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BATSE FLARE OBSERVATIONS IN SOLAR CYCLE 22

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1. INTRODUCTION

As much as 10^{32} ergs can be released during a solar flare in times as short as 100 to 1000 s, with intense emission detected over most of the electromagnetic spectrum. It is believed that this energy comes from the dissipation of the non-potential components of strong magnetic fields in the solar atmosphere, possibly through magnetic reconnection. Much of the energy appears in the form of high-energy particles and hot plasma, with accelerated electrons with energies of tens of keV probably containing a major fraction. The most direct diagnostic of these energetic electrons is the hard x-ray and gamma-ray bremsstrahlung that they emit as they move from the acceleration site through the solar atmosphere. This bremsstrahlung is emitted before the electrons are thermalized in the ambient atmosphere and, thus, retains unique information about the energy release, energy transport, and particle acceleration processes of the flare that are not available in the radiation signatures of the thermal plasma.

The Hard X-ray Burst Spectrometer (HXRBS) group at Goddard Space Flight Center has developed and is maintaining a quick-look analysis system for solar flare hard x-ray data from the Burst And Transient Source Experiment (BATSE) on the recently launched Compton Gamma-Ray Observatory (GRO) (Fishman et al. 1989). The instrument consists, in part, of 8 large planar detectors, each 2025 cm^2, placed on the corners of the GRO spacecraft with the orientation of the faces being those of a regular octahedron. Although optimized for the detection of gamma-ray bursts, these detectors are far more sensitive than any previous spacecraft-borne hard x-ray flare instrumentation both for the detection of small microflares and the resolution of fine temporal structures. The data in this BATSE solar database are from the DISCLA (Discriminator Large Area) rates. From each of eight detectors there are hard x-ray data in 4 energy channels, 25-50, 50-100, 100-300, and >300 keV with a time resolution of 1.024 seconds. These data are suitable for temporal correlation with data at other wavelengths and they provide a first look into the BATSE and other GRO instrument flare data sets. The BATSE and other GRO principal investigator groups should be contacted for the availability of data sets at higher time or spectral resolution or at higher energies.

2. BATSE DATABASE

Since the beginning of BATSE science operations on 19 April through 19 September 1991, 1262 solar flares had been detected in hard X-rays above 25 keV with the Large Area Detectors (LAD). Their distribution vs. time is shown in Figure 1 together with that for flares observed with the Solar Maximum Mission Hard X-ray Burst Spectrometer (SMM/HXRBS) from February 1980 through November 1989. These rates have not been scaled for the instrument duty cycle which varied some due mainly to the phasing of orbital parameters. Solar flares were reliably detected in the HXRBS data down to a count rate of 30 counts s^{-1} above background for the 70 cm^2 detector area and 400 counts s^{-1} in the BATSE LAD data where this rate is scaled to that of a single LAD of 2000 cm^2 pointing directly at the Sun. The BATSE instrument has a sensitivity which is roughly three times that of HXRBS due to its larger area, despite a higher background per unit area and a thick aluminum window which significantly attenuates the solar spectrum at oblique angles. The strong activity in June 1991 during the passage of Active Region 6659 across the solar disk produced the peak during the time of the BATSE measurements although it was well below the frenetic level of activity seen during the passage of Active Region 5395 in March of 1989. Starting from the commencement of BATSE observations, the level of activity appears more uniform than during the earlier time period of

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HXRBS measurements in Cycle 22. This greater uniformity may be because BATSE has been able to detect flares down to an intrinsically smaller flux than possible with the HXRBS detector. Flares in both data sets were found by visually inspecting the count rate for transient events which satisfied the directional, spectral, and temporal characteristics of a solar flare and which were sometimes corroborated with lists of optical, radio, and soft x-ray flares provided through the Space Environment Laboratory.

