied to convert count rates to photon fluxes. The accumulation time was increased to 20 s before the flare impulsive stage in order to maintain positive count rates (particularly in the 6–25 keV energy range).

The fluxes recorded by \textit{RHESSI} in the 6–10 keV band during the flare were slightly enhanced by a background that slowly decreased during the flare, while the fluxes in the 10–20 keV and 20–34 keV energy bands were enhanced by steady background fluxes. Above 34 keV the HXR background dominates over the emission of the flare, so the fluxes above this energy were not analyzed. In the case of the \textit{RHESSI} data, a background is usually modeled as a linear or higher-order polynomial interpolation between the averaged fluxes recorded before and after the flare. As the time period investigated here is very short, a linear fit to the background rates before and after the flare is adequate for our purposes. For energies <12 keV, the linear fit was to background rates at 12:11 UT and 12:30 UT; for energies >12 keV, the corresponding times were 12:20 UT and 12:29 UT. The background fluxes were also removed from \textit{GOES} data using a linear fit of fluxes before and after the flare.

During the impulsive phase, \textit{RHESSI} spectra show both thermal and (at higher energies) nonthermal components. \textit{RHESSI} spectra were fit using a forward and backward automatic fitting procedure, starting from a maximum of the impulsive phase, when the nonthermal component was strong and clearly visible. Automatically evaluated parameters of the fit of the thermal and nonthermal components were controlled and corrected when the time variations were too rapid. The correction procedure consisted of four steps. First, the corrected parameter was fixed using a value selected to obtain a first-guess fit of the observed spectrum. Second, all remaining parameters of the fit were optimized automatically. Third, the
were determined based on the thick-target model and used as the parameters of the injected NTE beams in the numerical model of the RHESSI thick-target version 2 analysis software. The thick-target model was applied to the spectra recorded during the beginning of the described procedure of the parameter correction was corrected parameter was freed and the automatic fit of the spectrum was repeated. At the end of the correction procedure, values of $\chi^2$ and residuals were controlled. Generally, all the fitted parameters evolved in a quasi-continuous manner, and the described procedure of the parameter correction was applied to the spectra recorded during the beginning of the flare only. We applied the “single-temperature thermal plus thick-target version 2” model fits (vth + thick2) in the RHESSI analysis software. The thick-target model (version 2) was defined by the total integrated electron flux $N_{\text{int}}$, the power-law index of the electron energy distribution $\delta$, and the low-energy cutoff of the electron distribution $E_v$. Figure 3 shows three examples of the spectra taken during the pre-impulsive and impulsive phases of the flare and just after the impulsive phase.

X-ray images of the flare were constructed using RHESSI data collected with the subcollimators 3F, 4F, 5F, 6F, 8F, and 9F. The PIXON imaging algorithm was applied with the effective pixel size of 1″. Photons were integrated in time steps of 8 s to obtain adequate signal-to-noise ratios (Metcalf et al. 1996; Hurford et al. 2002). The energy ranges of 6–12 keV, 12–25 keV, and 23–34 keV were selected in order to best portray the flare structures. The images restored in the 6–12 keV energy range (see Figure 4, right panel) show an elongated bright structure, located between two Hα brightenings seen in the chromosphere. The 12–25 keV images (see Figure 4, left panel) show a compact emission source, which coincided with the central part of an extended structure visible in the 23–34 keV energy band. The magnetograms obtained with the SDO/HMI instrument (Scherrer et al. 2012) were used to determine magnetic polarities in the flare region, providing an additional confirmation of the proper selection of the loop footpoints. The opposite ends of the extended structure in the 23–34 keV energy band were located in the regions having opposite magnetic polarities. Images recorded at the same time by the SDO/AIA instrument (see Lemen et al. 2012) in the left panel: co-aligned SDO/AIA 94 Å (image) and RHESSI hard X-ray 12–25 keV and 23–34 keV (blue and red contours, respectively) emissions of the 2013 June 21 flare. The RHESSI 23–34 keV contours are displayed at 16.5%, 20%, 30%, 50%, and 70% of maximum signal; the RHESSI 12–25 keV contour is drawn at 50%, 80%, and 90% of maximum signal. Right panel: co-aligned SDO/AIA 94 Å (image), MSDP/Hα (yellow contours), and RHESSI 6–12 keV (red contour) emission. The Hα contours are drawn at 70%, 80%, and 90% of maximum of the signal. The RHESSI 6–12 keV contour is drawn at 50% of maximum signal. The integration time of the RHESSI fluxes was 64 s, and the fluxes were recorded between 12:21:06 UT and 12:22:10 UT. The MSDP image was taken at 12:21:36.35 UT.
94 Å band show an extended and multithreaded structure, similar to the elongated emission source recorded in Hα. Images recorded by SDO/AIA in the 171 Å band between 12:19:50 UT and 12:23:01 UT clearly show that the flare occurred in a part of a complex system. Owing to the broad wavebands of the SDO/AIA EUV filters, a full interpretation of the revealed structures is challenging.

