STEREOSCOPIC OBSERVATIONS OF THE HARD X-RAY SOURCE IN THE GIANT SOLAR FLARE ON 2003 NOVEMBER 4

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ABSTRACT

The hard X-ray source in the "giant" solar flare on 4 November 2003 (~1947 UT) was observed by instruments aboard two spacecraft: RHESSI, located near the Earth, and Ulysses, located at ~ 114 degrees west of the Sun-Earth line at a distance of 5.28 AU from the Sun. The flare "view angles" for Ulysses and RHESSI were ~ 31^o West and 83^o East respectively. While Ulysses observed hard X-rays during most of the flare, RHESSI observations covered only the early rise and part of the decay of the flare. The maximum of the flare could not be observed by RHESSI because of satellite night. The H-alpha flare (importance 3B) was located at S19 W83 in the active region NOAA 10486. GOES observations of the associated soft X-ray emission saturated during the period 1943-1958 UT. It has been estimated that the soft X-ray maximum occurred at ~1947 UT with peak flux equivalent to NOAA class ≥ X28. OVSA radio observations show that the flare produced intense microwave emission, the peak flux at 15.4 GHz being ~ 60000 sfu at ~1945 UT. Intense type II, III and IV radio bursts have also been reported at metric and decimetric wavelengths. RHESSI has provided 10-100 keV X-ray images and spectra during 1930-1938 UT (the early rise of the flare) and 10-30 keV images and spectra during 2016-2114 UT (a part of the late decay of the flare). Ulysses observed an increase in 25-150 keV X-rays from 1933 UT to 2015 UT with the maximum at ~1944 UT in close time coincidence with the maximum in 15.4 GHz radio emission and ~3 min before the maximum in the soft X-ray emission. This indicates that the X-ray emission observed by Ulysses was mostly non-thermal. An assumed hard X-ray spectrum of ~ $E^{-3.5}$ photons cm^{-2} sec^{-1} keV^{-1} for >20 keV photons, leads to an energy dissipation rate of ~ 6.4 x 10^{31} ergs sec^{-1} at the time of the hard X-ray maximum. The total energy in >20 keV electrons released during the flare is estimated to be ~ 1.3 x 10^{34} ergs.

Subject headings: Sun: activity ---- Sun: flares ---- Sun: X-rays

1. INTRODUCTION

During a period of six months near the maximum in the last solar activity cycle (cycle 22), eleven very large solar flares were observed by the hard X-ray spectrometer on the interplanetary spacecraft Ulysses (Kane et al. 1995). In several of these flares the intensity of both the soft and hard X-ray emission was so large that the X-ray instruments on near-Earth spacecraft such as GOES were severely saturated and hence could not make meaningful measurements of the flare. On the other hand, the instrument on the

Ulysses spacecraft, located at a distance of several AU from the Sun, was exposed to a much smaller X-ray flux and hence was considerably less affected by the saturation/pulse pileup effects. The Ulysses measurements indicated that, in each of the eleven solar flares, the ≥ 20 keV non-thermal electrons at the Sun dissipated energy in the flare region at a rate of $\geq 10^{31}$ ergs/sec, the total energy dissipated during one flare being 10^{33}-10^{34} ergs. The energy released during these flares was much larger (a factor of 10–100) than the energy released during some "large" flares studied earlier, e.g. the flare on 1972 August 4 (Lin & Hudson 1976). Therefore the eleven flares observed by Ulysses were identified as "giant flares" which require that essentially all the available energy in the relevant active region be released during the short duration of one flare.

Because of the implications of such a large rate of energy release for the models of particle acceleration and energy release in solar flares, it is important that the past observations of "giant" solar flares be repeated during the present solar cycle (cycle 23). Such an opportunity was presented recently by the very large solar flare on 2003 November 4 which seems to have many characteristics of a giant solar flare. The Ulysses instrument, which has been in operation since 1990, measured the counting rate of 25-150 keV X-rays during the flare. The imaging hard X-ray spectrometer on RHESSI has obtained images and spectra of 10-200 keV X-rays during the early rise (precursor) and late in the decay of the flare. We present here these hard X-ray observations of the 2003 November 4 flare and compare them with the observations of giant solar flares made in the past.

