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Measurements of Gamma-Ray Bursts with GLAST

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Abstract The next large NASA mission in the field of γ-ray astronomy is the Gamma-Ray Large Area Space Telescope (GLAST), which is scheduled for a launch end of 2007. This satellite consists of the main instrument LAT (Large-Area Telescope) which is sensitive in the energy range between 10 MeV and > 300 GeV, and a secondary instrument, the Gamma-Ray Burst Monitor (GBM), sensitive from 10 keV to 30 MeV. This omnidirectional monitor is an important instrument for γ-ray burst (GRB) science with GLAST, as it provides the link between the majority of the γ-ray busts emitting at lower energies and the high-energy events of γ-ray bursts and other transients. It will also serve as a trigger to increase the detection rate of γ-ray burst with the LAT. The GBM will provide real-time burst locations over a wide field-of-view (FoV) with sufficient accuracy to repoint the whole GLAST spacecraft. Time-resolved spectra of bursts recorded with LAT and the burst monitor will allow the investigation of the relation between the keV and the MeV–GeV emission from GRBs over seven decades in energy and will provide new insights into the physics of GRBs in general. In addition, the excellent localization of GRBs by the LAT will stimulate follow-up observations at other wavelengths which may yield clues about the nature of the burst sources.

Key words: instrumentation: detectors — gamma-rays: bursts

1 INTRODUCTION

Gamma-ray bursts are still one of the most fascinating research topics in astrophysics. Until now, since their discovery 38 years ago by the Vela satellites in 1967 (Klebesadel et al. 1973), this phenomenon is still not completely understood. The first major breakthrough in this field was obtained with the BATSE detectors on NASA's Compton Gamma-Ray Observatory (CGRO) mission. BATSE registered 2704 bursts in the ten years of the CGRO mission. This bursts showed an inhomogeneous and isotropic distribution over the entire sky (Paciesas 1999). It was the Italian/Dutch satellite BeppoSAX (Boella et al. 1997) which revealed the cosmological nature of GRBs with the identification of the first X-ray afterglow in 1997 (Costa et al. 1997) which triggered the first successful follow-up observation at optical wavelengths (van Paradijs et al. 1997). This finally ruled out the Galactic population models. The redshifts obtained to date for about 50 GRBs range from $z = 0.01$ to $z = 4.5$. Evidence from previous observational data and new measurements obtained with the Swift satellite strongly suggests that GRBs lasting longer than two seconds are associated with hypernovae and the formation of black holes (Galama et al. 1998, Stanek et al. 2003, Hjorth et al. 2003, Burrows et al. 2005). Shorter bursts are believed to originate from mergers of compact binaries.

The study of γ-ray bursts is one of the scientific objectives of the GLAST mission (Michelson 2003). This was motivated by observations of γ-ray bursts in the high-energy range above 50 MeV by EGRET onboard CGRO: The delayed emission of γ-rays more than 1 hour after the burst start time was unexpected. In

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GRB 940217 an 18 GeV γ-photon was found in this extended emission (Hurley et al. 1994). This delayed emission is in contrast to the characteristics of most of the bursts observed in the BATSE energy range, which have a maximum duration of several 100 s only.

Still an open question is, how these γ-rays are produced and how the high-energy emission is related to the low-energy emission.

Two emission processes are discussed:

– inverse-Compton scattering of photons by relativistic electrons either in external shocks (Meszaros et al. 1994) or in internal shocks (Papathanassiou & Meszaros 1996) during the prompt phase of the γ-ray burst.
– Proton-Neutron collisions with production of π^0-Mesons which decay to γ-rays of ~ 80 MeV which are boosted to GeV energies (Boettcher & Dermer 1998). Estimations show that the 1–10 GeV flux of this process should be detectable for the Large-Area Telescope for bursts which are closer than $z \approx 0.1$.

