GRB 081024B and GRB 140402A: Two Additional Short GRBs from Binary Neutron Star Mergers

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Abstract

Theoretical and observational evidences for a two-fold classification of short bursts have been recently obtained: (1) short gamma-ray flashes (S-GRFs), with isotropic energy $E_{iso} < 10^{52}$ erg and no black hole (BH) formation, and (2) authentic short gamma-ray bursts (S-GRBs), with isotropic energy $E_{iso} > 10^{52}$ erg showing evidence of BH formation in the binary neutron star merging process. The signature for BH formation is the onset of high-energy (0.1–100 GeV) emission, coeval to the prompt emission, in all S-GRBs. No GeV emission is expected nor observed in S-GRFs. In this paper, we present two S-GRBs, GRB 081024B and GRB 140402A, in addition to the already identified S-GRBs, GRB 090227B, GRB 090510, and GRB 140619B. We also return to the absence of GeV emission in the S-GRB 090227B, at an angle of 71° from the Fermi-LAT boresight. All of the correctly identified S-GRBs correlate with high-energy emission, implying no significant presence of beaming in GeV emission. The existence of a common power-law behavior in the GeV luminosities, following the BH formation, when measured in the source rest frame, points to a commonality in the mass and spin of the newly formed BHs in all S-GRBs.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 081024B, GRB 140402A) – stars: neutron

1. Introduction

Gamma-ray bursts (GRBs) have been historically divided into a two-fold classification based on the observed $T_{90}$ duration of their prompt emission: short GRBs with $T_{90} < 2$ s and long GRBs with $T_{90} > 2$ s (Mazets et al. 1981; Dezalay et al. 1992; Klebesadel 1992; Kouveliotou et al. 1993; Tavani 1998).

The progenitor systems of short bursts have traditionally been identified with binary neutron star (NS) and NS–black hole (BH) mergers (see, e.g., Goodman 1986; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1991; Meszaros & Rees 1997; Rosswog et al. 2003; Lee et al. 2004; Belczynski et al. 2006; Berger 2014). This assumption has received observational support from their localization, made possible by the X-ray emission of the afterglow, with large offsets from their hosts galaxies, both late- and early-type galaxies with no star formation evidence (see, e.g., Fox et al. 2005; Gehrels et al. 2005; Berger 2014).

A vast activity of numerical work on relativistic magnetohydrodynamical (MHD) simulation using the largest facilities in the world (equipped with supercomputers with peak performances of 6.8 PLOPS, see Siegel et al. 2014; 13.3 PLOPS, see Ruiz et al. 2016; and 10.51 PLOPS, seeKiuchi et al. 2014) have been developed with the declared goal of finding a jetted emission, which they considered, without convincing observational support, to be a necessary step in developing short GRB models in merging binary NS–NS or binary BH–NS systems (see, e.g., Rezzolla et al. 2011; Shibata et al. 2011; Kiuchi et al. 2014; Siegel et al. 2014; Paschalidis et al. 2015; Ruiz et al. 2016). It is interesting that they themselves recognized the shortcoming of their approach: “...there is microphysics that we do not model here, such as the effects of a realistic hot, nuclear EOS [equation of state] and neutrino transport” (see, e.g., Ruiz et al. 2016, p. 5). They also expected that such models would be further confirmed by the observation of gravitational waves (GWs) by aLIGO (see, e.g., Brown et al. 2004).

There is no observational signature for the role of MHD activities in GRBs, nor, as we show in this paper, for jetted emission in X-rays and $\gamma$-rays, as well as in the ultrarelativistic GeV emission of short bursts (see Section 5). On the contrary, also in the case of short GRBs, we have strong evidence for the necessary occurrence of hypercritical accretion processes, as already shown in long GRBs, with the fundamental roles played by neutrino emission (Zel’dovich et al. 1972; Ruffini & Wilson 1973; Rueda & Ruffini 2012; Fryer et al. 2014) and the value of the NS critical mass $M_{crit}^{\text{NS}}$ (Rottone et al. 2011a, 2011b; Rueda et al. 2011, 2014; Belvedere et al. 2012, 2014, 2015; Rueda & Ruffini 2013; Cipollitta et al. 2015; see also Fryer et al. 2014, 2015b; Becerra et al. 2015, 2016). We also established firm upper limits on the observation of GWs from short GRBs by aLIGO (Oliveira et al. 2014; Ruffini et al. 2015, 2016b).

Our approach is markedly different from traditional ones. Since Ruffini et al. (2001a, 2001b, 2001c), we started:

(a) daily systematic and independent analyses of the GRB data in X-rays and $\gamma$-rays and GeV emission from Beppo-SAX
(see, e.g., Frontera 2015), Swift (Barthelmy et al. 2005), Fermi (Meegan et al. 2009), Konus-WIND (Aptekar et al. 1995), and AGILE (Tavani et al. 2009). We extended our data analysis to optical and radio data.

(b) We have developed theoretical and astrophysical models based on quantum and classical relativistic field theories.

(c) At every step, we verified that the theoretical considerations are consistent with the observational data.

In this article, we mainly address the study of NS–NS mergers and only at the end do we refer to BH–NS binaries.

In Ruffini et al. (2015), a further division of the short bursts into two different subclasses has been proposed, and specific observable criteria characterizing this division have been given there:

1. The first subclass of short bursts is characterized by isotropic energies $E_{\text{iso}} \lesssim 10^{52}$ erg and rest-frame spectral peak energies $E_{p,i} \gtrsim 2$ MeV (Zhang et al. 2012; Calderone et al. 2015). In this case, the outcome of the NS–NS merger is a massive NS (MNS) with additional orbiting material (Ruffini et al. 2016c). An alternative scenario leads to a new binary system comprising an MNS and a less massive NS or a white dwarf (WD). For specific mass ratios, a stable mass-transfer process may occur from the less massive to the MNS (see, e.g., Clark & Eardley 1977; Bildsten & Cutler 1992, and references therein). Consequently, the donor NS moves outward by losing mass and may also reach beta-decay instability, becoming a low-mass WD. In view of their moderate hardness and their low energetics, we have indicated such short bursts as short gamma-ray flashes (S-GRFs; see Ruffini et al. 2016c). There, the local rate of S-GRFs has been estimated to be $\dot{\rho}_0 = 3.6^{+1.6}_{-1.0} \text{ Gpc}^{-3} \text{ yr}^{-1}$.

2. The second subclass corresponds to the authentic short GRBs (S-GRBs) with $E_{\text{iso}} \gtrsim 10^{52}$ erg and $E_{p,i} \gtrsim 2$ MeV (Zhang et al. 2012; Calderone et al. 2015). In this system, the NS–NS merger leads to the formation of a Kerr BH with additional orbiting material, in order to conserve energy and angular momentum (Ruffini et al. 2016a, 2016c). A further characterizing feature of S-GRBs absent in S-GRFs is the presence of 0.1–100 GeV emission, coeval to their prompt emission and showing evidence of the activity of a newly born BH. In Ruffini et al. (2016c), the local rate of S-GRBs has been estimated to be $\dot{\rho}_0 = (1.9^{+2.9}_{-1.1}) \times 10^{-3} \text{ Gpc}^{-3} \text{ yr}^{-1}$. The impossibility of detecting the observed short GRB 140619B with LIGO was evident (see Figure 12 in Ruffini et al. 2015). We return again in this article to the issue of non-detectability of GWs for S-GRBs.

The above relative rate of these two subclasses of short bursts has been discussed and presented in Ruffini et al. (2016c). There, it has been shown that S-GRFs are the most frequent events among short bursts. This conclusion is in good agreement with the NS–NS binaries observed within our Galaxy: only a subset of them has a total mass larger than $M^\text{SN}_{\text{crit}}$ and can form a BH in their merging process (Ruffini et al. 2015). There, in Figure 3, it was assumed that $M^\text{SN}_{\text{crit}} = 2.67 M_\odot$ for a non-rotating NS by imposing global charge neutrality and using the NL3 nuclear model (see, e.g., Cipollutta et al. 2015). Similar conclusions have also been independently reached by Fryer et al. (2015a) and Lawrence et al. (2015).

