Interaction of particles beams with chromosphere during impulsive phase of solar flares

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Introduction

The high time-resolution observations of profiles and light curves of the Hα line provide comprehensive information on the dynamic processes during the solar flares, especially during the impulsive stages of the flares.

We present here results of investigation of time and spatial correlations between Hα, X-ray, and UV emissions, as well as the evolution of so-called EDL's (Energy Deposition Layers) of two medium-class solar flares: the C1.6 flare in the NOAA 11564 active region (S13W58) at 10:20 UT on 2012 September 10 and the C1.1 flare in the NOAA 11772 active region (S15W31) at 12:20 UT on 2013 June 21. Both flares have had similar GOES-classes, but very different „hardness" of X-ray emission during their impulsive phases.

The observational data are compared with numerical models of the flares. We applied a single-loop one-dimensional hydrodynamic (1D-HD) model. The evolutions of the EDLs during the various phases of the flares are compared with variations of the HXR and Hα emissions. Variations of shapes of the Hα line profile during the impulsive heating of the plasma by the NTEs (Non-Thermal Electrons) in sub-second resolution are also presented.

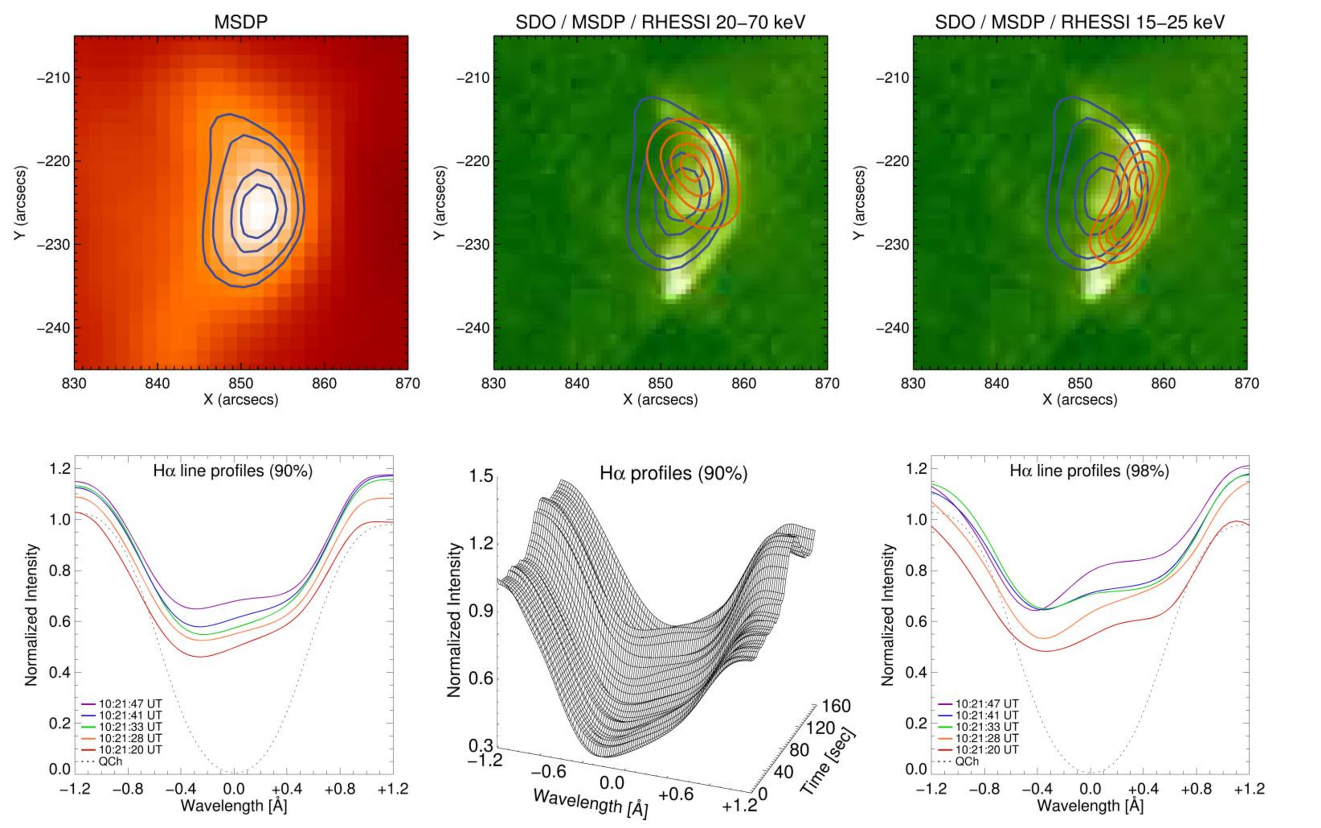


Fig.1. Spatial correlation of the flare emission for C1.6 solar flare on 2012 Sep 10. Hα line centre image and Hα contours (upper-left); UV 94 Å image and HXR (blue) and Hα (orange) contours (upper-middle and upper-right). The Hα line profiles (90% and 98% isocontour) for selected times during impulsive phase (lower-left and lower-right) and 160 sec. Full time-cadence series of the mean Hα line profiles of a part of the flaring kernel (delimited by isocontour 90%) is at lower-middle panel. [*Radziszewski et. al, 2020*]

Numerical model

