Subsecond pulsations in hard X-rays of August 19, 1998 flare according to BATSE/CGRO data

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Abstract. Detection of ms -spikes and quasi -periodic subsecond pulsations in the solar flare hard X-rays (HXR) provides useful information about the processes of electron acceleration and transport along the flare magnetic loops. To search for HXR pulsations, we processed the data of BATSE/CGRO spectrometer of high temporal resolution 0.016 s and 0.064 s. BATSE energy range is about 20 keV – 1 MeV. For the powerful solar flare SOL1998:08:19T21:39:21 the FFT and wavelet analysis show the presence of HXR pulsations of ~ 0.16 – 0.25 s. BATSE data was analyzed for six energy channels 28.8 – 33.1 keV, 37.1 – 41.8 keV, 46.6 – 55.8 keV, 55.8 – 64.6 keV, 64.6 – 74.0 keV, and 74.0 – 99.1 keV. HXR-spikes were detected. The spike shape is practically triangular with FWHM about 100 ms. Simulations of kinetic models of electron transport with short pulses showed that when the duration of an individual spike is longer than ~ 80 ms, the smearing of pulses practically does not occur. Injection pulses shorter than 30 – 60 ms are not preserved even with a strongly anisotropic distribution of accelerated electrons and a small gradient of the magnetic field. In the isotropic case at the looptop, the decay phase of the X-ray spikes becomes longer compared to the rising phase which is not true for the anisotropic case. The pulse smearing effect is stronger for the softer energy spectra of accelerated electrons.

1. Introduction

HXR time series of solar flares, registered by the Burst And Transient Source Pulsations (BATSE) spectrometer on Compton Gamma Ray Observatory (CGRO) [1], are studied for the goal to find ms-time structure (spike) and quasi-periodic pulsations (QPP). Solar flare emission at sub-second timescales was reported in hard X-ray (HXR) observations by satellite-borne Solar Maximum Mission (SMM) [2-5]. On Hard X-Ray Burst Spectrometer HXRBS/SMM with time resolutions of 128 ms and 10 ms Kiplinger [4] found that 53 out of nearly 3000 flares produce several hundred fast spikes with durations as short as 45 ms. These energetic spikes on short timescales are believed to be nonthermal in nature. Dennis [6] showed that only about 10% of all SMM flares with a high counts rate detected by HXRBS showed variations on a subsecond time-scale. Subsecond time structures were detected practically in all flares recorded in flare mode on more sensitive spectrometer BATSE/CGRO. The distribution of pulse width shows that the HXR spikes with duration 0.1 – 1.0 s were most typical. Cheng [7] present a preliminary statistical investigation of temporal and spectral properties of HXR spikes detected by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI). They detected 184 spikes in 94 out of 322 flares. The time duration of the spikes vary from 0.2 to 2 s, which is not dependent on photon energies. The spikes exhibit symmetric time profiles with no significant
difference between rise and decay times. Among the most energetic spikes, nearly all of them have harder count spectra than their underlying slow-varying component. Also, soft and hard X-ray QPP of ten-minute time interval were found [8].

In the paper, we examine both the subsecond time structures of spikes and similar spectral composition of high-frequency HXR time series for SOL1998:08:19T21:40. To explain the HXR spike structure detailed simulation of the propagation accelerated electrons along flaring loop plasma is performed.

2. Observations

We studied a powerful X3.9 flare that occurred in 1998 on August 19. It starts at 21:39:21 UT, and then reaches its first global maximum at around 21:40:31 UT (figure 1, left panel). The time cadence of BATSE light curves in MER mode is 0.064 s, in the burst-mode. Figure 1 (right panel) shows the light curves at two HXR channels from BATSE/CGRO, 28.8 – 33.1 keV and 46.6 – 55.8 keV, after subtraction of the low-frequency trend. The time profile (in the left) detects individual bursts lasting tens of seconds. A similar time structure is more evident in high-frequency HXR (in the right). However, shorter pulses of subsecond duration may also be present (see later).

![Figure 1. Left - the time profiles of HXR for the six energy ranges; vertical lines denote the time series fragments that were analyzed with spectral methods; red box marks fragments for spikes analysis; Right - the HXR high-frequency components of the two time profiles after subtraction of the low-frequency trend.](image)

3. HXR spikes and QPP analysis of the 1998 August 19 solar flare

To analyze the HXR spikes and QPP, we decompose the light curve into slowly varying low-frequency signal and rapidly varying high-frequency signal (figure 1). The slowly varying signal is obtained by smoothing the original time series with a cubic spline. The high-frequency signal is obtained by subtraction the slowly varying signal from the original data. The spectral analysis of the high-frequency HXR time series was performed using wavelet and fast Fourier transforms. The method of wavelet transform used in this work corresponds to the procedure described in [9]. As the mother wavelet, we selected the Morlet function. We have calculated the wavelet power spectra as well as the global wavelet spectra (figure 3). The red and white noise levels are shown too. Another method of spectral analysis used in this work is the fast Fourier transform. The significance of a peak in the obtained Fourier periodogram is evaluated by the Monte Carlo method with the red-noise model.

