GBM - a Gamma-Ray Burst Monitor for GLAST

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ABSTRACT

One of the scientific objectives of the GLAST mission is the study of γ-ray bursts (GRBs) which will be measured by the Large-Area Telescope, the main instrument of GLAST, in the energy range from ~20 MeV to ~300 GeV. In order to extend the energy measurement towards lower energies a secondary instrument, the GLAST Burst Monitor (GBM) will measure GRBs from ~10 keV to ~25 MeV and will thus allow the investigation of the relation between the keV and the MeV-GeV emission from GRBs. The GBM consists of 12 circular NaI crystal discs and 2 cylindrical BGO crystals. The NaI crystals are optimized for gamma radiation from ~10 keV to ~1 MeV and the BGO crystals from ~150 keV to ~25 MeV. The NaI crystals are oriented in such a way that the measured relative counting rates allow a rapid determination of the position of a γ-ray burst within a wide FoV of ~8.6 sr. This position will be communicated within seconds to the LAT which may then be reoriented to observe the long-lasting high-energy γ-ray emission from GRBs. This will allow the exploration of the unknown aspects of the high-energy burst emission and their connection with the well-known low-energy emission. Another important feature of the GBM is its high time resolution of ~10 μs for time-resolved γ-ray spectroscopy.

Keywords: γ-ray bursts, γ-ray instruments, instrumentation, γ-ray astronomy

1. INTRODUCTION

Since the discovery of the afterglows from γ-ray bursts (GRB) by BeppoSAX γ-ray burst studies became one of the most exciting branches of modern astrophysics. The fascination GRBs exert on astrophysicists lies in the multitude of phenomena which can be investigated ranging from compact-object physiscs through star formation and stellar evolution to particle acceleration and cosmology. Although a big step forward has been made in recent years in the understanding of these exotic events many questions still remain open. One of them is an explanation for an observation which was made by EGRET in 1994. During that year this instrument observed a GRB and detected a delayed emission at high γ-ray energies (> 50 MeV) which lasted about 1.5 hours after the onset of the burst.[1] The γ-ray with the highest energy of ~18 GeV was detected about 1.3 hours after the start of the burst. Though several other GRBs with high-energy afterglows have been detected by EGRET the relation of this high-energy emission with the low-energy emission is not yet understood. It is one important goal of NASA's GLAST mission to tackle this problem and to shed light on the underlying physical processes.

GLAST is equipped with two instuments, the large-area telescope (LAT) and the GLAST burst monitor (GBM). Whereas the LAT, the main instrument of GLAST (for a description see 2), is devoted to the measurement of γ-rays from ~20 MeV to ~300 GeV (~10 MeV - ~500 GeV), the GBM, GLAST's secondary instrument, will measure X-rays and low-energy γ-rays from ~10 keV to ~25 MeV (~5 keV - ~30 MeV) (if the well-disposed reader finds different limits in the publications 3, 4 and 5, then because requirements and goals were intermingled. Here the requirements are given with the goals in brackets.).

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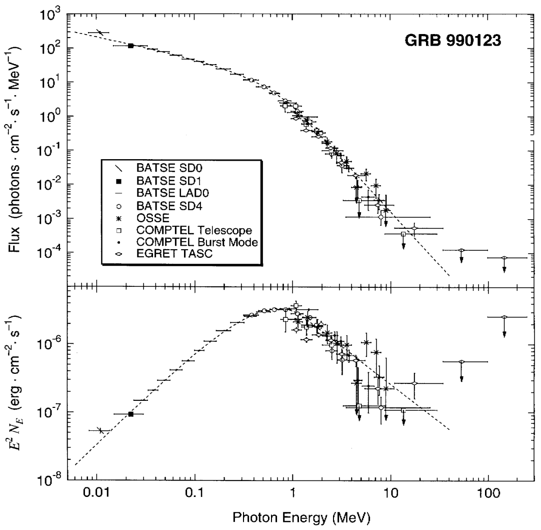

Figure 1. A typical spectrum of a GRB is characterised by a break in the spectrum and power laws on either side of the break energy.

