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The High Energy Photons Emission from Solar Flares Observed by SZ2-XD

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Abstract: More than a hundred solar X-ray flares with intensities covering C to X-classes have been observed by SZ2/XD in the energy band of ∼10-800 keV during the year 2001. In this paper, we present the analysis results for three X-class solar flares SF010402, SF010406 and SF010415, which shown different characteristics of high energy photon emission. In particular, two lines feature around 440 keV and 720 keV have been found from the spectrum of SF010415, a X14.4-class flare occurred at 15 April 2001. Its spectral evolution traced the initial accelerating process of ion particles. Comparing with SOHO and other observations, the occurred time of this event was coincided with the period when the ejection matter was running away. It may provide the evidences to explain the origin of the line feature.

Introduction

SZ2/XD[1, 2] is an X/γ detector set including two NaI sub-detectors to cover the energy band of 10-200 keV for XD1 and 40-800 keV for XD2. The detector was designed for GRB detection mainly. There were 40 ms, 200 ms, and 1 sec time scale for trigger mode so as to observe not only gamma-ray bursts but also solar flares. For each of triggered burst-like event, a 64-channel energy spectrum was accumulated for the 40 sec of the background data in time resolution of 1 sec, and for the 128 second of the burst data in each of 40 ms. Beside, the total counting rate for each of the detectors can be measured for longer time.

The detector set was installed and operated on board of SZ2, a Chinese spacecraft with the orbit about 400 km and the inclination of 42 degree, for 160 days between 10 January and 25 June in 2001. More than a hundred solar X-ray flares with intensities covering C to X-classes have been observed. We investigated the light curve and the spectrum of all the triggered solar flares. In this paper, we present the analysis results of XD2 data, for three of the X-class solar flares, SF010402, SF010406 and SF010415, which shown different characteristics of high energy photon emission.

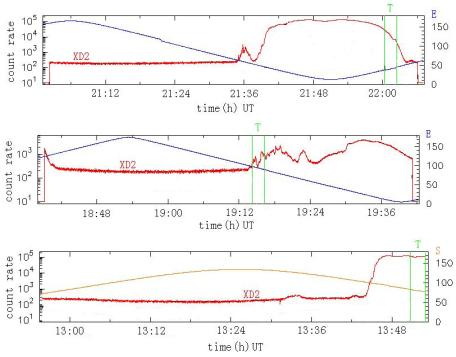

Figure 1: The light curve of three X-class solar flares, SF010402 (top), SF010406 (middle), and SF 010415(bottom).

The data and the analysis

SZ2/XD observed three X-class flares during its flight. Their light curves observed by XD2 in 40-840 keV range are shown in Figure 1.

In the plots, the time interval between the two green lines is the period with spectrum data accumulated. The number on the right side of the figures is in unit of degree. For SF010402 and SF010406, it is the direction of the Sun to the detector axis, during the axis pointing to the anti-earth direction (see the blue curves). For SF

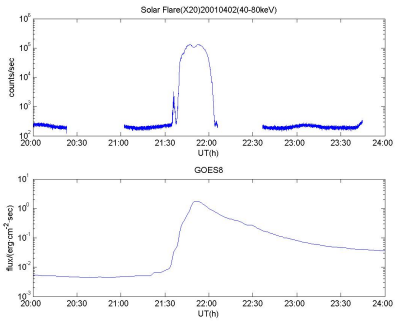

Figure 2: The light curve of SF010402, compared with GOES

010415, the detector axis is pointing to the Sun, while the orange curve gives the local direction of earth center related to the detector axis.

By using HEASARC XSPEC software, and sometime CERN ROOT, the observed spectrum and their time evolution were investigated. The energy response matrix of the detector was generated by simulation using GEANT4 and verified with the experimental calibration data.

Results and discussions

A) The flare SF010402

SF010402 is an X20 flare started from 21:38 UT in 2 April 2001, the most intense solar flare since 1989, and a solar proton event too. It associated with a CME event occurred at NOAA 9393(N17, W67). The speed of the mass ejection was higher than 2000 km/s[3]. The counting rate of XD2 during its peak time is in factor of 500 higher comparing with the background, and reaches to more than 130k cts/sec. It caused the 16-bit variable overflowed twice, and the spectrum was re-started for accumulation for several times (because of special settings in software), so that the recorded spectrum data was started from 22:00:16 and happened in the flare's fall weaken Phase. The light curve was typical for a SEP event comparing with GOES observation (Figure 2). Figure 3 shown the spectrogram. It may be seen that the spectrum become harder by the time. Table 1 listed the parameters of the spectrum fitted by power law $KE^{-\lambda}$ in three different time intervals.

