AGILE DETECTION OF DELAYED GAMMA-RAY EMISSION FROM THE SHORT GAMMA-RAY BURST GRB 090510

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Received 2009 August 4; accepted 2009 September 11; published 2009 December 18

ABSTRACT

Short gamma-ray bursts (GRBs), typically lasting less than 2 s, are a special class of GRBs of great interest. We report the detection by the AGILE satellite of the short GRB 090510 which shows two clearly distinct emission phases: a prompt phase lasting \( \sim 200 \) ms and a second phase lasting tens of seconds. The prompt phase is relatively intense in the 0.3–10 MeV range with a spectrum characterized by a large peak \( \gamma \)-ray energy data are complemented by those of other detectors on board AGILE and Fermi: GRB 090510, the second short-GRB detected above 100 MeV. The first short-GRB was detected above a few MeV. The first short-GRB detection in the gamma-ray energy band was by Fermi: GRB 081024B (lasting about 0.8 s in the MeV range) was detected up to 3 GeV within the first 5 s after trigger (Omodei et al. 2008; Connaughton et al. 2008). We report here the AGILE detection of GRB 090510, the second short-GRB detected above 100 MeV.

The Italian AGILE satellite for gamma-ray astronomy has been operating since 2007 April (Tavani et al. 2009). The Gamma-Ray Imaging Detector (GRID; Barbiellini et al. 2002) on board AGILE covers one fifth of the sky in the 30 MeV–30 GeV energy range. This large field of view, together with a gamma-ray detection deadtime of order of \( \sim 100 \) \( \mu s \), makes it particularly suited for the observation of GRBs. The GRID high-energy data are complemented by those of other detectors on board the satellite, which operate in different energy ranges.

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most energetic explosions in our universe but only a few bursts were detected at gamma-ray energies above 100 MeV. The EGRET instrument on board the Compton Gamma Ray Observatory during its six-year lifetime detected five GRBs above 100 MeV Dingus (2001). Today, the currently operating AGILE and Fermi satellites have doubled the sample of GRBs detected at these energies (e.g., Giuliani et al. 2008; McEnery et al. 2008; Abdo et al. 2009). However, the great majority of GRBs with detected photons above 100 MeV are long bursts with typical durations above 2 s: they are possibly associated with stellar explosions of massive stars. Much less is known about the high-energy proprieties of short GRBs that show durations below 2 s. These short events are usually hard compared to the average properties of GRBs and are believed to be associated with the coalescence of neutron-star binaries (but see Zhang et al. 2009 for a more thorough discussion of the GRB classification and possible origin of the different classes). It is then very important to establish the gamma-ray properties of short GRBs. Before the advent of AGILE and Fermi no short-GRB was detected above a few MeV. The first short-GRB detection in the gamma-ray energy band was by Fermi: GRB 081024B (lasting about 0.8 s in the MeV range) was detected up to 3 GeV within the first 5 s after trigger (Omodei et al. 2008; Connaughton et al. 2008). We report here the AGILE detection of GRB 090510, the second short-GRB detected above 100 MeV.

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Key words: gamma rays: bursts
Super-AGILE provides GRB localizations, light curves, and spectra in the 18–60 keV range (Feroci et al. 2009, 2007; Del Monte et al. 2008). The Mini-Calorimeter (MCAL), besides being used as part of the GRID, can be used to autonomously detect and study GRBs in the 0.35–100 MeV range with excellent timing (Labanti et al. 2009; Marisaldi et al. 2008). Finally, GRB light curves in the hard X-ray band can be obtained also from the GRID anti coincidence scintillator panels (Perotti et al. 2006).

2. GRB 090510

The GRB 090510 was discovered and precisely localized by the Swift satellite (Gehrels et al. 2004) with coordinates (J2000) R.A. = 22h14m12.47, decl. = −26°35’00”/4 (Hoversten et al. 2009). This burst was quite bright, with peak flux ∼10 ph cm⁻² s⁻¹ in the energy band 15–150 keV Ukwatta et al. (2009), and was independently detected also by Konus-Wind Golenetskii et al. (2009), Suzaku-W AM Ohmori et al. (2009), and Fermi-GBM Guiriec et al. (2009). The main emission lasts about 0.2 s with a multi-peak structure. Follow-up observations of the optical transient of GRB 090510 led to the determination of the redshift \( z \sim 0.903 \pm 0.003 \) (Rau et al. 2009).