The complimentary nature of these two intruments becomes obvious when one looks at a typical GRB spectrum (see Figure 1). It is characterised by a pronounced break with a break energy E_p between ~100 keV and ~1 MeV. The distribution of observed break energies peaks at ~250 keV.[6] At E_p the energy flux reaches a maximum. Because of the sparse measurements of GRB spectra above ~10 MeV the break energy is often only loosely defined and the corresponding distribution may be biased by instrumental selection effects (see 7). With the two instruments of GLAST this deficiency will be overcome and the distribution of E_p will be measured with less bias (especially because the biases of the two instruments will compensate each other).

Since in the standard fireball models E_p is proportional to $\sqrt{n} \cdot \Gamma^4$ with n the density of the surrounding medium and Γ the Lorentz factor,[8] one learns something about these quantities by measuring E_p. Because of the strong dependence of E_p on Γ the beamed fireball models predict a wide range of E_p in contrast to observations.[9] The improved distribution of E_p measured with GLAST will help to resolve this issue.

Another interesting question concerns the extension of the emission spectra towards higher energies. The observations obtained sofar suggest that this part of the spectrum can be described by a power law with the power-law indices ranging from ~-3.5 to ~-1.4.[10] It is obvious that spectra with an index > -2 cannot extend towards infinity because of limitation of total energy. Therefore these spectra must cut-off somewhere. So far such a cut off has never be observed. With GLAST it will be possible to measure this cut-off for the first time.

2. THE GLAST MISSION

The GLAST mission is mainly devoted to the measurement of high-energy γ-rays. In order to achieve its scientific goals an instrument with a higher sensitivity and with a better location accuracy than previous instruments is required. The LAT, the main instrument of GLAST, uses the same physical detection technique as EGRET (pair creation) to measure γ-rays, however making use of an advanced technical concept. The LAT is composed of an array of towers of pair-conversion tracker stacks made from Silicon-strip detectors which lead to a large collection area and an excellent imaging capability over a wide field of view (FoV) for γ-rays in the energy range from ~20 MeV to ~300 GeV. The instrument reaches a point-source sensitivity of $\sim 4 \cdot 10^{-9}$ photons/(cm^2 s) above 100 MeV for an observation time of one year (10-30 times more sensitive. than EGRET). Within its large FoV of >2 sr it will locate sources from ~5' at low energies down to ~30" at the highest energies. The main scientific goals of the LAT are the study of particle acceleration in the universe by which process finally γ-rays are created. By studying these γ-rays one learns something about the most-energetic phenomena occurring

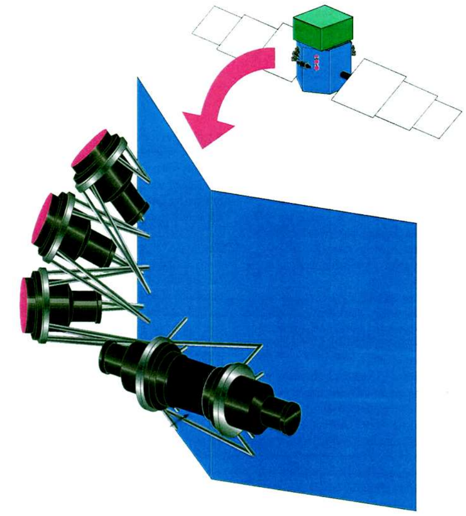

Figure 2. A possible arrangement of the GBM detectors. Shown are 3 of 12 NaI detectors and one of two BGO detectors.

in the universe. GRBs are among these and it is one of the main goals of GLAST to study these enigmatic explosions in more detail than it was possible with previous intruments. Outstanding results on GRBs are expected from these observations. The LAT alone, however, suffers from some deficiencies and is not a perfect GRB detector: it cannot perform measurements below ~20 MeV, it has insufficient trigger conditions for weak bursts and it possesses only a rather small FoV.

Since in addition most of the knowledge about GRBs originates from observations at low γ-ray energies where the bulk of the energy flux is emitted and all the phenomenological and characteristic features of GRBs were found by BATSE GLAST was equipped with an instrument, the GBM, which measures GRBs in this energy range. With these two instruments together the above-mentioned deficiencies of the LAT alone can be overcome. In addition these two instruments will be able to measure energy spectra of GRBs over an unprecedented energy range of six decades.

GLAST will be carried with a Delta rocket into a low-earth orbit in order to stay below the radiation belts and in order to be shielded from the energetic cosmic-ray particles.

