Time-resolved hard X-ray spectra of the solar flares with the Suzaku HXD-WAM

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Abstract

The solar flares are one of the biggest energy-release phenomena driven by magnetic reconnections in the solar atmosphere. The electrons accelerated by magnetic reconnections radiate hard X-ray emissions via non-thermal bremsstrahlung at the foot-points and/or the loop-top (Masuda et al. 1994). Observationally, the emission exhibits power-law spectral shapes, which in turn represent the energy distributions of the accelerated electrons. In addition, Ishikawa et al. (2011) describes that the X-ray peak of a foot-point delays ~10 sec from that of the loop-top emission due to the transit time of the accelerated electrons from the loop-top to the foot-points. However, finer time bins and pile-up corrections are needed to investigate the detailed transfer of the accelerated electrons.

We performed time-resolved spectroscopy of the solar flares observed by the Suzaku HXD-WAM, which is the BGO scintillator surrounding the Suzaku hard X-ray detector and was used as all sky monitor in the 50-5000 keV (Yamaoka et al. 2009). In our analyses, we studied the time evolution of photon indices and fluxes every 1 sec, after taking into account pile-up corrections using the Geant4-based pile-up simulator (Yasuda et al. 2015). As a result, we found that the peak time of the flux in the high energy band (520-5000 keV) is later than that in the low energy band (50-110 keV). This result supports the picture described in Ishikawa et al. (2011) that the accelerated electrons at the loop-top precipitate into the foot-points after several seconds.

1. Solar flares

- The solar flares are driven by magnetic reconnections in the solar atmosphere.
- The accelerated electrons radiate hard X-ray emissions via non-thermal bremsstrahlung at the foot-points and/or the loop-top [1].
- Observationally, the emission exhibits power-law spectral shapes, which in turn represent the energy distributions of the accelerated electrons.

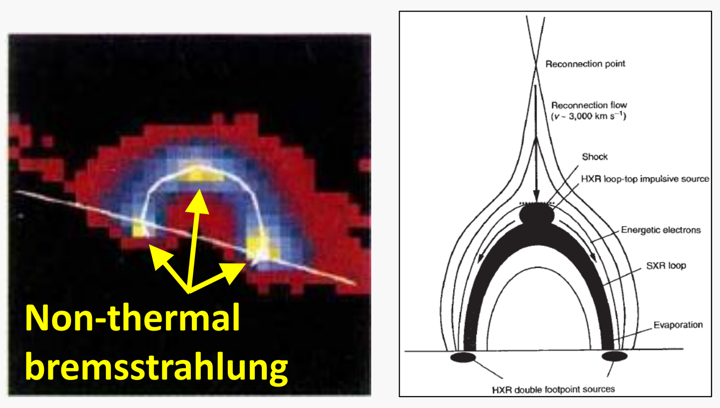

Fig. 1 Left : Hard X-ray source observed by *Yohkoh* [1]
Right : The magnetic-field geometry for reconnection [1]

Previous study with *RHESSI*

Ishikawa et al. (2011) reports that the X-ray peak of a foot-point delays about 10 sec from that of the loop-top emission due to the transit time of the accelerated electrons from the loop-top to the foot-points [2].

Finer time bins and pile-up corrections are needed to investigate the detailed transfer of the accelerated electrons.

In this study

We performed time-resolved spectroscopy of the solar flares observed by the Suzaku HXD-WAM, with finer time bins taking into account pile-up corrections.

2. Suzaku HXD-WAM

Wide band All sky Monitor (WAM) is the BGO scintillator surrounding the Suzaku hard X-ray detector [3].

WAM0 faces the sun.

Tab. 1 Characteristics of the Suzaku HXD-WAM

Number of detectors	4 units
Energy range	50-5000 keV
Field of view	2π sr (per side)
Effective area	400 cm² @ 1 MeV (per side)
Time resolution	1 sec