We have identified three authentic S-GRBs: GRB 090227B (Muccino et al. 2013), GRB 090510 (Ruffini et al. 2016a), and GRB 140619B (Ruffini et al. 2015). All of them populate the high-energy part of the $E_{p,i} - E_{\text{iso}}$ relation for short bursts (Zhang et al. 2012; Calderone et al. 2015; Ruffini et al. 2016a) and have $E_{\text{iso}} > 10^{52}$ erg. We have analyzed the above three S-GRBs within the fireshell model (see, e.g., Ruffini et al. 2010). The transparency emission of the $e^+e^-$ plasma (the P-GRB emission), the onset of prompt emission, and the correlation between the spike emission of the prompt and CBM inhomogeneities have led to the most successful test and applicability of the fireshell model.

A further and independent distinguishing feature between S-GRFs and S-GRBs has been found thanks to Fermi data: when these three S-GRBs fall within the Fermi-LAT field of view (FoV), GeV emission related to the emission from a newly born BH occurs, starting soon after the P-GRB emission.

In this paper, we present two additional S-GRBs: GRB 081024B and GRB 140402A. The S-GRB 081024B is historically important since that source provided the first clear detection of a GeV temporally extended emission from a short burst (Abdo et al. 2010). From the application of the fireshell model to this S-GRB, we theoretically derived its redshift, $z = 3.12 \pm 1.82$, and, therefore, $E_{\text{iso}} = (2.6 \pm 1.0) \times 10^{52}$ erg, $E_{p,i} = (9.6 \pm 4.9)$ MeV, and $E_{\text{LAT}} = (2.79 \pm 0.98) \times 10^{52}$ erg. For the S-GRB 140402A, we theoretically derived a redshift $z = 5.52 \pm 0.93$, which gives $E_{\text{iso}} = (4.7 \pm 1.1) \times 10^{52}$ erg and $E_{p,i} = (6.1 \pm 1.6)$ MeV. A long-lived GeV emission with 800 s has been reported (Bissaldi et al. 2014). The total energy of the brightest GeV emission is $E_{\text{LAT}} = (4.5 \pm 2.2) \times 10^{52}$ erg.

We also updated the analysis of the GeV emission of the S-GRB 090227B. The apparent absence of GeV emission has already been discussed in Ruffini et al. (2015), recalling that this source was outside the nominal LAT FoV, and only photons in the LAT low-energy (LLE) channel and a single transient-class event with energy above 100 MeV were associated with this GRB (Ackermann et al. 2013). A further updated analysis would indicate that, in view of the missing observations, in no way can the absence of GeV emission before ~40 s in the source rest frame be inferred.

From the analyses of the two additional S-GRBs, 081024B and 140402A, and the further check for GeV emission associated with the S-GRB 090227B, we conclude that all S-GRBs correlate with high-energy emission, implying no significant presence of beaming in GeV emission.

In Section 2, we briefly recall the fireshell model and its implications for S-GRBs. In Sections 3 and 4, we report the data analyses of the S-GRBs 081024B and 140402A, respectively, and show their theoretical interpretation within the fireshell model: from the theoretical inference of their cosmological redshift, their transparency emission parameters, to the details of the circumburst media where they occurred. In Section 5, we summarize the properties of the GeV emission of all S-GRBs and show the characteristic common power-law behavior of the rest-frame 0.1–100 GeV luminosity light curves. We also discuss the minimum Lorentz factor of the GeV emission $\Gamma_{\text{min}}^\text{GRB}$ obtained by requiring that the outflow must be optically thin to GeV photons (namely, to the pair-creation process), as well as its possible energy source, i.e., the matter accreting onto the newly formed BH. In Section 6, we indicate that there is no evidence in favor of or against a common behavior of X-ray afterglows of S-GRBs in view of the limited
observations. In Section 7, we briefly address the issue of the possible emission of short bursts from BH–NS binaries leading to ultrashort GRBs (U-GRBs; see Fryer et al. 2015b; Ruffini et al. 2016c). In Section 8, we infer our conclusions.

2. The Fireshell Model

In the fireshell model (Ruffini et al. 2001a, 2001b, 2001c), the GRB acceleration process consists of the dynamics of an optically thick $e^+e^-$ plasma of total energy $E_{\text{tot}}^{\text{u}}$, the fireshell. Its expansion and self-acceleration are due to the gradual $e^+e^-$ annihilation, which has been described in Ruffini et al. (1999). The effect of baryonic contamination on the dynamics of the fireshell has been considered in Ruffini et al. (2000), where it was shown that even after the engulfment of baryonic mass $M_B$, quantified by the baryon load $B = M_Bc^2/E_{\text{tot}}^{\text{u}}$, the fireshell still remains optically thick and continues its self-acceleration up to ultrarelativistic velocities (Aksenov et al. 2007, 2009). The dynamics of the fireshell in the optically thick phase up to the transparency condition is fully described by $E_{\text{tot}}^{\text{u}}$ and $B$ (Ruffini et al. 2000). In the case of long bursts, it is characterized by $10^{-4} \lesssim B < 10^{-2}$ (Izzo et al. 2012; Patricelli et al. 2012; Penacchioni et al. 2012, 2013), while for short bursts, we have $10^{-5} \lesssim B \lesssim 10^{-4}$ (Muccino et al. 2013; Ruffini et al. 2015, 2016a).

The fireshell continues its self-acceleration until the transparency condition is reached; then, a first flash of thermal radiation, the P-GRB, is emitted (Ruffini et al. 1999, 2000, 2001b). The spectrum of the P-GRB is determined by the geometry of the fireshell, which is dictated, in turn, by the geometry of the pair-creation region. In the case of a spherically symmetric dyadosphere, the P-GRB spectrum is generally described by a single thermal component in good agreement with the spectral data (see, e.g., Muccino et al. 2013; Ruffini et al. 2015). In the case of an axisymmetric dyadotorus, the resulting P-GRB spectrum, which resembles a power-law spectral energy distribution with an exponential cutoff (Ruffini et al. 2016a), is a convolution of thermal spectra of different temperatures.

After transparency, the accelerated baryons (and leptons) propagate through the circumburst medium (CBM). The collisions with the CBM, assumed to occur in the fully radiative regime, give rise to the prompt emission (Ruffini et al. 2001b). The spectrum of these collisions, in the comoving frame of the shell, is modeled with a modified blackbody (BB) spectrum, obtained by introducing an additional power law at low energy with a phenomenological index $\bar{\alpha}$, which describes the departure from the purely thermal case (see Patricelli et al. 2012 for details). The structures observed in the prompt emission of a GRB depend on the CBM density $n_{\text{CBM}}$ and its inhomogeneities (Ruffini et al. 2004), described by the fireshell filling factor $\mathcal{F}$. This parameter is defined as the ratio between the effective fireshell emitting area $A_{\text{eff}}$ and the total visible area $A_{\text{vis}}$ (Ruffini et al. 2002, 2005). The $n_{\text{CBM}}$ profile determines the temporal behavior (the spikes) of the light curve. The observed prompt emission spectrum results from the convolution of a large number of modified BB spectra over the surfaces of constant arrival time for photons at the detector (EQUiTemporal Surfaces, EQTS; Bianco & Ruffini 2005a, 2005b) over the entire observation time. Each modified BB spectrum is deduced from the interaction with the CBM and it is characterized by decreasing temperatures and Lorentz and Doppler factors.

The duration and, consequently, the moment at which the burst emission stops are determined by the dynamics of the $e^+e^-$ plasma. The short duration is essentially due to the low baryon load of the plasma and the high Lorentz factor $\Gamma \approx 10^4$ (see Figure 2 in Ruffini et al. 2001b and Figure 4 in Muccino et al. 2013).

The description of both the P-GRB and the prompt emission requires the appropriate relative spacetime transformation paradigm introduced in Ruffini et al. (2001c): it relates the observed GRB signal to its past light cone, defining the events on the worldline of the source that is essential for the interpretation of the data. This requires knowledge of the correct equations relating the comoving time, the laboratory time, the arrival time, and the arrival time at the detector corrected by the cosmological effects.