This GRB occurred at the border of the standard AGILE-GRID field of view, at an off-axis angle of 61°. At this large off-axis angle, the AGILE-GRID effective area is \( \sim 100 \) cm² for photon energies above 25 MeV. A quick look analysis of the GRID data showed an excess of photons above 30 MeV, while no detections up to few MeV. A quick look analysis of the AGILE data showed an excess of photons above 25 MeV. A quick look analysis of the GRID data showed an excess of photons above 30 MeV, while no detections up to few MeV.

3. AGILE TIMING AND SPECTRAL DATA

In the following, we refer all the times to \( T_0 \) corresponding to 00:23:00.5 UT of 2009 May 10. This corresponds to the time of the sharp initial increase of the GRB light curve in the MCAL detector. Based on the properties of the 0.3–10 MeV and \( \geq 25 \) MeV emissions of GRB 090510 showing a clear dichotomy between the low- and high-energy gamma-ray emissions, we define two time intervals, Interval I from \( T_0 \) to \( T_0 + 0.20 \) s and Interval II from \( T_0 + 0.20 \) s to \( T_0 + 1.20 \) s (see Figure 2).

3.1. The Prompt Phase (Interval I)

The light curves of GRB 090510 obtained with the AGILE-MCAL in the 0.3–10 MeV are shown in Figure 1. As seen by MCAL, the burst has a duration (T90) of 184 ± 6 ms. During the T90 time interval MCAL recorded from the source more than 1000 counts above 330 keV, with an expected background of 60 counts over the same time interval. The peak flux of 18,000 counts s⁻¹ in a 1 ms time bin was reached at time \( T_0 + 0.024 \) s. To date, this is the brightest short burst detected by MCAL in the GRID field of view. In the T90 time interval the observed emission can be divided into three main pulses, each of them showing millisecond time variability. At \( T_0 - 0.55 \) s a soft precursor lasting 15 ms is detected up to 700 keV, while at \( T_0 + 0.29 \) s another 15 ms peak is evident, with significant detection up to few MeV.

Most of the soft-gamma emission (\( E \leq 10 \) MeV) is concentrated in Interval I (between \( T_0 \) and \( T_0 + 0.20 \)), where no high-energy (\( E \geq 25 \) MeV) photons were detected. We derive the flux spectrum for the Interval I using the MCAL data. We find that the averaged MCAL spectrum is well described by a power-law model with exponential cutoff (reduced \( \chi^2 \) of 0.8 for 23 dof). The photon index is \( \alpha_1 = 0.65 \pm 0.32 + 0.28 \) and the exponential cutoff energy is \( E_c = 2.8 \pm 0.6, \pm 0.9 \) MeV. The integrated fluence (500 keV \( \leq E \leq 10 \) MeV) during this interval is \( F = 1.82 \pm (0.41, \pm 0.09) \times 10^{-7} \) erg cm⁻², all the errors for MCAL results reported throughout this paper are at the 90% confidence level. The GRID upper limit (at 3\( \sigma \) c.l.) is consistent with the extrapolation of this spectrum. The top panel of Figure 4 shows the Interval I spectrum. We also notice a substantial soft-to-hard spectral evolution during Interval I. If we define a hardness ratio as \( HR = (counts \ above \ 1 \ MeV)/(counts \ below \ 1 \ MeV) \), we obtain \( HR \sim 0.6 \pm 0.1 \) during the first peak (between \( T_0 \) and \( T_0 + 0.12 \)) and \( HR \sim 0.9 \pm 0.1 \) during the second phase of Interval I (between \( T_0 + 0.12 \) and \( T_0 + 0.20 \)).