2. HARD X-RAY INSTRUMENTS ON ULYSSES AND RHESSI

The hard X-ray observations reported here were made with instruments aboard two spacecraft, Ulysses and RHESSI. The Solar X-Ray/Cosmic Gamma-Ray Burst Experiment on Ulysses, which has been in operation since its launch in 1990, has been described by Hurley et al. (1992) and Kane et al. (1993). The sensor consists of two CsI(Tl) scintillators with an effective area of ~ 20 cm^2. The low energy threshold, determined by the entrance window, is ~ 11 keV. The overall detection efficiency at that energy is ~ 10%. Normally the instrument operates in the "real time mode" where the integral counting rate in the nominal 25-150 keV energy range is continuously recorded. The time resolution is 0.25-2.00 sec depending on the telemetry rate. In case of a rapid increase in the counting rate, as in the case of a cosmic gamma-ray burst or a solar flare, the "burst mode" is triggered where X-ray spectrum in the nominal 15-150 keV range is saved in the memory to be read back in the telemetry at a later time. In case of additional solar X-ray or cosmic gamma-ray bursts, a priority system decides which spectra are saved in the memory. Consequently, the spectrum for a burst may not be available even if the integral counting rate for that burst is recorded by the instrument. An on-board ^{241}Am X-ray source provides 60 keV X-rays for in-flight calibration of the Ulysses detectors. The instrument has also been inter-calibrated in the past with other hard X-ray spectrometers such as the one on Yohkoh (Kane et al. 1998). Recent comparison with RHESSI indicates that the calibration of the Ulysses instrument is satisfactory.

The response of the Ulysses instrument to an intense flux of thermal or non-thermal X-rays has been discussed in detail earlier (Kane et al. 1995). The estimated response is based on the calibration of the instrument in the laboratory and computations using a Monte Carlo model. The integral rate data presented here include appropriate corrections for the dead-time effects and counter overflow. Moreover, the time of observation and the photon spectra are normalized to the Earth's distance from the Sun.

The Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) has been described extensively in the literature (cf. Lin et al. 2002). The basic spectral and temporal resolution of the observations is ~ 2 keV and 4 sec respectively. The 10–200 keV X-ray images relevant to the present study were obtained with a spatial resolution of 4-6 arc-sec and were averaged over time intervals of 1-6 min. In order to reduce the incident photon flux to a level suitable for measurements by the instrument, "thick" and/or "thin" shutters (attenuators) are moved automatically (or on command) into the path of the X-rays incident on the detector. During the 2003 November 4 flare, the attenuator mode switched between A1 (thin shutter) and A3 (thick and thin shutters).

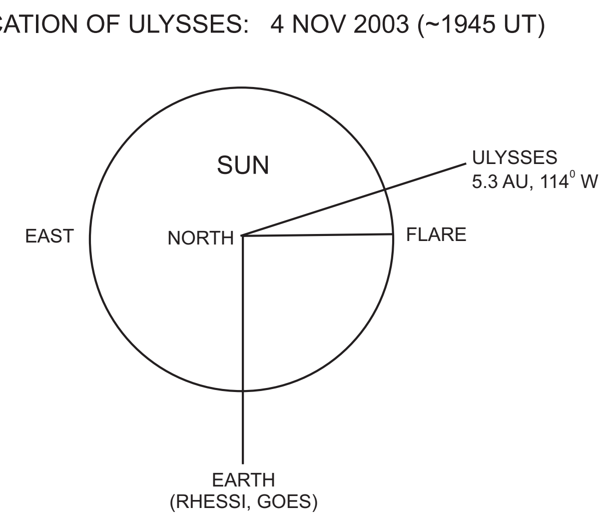

Fig. 1. -- The locations of Ulysses, RHESSI and GOES spacecraft (projected on the ecliptic plane) relative to the Sun-Earth line. The location of the 4 November 2003 flare on the solar disk is also shown.