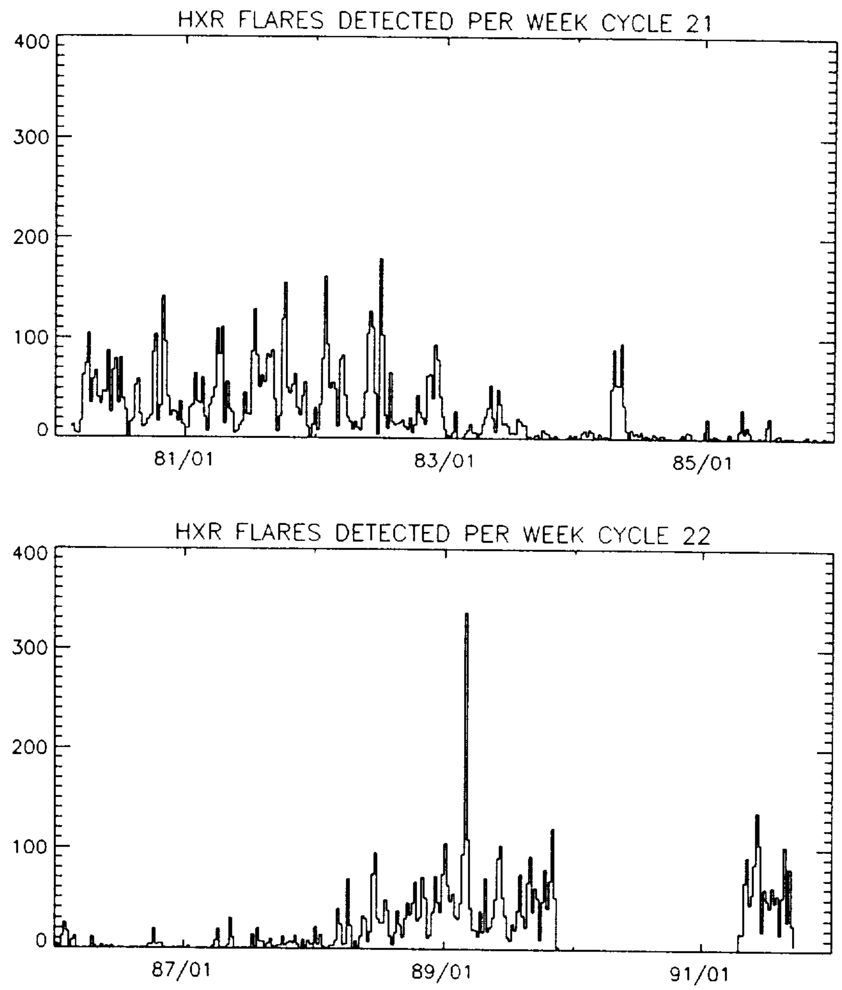

Fig. 1. The distribution of hard x-ray flares vs. time during solar Cycles 21 and 22 measured with HXRBS from February 1980 through November 1989 and measured with BATSE from April 1991 through September 1991. The rates are computed by taking the number of flares detected and dividing by the total time interval without any corrections for the detector duty cycle which typically ranged from 40-60%.

Figure 2 presents the distribution of peak hard x-ray count rates for four time periods including Cycle 21 measured with HXRBS from 80/02/14 - 86/12/31, the full SMM mission from 80/02/14 - 89/11/15, Cycle 22 measured with HXRBS from 87/01/01 - 89/11/15, and Cycle 22 measured with BATSE from 91/04/19 - 91/09/20. The fluxes are background subtracted and the BATSE data have been corrected for solar aspect and normalized to the smaller area of the HXRBS detector. The characteristic slope of these distributions is obtained by fitting a power law over three decades in peak rate from just above the knee caused by the roll-off at the detector sensitivity threshold to a HXRBS flux of ~50,000 s^{-1}. The indices corresponding to the time periods above are respectively -1.75±0.01, -1.73±0.01, -1.66±0.02, and -1.61±0.03. The fact that these distributions are well fit by featureless power laws has been taken as evidence that solar flares are avalanches of many small reconnection events (Lu & Hamilton 1991). While all of these indices are close to -1.7 there is a statistically significant difference between those from Cycle 21 and Cycle 22. However, the Cycle 22 measurements were made with HXRBS near the end of the mission when the detector's low energy sensitivity had been degraded and with the BATSE LAD's which have the aforementioned aluminum windows which reduces their low energy response. This fact could have resulted in flatter number-size distributions since the smaller flares tend to have softer photon energy spectra which would reduce their peak rates relative to the larger flares with harder spectra. If these differences in the logarithmic slope prove to be true characteristics of the two solar cycles then this would suggest some intrinsic difference in the flare process from cycle to cycle.