3. DESCRIPTION OF THE GBM

The GBM will be realised by a collaboration between the gamma-ray burst group of the Marshal Space-Flight Center (MSFC) and the University of Alabama (UAH) in Huntsville, USA, and the gamma-ray group of the Max-Planck-Institut für extraterrestrische Physik (MPE) in Garching, Germany. The MPE is responsible for the manufacturing of the detectors and the power supplies, while MSFC/UAH is responsible for the project management, the digital-processing unit (DPU) and the integration activities. The calibration, the operation of the instrument in flight and the processing and analysis of the data will be shared equally between both groups.

3.1. The Detectors

The GBM shall measure γ-rays from ~10 keV to ~25 MeV (~5 keV - ~30 MeV). Since no detector material exists which covers this energy range with a high-enough sensitivity the GBM uses two different kind of scintillator materials: NaI and BGO. The NaI crystals are 1.27 cm (0.5") thick circular crystal discs (diameter 12.7 cm) with a 0.22 mm thick Be window which are viewed by one PMT. The GBM utilizes 12 of these detectors. They are mounted onto the spacecraft such that each of them is viewing the sky in a different direction (an example of a possible mounting configuration is shown in Figure 2). With this arrangement a wide FoV of ~8.6 sr will

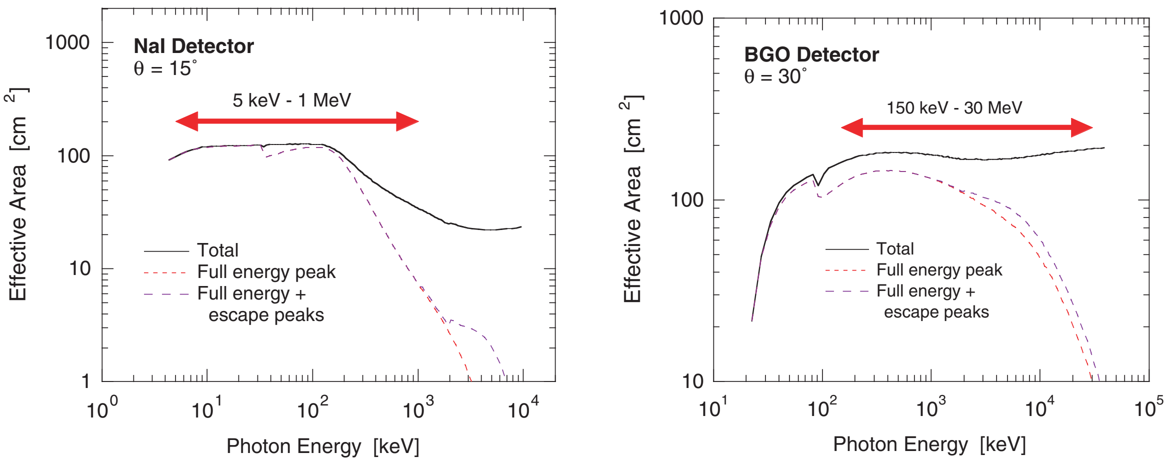

Figure 3. The effective areas of NaI (left) and BGO (right) as a function of energy.

be obtained allowing the derivation of the arrival direction of a GRB from the relative counting rates measured in each detector (the same method as was applied successfully by BATSE).

Since the effective area of the NaI detectors drops above ∼200 keV (see Figure 3) no overlap with the LAT measurements (E > ∼20 MeV) is possible with the NaI detectors alone. Therefore two cylindrical BGO crystals will be mounted on two opposite sides of the GLAST spacecraft which are sensitive to γ-rays from ∼150 keV to ∼25 MeV (∼100 keV - ∼30 MeV) (see Figure 3). This energy range overlaps on the low side with the one of the NaI detectors and on the high side with the one of the LAT. These overlaps are important for inter-instrument calibration. The two BGO crystals have a diameter and a length of 12.7 cm (5"). They are viewed on both sides by PMTs whose analogue signals are summed.

3.2. The Digital-Processing Unit (DPU)

The signals of all 14 detectors are fed to PHAs in the DPU where they will be digitized. The tasks of the DPU are manifold: apart from the digitization of the PMT signals it will time-tag the signals, it will sort the data in different data types for transmission to ground and it will carry out data-processing tasks with the aim to perform a rapid (< 2 s) burst location to $\leq 20°$ ($\leq 15°$). The DPU will monitor and control the whole GBM instrument. Figure 4 shows a block diagram of the GBM with its interfaces.