2 THE LARGE-AREA TELESCOPE OF GLAST

The GLAST spacecraft carries two instruments, a main instrument LAT (Michelson 2003), and a secondary instrument, the GBM (von Kienlin et al. 2004). The LAT uses basically the same physical process as EGRET to measure γ-rays in the energy range from ~ 10 MeV to ~ 300 GeV, the pair-production process, but employing a more advanced detection technology. Instead of using a spark chamber, silicon-strip detectors will be used to measure the tracks of the electron-positron pairs. With this technique a sensitivity which is more than 30 times better than the one of EGRET will be obtained. The LAT will also have a good energy resolution of ~ 10% and a FoV of 2–3 sr. Within this field-of-view it will be able to localize γ-ray point sources with an accuracy between 30′′ and 5′. With this improved properties, the LAT will locate and observe between 50 and 150 bursts per year.

However, the LAT alone is not an optimal burst detector since the high-energy measurements on their own do not allow a unique classification of GRBs because the break energy E_b which characterizes a burst spectrum (Band et al. 1993), is in the region 100–500 keV and this is far below the LAT energy threshold of 10 MeV. Furthermore, γ-ray bursts have their maximal luminosity around the break energy. Because of the relatively high energy threshold of the LAT, no link to the BATSE data archive would be possible where most of the information and knowledge about GRBs is concentrated.

Another disadvantage of the LAT is that a precise determination of the high-energy power-law index β is difficult with only the LAT data. Additional low-energy measurements are favourable for this purpose.

3 THE GLAST BURST MONITOR

It will be the task of the GBM to overcome the deficiencies of the LAT (in relation to γ-ray bursts) described in the section above. The purpose of the GBM is to augment GLAST's capabilities to study GRBs by extending the spectral response towards lower energies, to increase the number of bursts observed by the LAT by performing an on-board localization of the arrival direction of a GRB, and to perform time-resolved spectroscopy. These goals can be achieved by an arrangement of 12 thin NaI (Tl) detectors which are inclined to each other to derive the position of GRBs from the measured relative counting rates (BATSE principle). The position of a burst as derived by the GBM will be communicated to the LAT to allow a repointing to observe bursts which occur outside the LAT FoV thus increasing the number of observed GRBs. The NaI crystals have a diameter of 12.7 cm (5′′) and a thickness of 1.27 cm (0.5′′). Each crystal is viewed by one photomultiplier tube (PMT). The NaI crystals measure γ-rays from ∼10 keV to ~ 1 MeV.

In order to get a spectral overlap with the LAT, two BGO detectors will be mounted on two opposite sides of the GLAST spacecraft. The two BGO crystals are sensitive to γ-rays from ∼150 keV to ∼25 MeV. This energy range overlaps at the low-energy end with the energy range of the NaI detectors and on the high-energy side with the LAT. This is important for inter-instrument calibration. The two cylindrical BGO crystals have a diameter and length of 12.7 cm (5′′) and are viewed on both sides by PMTs whose signals are summed. The arrangement of the GBM detectors is shown in Figure 1.

3.1 Performance and Properties of the GBM

Over the full energy range an effective area between 100 cm^2 and 200 cm^2 per detector is achieved (see Figure 2). The energy spectrum of a burst can be measured with an energy resolution of $\sim 30\%$ FWHM at

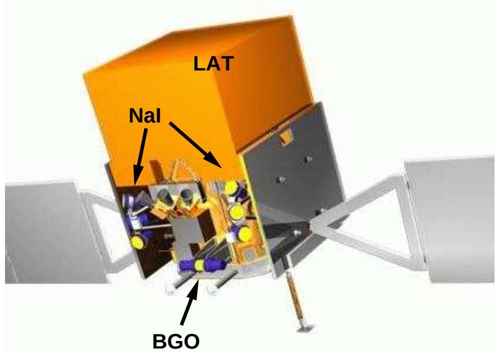

Fig. 1 A schematic view of the main body of the GLAST satellite with the detectors of the Gamma-Ray burst monitor (GBM) emphasized. The 12 NaI-detectors are mounted in 4 groups on the outside of the satellite (two groups are visible in this view). Each group is equipped with 3 NaI-detectors viewing in different directions. The two BGO-detectors are mounted on opposite sides of the satellite (one is visible in this view). *Original image from SpectrumAstro.*

