X-ray of the 2017 September 10 Solar Flare

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Abstract. The analysis of soft and hard X-ray radiation of behind the limb solar flare SOL2017-09-10T15:35 according to the RHESSI data was carried out. The plasma parameters were determined: emission measure, temperature, density. Sources of hard X-ray radiation >30 keV are observed for several hours after the maximum of the flare. It indicates the long-term processes of acceleration of electrons in the solar corona. The rise of the X-ray source during 6.5 hours was ~70 arcsec. It was proposed also an alternative method for determining the plasma density, based on cross-correlation analysis of time series (time delay method).

1. Introduction

The SOL2017-09-10T15:35 behind the limb flare was detected in different wavelength ranges by GOES, RHESSI, EOVSA, Fermi, SDO, Hinode, IRIS [1],[2],[3]. X-ray precursor at 15:26:28 UT registered by GOES-15 (Geostationary Operational Environmental Satellite) with 1–8 Å associated with EUV loop. The location of the loop on a Sun disc was -150°950". Ten minutes later, the flare started at 15:35 UT. X-ray flux (1-8 Å) increases, UV images (94Å) show the rapid rise of the loop system to a height of 1030". At 15:41-15:45 UT there is a release of hot plasma in the form of a bubble and the formation of a cusp-magnetic structure. The X-ray flux 1-8Å reached the peak at 16:06 UT. Later within 12 hours the intensity of soft X-rays slowly decreased exceeding similar for flares of C-class. At this long flare stage, a system of bright loops (arcade) is clearly visible in the EUV wavelengths. The flare was accompanied by a coronal mass ejection [4],[5]. Ultraviolet data show the ignition of the post-flare arcade, raising the magnetic rope, the formation of the current sheet and the cusp-structure [6],[7],[8],[9],[10],[11],[12]. Behind the limb events due to the shading of bright footpoints and a transverse line of sight provide a unique opportunity to assess the parameters of plasma and accelerated electrons in the coronal part of the active region [13],[14]. For such events, devices without spatial resolution but with high temporal resolution can be used as well.

2. Hard X-ray energy spectra

A typical hard X-ray spectrum can be described by power-law function in the hard X-ray (HXR) range of 25-300keV [15]. Two models of thick and thin targets are considered in the theory of bremsstrahlung radiation. Herewith, impulsive and continuous injection of accelerated electrons is considered too. Continuous injection of electrons is realized if its characteristic time is much longer than the Coulomb collision time. The thick target model involves the injection of an electron beam into a dense plasma, where accelerated electrons rapidly lose energy by collisions and generate X-rays instantly [16]. For a thin target, energy losses via collisions are negligible. In solar flares, the X-ray spectrum is most likely a superposition of quasi-thermal radiation and bremsstrahlung of accelerated...
electrons in thin and thick targets [17]. Most commonly considered the thin target model of X-rays is realized in the loop top contrary to the thick target more adequately describes the hard X-rays from footpoints of magnetic loops.

To analyze the spectra of hard X-rays, 3F detector onboard The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) was used [18]. Analyzing the energy spectrum of this powerful event (counting rate > 10$^4$ counts s$^{-1}$ detector$^{-1}$) we take into account the pileup effect by the function “pileup mod” in OSPEX. The comparison of double-thermal component and one-thermal component was made. We chose a combination of the one-thermal component with broken power-law function in HXR range (thin or thick target models “thin2, thick2”). The selected models of the emission describe the X-rays of SOL2017-09-10T15:35 equally reliably, according to the Chi-square criterion (figure 1).

![RHESSI spectra using the forward-fitting method with a correction for pile-up effects (pileup mod), thermal component (vth), and a) a thin-target power-law (thin2), b) a thick-target power-law (thick2) at time moment near the maximum of HXR flux of the flare.](image)

Figure 1. RHESSI spectra using the forward-fitting method with a correction for pile-up effects (pileup mod), thermal component (vth), and a) a thin-target power-law (thin2), b) a thick-target power-law (thick2) at time moment near the maximum of HXR flux of the flare.

Parameters of the thin2 function at peak time: $\delta_1=6.3\pm0.3$, $E_{\text{break}}=60.2\pm3.1$ keV, $\delta_2=2.6\pm0.1$, $E_{\text{lowcutoff}}=19.8\pm0.4$ keV; thick2: $\delta_1=8.6\pm0.3$, $E_{\text{break}}=72.1\pm3.7$ keV, $\delta_2=4.0\pm0.1$, $E_{\text{lowcutoff}}=21.5\pm0.7$ keV.