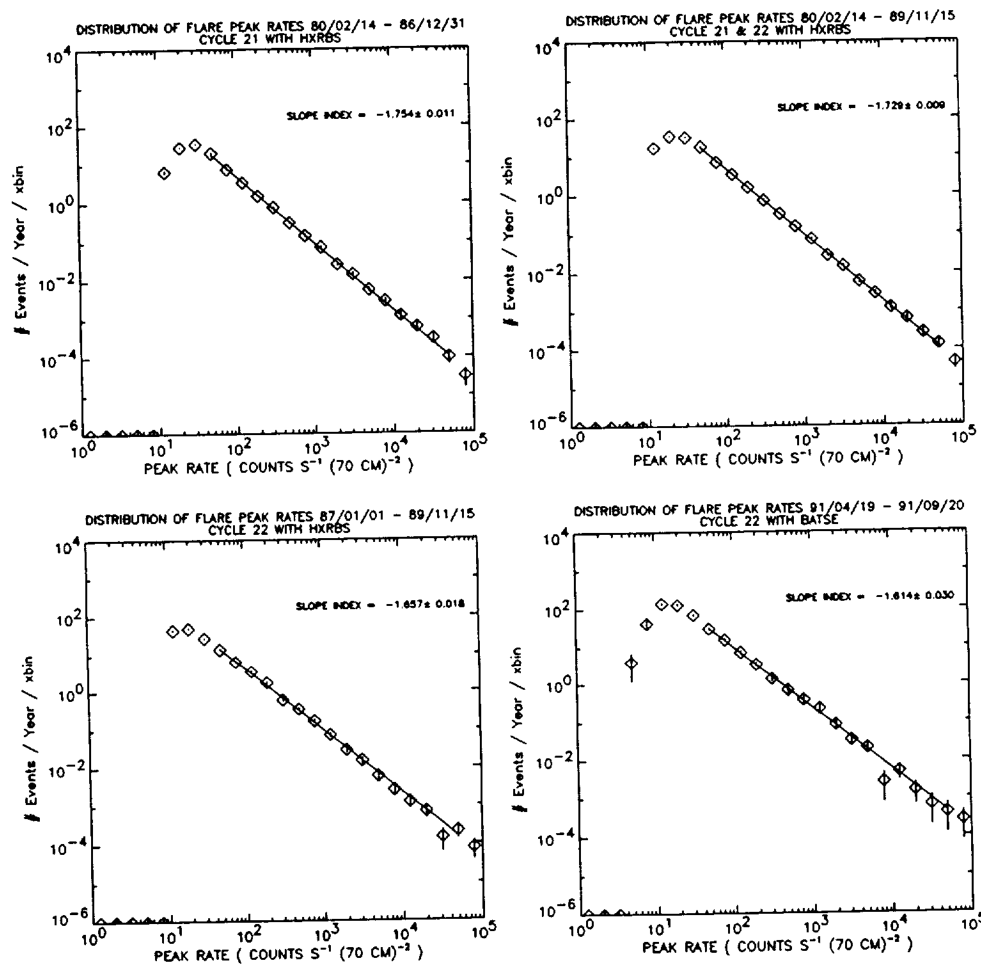

Fig. 2. The number of flares vs. peak flux for four time periods measured with HXRBS and BATSE. The event rates are not corrected for the detector duty cycles. The BATSE flux has been normalized to that expected from a HXRBS detector pointed directly at the Sun.

3. FAST RISING HARD X-RAY SPIKES

Hundreds of fast hard x-ray spikes were observed with HXRBS having durations of less than 1 s, some with rise and decay times of some tens of milliseconds (Kiplinger et al., 1983). The existence of such variations in hard X-rays offers the opportunity to correlate variations at differing energies on timescales that are considerably less than one second. For non-thermal models, the observed hard x-ray time profile is the convolution of the temporal evolution of the electron acceleration process with propagation effects associated with the beam of electrons interacting in the target (Emslie, 1983). For typical flare loop dimensions of 1-5 X 10^4 km, 50 keV electrons will traverse the loop in 0.1-0.5 s or longer depending upon their pitch angle with respect to the loop's magnetic field. Hence, spectral observations on these timescales can resolve electron time-of-flight effects and constitute a critical test of the thick-target model.

The flare on 17 June 1991 at 1:11:30 UT is just such a fast rising flare which offers the opportunity to test this model. In Figure 3 the time history of this flare is presented for the 50-100 keV and 100-300 keV energy channels at time resolutions of 1.024 s and 0.064 s. The flare is a GOES class C5.9 with no known optical counterpart despite good seeing from Big Bear Solar Observatory (private communication). The hard x-ray burst is moderately hard with a spectral index of about 4 as determined from the ratios of the DISCLA channels. The second row of frames shows the time structures around 1:11:30 UT at the higher resolution. The burst rises from near background levels to maximum in about 400 ms and falls in a comparable time. The time histories in the third row are simulations of what HXRBS data would have been for an identical flare. While the peaks are visible in the simulated HXRBS data, the statistics would have been too poor to enable any meaningful time-resolved spectral analysis for time-of-flight effects. In the HXRBS data, it seemed that fast time structures were a more common feature at fluxes which were too low for quantitative analysis. However, this event shows that data from such flares obtained with the BATSE LADs are ideal for this kind of study.