3. OBSERVATIONS OF 2003 NOVEMBER 4 FLARE

A very large solar flare occurred on 2003 November 4 (~ 1947 UT) in the active region NOAA 10486. The H-α flare (importance 3B) was located near the west limb of the Sun at S19, W83. The associated 15 GHz radio burst, observed by the Owens Valley Solar Array (OVSA), reached a peak flux of 60000 sfu at 1944 UT. The X-ray emission associated with the flare was observed by instruments aboard the interplanetary spacecraft Ulysses and Earth-satellites RHESSI and GOES. The locations of these spacecraft (projected on the ecliptic plane) relative to the Sun-Earth line and the location of the flare on the Sun are shown schematically in Figure 1. Ulysses was located at ~ 24 degrees behind the west limb at a distance of 5.3 AU from the Sun. The flare "view angles” for Ulysses and RHISSI/GOES instruments were ~ 31° West and ~ 83° East respectively. The flare was therefore in full view of the Ulysses instrument. Moreover, the X-ray flux incident on the Ulysses instrument was smaller than that at the near-Earth instruments by a factor of 27.6. The flare was also in full view of both GOES and RHESSI instruments provided the X-ray source did not extend spatially beyond the west limb of the Sun.

Figure 2 shows the time-variation of (1) 0.5-4.0 A X-ray emission observed by the GOES instrument, (2) integral counting rate of 25-150 keV X-rays observed by Ulysses instrument at the location of Ulysses (5.3 AU from the Sun), and (3) integral counting rate of X-rays > 20 keV observed by RHESSI. For reference, the time of maximum for the 15 GHz radio emission observed by the Owens Valley Solar Array (OVSA) is indicated by an arrow at the top of the figure. The attenuator mode for RHESSI switched between A1 and A3 during the observation period. The rates shown are normalized to attenuator mode A3.

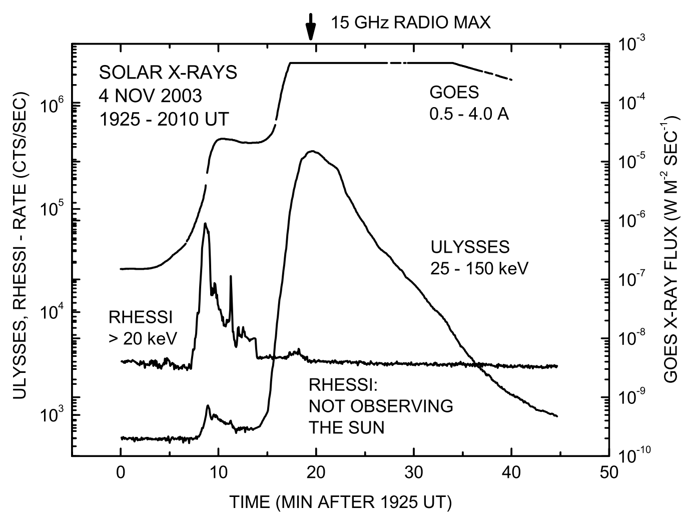

Fig. 2. -- The time-variation of (1) 0.5-4.0 A X-ray emission observed by the GOES instrument, (2) integral counting rate of 25-150 keV X-rays observed by the Ulysses instrument at the location of Ulysses (5.3 AU from the Sun), and (3) integral counting rate of X-rays > 20 keV observed by RHESSI. For reference, the time of maximum for the 15 GHz radio emission observed by the Owens Valley Solar Array (OVSA) is indicated by an arrow at the top of the figure. After 1938 UT RHESSI entered the satellite night and hence could not observe the flare.

The soft X-ray burst associated with the flare has been classified as GOES class X28. The GOES observations (Figure 2) show a precursor maximum at ~ 1935 UT followed by a rise towards the main maximum. However, the GOES instrument saturated several minutes before reaching the soft X-ray maximum and remained saturated for ~ 15 min. Although the exact time of the soft X-ray maximum could not be determined, it appears that the soft X-ray emission reached its maximum several minutes after the maximum in the hard X-ray and microwave radio emissions. This is confirmed by the additional analysis of the GOES observations conducted by Kiplinger and Garcia (2004). They have estimated that the soft X-ray flare was probably of GOES class X30.6 with a maximum at 1947 UT. According to their analysis, a maximum temperature of 4.2×10^7 K probably occurred at ~ 1942 UT and the emission measure probably reached its maximum value of ~ 1.6×10^{51} cm^{-3} at ~ 1948:40 UT.

Ulysses observations of the flare consist of the 25-150 keV integral counting rate covering the period 1920-2100 UT (Figure 2). Significant increase above the background was detected only during the period 1932-2020 UT. No spectra were recorded during this period. After a precursor maximum at ~ 1933 UT, Ulysses counting rate increased rapidly to a maximum at ~ 1944 UT in close time coincidence with the 15 GHz radio maximum. By the time the GOES instrument recovered from saturation, Ulysses counting rate had already decreased by a factor of ~ 100 from its maximum value.

