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St. Petersburg Polytechnical University Journal: Physics and Mathematics 1 (2015) 199–206

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Simulation of hard X-ray time delays in solar flares☆

Yuri E. Charikov[a,b,*], Veronika I. Globina[b,c], Andrei N. Shabalin[b], Eugenia P. Elfimova[a]

[a] Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya St., St. Petersburg 195251, Russian Federation
[b] Ioffe Physical-Technical Institute of the Russian Academy of Sciences, 26 Politekhnicheskaya St., St. Petersburg 194021, Russian Federation
[c] Central Astronomical Observatory at Pulkovo, 65 Pulkovskoe Sh., St. Petersburg 196140, Russian Federation

Available online 30 July 2015

Abstract

Hard X-ray radiation (HXR) time delays have been studied. HXR was recorded during solar flares using the BATSE spectrometer. Time-delay energy spectra were obtained for 82 flares; the spectra were classified under three species: decreasing spectra, increasing spectra and *U*-shaped ones with increasing quantum energy.

The spectra were derived from HXR integral over the active region. They were interpreted on the basis of a model of kinetics of accelerated electrons propagating in the flaring loop with the given plasma concentration distribution and magnetic field configuration. The kinetics in question is governed by the processes of Coulomb scattering, reflecting in the converging magnetic field, and with the return current factored in. Solving the time-dependent relativistic Fokker–Planck equation for the given initial conditions allowed to find the time-dependent electron distribution function along the loop. The brightness distribution of the bremsstrahlung of HXR derived from the electron distribution functions was calculated for different quantum energies along the flaring loop and used to plot the time-delays spectra. The calculated data showed that decreasing time-delay spectra were tractable assuming regions of electrons acceleration and injection were separated. The distinction between time-delays spectra from the looptop and footpoints was established. Hence the measurements with high resolving power may produce comprehensive data on the processes of electron transport and acceleration during solar flares.

Keywords: Sun; Flare; X-rays; Transport electron; Time delay.

1. Introduction

Analyzing the time delays of flare electromagnetic radiation in a wide energy range supplies data on the energy spectra dynamics as well as on the specifics of electron acceleration and propagation in loop structures of the magnetic field during solar flares. A detailed study of hard X-ray radiation (HXR) time delays was first conducted using the data obtained from the BATSE spectrometer measurements at the Compton satellite [1,2]. The spectrometer's high time resolution allowed to find delay values lying within the range from milliseconds to seconds and to analyze their energy spectra. Refs. [1,2] have pursued the goal of finding the dependence of the delay spectrum on the HXR energy of the specific form $E^{-0.5}$ or $E^{1.5}$ (E is the mean electron energy in each

☆ Peer review under responsibility of St. Petersburg Polytechnic University.

* Corresponding author at: Peter the Great St. Petersburg Polytechnic University, 29 Politekhnicheskaya St., St. Petersburg, 195251, Russian Federation.

E-mail addresses: Yuri.Charikov@mail.ioffe.ru (Yu.E. Charikov), gvi1109@gmail.com (Veronika I. Globina), taoastronomer@gmail.ru (Andrei N. Shabalin), elfimovaevgeniya@gmail.com (Eugenia P. Elfimova).

http://dx.doi.org/10.1016/j.spjpm.2015.07.003

(Peer review under responsibility of St. Petersburg Polytechnic University).

channel), which would be consistent with the hypothesis (alternative) of free electron transit in a flaring loop or of electron trapping into this loop with subsequent electron scattering into the loss cone.

We should note that the expected dependences of the delay spectra on energy were obtained with the simplified assumptions of transfer and radiation of accelerated electrons in the solar flare plasma. Besides, the BATSE spectrometer has no spatial resolution and thus only detected the radiation from the whole flare. However, the processes of electron acceleration, injection, transfer and bremsstrahlung do influence the time-delay spectrum on the whole, so the above-described dependences are unlikely to be expected. The time-delay spectra are also likely to be different at the top and at the footpoints of a magnetic loop.

Based on the above, the present study aims at solving a more feasible task of obtaining and interpreting time-delay spectra from both the whole loop and its separate parts.