B) The flare of SF010406

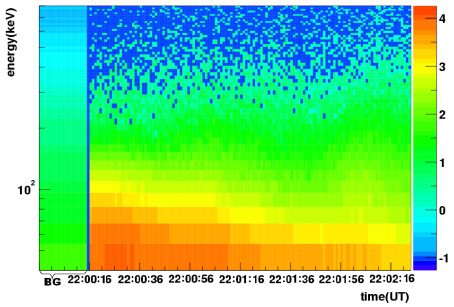

Figure 3: The observed spectrogram of SF010402, Energy in log scale versus time(UT), the color indicates the counting rate per channel in log scale. The left side is the background spectrum for comparison.

Table 1: Results fitted by power law, K is in unit of $\mathrm{photons/cm^2/s}$ at 1 keV, λ is power law index.

time(s)	λ	K	χ^2/ndf
0-50	6.13±0.03	$(3.2 \pm 0.4) \times 10^{11}$	3.6
50-90	4.40±0.03	$(3.7 \pm 0.5) \times 10^{7}$	2.7
90-128	4.7±0.1	$(3.5 \pm 2.1) \times 10^{7}$	3.0

SF010406 is an X5.6 flare started from 19:10UT in 6 April 2001. It occurred in NOAA 9415 (S21, E21) [4]. It is not a SEP event. XD was triggered in its pulsed phase at 19:14:08. The spectrum (Figure 4,5, Table 2) show not much differences during the time intervals of two minutes.

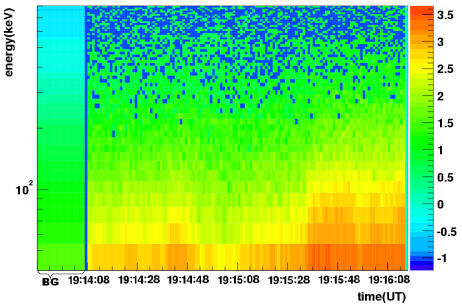

Figure 4: The observed spectrogram of SF010406. Energy in log scale versus time(UT), the color indicates the counting rate per channel in log scale. The left side is the background spectrum for comparison.

C) The flare of SF010415

SF010415 is an X14.4 flare started from 13:43UT in 15 April. It occurred in the same active region

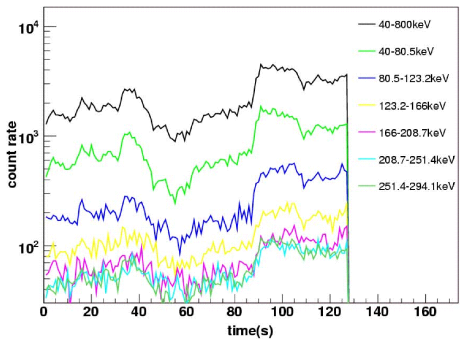

Figure 5: The observed total counting rate (top line), and counting rate for different energy bands. The horizontal axis is started from the trigger time.

Table 2: Result of power law fitting (the correction of solar zenith angle has not been implemented yet.).

time(s)	λ	K	χ^2/ndf
0-50	4.16±0.08	$(8.5 \pm 0.3) \times 10^5$	1.5
50-87	3.62±0.04	$(1.3 \pm 0.2) \times 10^5$	2.2
87-128	3.84±0.12	$(1.2 \pm 0.7) \times 10^5$	0.7

of NOAA 9415 as SF010406, but close to the edge of the Sun surface (S20, W85). It is a well-know event as it has strong blast proton emission, associated with big CME event, radio emission and ion ejection[5, 6]. In particular, although it is not as bright as SF010402 in GOES energy band, but it has more intense proton flux. And a very strong Ground Base Enhancement (GLE) happened, for example, Oulu Neutron monitor had 58% flux enhancement. The counting rate of XD2 during the peak time reached also to 140k cts/sec. For the same reason, the spectrum data was delayed and started from 13:50:58. It was just in the peak time of GOES X-ray light curve (see Figure 9). In addition, there were two lines feature were obviously recorded in XD2 spectrum. Figure 6 shows the observed spectrogram of this event. Two lines feature and the spectrum variation can be clearly see, the flux getting down in lower HX band, after 15s the spectrum become harder by time (Figure 7) and stable after 80 sec, then second line is obviously formed. All this happened within two minutes of observation.

Where are the lines come from? There are two possible models.

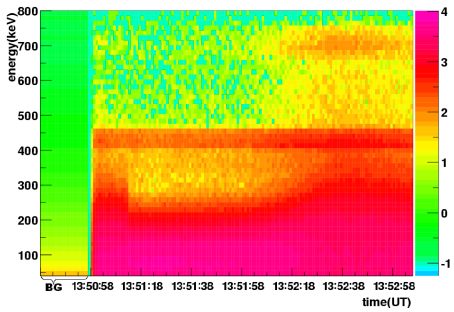

Figure 6: observed spectrogram of SF010415, Energy in linear scale versus time(UT). the color indicates the counting rate per channel in log scale.