4. THE PRECURSOR HARD X-RAY BURST

RHESSI was observing the Sun from 1925 UT to 1935 UT (Figure 2). After 1935 UT RHESSI entered the “satellite night” and could not observe the Sun until ~ 2056 UT. RHESSI observations therefore covered the early rise and late decay of the 2003 November 4 flare but did not cover the principal maximum.

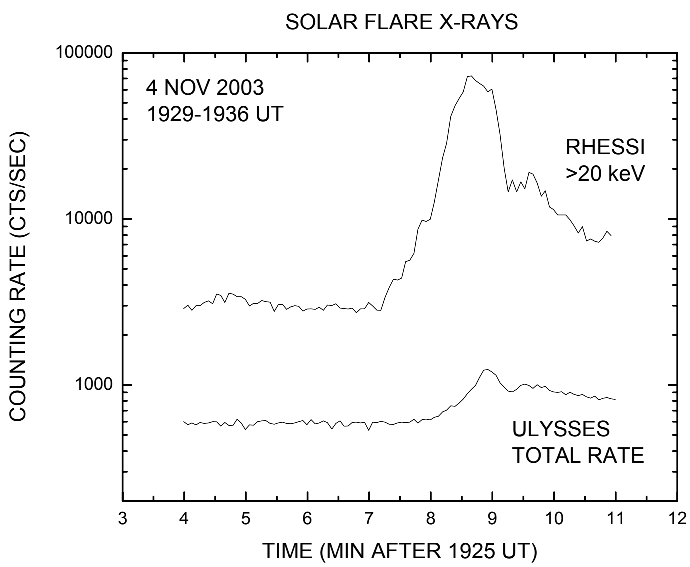

Fig. 3. --- The integral (25-150 keV) counting rate of Ulysses instrument and the counting rate of X-rays > 20 keV observed by RHESSI during the “precursor” hard X-ray burst associated with the 4 November 2003 solar flare.

The Ulysses and RHESSI counting rates during the precursor hard X-ray burst are shown in Figure 3. Although there is a general similarity between the Ulysses and

RHESSI lightcurves, the times of maximum and the rates of rise and decay seem to differ significantly. It appears that although most of the hard X-ray source was in full view of both the instruments, some parts of the source were partially occulted from the view of RHESSI.

In order to compare further the RHESSI and Ulysses observations of the precursor X-ray burst, a double power law photon spectrum of the following form was fitted to the RHESSI observations: $J(E) \sim E^{-\gamma}$ photons cm^{-2} sec^{-1} keV^{-1} where $\gamma = \gamma_1$ for $E \leq E_{br}$ and $\gamma = \gamma_2$ for $E \geq E_{br}$, E_{br} being the "breakpoint" photon energy (keV). The expected counting rate of the Ulysses instrument due to this spectrum was then computed and compared with the observed counting rate of Ulysses. The results obtained were as follows:

(a) For the period 1932:40-1933:40 UT covering the onset through the maximum of the precursor, the spectral parameters were $\gamma_1 = 4.47$, $\gamma_2 = 4.82$, $E_{br} = 49.0$ keV. The computed and observed counting rates were 60.7 and 79.5 counts/sec respectively. The observed and computed rates thus agreed within ~30%.

(b) For the period 1934:00-1936:00 UT covering the decay of the precursor, the spectral parameters were $\gamma_1 = 7.55$, $\gamma_2 = 5.61$, $E_{br} = 37.3$ keV. The computed and observed counting rates were 119.5 and 320.6 counts/sec respectively. The observed rate was larger than the computed rate by a factor of ~ 2.7.