It is interesting to compare and contrast the masses, densities, thicknesses, and distances of the CBM clouds from the BH, both in short and long bursts. In S-GRBs, we infer CBM clouds with masses of $10^{22}–10^{25}$ g and sizes of $\approx 10^{15}–10^{16}$ cm, at typical distances from the BH of $\approx 10^{16}–10^{17}$ cm (see Sections 3.2.2 and 4.2.2, and Ruffini et al. 2016a)— indeed, these are very similar to the values inferred in long GRBs (see, e.g., Izzo et al. 2012). The different durations of the spikes in the prompt emission of S-GRBs and long bursts depend, indeed, on the different values of $\Gamma$ of the accelerated baryons and not on the structure of the CBM; in long bursts, we have $\Gamma \approx 10^3–10^4$ (see, e.g., Izzo et al. 2012), while in S-GRBs it reaches the value of $\Gamma \approx 10^5$ (see, e.g., Ruffini et al. 2016a; see Sections 3.2.2 and 4.2.2).

The evolution of an optically thick baryon-loaded pair plasma is generally described in terms of $E_{\text{tot}}^{\text{u}}$ and $B$, and it is independent of the way the pair plasma is created. This general formalism can also be applied to any optically thick $e^+e^-$ plasma, like the one created via the $\nu\bar{\nu} \rightarrow e^+e^-$ mechanism in an NS merger as described in Narayan et al. (1992), Salmonson & Wilson (2002), and Rosswog et al. (2003).

Only in the case where a BH is formed does an additional component to the fireshell emission occur in both S-GRBs and binary-driven hypernovae (BdHNe; long GRBs with $E_{\text{iso}} > 10^{52}$ erg—details in Ruffini et al. 2017); at the end of the P-GRB phase: the GeV emission observed by Fermi-LAT and AGILE. As outlined in this article, this component has a Lorentz factor $\Gamma > 300$ and, as we will show in Section 5, it appears to have a behavior universal to both S-GRBs and BdHNe. It is, however, important to recall that the different geometries present in S-GRBs and BdHNe lead, in the case of BdHNe, to the absorption of the GeV emission in some specific cases (Ruffini et al. 2017).

3. The S-GRB 081024B

3.1. Observations and Data Analysis

The short-hard GRB 081024B was detected on 2008 October 24 at 21:22:41 (UT) by the Fermi-GBM (Connaughton & Briggs 2008). It has a duration $T_0 \approx 0.8$ s and exhibits two main peaks, the first one lasting $\approx 0.2$ s. Its location (R.A., decl.) = (322°29, 21°204) (J2000) is consistent with that reported by the Fermi-LAT (Omodei 2008). The LAT recorded 11 events with energy above 100 MeV within 15° from the position of the burst and within 3 s from the trigger time (Abdo et al. 2010). Emission up to 3 GeV was seen within $\sim 5$ s after the trigger (Omodei 2008).
The time-integrated analysis was performed in the time interval from $T_0 - 0.064$ s to $T_0 + 0.768$ s which corresponds to the $T_{90}$ duration of the burst and $T_0$ is the trigger time. We have fitted the corresponding spectrum with two spectral models: Comptonized (Compt; i.e., a power-law model with an exponential cutoff) and Band (Band et al. 1993); see Figure 2 and Table 1. The Compt and the Band models provide similar values of the C-STAT (see Table 1). Therefore, the best fit is the Compt model because it has one parameter fewer than the Band one.

3.1.2. Time-resolved Spectral Analysis of the Fermi-GBM Data

We have also performed the time-resolved analysis using 16 ms bins. After the rebinning, the GBM light curves still exhibit two pulses: the first pulse observed before the onset of the LAT emission, from $T_0 - 0.064$ s to $T_0 + 0.128$ s, and the following emission, from $T_0 + 0.128$ s to $T_0 + 0.768$ s, hereafter dubbed the $\Delta T_1$ and $\Delta T_2$ time intervals, respectively.

As proposed in Ruffini et al. (2015), the emission before the onset of the LAT emission corresponds to the P-GRB emission, while the following emission is attributed to the prompt emission (see Section 2).

The spectrum of the $\Delta T_1$ time interval, which can be interpreted as the P-GRB emission, is equally best fit, among all the possible models, by a BB model and by a Compt spectral model. Figure 3 and Table 1 illustrate the results of this time-resolved analysis. From the difference in the C-STAT values between the BB and the Compt models ($\Delta$C-STAT = 9.88; see Table 1), we conclude that the simpler BB model can be excluded at $>3\sigma$ confidence level. Therefore, the best fit is the Compt model.

As in the case of GRB 090510, a Compt spectrum for the P-GRB emission can be interpreted as the result of the convolution of BB spectra at different Doppler factors arising from a spinning BH (see Section 2 and Ruffini et al. 2016a).

The spectrum of the $\Delta T_2$ time interval, which can be interpreted as the prompt emission, is equally best fit by a power-law (PL) model and a Compt spectral model (see Figure 4 and Table 1). The PL and the Compt models are equivalent, though the Compt model slightly improves the C-STAT statistic. However, because of the unconstrained value for the peak energy of the Compt model $E_p$, we conclude that the PL model represents an acceptable fit to the data.

3.2. Theoretical Interpretation within the Fireshell Model

We proceed to the interpretation of the data analysis performed in Section 3.1 within the fireshell model.

3.2.1. The Estimate of the Redshift

Identifying the P-GRB and the prompt emission is fundamental in order to estimate the source cosmological redshift and, consequently, to determine all of the physical properties of the $e^+e^-$ plasma at the transparency point (Muccino et al. 2013; Ruffini et al. 2015). The method introduced in Muccino et al. (2013) allows the source redshift from the two main observational constraints, the observed P-GRB temperature $kT$, related to the theoretically computed rest-frame temperature $kT_{\text{blue}} = kT (1 + z)$, and the ratio between the P-GRB fluence $S_{\text{BB}} = F(\Delta T_i)\Delta T_i$ and the total one $S_{\text{tot}} = F(T_0)T_{90}$, which represents a good redshift independent approximation for the ratio $E_{P,\text{GRB}}/E_{e^+e^-}$ (see Table 1), to be determined. A trial
error procedure is then started, using various sets of values for \(E_{\text{ee} \text{tot}}\) and \(B\) to reproduce the observational constraints. Each of these sets of values provides various possible values for the redshift \(z\) from the relation between \(kT\) and \(kT_{\text{blue}}\). The closure condition is represented by \(E_{\text{iso}}(z) = E_{\text{ee} \text{tot}}\), where \(E_{\text{iso}}\) is computed taking into account the \(K\)-correction on \(S_{\text{tot}}\) (Schaefer 2007). The redshift verifying the last condition and the corresponding values of \(E_{\text{ee} \text{tot}}\) and \(B\) is the correct one for the source. The theoretical redshift \(z = 3.12 \pm 1.82\) together with all of the other quantities so far determined are summarized in Table 2 (for further details on the method, see, e.g., Ruffini et al. 2015). The analogy with the prototypical source GRB 090227B \((B = 4.13 \times 10^{-5};\) Muccino et al. 2013\)), GRB 140619B \((B = 5.52 \times 10^{-5};\) Ruffini et al. 2015\)), and GRB 090510 \((B = 5.54 \times 10^{-5};\) Ruffini et al. 2016a) is very striking.

The self-consistency of the above theoretical method to estimate the redshift has been tested in S-GRB 090510 (Ruffini...)