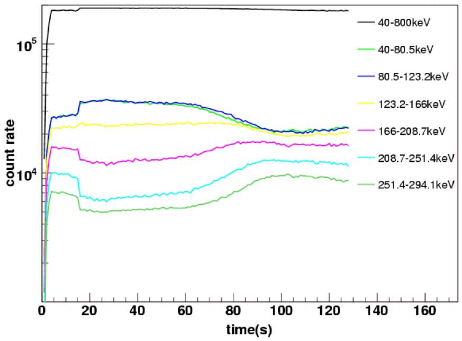

Figure 7: The light curve in different energy band in total and in 40-300 keV.

1), From the de-excited ion particles. The line around 440 keV can be produced by (α, α) interaction, the accelerated particles have interaction with in corona (rich helium ion); or by excited ions of ^{7}Be$*$ (439 keV) and ^{7}Li$*$ (478 keV). The line around 730 keV could be produced by excited ions of ^{10}B$*$ (717 keV).

2), From electron positron annihilation (511keV) and de-excited ^{56}Fe$*$ (847keV). But in this case, about $(12 \sim 14)\%$ red shift needed for both the lines, which implicate that the electrons and irons are all running away in a high speed reach to $\sim 4 \times 10^7$ m/s.

To find the evidence for which of the above model possible, we investigated the time relation between different observations. All information is listed in Table 4, and Figure 9.

The time of this bright flare from various measurement are well coincided around the peak period of 13:38-14:00UT including GOES, SZ2/XD, H_α, radio and EIT observations.

Table 3: Fitting results of SF010415

a) by broken power law for the HX band of 100-300 keV.

time(s)	energy(keV)	λ_1	E_0	λ_2	K	χ^2/ndf
15-55	110-320	1.52±0.04	211±1.7	7.3±0.2	3224	3.0
85-128	100-320	-0.49±0.04	244±3.5	3.1±0.2	0.025	3.2

b) by power law and two Gaussian lines for the energy band of 260-840 keV.

time(s)	energy (keV)	λ	Gauss Mean E_1	Gauss Mean E_2	K	χ^2/ndf
15-55	260-800	3.1±0.5	449±1.4	744±12.7	1.4E+06	15.2
85-128	260-800	4.92±0.04	441±9.6	729±4.9	3.0E+11	18.4

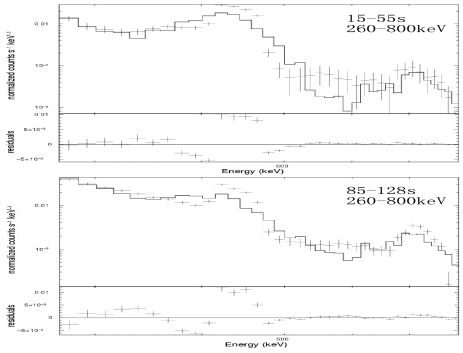

Figure 8: Fitting result by a single power law and two Gaussian lines.

Table 4: SF 010415 Timing overview

	ST	Peak	End	(Time in UT)
GOES	13:19	13:50	15:30	
H_α	13:36	13:49	15:35	
SZ/XD	13:44	13:47	13:51[S]	[S]Spectrum data started
Neutron	14:00			Oulu CR station
3 GHz radio		14:17		
0.8-1.3 GHz	13:37	13:45		-4.7NHz/s, TRACE 1st CME
0.8-2.0 GHz	13:44	-13:54:20		-10 MHz/s, TRACE 2st CME
LASCO-C2		14:30[a]	16:00[b]	[a]Big CME, [b]Particle peak
EIT 195 Å	13:48	14:00		

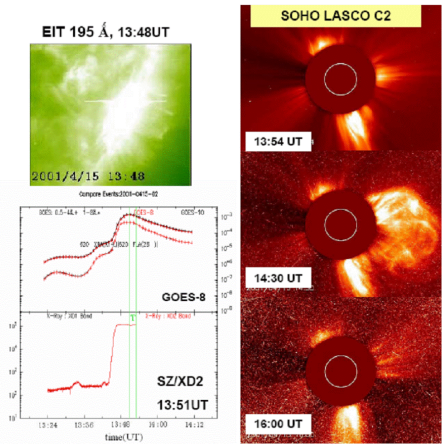

Figure 9: The pictures in the right side were captured from a movie of LASCO C2 observation in 1-27 April 2001[7]. The movie shows very clearly that during the flare, the ejection was to the direction of away from us. Then the peak time of a big CME was happened at 14:30, and LASCO observed particles at the peak time around 16:00. This indicates the second model feasible, more discussions will be presented in another paper.

In summarize, the spectrum of SF010415 observed by SZ2/XD traced an initial accelerating process of ion particles, and maybe also electrons. Comparing with SOHO and other observations, the occurred time of this event was coincided with the period when the ejection matter was running away. It may provide the evidences to explain the origin of the line feature.

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