THE SAMPLE OF GAMMA-RAY BURSTS OBSERVED WITH SPI-ACS

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ABSTRACT

The SPI anticoincidence shield consists of 91 BGO crystals and is operated as a nearly omnidirectional gamma-ray burst detector above 75 keV. Since the start of the mission 269 gamma-ray burst candidates have been detected. 110 bursts have been confirmed with the instruments included in the 3rd Interplanetary Network. Here we present a preliminary statistical analysis of the SPI-ACS sample of gamma-ray bursts and gamma-ray burst candidates; in particular we discuss the duration distribution of the bursts. A prominent population of short burst candidates (duration <200 ms) is found which is discovered to be strongly contaminated by cosmic-ray nuclei interacting in the detectors.

1. INTRODUCTION

The detection and investigation of cosmic gamma-ray bursts (GRBs) is one of the important scientific objectives of the INTEGRAL mission. Although discovered more than three decades ago (Klebesadel et al. 1973) the GRB phenomenon is still challenging, with many open questions to solve. It has long been known that there are two distinct classes of GRBs which differ observationally in duration and spectral properties. This was quantified using data from the Burst and Transient Source Experiment (BATSE) detectors (Fishman et al. 1989) aboard NASA's Compton Gamma-ray Observatory (CGRO). The sample of more than one thousand bursts included in the 4^{th} BATSE catalogue displayed a strong bimodal distribution, with one group having short durations (<1 s) and hard energy spectra, while the other was of longer duration (seconds to minutes) with spectra peaking at softer energies.

We know now that at least some of the long-duration GRBs mark the deaths of massive stars at cosmological distances. The cosmological nature of GRBs was demonstrated with the detection of the first afterglows by BeppoSAX and the measurement of redshifts (Costa et al. 1997). The small sample of bursts with measured redshifts (∼30) presently extends from z=0.0085 to z=4.511. Observational proof that GRBs are connected with hypernovae and thus with the final stages of the evolution of massive stars comes from the detection of supernova signatures in the afterglow spectra of GRB 030329 (Hjorth et al. 2003, Stanek et al. 2003).

The INTEGRAL mission contributes to GRB science in two ways. (i) For bursts which occur in the field of view (FoV) of the Spectrometer SPI and of the imager (IBIS), INTEGRAL provides accurate positions for rapid ground and space-based observations. Also high energy spectra in the range of 20 keV to 8 MeV are provided (see von Kienlin et al. 2003 for a summary). (ii) The anticoincidence shield of SPI (SPI-ACS) acts as an omnidirectional GRB detector and produces time profiles with a resolution of 50 ms.

2. GAMMA-RAY BURST DETECTION CAPABILITIES OF SPI-ACS

The anticoincidence shield consists of 91 $Bi_4Ge_3O_{12}$ (BGO) crystals with a total mass of 512 kg. It provides a large (∼0.3 m^2) effective area for the detection of gamma-ray bursts. Each of the crystals is viewed redundantly by two photomultipliers and only the total event rate of all the crystals is telemetered to Earth with 50 ms time resolution. Therefore, the SPI-ACS setup does not provide any spatial or spectral resolution. Unfortunately, the energy range is not exactly known either, as the thresholds of the individual photomultipliers are different due to different light yields of the crystals. The lower energy threshold can only be estimated to be ∼75 keV. Nothing accurate can be said about the upper end of the energy range, except that it is above 10 MeV (for more details see von Kienlin et al. 2003). As the SPI-ACS surrounds the spectrometer nearly completely, it provides a quasi-omnidirectional field of view.

SPI-ACS is part of the INTEGRAL Burst Alert System (IBAS; see Mereghetti 2004, these proceedings). A software trigger algorithm searches for an excess in the overall count rate with respect to a running average background. For each trigger an ASCII light curve (5 s pre-trigger to 100 s post-trigger) and the spacecraft ephemeris are stored and made publicly available[1].