The 1D-HD numerical models of the flares were calculated using the modified hydrodynamic 1-D Solar Flux Tube Model (Mariska et al., 1982, 1989 and Falewiczet al., 2009). The models were calculated under the basic assumption that plasma confined inside the flaring loops was heated only by variable in time beams of the non-thermal electrons. The basic parameters of the NTE beams were derived from HXR spectra recorded by the RHESSI satellite. Steady-state spatial and spectral distributions of the NTEs along the flaring loops were calculated for every time step of the models using the Fokker-Planck formalism. More information one can found in: Radziszewski et. al, 2020 and *Falewicz, Radziszewski et. al, 2017*.

Abstract

Energy transport by fast, non-thermal particles from primary energy release place - located in the top of flaring loop - to the loop foot-points, plays very important role in solar flares. A fully understanding of the processes of energy transport and energy deposition in the chromosphere during flares requires high (sub-second) cadence observations and appropriate numerical models.

The analysis of two compact solar flares having similar GOES-class (C1.1 and C1.6), but different „hardness" of the X-ray emission during the impulsive phase is presented. Variations of the positions and the vertical extent of the energy deposition layers (EDLs) as well as variations of the flaring spectra and emission intensities recorded in the Hα hydrogen line are also studied.

The variations of the HXR fluxes and Hα intensities during the impulsive phase of the flares were well-correlated and agreed with the variations of the calculated positions and vertical extents of the EDLs. Impulsive variations of the Hα emission were caused by individual, short-lived episodes of energy deposition by the electron beams on various depths in the chromospheric plasma.

The investigated flares were observed in Hα line with very high time resolution of 0.05 sec (20 spectra-images per second) using the Multi-Channel Subtractive Double Pass (MSDP) spectrograph at Białków Observatory (University of Wrocław, Poland), as well as by GOES and RHESSI satellites in X-ray domain. The numerical models were calculated assuming that the external energy is delivered to the flaring loop only by non-thermal electrons.

