GRB 090227B: THE MISSING LINK BETWEEN THE GENUINE SHORT AND LONG GAMMA-RAY BURSTS

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ABSTRACT

The time-resolved spectral analysis of GRB 090227B, made possible by the Fermi-GBM data, allows us to identify in this source the missing link between the genuine short and long gamma-ray bursts (GRBs). Within the Firehose model of the GRBs we predict genuine short GRBs: bursts with the same inner engine of the long bursts but endowed with a severely low value of the baryon load, \( B \lesssim 5 \times 10^{-5} \). A first energetically predominant emission occurs at the transparency of the \( e^+e^- \) plasma, the Proper-GRB (P-GRB), followed by a softer emission, the extended afterglow. The typical separation between the two emissions is expected to be of the order of \( 10^{-3} \) to \( 10^{-2} \) s. We identify the P-GRB of GRB 090227B in the first 96 ms of emission, where a thermal component with the temperature \( kT = (517 \pm 28) \) keV and a flux comparable with the non-thermal part of the spectrum is observed. This non-thermal component as well as the subsequent emission, where there is no evidence for a thermal spectrum, is identified with the extended afterglow. We deduce a theoretical cosmological redshift \( z = 1.61 \pm 0.14 \). We then derive the total energy \( E_{e^+e^-}^{\text{tot}} = (2.83 \pm 0.15) \times 10^{53} \) erg, the baryon load \( B = (4.13 \pm 0.05) \times 10^{-5} \), the Lorentz factor at transparency \( \Gamma_B = (1.44 \pm 0.01) \times 10^5 \), and the intrinsic duration \( \Delta t' \sim 0.35 \) s. We also determine the average density of the circumburst medium (CBM), \( \langle n_{\text{CBM}} \rangle = (1.90 \pm 0.20) \times 10^{-5} \) particles \( \text{cm}^{-3} \). There is no evidence of beaming in the system. In view of the energetics and of the baryon load of the source, as well as of the low interstellar medium and of the intrinsic timescale of the signal, we identify the GRB progenitor as a binary neutron star. From the recent progress in the theory of neutron stars, we obtain masses of the stars \( m_1 = m_2 = 1.34 M_\odot \) and their corresponding radii \( R_1 = R_2 = 12.24 \) km and thickness of their crusts \( \sim 0.47 \) km, consistent with the above values of the baryon load, of the energetics and of the time duration of the event.

Key words: gamma-ray burst: general – gamma-ray burst: individual (GRB 090227B)

Online-only material: color figures

1. INTRODUCTION

The understanding of gamma-ray bursts (GRBs) is among the most fascinating and profound conceptual problems of relativistic astrophysics. Observations at high energies from space missions, such as BATSE (Meegan et al. 1992), Beppo-SAX (Metzger et al. 1997), Swift Burst Alert Telescope (BAT; Gehrels et al. 2005), AGILE (Tavani et al. 2008), Fermi Gamma-Ray Burst Monitor (GBM; Meegan et al. 2009), and others have revealed that GRBs emit almost the energy equivalent to a solar mass in a few seconds of the time of the observer. This allows the observability of these sources over the entire visible universe.

The first systematic analysis on the large sample of GRBs observed by the BATSE instrument on board the Compton Gamma-Ray Observer satellite (Meegan et al. 1992) evidenced a bimodal temporal distribution in the \( T_{90} \) observed duration of prompt emission of GRBs. The “long” and “short” GRBs were defined as being longer or shorter than \( T_{90} = 2 \) s.

Another fundamental progress was achieved by Beppo-SAX with the discovery of a prolonged soft X-ray emission, the “afterglow” (Costa et al. 1997), following the traditional hard X-ray emission observed by BATSE, that was called the “prompt emission.”

In recent years, the observations by the Swift satellite (Gehrels et al. 2005) evidenced the existence of a possible third class of burst, presenting hybrid properties between the short and the long ones: the Norris–Bonnell sources (Norris & Bonnell 2006). The prompt emission of these sources is characterized by an initial short spike-like emission lasting a few seconds, followed by a prolonged softer extended emission lasting up to some hundred seconds. They were initially indicated in the literature as “short GRBs with an extended emission.”

In parallel, the theoretical progress in the Firehose model of GRBs (see Ruffini et al. 2001a, 2001b, 2001c) has led to an alternative explanation of the Norris–Bonnell sources as “disguised short bursts” (Bernardini et al. 2007, 2008; Caito et al. 2009, 2010; de Barros et al. 2011): canonical long bursts exploding in halos of their host galaxies, with \( \langle n_{\text{CBM}} \rangle \sim 10^{-3} \) particles \( \text{cm}^{-3} \) (see Section 2.3).