The DPU generates two basic types of data, timing data and spectral data. They are produced from the continuous stream of data coming from the PHAs of the detectors by binning them in the time and energy domain with fixed bin sizes. The ITIME (Internal TIME) data contain the continuous stream of the counting rates (integrated over 16 ms) from each GBM detector in 8 different energy channels, whereas the ISPEC (Internal SPECtrum) data contain the counting rates (integrated over ∼1 minute) from each GBM detector in 128 energy channels. The flight software of the DPU will use the ISPEC data for the automatic gain control (see end of this section) and the ITIME data for the trigger algorithm. From the already prebinned data two other data types, CSPEC (Continuous SPECtrum) and CTIME (Continuous TIME), with different integration time and energy binning will be created. The bin sizes of these data can be controlled by independent commands from ground.

The CTIME data contain the counts per time bin for 8 energy channels from each GBM detector. The time resolution of these data will be adjustable by command in steps of multiples of 64 ms starting at 64 ms (the number of steps will be ≥ 4). The boundaries of each time bin will be recorded with an accuracy of <10 μs relative to the universal time provided by the spacecraft. The CSPEC data contain the energy spectrum of each individual detector with 128 pulse-height channels. The time resolution of these data will be adjustable via command in steps of multiples of 1.024 s starting at 2.048 s (the number of steps will be ≥ 8).

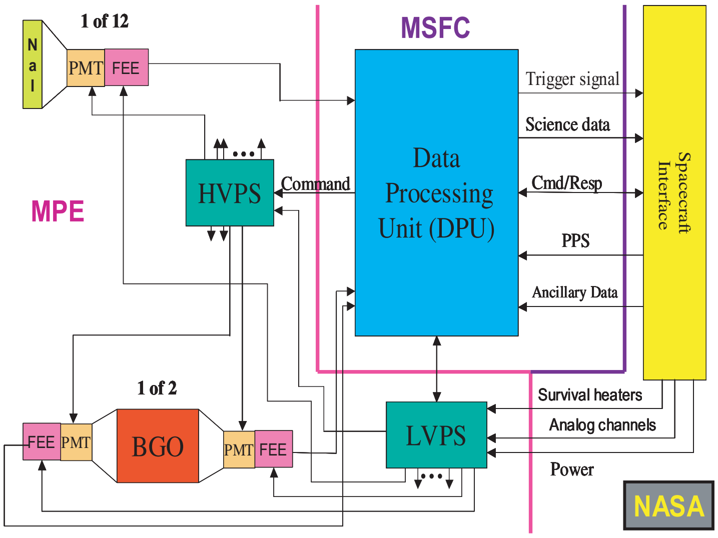

Figure 4. The block diagram of the GBM with the different interfaces.

Whereas these continuous data contain mainly the information about the background the relevant information about a burst is included in the trigger data TTE (Time-Tagged Events) and TIGDAT (TRIGger DATa). Whenever an increase of the counting rate with a significance of $\geq$4.5σ is detected by the trigger algorithm of the DPU digitized pulse-height events from all GBM detectors will be acquired. These time-tagged events (TTE) will be tagged with 32 bits. In addition the DPU software will calculate within $\leq$2 s the position of the burst on the sky from the relative counting rates of the detectors with an accuracy of $\leq 20°(\leq 15°)$. For each event the detector identifier, the digitised pulse height (with 128-channels resolution), the position and the time of the occurrence of the event relative to the UTC with an accuray of $\leq$10 μs will be recorded. The boundaries of the pulse-height channels are not fixed, but can be redefined from the linear ADC channels via programmable look-up tables stored in the memory of the DPU. A total of $\geq$ 250 000 time-tagged events from all detectors can be collected continuously and stored in a FIFO ring buffer.

The trigger data TRIGDAT contain information about the triggered event. These include the burst location, the burst duration, the burst intensity and spectral parameters (like hardness ratio) and a classification of the burst (i. e. γ-ray burst, solar-flare event, atmospheric event etc.).

Since spectroscopy is an important goal of the GBM, stability of pulse-height electronics is a key issue. Drifts of the light output of the crystals (which depends on the temperature) and gain changes of the PMTs can shift the energy-pulse-height relation. Therefore an active gain control will be foreseen in the DPU to compensate these gain changes by adjusting the HV of the corresponding PMT. For this the peak position of the 511 keV background line is measured. If a deviation from the face value is detected the corresponding HV value is automatically adapted. The HV value can be changed in steps of $\sim$2 V whichh allows a control of the gain to better than 2%.