### Table 1

| \(\Delta T\) | Model | \(K\) \((\text{ph keV}^{-1} \text{cm}^{-2} \text{s}^{-1})\) | \(kT\) \((\text{keV})\) | \(E_p\) \((\text{MeV})\) | \(\alpha\) | \(\beta\) | \(F\) \((\text{erg cm}^{-2} \text{s}^{-1})\) | C-STAT/DOF |
|---|---|---|---|---|---|---|---|---|
| \(T_{90}\) | Compt | \((6.39 \pm 0.69) \times 10^{-3}\) | 2.3 \pm 1.2 | \(-1.02 \pm 0.11\) | \((2.27 \pm 0.87) \times 10^{-6}\) | 383.89/356 |
| Band | \((6.51 \pm 0.92) \times 10^{-3}\) | 1.9 \pm 1.7 | \(-1.01 \pm 0.15\) | \(-2.2 \pm 1.1\) | \((2.9 \pm 1.5) \times 10^{-6}\) | 383.23/355 |
| \(\Delta T_1\) | BB | \((4.0 \pm 1.7) \times 10^{-3}\) | 152 \pm 20 | 1.33 \pm 0.59 | \(-0.48 \pm 0.27\) | \((2.42 \pm 0.40) \times 10^{-6}\) | 343.54/357 |
| Compt | \((9.8 \pm 1.9) \times 10^{-3}\) | 10.95(unc) | \(-1.37 \pm 0.07\) | \(-1.28 \pm 0.11\) | \((3.5 \pm 2.0) \times 10^{-6}\) | 390.57/356 |
| \(\Delta T_2\) | PL | \((4.60 \pm 0.53) \times 10^{-3}\) | \(-1.37 \pm 0.07\) | \((-1.37 \pm 0.07\) | \(5.0 \pm 1.5\) \times 10^{-6}\) | 392.2/357 |
| Compt | \((4.80 \pm 0.59) \times 10^{-3}\) | \(-1.28 \pm 0.11\) | \((-1.28 \pm 0.11\) | \((3.5 \pm 2.0) \times 10^{-6}\) | 390.57/356 |

Note. Each column lists the GRB, the time interval \(\Delta T\), the spectral model, the normalization constant \(K\), the BB temperature \(kT\), the Compt peak energy \(E_p\), the low-energy \(\alpha\) and the high-energy \(\beta\) photon indexes, the 8 keV–40 MeV energy flux \(F\), and the value of the C-STAT over the number of degrees of freedom (DOF).
3.12 ± 1.82  2.64 ± 1.00  4.6 ± 2.8  6.7 ± 4.8  50 ± 26  1.10 ± 0.24  5.6 ± 2.1  1.39 ± 0.76

Table 2
P-GRB and Prompt Emission Parameters of the S-GRBs 081024B within the Fireshell Model

| Prompt | Cloud | r (cm) | Δr (cm) | MCBM/(10^4 cm^-2) | E_{F-GRB}/E_{e^-e^+} (%) | Γ_{tot}/10^4 | n_{CM}/(10^{12} cm^-3) | kT_{blue} (MeV) |
|--------|-------|--------|---------|-------------------|--------------------------|-------------|-------------------------|----------------|
| 1st    | 5.5 × 10^16 | 0.5 × 10^16 | 0.90 ± 0.70 | 3.1 ± 2.4 | 9.0 ± 7.0 | 1.10 | 2.90 × 10^10 |
| 2nd    | 6.0 × 10^16 | 0.8 × 10^16 | 0.10 ± 0.02 | 0.69 ± 0.14 | 0.52 | 6.60 × 10^14 |
| 3rd    | 6.8 × 10^16 | 0.7 × 10^16 | 1.00 ± 0.20 | 7.5 ± 1.5 | 0.51 | 7.68 × 10^14 |
| 4th    | 7.5 × 10^16 | 0.3 × 10^16 | 3.50 ± 0.70 | 12.9 ± 2.6 | 98 ± 53 | 0.40 | 1.08 × 10^15 |
| 5th    | 7.8 × 10^16 | 0.7 × 10^16 | 20.0 ± 4.00 | 196 ± 39 | 0.29 | 1.55 × 10^15 |
| average|               |         |          |                   |                         |             | 3.18 ± 0.74            |

Note. The list of P-GRB parameters (upper part of the table): the inferred redshift z; the e^+e^- plasma energy E_{e^-e^+}; the baryon load B and the corresponding baryonic mass M_B; the P-GRB energy E_{F-GRB}; the Lorentz factor Γ_{tot}; the radius of the fireshell r_{CM}; and the temperature blueshifted toward the observed kT_{blue} computed at the transparency point. The CBM properties inferred from the prompt emission simulation (lower part of the table) are the number of CBM clouds, the distance r from the BH, the thickness Δr, the number density distribution n_{CM}, the total mass M_{CM}, the filling factors R, the Lorentz factor after each collision Γ, and the total transversal sizes d_{CM} of the fireshell visible area. The average number density is indicated at the end of the n_{CM} column.

In this case, a theoretical redshift z_{th} = 0.75 ± 0.17 has been derived, in agreement with the spectroscopic measurement z = 0.903 ± 0.003 (Rau et al. 2009).

3.2.2. Analysis of the Prompt Emission

In the fireshell model, the prompt emission light curve is the result of the interaction of the accelerated baryons with the CBM (see above and, e.g., Ruffini et al. 2002, 2006; Patricelli et al. 2012). After the determination of the initial conditions for the fireshell, i.e., E_{e^-e^+} and B (see Table 2), to simulate the prompt emission light curve of the S-GRB 081024B (see Figure 1) and its corresponding spectrum, we derived the CBM number density and the filling factor R distributions and the corresponding attached errors (see Table 2 and Figure 5, top panel). The average CBM number density inferred from the prompt emissions of GRB 081024B is <n_{CBM}> = (3.18 ± 0.74) × 10^{-4} (see Table 2) and is larger than that of GRB 140619B, <n_{CBM}> = (4.7 ± 1.2) × 10^{-3} cm^{-3} (Ruffini et al. 2015), and GRB 090227B, <n_{CBM}> = (1.90 ± 0.20) × 10^{-5} cm^{-3} (Muccino et al. 2013), but still typical of S-GRB galactic halo environments.

The simulation of the prompt emission light curve of the NaI n9 (8–900 keV) data of GRB 081024B is shown in Figure 5 (middle panel). The short timescale variability observed in the S-GRB light curves is the result of the large values of the Lorentz factor (Γ ≈ 10^4; see Table 2). Under these conditions, the total transversal size of the visible fireshell area, d_{CM}, is smaller than the thickness of the inhomogeneities (∼10^16 cm; see the values indicated in Table 2), justifying the spherical symmetry approximation (Ruffini et al. 2002, 2006; Patricelli et al. 2012) and explaining the insignificant "broadening" in the arrival time of the luminosity peaks.

The corresponding spectrum is simulated by using the spectral model described in Patricelli et al. (2012) with the phenomenological parameters α = −1.99. The rebinned data within the ΔT_{2} time interval agree with the simulation, as shown by the residuals around the simulated fireshell spectrum (see Figure 5, bottom panel).
4. S-GRB 140402A

4.1. Observations and Data Analysis

The short-hard GRB 140402A was detected on 2014 April 2 at 00:10:07.00 (UT) by Fermi-GBM (Jenke & Yu 2014). The duration of this S-GRB in 50–300 keV is $T_{90} = 0.3$ s. It was also detected by Fermi-LAT (Bissaldi et al. 2014) with a best on-ground location (R.A., decl.) = (207°59′2, 5′971′) (J2000), consistent with that from the GBM. More than 10 photons were detected above 100 MeV and within $10^8$ from the GBM location, which spatially and temporally correlates with the GBM emission with high significance (Bissaldi et al. 2014).

This burst was also detected by Swift-BAT (Cummings 2014), with a best location (R.A., decl.) = (207°59′2, 5′971′) (J2000). No source was detected in the Swift-XRT data (Pagani 2014a) after two pointings in PC mode, from 33.3 ks to 51.2 ks and from 56 ks to 107 ks. These two observation sets are within the $3\sigma$ upper limit of $\nu < 19.8$ mag and of $r > 25.0$ mag to be set. Consequently, no host galaxy has been associated with this burst and, therefore, no spectroscopic redshift has been determined.