The aim of this article, using the data obtained by the Fermi-GBM satellite (Meegan et al. 2009), is to probe the existence of a yet new class of GRBs which we define here as “genuine short GRBs,” theoretically predicted by the Firehose model (Ruffini et al. 2001b, 2002). This class of canonical GRBs is characterized by severely small values of the baryon load, \( B \lesssim 10^{-5} \) (see Figure 1). The energy emitted in the Proper-GRB (P-GRB) is predominant and the characteristic duration is expected to be shorter than a fraction of a second (see Section 2.4).

We have started a search for these genuine short GRBs among the bursts detected by the Fermi-GBM instrument in its first three years of mission. The initial list of short GRBs was reduced requiring that no prominent X-rays and optical afterglows be observed. Among these bursts we have identified GRB 090227B. From its observed light curves, we have performed the spectral analysis of the source, and within the theory we have inferred its cosmological redshift, and all the
basic parameters of the burst, as well as the isotropic energy, the Lorentz $\Gamma$ factor at transparency, and the intrinsic duration. In Section 2, we recall the relevant properties of the Fireball model. In Section 3, we report the observation of GRB 090227B by the different satellites and the data analysis. In Section 4, we determine all the parameters characterizing GRB 090227B within the Fireshell scenario, including the redshift. In Section 5, we provide an estimation of the lower limit on the Lorentz $\Gamma$ factor from the definition of opacity, finding the agreement with the theoretically determined Lorentz $\Gamma$ factor. In the conclusions we show that GRB 090227B is the missing link between the genuine short and the long GRBs, with some common characteristics between the two classes. Further analysis of genuine short GRB with a yet smaller value of $B$ should lead to P-GRB with a yet more pronounced thermal component. We identify the progenitor of GRB 090227B as a symmetric binary system of two neutron stars, each of $\sim 1.34 M_\odot$.

2. THE FIRESHELL VERSUS THE FIREBALL MODEL AND THE ISSUE OF THE PHOTOSPHERIC EMISSION

Soon after the announcement of the discovery of GRBs (Strong et al. 1975), Damour & Ruffini (1975) proposed to explain the energy source of GRBs in terms of the $e^+e^-$ pair plasma created in the process of vacuum polarization during the formation of a Kerr–Newman black hole. They mentioned that the energetics to be expected in this model is approximately $10^{34}-10^{35}$ erg for a $10 M_\odot$ black hole. At the time nothing was known about the energetics of GRBs, their distance being unknown. They did not pursue further the details of the model pending additional observational evidence.

The idea of the role of an $e^+e^-$ pair plasma as energy source of GRBs was proposed again and independently by Cavallo & Rees (1978). They proposed a sudden release of energy in a process of gravitational collapse leading to a large number of $e^+e^-$ pairs, whose instantaneous annihilation would lead to a vast release of energy pushing on the circumburst medium (CBM): the concept of “fireball.”

The concept of fireball was further examined by Goodman (1986), who quantified the dynamical effects of the expansion of the fireball computing the effect of the blueshift due to the bulk Lorentz $\Gamma$ factor on the observed temperature. Shemi & Piran (1990) were among the first to compute the dynamics of such a fireball in presence of baryonic matter, described by the adimensional parameter $\eta = E_0/M_{B}c^2$, in which $E_0$ is the initial total energy of the fireball. They clearly pointed out that for large values of $\eta$, photons carry most of the energy of the fireball. In the opposite regime most of $E_0$ is converted in the kinetic energy of the baryons and only a small fraction is carried away by the photons at transparency. Further works were presented by Meszaros et al. (1993), Piran et al. (1993) and Katz (1994).

After the discovery by Beppo-SAX (Costa et al. 1997) of the cosmological nature of GRBs (van Paradijs et al. 1997), it became clear that the energetics presented by Damour & Ruffini (1975) was indeed correct and their work represented one of the handful GRB models still viable (Ruffini 2001). The return to the model led to a further step in the comprehension of GRBs (Ruffini et al. 1999, 2000) with the detailed analysis of the rate equation that accounts for the gradual annihilation of the pairs, in a relativistic expanding shell, during the entire optically thick acceleration phase of GRBs: the concept of “Fireshell.”

The main differences between the fireball and the Fireshell scenarios are outlined in Bianco et al. (2006), while Akesson et al. (2007) definitely proved that in an optically thick $e^+e^-$ plasma the annihilation of the pairs does not occur instantaneously, as originally assumed by Cavallo and Rees. Instead, the optically thick $e^+e^-$ plasma reaches the thermal equilibrium in a very short timescale, $\sim 10^{-12}$ s, and then dynamically expands following the approach in Ruffini et al. (1999, 2000).