Since December 2002 SPI-ACS has been an important member of the 3^{rd} Interplanetary Network (IPN) of γ-ray burst detectors, which provides burst localizations using the triangulation method (Hurley 1997; Hurley et al. 2004, these proceedings). By studying triangulations of bursts with accurately known positions such as Soft-Gamma-ray Repeaters and GRBs with counterpart detections, the absolute timing uncertainty of SPI-ACS was estimated to be of the order of 100 ms. Recently, additional triangulations of some bursts with precisely known localizations using Konus-Wind and/or Helicon-Coronas-F instruments in conjunction with SPI-ACS data revealed a systematic timing inaccuracy such that the SPI-ACS was lagging behind UTC by 134±12 ms (Golenetskii, Mazets, Pal'shin & Frederiks, private communication 2004). We further investigated the timing error and confirmed a 125±25 ms lag by comparing the rise of (most likely) particle-induced short events in SPI-ACS and corresponding saturations in the Ge-detectors of SPI (see below). Starting with events which occurred after April 2 2004 11:00 UTC this time lag of 125 ms has been corrected for in the publicly available SPI-ACS data files by a fix in the software. The origin of this offset is still unknown.

3. SAMPLE SELECTION

A thorough and robust selection is required for a decent statistical study of the GRBs detected in the SPI-ACS overall count rate. As SPI-ACS lacks an imaging capability, a direct selection by localization, which would distinguish particle or solar flare events, is not feasible. Although localization, or at least the confirmation of non-solar system origin, can be provided by the instruments participating in the IPN, the remaining events would form a conservative sample. A fraction of the real GRBs would escape selection due to the different sky coverage and energy ranges of the instruments. In order to analyze the entire sample of GRB candidates detected with SPI-ACS, we therefore define our selection criteria independent of the confirmation by other instruments and base it on the only measurable quantity from the SPI-ACS data, the observed light curve.

An event is included in the sample as a GRB candidate when the total significance, S, above the background, B, exceeds S=12σ in any time interval during the event. Here, 1σ corresponds to $1.6\times\sqrt{B}$, where the factor 1.6 takes into account the measured deviation of the background noise from a Poissonian distribution (von Kienlin et al. 2003, Ryde et al. 2003). In order to test an individual event for the selection criterium, the significance of the 50 ms bin with the highest count rate is first calculated. If $S \geq 12\sigma$ the event is treated as a GRB candidate and included in the preliminary sample (see Fig. 1a–d & f). Otherwise, the integrated S of the highest count rate bin together with the neighbouring bin with the next highest count rate is computed and checked against the threshold. The procedure is continued until $S \geq 12\sigma$ or the 105 s SPI-ACS count rate window around the event is entirely tested without reaching the threshold. In that case the event is ignored. GRB 030903 (Fig. 1e) is an example of a faint event in the sample which required the integration of the significance of adjacent bins. Each event in the primary sample is subsequently checked for solar or particle origin using JEM-X and the GOES web page[2] and IREM, respectively.

4. RESULTS

Using the selection criteria described in the previous section, a total of 269 GRB candidates were detected during the first 15 months (Nov 11 2002 – Feb 11 2004) of the mission. 110 candidates have been confirmed by detections with other gamma-ray burst instruments. Taking the elapsed mission time into account, this gives a rate of 215 candidates and 88 confirmed bursts per year selected according to our criteria. For comparison, Lichti et al. (2000) predicted the rate of GRBs prior the start of INTEGRAL to be ∼160 per year at a 10σ level.

In addition to the number of events, the SPI-ACS overall detector count rate provides the possibility to derive the burst duration in the instrumental observer frame and the variability of the light curve. As no spectral information exist (only events above ∼75 keV are recorded), typical burst parameters like fluence and peak flux cannot be derived from the data. Only quantities like the total integrated counts and the counts at the burst maximum can be extracted from the light curve. Here we will focus on the observer frame duration and its distribution and will discuss the findings. Additional statistical properties are presented elsewhere (Ryde et al. 2003) and will be extensively discussed in Rau et al. (2004, in preparation).

For the observer frame duration of GRBs typically the T_{90} value is used. This measure corresponds to the time interval in which 90% of the burst emission (starting at 5% and finishing at 95%) is observed. The distribution of T_{90} for the sample of SPI-ACS burst candidates is shown in Fig. 2. For comparison the distribution derived from 1234 GRBs contained in the 4^{th} BATSE GRB catalogue (Paciesas et al. 1999), scaled to the elapsed mission time of INTEGRAL, is included.