4.1.1. Time-integrated Spectral Analysis of the Fermi-GBM Data

In Figure 6, we reproduced the 16 ms binned GBM light curves corresponding to the detectors NaI–n3 (8–260 keV, top) and BGO–b0 (0.26–20 MeV, lower panel) detectors. The vertical dashed line marks the onset of the LAT light curve (see Figure 7).

Figure 5. Results of the prompt emission simulation of the S-GRB 081024B. Top: the CBM number density (black line) and errors (red shaded region). Middle: comparison between the simulated prompt emission light curve (solid red curves) and the NaI–n9 (8–900 keV) data. Bottom: comparison between the simulated spectrum (solid red curve) and the NaI–n9 (purple squares), NaI–n9 (blue diamonds), and the BGO–b1 (green circles) spectra within the $\Delta T_2$ time interval. The residuals are shown in the subplot.

Figure 6. Background-subtracted light curves of GRB 140402A: the 16 ms binned light curves from the NaI–n3 (8–260 keV, upper panel) and BGO–b0 (0.26–20 MeV, lower panel) detectors. The vertical dashed line marks the onset of the LAT light curve (see Figure 7).

Figure 7. Upper panel: the background-subtracted 200 ms binned high-energy (0.1–100 GeV) light curve, without error bars. Lower panel: the energy light curve of the detected high-energy photons.
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Figure 8. BB (left plot) and Compt (right plot) spectral fits on the combined NaI–n0, n1, and n3+BGO–b1νEγ data of GRB 140402A in the T90 time interval.

Table 3
Results of the Spectral Analyses of the S-GRB 140402A

| ΔT       | Model | K (ph keV⁻¹ cm⁻² s⁻¹) | kT (keV) | Em (MeV) | α  | F (erg cm⁻² s⁻¹) | C-STAT/DOF |
|----------|-------|------------------------|----------|----------|----|-----------------|-------------|
| T90      | BB    | (2.43 ± 0.75) × 10⁻⁷   | 173 ± 18 | 0.94 ± 0.24 | 0.12 ± 0.37 | (2.26 ± 0.31) × 10⁻⁶ | 527.65/483  |
|          | Compt | (7.0 ± 1.4) × 10⁻³     |          |          |    | (2.77 ± 0.62) × 10⁻⁶ | 521.66/482  |
| ΔT1      | BB    | (1.67 ± 0.69) × 10⁻⁷   | 242 ± 34 | 1.20 ± 0.32 | 0.43 ± 0.51 | (6.0 ± 1.1) × 10⁻⁶ | 441.01/483  |
|          | Compt | (7.1 ± 2.6) × 10⁻³     |          |          |    | (6.9 ± 1.8) × 10⁻⁶ | 439.61/482  |
| ΔT2      | BB    | (5.0 ± 2.2) × 10⁻⁷     | 122 ± 18 | 0.70 ± 0.25 | 0.07 ± 0.54 | (1.17 ± 0.22) × 10⁻⁶ | 500.42/483  |
|          | Compt | (7.5 ± 2.0) × 10⁻³     |          |          |    | (1.52 ± 0.46) × 10⁻⁶ | 497.57/482  |

Note. Each column lists the GRB, the time interval ΔT, the spectral model, the normalization constant K, the BB temperature kT, the compt peak energy Em, the low-energy photon index α, the 8 keV–40 MeV energy flux F, and the value of the C-STAT over the number of degrees of freedom (DOF).

panel) and BGO–b0 (0.26–20 MeV, second panel), and the 0.2 s binned high-energy light curve (0.1–100 GeV, bottom panel). Also, for this burst, all of the light curves are background subtracted.

The NaI light curve shows a very weak and short pulse, almost at the background level, while the BGO signal exhibits two substructures with a total duration of ≈0.3 s. The vertical dashed line in Figure 6 represents the onset of the LAT emission, soon after the first pulse seen in both GBM light curves. The background-subtracted LAT light curve within 100 s after the GBM trigger and the corresponding 20 photons with energies higher than 0.1 GeV are shown in Figure 7.

We performed the time-integrated spectral analysis in the time interval from T0 − 0.096 s to T0 + 0.288 s (hereafter T90). To increase the poor statistics at energies ≤260 keV, we also included the data from the NaI–n0 and n1 detectors in the spectral analysis. Among all of the possible models, BB and Compt equally best fit the above data (see Figure 8 and the results listed in Table 3). From the value ΔC-STAT = 5.99 between the above two models (see Table 3), we conclude that the Compt model is an acceptable fit to the data. Similar to GRB 140619B (Ruffini et al. 2015), in the case of GRB 140402A, the low-energy index of the Compt model is consistent with α ≈ 0. From theoretical and observational considerations of the onset of the GeV emission (see Section 2 and Figure 6), we investigate the presence of a spectrum consistent with a BB one, which corresponds to the signature of the P-GRB emission for a moderately spinning BH (see Ruffini et al. 2016a).

4.1.2. Time-resolved Spectral Analysis of the Fermi-GBM Data

The first spike (see Figure 6), observed before the onset of the GeV emission, extends from T0 − 0.096 s to T0 (hereafter ΔT1). Again, the BB and Compt spectral models equally best fit the above data. As shown in Figure 9 and Table 3, the above two models are almost indistinguishable, with the low-energy index of the Compt model α = 0.43 ± 0.51 being consistent within almost the 1σ level with the low-energy index of a BB (α = 1). We conclude that the BB model is an acceptable fit to the data and identify the first pulse in the light curve with the P-GRB emission.

The spectrum of the emission in the time interval from T0 to T0 + 0.288 s (hereafter ΔT2) reveals that a Compt model slightly better fits the data points at ≈1 MeV, and its low-energy index α = 0.07 ± 0.54 indicates that the energy distribution is somehow broader than that of a BB model (see Figure 10 and Table 3). The Compt model is consistent with the modified BB spectrum adopted in the fireshell model for the prompt emission (Patricelli et al. 2012). Therefore, we identify the ΔT2 time interval with the prompt emission.

4.2. Theoretical Interpretation within the Fireshell Model

We proceed to the interpretation of the data analysis performed in Section 4.1 within the fireshell model.
4.2.1. The Estimate of the Redshift

After having identified the P-GRB emission of the S-GRB 140402A (see Section 4.1.2), we follow the same loop procedure recalled in Section 3.2.1 to infer the redshift, \( z \), and \( B \) of the source. The results of this method are summarized in Table 4. In particular, the theoretically derived redshift for this source is \( z = 5.52 \pm 0.93 \). Again, the analogy with the S-GRBs 081024B (see Section 3.1.2), GRB 090227B (Muccino et al. 2013), 140619B (Ruffini et al. 2015), and 090510 (Ruffini et al. 2016a) is very striking.

### Table 4

| P-GRB and Prompt Emission Parameters of the S-GRB 140402A within the Fireshell Model |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| z                                | \( E_{34}^{\text{tot}} \) (10\(^{52}\) erg) | \( B / 10^{-5} \) | \( M_b / (10^{-3} M_\odot) \) | \( E_{P,GRB}/E_{34}^{\text{tot}} \) (%) | \( \Gamma_b / 10^4 \) | \( r_b / (10^{12} \text{ cm}) \) | \( kT_{blue} \) (MeV) |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 5.52 \( \pm \) 0.93              | 4.7 \pm 1.1     | 3.6 \pm 1.0     | 9.5 \pm 3.4     | 54 \pm 16       | 1.30 \pm 0.13   | 6.66 \pm 0.91   | 1.58 \pm 0.22   |

#### Prompt

| Cloud | \( r \) (cm) | \( \Delta r \) (cm) | \( n_{\text{CBM}} / (10^{-4} \text{ cm}^{-3}) \) | \( M_{\text{CBM}} / (10^{22} \text{ g}) \) | \( R / 10^{-9} \) | \( \Gamma / 10^4 \) | \( d_e \) (cm) |
|-------|--------------|------------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| 1st   | \( 1.0 \times 10^{16} \) | \( 1.4 \times 10^{16} \) | 6.0 \pm 2.0                      | 5.4 \pm 1.8     | 4.7 \pm 0.45    | 1.30            | 6.64 \times 10^{10} |
| 2nd   | \( 2.4 \times 10^{16} \) | \( 2.6 \times 10^{16} \) | 24.0 \pm 3.0                     | 187 \pm 23      | 0.92            | 1.49 \times 10^{14} |
| average |               |                  | 15.4 \pm 2.5                    | 1.76 \pm 0.38   |               |                 |                 |

Note. For the P-GRB parameters (upper part of the table) and the CBM properties (lower part of the table), inferred from the prompt emission simulation, we refer to Table 2.

