GRB 110731A within the IGC paradigm

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Abstract. Bright gamma-ray burst (GRB) 110731A was simultaneously observed by *Fermi* and *Swift* observatories, with a follow up optical observation which inferred the redshift of $z = 2.83$. Thus, available data are spanning from optical to high energy (GeV) emission. We analyze these data within the induced gravitational collapse (IGC) paradigm, recently introduced to explain temporal coincidence of some long GRBs with type Ic supernovae. The case of binary-driven hypernova (BdHN) assumes a close system, which starts as an evolved core - neutron star binary. After the core-collapse event, the new NS - black hole system is formed, emitting the GRB in the process. We performed the time-resolved and time-integrated analysis of the *Fermi* data. Preliminary results gave isotropic energy $E_{\text{iso}} = 6.05 \times 10^{53}$ erg and the total P-GRB energy of $E_{\text{P-GRB}} = 3.7 \times 10^{52}$ erg. At transparency point we found a Lorentz factor $\Gamma \sim 2.17 \times 10^3$, laboratory radius of 8.33×10^{13} cm, P-GRB observed temperature of 168 keV and a baryon load $B = 4.35 \times 10^{-4}$. Simulated light-curve and prompt emission spectra showed the average circum burst medium density to be $n \sim 0.03$ particles per cm^3 . We reproduced the X-ray light-curve within the rest-frame of the source, finding the common late power-law behavior, with $\alpha = -1.22$. Considering these results, we interpret GRB 110731A as a member of a BdHNe group.

1 Introduction

Gamma-ray bursts (GRBs) are known to be the most luminous events in the universe. The data provided by CGRO/BATSE observations showed that the T_{90} distribution of the observed bursts is bimodal in structure [1]. Since then, GRBs are traditionally divided into long/soft and short/hard bursts with the separation of about 2 seconds in the observed frame [2]. This division came prior to the redshift measurements. Once X-ray observations provided more accurate positions, optical telescopes could determine the distance at which the GRBs occurred, confirming their cosmological origin. Thanks to their extreme brightness, GRBs are detectable up to redshift $z \approx 9$ (see, e.g., [3]). With redshifts available, correlations between burst observables could facilitate the use of GRBs as standard candles, constraining the expansion history of the universe. The separation in long and short GRBs was still present when one inquired into their rest-frame properties. For example, the $E_{\text{iso}} - E_p$ dependence for long bursts follows Amati relation [4, 5], where E_{iso} is the burst isotropic energy and E_p is the rest-frame peak energy in the $\nu F(\nu)$

spectrum. The short GRBs on the other hand follow a different relation (see, e.g., [6–8]). Therefore, it is generally accepted that long and short GRBs have different progenitors, where the first are the result of a gravitational collapse event (see [9, 10]) while the latter originate from compact mergers [11, 12]. However, there are still doubts regarding the dominant mechanism of long GRBs.

Connection between some long GRBs and type Ib/c supernovae (SNe) has been known since GRB 980425/SN 1998bw observations [13]. The induced gravitational collapse (IGC) paradigm has been introduced in the past years to explain this temporal coincidence in the case of binary-driven hypernovae (BdHNe): long, extremely energetic bursts ($E_{\text{iso}} > 10^{52}$ erg) with high rest-frame peak energies ($E_p > 200$ keV) up to some MeV. The model invokes a close binary system consisting of a neutron star (NS) and a carbon-oxygen (CO) core close to a core-collapse event (see, e.g., [14–16]). A well-determined time sequence is implied, where each stage is expected to have distinctive observational properties:

Hypercritical accretion. After the CO core SN explosion, the companion NS gains mass via hypercritical accretion of the ejected material. Spectrum is described with an expanding thermal component ($\sim 10^{9-10}$ cm) plus an ex-

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tra power-law (PL). The black body (BB) temperature decreases with time following a broken PL [17].

