Time-resolved hard X-Ray hardness variation of solar flares observed by *Suzaku* Wide-band All-sky monitor

Akira Endo[1], Kouichi Morigami[1], Makoto Tashiro[1], Yukikatsu Terada[1]
Kazutaka Yamaoka[2], Eri Sonoda[3]
Takashi Minoshima[4], Säm Krucker[5], and HXD-WAM team

[1] Department of Physics, Saitama University, Shimo-Okubo, Sakura-ku, Saitama-shi, Saitama, Japan
[2] Department of Physics and Mathematics, Aoyama Gakuin University, Sagamihara, Kanagawa, Japan
[3] Department of Applied Physics, University of Miyazaki, Miyazaki-shi, Miyazaki, Japan
[4] Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan
[5] Space Sciences Laboratory, University of California, Berkeley, 7 Gauss Way, Berkeley, USA
E-mail: akira@heal.phy.saitama-u.ac.jp

Abstract

Results of solar flare observations in the hard X-ray band with the *Suzaku* Wide-band All-sky Monitor (WAM) are reported. On June 2009, 108 solar flares (*GOES* class X:16, M:29, C:46, B:17) have been detected with the WAM since the launch. One of the brightest flares WAM detected was the event occurring on 2006 December 13. It lasted for more than 700 seconds even in above 500 keV. This event was simultaneously observed by the solar missions *Hinode* and *RHESSI* in soft and hard X-ray region respectively, and by Nobeyama Radio Observatory in radio. Thanks to the large effective area up to 800 cm^2 of the WAM, we were able to study 1-sec variations of the hardness of this flare and find the Soft-Hard-Harder phenomena in the hard X-ray emission. This feature is similar to the previous reports on the footpoint emission of the flare loop by Minoshima et al. (2009) using *RHESSI* especially in the high energy region (above 200 keV), hardness ratio kept hardening after the maxima of the flux. In addition to that detailed study, we performed systematic studies on 21 solar flares detected with the WAM. Among these 21 flares, 7 events showed Soft-Hard-Soft behavior, 9 events showed Soft-Hard-Harder behavior, and rest 5 showed consistent with being flat hardness.

Key words: acceleration of particles – Sun: flares – Sun: X-rays, gamma rays

1. Introduction

In solar flares, particle acceleration is thought to be caused by magnetic reconnection, as observationally confirmed with the *Yohkoh* satellite (Masuda et al. 1994, 1995). A hard X-ray emission which sometimes reaches up to several MeVs, is produced via bremsstrahlung process when nonthermal electrons go into the solar chromosphere along magnetic loops (footpoints). Additionally, nonthermal electrons produce a microwave emission at the loop, and a soft X-ray emission are radiated from a thermal plasma filled in the loop. But the mechanism is not clarified of energy transfer from the particle acceleration to the nonthermal/thermal emission. To solve the enigma of particle acceleration, the two keys – spacial geometry (image) and time evolution (light curve and spectrum) are needed.

2. The *Suzaku* Wideband All-sky Monitor

Suzaku Hard X-ray Detector (HXD) is surrounded by BGO crystals to reject background events of the on-axis observation of the HXD PIN and GSO, functioning as an all-sky monitor, called WAM (Wide-band All-sky Monitor). The main feature of the WAM is a large effective area reaching 400 cm^2 event at high energy band as 1 MeV per side and a wide energy range of 50 – 5000 keV bandpass (for details, see Yamaoka et al. 2009). WAM is an ideal instrument for hard X-ray transient objects like solar flares, gamma-ray bursts, soft gamma-ray repeaters, and so on. Currently (from 2005 to 2009), 108 solar flares at variable *GOES* class have been detected with the WAM after the launch (see table 1). Thanks to the large effective area of the WAM, we can resolve 1 or a few sec time evolution of their spectra. In the following analysis, we use polynomial function fitting method to subtract background.

Table 1. The solar flares detected with WAM from launch (2005/07 - 2009/06).