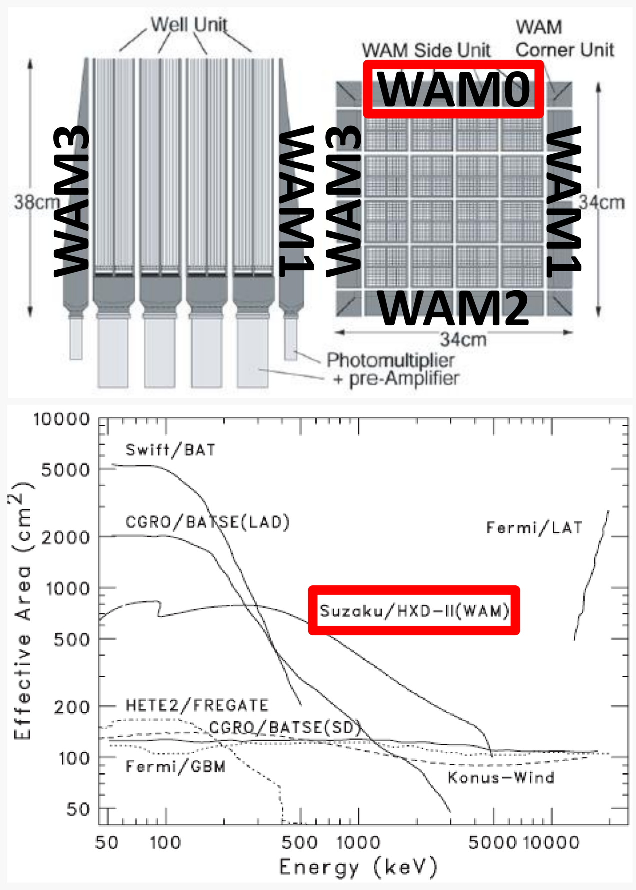

Fig. 2 Upper : Schematic view of the HXD [3]
Lower : Effective area of WAM [3]

3. Observations and Data reduction

WAM has observed 756 solar flares from 2005 to 2015.

Event selection
- X class of *GOES* *1 classes
- Detected ≥ 500 keV band
- No earth occultation and SAA during the event

We analyzed 10 events
(Only 1 event is affected by the pile-up effect)

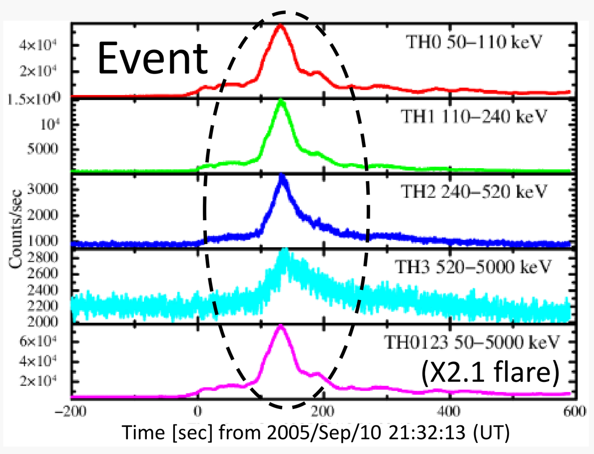

Fig. 3 WAM0 light curve

Observed spectra are represented with single power-law or double power-law functions.

single power-law : $A(E) = KE^{-\alpha}$
double power-law : $A(E) = K_1E^{-\alpha_1} + K_2E^{-\alpha_2}$

We derived the time evolution of photon indices and fluxes in every 1 sec time-resolved spectra during T_{90} *2 of each event.

We took into account pile-up corrections using the Geant4-based pile-up simulator [4].
(We compared the observed spectrum and the simulated spectrum using chi-squared test)

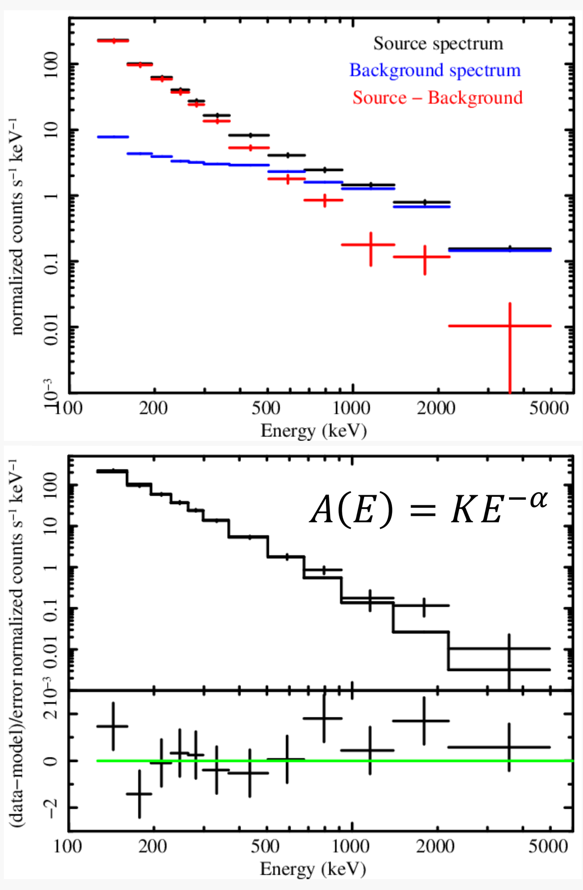

Fig. 4 Upper : WAM0 spectrum
Lower : Fitting result

*1. *GOES* : American satellite observing the soft X-ray emission of solar flares
*2. T_{90} : The time duration that the sum of 50-5000 keV counts reaches 5 % to 95 % in the entire event