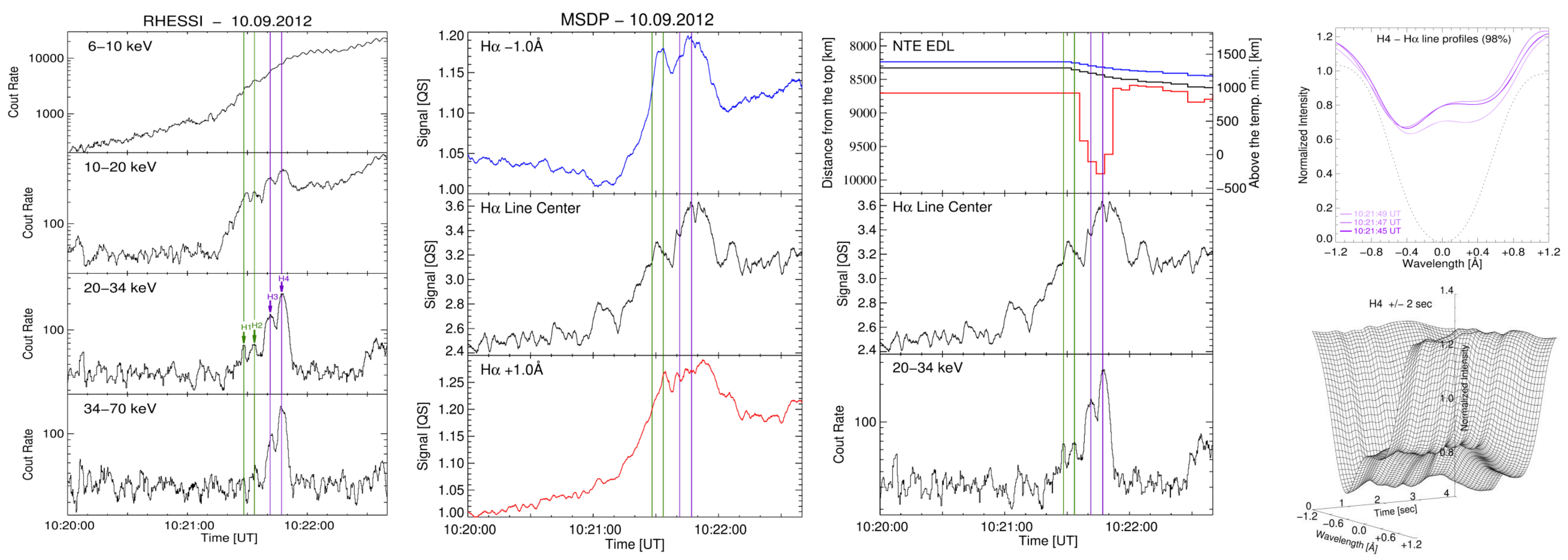


Fig.2. Left column: X-ray light curves (demodulated to 250 ms time resolution) recorded by RHESSI in energy ranges: 6–10 keV, 10–20 keV, 20–34 keV, and 34–70 keV during the impulsive phase of C1.6 solar flare on 2012 Sep 10. Vertical lines (H1 - H4) indicate maxima (pulses) of the HXR emission observed in the 20-34 keV energy range. Second column: Hα line light curves recorded in λ = $H\alpha_0$ – 1.0 Å, λ = $H\alpha_0$, and λ = $H\alpha_0$ + 1.0 Å with the HT-MSDP system. Third column: Time variations of the numerically modeled position and the vertical extent of the EDL and observed emissions in the Hα line centre and HXR (20–34 keV). Right column: Hα line profiles of the brightest part of the flaring kernel delimited with an isocontour of 98% of the highest intensity in the Hα line centre recorded at the H4 peaks of the HXR (± 2 sec) and four-second-long series of the mean Hα line profiles of the same part of the flaring kernel with visible sub-second variations. All light curves in Fig.3 were smoothed with a one-second-wide boxcar filter. [*Radziszewski et. al, 2020*]

Results

Using high time resolution (0.05 s) spectra obtained with the MSDP spectrograph, reconstructed quasi-monochromatic images as well as the RHESSI data, we determined variations of the emissions in the Hα line and the HXR range of the individual flaring kernels during the short-lasting and spatially limited emissions caused by NTEs. During the impulsive phases of both C1-class solar flares, the Hα and X-ray emissions were very well correlated in time, so increases in the emission of the chromosphere in the Hα line were detected very shortly after the HXR pulses.

During the C1.6 flare on 2012 September 10, the maximum of the Hα emission (in the line centre and the wings) was correlated in time with the most strong pulse of HXR marked as H4 in Fig. 2. During the H4 pulse, very fast (sub-second) variations of the Hα line profile and brightness were observed (Fig. 2 - right column). During the maximum of the HXR emission, the upper boundary of the energy deposition layer (EDL) was at an altitude of HU = 1325 km above the temperature minimum while the lower boundary was at an altitude of HD = −300 km, i.e. below the temperature minimum.

In contrary, the C1.1 flare on 2013 June 13, reached maximum of Hα emission after impulsive phase, during maximum of thermal SXR emission, which indicates that thermal conductivity played a dominant role in the transport of energy to the chromosphere in this case. During the impulsive phase, non-thermal signatures were clearly visible in the Ha light curve, but well before the emission maximum was reached (Fig.4). The comparison of the X-ray spectra of both flares is shown in Fig. 3. More detailed information about both flares and extensive analysis is in: *Radziszewski et. al, 2020* and *Falewicz, Radziszewski et. al, 2017*.