A remarkable absence of gamma-ray events during Interval I is evident. In fact the first GRID events are detected only at the...
end of the prompt emission. Note that a backward extrapolation to $t = T_0 + 0.01$ s of the GRID power-law light curve of Figure 3, discussed in the next section, would predict 28 photons in Interval I, while none was observed.

3.2. The Delayed Emission Phase: Interval II and Tail

The phase immediately following the sharp decay of the MeV flux at the end of Interval I shows a significant tail of MeV emission and the presence of a strong gamma-ray component above 30 MeV. We consider here the Interval II and a following tail of emission (lasting up to $T_0 + 10$ s).

During Interval II and tail, MCAL continues to detect significant emission in the 500 keV–10 MeV energy range with a spectrum significantly different from that of Interval I. Indeed, the derived power-law distribution has now photon index $\alpha_2 = -1.58(-0.11, +0.13)$. Significant emission is detected in the MCAL highest energy channels with no sign of cutoff. The Interval II fluence in the energy range 0.5–10 MeV range is $F_2 = 3.1(-0.7, +0.6) \times 10^{-6}$ erg cm$^{-2}$.

To search for emission above 30 MeV, we selected GRID gamma-ray events within 15$^\circ$ of the burst position. For this analysis we used all the GRID events with reliable direction and energy reconstructions, resulting in 15 events in the time interval from $T_0$ to $T_0 + 10$ s. The expected number of background events in this time interval is 1.4, implying that the GRB is detected above 30 MeV with a $\geq 5\sigma$ statistical significance.

The energy and arrival times of the GRID events are compared with the MCAL light curve in Figure 2. The GRB high-energy emission lasts for a few tens of seconds after the end of Interval I. The time evolution of the gamma-ray emission from GRB 090510 can be remarkably well described by a power-law decay, as shown in Figure 3(top panel). We model it with a function given by

$$F(t) \propto t^{-3} \quad \text{for} \quad t \geq T_0 + T_1$$

(1)

and $F(t) = 0$ for $t \leq T_0 + T_1$ and find that $T_1 = 0.2$ s, and $\delta = 1.30 \pm 0.15$ give the highest probability to reproduce the observed times of arrival. The corresponding power law is plotted in the Figure 3 (top panel). The background flux measured in the 1000 s before trigger is also shown in figure by the dashed horizontal line.

The energy distribution of the GRID photons during the time interval $T_0$ to $T_0 + 10$ s is consistent with a power-law spectrum of photon index $\alpha_3 = 1.4 \pm 0.4$ ($1\sigma$ c.l.). For this spectrum the 25 MeV–500 MeV fluence in the same time interval is $(1.51 \pm 0.39) \times 10^{-1}$ ph cm$^{-2}$, corresponding to $F_3 = (2.90 \pm 0.75) \times 10^{-5}$ erg cm$^{-2}$.

To compute the GRID flux in Interval II, we assumed the same spectrum measured in the long “tail” between $T_0$ and $T_0 + 10$ (photon index $-1.45 \pm 0.07$), and extrapolated the light curve with the best fit power-law decay. This gives $F'_2 = 2.12 \times 10^{-5}$ erg cm$^{-2}$ (25 MeV $\leq E \leq 500$ MeV).

The MCAL + GRID spectrum of Interval II is shown in the bottom panel of Figure 4.
1. The broadband emission of GRB 090510 shows very distinct radiation phases during Interval I and the following delayed emission phase. Prompt gamma-rays above 30 MeV are absent during Interval I, but they constitute a crucial component during Interval II and the following tail. Remarkably, this is the first case of a delayed rise of the gamma-ray emission above 25 MeV detected in a short GRB. A similar behavior was shown by the long GRB 080916C Abdo et al. (2009). This fact suggests that the same process responsible for high-energy gamma-ray production takes place, in both long and short GRBs, independently from the central engine.