GOES class	Number of flares
X	16
M	29
C	46
B	17
Total	108

3. Solar flare on 2006 December 13

Since the most bright events in the table 1 causes pile-ups and large dead times, so we selected solar flares with moderate flux to avoid these effects. Among them, the event on 2006 December 13 shows very hard (>500 keV) components, and continues for over 700 sec, and was simultaneously observed with many other instruments. So it is suitable for studies of spectral variation of solar flare. This flare started at 02:20 UT, 2006 December 13 in the solar disk center region (S06, W22). The *GOES* class was X3.4. Soft X-rays, nonthermal hard X-rays and microwaves were observed for more than 1 hour with *Hinode*, *RHESSI*, and Nobeyama Radio Observatory (Minoshima et al. 2009) simultaneously (Fig. 1). The WAM also observed the flare, covering first intense impulsive phase. The obtained hardness ratio at this phase shows Soft-Hard-Harder behavior, which implies that electron acceleration continued more than 10-100 sec.

4. Hard X-ray variations measured with WAM

We performed hardness ratio variation studies between 50-110 keV and 110-240 keV band on 21 solar flares detected with WAM. Among these flares, 7 events showed Soft-Hard-Soft (SHS) behavior, 9 showed Soft-Hard-Harder (SHH), and 5 showed little change in hardness during flare (Flat). The number ratio of the categories (table 2) is different from the results by Silva et al. (2000). This apparent discrepancy is explained by following reasons. (1)We employed higher energy band (>200 keV) than that employed by Silva et al. (<200 keV). (2)These two ratios are similar if we regard our "Flat", that is not employed in Silva et al., as SHS. (3)Slight discrepancy between the two ratios may caused by the harder (above to 200 keV) component, which is expected to reflect acceleration process out of the reconnection points. Further discussions will be published in near future by Endo et al. 2010.

Table 2. Percentages of observed hard X-rays hardness behavior

Hardness behavior	This work [%]	Silva et al. (2000) [%]
Soft-Hard-Harder	43	32
Soft-Hard-Soft	33	68
Flat	24	–

References

A. V. R. Silva, H. Wang et al., 2000, ApJ, 545, 1116
K. Yamaoka et al. 2009, PASJ, 61, 35
M. J. Aschwanden, 2002, Space Science Reviews 101:1-227
S. Masuda, T. Kosugi et al. 1994, Nature, 371, 495
S. Masuda, T. Kosugi et al. 1995, PASJ, 47, 677-689
T. Minoshima, S. Imada et al. 2009, ApJ, 697, 843

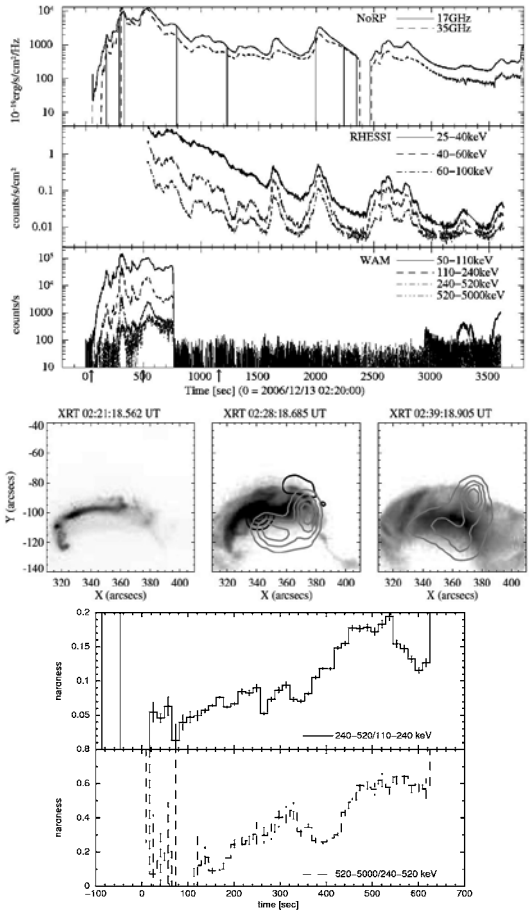

Fig. 1. Top panel: NoRP (microwave), *RHESSI* (hard X-ray), and WAM (hard X-ray) light curves. The epoch between 0-500 sec (*RHESSI*) and 700-3000 sec (WAM) corresponds to the earth occultation of the Sun. Middle: Soft X-ray images with *Hinode* XRT and NoRH 34 GHz (gray contours), *RHESSI* 35-100 keV (black contours). Each time is displayed on Top with arrow (from Minoshima et al., 2009). Bottom: Hardness ratios of the first impulsive event around t=500 sec between 240-520 keV, 110-240 keV, and 520-5000 keV, taken with *Suzaku* WAM.