2. The technique of processing the time series of solar flare HXR

The technique of processing the experimental data obtained using the BATSE spectrometer for simple single-pulse events is described in Ref. [3]. In essence, the technique entails constructing a mutual correlation function (MCF) for all pairs of time series from the studied energy range from 20 keV to 2 MeV and subsequently interpolating three points near the function maximum with a second- or fourth-degree polynomial.

In contrast with the technique of Ref. [3], the present work assessed time-delay errors by the Monte Carlo method when constructing the time-delay spectra of solar flares from the BATSE measurements [4]. The BATSE data contains error arrays related to finding the quantum counting rate for each flare. The delay error is calculated for $N = 100$ (N is the number of iterations). Based on the BATSE data, time series with a Gaussian spread of counts in each bin are generated at each iteration, and the time delay value is found. Then the obtained values are sorted in ascending order and numbered from 1 to 100 (generally, from 1 to N). The value matching the number 50 ($N/2$) is taken as the final time delay value t_d. The lower and the upper boundaries of the confidence interval at the 68% level are determined by the values numbered 16 ($N \cdot 0.16$) and 84 ($N \cdot 0.84$), respectively ($t_{d\ \mathrm{dn}}$ and $t_{d\ \mathrm{up}}$). The error is found by the formula

$$\Delta = (1/2 \cdot [(t_{d\ \mathrm{up}} - t_d)^2 + (t_{d\ \mathrm{dn}} - t_d)^2])^{1/2}.$$

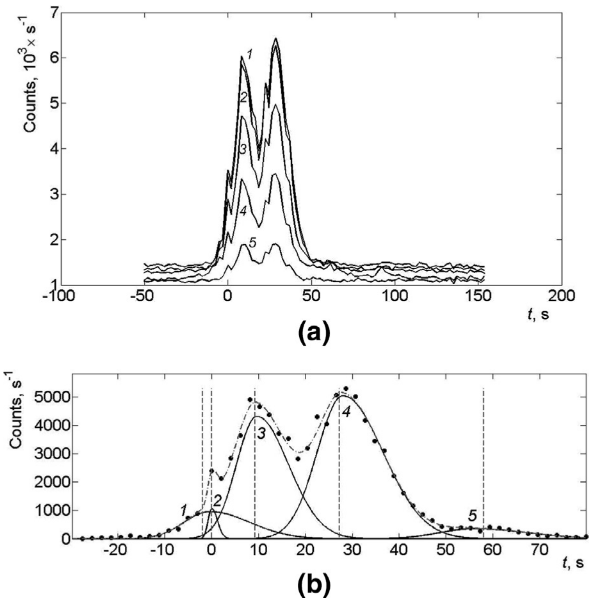

Fig. 1. Time profiles (1–5) of the 1450 solar flare (a) and the decomposition of its profile 1 into 5 pulses (1′–5′) (b).

The analysis of multi-peaked events is another important addition to studying HXR solar flare time delays (previously only single-peaked flares were selected). In this case, after the multi-peaked HXR structure was decomposed, a correlation analysis was carried out for both the entire time series and the individual pulses. A problem, that arises when decomposing a complex time HXR structure, is choosing the pulse shape that the initial profile is decomposed into. In this study we chose the shape observed more frequently than others for short single pulses; it increases sharply and decreases smoothly. The following function was chosen to describe this pulse shape:

$$f = \begin{cases} y = y_0 + He^{-0{,}5\left(\frac{x-x_c}{w_1}\right)^2}, & (x < x_c) \\ y = y_0 + He^{-0{,}5\left(\frac{x-x_c}{w_2}\right)^2}, & (x < x_c) \end{cases},$$

where functions $y(x)$ describe the pulse-line profile; y_0 is a noise level; H is a pulse height; w_1, w_2 are pulse-shape parameters, x_c is the position in x-axis.

The coefficient specifying the ratio of the parameters w_1 and w_2 that determine the pulse shape was found from approximating the 2028 flare from the BATSE Catalog (30.10.92, 22:53:31 UT). Then, using the 1450 flare from the BATSE Catalog (29.02.1992, 7:39:48 UT, X-ray class GOES C1.7) as an example, we are going to study decomposing HXR into individual pulses. Time profiles of the selected flare are shown in Fig. 1a.