Systematic studies of spectral break-up of solar flares in the hard X-ray band with the Suzaku HXD-WAM

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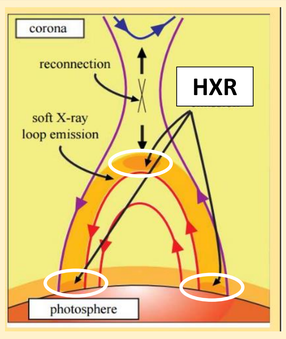
abstract

The hard X-ray and gamma-ray continuum components in solar flares are considered as Bremsstrahlung emission by accelerated non-thermal electrons. The energy spectra are normally well described by the single power-law shape. However, several authors reported that some flares show hardening spectral shape at higher than 300 keV. Such hardening shape is called as spectral "break-up." Although one of the reasons may be nuclear gamma-ray lines emissions, the break-up is also found in electron-dominated events, i.e., flares showing no nuclear gamma-ray lines. Therefore, at least the spectral break-up of electron-dominated flares is caused by intrinsic feature of energy distribution of source electrons. In this presentation, the results of analysis about spectrum break-up using the Suzaku Wide-band All-sky Monitor(WAM) are summarized. The Suzaku WAM is the BGO anti-coincidence shields of the Hard X-ray Detectors (HXD) facing four sides. The WAM is also used for the all sky monitor in the 50 to 5,000 keV band with the large effective area of 400 cm^2 at 1 MeV per side. Among 756 solar flares detected by WAM, 14 flares are found to have non-single power-law spectra, indicating electron break-up phenomena or contamination of gamma-ray lines. The properties of these flares will be presented.

Solar flare



Sketch of the reconnection model. [1]

・Driven by magnetic reconnection.
mechanism of high energy particle acceleration is still in debate.

・In the hard X-ray ~ γ-ray(100 – 500 keV) band, spectra are **typically** well described by the single power-law $\boldsymbol{A(E) = KE^{-\Gamma}}$ from non-thermal bremsstrahlung by accelerated electrons

・**However, some flares exhibit spectral "break-up" $\geq$ 300 keV**

・This break-up can be caused by some reasons, e.g., contamination of gamma-ray lines ≥ 500 keV, difference of radiation site; foot-point/loop-top (**see P02**), and so on.

・Especially, Li et al. (2013)[2] suggested the scenario, "**intrinsic hardening in electron spectrum** by diffusive shock acceleration at a termination shock with a finite width."

previous study Li et al. (2013)

・At least in electron-dominated flare(no clear signal of gamma-ray lines), the break-up should reflect intrinsic electron distribution break-up. The scenario is followings;

If shock has finite width, particle spectrum is modified; $p^{-\alpha} \Rightarrow \boldsymbol{p^{-(\alpha+1/\beta)}}$

$\boldsymbol{\beta}$ has **momentum dependence**, and

low *E*/high *E* electrons resonate with dissipation/inertial range of turbulence

That leads **two different $\boldsymbol{\beta}$ $\Rightarrow$ break-up occurred**

$\boldsymbol{k_B}$ $\equiv$ boundary wavenumber of two ranges, **is related to break energy**

・This scenario leads anti-correlation between photon index1 (below the break) vs break energy.

・Also, the systematic study based on this scenario has been reported by Kong et al. (2013)[3]

This Study

Reports of spectral analysis for break-up structure with WAM observations according to previous study, assuming foot-point radiations only.

The Suzaku HXD/WAM

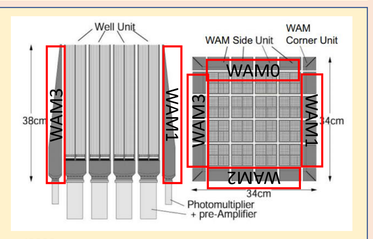
Wide band All sky Monitor (WAM)

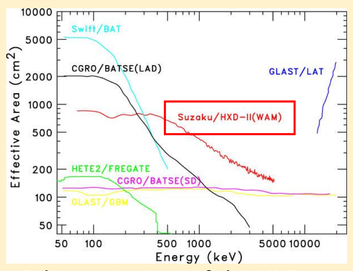
・Active shield of Suzaku onboard Hard X-ray Detector