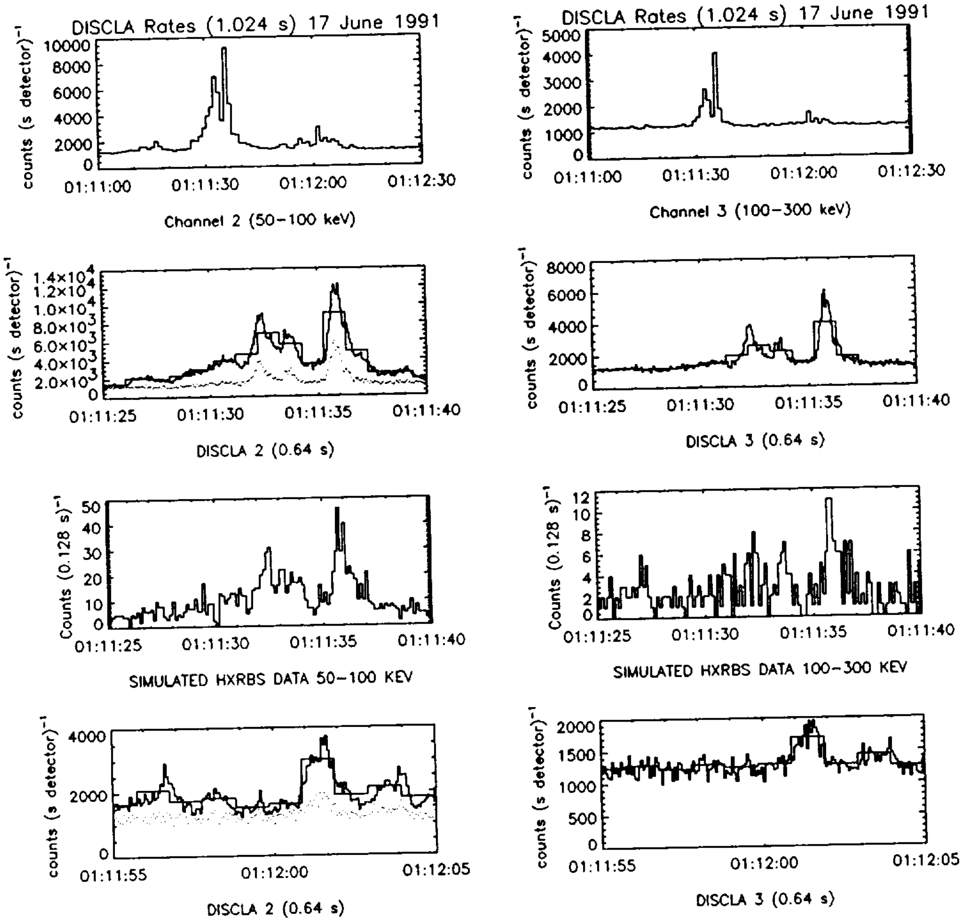

Fig. 3. The time history of a fast rising spike flare on 17 June 1991 observed with the BATSE LADs. The top row of panels shows the BATSE DISCLA rate from the two most sunward pointing detectors at a time resolution of 1.024 s in channel 2 (on the left) and channel 3. Below each panel the geometric area of the included BATSE detectors are given in terms of the cosine of zenith angle of the Sun so negative values indicate detectors facing away from the Sun. The DISCLA energy channels are also indicated although channel 6 refers to the charged-particle detector rate. The two frames below are from the same detectors in the same energy ranges at a time resolution of 0.64 s for the time structures around 1:11:30 UT. The dots in the left hand frame shows the time history of DISCLA channel 3 and the histogram shows channel 2. The overlay shows the 1.024 s resolution data from the frame above. The plots in the third row are of a simulation of the count rate which would have been seen by HXRBS for an identical flare at the time resolution of HXRBS, 0.128 s. The bottom frames are similar to the second row except that it expands the structures near 1:12:00 UT.