The main geometric characteristics of the flaring loops were evaluated using the RHESSI images. The effect of the perspective foreshortening was reduced using the method of Aschwanden et al. (1999). The cross section of the loop was assumed to be constant along the loop, and it was estimated as a mean area of both loop footpoints, arbitrarily delimiting using 30% contours of their local maximum fluxes in the 20–34 keV range. The areas and positions of the centroids of the footpoints were calculated using the SSW CENTROID procedure. The resulting cross section of the loop was equal to $S = (1.65 \pm 1.04) \times 10^{17}$ cm$^2$. The 30% contour was selected as the delimiter of the footpoints in accordance with our previous work (see Falewicz et al. 2011; Falewicz 2014; Falewicz et al. 2015) in order to moderate the mean density of the energy flux in the loop, while in the 1D–HD numerical models the energy is formally delivered uniformly over the whole cross section of the loop. The half-length of the loop equal to $L_0 = (8.81 \pm 1.13) \times 10^5$ cm was estimated as a distance between centroids of the feet, under the assumption that the loop was semicircular.

Assuming a perpendicular position of the semicircular flaring loop on the solar surface, the apparent positions of the centroids of the footpoints observed in various energy bands can be easily converted into heights above the solar surface. In the case of the brighter, northwest footpoint of the flaring loop during the impulsive phase, the centroids were shifted by $\Delta s = 1\,\prime\prime$ when observed in the slightly overlapped 15–26 keV and 23–34 keV energy bands. The formal errors of the calculated positions of the centroids are about $\delta = 1\,\prime\prime$.5. The measured angular distance of the centroids is equivalent to a vertical extent of $\Delta h = 2550$ km. The relatively low energy fluxes emitted by the flare prevented an application of images restored in the non-overlapping energy bands and the evaluation of the vertical extents before and after the maximum.

The flare was also observed in the Bialkowski Observatory of the University of Wroclaw, Poland, using the MSDP spectrograph and the HT. The HT has a Jensch-type coelostat with two 30 cm flat mirrors and a 15 cm f/27 achromatic main objective. The entrance window of the MSDP spectrograph covers an area of $942 \times 119$ arcsec$^2$ on the Sun when illuminated by the HT. The 2D spectra-images are formed with a nine-channel prism box and are recorded with an Andor iXon3 885 camera (1002 × 1004 px$^2$, 1 px$^2 = 1.6$ arcsec$^2$). The time cadence was 20 images per second during the observations. Raw observations were reduced using standard reduction procedures. Extended information concerning the high time resolution spectro-imaging observations and data reduction were given previously (Radziszewski et al. 2006, 2007, 2011; Radziszewski & Rudawy 2013). For each spectra-image we calculated (i) Hα line spectra in the range of $\Delta \lambda = \pm 1.2$ Å from the Hα line center ($\lambda = 6562.8$ Å, marked next as H$\alpha_0$) for all pixels of the field of view (FOV); (ii) the quasi-monochromatic images of the entire region, reconstructed in 13 wavebands 0.06 Å wide each, and separated by 0.2 Å from each other over the Hα line profile; and (iii) the light curves of selected flaring kernels in various wavelengths over the range $\Delta \lambda = \pm 1.2$ Å from the central wavelength (H$_\alpha$).

Ground-based observations of the Sun are always affected by a variable atmospheric seeing, causing deformations of apparent shapes and variations of the brightness of recorded structures. The collected data are also influenced by telescope guiding errors. Special procedures were applied to correct all these effects (see Radziszewski et al. 2007, for details). The Richardson–Lucy deconvolution algorithm was also applied to enhance the quality of the resultant MSDP images (Richardson 1972; Lucy 1974). The continuum filtergrams taken with the SDO/HMI telescope were used for the exact alignment of the Hα ground-based and satellite observations.

The time resolution of the X-ray light curves recorded with RHESSI is limited to 4 s by the spacecraft spin. For a qualitative comparison of the observed X-ray and Hα light curves, X-ray data with 0.25 s time resolution were obtained using the demodulation program prepared by Hurford and available in the SSW package (G. I. Hurford 2004, private communication). To be consistent with our previous papers, the observed time variations of the Hα light curves were compared with the time variations of the X-ray light curves measured for slightly altered energy bands: 3–10 keV, 10–20 keV, and 20–34 keV (see, e.g., Radziszewski et al. 2007, 2011).

3. Numerical Model of the Flare

A solar flaring loop is a 3D object possibly having a complex, multithreaded internal structure. Ground-based and satellite-based instruments are not able to resolve the internal structure of flaring loops, as well as heating episodes and thermodynamic evolution of the individual threads. The flaring loops are also surrounded by a dynamic environment of a solar active region, dominated by evolving and restructuring magnetic fields. Many basic parameters of the numerical models have to be approximated or freely chosen owing to the incompleteness of the available observational data. For example, a number of the internal threads (i.e., the filling factor of the observed macroscopic loop) and individual lengths of the threads have to be chosen, while the short flux tubes evolve much faster than the long ones owing to the influence of the thermal conductivity and the mean plasma parameters of a set of small flux tubes (see, e.g., Klimchuk et al. 2008, and references therein). The results of the calculations depend also on an adapted model of an energy deposition mechanism inside the threads. For these reasons, substantial differences between evolutions of the observed and numerically modeled flaring loops are unavoidable despite the complexity of the codes currently applied. To solve this complex problem, Warren (2006) elaborated a multithreaded and time-dependent model of the so-called Masuda flare observed on 1992 January 13. He showed that the discrepancies between the simulations and observations may be reduced using a multithreaded 1D–HD model, but only by approximating the numerous auxiliary parameters, e.g., the number of threads or the time sequence of the energy deposition episodes inside individual threads. Falewicz et al. (2015) investigated a 2D model of the flaring loop having a continuous distribution of the parameters of the plasma across the loop and powered by a variable energy flux. This model was also compared with the relevant 1D–HD models. They found that multithreaded and multidimensional numerical models of the flare with correctly selected spatial...
distributions of the input energy and a realistic physical model of the loop can produce results similar to the results of the 2D models, as well as that 1D–HD models ensure general correctness of the obtained results and approximate real flaring structures. The 2D or even 3D time-dependent numerical models of the flaring loops basically allow many important properties of the flares to be accounted for, like the internal structure of the magnetic field inside the observed flaring loops, interaction between the threads, and the individual time sequences of the energy deposition episodes in the individual threads. However, the observational limitations imposed by the currently available solar instruments do not allow any qualitative measurements of these characteristics, and the computation times of the 2D (or 3D) models are significantly greater than those of the 1D models. Thus, taking into account all limitations of the 1D–HD models, they still remain a valuable tool in investigations of the solar flares thanks to their moderate complexity and moderate volume of the necessary calculations. The 1D–HD models have also been applied with success in the analysis of flares, leading to some understanding of the physics of the plasma inside flaring loops (see, e.g., Fisher et al. 1985a, 1985b, 1985c; Mariska & Poland 1985; Mariska et al. 1989; Serio et al. 1991; Reale et al. 1997; Falewicz et al. 2009a, 2009b, 2011; Siarkowski et al. 2009; Falewicz 2014, and many others).