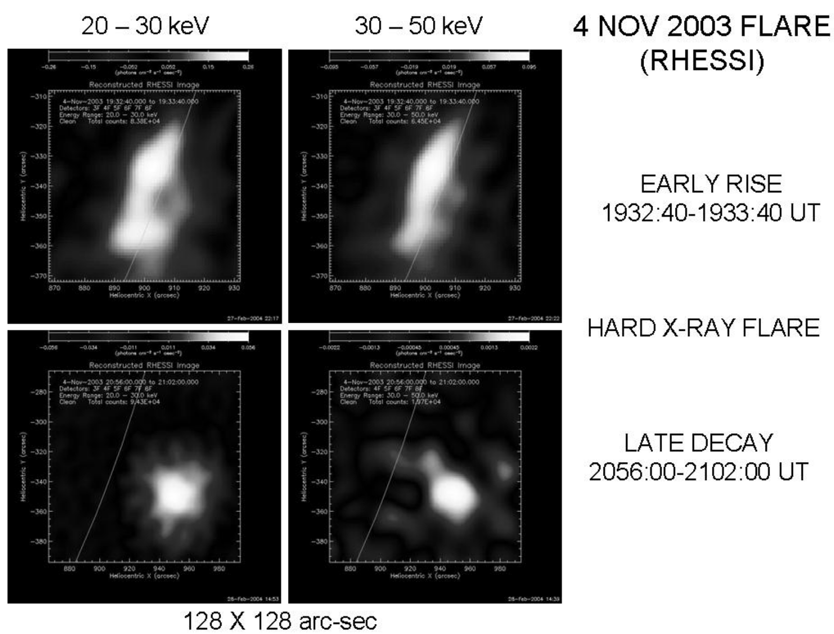

Fig. 4. -- Images of the 20-30 keV and 30-50 keV X-ray sources obtained by RHESSI during the period of the precursor maximum (1932:40-1933:40 UT) and late in the decay (2056:00-2102:00 UT). The solar limb is also shown. The hard X-ray sources were close to the west limb of the Sun during the early rise in the flare. However, during the late decay, the hard X-ray source is high in the corona with no detectable emission on the solar disk.

The difference between the observed and computed counting rates of the Ulysses instrument during the decay of the precursor represents the difference between the hard X-ray fluxes observed by Ulysses and RHESSI at that time. The difference could be caused by one or both of the two factors: (1) "directivity" (anisotropy) of the hard X-ray source, and (2) partial occultation of the hard X-ray source by the photosphere from the view of the RHESSI instrument. The extensive stereoscopic observations of the directivity of flare-associated hard X-ray sources during the last solar activity cycle (cycle 22) have shown that the directivity is small (Kane et al. 1980, 1988, 1998). The good agreement between the observed and expected counting rates during the rise and maximum of the precursor confirm this earlier finding. Partial occultation of the hard X-ray source is therefore likely to be the cause of the observed difference. It appears that during the rise and maximum of the precursor burst, most of the hard X-ray source was located on the visible solar disk in full view of both the instruments. However, during the decay of the precursor burst, there were additional components of the hard X-ray source behind the solar limb which were occulted from the view of RHESSI.

Images of the 20-30 keV and 30-50 keV X-ray sources obtained by RHESSI during the period of the precursor maximum (1932:40-1933:40 UT) and late in the decay (2056:00-2102:00 UT) are shown in Figure 4. The solar limb is also shown. During the early phase of the flare the hard X-ray source was located on the solar disk inside the west limb of the Sun. It is possible, however, that the hard X-ray source extended beyond the west limb and hence a part of the source was occulted from the view of RHESSI. During the late decay in the flare there is no detectable hard X-ray source on the solar disk. Instead, a relatively compact source is present in the corona at a height of ~ 20000 km above the solar limb. This source is similar to the coronal hard X-ray sources observed by RHESSI in other solar flares (Kane & Hurford 2003, Kane et al. 2003).

5. ENERGETIC ELECTRONS AT THE SUN

Impulsive hard X-ray emission in solar flares is generally interpreted as thick-target bremsstrahlung produced in the chromosphere by non-thermal electrons accelerated during the flare. Several models have been developed to describe the hard X-ray source in a flare (cf. Holman, Kundu and Kane 1989; McTiernan and Petrosian 1990; Brown, Emslie and Kontar 2003; Holman 2003). The incident hard X-ray spectrum is often a single or double power law ~ $E^{-\gamma}$ photons cm^{-2} sec^{-1} kev^{-1}, E being the photon energy and the index γ = 2.0-6.0, the most common value being γ = 3.5 (Bromund, McTiernan & Kane 1995). Ulysses observations of the integral hard X-ray counting rate can be used to estimate the energy carried by the energetic electrons at the Sun.