4. GIANT FLARES OF JUNE 1991

During June of 1991 there were six large flares with a soft x-ray size of GOES class X10 or higher, four of which were well observed with BATSE on 4, 6, 9 and 11 June. Of these, the most intense in hard X-rays was the flare of 4 June 1991 from region 6659 at N30E65 which started at 3:37 UT, continued through the end of the orbit at 4:10 UT and well into the daytime portion of the next orbit. The time history of the flare is shown in three energy-loss bands in Figure 4 although the rate shown in the top frame from 3:39-3:42 UT is severely distorted due to an extremely high detector count rate in excess of 10^6 counts s^{-1}. The large area of the BATSE detectors makes them sensitive to small flares, but it also makes them prone to saturation, i.e. severe deadtime and pulse pile-up problems, during the largest solar flares. However, the BATSE instrument is comprised of 16 independent x-ray detectors some of which are always masked from the direct solar flux. Thus, during large flares, the backside detectors give the most accurate indication of the hard x-ray flux when the frontside detectors are saturated. However, it is more difficult to deconvolve the counting rates in the different energy-loss channels into a photon spectrum because the photon path to the detector involves either a Compton scattering or transmission through considerable passive material. The bottom frame of Figure 4 is from channel 6 which is the event rate in the plastic scintillator normally used to reject energetic particle events in the LADs. This detector is also sensitive to energy-loss events from photons with energies in excess of 1 MeV without any of the pileup effects in the LADs because of the high threshold and an interaction cross-section of about 5%. The peak at 3:41 UT corresponds to a rate of photons above an MeV of ~300 cm^{-2} s^{-1} which is larger than for any flare observed with SMM. Also, it is possible to estimate the peak hard x-ray flux from the backside detector rates and by extrapolating the high energy flux to lower energies. While the maximum flare rate seen with HXRBS was slightly over 200,000 s^{-1} during 9.75 years of operation, our estimate for the flux for the 4 June 1991 flare is 2-4 times as great with an uncertainty of at least 50%.

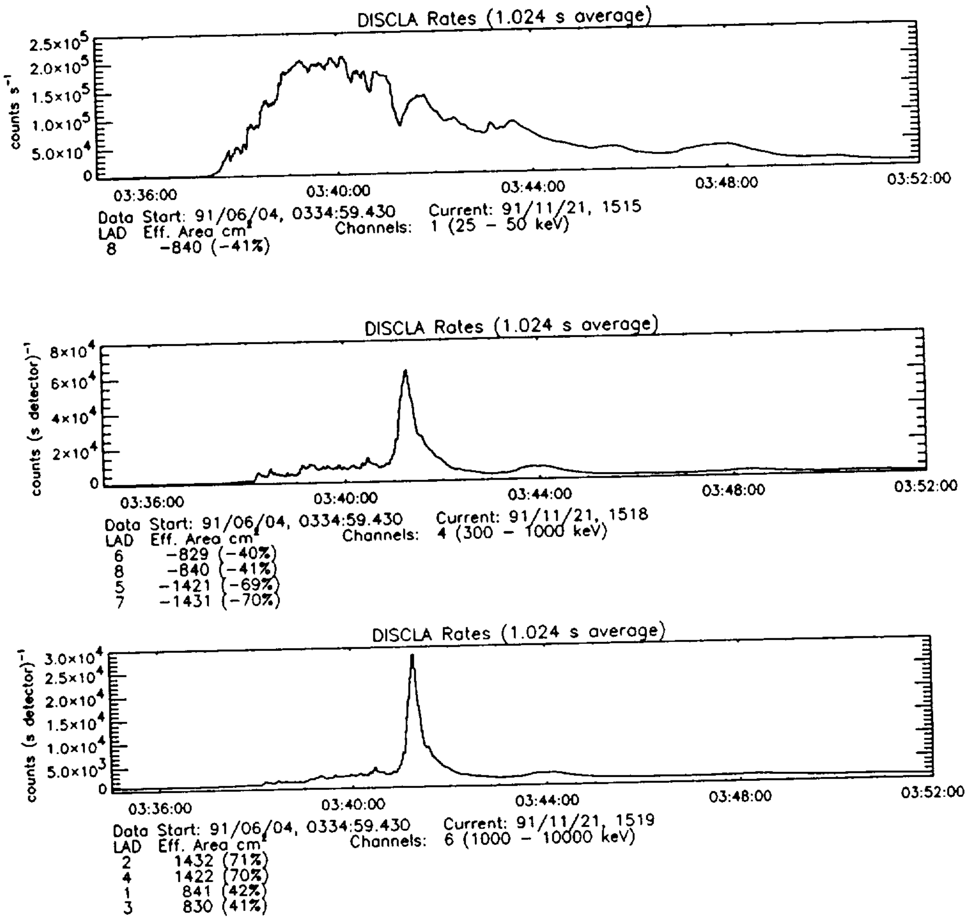

Fig. 4. Hard x-ray count rate history of the giant flare of 4 June 1991. The top two frames are the energy-loss rates in the backside detectors in two energy channels, 25-50 keV and 300-1000 keV. Although these detectors are shielded from the direct flare flux, the count rates were still too high to accurately measure the peak at 3:41 UT. The bottom rate was obtained from the sum of all of the frontside charged-particle detectors which are sensitive to photons of energies greater than 1 MeV and therefore did not become saturated by the lower energy photons. The peak corresponds to a photon rate of more than 300 cm^{-2} s^{-1} above an MeV.

