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Search for delayed GRB emission with INTEGRAL

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Since its launch in October 2002, INTEGRAL has detected and localized 66 γ–ray bursts (GRBs). The ISGRI detector layer of the IBIS instrument is sensitive in the 15 keV to 1 MeV energy range and can be used to investigate any observable late post-burst emission in this energy range. Such emission may be produced by the relativistic GRB outflow interacting with the radiation from a potential stellar companion or by late central engine activity. An extended search for the signature of the late emission was performed at times 1 hour, 5 hours and 10 hours after the prompt burst emission and also over the maximum available integration time. For this study we selected 3 of the brightest bursts (in terms of peak flux) and 3 of the longest GRBs that have late time observations available. The upper limits obtained in this analysis are used to constrain the post-burst emission models.

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1. Introduction

The standard paradigm links the origin of the long GRBs with collapsars while short GRBs may have neutron star mergers as progenitors [1]. However, there are also several GRB models, discussed later hereafter, which may be valid for a subclass of the long GRBs predicting the existence of delayed emission at energies traditionally associated with the prompt emssion, aside from the regular X-ray, optical, infra-red and radio afterglow [2], [3], [4], [5]. However, in some bursts the division between the prompt emission and the X-ray afterglow may not be clear e.g. in the case of GRB 060714 [6]. Delayed high-energy emssion > 100 MeV has been observed from a number of GRBs with the Fermi LAT [7], [8], [9], [10] and CGRO EGRET [11]. There also exists an earlier positive search for signal above background up to ~ 200 s after CGRO BATSE bursts when the lightcurves of 400 long GRBs were summed. The sensitivity of that technique was estimated to be a few times 10^{-9} ergs cm^{-2}s^{-1} [12].

An extended search for the signature of such late emission from INTEGRAL GRBs is presented here in the context of the decaying magnetar and nearby binary interaction models.

1.1 Decaying magnetar outflow interacting with post-explosion photons

A continually decreasing post-burst relativistic outflow, such as that emitted by a decaying magnetar [13], [14], [15], [16], may last for periods of days or longer after the burst, and can be efficiently re-processed by the ambient soft photon field radiation. Photons produced either by the post-explosion expansion of the progenitor stellar envelope or by a binary companion provide targets for the relativistic outflow to interact with and produce high-energy X-rays or γ–rays [17].

The estimated flux integrated over the exposure time of ~ 1 day can reach values of $\sim 5\times10^{-5}$ph cm^{-2}s^{-1} (6×10^{-9}ergs cm^{-2}s^{-1}) in the 20 – 500 keV energy range in the case of a millisecond magnetar-like source interacting with the scattered γ–rays from a peculiar Ib/c SNR of greater than usual brightness or a high-luminosity stellar companion (i.e. $> 10M_\odot$) at redshift ~ 0.5. The magnetic field of the magnetar is believed to be $\sim 10^{14}$ G and therefore the derived γ–ray luminosity is $\sim 10^{47}$erg s^{-1} [17].

1.2 Close binary progenitors of long γ–ray bursts

The strong dependence of the neutrino annihilation mechanism on the mass accretion rate along with the Swift observations of the shallow decay phase and late X-ray flares, assuming they indicate activity of the central engine, make it difficult to explain the very long GRBs with durations in excess of 100 seconds in the collapsar model [18], [19]. These long GRBs might also provide indirect evidence for an electromagnetic origin of the jets with the magnetic stresses caused by the rotation focusing and accelerating the jet's flow.

A particularly interesting version of the binary progenitor model involves the merger of a Wolf-Rayet star with an ultra-compact companion, e.g. a neutron star or a black hole, allowing a long-lived accretion disk to be formed. The relevant accretion time in these binary systems can be $t_{\rm acc} \sim 1$ day [19] and the emission can be seen in the energy range of hard X-rays overlapping the INTEGRAL IBIS energy range. These events are assumed to appear at very high redshifts $z \gtrsim 10$. The expected total flux density is relatively low, 10^{-7}erg cm^{-2}s^{-1}, but not prohibitive, if standard compact object properties are used (stellar mass of $M \approx 10^3 M_\odot$, radius of $R \approx 10^{12}$cm, and rotation $\sim 50\%$.

2. Method

The IBIS/ISGRI instrument on-board INTEGRAL operates in the 15 keV – 1 MeV energy range [20] and has 16384 CdTe detectors, located 3.4 m from a tungsten mask which projects a shadowgram onto the detector plane. Maps of the sky are reconstructed by decoding the shadowgram with the mask pattern. Since the upper tail of the operational energy region works in Compton scattering mode, the best sensitivity is achieved between 20 and 400 keV in photoelectric mode.