3.3. The Trigger Criteria

The counting rates of the detectors measured with $\geq$1.024 s long time intervals (for details see section 3.2) will be searched for rapid count-rate increases in the energy interval from $\sim$50 keV to $\sim$300 keV. When such a fast and sudden count-rate increase has been detected, this event will be time tagged and a burst alert will be created if the following conditions are met:

- the count-rate increase above background must be detected with a statistical significance of at least 4.5σ
- such counting-rate increases must be observed in at least two neighbouring NaI crystals

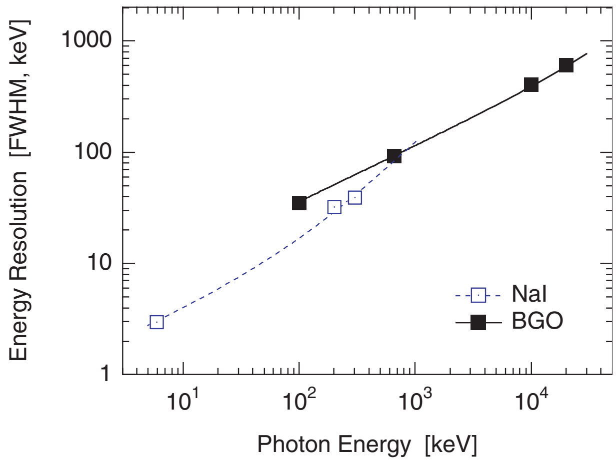

Figure 5. The energy resolution of the GBM detectors as a function of energy.

- the on-board software must be able to calculate an unambiguously position from the relative counting rates of the different detectors

- the estimated position must lie in the sky and not on the earth.

4. THE INTERACTION BETWEEN THE GBM AND THE LAT

4.1. Burst Alerts

Whenever the criteria of the section 3.3 are fulfilled and a burst has triggered a one-bit trigger signal will be sent to the LAT within 5 ms of the start of the trigger. The purpose of this quick alert is to notify the LAT that a burst has occurred and that more information on the burst characteristics, as described in the next section, will follow.

Another purpose of this alert signal is to initiate a transfer of the GBM data via the spacecraft to ground where a refined position will be automatically calculated (with an accuracy of $\leq 3°$). This refined position will be available few minutes after the burst occurrence and to be distributed via the GCN to interested observers to enable afterglow observations. An even better position with an accuracy of $< 1.5°$ will finally be derived within several days by a subsequent refined analysis.

4.2. Information Flow

Shortly after triggering the on-board software will produce a TRIGDAT record within ≤ 2 s. This TRIGDAT record will be transmitted to the spacecraft in order to notify that the TDRS link should be activated. The TRIGDAT record contains information about the best estimate of the position, some spectral parameters, the flux and fluence of the burst, an event classification and an estimate of the reliability of the classification and the location.

With the burst in progress the on-board GBM-localization algorithm continues to improve the burst position. In addition the GBM software will derive a repoint recommenation and the location which should be used by the LAT for the repoint. This information will be communicated to the LAT to decide whether a repointing of the whole spacecraft (with a slew rate of $\geq 75°/10$ minutes) appears scientifically advantageous (e. g. for a sufficiently bright and hard burst that was originally not in the field-of-view (FoV) of the LAT). Because of the large FoV of the LAT a coarse location accuacy of $\leq 20°(\leq 15°)$ is sufficient for this purpose.

However there are other clients for the GBM-GRB positions. These are mainly telescopes on ground which would like to observe the optical and infrared afterglow. For those observers a more sophisticated algorithm shall determine an improved position within ≤ 30 s. Since there is no need on board for such a highly accurate