BH formation and the P-GRB. The companion NS reaches critical mass and collapses into a BH. This leads to a formation of an optically thick e^+e^- plasma – the *fireshell* of total energy E^{tot} [18, 19]. The fireshell expands and self-accelerates due to the e^+e^- annihilation up to ultra-relativistic velocities, until the transparency condition has been reached. The dynamics of the fireshell up to this point are fully described with E^{tot} and the baryon load $B = M_{\text{BC}}^2/E^{\text{tot}}$, where M_{B} is the mass of the baryons engulfed by the plasma. In the case of long GRBs, it is characterized by $10^{-4} \lesssim B < 10^{-2}$. The proper-GRB (P-GRB) is then emitted, with a spectrum defined by the geometry of the pair-creation region. PL with an exponential cutoff is expected in the case of axial symmetry. After the transparency has been achieved, evidence of a BH formation is seen in form of high energy photons (up to few GeV). The BdHN scenario invokes the BH formation. X-ray flashes (XRFs) are less energetic sub-class of long GRBs, where the NS only gains mass, and there is no BH formation.

Canonical GRB emission. After the transparency emission, the optically thin shell of baryons collides with a circum burst medium (CBM) of density n_{CBM} , giving rise to the prompt emission. The CBM is modeled by the filling factor, which takes into account filamentary structures of the medium, $R = A_{\text{eff}}/A_{\text{vis}}$. Here, A_{eff} is the area covered by the CBM clouds while A_{vis} is the total observable area [8, 15]. The prompt emission occurs at $\sim 10^{15-17}$ cm [17].

X-ray afterglow. Rest-frame X-ray light-curves show precise behavior consisting of three PL segments: starting at the endpoint of the prompt emission, followed by a plateau phase, and ending by a late constant PL decay [20, 21]. While plateau shrinks as a function of the increasing E_{iso} , the late PL decay is common to all sources after $\approx 10^4$ s in the rest-frame, with typical slopes of $-1.7 \lesssim a_x \lesssim -1.3$ [22, 23]. In the case of XRFs, light-curves are less energetic and more chaotic, not exhibiting these properties. The emitting region inferred for some BdHNe sources suggested that the origin of the X-ray emission has the initial size of $\sim 10^{12}$, meaning that the place of origin is SN ejecta, not the GRB.

SN remnant detection in optical. Optical SN emission due to the ^{56}Ni decay is expected after $\sim 10 - 15$ days in the source rest-frame, and it is currently detectable only up to $z \lesssim 1$. In the end, system that began as a CO core - NS binary now consists of a newly born NS (ν -NS) and a BH.

In this work we shortly summarize relevant observations of the energetic GRB 110731A. We use these data to search for the BdHN scenario signatures described above. We perform time-integrated and time-resolved spectral analysis and study the results within the IGC model. From this we derive the baryon load, Lorentz factor at transparency point and P-GRB energy. We proceed to simulate the light-curve and spectra to obtain the average densities of CBM.

2 Analysis of *Fermi*/GBM data

Gamma-Ray Burst Monitor (GBM, [24]) onboard *Fermi* observatory was specially designed for GRB studies. Having 12 sodium iodide (NaI) detectors (8 keV–1 MeV) and 2 bismuth germanate detectors (250 keV–40 MeV), it covers the energy range of 8 keV – 40 MeV. Large Area Telescope (LAT, [25]) is the second instrument onboard *Fermi*, able to detect photons with energies up to more than 300 GeV. GRB 110731A triggered the GBM [26] at 11:09:29.94 (UT) on 2011 July 31 (T_0). The GRB was already in the LAT field of view ($\approx 3^\circ$), so both instruments observed the burst from early on. Using LAT data burst was preliminarily localized at (R.A., J2000) = $-280^\circ.39$, (decl., J2000) = $-28^\circ.53$. We downloaded the time-tagged event (TTE) data of the triggering detectors NaI-n0 & NaI-n3, and of the corresponding BGO-b0 detector, from the NASA *Fermi* Web site¹. Software package RMFIT² was used to perform the time-integrated and time-resolved spectral analysis of the TTE data. Data preparation included subtracting the background by fitting it to a low order polynomial and excluding the overflow channels. We reproduced the LAT and GBM (background subtracted) light-curves in various energy bands (see figure 1) using the TTE data (GBM) and 'P8R2_TRANSIENT020'-class events (LAT). The light-curve, starting around $T_0 - 0.4$ s can be described as a complex single-peak structure lasting up to ≈ 10 s, with a sudden decrease after ≈ 7.3 s.