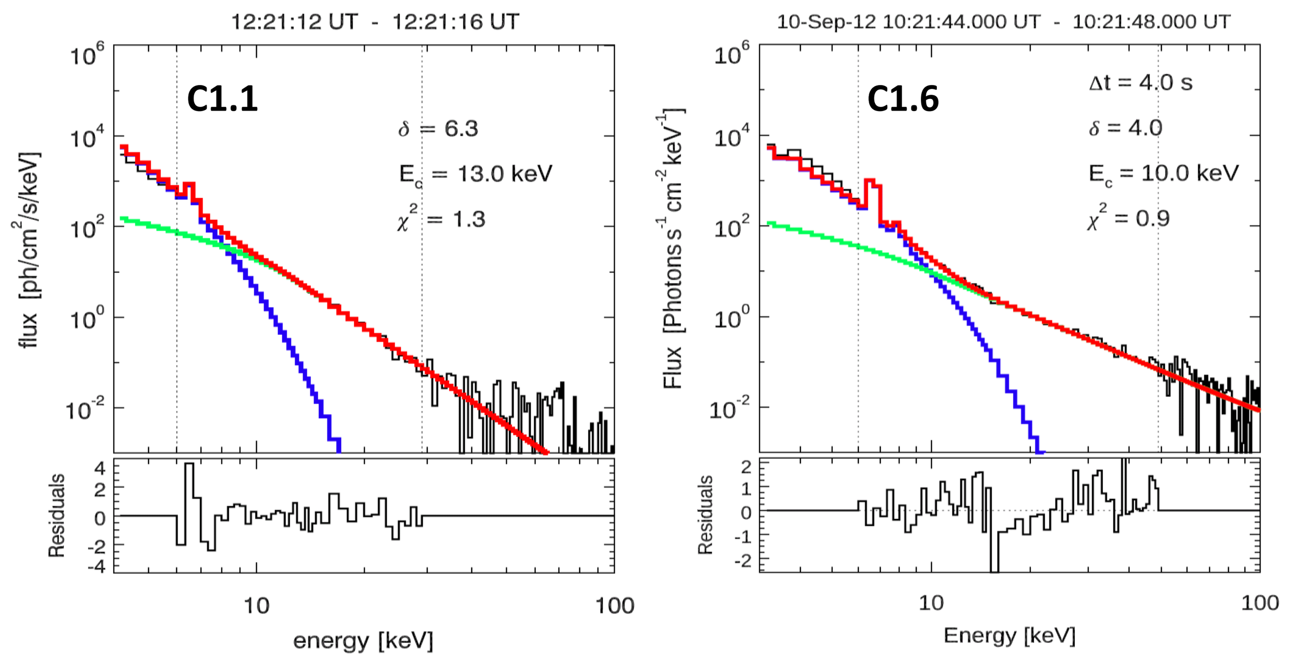
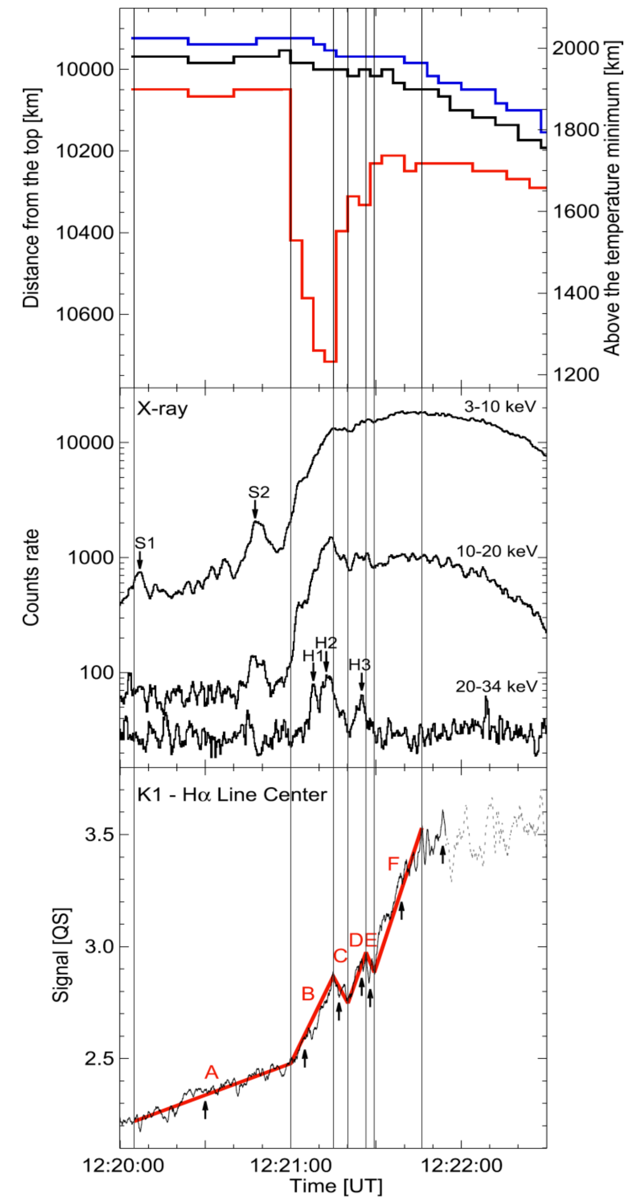