The 1D–HD numerical model of the flare on 2013 June 21 was calculated using the modified hydrodynamic 1D Solar Flux Tube Model (see Mariska et al. 1982, 1989; Falewicz et al. 2009a, for details). It was assumed that the flare plasma was heated only by time-variable NTE beams, as has been found for some flares by Falewicz et al. (2011) and Falewicz (2014). However, this may not always be the case, and some additional energy source is needed (Liu et al. 2013; Aschwanden et al. 2016).

The numerical model of the flaring loop was prepared using numerous specific geometric and thermodynamic parameters. The loop length and cross section, the initial pressure at the transition region, and plasma temperature were estimated from RHESSI observations. To obtain agreement between synthetic and observed X-ray light curves, the radius of the loop was refined arbitrarily in the range of one RHESSI pixel (or \(\pm 725 \text{ km}\)), and the cross section of the loop applied in the numerical model was equal to \(S = 1.01 \times 10^{7} \text{ cm}^{2}\). The applied cross section agrees well with the area of the structures observed by the SDO/IAI telescope in the 94 Å band. A constant magnetic field strength of 200 G was assumed, following estimates of Schmelz et al. (1994) and Aschwanden (2005).

The observed and synthesized X-ray light curves calculated for the 1D–HD model of the flare were compared in three energy bands: 6–10 keV, 10–20 keV, and 20–34 keV. The synthesized X-ray fluxes were calculated in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\). The observed X-ray fluxes were converted to the photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) unit using the instrumental response matrix with diagonal coefficients only. Thus, the secondary factors influencing RHESSI data and described by the off-diagonal elements of the response matrix, like the K-escape and the Compton scattering, were not taken into account. The applied method is valid because all investigated energy bands lay above the count-rate peak of the analyzed flare, which was equal to about 6 keV (the attenuators were not activated during the whole event and remained in the A0 state), while off-diagonal contributions are significant only below the count-rate peak. The method used introduces an insignificant systematic error of a few percent only. Time variations of the GOES 1–8 Å and GOES 0.5–4 Å light curves were also computed. The detailed description of the method used for calculation of the GOES light curves can be found in Falewicz (2014).

The steady-state spatial and spectral distributions of the NTEs in the loop were calculated for each time step of the model using a Fokker–Planck model (McTiernan & Petrosian 1990). The input data consisted of an injected energy flux, an isotropic distribution of NTEs at the top of the loop, a model of a distribution of the plasma parameters along the flaring loop, and a model of the magnetic field. 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. The thermal emission measure of the optically thin plasma was based on the X-ray continuum line emission calculated using the CHIANTI (version 7.1) atomic code (Dere et al. 1997; Landi et al. 2006). For the plasma temperatures above \(10^{5} \text{ K}\) the element abundances are based on a coronal abundance set (Feldman & Laming 2000), while below \(10^{5} \text{ K}\) photospheric abundances were applied. To compare the synthesized and the observed fluxes, the calculated thermal and nonthermal emission and the estimated observed background emission were summarized.

Figure 5 shows time variations of the main parameters of the NTE beams powering the flare during the pre-impulsive and impulsive phases of the flare. The parameters were derived using the thick-target model (version 2; see Falewicz 2014, for extended discussion). The flux of the nonthermal energy \(P_{\text{nth}}\) was calculated using the formula proposed by Tandberg-Hanssen & Emslie (1998). During the pre-impulsive and impulsive phases of the flare, \(P_{\text{nth}}\) varied between \(P_{\text{nth}} = 1.7 \times 10^{24} \text{ erg s}^{-1}\) and \(P_{\text{nth}} = 1.9 \times 10^{27} \text{ erg s}^{-1}\). It reached the first local maximum at 12:20:40 UT, the second at 12:21:08 UT, and the third at 12:21:36 UT. The highest local maximum at 12:21:08 UT occurred during the impulsive phase of the flare. A strong increase of the \(P_{\text{nth}}\) before the second maximum was accompanied by an abrupt decrease of the electron spectral index \(\delta\). At the same moment, the energy spectra of the NTEs hardened in accordance with the soft-hard-soft pattern presented by the majority of solar flares during their impulsive phases (see, e.g., Grigis & Benz 2004). The first and second local maxima of the \(P_{\text{nth}}\) were also correlated with local maxima of the light curves recorded by RHESSI in the 10–20 keV and 20–34 keV energy ranges. The calculated values of the low-energy cutoff \(E_{c}\) varied during the investigated period of the flare between 13 and 24 keV. These variations are introduced by the algorithm applied, which forces the observed and synthetic RHESSI 6–10 keV fluxes to be equal by changing the absorbed energy amount. The amplitude and timescale of the variations of the calculated \(E_{c}\) agree with the estimated ranges and timescales of the \(E_{c}\) variations that have been given by various authors for flares with higher GOES classes (see, e.g., Holman et al. 2003; Sui et al. 2007; Hannah et al. 2008; Warmuth et al. 2009a, 2009b; Falewicz et al. 2011).