Regardless of the low statistics, a bimodality in the distribution, comparable to what was seen with BATSE, is found in the SPI-ACS sample. A long-duration population with a maximum at ∼40 s and

[1] http://isdcarc.unige.ch/arc/FTP/ibas/spiacs/

[2] http://www.sec.noaa.gov

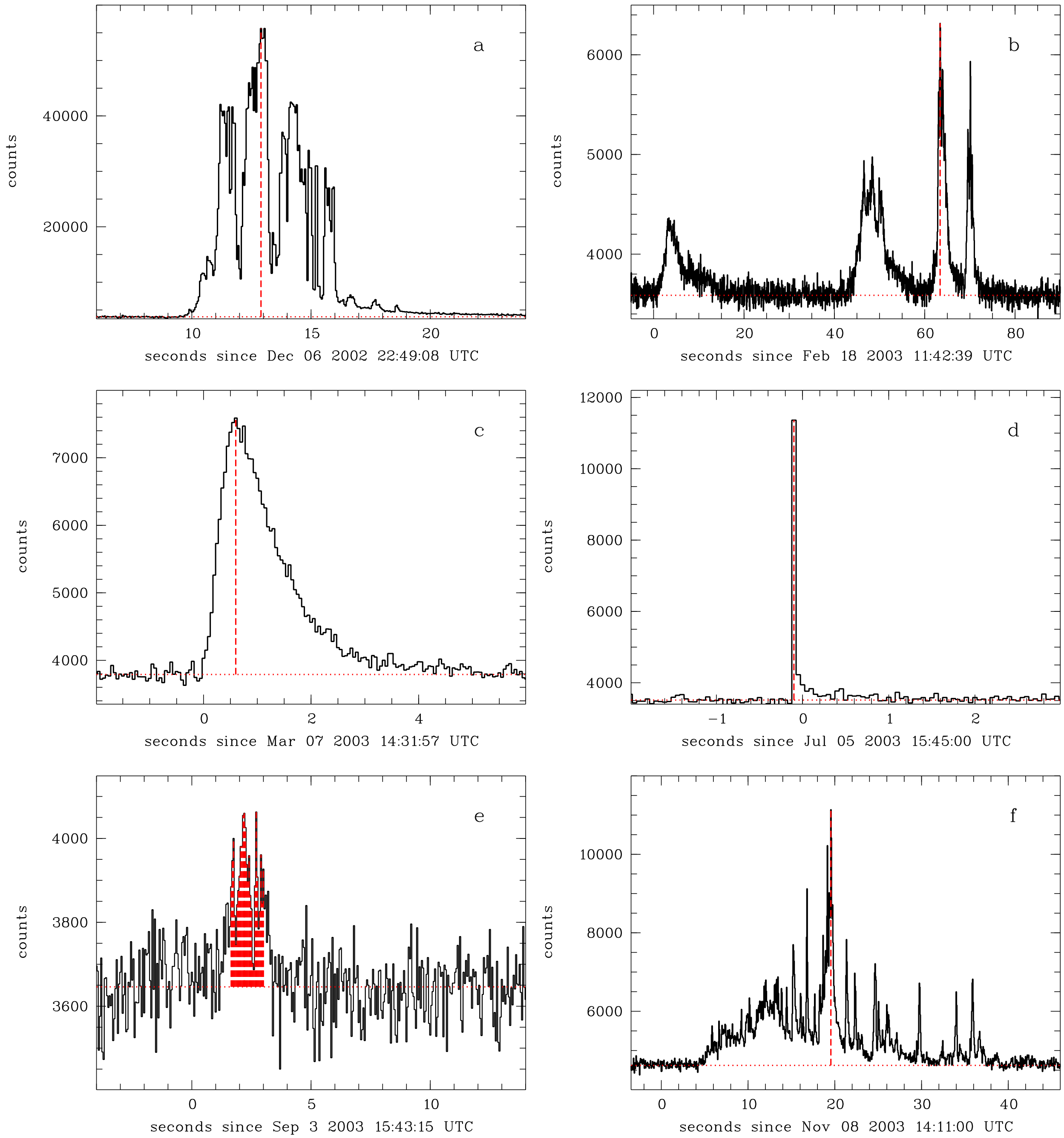

Figure 1. SPI-ACS overall count rate light curves with 50 ms time binning for a selection of GRB candidates from our sample. The horizontal dotted lines mark the background and the vertical dashed lines show the number of bins sufficient for including the event in the GRB sample following the selection criteria described in the text. a) the exceptionally bright GRB 021206, triangulated using Ulysses, RHESSI, Mars Odyssey and Konus-Wind (Hurley et al. 2003c); b) GRB 030218, also seen by Ulysses (Hurley et al. 2003a); c) bright, intermediate duration GRB 030307, triangulated using Ulysses, Konus-Wind, HETE (FREGATE) and RHESSI (Hurley et al. 2003b); d) short event from July 5 2003, observed only by SPI-ACS; e) faint GRB 030903, also observed by Ulysses, Mars Odyssey (HEND) and Konus-Wind (Hurley et al. 2003d); f) GRB 031108, also observed by Ulysses, Konus-Wind, Mars Odyssey (HEND+GRS) and RHESSI (Hurley et al. 2003e).