Figure 1. LAT and GBM (NaI & BGO, background subtracted) light-curves of GRB 110731A. Top two panels show NaI-n0 (8–260 keV, top panel) and BGO-b0 (0.26–40 MeV, middle panel) data with 0.2 s binning. The vertical dashed line at $T_0 \sim 2.4$ s indicates the onset of high energy emission observed by LAT (bottom panel, 0.5 s binning).

We performed a time-integrated analysis using the GBM energy range (8 keV – 40 MeV) and approximate GBM- T_{90} interval [0.19 s, 7.9 s]. Three different empirical models were tested: a simple power-law (PL), a

¹ <ftp://legacy.gsfc.nasa.gov/fermi/data/gbm/bursts/>

² fermi.gsfc.nasa.gov/ssc/data/analysis

Table 1. Best-fit parameters of models used for the time-integrated ([0.19 s, 7.9 s]) spectral analysis. The reference energy is fixed to 100 keV. The energy flux is evaluated for the 10–1000 keV range.

Model	E_p (keV)	α	β	Γ_{PL}	F (erg cm ⁻² s ⁻¹)	C-STAT/DOF
PL	-	-	-	-1.51 ± 0.01	$(2.600 \pm 0.026) \times 10^{-6}$	1921.9/362
Compt	344.5 ± 12.8	-0.86 ± 0.03	-	-	$(2.815 \pm 0.045) \times 10^{-6}$	618.4/361
BAND	324.1 ± 17.3	-0.85 ± 0.03	-2.50 ± 0.15	-	$(2.803 \pm 0.040) \times 10^{-6}$	612.9/360

power-law with the exponential cutoff (Compton) and the Band function [27]. The goodness of the fit was measured using C-statistic [28], requiring an improvement by $\Delta C\text{-stat}=9$ for every degree of freedom (DOF). Compton-fit showed a significant improvement over the power-law fit. Band function, having one parameter more, improved the fit by $\Delta C\text{-stat}\approx 6$. The Compton was therefore considered the best-fit model with parameter values of $E_p = 344.5(\pm 12.8)$ keV and $\alpha = -0.86(\pm 0.03)$ (see table 1). In order to calculate the isotropic energy E_{iso} , we fitted the Band function using the entire observed emission interval [-0.38 s, 10.56 s]. This avoids flux underestimation due to the Compton model and detector sensitivity (see, e.g., [29]). The best-fit parameters were: $\alpha = -0.91^{+0.03}_{-0.03}$, $\beta = 2.19^{+0.07}_{-0.09}$, with $E_p = 319.4^{+18.9}_{-16.8}$ keV. E_{iso} was obtained using

$$E_{\text{iso}} = \frac{4\pi d_1^2}{(1+z)} S_{\text{bol}}, \quad (1)$$

where d_1^2 is the luminosity distance, z is the redshift and S_{bol} is the bolometric fluence in the $1/(1+z)$ keV to $10^4/(1+z)$ keV frame:

$$S_{\text{bol}} = S_{\text{obs}} \frac{\int_{1/(1+z)}^{10^4/(1+z)} E\phi(E)dE}{\int_{E_{\text{min}}}^{E_{\text{max}}} E\phi(E)dE}. \quad (2)$$

Here, ϕ is the Band model obtained from the spectral fit and $S_{\text{obs}} = \Delta t F_{\text{obs}}$, where F_{obs} is the mean energy flux in the $(E_{\text{min}}, E_{\text{max}})$ detection band and Δt is the time interval of the spectral fit. We find the value of $E_{\text{iso}} = 6.05(\pm 0.09) \times 10^{53}$ erg.