The temperatures and emission measures calculated from the RHESSI spectra and those representative of the numerical 1D–HD model of the flare are given in the left column of Figure 6. The temperatures and emission measures calculated from the observed GOES fluxes and those computed using the numerical model are given in the right column of Figure 6. The
temperatures and emission measures were derived using the spectral fit of the thermal component of the RHESSI spectra. The temperatures representative of the numerical model and given in Figure 6 are equal to the temperatures of the plasma having the highest differential emission measure. The emission measures were calculated as integrals of the computed differential emission measures for plasma having temperatures greater than 1 MK. Before the maximum of the impulsive phase, the temperatures of the plasma derived from RHESSI spectra were systematically higher than the temperatures calculated using the numerical model for the period. At the beginning of the pre-impulsive phase the differences between both temperatures were of the order of 2 MK, but later they decreased gradually to less than 1 MK and completely vanished during the impulsive phase at 12:21:30 UT. At 12:21:12 UT and 12:21:20 UT the difference temporarily increased to about 4 and 3 MK, respectively, due to momentary increases of temperature derived from RHESSI spectra for the respective accumulation periods. The emission measures derived from RHESSI spectra were systematically lower than the synthesized ones by a factor not greater than 3–4, but during the maximum of the impulsive phase, at about 12:21:30 UT, the derived and synthesized emission measures were nearly the same.

The synthetic GOES-15 0.5–4 Å and 1–8 Å fluxes, calculated from the numerical model, follow qualitatively the observed fluxes, though the synthesized 1–8 Å flux was always slightly higher than the observed flux. The synthesized 0.5–4 Å flux was slightly higher than the observed one at the beginning of the flare only, but after 12:21:45 UT it became a factor of 2–3 lower. At the flare beginning, the temperatures calculated from GOES-15 data and synthesized GOES temperatures were similar. However, after 12:21:00 UT the modeled temperatures were always lower than the observed values, and at 12:21:20 UT the difference reached ~2.5 MK. We believe this to arise through the variations of the ratio of 0.5–4 Å to 1–8 Å flux, which causes differences in estimated temperature and emission measure (White et al. 2005). The calculated emission measures were systematically greater than the emission measures derived from observations by a factor of about four.

The synthesized and observed total fluxes measured in the 6–10 keV, 10–20 keV, and 20–34 keV energy bands are shown in Figure 7. The observed and synthesized light curves agree well during the flare impulsive phase. In the 20–34 keV energy band the emission is mostly caused by nonthermal processes, and thus the time variations of the nonthermal component define the time variations of the total emission in this energy band. The relative contribution of the nonthermal component decreases in the lower energy bands, where the thermal component plays a dominant role. The agreement of the observed and synthesized light curves in the 10–20 keV energy band is worse than for the higher and lower energy ranges, but the overall time course of the synthesized light curve, up to the impulsive phase of the flare, mimics qualitatively the observed one but is below the observed light curve. In the lowest energy band of 6–10 keV the thermal component dominates, although during the impulsive phase of the flare the nonthermal component also adds a small contribution to the total flux. The course of the synthesized emission in the 6–10 keV energy band is identical to the observed emission as a result of the applied method of the $E_{\text{c}}$ fitting.

An example of the calculated spatial distribution of the X-ray emission along the flaring loop during the impulsive phase of the flare is given in Figure 8. Strong impulsive brightenings at the loop footpoints and a much weaker and less well-defined nonthermal emission source at the top of the loop are evident. After 12:21:18 UT, the emission of the flare was dominated by the thermal emission (see Figure 7, middle panel), and the top of the loop was the brightest in the 12–25 keV energy band (see Figure 4).

The energy deposition rates were calculated using the approximative formula given by Fisher (1989). The NTEs deposited most of the energy inside a layer of limited width, called hereafter the energy deposition layer (EDL). The upper boundary of the EDL was defined as a plasma layer where the deposited energy flux starts to increase rapidly nearby the chromosphere; the lower boundary of the EDL was selected arbitrarily at an energy flux level of 0.01 erg s$^{-1}$ cm$^{-3}$ (see Figure 9, upper panel, where the time variations of the H$\alpha$ light curves are compared with X-ray light curves in three energy bands).

During the early phase of the flare (before 12:20:40 UT), the RHESSI X-ray fluxes in the 10–20 keV and 20–34 keV energy bands remained almost constant (Figure 9, middle panel), and the maximum flux of the deposited energy was only ~10 erg s$^{-1}$ cm$^{-3}$, causing gradual heating of the local plasma. RHESSI observed a pre-flare X-ray increase in the 3–10 keV energy band at about 12:20:25 UT. A well-defined X-ray...
The Astrophysical Journal, 847:84 (14pp), 2017 October 1

Falewicz et al.

impulse was recorded at the end of the pre-impulsive phase at about 12:20:45 UT in the 20–34 keV band and a little later in the lower energy bands. Due to the gentle evaporation of hot plasma caused by an ongoing low-intensity heating, the EDL maintained nearly constant thickness of about 125 km up to 12:21:00 UT, when it extended from \( L = 9925 \) km up to \( L = 10,050 \) km, if counted from the top of the loop, or equivalently it extended between the altitudes \( H = 1900 \) km and \( H = 2025 \) km above the temperature minimum (Figure 9, upper panel).