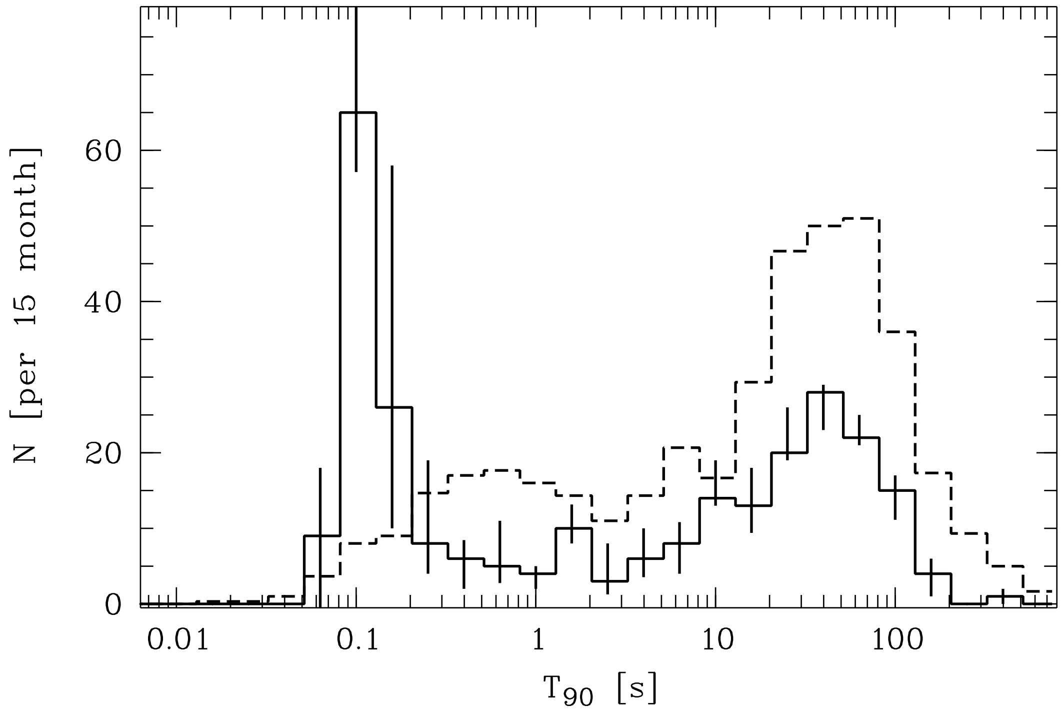

Figure 2. Distribution of T_{90} for all GRB candidates (solid line) and for 1234 GRBs from the 4^{th} BATSE GRB catalogue (Paciesas et al. 1999; dashed). In order to compare with the SPI-ACS detections, the BATSE distribution is scaled to the elapsed INTEGRAL mission time (15 months). The known bimodality is present in our sample, but note the very large fraction of short events compared to the sample of BATSE bursts.

a short-duration population peaking at 0.1 s are observed. While the long-duration events resemble the BATSE results closely, a clear deviation is detected for the short events. In the SPI-ACS sample the short burst candidates are dominated by 0.1–0.15 s events while for BATSE the distribution was much more smooth and peaked at 0.6 s. Also the ratio of short to long events is significantly different. While the 4th BATSE catalogue included ∼70% long and ∼30% short bursts, in the SPI-ACS sample the short burst candidates make ∼50% of the total events. Also noticeable is the peak of the distribution at 0.1 s. Unfortunately, as this is close to the time resolution of SPI-ACS, this population cannot be further resolved.