In the meantime, the BATSE observations led to a phenomenological classification of GRBs, based on their observed duration, into “long” and “short” GRBs (Klebesadel 1992; Dezalay et al. 1992; Kouveliotou et al. 1993; Tavani 1998). Initially this fact was interpreted in terms of different progenitors for these two classes (see Blinnikov et al. 1984; Woosley 1993; Paczynski 1998).

In 2001 an interpretation within the Fireshell model was proposed to explain the differences between the short and the long GRBs. This interpretation was based on the baryon load $B$ (inverse of $\eta$). In this picture, both long and short GRBs originate from the same basic machine, the dyadotorus, from an implosion leading to the formation of a Kerr–Newman black hole (Ruffini 2009). The long bursts correspond to GRBs with $B \gtrsim 3.0 \times 10^{-4}$ and the short ones to GRBs with $B \lesssim 10^{-5}$ (Figure 1). For $10^{-5} \lesssim B \lesssim 3.0 \times 10^{-4}$ it depends also on the value of the total energy of the pairs $E_{\gamma}^{\rm tot}$ (see Figure 2). The short bursts should have in the limit of $B \to 0$ no afterglow. This was followed in 2002 by a further theoretical work also evidencing the relevance of an additional parameter influencing the interpretation of the above classification: the average density of the environment CBM (Ruffini et al. 2002, 2004, 2005b). This led to the new concept of “disguised short” GRBs (Bernardini et al. 2007, 2008; Cairo et al. 2009, 2010; de Barros et al. 2011).

Let us briefly discuss in more detail the Fireshell model. As we have noted, the GRBs originate from the process of vacuum polarization occurring in the formation of a black hole, resulting in pair creation (Damour & Ruffini 1975; Ruffini & Xue 2008; Ruffini et al. 2010). The formed $e^+e^-$ plasma, with total energy $E_{\gamma}^{\rm tot}$, reaches the thermal equilibrium almost instantaneously (Akesson et al. 2007). The annihilation of these pairs occurs gradually and it is confined in an expanding shell, called Fireshell, which self-accelerates up to ultrarelativistic velocities (Ruffini et al. 1999), and engulfs the baryonic matter (of mass $M_0$) left over in the process of collapse, which thermalizes with the pairs due to the large optical depth (Ruffini et al. 2000). The baryon load is measured by the dimensionless parameter

![Figure 1. Energy emitted in the extended afterglow (solid green curve) and in the P-GRB (solid red curve) in units of $E_{\gamma}^{\rm tot} = 1.77 \times 10^{53}$ erg (dashed horizontal line), as functions of $B$. The crossing point, corresponding to the condition $E_{\gamma}^{\rm GRB} \equiv 50\% E_{\gamma}^{\rm tot}$, marks the division between the genuine short and disguised short and long GRBs region. (A color version of this figure is available in the online journal.)](image-url)
In the co-moving frame

Doppler blue-shifted toward the observer

Figure 2. Main quantities of the Fireshell model at the transparency for selected values of $E_{\text{tot}}^{\text{e}}$: the radius in the laboratory frame, the comoving frame and blueshifted toward the observer temperatures of the plasma, the Lorentz $\Gamma$ factor, and the fraction of energy radiated in the P-GRB and in the extended afterglow as functions of $B$. In these simulations a sudden transition between the optically thick adiabatic phase and the fully radiative condition at the transparency has been assumed.

(A color version of this figure is available in the online journal.)

$B = M_B c^2 / E_{\text{tot}}^{\text{e}}$. The Fireshell continues to self-accelerate until it reaches the transparency condition and a first flash of radiation, the P-GRB, is emitted (Ruffini et al. 2001b). The radius at which the transparency occurs, the theoretical temperature, the Lorentz factor, as well as the amount of the energy emitted in the P-GRB are functions of $E_{\text{tot}}^{\text{e}}$ and $B$ (see Figure 2).