2. The prompt phase (Interval I) spectrum is peaked at $E_p = 3.78$ MeV. Comparing with other short GRBs (see Ghirlanda et al. 2009) we find that the $E_p$ for GRB 090510 is the highest peak energy ever recorded for a short GRB (about 2.4σ greater than the mean value for short GRBs). Also the rest-frame peak energy ($E_{p}^{\text{rest}} = 7.19(-1.54, +2.31)$ MeV) for GRB 090510 is greater than the $E_{p}^{\text{rest}}$ for the other short GRBs with known redshift. The large value of $E_{p}^{\text{rest}}$, combined with a quite usual value of the isotropic (comoving) energetics ($E_{\text{iso,1}} = 3.91(-0.88, +1.91) \times 10^{52}$ erg in the whole energy range) and peak luminosity ($L_{\text{iso,1}} = 7.74(-1.74, +3.79) \times 10^{53}$ erg s$^{-1}$), implies that GRB 090510 does not follow either the $E_{\text{iso}} - E_{\text{iso}}$ Amati relation (Amati et al. 2002) or the $E_{p}^{\text{iso}} - L_{\text{iso}}$ Yonetoku relation (Yonetoku et al. 2004). To our knowledge, this is the first short GRB that does not follow the Yonetoku relation. No significant emission is detected above 10 MeV, implying a rather strong constraint on any possible power-law emission above $E_c$ ($\beta < -3.2$ at the 90% confidence level).

3. The prompt phase shows a significant soft-to-hard spectral evolution. As can be inferred from Figure 1 and from the MCAL and GRID contributions to the emission, we obtain for the delayed phase $E_{\text{iso,2}} = 4.8 \times 10^{52}$ erg.

4. Gamma-ray emission above 25 MeV extends in time for tens of seconds, i.e., well beyond the prompt phase duration, and shows a temporal behavior consistent with a power law of index $\delta = 1.30 \pm 0.15$.

5. The total isotropic energy of Interval II and tail is larger than that of Interval I: by summing the MCAL and GRID contributions to the emission, we obtain for the delayed phase $E_{\text{iso,2}} = 4.8 \times 10^{52}$ erg.

6. The temporal index $\delta = 1.3$ is substantially different from that ($\delta' = 0.75$) subsequently measured by Swift-XRT between 80 and 1400 sec after trigger Grupe et al. (2009). This last phase can be attributed to an afterglow with spectral and temporal characteristics in agreement with expectations of fireball models (Zhang et al. 2006).

High-energy emission from GRB 090510 can have different physical origins at different phases. It is possible to evaluate a lower limit for the Lorentz factor of the emitting regions in Intervals I and II, on the basis of their spectral features and time-scale variability (Lithwich et al. 2001).

During Interval I the energy of the highest bin of the spectrum with significative detection is $E_{\text{max}} = 20$ MeV. A physical scenario with the minimum Lorentz factor compatible with the data corresponds to a shell, optically thick for photons of energy greater than $m_e c^2$ (in the shell rest frame), moving with $\Gamma_r > (1 + z) E_{\text{max}} / m_e c^2 \approx 80$. Otherwise, assuming that the emitting region is optically thin also for photons with energy greater than $m_e c^2$, a larger Lorentz factor is needed ($\Gamma_r > 150$) due to the fast variability during this phase, according to Equation (5) in Lithwich et al. (2001).

Emission during Interval II and following tail appears to be of a very different nature, and is clearly non-thermal. Several mechanisms can be at work, depending on the external environment and radiative conditions. Both synchrotron and inverse Compton (IC) emitting regions characterized by impulsively energized particles can be important contributors. The ultimate origin of fast and efficient acceleration is believed to be hydrodynamical shocks produced by expanding matter ejecta. Internal (IS) and external (ES) shocks can in principle contribute to both the synchrotron and IC emissions, and several models have been recently proposed to address the issue of the prompt versus the so-called delayed high-energy emission from GRBs. During Interval II the larger photon energy detected is $E_{\text{max}} = 350$ MeV. The minimum Lorentz factor compatible with $E_{\text{max}}$ is $\Gamma_{\text{II}} > 200$.

We postpone an investigation of these issues to forthcoming publications.

The AGILE Mission is funded by the Italian Space Agency (ASI) with scientific and programmatic participation by the Italian Institute of Astrophysics (INAF) and the Italian Institute of Nuclear Physics (INFN).
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