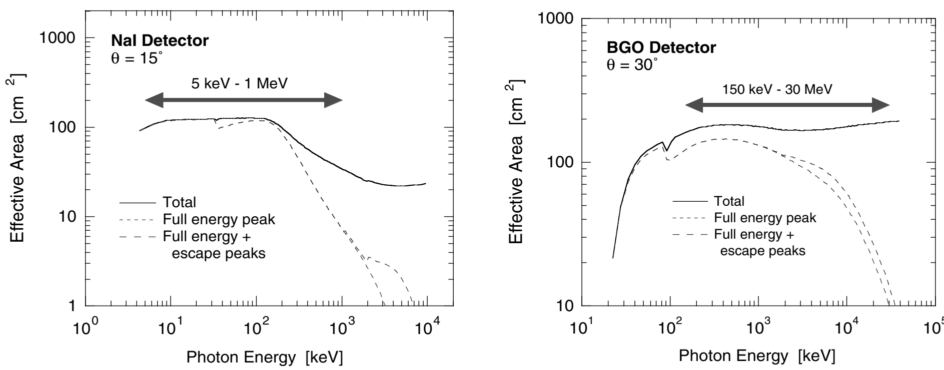

Fig. 2 The effective areas of GBM NaI (Tl) (left) and BGO (right) as a function of energy.

14 keV and $\sim$ 7% at 4.43 MeV. Based on background estimations one can expect a sensitivity better than 0.6 γ (cm^2 s) on-board. With this sensitivity the GBM will trigger on ~ 150 bursts per year. A much higher sensitivity of 0.35 γ (cm^2 s) (5 σ), however, will be reached by a detailed analysis of the data on ground.

The localization accuracy on-board for most of the bursts will be better than $15°$. Again, the ultimate location accuracy for bright bursts (limited by systematic errors) will be better than $1.5°$ after a detailed analysis on ground.

3.2 Trigger Criteria and the Interaction with the LAT

To generate a trigger, the counting rates of the GBM detectors, measured during multiple time intervals ($>$16 ms) and multiple energy ranges, will be searched for significant increases. When 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 4.5 σ;
- such counting-rate increases must be observed in at least two NaI crystals;
- the lightcurves measured in the different detectors must be similar;

- 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.

Whenever this criteria are fulfilled a trigger signal will be sent to the LAT within 5 ms. Using the highest-energy photons of the LAT, a highly accurate position ($\sim 1'$) will be computed on ground in near-real time ($\sim$ 16 min) and this position as well as the one derived by the GBM will be broadcasted to interested observers worldwide via the Gamma-ray bursts Coordinates Network (GCN).

4 SCIENTIFIC GOALS AND EXPECTED RESULTS

The characteristic features of GRBs at energies below $\sim$ 1 MeV, where in most cases the maximum of the emission lies, are known from BATSE observations. However, the information at higher energies is still sparse. Since only very few GRBs were detected by EGRET, the average high-energy power-law index β is poorly known. With the LAT and the GBM β can be measured for the first time quite accurately because of the wide range in energy covered. 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. The GLAST measurements will also allow the investigation of the evolution of the high-energy power-law index β.

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DISCUSSION

STEFANO COVINO: How rapid could the satellite point to a new target in case of a GRB or any other unexpected event?

HELMUT STEINLE: The design for a slew is for 75 degrees in 10 minutes (5 minutes is the goal) following an automated trigger. However it has to be taken into account, that the field-of-view of the LAT is very large ($>$ 2 sr) and thus most of the time only much smaller angles than 75 degrees have to be achieved.