In recent years a systematic analysis of the possible presence of a thermal component in the early phases of the prompt emission of GRBs has been performed using the earlier data from BATSE through the latest data from Fermi (Ryde 2004; Ryde & Pe'er 2009; Guiriec et al. 2011). The presence of episodes with a significant thermal component lasting typically from 20 to 50 s has been evidenced. In some specific cases the thermal component has been shown to vary with time following a broken power law (Ryde 2004; Ryde & Pe'er 2009). This problematic has led to the study of the so-called photospheric emission (Rees & Mészáros 2005; Pe’er et al. 2005, 2006; Lazzati & Begelman 2010). It has been pointed out (Ruffini et al. 2011; Izzo et al. 2012a, 2012b; Penacchioni et al. 2012) that a marked difference exists between these prolonged emissions occurring at $\Gamma \sim 1$ and the specific ones of the $e^+e^-$ recombination occurring at ultrarelativistic regimes, $\Gamma > 10^2$, and lasting at most a few seconds. In the specific cases of GRB 970828 (Izzo et al. 2012a), GRB 090618 (Izzo et al. 2012b) and GRB 101023 (Penacchioni et al. 2012) the existence of these two components has been evidenced. The first component, at $\Gamma \sim 1$, has been associated with the Proto Black Hole, while the one at $\Gamma \geq 10^2$ has been identified with the P-GRB emission ($\Gamma = 495$, for GRB 090618, $\Gamma = 143$, for GRB 970828, and $\Gamma = 261$ for GRB 101023).

2.1. The Extended Afterglow Emission

After transparency, the residual expanding plasma of leptons and baryons interacts with the CBM and, due to these collisions, starts to slow down giving rise to a multi-wavelength emission: the extended afterglow. Assuming a fully radiative condition, the structures observed in the extended afterglow of a GRB are described by two quantities associated with the environment: the CBM density profile $n_{\text{CBM}}$, which determines the temporal behavior of the light curve, and the Fireshell surface filling factor $R = A_{\text{eff}} / A_{\text{vis}}$, in which $A_{\text{eff}}$ is the effective emitting area of the Fireshell and $A_{\text{vis}}$ its total visible area (Ruffini et al. 2002, 2005a). This second parameter takes into account the inhomogeneities in the CBM and its filamentary structure (Ruffini et al. 2004). The emission process of the collision between the baryons and the CBM has been assumed in the comoving frame of the shell as a modified blackbody spectrum...
Figure 3. Plots of the arrival time separation $\Delta t_\text{d}$ between the P-GRB and the peak of the extended afterglow as function of $B$ for four different values of $E_\text{tot}^{\text{int}}$, measured in the source cosmological rest frame. This computation has been performed assuming four constant CBM density $n_{\text{cbm}} = 1.0, 1.0 \times 10^{-1}, 1.0 \times 10^{-3}, 1.0 \times 10^{-5}$ particles cm$^{-3}$.

(A color version of this figure is available in the online journal.)

(Patricelli et al. 2012), given by

$$
\frac{dN_j}{dV d\epsilon} = \frac{8\pi}{h^3 c^3} \left( \frac{\epsilon}{kT} \right)^a \frac{\epsilon^2}{\exp(\epsilon/kT) - 1},
$$

where $a$ is a phenomenological parameter. It is appropriate to clarify that this emission is different from the photospheric one due to the $e^+e^-$ plasma annihilation, since it originates from the interactions between the baryons and the CBM in an optically thin regime.

The observed GRB non-thermal spectral shape is then produced by the convolution of a very large number of modified thermal spectra with different temperatures and different Lorentz and Doppler factors. This convolution is performed over the surfaces of constant arrival time for the photons at the detector (EQuiTemporal Surfaces, EQTS; Bianco & Ruffini 2005a, 2005b) encompassing the total observation time. The observed hard-to-soft spectral variation comes out naturally from the decrease with time of the comoving temperature and of the CBM density $n_{\text{CBM}}$.

Assuming the spherical symmetry of the system, the isotropic energy emitted in the burst, $E_{\text{iso}}$, is equal to the energy of the $e^+e^-$ plasma, $E_{\text{tot}}^{\text{int}}$, and the GRB bolometric light curve is composed of the P-GRB and the extended afterglow. Their relative energetics and observed time separation are functions of the energy $E_{\text{tot}}^{\text{int}}$, of the baryon load $B$, and of the CBM density distribution $n_{\text{CBM}}$ (see Figure 3). In particular, for decreasing $B$, the extended afterglow light curve “squeezes” itself on the P-GRB and the P-GRB peak luminosity increases (see Figure 4).

To reproduce the shape of the light curve for each CBM clump we must determine the filling factor $\mathcal{R}$, which determines the effective temperature in the comoving frame and the corresponding peak energy of the spectrum, and the CBM density $n_{\text{CBM}}$, which determines the temporal behavior of the light curve. It is clear that, since the EQTS encompass emission processes occurring at different comoving times weighted by their Lorentz and Doppler factors, the fit of a single spike is not only a function of the properties of the specific CBM clump but of the entire previous history of the source. Due to the nonlinearity of the system and to the EQTS, any change in the simulation produces observable effects up to a much later time. This brings us to an extremely complex procedure by trial and error in the data simulation to reach the uniqueness.