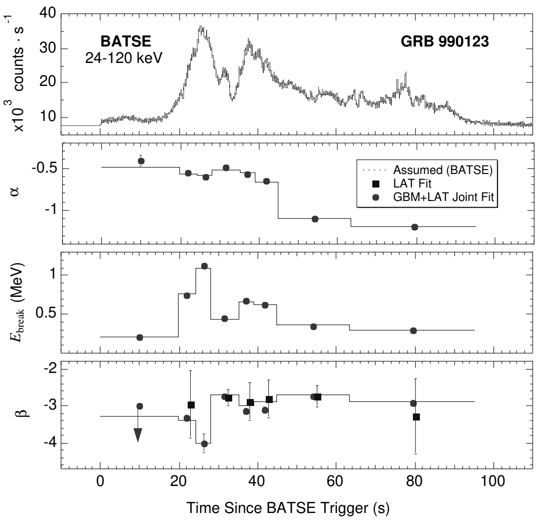

Figure 6. The lightcurve of GRB 990123 and the simulation of the evolution of the spectral parameters α, E_p and β. Please take note of the small error bars in the lowest plot for the combined GBM-LAT data.

position this software will be installed and run on ground. The on-board software must only transmit the relevant information fast enough to ground in order to allow the ground-based software the performance of its task. The expected position accuracy will be of the order of 1°.

Since this position accuracy is still too coarse for some of the large optical telescopes the plan is to get a better position using the LAT data. For this the highest-energy photons of the LAT events of a sufficiently bright, spectrally hard burst will be telemetered to ground, where a highly accurate LAT position will be computed in near-real time. This refined position (with an accuracy of ∼1 arcmin) will then be distributed via the GCN to interested observers within ∼16 minutes.

5. PERFORMANCE AND PROPERTIES OF THE GBM

The two plots of Figure 3 indicate that over the full energy range an effective area between 100 cm^2 and 200 cm^2 per detector is achieved. The energy spectrum of a burst can be measured with the resolution as shown in Figure 5. It increases from ∼60% FWHM at 6 keV to ∼3% at 20 MeV. Based on background estimations one can expect with the trigger scheme explained in section 3.3 an on-board sensitivity of $< 0.6\ \gamma/(\mathrm{cm}^2\ \mathrm{s})$. With this sensitivity the GBM will trigger on ∼200 bursts/year. A much higher sensitivity of $\sim 0.35\ \gamma/(\mathrm{cm}^2\ \mathrm{s})$, however, will be reached on ground where a search for weak untriggered bursts is planned.

6. EXPECTED RESULTS

From BATSE observations a lot about the characteristic features of GRBs at energies below ∼1 MeV is known, where in most cases the maximum of the emission lies. However, the information at higher energies is sparse in spite of the observations by COMPTEL and EGRET. Since only very few GRBs were detected by EGRET, especially the power-law index β of the high-energy emission is poorly known. With the two instruments of GLAST, the LAT and the GBM, this index can be measured for the first time quite accurately because of the large lever arm, and put in relation to the low-energy emission. This will allow the classification of these bursts and will answer the question of how they fit into the complete burst population. It may also help to entangle the problem how these high-energy γ-rays can escape their source region without being absorbed via γ-γ interactions with lower-energy photons.

By measuring the relation between the low-energy and high-energy emission the questions of the hard-to-soft evolution of the low-energy power-law index α and the hardness-intensity correlation can be investigated. A new feature of the GLAST measurements will be to allow the investigation of the evolution of the high-energy power-law index β. In Figure 6 an example is shown how this parameter can be constrained by the combined measurements of both GLAST instruments. Whereas the low-energy power-law index α shows the typical hard-to-soft evolution, an anticorrelation with intensity seems to be present for β. Observations with the GBM will help proving or disproving this anticorrelation with reduced uncertainty if one combines the data of both GLAST instruments.

In a recent paper a new method to measure the redshift of long GRBs from γ-ray data alone has been proposed.[11] The basis of this method is a peak-flux ratio of two different energy channels. This method was calibrated using eight GRBs for which the redshifts were known from optical afterglow observations. However, this method is applicable only for bright bursts which have redshifts ≤ 4 the reason being that the BATSE energy threshold was at ~ 20 keV only and that for GRBs with $z > 4$ the low-energy photons are shifted below this threshold energy. If this method proves to be correct then it can be applied to the GBM data as well. Because of the lower threshold of the GBM of ≤ 10 keV it should be possible to derive higher redshifts than from the BATSE data. This would allow a more thorough investigation of all the correlations which have been reported recently (see for example papers 12 and 13).

At the end an aspect of the GBM should be mentioned which is not related to GRBs. Since the GBM watches with its wide FoV continuously a large portion of the sky it can be used similar as BATSE as a sensitive monitor for transient X- and γ-ray sources.

ACKNOWLEDGMENTS

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