4.2.2. Analysis of the Prompt Emission

Similarly to the case of the S-GRB 081024B (see Section 3.2.2), to simulate the prompt emission light curve of the S-GRB 140402A (see Figure 6) and its corresponding spectrum, we derived the CBM number density and the filling...
factor $\mathcal{R}$ distributions (see Table 4 and Figure 11, top panel). Also, in this case, the inferred values fully justify the adopted spherical symmetry approximation (Ruffini et al. 2002, 2006; Patricelli et al. 2012) and explain the negligible “dispersion” in arrival time of the luminosity peak.

The average CBM number density in the case of GRB 140402A is $\langle n_{\text{CBM}} \rangle = (1.54 \pm 0.25) \times 10^{-3}$ (see Table 4), which is similar to that inferred from GRB 081024B. The simulation of the prompt emission light curve of the BGO–$b$0 (0.26–40 MeV) data of GRB 140402A is shown in Figure 11 (middle panel). The simulation of the corresponding spectrum requires a phenomenological parameter $\tilde{\alpha} = -0.9$. Figure 11 (bottom panel) displays the agreement between the rebinned data from the $\Delta T_2$ time interval and the simulation.

5. The GeV Emission in S-GRBs

Before going into more detail on the general properties of the S-GRB GeV emission, we briefly summarize the observational features and the data analysis of the high-energy emission of the S-GRBs 081024B and 140402A, and then we turn to a new analysis of the absence of the GeV emission in the S-GRB 090227B.

5.1. The GeV Emission of the S-GRBs 081024B and 140402A

We downloaded the LAT event and spacecraft data\(^1\) selecting the observational time, the energy range, and the source coordinates (Bissaldi et al. 2014). We then made cuts on the data set time and energy range, position (Bissaldi et al. 2014), region of interest (ROI) radius (typically\(^10^\), and maximum zenith angle.\(^1\) Within the event selection recommendations for the analysis of LAT data using the Pass 8 Data (P8R2), we adopted the burst and transient analysis (for events lasting $<200$ s) with an energy selection of $0.1–500$ GeV, an ROI-based zenith angle cut of $100^\circ$, event class 16, and the instrument response function P8R2_TRANSIENT020_V6.\(^1\) The additional selection of the good time intervals (GTIs) when the data quality is good (DATA_QUAL>0) is introduced to exclude time periods when some spacecraft event has affected the quality of the data (in addition to the time selection to the maximum zenith angle cut introduced above).

In the case of the S-GRB 081024B, we obtained the GeV light curve and the observed photon energies shown in Figure 1 (third and fourth panels), which are in agreement with those reported in Ackermann et al. (2013). In the case of the S-GRB 140402A, we obtained the GeV light curve shown in Figure 7 (upper plot). About 20 photons with energies higher than 0.1 GeV have been detected within 100 s after the GBM trigger (see Figure 7, lower panel). The highest energy photon is a 3.7 GeV event, which is observed at $T_0 + 8.7$ s.

Then, we built up the rest-frame 0.1–100 GeV light curve of the S-GRBs 081024B and 140402A. For the S-GRB 081024B, we rebinned its GeV emission luminosity light curve into two bins, as displayed in Ackermann et al. (2013). For the S-GRB 140402A, we rebinned it into two time bins with enough photons to perform a spectral analysis: from $T_0$ to $T_0 + 0.6$ s, and from $T_0 + 0.6$ s to $T_0 + 20$ s.

The resulting luminosity light curves follow a common power-law trend with the rest-frame time which goes as $\nu^{-1.29\pm0.06}$ (see dashed black line in Figure 12). All the light curves are shown from the burst trigger times on, while in the case of the S-GRB 090510 it starts after the precursor emission, i.e., from the P-GRB emission on (see Ruffini et al. 2016a for details). The GeV emission of the S-GRB 140402A is the second longest in time duration after GRB 090510, which exhibits a behavior in common with the light curves of the other S-GRBs after the $\sim$1 s rest-frame time (see Figure 12).

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\(^1\) [Link to Fermi data](http://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi)

\(^1\) The maximum zenith angle selection excludes any portion of the ROI that is too close to the Earth’s limb, resulting in elevated background levels.

\(^1\) [Link to Cicerone Data Exploration](http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Data_Exploration/Data_preparation.html)
Figure 12. Rest-frame 0.1–100 GeV isotropic luminosities of the S-GRBs 081024B (orange empty diamonds), 090510 (gray filled circles), 140402A (red filled squares), and 140619B (green empty squares). All of the light curves are shown from the burst trigger times on, while in the case of the S-GRB 090510 it starts after the precursor emission, i.e., from the P-GRB emission on (see Ruffini et al. 2016a for details). The dashed black line marks the common behavior of all of the S-GRB light curves, which goes as $r^{-1.29±0.06}$.

Table 5

S-GRB Prompt and GeV Emission Properties

| GRB     | $z$     | $E_{p,i}$ (MeV) | $E_{iso}$ (10$^{52}$ erg) | $E_{min}^{iso}$ (GeV) | $\Gamma_{GRB}^{min}$ | $E_{LAT}$ (10$^{52}$ erg) | $M_{E_{GRB}}^{acc}$ ($M_\odot$) | $M_{E_{LAT}}^{acc}$ ($M_\odot$) |
|---------|---------|-----------------|---------------------------|-----------------------|----------------------|---------------------------|-------------------------------|-------------------------------|
| 081024B | 3.12 ± 1.82 | 9.56 ± 4.94 | 2.64 ± 1.00 | 3 | $≥779$ | $≥2.79 ± 0.98$ | $≥0.04$ | $≥0.41$ |
| 090227B | 1.61 ± 0.14 | 5.89 ± 0.30 | 28.3 ± 1.5 | … | … | … | … | … |
| 090510  | 0.903 ± 0.003 | 7.89 ± 0.76 | 3.95 ± 0.21 | 31 | $≥551$ | $≥5.78 ± 0.60$ | $≥0.08$ | $≥0.86$ |
| 140402A | 5.52 ± 0.93 | 6.1 ± 1.6 | 4.7 ± 1.1 | 3.7 | $≥354$ | $≥4.5 ± 2.2$ | $≥0.06$ | $≥0.66$ |
| 140619B | 2.67 ± 0.37 | 5.34 ± 0.79 | 6.03 ± 0.79 | 24 | $≥471$ | $≥2.34 ± 0.91$ | $≥0.03$ | $≥0.35$ |

Note. The columns list $E_{p,i}$, the maximum GeV photon observed energy $E_{iso}^{min}$, the minimum Lorentz factor of the GeV emission $\Gamma_{GRB}^{min}$, the LAT observed energy $E_{LAT}$, and the amount of infalling accreting mass corotating (counterrotating) with the BH $M_{E_{GRB}}^{acc}$ ($M_{E_{LAT}}^{acc}$), needed to explain $E_{LAT}$.

Table 5 lists the redshift, $E_{p,i}$, $E_{iso}$ (in the rest-frame energy band 1–10,000 keV), and the GeV isotropic emission energy $E_{LAT}$ in the rest-frame energy band 0.1–100 GeV of the five authentic S-GRBs discussed here. These values of $E_{LAT}$ are simply obtained by multiplying the average luminosity in each time bin by the corresponding rest-frame duration and then by summing up all the contributions for each bin. However, these estimates represent lower limits to the actual GeV isotropic emission energies, since at late times the observations of GeV emission could be prevented due to the instrumental threshold of the LAT.