・Also used for the all sky monitor

・4 independent units. WAM0 faces the Sun.

observation period	2005/Aug ~ 2015/May
energy band	50 ~ 5000 keV
solid angle	2π sr
effective area	400 cm^2 @1 MeV per side
time resolution	1 sec





Schematic view of the HXD
And Effective area of WAM [4,5]

Observation & Analysis

Event selection & Spectral analysis

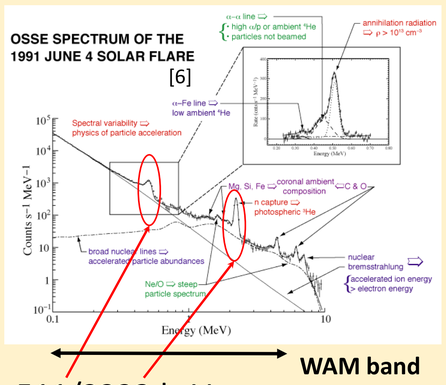
*1: **Geostationary Operational Environmental Satellite** GOES is the weather satellite, and also observes soft X-ray from the Sun. GOES determines magnitude class of solar flare, "GOES class" using soft X-ray flux peak.

・Simultaneous observations with GOES satellite *1.

・Detected in $\geq$ 500 keV band.

・No effects of Earth occultation, SAA, and pileup.

・**14 events rejected a single power-law model with p-value $\leq$ 0.05**



Spectral Analysis

1. Fit with broken power-law
2. Fit with broken power-law + 2 gaussians centered on 511/2223 keV *1

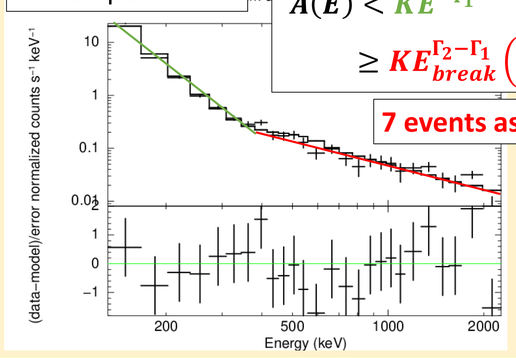
to check whether gamma-ray lines exists or not, as a contamination*2

*1 511 keV: annihilation line 2223 keV: neutron capture both are strong compared to other γ-ray lines
*2 this time, if more than one line remains in fit with 68% confidence level, we defined "there is contamination"

broken power-law

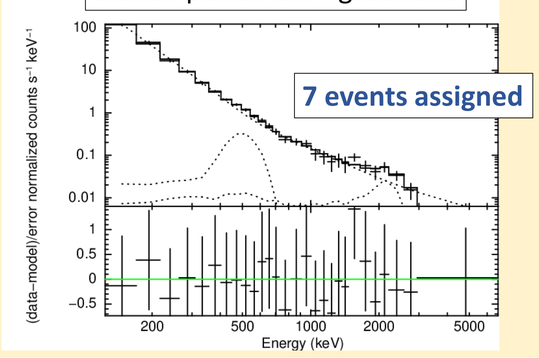
$$\boldsymbol{A(E) < KE^{-\Gamma_1}}$$
$$\boldsymbol{\geq KE_{break}^{\Gamma_2-\Gamma_1}\left(\frac{E}{1\mathrm{keV}}\right)^{-\Gamma_2}}$$