We proceed to the time-resolved spectral analysis and P-GRB identification. P-GRB is expected in the form of the first flash of thermal radiation, once the e^+e^- plasma reaches transparency point. This takes place before the evidence of the BH formation, and thus, before the high energy emission (~ 2.4 s). Expected spectra is thermal (spherically symmetric case) or Compton, produced by a convolution of many instantaneous co-moving spectra with different temperatures (axially symmetric case). Therefore, in order to identify the P-GRB, we selected the times before the high energy emission using a time binning criteria of $S/N = 15$, and fitted six different models to each bin: power-law, Compton, Band and the same three empirical models with added black body (BB) component. We adopted the same criteria of $\Delta C\text{-stat}=9$ for every degree of freedom. For every time bin Compton was showed to be the best-fit model (similar as [30], see table 2).

The effective temperature was calculated using $kT = E_p/3.92$, or $kT^{\text{RF}} = E_p(1+z)/3.92$ for the rest-frame

value. We identified the P-GRB as the emission up to $T_0 + 0.68$ s, at which point the temperature starts to drop (see figure 2). This coincides with the light-curve maximum. The Compton-fit parameters of this interval are: $E_p = 171.9(\pm 17.1)$ keV, $\alpha = -1.08(\pm 0.08)$ and $A = 0.0631(\pm 0.0077)$ p/s cm² keV, where A is the amplitude. They were used to obtain the P-GRB energy $E_{\text{P-GRB}} = 3.7 \times 10^{52}$ erg and the rest-frame temperature $kT^{\text{RF}} = 167.9$ keV.

Figure 2. Temporal evolution of the E_p spectral parameter within the Compton model. Bars represent $\pm 1\sigma$ error intervals. Time is given in the observer frame with the binning criteria of $S/N=15$.

2.1 Light-curve and spectra simulation

The obtained energy values for E_{iso} and $E_{\text{P-GRB}}$ served as an input in our numerical code. Calculated value of the baryon load was $B = 4.35 \times 10^{-4}$. At the transparency point, the laboratory radius was 8.33×10^{13} cm and the P-GRB observed temperature 168 keV, with Lorentz factor $\Gamma \sim 2.17 \times 10^3$. We simulated the light-curve and the prompt emission spectrum (see figure 3 and figure 4). The resulting average CBM value was $n \sim 0.03$ particles cm³.

3 Swift/XRT observations

In addition to *Fermi*, GRB 110731A triggered many other observatories, including the burst alert telescope (BAT) onboard *Swift* [31]. Besides BAT, *Swift* spacecraft [32]

Table 2. C-STAT values of 6 models used in the time-resolved spectral analysis, with bin duration given in the first column. E_p value of the best fitting Compton model is given in the second column.

Time bins (s)	Best-fit Compt		C-STAT/DOF other models				
	E_p (keV)	C-STAT/DOF	PL	PL+BB	Compt+BB	Band	Band+BB
[−0.38, 0.19]	$155.7^{+26.9}_{-0.0}$	413.2/361	429.7/362	413.8/360	412.5/359	413.2/360	413.1/358
[0.19, 0.40]	$168.9^{+21.6}_{-0.0}$	368.3/361	403.0/362	366.7/360	361.9/359	368.3/360	-NaN/358
[0.40, 0.53]	$184.7^{+34.5}_{-24.6}$	319.1/361	361.8/362	332.7/360	314.9/359	319.0/360	315.1/358
[0.53, 0.67]	$181.9^{+38.9}_{-26.8}$	331.6/361	359.8/362	332.4/360	331.1/359	330.0/360	329.8/358
[0.67, 0.92]	$149.3^{+19.8}_{-15.3}$	362.3/361	421.3/362	364.5/360	362.2/359	361.7/360	360.1/358
[0.92, 1.13]	$141.7^{+24.8}_{-19.7}$	373.7/361	425.8/362	369.1/360	361.4/359	362.0/360	361.2/358
[1.13, 1.36]	$148.5^{+25.8}_{-19.3}$	357.7/361	393.2/362	359.3/360	357.2/359	358.1/360	358.7/358
[1.36, 1.58]	$237.3^{+42.3}_{-0.0}$	365.1/361	391.8/362	368.9/360	363.4/359	364.4/360	363.9/358
[1.58, 1.81]	$242.8^{+47.3}_{-34.5}$	366.9/361	429.5/362	380.3/360	361.6/359	365.0/360	361.5/358
[1.81, 2.11]	$301.0^{+54.2}_{-0.0}$	431.8/361	455.8/362	433.8/360	425.9/359	430.2/360	424.1/358
[2.11, 2.40]	$243.2^{+42.4}_{-31.6}$	421.6/361	487.5/362	419.6/360	418.7/359	421.8/360	418.6/358