The impulsive phase of the flare started at about 12:21:00 UT in the 20–34 keV range and a few seconds earlier in lower energy bands. At the same time the EDL substantially widened,
Three well-distinguishable brief increases of the 20–34 keV X-ray flux were observed during the impulsive phase of the flare, at 12:21:08 UT, 12:21:13 UT, and 12:21:25 UT, respectively. These impulses are marked as H1, H2, and H3 in the middle panel of Figure 9. The second and third impulses were also noticeable in the 3–10 keV and 10–20 keV energy bands. The EDL shrunk to roughly $D = 425$ km at 12:21:17 UT after the H2 impulse and to $D = 250$ km at 12:21:28 UT after the H3 impulse. The EDL then gradually became even narrower, and simultaneously the X-ray emission substantially faded in all energy bands. Between 12:21:00 UT and 12:22:20 UT the upper boundary of the EDL persistently lowered from $H = 2025$ km to $H = 1900$ km above the temperature minimum, due to the induced plasma evaporation. The maximum of the deposited energy flux moved in accordance with the upper boundary of the EDL. However, the abrupt increase of the extent of the EDL during the impulsive phase of the flare was caused mostly by changes of the position of the lower boundary due to an increased flux of the high-energy NTEs precipitating further along the loop from the near loop-top release region to the dense plasma above the temperature minimum.

**4. Time Variations of the Observed H α Emission**

Two K1 and K2 Hα flaring kernels were the brightest and the most active flaring structures visible in the H α light in the observed active region during the whole life span of the flare. The kernels were located close to both ends of the extended loop-like structure visible in the X-ray images. Between 12:20:00 UT and 12:21:55 UT the seeing conditions in the Białkow Observatory were very good, but later the clouds disturbed the observations. Thus, the variations of the H α emission after 12:21:55 UT are not investigated.

The K1 kernel started to brighten in the H$_{\alpha 0}$, H$_{\alpha 0} \pm 0.35$ Å, and H$_{\alpha 0} \pm 0.7$ Å wavelengths immediately after the SXR impulse observed in the 3–10 keV energy band at 12:20:07 UT (the impulse is marked as S1 in Figure 9, middle panel), at the beginning of the pre-flare phase. The main stages of the emission of the K1 kernel in the H$_{\alpha 0}$ wavelength are marked with thick red lines and with capital letters from A to F in the lower panel of Figure 9. The emission of the K1 kernel in the blue wing of the H$_{\alpha}$ line at H$_{\alpha 0} - 0.35$ Å started to increase 20 s later, at about 12:20:30 UT (see Figure 10, left column, middle panel). The light curves of the K1 and K2 kernels shown in Figures 9 and 10 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, so the influence of the solar rotation and plasma motions along the flaring loop is removed. The emission of the K1 in the line center H$_{\alpha 0}$ during the pre-flare phase of the flare is marked by A. Immediately after the beginning of the impulsive phase, the K1 kernel brightened very rapidly in the H$_{\alpha 0}$ band (phase B). This stage of evolution of the H$_{\alpha 0}$ light curve of the K1 kernel ended abruptly at 12:21:15 UT, just after the X-ray impulse H2. The time delay between the maximum of the H2 impulse, recorded at 12:21:13 UT in the 20–34 keV energy band, and the corresponding maximum of the H$_{\alpha 0}$ light curves of the K1 kernel was equal to only 2 s in all five wavelengths: H$_{\alpha 0}$, H$_{\alpha 0} \pm 0.35$ Å, and H$_{\alpha 0} \pm 0.7$ Å (Figure 10, left panel). Later, up to 12:21:20 UT, the H$_{\alpha 0}$ emission of the K1 faded gradually in accordance with the decreasing X-ray fluxes recorded in all investigated energy bands (stage C). At 12:21:20 UT the emission of the K1 started to increase again, simultaneously
with the beginning of the H3 X-ray impulse recorded in the 20–34 keV energy band (stage D). The growth of the emission stopped at 12:21:27 UT, simultaneously with the end of the H3 impulse. A brief subsequent decline of the emission of the K1 (stage E) occurred between 12:21:27 UT and 12:21:29 UT, when the X-ray flux in the 20–34 keV remained stable, but the
fluxes in the 3–10 keV (mostly thermal) and 10–20 keV bands slightly decreased. The subsequent growth of the K1 emission in the Hα light (stage F) occurred during the post-impulsive phase of the flare, when the X-ray emission stabilized in the 10–20 keV and 20–34 keV energy bands, but the emission in the 3–10 keV energy band still rose owing to the increasing volume of the hot evaporated plasma. The emission of the K2 kernel in the Hα wavelength increased at 12:20:30 UT, roughly 20 s after the start of the emission of the K1 kernel (Figure 10, right panel). The time variations of the emission of the K2 kernel were similar to the variations of the K1 kernel. However, during stage C the emission of the kernel K2 remained nearly constant in the Hα wavelength.