SOL 1998-08-19T21:40. For the time interval highlighted in figure 1 by red box HXR high-frequency components are represented in figure 2 (left) for the three energy ranges. Let's pay attention to the HXR spikes of about 47 s. Count rates in 37 – 48 keV and 55 – 73 keV energy bands of these spikes exceed 3σ confidence level. The shape of the HXR-spike of 37 – 48 keV is shown in detail in figure 2 (right). Take into account that 6 time points form practically symmetrical HXR spike profile.
The spike shape is triangular with the full width at half maximum (FWHM) about 100 ms. The spike of 55 – 73 keV is 130 ms ahead of the spike of 37 – 46 keV.

**Figure 2.** SOL 1998-08-19T21:40. Left - high-frequency component of HXR time profiles of fragment marked by the red box in figure 1 for different energies; right - HXR-spike of 37 – 48 keV.

The spectral analysis was applied to BATSE HXR data with a temporal resolution of 64 ms. We analyzed HXR from six energy channels: 28.8 – 33.1 keV, 37.1 – 41.8 keV, 46.6 – 55.8 keV, 55.8 – 64.6 keV, 64.6 – 74.0 keV, and 74.0 – 99.1 keV (figure 1, left). The spectral analysis revealed the presence of QPP of ~ 0.16 – 0.25 s in all considered energy ranges. These pulsations are significant at a level of 95% or 99% above the red-noise. Figure 3 presents the wavelet power spectra and the global wavelet spectra for the time profiles shown in figure 1 (right). Figure 4 shows the Fourier periodograms of HXR signals obtained with the fast Fourier transform.

**Figure 3.** Wavelet power spectra (with enlarged fragments) and global wavelet spectra with the white and red noise levels for the time profiles presented in the right panel of figure 1. In the wavelet power spectra, blue and black contours mark significance levels of 95% and 99% above the red-noise.
Figure 4. Fourier periodograms for signals presented in figure 1. Red circles mark harmonics significant at a level of 99% above the red noise.

4. Hard X-ray spike simulations
To explain HXR spike structures we consider numerical solutions of the time-dependent one-dimensional kinetic equation [10]. The electron injection function time profile consists of three separate Gaussian pulses with FWHM = 16.7 ms (figure 5, bottom panel, right axis, dash-dotted line). Take a magnetic loop length of $l = 6 \times 10^9$ cm. Let the ratio of the magnetic field at the footpoint to the minimum at the looptop to be $B_{\text{max}} / B_0 = 2$ (a faint gradient of the magnetic field). Accelerated electrons were injected at the looptop with space distribution in the form of a Gaussian profile with FWHM = $3.33 \times 10^7$ cm. The injection function is factorized in the energy, pitch-angle, space and time. The energy part described by a power law with spectral index $\delta = 3$, pitch-angle distribution is the high anisotropic distribution $S(\alpha) = \cos^{12}(\alpha)$. The plasma density in the corona-chromosphere transition region corresponds to two possible model distributions formed during the flare increasing phase (figure 5, top panel). HXR from the looptop is negligible due to the high anisotropy of the accelerated electron beam going into the loss cone (bottom panel, left axis, gray full line) and low plasma density in the corona. HXR at the footpoints of the loop (bottom panel, left axis, dash, and full lines) peaks after 0.18 s (the characteristic time of flight of the loop by accelerated electrons). Let's pay attention, the HXR time profile no longer represents three-pulse structure at the footpoints (figure 5, bottom panel). Thus, it is obvious that pulses with FWHM ~ 20 ms do not retain their fine temporal structure during the propagation of accelerated electrons in a magnetic loop.