In Fig. 3 we show the duration distribution for the confirmed GRBs in the SPI-ACS sample. While ∼80% of the long-duration bursts are confirmed less than 6% of the short duration candidates were detected by other γ-ray instruments. Although the small number statistics still do not allow a quantitative statement to be made about the confirmed (short & long) burst distribution, it is similar to the BATSE results. Thus, the question of the origin of the unconfirmed short population arises, which will be discussed in the following section.

5. ORIGIN OF THE SHORT EVENTS

There are various possible explanations for the significant excess of unconfirmed 0.1–0.15 s long events in the SPI-ACS sample. (i) SPI-ACS observes a 'real' population of short very hard GRBs which has gone undetected up to now due to the lack of sensitivity at very high energies. The finding that the ratio of short to long burst candidates is larger for SPI-ACS than for BATSE can for instance be explained with the latter being sensitive in a lower energy range (50–320 keV) than SPI-ACS (∼75 keV to >10 MeV). However, several γ-ray instruments which are now in orbit have the capability to detect such hard events. This was demonstrated for the event of December 14 2003. Observations with the Gamma-Ray Spectrometer (GRS) aboard Mars Odyssey demonstrated that this very bright short (0.3 s) burst had a very hard spectrum peaking at ∼2 MeV (Hurley et al. 2003f). This event was simultaneously detected by Konus-Wind and Helicon-Coronas-F (Golenetskii et al. 2003a, 2003b). So the fact the majority of the SPI-ACS short events are only detected by the SPI-ACS, but not by other instruments, argues against a new population. (ii) A small contribution to the short burst population might also arise from soft Gamma-ray repeaters (SGRs). SGRs are a small class (5 known members) of objects that are characterized by brief (typical ∼100 ms), very intense (∼10^{44-45} erg) bursts of hard

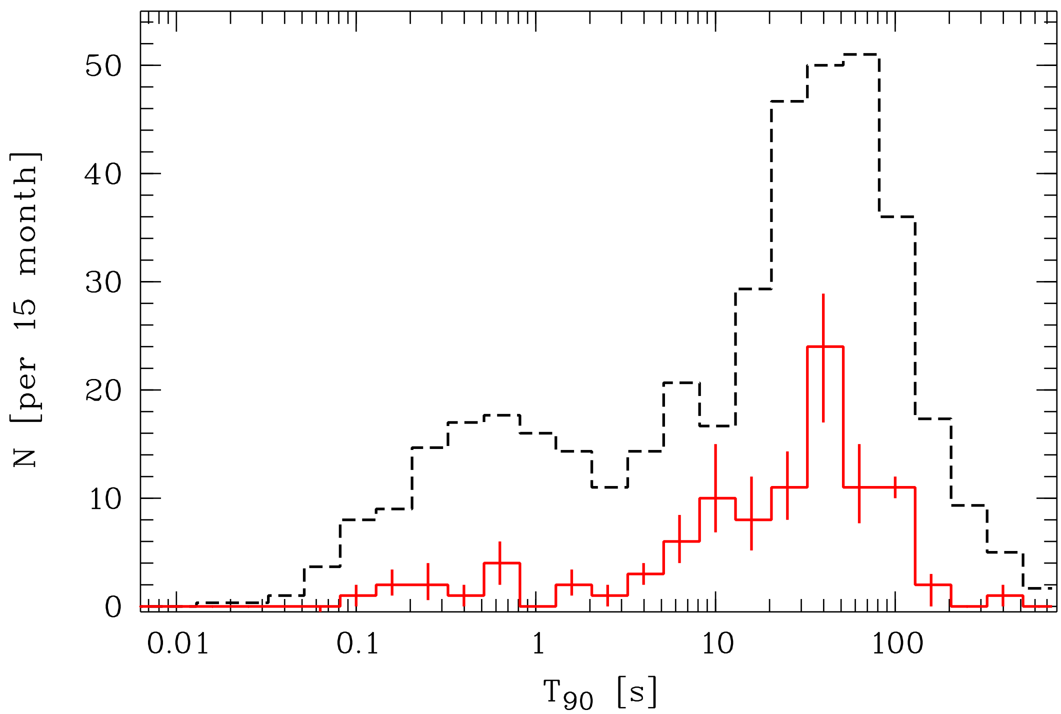

Figure 3. Same as Fig. 2 except that here only the sample of confirmed SPI-ACS bursts (solid line) is shown. A comparison with Fig. 2 shows that only a small fraction of the short events was confirmed while nearly all long-duration bursts were also seen with other instruments.