Figure 3. Simulated and NaI-n3 detector (0.2 s binning) light-curve of GRB 110731A. Red vertical line at 0.69 s marks the end of the P-GRB. The dashed line marks the end of the simulation for the spectra. **Figure 4.** Simulated $\nu F(\nu)$ spectra of the prompt emission, superimposed on the joined NaI-n0, n3 & BGO-b0 observed spectra.

harbors X-ray (XRT) and UV/optical (UVOT) telescopes, intended for the afterglow observations. Available multi-wavelength data make this burst a good candidate to investigate the IGC paradigm. The XRT began observations 56 s after the BAT trigger, where first 8 s were taken while

Swift was still slewing. The GBM and LAT localizations are consistent with the position provided by *Swift*. Redshift $z=2.83$ was provided by spectroscopic observations done by GMOS-N [33]. This enabled the XRT light-curve to be transformed to the 0.3–10 keV rest-frame energy range, plotted as a function of the rest-frame time (see figure 5). The GRB 110731A light-curve is superimposed on the X-ray luminosity light-curves of other BdHNe for comparison of the common late power-law behavior, typical for BdHNe. Non-existence of the plateau phase is in agreement with the high E_{iso} of this burst. Furthermore, the PL index $\alpha = -1.22$ is within the limits presented in [22, 23].

Figure 5. Rest-frame luminosity light-curve of GRB 110731A in the 0.3–10 keV range (orange), superimposed on other BdHNe light-curves (grey): 050525, 060729, 061007, 080319B, 090618, 091127, 100816A, 111228A, 130427A [34]. All GRBs have known redshift.

4 Conclusion and future perspectives

The mechanism responsible for the prompt emission of GRBs is still a debated issue. The origin of the GRB prompt emission in a BdHNe scenario is a consequence of a well-determined sequence of a binary system interaction. Being observed by multiple observatories, GRB

110731A makes a good candidate for investigation of the expected BdHNe signatures. The light-curve showed no evidence of the hypercritical accretion phase, which possibly remains under the detection level, considering the large distance of this GRB ($z = 2.83$). Calculated isotropic energy $E_{\text{iso}} = 6.05 \times 10^{53}$ erg is well above the BdHNe lower limit of $\sim 10^{52}$ erg. Using the calculated E_{iso} and P-GRB identified via time-resolved spectral analysis, we inferred the baryon load of $B = 4.35 \times 10^{-4}$, which is within the expected limits for long GRBs. LAT detected a high energy emission ~ 2.4 s after the the GBM trigger, expected in the BdHNe case as a signature of a BH formation. X-ray rest-frame luminosity light-curve showed typical late PL behavior, shared between the other members within the BdHNe group.

This preliminary analysis showed that GRB 110731A is a strong BdHN candidate. Still, in our ongoing analysis we will check the influence of the background selection, bad channels and different binning on the obtained parameters. We will investigate the use of different models and compare these results with the rest of the BdHNe sample.

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