5.2. Reanalyzing the GeV Emission of the S-GRB 090227B

We performed the unbinned likelihood analysis method which is preferred when the number of events is expected to be small, for the S-GRB 090227B. We took spectra within 1 s, 10 s, 100 s, and 1000 s after the burst trigger. The background point-like sources and diffuse (galactic and extragalactic) emission within 10° from the GRB position are taken from the LAT 4-year Point Source Catalog (3FGL). The test statistic (TS) computed from the above likelihood analysis is $TS \leq 1$ in each time interval ($TS > 25$ corresponds to 5σ of significance); therefore, no significant GeV emission can be associated with this GRB. A single GeV photon with energy 1.59 GeV at time 896 s after the trigger and within 1° from the GRB has been found. Considering the above background models, we computed the probability of this photon belonging to this GRB. The likelihood analysis gives a probability of this photon correlating with GRB 090227B of 0.36%, while its probability of being a photon from the diffuse background is $>99%$.

The results of this analysis are in agreement with those reported in Ackermann et al. (2013). There, it is also stated that an autonomous repoint request by Fermi-GBM brought the LAT down to $≥20°$ after $≈300$ s and, therefore, the source entered the optimal LAT FoV. Using the S-GRB common power-law trend $r^{-1.29±0.06}$ (see the dashed black line in Figure 12), we computed the expected energy fluxes of the GeV emission of the S-GRB 090227B, $f_1$, at the time of $≈300$ s when the source entered the LAT FoV, and $f_2$, at 896 s when the diffuse background photon was detected. We assumed a power-law spectrum with a typical value of the photon index of $−2$ and obtained $f_1 = (1.09 ± 0.16) \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ and $f_2 = (2.65 ± 0.39) \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. These computed...
fluxes are within the Fermi-LAT sensitivity of the Pass 8 Release 2 Version 6 Instrument Response Functions,\(^\text{15}\) which is approximately \(10^{-11}\) erg cm\(^{-2}\) s\(^{-1}\). Therefore, we can conclude that the GeV emission associated with the S-GRB 090227B ceased before 300 s, when the source entered the LAT FoV.

### 5.3. Lower Limits on the GeV Emission Lorentz Factors in S-GRBs

Following Lithwick & Sari (2001), it is possible to derive a lower limit on the Lorentz factor of the GeV emission \(\Gamma_{\text{GeV}}^{\text{min}}\) by requiring that the outflow must be optically thin to high-energy photons, namely, to the pair-creation process. Using the maximum GeV photon observed energy \(E_{\text{obs}}^{\text{max}}\) in Table 5, for each S-GRB, various lower limits on the GeV Lorentz factors can be derived from the time-resolved spectral analysis. For each S-GRB, we estimate lower limits in each time interval of the GeV luminosity light curves in Figure 12. Then, the \(\Gamma_{\text{GeV}}^{\text{min}}\) for each S-GRB was then determined as the largest among the inferred lower limits (see Table 5). The GeV photons are produced in ultrarelativistic outflows with \(\Gamma_{\text{GeV}}^{\text{min}} \gtrsim 300\).

### 5.4. The Energy Budget of the GeV Emission in S-GRBs

Ruffini et al. (2016a) proposed that the 0.1–100 GeV in S-GRBs (see Figure 12) is produced by the mass accretion onto the newborn Kerr–Newman BH. The amount of mass that remains bound to the BH is given by the conservation of energy and angular momentum from the merger moment to the BH birth. We can estimate lower limits of the needed mass to explain the energy requirements \(E_{\text{LAT}}\) in Table 5 by considering the above accretion process onto a maximally rotating Kerr BH. In this case, depending whether the infalling material is in a co- or counterrotating orbit with the spinning BH, the maximum efficiency of the conversion of gravitational energy into radiation is \(\eta_b = 42.3\%\) or \(\eta_c = 3.8\%\), respectively (see Ruffini & Wheeler 1969 in problem 2 of Section 104 in Landau & Lifshitz 2003). Therefore, \(E_{\text{LAT}}\) can be expressed as

\[
E_{\text{LAT}} = f_b^{-1} \eta_b M_{\text{acc}}^0 c^2,
\]

where \(f_b\) is the beaming factor which depends on the geometry of the GeV emission and \(M_{\text{acc}}^0\) is the amount of accreted mass corresponding to the choice of the efficiency \(\eta_b\). The observational evidence that the totality of S-GRBs exhibit GeV emission and that its absence is due to the instrumental absence of alignment between the LAT and the source at the time of the GRB emission (see Section 5.2) suggests that no beaming is necessary in Equation (1). Therefore, in the following, we set \(f_b = 1\). The corresponding estimates of \(M_{\text{acc}}^0\) in our sample of S-GRBs are listed in Table 5.

### 6. On the Detectability of the X-Ray Emission of S-GRBs

GRB 090510 is the only S-GRB with a complete X-ray afterglow (see Figure 13(a) and Ruffini et al. 2016a). Only upper limits exist for the X-ray afterglow emission of the other S-GRBs and no special features are identifiable.

As an example to give evidence of the difficulty of measuring the X-ray afterglow in S-GRBs, we computed the observed X-ray flux light curve of GRB 090510, actually observed at \(z_{\text{fin}} = 0.903\), as if it occurred at the redshifts of the other S-GRBs, i.e., \(z_{\text{fin}} = 1.61, 2.67, 3.1\) and 5.52. This can be attained in four steps.

1. In each time interval of the X-ray flux light curve \(f_{\text{obs}}\) of GRB 090510, we assume that the best fit to the spectral energy distribution is a power-law function with photon index \(\gamma\), i.e., \(N(E) \propto E^{-\gamma}\).
2. In the rest-frame of GRB 090510, we identify the spectral energy range for a source at redshift \(z_{\text{fin}}\), which corresponds to the 0.3–10 keV observed by Swift-XRT, i.e.,
   \[
   0.3 \left(\frac{1 + z_{\text{fin}}}{1 + z_{\text{fin}}}ight) - 10 \left(\frac{1 + z_{\text{fin}}}{1 + z_{\text{fin}}}\right) \text{keV}.
   \]
3. We rescale the fluxes for the different luminosity distance \(d_l\). Therefore, the observed 0.3–10 keV X-ray flux light curve \(f_{\text{fin}}\) for a source at redshift \(z_{\text{fin}}\) is given by
   \[
   f_{\text{fin}} = f_{\text{obs}} \left[ \frac{d_l(z_{\text{fin}})}{d_l(z_{\text{fin}})} \right]^2 \frac{\int_{0.3}^{10} \frac{N(E)E\text{d}E}{0.3\text{keV}} \text{d}E}{\int_{0.3}^{10} \frac{N(E)E\text{d}E}{0.3\text{keV}}} = f_{\text{obs}} \left[ \frac{d_l(z_{\text{fin}})}{d_l(z_{\text{fin}})} \right]^2 \left(\frac{1 + z_{\text{fin}}}{1 + z_{\text{fin}}}\right)^{2-\gamma}.
   \]
4. We transform the observational time \(t_{\text{fin}}\) of GRB 090510 at \(z_{\text{fin}}\) into the observational time \(t_{\text{fin}}\) for a source at \(z_{\text{fin}}\) by taking into account the time dilation due to the cosmological redshift effect, i.e.,
   \[
   t_{\text{fin}} = \left(\frac{1 + z_{\text{fin}}}{1 + z_{\text{fin}}}\right) t_{\text{fin}}.
   \]

Figure 13 shows that all of the computed flux light curves are well below the observational upper limits provided by the Swift-XRT repointings.