X-rays and soft gamma-rays. They are generally located near the Galactic plane. It is likely that they originate from strongly magnetized neutron stars, or magnetars (Duncan & Thompson 1992). As the light curve shapes are similar, events in the SPI-ACS rate originating from SGRs cannot be easily distinguished from short GRBs without the localization by triangulation with other instruments. (iii) A significant contribution to these short events comes from instrumental effects and/or cosmic-ray events. This cannot be ruled out.

A detailed study of the population of short events revealed that a significant fraction is accompanied by the simultaneous saturation of one or several Ge-detectors of the spectrometer. An example for an event on December 1 2003 is shown in Fig. 4. At the time of the significant rate increase in SPI-ACS over ∼50 ms the Ge-detectors #9 and #10 went into saturation and stayed there for ∼4 and ∼20 s, respectively. A statistical analysis of the data of the mission shows that a saturation event occurs approximately every four hours and that nearly all of these events have a simultaneous rate increase in SPI-ACS. An independent search for short events in the SPI-ACS overall count rate found ∼15 events per hour at a 4.5σ level. Thus approximately every 60th short SPI-ACS event coincides with a saturation in the Ge-detectors. Note, the chance coincidence of the SPI-ACS events happen at the same time as the saturation in the Ge-detectors is $\sim 3\times 10^{-8}$, which makes the causal connection evident.

These observations suggest a particle origin for at least a fraction of the short burst candidates. The most natural explanation for the saturation of the Ge-detectors is the deposit of a large energy amount in the crystals. A very energetic cosmic-ray particle can hit a BGO crystal and deposit part of its energy, thus producing the short count rate increase (see below for a discussion). Depending on the flight direction, the particle can further hit one or several Ge-detectors and cause the saturation, or pass through the BGO for a second time, or not interact again. The probability of a particle hitting the SPI-ACS and Ge-detectors can be estimated from the geometry of the instrument to be ∼1/40 of the probability to pass only through the anticoincidence shield. This is in rough agreement with the rate of SPI-ACS short events that coincide with saturations. Therefore, from this simple assumption one can conclude that at least a significant fraction of the unconfirmed short burst candidates can originate from cosmic-ray particles hitting the instrument. Comparing the rate of events in the SPI-ACS with the observed rate of cosmic-rays as a funtion of energy (Cronin et al. 1997), the energy for a single particle can be estimated to be ∼300 GeV and above.

Most of the saturation events occur in a single Ge-detector. Hits in several detectors are significantly less frequent. If the saturation is caused by a single particle then a particle passing through the coded mask will only deposit energy in one detector as the cross-section for hitting more than one Ge-crystal is