Although the extremely high hard x-ray flux makes much of the BATSE LAD data unsuitable for detailed quantitative analysis near the flare peak, the high sensitivity of BATSE can be put to good use at the start and during the decay phase of the flare. In Figure 5 the flare start is shown in three energy channels using the two most sunward detectors. The hard X-rays are detectable just at 3:37:00 UT in channel 1 (25-50 keV) and the rate climbs quickly within a few seconds without any evidence of pre-flare activity. The 50-100 keV rate does not increase until 3:37:07 UT and only rises steeply after 3:37:15 UT. The 100-300 keV rate starts to rise at 3:37:20 some 20 seconds after the flare start at lower energy. In fact, the photon spectrum must be steeper than a power-law index of -6 during the initial stages of the flare even though it probably hardens to a value between -2 and -3 near the peak. As soft as the flare spectrum is at the start, it is interesting that there is a persistent high energy component more than 25 minutes after the peak at 3:41 UT. In Figure 6 the count rates are shown from the lowest to the highest energies near the end of the daytime portion of the spacecraft orbit. Just after 4:08 UT the Sun passes behind the GRO horizon and the extinction of the flux is clear at all energies, even above 1 MeV. The extinction takes longer at high energy because the attenuation cross-section of the atmosphere decreases with energy.

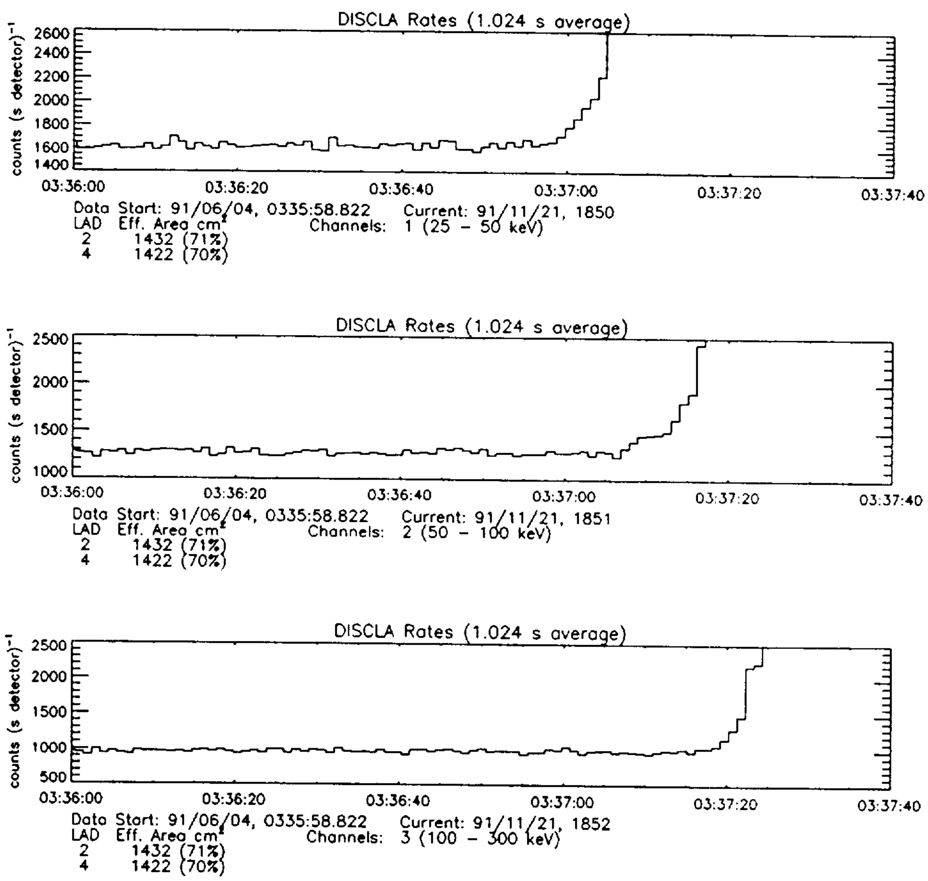

Fig. 5. Start of the 4 June 1991 flare at three energies, 25-50, 50-100, and 100-300 keV. The detectors did not begin to suffer extreme pile-up problems until after the end of these plots at 3:37:40 UT.