Fig.3. RHESSI spectras recorded during the impulsive phase of the C1.1 flare on 2013 June 21 flare (left panel) and C1.6 flare on 2012 September 10 (right panel). The spectras were fit with the single-temperature thermal model (blue line) and thick-target model (green line). The total fitted spectra are red. Obtained values of δ are different: δ = 6.3 for C1.1 flare and δ = 4.0 for C1.6. Dotted vertical lines delimit energy ranges used for fitting. The E_c and δ parameters were calculated using the thick-target model and the parameterized models of the injected NTE beams. [*Falewicz, Radziszewski et. al, 2017* and *Radziszewski et. al, 2020*]



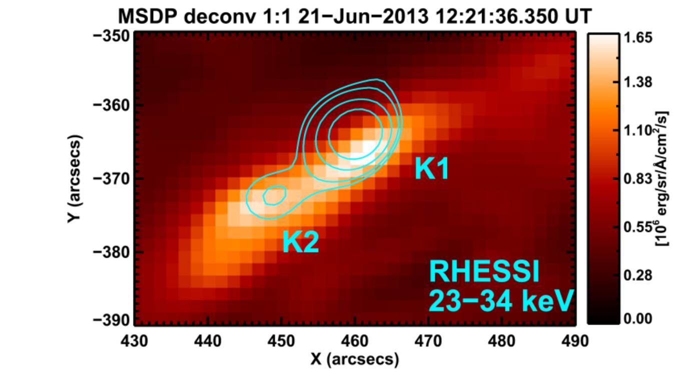


Fig.4. Upper-right panel: spatial correlation of the Hα emission (image) and the RHESSI HXR 23-34 keV emission (contours: 16.5%, 20%, 30%, 50% of the max signal) of the C1.1 solar flare on 2013 June 21. Two bright Hα flaring kernels are marked K1 and K2. Left column: time variations of the calculated position and extent of the NTE EDL, the X-ray emission in various energy ranges, and the observed Hα line centre emission of the K1 flaring kernel during the 2013 June 21 flare. Upper-left panel: position of the maximum of the NTE deposited energy flux (black line), with lower and upper boundaries of the energy deposition region (red and blue lines, respectively). Middle-left panel: RHESSI X-ray emission in the 3-10 keV, 10-20 keV, and 20-34 keV energy ranges (demodulated to 250 ms time resolution). H1 - H3 indicate HXR impulses. Lower-left panel: Hα line centre light curve of the K1 kernel (time res. 50 ms). More detailed description in *Falewicz, Radziszewski et. al, 2017*.

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Conclusions

- Flares with the same GOES classes do not must have the same dominant mechanisms of energy transport to the chromosphere (particle beams / thermal conduction).
- The Hα emission of the flaring kernels is very well correlated in time and in space with HXR impulsive brightenings during the impulsive phases of the solar flares (when energy is carried by beams of the NTEs).
- During the strong pulses of the HXR emission (well noticeable in the X-ray light curves), changes of the Hα line profile occur in much less than a second.
- High-time resolution numerical modelling of the flaring loops allows one to calculate the spatial extents and locations of the energy deposition layers (EDLs).

References

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