The time variations of the emissions of the K1 and K2 kernels in opposite line wings were different. At \( \Delta \lambda = \pm 0.7 \text{ Å} \) from the Hα line center, the emission of both kernels was stronger in the red wing than in the blue wing. However, at \( \Delta \lambda = \pm 0.35 \text{ Å} \) from the line center the K2 kernel was brighter in the blue wing, but the K1 was slightly brighter in the red wing (Figure 10). During the entire period, the profile of the Hα line emitted by the K2 kernel was persistently redshifted, while the Hα line emitted by the K1 kernel did not show any significant shift. The mean Hα line profiles of the kernels K1 and K2 are shown in Figure 11 for seven selected moments showing main stages of the evolution of the K1 kernel. The same moments are also marked by seven vertical arrows in Figure 9. The time resolution of the spectral observations was 0.05 s. The bandwidth of the profiles is limited to \( \pm 1.0 \text{ Å} \) from the Hα line center. The mean Hα line profile of the nearby quiet solar chromosphere (QS) is also shown (black line).

![Figure 11](image1)

**Figure 11.** Averaged Hα line profiles emitted by the flaring kernels K1 (left panel) and K2 (right panel) during the 2013 June 21 solar flare at 12:20:30 UT (violet), 12:21:05 UT (dark blue), 12:21:17 UT (light blue), 12:21:25 UT (green), 12:21:28 UT (orange), 12:21:39 UT (yellow), and 12:21:54 UT (red). The relevant emission intensities in the Hα line center are marked with horizontal dotted lines with the same colors. The same times are indicated by the vertical arrows in Figure 9. The time resolution of the spectral observations was 0.05 s. The bandwidth of the profiles is limited to \( \pm 1.0 \text{ Å} \) from the Hα line center. The mean Hα line profile of the nearby quiet solar chromosphere (QS) is also shown (black line).

![Figure 12](image2)

**Figure 12.** Averaged Hα net emission from the flaring kernels K1 and K2 during the 2013 June 21 solar flare between 12:20:00 UT and 12:22:30 UT.

The variations of the wing-to-line-center intensity ratios (IRs), particularly the IRs measured in the selected wavelengths...
in the line wings of the H\textalpha line at $\Delta \lambda = \pm 0.35$ Å, $\Delta \lambda = \pm 0.5$ Å, and $\Delta \lambda = \pm 0.7$ Å in the line center H\textalpha, are given in Figure 13, where the wavelengths are corrected for Doppler effect, i.e., corrected for bulk plasma motions being measured from the FWHM center. Vertical gray lines indicate the same moments as in Figure 9. Upper panel is the same as in Figure 9.

**Figure 13.** Time variations of the wing-to-line-center (i.e., wing-to-core) IRs of the flaring kernels K1 and K2 for wavelengths $\Delta \lambda = \pm 0.35$ Å, $\Delta \lambda = \pm 0.5$ Å, and $\Delta \lambda = \pm 0.7$ Å from the H\textalpha line center (all wavelengths are corrected on Doppler effect, i.e., corrected for bulk plasma motion, being measured from the FWHM center).

5. Discussion and Conclusions

Results from a 1D–HD numerical model of the C1.1 GOES-class solar flare observed on 2013 June 21 in the NOAA 11772 active region are presented here. The model is calculated using geometric and thermodynamic parameters derived from RH\textsc{eesi} data and is powered by the energy deduced from RH\textsc{eesi} X-ray spectra on the assumption that NTEs delivered external energy to the flaring loop. The RH\textsc{eesi} spectra of the flare show a clear nonthermal component, particularly during emission at $\Delta \lambda = \pm 0.7$ Å) and 2.1 s (the X-ray impulse at 12:21:25 UT and H\textalpha emission at $\Delta \lambda = \pm 0.7$ Å).
the impulsive phase, from which the NTE energy flux can be derived. The low-energy cutoff energies of the electron beams were automatically optimized at each time step of the calculations by fitting synthetic flux to the flux recorded by \textit{RHESSI} in the 6–10 keV energy band.

Substantial differences between the observed and the synthesized light curves are noticeable in the 10–20 keV energy range. An underestimation of the plasma’s thermal emission can be attributed to two main factors. First, the spatial distribution of the local thermodynamic and kinematic parameters of the plasma in the numerical model does not strictly match the actual spatial distribution of the plasma inside the real flaring loop. Second, the assumed power-law energy spectrum of the injected NTEs also caused some differences between the modeled and observed X-ray fluxes in the 10–20 keV energy band. Liu et al. (2009) showed, using the Fokker–Planck model of the particle transport, that if the energy spectrum of the injected NTEs is shaped by a stochastic acceleration, there appear higher coronal temperatures and densities, larger upflow velocities, and faster increases than if the electron energy spectrum is of power-law type. This is because the energy spectrum of the injected electrons ranges smoothly from a quasi-thermal component to a nonthermal tail. The injected beam of electrons generally includes much energy in the form of low-energy electrons that deposit their energy primarily in the upper part of the loop, and indirectly enhances the evaporation. Thus, the thermal emission component could give a greater contribution to the total flux in the 10–20 keV energy range. In the higher energy range of 20–34 keV, which is dominated by the nonthermal component, the differences between the modeled and the observed fluxes are much smaller.