The possible late emission described in the theoretical models falls well within the IBIS energy range. To detect or constrain the late emission the following procedure was adopted:

1. We created a database of all INTEGRAL bursts. The INTEGRAL satellite observed 66 GRBs to the end of September 2009. The properties of most of them have been analyzed and catalogued [21], [22].
2. For each burst we checked the availability of late time observations of the same location +1 hour, +5 hours and +10 hours after the prompt emission, reducing the sample size by approximately one half.
3. We then selected the 3 brightest GRBs in terms of peak flux and the 3 longest GRBs in terms of T_{90}. We note that all of the selected GRBs, with the exception of GRB 060912B, have a reported X-ray afterglow and belong to the long GRB classification. The brightest INTEGRAL burst, GRB 041219A [24], that has been used for polarisation measurements [25], had no late time observations available.
4. The standard analysis was performed to obtain the GRB image, position, spectrum and lightcurve for each of the 6 bursts.
5. These 6 selected GRB late post-emission candidates were searched for a signal above background in the image, spectrum and lightcurve assuming that the source position is the same as the original GRB. Three energy bands: 20 – 50 keV, 50 – 400 keV and range 20 – 400 keV were examined.

3. Results

No source was detected by the automatic sextractor routine in the latest offline software analysis package *OSA 8.0* [26] down to a signal to noise ratio of 1.5 at the position of the GRB after the burst event. No significant signal above the background level was detected in the post-burst lightcurves extended to late times.

Beyond the standard analysis, in each image we used a window of 5×5 pixels centered on the source position and compared it to the average background level obtained in five windows around the source where no other source was detected. The results would be promising if the source position showed higher flux than the background. The results are summarized in Table 1.

The flux upper limits (shown in Figure 1) were calculated by analyzing the spectra without automatic background subtraction. The obtained flux at the position of a GRB was compared to the flux from 5 nearby "empty" positions where no other source detected and no deviation was found. The average background level was assumed to correspond to 1σ significance level, the search was performed in two regimes, for sources $> 3\sigma$ and for $> 1.5\sigma$. The fluxes in the units of ergs $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are estimated for a general GRB Band spectrum ($E_p = 200$ keV, $\alpha = -0.5$, $\beta = -2.5$) [23].