7 events assigned



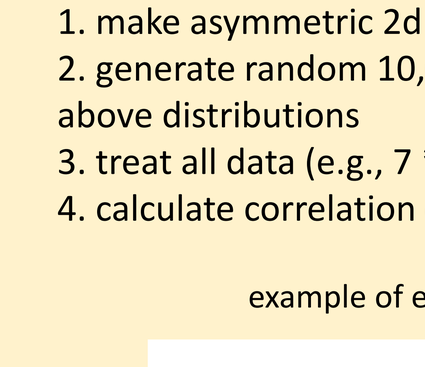
broken power-law +gaussians

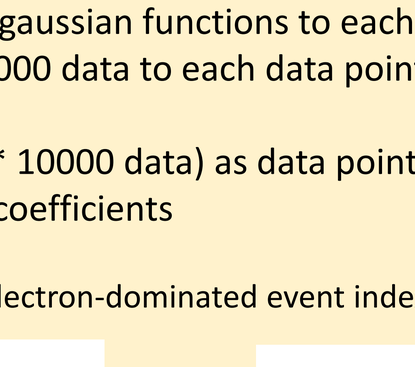
7 events assigned



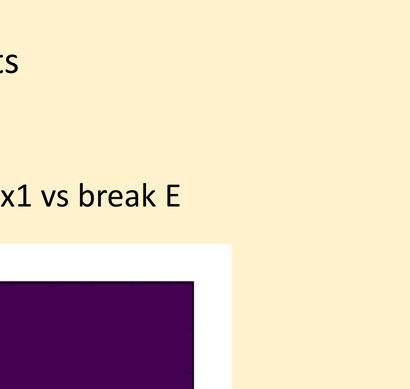
Results

* errors are 68% confidence level





・Li et al. (2013) predicts anti-correlation between **index1** vs **break energy** on electron-dominated events



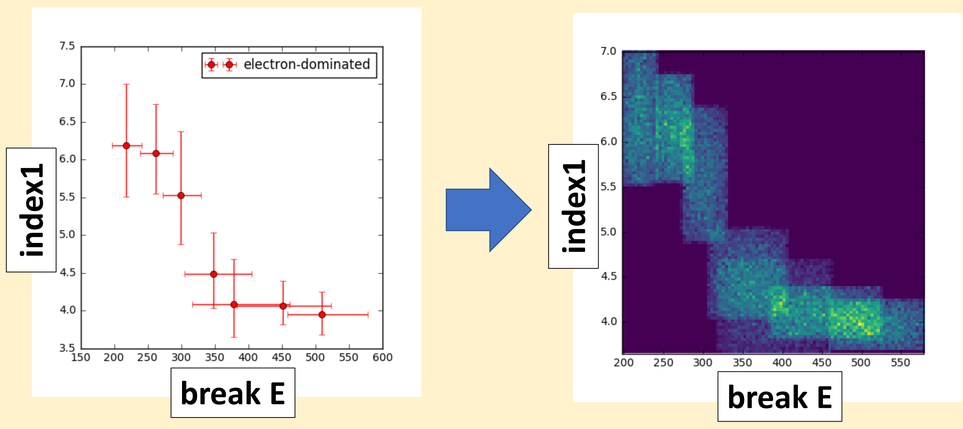
results of Kong et al. (2013)
red: Events in the Literature
black: Events from *SMM* only

correlation coefficients

calculate correlation coefficients considering errors as follows

1. make asymmetric 2d gaussian functions to each data using each error
2. generate random 10,000 data to each data point according to the above distributions
3. treat all data (e.g., 7 * 10000 data) as data points
4. calculate correlation coefficients

example of electron-dominated event index1 vs break E



	all(14)	electron-dominated (7)	gamma-ray lines(7)	Kong et al. (2013) Only *SMM* (23)
index1 vs break E	-0.713	-0.853	-0.075	−0.709
index2 vs break E	0.296	0.353	-0.005	0.126

・**anti-correlation on electron-dominated "index1 vs break E"**
・**show a weaker correlation on "index2 vs break E" than "index1 vs break E"**
・This trends agree with results of Kong et al. (2013)

Summary

・We carried out systematic spectral analysis for 14 events which reject a single power-law model observed with WAM.

・In 14 events, while 7 events result in having a contamination by gamma-ray lines, other 7 events indicate electron-dominated events.

・Anti-correlation between photon index1 and break E is found in electron-dominated events, but not in gamma-ray line events.

・Lack of strong correlation between photon index2 and break E is shown in electron-dominated events.

・This trends agree with the scenario of Li et al. (2013) and results of Kong et al. (2013); the systematic study with *Solar Maximum Mission* satellite.

Reference

[1] Jonathan, P,E. 2008, *Phil. Trans. R. Soc. A,* 366, 4489
[2] Li et al. 2013, *ApJ*, 769, 22
[3] Kong et al. 2013, *ApJ*, 774, 140
[4] Yamaoka et al. 2009, *PASJ*, 61, 35
[5] Yamaoka et al. 2017, *PASJ*, 69, R2
[5] Murphy et al. 1997, *ApJ*, 490, 883