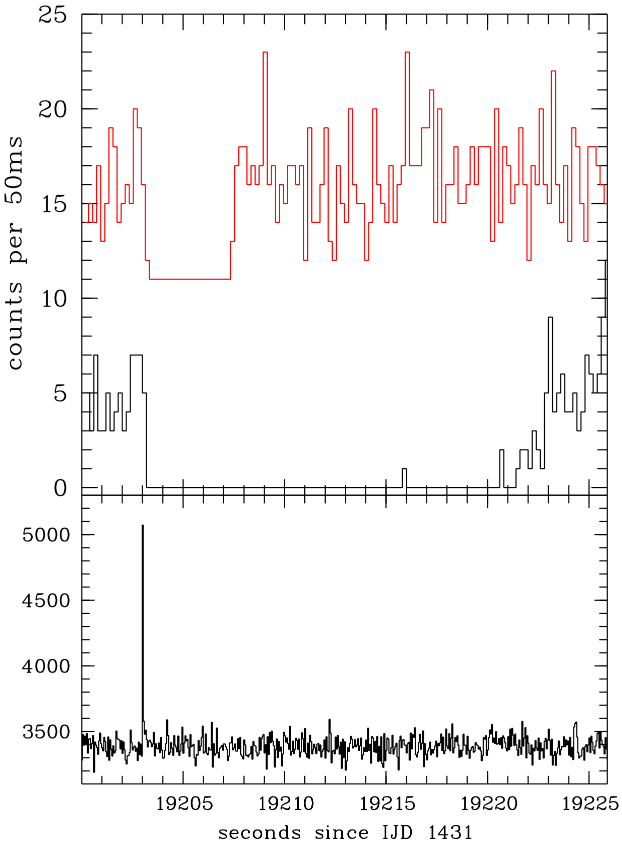

Figure 4. Short event on December 1 2003 with simultaneous saturation in the Ge-detectors #9 (upper) and #10 (lower). The upper curve (detector #9) is offset for better visibility.

very low. A particle hitting the detector plane with an angle not perpendicular to the detector plane can deposit energy (and cause saturation) in several detectors. That is in agreement with the observation that saturation events in more than one detector are always accompanied by a clear SPI-ACS count rate increase, while a small fraction of the saturation events in single detectors show no corresponding signal in the SPI-ACS overall rate.

In the case of a particle shower the number of detector hits depends on the width of the distribution of the secondary particles and on the inclination angle. In IBIS/PICsIT strong bursts (2500 counts) of up to 170 ms of particle-induced showers are observed (Segreto 2002). These showers are thought to be produced by cosmic-ray hits on the satellite or detector structure. As a consequence of the interaction of the primary particle with matter, high-energy photons and electron-positron pairs are created. These in turn produce a cascade of secondary electrons and photons via bremsstrahlung and pair production. The time profiles of the events observed in PICsIT are rather complex and both straight tracks and closed areas are visible (Segreto 2002). These observations are similar to what is observed with the saturation in SPI and thus support the idea of cosmic-rays as an origin of the short SPI-ACS events.

The assumption was made above that the passage of a very energetic particle produces the observed short increase of the SPI-ACS overall rate. One possibility is that the deceleration of the particle in the BGO crystal produces a long-lasting (50-150 ms) phosphorescent afterglow energetic enough to produce recurrent triggers of the electronics. BGO was originally selected for SPI-ACS because of its short decay times and very low phosphorescence compared to e.g. CsI(Na) and NaI(Tl). It has decay times of 60 ns and 300 ns where the second is by far the more probable (90% vs. 10% for the 60 ns) and additionally a so-called afterglow (not to be confused with the GRB afterglow) of 0.005% is expected at 3 ms. The afterglow originates from the presence of millisecond to even hour long decay time components and is believed to be intrinsic and correlated to certain lattice defects.

In order to produce a single count in the SPI-ACS rate, a minimum of 75 keV (the lower energy threshold) has to be accumulated during an integration time of 600 ns. With a total light yield for BGO of 8000-10000 photons/MeV, this corresponds to ∼750 photons. Assuming a typical decay law of $I(t)=I_0*e^{-t/\tau}$ shows that the radiation will decrease to 0.005% at 3 μs. Thus the decay is so fast that only a small number of counts (∼3) will be produced. From the afterglow properties the minimum original excitation energy can be estimated. For instance, to have 1000 recurrent triggers (a count rate increase of 1000) in a single crystal, the afterglow must be bright enough to be above the 75 keV threshold for ∼3 ms (integration time + dead time). The 0.005 % afterglow emission at 3 ms thus corresponds to a ∼1.6 GeV initial excitation using the photon yield given above. Therefore, particles which deposit ∼1.6 GeV or more in a crystal can indeed be the origin of the short event population in SPI-ACS. Short events showing similar temporal behaviour were already discussed for CsI(Na) and CsI(Tl) crystals exposed to primary cosmic radiation (Hurley 1978). The same conclusion for the origin, namely cosmic-ray nuclei in the iron group, was drawn. Note that CsI has a significantly more intense afterglow (0.1–1 % at 6 ms).

6. CONCLUSION

It is now clear that the prominent population of short burst candidates detected by SPI-ACS is probably strongly contaminated by cosmic-ray events. At present it is not feasible to disentangle the true short GRBs, with durations <0.2 s, from these events without a confirmation by other γ-ray instruments. Therefore, we can only give the approximate rate of GRBs observed by SPI-ACS with durations >0.2 s to be ∼140 (88 confirmed by other instruments) per year.

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