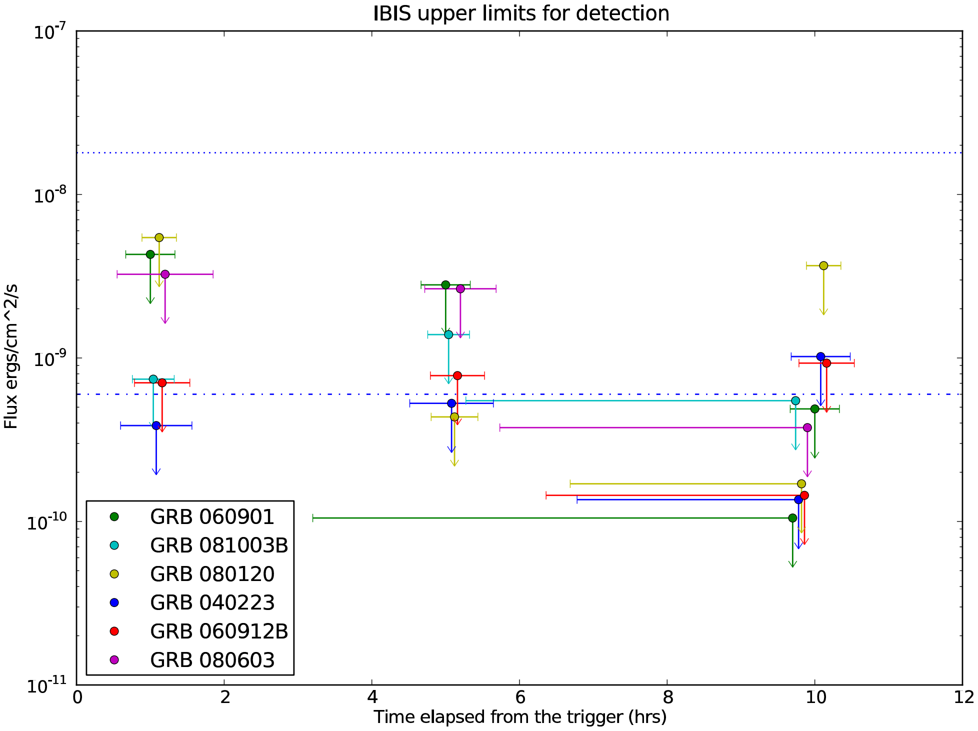

Figure 1: The IBIS detection limits placed on post-burst late emission obtained from the science windows 1 hour, 5 hours and 10 hours after the burst and from the mosaic made from all available observations up to 10 hours after the trigger. The length of the x-axis error bar represents the length of the exposure time. Flux limits based on the two discussed theoretical models are considered for the expected values of model-dependent parameters. The dashed-dotted horizontal line shows the flux of the sources based on the theoretical predictions of the decaying magnetar model with an associated magnetic field $\sim 10^{14}$ G and laying in the distance of $z = 0.5$. The data were integrated over the energy range from 20 to 400 keV. The dotted horizontal line shows the flux limit of the sources bases on the super-long GRBs expected at distance of $z \gtrsim 10$.

4. Conclusions

None of the reconstructed images for the 6 GRB late post-burst emission candidates showed a reliable detection up to 10 hours after the burst. There may be different reasons for these non-detections:

GRB	T_{90}	+1 hr				+5 hrs				+10 hrs				mosaic			
040223	258	x	x	x	58	x	x	x	68	x	x	x	48	x	x	x	180
060912B	200	x	x	x	45	x	x	x	44	x	x	x	45	x	x	x	210
080603	150	x	x	x	78	x	x	x	58	n/a	n/a	n/a	n/a	x	x	x	250
GRB	F_{peak}	+1 hr				+5 hrs				+10 hrs				mosaic			
060901	6.5	x	x	x	40	x	x	x	40	x	x	x	40	x	x	x	390
081003B	3.1	x	x	x	34	x	x	x	34	n/a	n/a	n/a	28	x	x	x	268
080120	3.0	x	x	x	28	x	x	x	28	x	x	x	28	x	x	x	118

Table 1: Three longest and three brightest INTEGRAL GRBs with the science windows available at $(T_0 + 1\ \text{hr})$, $(T_0 + 5\ \text{hrs})$ and $(T_0 + 10\ \text{hrs})$ after the prompt emission T_0. The mosaic column contains the sum of the images from all available science windows from time $(T_0 + 1\ \text{hr})$ up to $(T_0 + 10\ \text{hrs})$ after the burst. Each of the first three sub-columns for each time represents energy ranges 20–50 keV, 50–200 keV and 50–400 keV. The fourth sub-column gives the total exposure time in minutes, since science windows can be of unequal length and some science windows may be missing or excluded due to pointing. T_{90} is in seconds. Peak flux is in photons $\text{cm}^{-2}\text{s}^{-1}$. "x" stands for no detection and "n/a" is shown if the data were not available.

- The selected long GRBs 040223, 060912 and 080603 lasting from 150 to 258 s may not belong to the group of long GRBs predicted by the close-binary progenitor model. Alternatively, if the sub-category of very long GRBs exists it does not include all long bursts automatically. The lack of detection cannot exclude the models, however, it can place constraints on the parameter values of the models. The change of the model-related parameters can vary the predicted peak flux. The detailed study of the exact dependance of the peak flux is beyond the scope of this contribution and can be found in original model descriptions [19], or [17]. The emission might be present even for the default parameter setting but is too weak to be significantly detected within the available exposure time or the emission peak lies outside the IBIS energy window or the source lies further than $z \sim 0.5$, or the radiation mechanism is not as effective as expected in the case of the decaying magnetar model. A longer duration post-burst observation would help to further constrain the models.

- The post-GRB late emission candidates were not chosen wisely. It may be that the late X-ray or γ–ray activity is not proportional either to the peak flux of the prompt emission or to the duration of the burst and these GRB prompt emission properties have only minor or no effect on the classification of a GRB as a long super-collapsar or decaying magnetar. The search for delayed emission from other INTEGRAL bursts will be carried out to address this issue.

Additionally to this study, a few seconds delayed, very high energy emission reported by Fermi in some GRBs favors the idea that the delayed emission happens rather due to the external shock than long-lived central engine activity. This may point to the fact that significant emission could be detectable outside the IBIS energy region, which effectively covers only the range from 20 to 200 keV. Therefore, the contributions from several scientific missions and the joint observations over a much wider energy range, in combination with further analysis of other GRBs from the INTEGRAL catalogue, would be useful for further testing the models. Also any identification of a nearby GRB suspected of long lasting prompt emission activity might be relevant for further studies with gravitational wave detectors [28].

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