Consider three-pulse electron injection function with greater FWHM, namely 83 ms and different amplitude and duty cycle of pulses (figure 6, dotted line, $W(t)$, right axis). The plasma density corresponds to model No. 2 in figure 5. The solid curves (figure 6) show the footpoint hard X-ray of 29 – 58 keV for three models with different pitch-angle and energy distributions of accelerated electrons in the injection site. Namely, these are isotropic distributions $S(\alpha) = 1$, hard spectrum with spectral index $\delta = 3$ and $S(\alpha) = 1$, soft spectral index $\delta = 7$ and high anisotropic distribution $S(\alpha) = \cos^{12}(\alpha)$, $\delta = 3$. Dashed lines show looptop HXR fluxes. It is worth emphasizing that the HXR fluxes from the looptop for the models with a power-law index of $\delta = 3$ can be observed only for behind the limb events due to their low HXR brightness compared to the brightness of the footpoints. Analysis of the light curves in figure 6 allows us to conclude for longer electron injection pulses of ~ (80 – 1000) ms, the processes of accelerated electrons transport along the flare loop do not dramatically affect the time profile of X-ray radiation of 29 – 58 keV as it was for 16.7 ms pulses.
Figure 5. Two models of plasma density distribution (top panels). Accelerated electron function W(T) (bottom panel, right axis, dash dotted line). Hard X-ray fluxes (bottom panel) from the looptop and footpoints (correspond plasma densities presented on the top panel).

The main changes of the HXR response compared to initial electron pulses are: in the isotropic case at the looptop, the decay phase of the X-ray spikes becomes longer compared to the decay profile at the time of injection as a result of trapping of electrons due to magnetic mirroring. In the anisotropic case (orange dotted curve), the shape of the spike is preserved, but the FWHM increases. The conclusion is valid for fairly hard electron spectra with δ ~ 3. The plasma density at the looptop is less than 10^10 cm^-3 (figure 5). At the footpoints the shape of HXR spikes is symmetrical for the hard energy spectrum with δ ~ 3, the FWHM increases (black and orange curves). For the model with softer energy distribution (δ = 7), the closely spaced pulses of HXR are smearing at footpoints (figure 6).

5. Conclusions
In solar flare SOL 1998-08-19T21:40 HXR - spikes were detected. The typical spike shape is practically triangular with FWHM about 100 ms. The spectral analysis revealed the presence of QPP of ~ 0.16 – 0.25 s in all considered energy ranges. The modeling tasks in this paper included establishing the principal possibility of preserving the spike structure ~ 10 – 1000 ms of the accelerated electron source under "standard" conditions of a flaring magnetic loop (without turbulence and acceleration processes in the region of electron propagation). It was concluded that when the duration of an individual spike is longer than ~ 80 ms, the smearing of pulses practically does not occur. Shorter pulses less than 30 – 60 ms are not preserved even with a strongly anisotropic distribution of accelerated electrons and a small gradient of the magnetic field. In the isotropic case at the looptop, the decay phase of the X-ray spikes becomes longer compared to the rising phase which is not true for the anisotropic case.
Figure 6. Source of accelerated electrons (right axis, dotted line). Hard X-ray fluxes (normalized) from the looptop and footpoints for models: $S(\alpha)=\cos^{12}(\alpha)$, $\delta=3$; $S(\alpha)=1$, $\delta=3$ and $S(\alpha)=1$, $\delta=7$.

The pulse smearing effect is stronger for the softer energy spectra of accelerated electrons. Beyond the scope of this work remain questions of the influence of various turbulence modes, the plasma density at the looptop, and the magnetic field gradient. A detailed analysis of the influence of these and other plasma parameters on the HXR fine time structure will be highlighted in future works.

References
[1] Fishman G, Meegan C, Wilson R, Paciesas W and Pendleton G 1992 NASA Conference Publication vol 3137 pp 26–34
[2] Aschwanden M J, Benz A O, Dennis B R and Schwartz R A 1995 The Astrophysical Journal 455 347–65
[3] Dennis B R, Benz A O, Ramieri M and Simnett G M 1984 Solar Phys. 90(2) 383
[4] Kiplinger A L, Dennis B R, Emslie A G, Frost K J and Orwig L E 1983 The Astrophysical Journal 265 L99–104
[5] Kiplinger A L, Dennis B R, Frost K J and Orwig L E 1984 The Astrophysical Journal 287 L105–8
[6] Dennis B R 1985 Progress in Solar Physics (Netherlands: Springer) pp 465-90
[7] Cheng J X, Qiu J, Ding M D and Wang H 2012 Astronomy & Astrophysics 547 A73
[8] Foullon C, Verwichte E, Nakariakov V M and Fletcher L 2005 Astronomy & Astrophysics 440 L59–62
[9] Torrence C and Compo G P 1998 Bulletin of the American Meteorological Society 79 61–78
[10] Charikov Yu E, Shabalin A N and Kuznetsov S A 2017 Geomagnetism and Aeronomy 57 1009–17