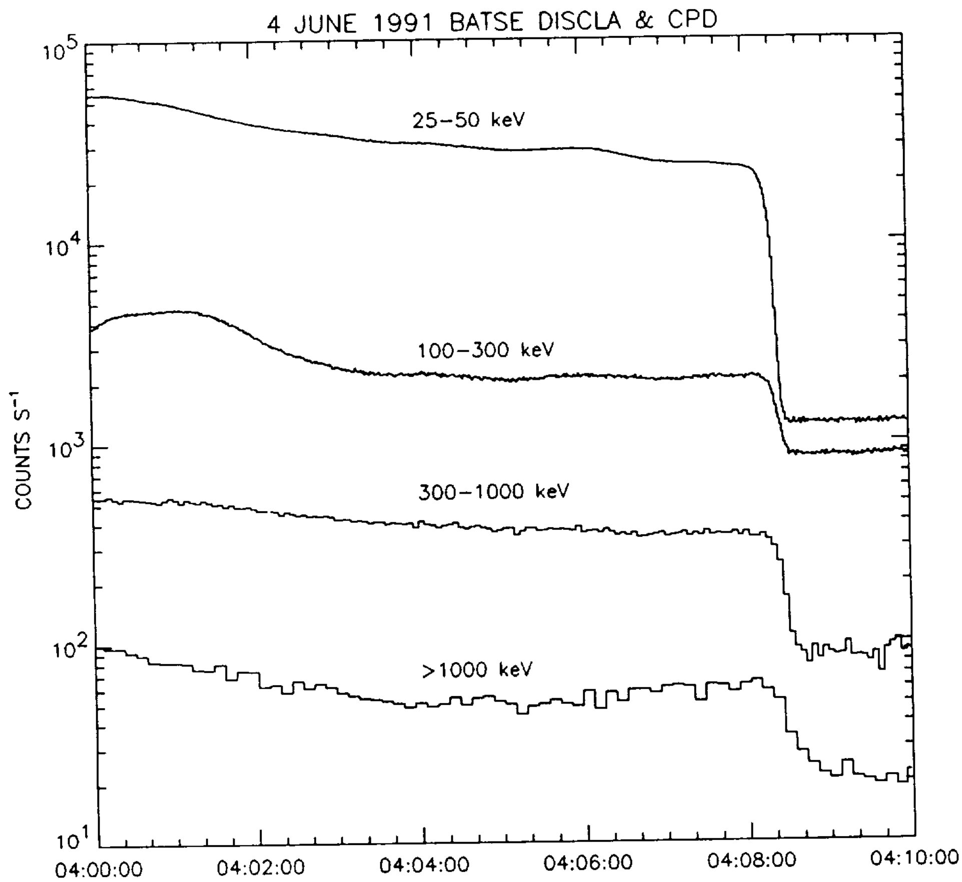

Fig. 6. Decay of the 4 June 1991 flare. These top three rates are from the sunward facing LADs and the bottom rate (>1000 keV) is from the sum of all eight charged-particle detectors. Just at 4:08:20 UT the GRO spacecraft enters night and the extinction of the solar flux is clearly seen.

GRO observed three more X10+ flares throughout their impulsive phases. They are all shown in Figure 7 at the highest energies observable with the BATSE LADs and charge-particle detectors starting at 1:04 UT on 6 June, at 1:36 UT on 9 June, and at 1:59 UT on 11 June at 1:59 UT. While none were as large as the 4 June flare all of the frontside detectors suffered saturation near the peak of the events.