The properties and basic assumptions of the applied 1D–HD numerical model were discussed above. Inconsistencies between the modeled spatial distribution of the plasma parameters and the actual distribution of the plasma parameters in the flaring loop were obviously caused by simplifications of the applied 1D–HD numerical code, rough estimation of the geometric parameters of the loop, errors in the restoration of the \textit{RHESSI} spectra, errors in the derivation of the NTE beam parameters, and an application of a simplified analytical formula of the heating function of the NTEs. The geometric characteristics of the modeled loop are estimated very inaccurately owing to the limited spatial resolution of the \textit{RHESSI} instrument and to the applied assumptions about the shape and position of the loop. Due to the small cross section of the flaring loop and the limited spatial resolution of \textit{RHESSI}, the formal uncertainty on the cross section of the modeled loop is 80%. The uncertainty of the cross section causes a proportional uncertainty of the local density of the delivered energy. The alternation of the local energy density substantially changes the resulting numerical model, e.g., by influencing the dynamics of plasma and altering the resulting class of the flare. The uncertainties of the fitting of the \textit{RHESSI} spectra, including the applied model of the fit and the uncertainties of the observational data, directly influence the estimated parameters of the NTE beams and their energy. Due to a complicated problem of the influence of the errors of the parameters on the resulting numerical model, the uncertainties of the model could only be estimated using the Monte Carlo method on the spectrum and other parameters, which will be evaluated in future work. The uncertainties introduced by the simplified analytical formula of the NTE heating function are less important. The differences between the heating function calculated using the approximate formula and the one calculated using the Fokker–Planck method are minor in the lower part of the loop but increase in the upper part of the loop, where the column mass is relatively low. Therefore, plasma in the lower part of the loop is powered by well-approximated energy flux. It must also be considered that real flaring loops possess the multithreaded internal structure, which is poorly resolved by the contemporary observing instruments, and which is not taken into account in the applied 1D–HD numerical models. Similarly, there are no direct methods to observe the heating episodes and the thermodynamic evolution of the individual threads. Despite all these limitations of the 1D–HD models, these models, when powered by the appropriate energy flux derived from the \textit{RHESSI} data, yield a good agreement of the predicted and observed X-ray fluxes during the impulsive phase of the flare, highlighting that these models sufficiently describe the plasma processes during the impulsive phase despite many simplifications, and show that the plasma heating during the impulsive phase is adequately powered by the NTEs.

The direct comparison of the calculated variations of the plasma characteristics in the numerical model of the flaring loop with the observed variations of the H$\alpha$ emission of the solar flare was possible only as a result of exceptional parameters of the applied spectrograph, which is capable of recording the H$\alpha$ line spectra with the very high cadence of 0.05 s, and for all pixels inside the FOV. These data allow one to reconstruct high-cadence series of the quasi-monochromatic images of the whole FOV and the light curves of the selected flaring kernels taken in various wavelengths. The time variations of the H$\alpha$ line profiles and the emission intensities in the selected wavelengths were compared with the spatial and the temporal variations of the main parameters of the 1D–HD numerical model, used particularly with time variations of the position and thickness of the EDL.

In accordance with our previous results (Radziszewski et al. 2007, 2011), the time variations of the X-ray fluxes in all investigated energy bands show good correlation, in both time and space, with the time variations of the H$\alpha$ line intensities and H$\alpha$ line profiles emitted by the H$\alpha$ flaring kernels, particularly for the K1 kernel during the pre-impulsive and impulsive phases of the flare. The observed responses of the H$\alpha$ line to the variations of the NTE heating were instantaneous or nearly so. For example, the time delay between the maximum of the H2 impulse, recorded at 12:21:13 UT in the 20–34 keV energy band, and the relevant local maxima of the H$\alpha$ emission of the K1 kernel was only 2 s in all five wavelengths (H$\alpha_0$, H$\alpha_0 \pm 0.35$ Å, and H$\alpha_0 \pm 0.7$ Å), illustrating the fast response of the chromosphere to the abrupt heating by the beam of NTEs and the immediate energy loss by radiation. The line cores and wings of the mean H$\alpha$ profiles of flaring kernel K1 and K2 exhibit fast increases of the emission and variations of the line shapes and shifts after 12:21 UT, during the impulsive phase of the flare, when the flux of the NTEs was highest and the EDL was most extended. The variable beams of the NTEs precipitated at that time through the plasma to the middle chromosphere, where the wings of the H$\alpha$ line are formed. Besides, NTEs collide also with atoms, and they can additionally ionize species, leading to an enhancement of an electron density in deposition layers, and causing an additive enhancement of the emission in the chromospheric lines, including H$\alpha$ (Berlicki et al. 2005).
After the impulsive phase of the flare, the enhanced emission in the core of the H\(\alpha\) line may be caused also by the conduction of energy (Czaykowska et al. 2001). The wing-to-center ratios of the mean H\(\alpha\) profiles decreased between 12:20 UT and 12:22 UT owing to increased emission in the line core. Usually cores of the chromospheric lines are significantly enhanced in flaring kernels, while sometimes their emission becomes higher than in the nearby continuum. However, the flare was a low-class event, and the core of the H\(\alpha\) line was not particularly bright. The decrease of the IRs suggests that significant energy was deposited by NTEs in the upper chromosphere, which should happen in the case of a weak flare with a low number of high-energy NTEs (Falewicz et al. 2009a; Reep et al. 2013). The line profiles emitted by the K1 kernel were generally symmetric during the flare, but some small brief shifts were observed during the rapid variations of the HXR emission. The variations of the H\(\alpha\) light curve of the K1 kernel were correlated in time with the variations of the HXR better than the same variations of the K2 kernel. The constant redshift (up to about \(+0.2\) \(\AA\)) of the H\(\alpha\) line profiles emitted by the K2 flaring kernel suggests a macroscopic downward plasma motion.