1. S-GRB 090227B, no repointings (see Figure 13(b)).
2. S-GRB 140619B, a repointing from 48.7 to 71.6 ks after the GBM trigger with an upper limit of \(2.9 \times 10^3\) counts s\(^{-1}\) (see Maselli & D’Avanzo 2014 and Figure 13(c)).
3. S-GRB 081024B, two repointings within the flux light curve in Figure 13(d). Each upper limit was set by using the lowest count rate among those of the uncataloged sources within the LAT FoV, later on confirmed as not being the burst X-ray counterparts: the first one at \(\sim 70.3\) ks after the trigger for \(\sim 9.9\) ks with a count rate of \(1.3 \times 10^{-3}\) counts s\(^{-1}\) (Guidorzi et al. 2008b), and the second one from 1.5 to 6.1 days with an average count rate of \(7.4 \times 10^{-4}\) counts s\(^{-1}\) (Guidorzi et al. 2008a).
4. S-GRB 140402A, two repointings (Pagani 2014a); the first from 33.3 to 51.2 ks with a count rate upper limit of \(3.6 \times 10^{-3}\) counts s\(^{-1}\), and the second from 56 to 107 ks with an upper limit of \(3.0 \times 10^{-3}\) counts s\(^{-1}\) (see Figure 13(d)).
We converted the above count rate upper limits into fluxes by multiplying with a typical conversion factor $5 \times 10^{-11}$ erg/cm$^2$/count (see, e.g., Pagani 2014b).

We conclude that there is no evidence in favor of or against a common behavior of the X-ray afterglows of S-GRBs in view of the limited observations.

These aspects are noteworthy since in the case of long GRBs, the X-ray emission has a very crucial role (Pisani et al. 2016; Ruffini et al. 2017), which is not testable in the case of S-GRBs.

7. On the Short Bursts Originating in BH–NS Mergers

As pointed out in Fryer et al. (2015b) and Ruffini et al. (2016c, 2016b), U-GRBs are expected to originate in the BH–NS binaries produced by the further evolution of BdHNe (see, e.g., Becerra et al. 2016; Ruffini et al. 2016c). We recall that BdHNN progenitor systems are composed of a carbon–oxygen core ($\text{CO} \_\text{core}$) and an NS in a close binary system. When the $\text{CO} \_\text{core}$ explodes as a supernova (SN) Ib/c, its ejecta starts a hypercritical accretion process onto the companion NS, pushing its mass beyond the value $M_\text{crit}^\text{NS}$, and leading to the formation of a BH. This BH, together with the new NS ($\nu\text{NS}$) produced from the SN event, leads to the progenitor systems of the U-GRBs.

The orbital velocities of the BH–NS binaries formed from BdHNe are high and even large kicks are unlikely to make these systems unbound (Fryer et al. 2015b). U-GRBs represent a new family of BH–NS binaries unaccounted for in current standard population synthesis analyses (see, e.g., Fryer et al. 2015b).

U-GRBs are expected to lead to harder and shorter bursts in $\gamma$-rays, which explains the lack of their observational identification (Fryer et al. 2015b), and possibly pose a great challenge as they are considered to emit fast radio bursts. They also could manifest themselves, before the merging, as pulsar –BH binaries (see, e.g., Tauris et al. 2015 and references therein).

8. Conclusions

We first recalled the division of short bursts into two different sub-lasses (Ruffini et al. 2015): S-GRFs, with $E_{\text{iso}} \lesssim 10^{52}$ erg, $E_{\nu, \text{p}} \gtrsim 2$ MeV, and no GeV emission; and authentic S-GRBs, with $E_{\text{iso}} \gtrsim 10^{52}$ erg, $E_{\nu, \text{p}} \gtrsim 2$ MeV, and with GeV emission present, which is always detected by Fermi-LAT, when operative (Ruffini et al. 2015).

We then focus on two additional examples of S-GRBs: GRB 081024B, with $E_{\text{iso}} = (2.6 \pm 1.0) \times 10^{52}$ erg and $E_{\nu, \text{p}} = (9.6 \pm 4.9)$ MeV (see Section 3), and GRB 140402A, with $E_{\text{iso}} = (4.7 \pm 1.1) \times 10^{52}$ erg and $E_{\nu, \text{p}} = (6.1 \pm 1.6)$ MeV (see Section 4).

We perform time-integrated and time-resolved spectral analyses on both of these sources (see Sections 3.1.1–3.1.2 and 4.1.1–4.1.2) and infer their cosmological redshifts ($z = 3.12$ for the S-GRB 081024B and $z = 5.52$ for the S-GRB 140402A; see Sections 3.1.2 and 4.2.1, respectively). We also identify their P-GRB spectral emission. The P-GRB emission of S-GRB 081024B exhibit the convolution of BB spectra at different Doppler factors arising from a spinning BH, in total analogy with S-GRB 090510 (see Sections 2 and 3.1.2 and Ruffini et al. 2016a). The P-GRB emission of S-GRB 140402A is consistent with a single BB, expected to occur for a moderately spinning BH (see Section 4.1.2 SND Ruffini et al. 2016a).

The baryon load mass $M_\text{b}$, the Lorentz $\Gamma$ factor, and the properties of the CBM clouds are in agreement with those of the other S-GRBs: $M_\text{b} \approx 10^{-6} M_\odot$, $\Gamma \approx 10^4$ (see Sections 3.2.1 and 4.2.1), distances of the CBM clouds $r \approx 10^{16}$ cm, and CBM densities $n_{\text{CBM}} \approx 10^{-3}$ cm$^{-3}$ (see Sections 3.2.2 and
In analogy to the other S-GRBs, we confirm that the GeV emission turns on after the P-GRB emission and is coeval with the occurrence of the prompt emission (see Section 5). All of these coincidences point to the fact that the GeV emission originates from the onset of the BH formation (see the spacetime diagrams in Figure 3 of Ruffini et al. 2016a).

Most noteworthy is that the existence of a common power-law behavior in the rest-frame 0.1–100 GeV luminosities (see Figure 12 in Section 5), following the BH formation, points to a commonality in the mass and spin of the newly formed BH in all of these S-GRBs. This result is explainable with the expected mass of the merging NSs, each one of M ≈ 1.3–1.5 M⊙ (Ozel & Freire 2016), and the expected range of the non-rotating NS critical mass MNS, crit ≈ 2.2–2.7 M⊙ leading to a standard value of the BH mass and of its Kerr parameter a/M ≈ 1 (Ruffini et al. 2015).

Finally, in all S-GRBs, the energetics of the GeV emission implies the accretion of \( M \gtrsim 0.03–0.08 M_\odot \) or \( M \gtrsim 0.35–0.86 M_\odot \) for co- or counterrotating orbits with a maximally rotating BH, respectively (see Section 5). This accretion process, occurring in both S-GRBs and BdHNe (Becerra et al. 2016), is currently being analyzed for the occurrence of r-process (Ruffini et al. 2014; Becerra et al. 2016).

In all of the identified S-GRBs, within the Fermi-LAT FoV, GeV photons are always observed (Ruffini et al. 2016a, 2016c). This implies that no intrinsic beaming is necessary for the S-GRB GeV emission. The Lorentz factor of the GeV emission is \( \Gamma_{\text{GeV}} \gtrsim 300 \).

From Figure 13 for S-GRBs and from Figure 14 for S-GRFs, we conclude that in both systems there is no evidence for the early X-ray flares observed in BdHNe (Ruffini et al. 2017).

Before closing, we return to the issue of GW detectability by aLIGO from S-GRBs. We have already shown evidence of their non-detectability by aLIGO in GRB 090227B (Oliveira et al. 2014) and GRB 140619B (Ruffini et al. 2015) by computing the signal-to-noise ratio (S/N) up to the contact point of the binary NS components. In both cases, each NS has been assumed to have mass \( M_{\text{NS}} = 1.34 M_\odot = 0.5 M_{\text{crit}} \). There, it was concluded that the GW signals emitted in such systems were well below the S/N = 8 value needed for a positive detection.

These considerations have been extended in Ruffini et al. (2016b) to all S-GRBs. It was concluded there that such signals might be detectable for sources located at \( z < 0.14 \) (i.e., at distances smaller than the GW detection horizon of 640 Mpc) for the aLIGO 2022+ run. GRB 090510, to date the closest S-GRB, is located at \( z = 0.903 \) (i.e., 5842 Mpc) and, therefore, is outside such a GW detection horizon. We can then conclude that for sources at distances larger than that of GRB 090510, like GRB 081024B (at \( z = 3.12 \)) and GRB 140402A (at \( z = 5.52 \)) analyzed in this paper, no GW emission can be detected.

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