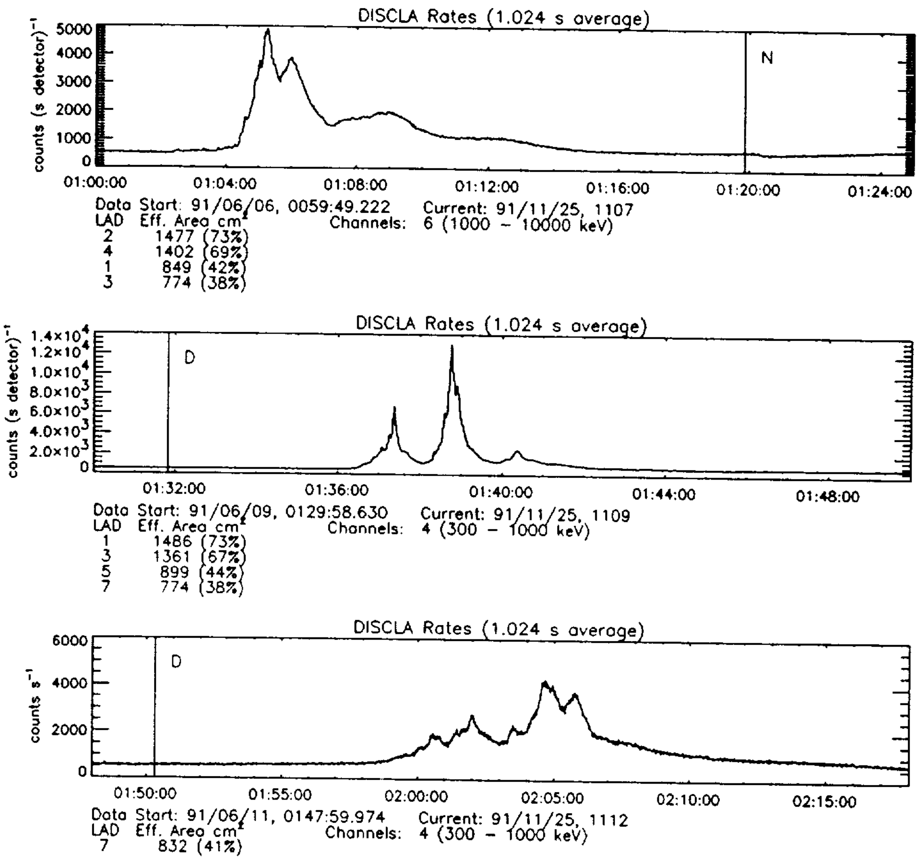

Fig. 7. High energy time histories of three gamma-ray flares observed with BATSE on 6 June, 9 June, and 11 June 1991.

5. HARD SPIKE EVENT OF 30 JUNE 1991

The high sensitivity obtained from the raw stopping power of these large detectors opens a new high time resolution window in the several hundred keV range. An example of the new phenomena available for study is provided by the flare on 30 June 1991 at 2:56 UT which occurs just before the spacecraft enters night. The four DISCLA energy bands are displayed in Figure 8. There was no reported optical counterpart for this GOES M5.0 event. There were strong microwave emission and Type III bursts. The flare profile is fairly smooth in the 25-50 and 50-100 keV bands with the peak at 2:56:31 UT. However, not the strong peak in the 300-1000 keV band at 2:56:28 UT which is not detectable in the lowest energy band. Presumably this peak must be masked by the intense flux at lower energy, but this also implies that the spectrum from this peak is extraordinarily flat, flatter than the power-law index of -3 to -4 which would characterize the spectrum below 100 keV based on the ratio of the two low energy channels. This flat impulsive spectrum is characteristic of the events reported above 10

MeV by Reiger and Marschhauser which they have designated as electron dominated flares. It should be possible to study the several hundred keV component of these flares using data from the BATSE LADs and Spectroscopy detectors.

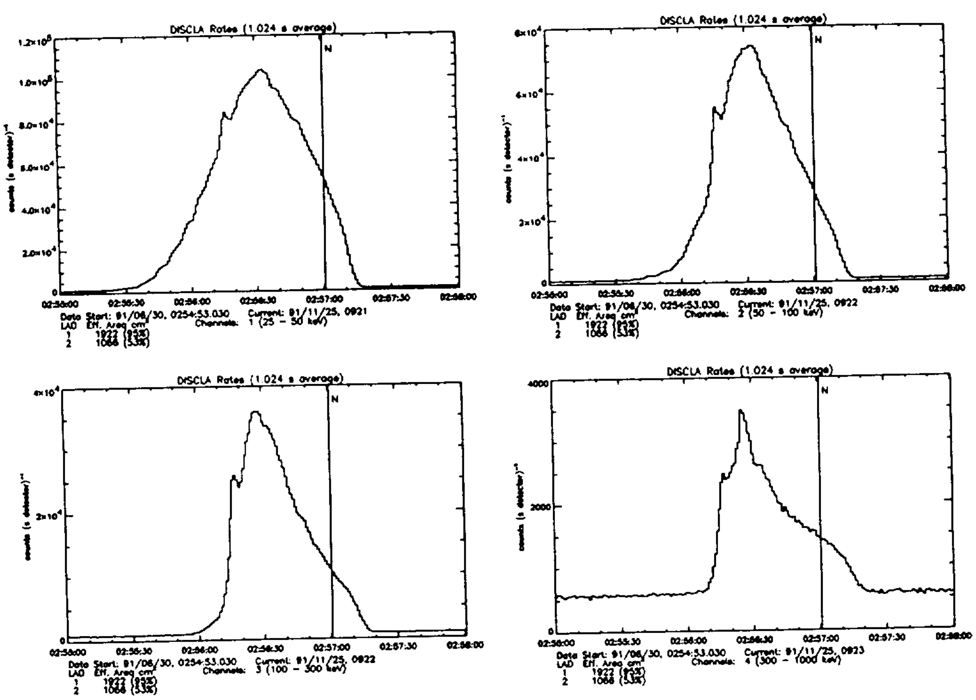

Fig. 8. High energy spike flare observed with BATSE at 2:56 UT on 30 June 1991. The four panels show the time history in the four DISCLA channels running from left to right and top to bottom in the energy ranges 25-50, 50-100, 100-300, and 300-1000 keV. Note that the impulsive spike visible at the highest energy at 2:56:28 UT is completely masked by the low energy time history

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