4. Results

4-1. The time evolution of photon indices

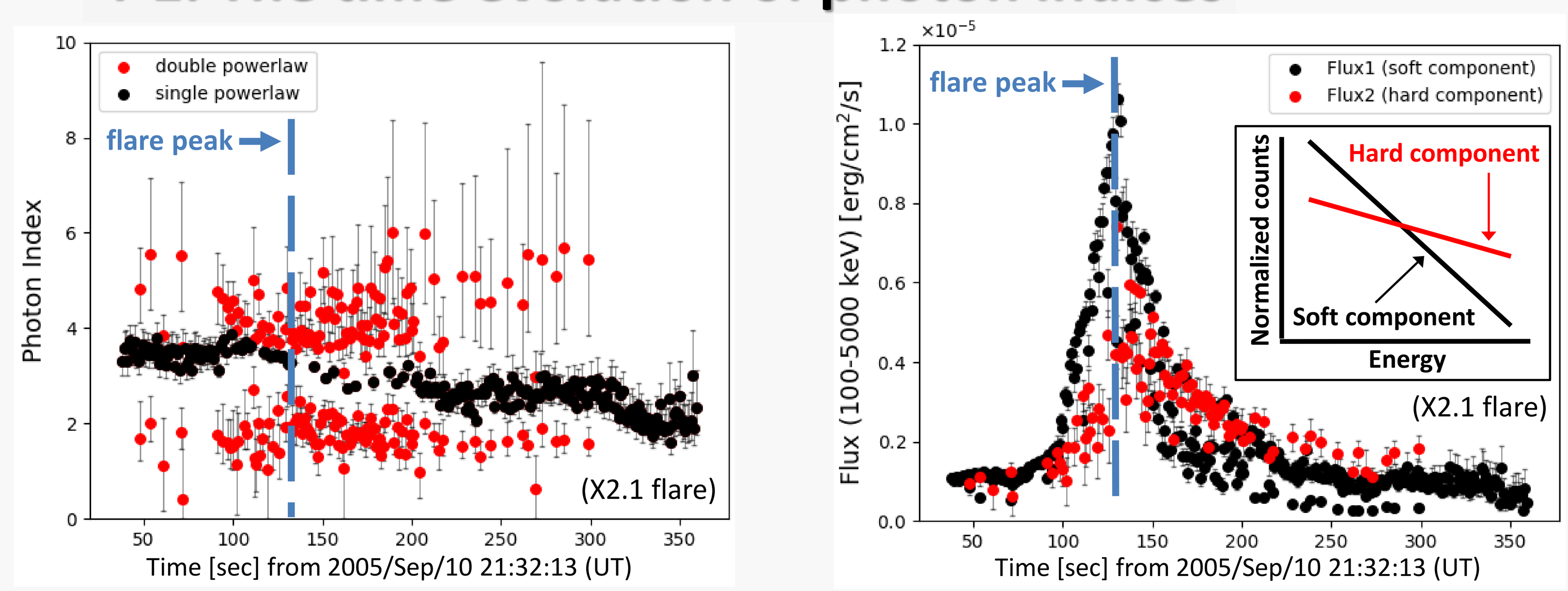

Fig. 5 Example of the time evolution of photon indices (Left) and two power-law components (Right)

- The spectra show double power-law shape from 100 s to 200 s.
- When the spectra show double power-law shape, the emission of the hard component delays from that of the soft component.

➡ **This spectral behavior suggests two different emission regions, which supports the time evolution from the loop-top (thin target) to the foot-points (thick target) proposed by Ishikawa et al. (2011).**

Pile-up corrections

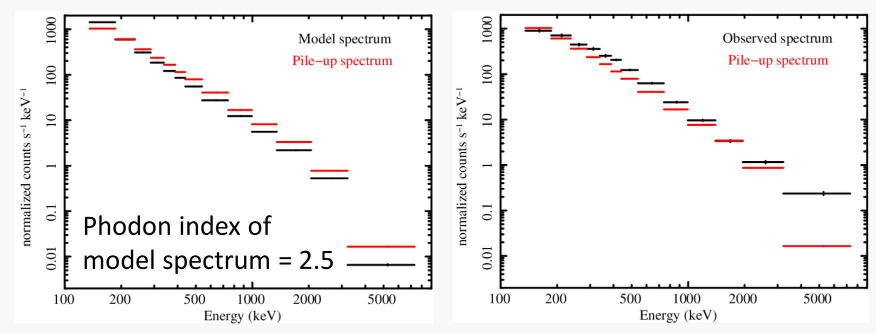

Fig. 6 Left : Result of pile-up simulation
Right : Comparison of the observed spectrum and the simulated spectrum

After pile-up corrections, the values of photon indices were changed by ~0.2 at the flare peak.