Since the hard X-ray spectrum incident on Ulysses is not available, we assume the differential spectrum of the $\geq$ 20 keV photons at the time of burst maximum to be a power law with index γ = 3.5. The maximum counting rate observed by Ulysses then requires the following photon spectrum at 1 AU:

$$j(E) = 4.7 \times 10^{9}\, E^{-3.5} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ kev}^{-1} \text{ at 1 AU} \quad \text{------------------------} \quad (1)$$

For a simple thick-target model with isotropic X-ray emission, the implied spectrum of ≥ 20 keV electrons at the Sun is then given by (Brown 1971; Hudson, Canfield, and Kane 1978):

$$N(E_e) = 1.8 \times 10^{44}\, E_e^{-4.5} \quad \text{electrons sec}^{-1}\ \text{kev}^{-1} \ \text{at the Sun} \quad \text{----------------------} \quad (2)$$

where E_e (keV) is the energy of electrons. For electrons with energy $E_e \geq 20$ keV, this leads to an injection rate of 1.4 x 10^{39} electrons/sec into the hard X-ray source, the corresponding energy dissipation rate being 6.4 x 10^{31} ergs/sec. For a ~ 200 sec FWHM (Full Width at Half Maximum) for the hard X-ray time profile, we find the total number of ≥ 20 keV electrons accelerated during the flare to be ~ 2.8 x 10^{41}. The total energy dissipated by these electrons during the flare is found to be 1.3 x 10^{34} ergs.

In the above computation we assumed the photon spectrum index to be $\gamma = 3.5$. If, instead, the index is assumed to be 2.5, the total dissipated energy is found to be 4.1 x 10^{33} ergs. On the other hand, an assumed index $\gamma = 4.5$ gives 2.8 x 10^{34} ergs for the total dissipated energy. Thus an uncertainty of ± 1 in the photon spectral index corresponds to approximately to an uncertainty of a factor ≤ 3 in the estimates of the rate of energy dissipation and the total energy dissipated during the flare.

5. ENERGY RELEASE AND THE ROLE OF THE ACTIVE REGION

The flare on 2003 November 4 (~ 1945 UT), which produced the largest soft X-ray burst observed so far, also produced the most intense hard X-ray burst observed during the present solar activity cycle (cycle 23). The Ulysses observations of the hard X-ray emission show that a total of ~ 3 x 10^{41} electrons with energy ≥ 20 keV were accelerated during this flare. The total energy carried by these electrons was ~ 1 x 10^{34} ergs. If we include the energy in the form of lower energy electrons and energetic ions the total energy released will be even larger. Also it is possible that additional energy is required to produce the flare-associated Coronal Mass Ejection (CME) and other mass motions. This flare therefore belongs to the class of "giant" flares observed during the last solar activity cycle (cycle 22).

Most models of solar flares assume that the magnetic field in the associated active region is the source of the energy released during the flare. For the active region NOAA 10486 the available energy prior to the 2003 October 29 flare has been estimated to be ~ 8 x 10^{33}ergs (Metcalf et al. 2004). If a comparable amount of energy was available also prior to the 2003 November 4 flare, the present observations indicate that essentially all the available energy was released during the short duration of the flare.

A study of the release and dissipation of energy during giant solar flares carried out by us earlier (Kane et al. 1995) indicated the inadequacy of the relevant active region to provide the rapid energy release necessary for the flare. Even when the total available energy in the active region is comparable to the energy released during the flare, release of all that energy during the short duration of the flare is expected to affect substantially the magnetic field structure of the active region. We are not aware of any observations which indicate large scale changes in an active region after a large flare. It is therefore possible that the instability that triggers the energy release during a solar flare affects the corona globally (rather than locally) so that resources from a substantial part of the corona inside as well as outside the active region are available for energy release and acceleration of particles.

Eleven giant solar flares were observed during the last solar activity cycle (cycle 22). Although only one giant flare has been observed during the present solar activity cycle (cycle 23), it produced one of the most intense hard X-ray burst and the largest soft X-ray burst ever observed. In most of the twelve giant flares the intense X-ray flux saturated (partially or fully) the soft X-ray and hard X-ray instruments located at ~ 1 AU from the Sun. The observations presented here have demonstrated very clearly the need for large dynamic range for the soft X-ray and hard X-ray instruments intended for solar flare observations. It is hoped that this need will receive full consideration in the design of the future X-ray instrumentation so that we will not miss again reliable and accurate observations of the most energetic (giant) solar flares.

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