Thermal soft X-rays allow us to determine the temperature of hot flaring plasma and the emission measure. At the time of peak X-ray flux $EM=(70.5\pm11.5)10^{49}$ cm$^{-3}$, $T=(20.3\pm0.6)$ MK. Evaluation of the emission measure allows to obtain the value of the plasma density according to $EM=n_e n_i V$. The high plasma temperature implies its complete ionization i.e. $n_e=n_i=n$. The assessment of the flaring plasma density depends on the accuracy of the determination the size (volume) of the X-ray source. The detectors 6F and 8F were chosen to obtain the X-ray images. Using the visibility forward fit algorithm the diameter of the soft X-ray source 9-12keV at the time of the peak flux was calculated $D=21.9\pm2.5$ arcsec or $D=(1.59\pm0.18)10^9$ cm. The plasma density $n=(6EM/\pi D)^{0.5}$ for the emission measure of $EM=(70.5\pm11.5)10^{49}$ cm$^{-3}$ is equal $n=(5.7\pm0.8)10^{11}$ cm$^{-3}$. Estimation of the size of the X-ray source allows to determine Estop energy. In plasma an electron loses the energy in Coulomb collisions. For electrons streaming in a plasma with a certain density with an energy less than Estop a thick target model is implemented, for electrons with an energy >Estop - a thin target. Electron energy losses in Coulomb collisions on a scale of the X-ray source are determined as follows:

$$\frac{dE}{dx} = \frac{2\pi ne^4 A_k}{E}$$
\[-\int_{E_0}^{E_{\text{thermal}}} E \frac{dE}{dx} \, dx = \int_0^l 2\pi n e^4 \Lambda_k \, dx, \quad E_{\text{thermal}} \ll E_0, \quad E_{\text{thermal}} \approx 0\]

\[E_0 = (4\pi n e^4 \Lambda_k l)^{0.5}\]  \hspace{1cm} (1)

where \(e\) - elementary charge, \(n\) - plasma density, \(\Lambda_k\) - Coulomb logarithm, \(l\) - size of a region, \(E_{\text{thermal}}\) - the electron final energy after collisions, we consider it is close to zero, \(E_0\) - the electron initial energy, corresponds to \(E_{\text{stop}}\) for region with given size \(l\) and plasma density \(n\).

Inserting the values of plasma density \(n(D)\) and size of a region \(l = D/2\) to the expression (1), we obtain:

\[E_{\text{stop}} \approx 2.2[(\pi \frac{EM}{D})^{0.5} e^4 \Lambda_k]^{0.5}\]  \hspace{1cm} (2)

For \(EM=(70.5 \pm 11.5)10^{49}\) cm\(^{-3}\) and source diameter \(D=21.9 \pm 2.5\) arcsec the value of electron energy is 44-52keV. It corresponds to the threshold value between thick and thin target models for obtained source parameters.

3. Hard X-ray time delay spectra

The study of the spectrum of hard X-ray time delays in the energy range 40-115keV is an additional method (along with the study of the energy spectra dynamics) for the analysis of the time and space evolution of accelerated electrons in flaring plasma. In the simple models of time of free flight (TOF) simultaneously accelerated high-energy electrons, streaming to the chromosphere, are ahead low-energy electrons and emit HXR in the dense plasma earlier. In this case, the time delay spectrum is decreasing with energy. In the trap plus precipitation model of electron capturing into a magnetic trap another time delay spectrum is realized - increasing with energy. In addition, the analysis of observational BATSE/CGRO data yields U-shaped spectra of time delays [19].

Such a shape of the spectrum at the looptop can be explained by the separation of the electron acceleration region and their injection into the closed loop structure of the magnetic field as, for example, in the model with collapsing trap [20],[21]. In this case, the physical processes corresponding to the decreasing part of the delay spectrum are similar to the free-flight model. The growing part of the spectrum appears due to electron capture in a magnetic loop [22],[23],[24]. Estop energy, estimated from (2), can be overrated from the analysis of the obtained U-shaped spectrum (figure 2) for the looptop source of the SOL2017-09-10T15:35. The minimum value of the time delay spectrum corresponds to \(E_{\text{stop}}\) as \(\epsilon_{\text{min}} = E_{\text{stop}}/q_E\).

![Figure 2. Normalized hard X-ray time delay spectrum](image-url)

To convert photon energy into electron energy, we use electron-to-photon energy conversion factor \(q_E\), which generally depends on the shape of the injected electron spectrum. We use \(q_E=1.124\) calculated by Aschwanden [15]. Multiplying a photon energy of 67-88keV by a factor of \(q_E\), we get the value of the electron stopping energy \(E_{\text{stop}}=75-98\)keV. The value of \(E_{\text{stop}}\) energy allows, using the
formula (2), to estimate the size of the source and to determine the plasma density in the source, regardless of the X-ray image processing methods. We get the values $D=4\text{arcsec} \sim (2.9 \cdot 10^8 \text{ cm})$ and $n \sim 7 \cdot 10^{12} \text{ cm}^{-3}$. From the steady-state equilibrium of the plasma in a magnetic field the lower limit of the magnetic field can be estimated by $nkT=B^2/8\pi$, $B \sim 700\text{G}$. For this event, the magnetic field at the looptop was also estimated from radio data [1], the maximum value of $B$ is $\sim 520\text{G}$.