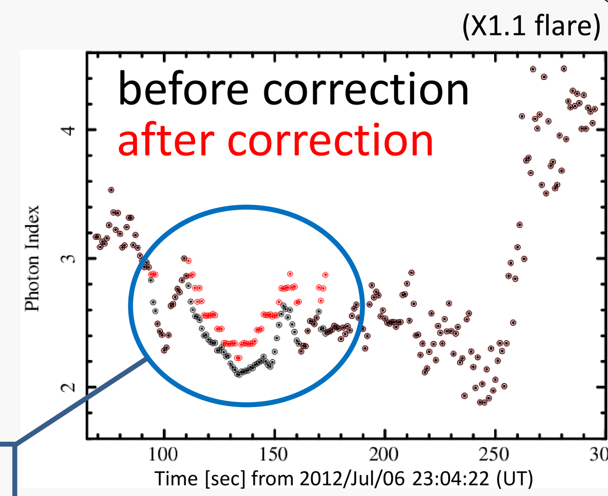

Fig. 7 Change of photon indices by taking into account pile-up corrections

4-2. The time evolution of the flux

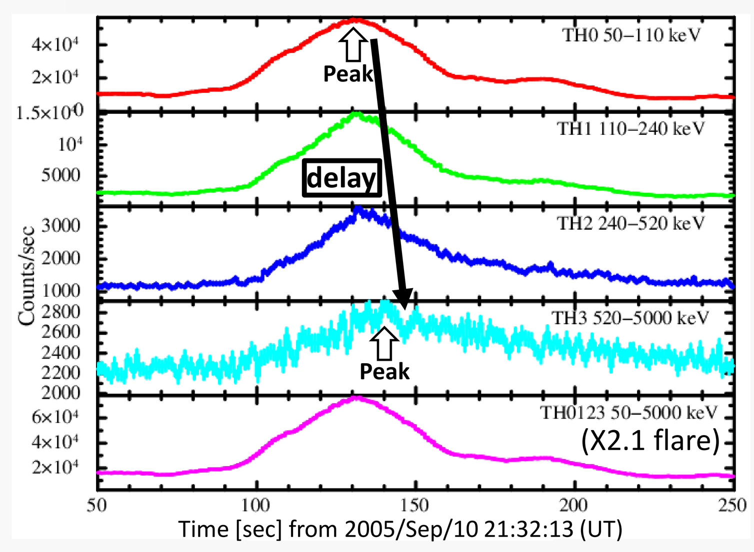

Fig. 8 Example of the flux in each energy band

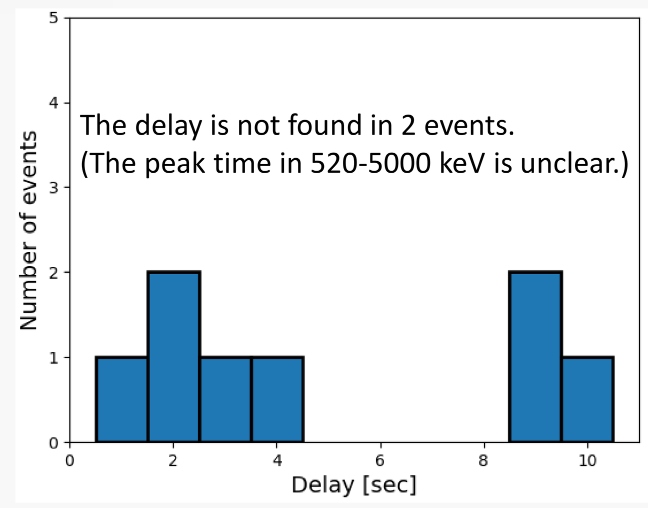

Fig. 9 Delay of the peak time of the flux in 520-5000 keV from that in 50-110 keV

- The peak time of the flux in the high energy band (520-5000 keV) is later than that in the low energy band (50-110 keV).
- The delay is 1-10 sec.

➡ **This supports the picture as shown in Ishikawa et al. (2011) that the accelerated electrons at the loop-top precipitate into the foot-points after several seconds.**

5. Summary

- We carried out time-resolved hard X-ray spectroscopy of 10 solar flares observed by the Suzaku HXD-WAM.
- The spectra show double power-law shape around the flare peak, in which the peak time in the high energy band (520-5000 keV) follows that in the low energy band (50-100 keV) by 1-10 sec.
- Our result supports the picture that the accelerated electrons at the loop-top precipitate into the foot-points after several seconds.

Reference

[1] Masuda et al. 1994, *Nature*, 371, 495
[2] Ishikawa et al. 2011, *ApJ*, 737, 48
[3] Yamaoka et al. 2009, *PASJ*, 61, 35
[4] Yasuda et al. 2015, *PASJ*, 67, 41
[5] Yamaoka et al. 2017, *PASJ*, 69, R2