The vertical extent and location of the EDL were derived from the numerical model under the assumption that the upper boundary of the EDL was located in the plasma layer, where the deposited energy flux starts to increase rapidly near the chromosphere. The lower boundary of the EDL was selected arbitrarily at the altitude at which the energy flux fell to 0.01 erg s\(^{-1}\) cm\(^{-3}\). Before the impulsive phase of the flare, the EDL maintained nearly constant thickness of about 125 km and extended between the altitudes \(H = 1900 \) km and \(H = 2025 \) km above the temperature minimum. During the flare impulsive phase, the calculated altitude of the lower boundary of the EDL abruptly fell and the effective thickness of the EDL quickly increased to about 725 km. This increase was caused by an enhanced flux of the energy deposited by NTEs, which precipitated deeper along the loop toward the temperature minimum. After the impulsive phase, the calculated extent of the EDL gradually shrank owing to the decreased flux of the delivered energy. At the same time the upper boundary of the EDL slowly declined owing to continuing chromospheric evaporation.

Assuming a semicircular loop geometry perpendicular to the solar surface, the apparent positions of the centers of gravity of a footpoint observed in various energy bands can be converted into their positions along the loop. For the brighter, northwest footpoint, during the impulsive phase of the flare the difference of altitudes was equal to 750 km in the case of the overlapped 15–26 keV and 23–34 keV energy bands. The numerically modeled thickness of the EDL during the impulsive phase of the flare was about 3.5 times smaller. However, the extent and altitude of the EDL in the 1D–HD model were derived on many assumptions, and the estimations of the relative positions of the foot observed in various energy bands were approximate only. The relatively low energy fluxes emitted by the flare prevented an application of images restored in the non-overlapping energy bands and the evaluation of the vertical extents before and after the maximum. The modeled variations of the size and location of the EDL yield interesting correlations with the H\(\alpha\) behavior during the impulsive phase, from which certain physical processes of energy deposition can be better understood. Furthermore, the comparison of the time evolution of the EDL position and thickness with the time variations of the H\(\alpha\) emission reveals that the variations of the H\(\alpha\) profiles and intensities are well correlated in time with the modeled variations of the plasma densities and temperatures in the footpoints of the flaring loop and modeled variations of the energy deposition depth. Before the impulsive phase, the mean intensity of the emission of the K1 kernel in the H\(\alpha\) wavelength slowly increased by about 11\%, up to 2.45 times the intensity of the H\(\alpha\) emission of the QS. Later, during the impulsive phase of the flare, the H\(\alpha\) intensity increased to 2.85 times the intensity of the emission of the QS, i.e., by another 16\%, and simultaneously the calculated lower boundary of the EDL abruptly fell and the calculated thickness of the EDL increased to 725 km. After the impulsive phase, the thickness of the EDL diminished again owing to the decreased flux of the energy, and for the same reason, the H\(\alpha\) emission decreased at the same time. Next, the H\(\alpha\) emission persistently increased again because the volume of the emitting plasma increased as a result of the plasma evaporation. The H\(\alpha\) profiles were shifted to longer wavelengths at that time, as a result of the slow downward motion of the emitting plasma.

Our results are consistent with the assumption that time variations of the H\(\alpha\) line profiles emitted by flaring kernels are caused primarily by temporal variations of penetration depths of NTE beams along flaring loops. The result emphasizes the importance of very fast variations of plasma properties in the lower part of flaring loops, where the chromospheric emission appears. The short, subsecond variations of the plasma parameters, revealed as a result of the numerical modeling, are comparable to the timescales of the chromospheric emission variations. The high time resolution spectral and photometric observations of the flaring kernels, easily achievable with the 2D imaging spectographs, are of a great value for the understanding of fast processes in the flaring chromosphere, as well as for investigations of the coupling between NTE beams, HXRs, and chromospheric emissions.

The authors acknowledge the anonymous referee for extended discussions and numerous, very constructive remarks, which allowed us to significantly improve the work. The authors acknowledge also the RHESST and SDO consortia for providing the excellent observational data. The numerical simulations were carried out using resources provided by the Wroclaw Centre for Networking and Supercomputing (http://wess.pl), grant no. 330. The research leading to the obtained results has received funding from the European Community’s Seventh Framework Programme ([FP7/2007-2013]) under grant agreement no. [606862]—F-CHROMA Project. P.R. was supported by the National Science Centre, Poland, under grant no. UMO-2015/17/B/ST9/02073. A.B. was supported by project no. 16-18495S of the Grant Agency of the Czech Republic and by the institutional grant RVO 67985815.

**ORCID iDs**

Robert Falewicz @ https://orcid.org/0000-0003-1853-2809

**References**

Abbett, W. P., & Hawley, S. L. 1999, ApJ, 521, 906

Allred, J. C., Hawley, S. L., Abbett, W. P., & Carlsson, M. 2005, ApJ, 630, 573

Antonucci, E., Alexander, D., Culhane, J. L., et al. 1999, in The Many Faces of the Sun: a Summary of the Results from NASAs Solar Maximum Mission, ed. K. T. Strong et al. (Berlin: Springer), 331

Antonucci, E., Gabriel, A. H., & Dennis, B. R. 1984, ApJ, 287, 917

Aschwanden, M. J. 2005, Physics of the Solar Corona: An Introduction with Problems and Solutions (2nd ed.; Berlin: Springer)