The U-shaped spectrum can also be explained by an alternative model that does not require such high $\sim 7 \cdot 10^{12} \text{ cm}^{-3}$ plasma density at the looptop. According to the modelling of the accelerated electron beam propagation in magnetic loops, the decreasing spectra of time delays at the looptop can be formed by the scattering on plasmons [22]. In the SOL2017-09-10T15:35 falling part of the X-ray delay spectrum extends to energies of the emitting electrons of the order of 80-100keV. In this case, it can be assumed that the efficiency of the turbulent scattering of accelerated electrons decreases sharply in the energy range higher >100 keV. Or the regions of maximum electron density with energies <100 keV and >100 keV do not coincide. This separation possibility is repeatedly was confirmed by model calculations [25]. In this case, the turbulence region should be localized in the region of the capture of low-energy electrons.

4. The space location of the X-ray sources

Soft and hard X-rays sources according to RHESSI were observed for several hours. The spatial location of the sources was changing with time. During the first 20 minutes of the flare, the displacement of the soft X-ray source was $\sim 20\text{ arcsec}$ (figure 3b).

![Figure 3. a) GOES Soft X-ray flux of SOL2017-09-10T15:35. b) The distance from the center of the Sun of the centroids of sources 9-12keV (used 6F and 8F detectors; at few moments in long-decaying phase only 8F detector was used – labeled). c) Time evolution of the velocity of X-ray sources.](image)

![Figure 4. RHESSI X-ray spectrum at the long-decaying phase 17:44:40 UT and residuals obtained using the forward-fitting method with two thermal components (vth) and power-law (1pow).](image)
At the time of the peak flux, the source was moved outwards at an average velocity of ~ 20 km/h (figure 3c). For the next 7 hours, local sources of hard X-rays were registered during the daytime parts of RHESSI orbits. At that time X-ray sources continue radial movement outward from the Sun. Figure 3 shows the time evolution of the height of the source location and velocity. Figure 5 shows four images of a combination of EUV and X-ray data at different moments.

The problem of the explanation of long existence powerful hard X-ray source arises: either there is a long-time generation of accelerated electrons in the corona, or it is the result of abnormally long cooling times. The X-ray spectrum at the long-decaying phase cannot be represented as a combination of thermal functions, and, despite the high value of background level, the power-law function is required to fit the high energy tail of hard X-rays (figure 4). This fact indicates the inability of explaining the observed hard X-rays only by thermal bremsstrahlung of hot plasma. At 17:30UT two hard X-ray sources were observed (figure 5c, RHESSI contours). The position of one of them coincides with the top of one of the post-flare UV-loops. The second one located higher in the corona and, in accordance with the EUV images, associated with the lower tip of the thin current sheet. This observation may indicate the trapping of electrons, which was accelerated in the current sheet and magnetic cusp-structure.

**Figure 5.** AIA 94, 131 Å images of the loop system with RHESSI X-ray contours at four different moments of the SOL2017-09-10T15:35.
5. Summary
The SOL2017-09-10T15:35 behind the limb flare was analysed. The location of the core of the EUV emission on a Sun disc was -150"950". The flare started at 15:35 UT with X-ray brightness (1-8A) increasing. AIA (94A, 131A) images show the rapid rise of the EUV loops up to the height of 1030" followed by brightness attenuation. The X-rays 1-8A reached the peak flux at 16:06 UT with the subsequent hours-long decrease in the flux. EUV images testify arcade of thin filaments in the upper part of which soft and hard X-ray sources are located. Using the visibility forward fit algorithm the size of the soft X-ray (9-12keV) source at the time of the peak flux was calculated D=(1.59±0.18)×10^9 cm. The plasma density from the emission measure of EM=(70.5±11.5)×10^49 cm^-3 is equal n=(5.7±0.8)×10^11 cm^-3. The processing of time data-sets of hard X-rays with energy 40-115keV revealed U-shape energy-dependent time delay spectrum. One explanation of the U-shape time delay spectra demands extremely dense plasma in the looptop source n~7·10^12, confined by the high magnetic field B~700G. Another possible explanation of U-shape time delay spectra is related to the plasma turbulence in plasma. The X-ray sources were observed for a few hours after flare peak time. The long existence of hard X-ray sources indicates the presence of an accelerating process in the coronal current sheet and magnetic cusp-structure within a few hours later flare peak time.

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