It is appropriate to recall that in the Fireshell model the two phases, the one preceding the $e^+e^-$ transparency and the following one, as well as their corresponding energetics, are directly linked by the Fireshell equations of motion (see...
Figure 2). Consequently, their agreement with the data cannot be independently adjusted and optimized.

2.2. The Canonical Long GRBs

According to this theory, the canonical long GRBs are characterized by a baryon load varying in the range $3.0 \times 10^{-4} \lesssim B \lesssim 10^{-2}$ and they occur in a typical galactic CBM with an average density $\langle n_{\text{CBM}} \rangle \approx 1$ particle cm$^{-3}$. As a result, the extended afterglow is predominant with respect to the P-GRB (see Figure 1).

2.3. The Disguised Short GRBs

After the observations by Swift of GRB 050509B (Gehrels et al. 2005), which was declared in the literature as the first short GRB with an extended emission ever observed, it has become clear that all such sources are actually disguised short GRBs (de Barros et al. 2011). It is conceivable and probable that a large fraction of the declared short duration GRBs in the BATSE catalog, observed before the discovery of the afterglow, are also members of this class. In the case of the disguised short GRBs, the baryon load varies in the same range of the long bursts, while the CBM density is of the order of $10^{-3}$ particles cm$^{-3}$. As a consequence, the extended afterglow results in a “deflated” emission that can be exceeded in peak luminosity by the P-GRB (Bernardini et al. 2007, 2008; Caito et al. 2009, 2010; de Barros et al. 2011). Indeed, the integrated emission in the extended afterglow is much larger than the one of the P-GRB (see Figure 1), as expected for long GRBs. With these understandings, long and disguised short GRBs are interpreted in terms of long GRBs exploding, respectively, in a typical galactic density or in a galactic halo density.

These sources have given the first evidence of GRBs originating from binary mergers, formed by two neutron stars and/or white dwarfs in all possible combinations, that have spiraled out from their host galaxies into the halos (Bernardini et al. 2007, 2008; Caito et al. 2009, 2010; de Barros et al. 2011). This interpretation has been supported by direct optical observations of GRBs located in the outskirt of the host galaxies (Sahu et al. 1997; van Paradijs et al. 1997; Bloom et al. 2006; Troja et al. 2008; Fong et al. 2010; Berger 2011; Kopač et al. 2012).

2.4. The Class of Genuine Short GRBs

The canonical genuine short GRBs occur in the limit of very low baryon load, e.g., $B \lesssim 10^{-5}$ with the P-GRB predominant with respect to the extended afterglow. For such small values of $B$ the afterglow peak emission shrinks over the P-GRB and its flux is lower than that of the P-GRB (see Figure 4).

The thermalization of photon-pair plasma is reached in a very short timescale at the beginning of the expansion phase and the thermal equilibrium is implemented during the entire phase of the expansion (Aksenov et al. 2007), therefore the spectrum of these genuine short GRBs is expected to be characterized by a significant thermal-like emission. Since the baryon load is small but not zero, in addition to the predominant role of the P-GRB, a non-thermal component originating from the extended afterglow is expected.

3. OBSERVATIONS AND DATA ANALYSIS

OF GRB 090227B

At 18:31:01.41 UT on 2009 February 27, the Fermi-GBM detector (Guiriec 2009) triggered and located the short and bright burst, GRB 090227B (trigger 257452263/090227772). The on-ground calculated location, using the GBM trigger data, was (R.A., Decl.) (J2000) = (11h48m36s, 32°10’12”). With an uncertainty of 1°77 (statistical only). The angle from the Fermi-LAT boresight was 72°. The burst was also located by the Inter-Planetary Network (IPN; Golenetskii et al. 2009a) and detected by Konus/Wind (Golenetskii et al. 2009b), showing a single pulse with a duration of $\sim 0.2$ s (20 keV–10 MeV). No X-rays...
and optical observations were reported on the GCN Circular Archive, thus the redshift of the source is unknown.

To obtain the *Fermi*-GBM light curves and the spectrum in the energy range 8 keV–40 MeV, we made use of the RMFIT program. For the spectral analysis, we have downloaded the TTE (Time-Tagged Events) files from the NASA Goddard Space Flight Center Web site\(^4\), suitable for short or highly structured (Time-Tagged Events) files from the NASA Goddard Space Center Archive, thus the redshift of the source is unknown.

We have performed a further analysis in the time interval from \(T_0 + 0.192\) s to \(T_0 + 0.896\) s, which we indicate as \(T_{\text{tail}}\). We have repeated the time-integrated analysis considering the same spectral models as the previous interval (see Table 1 and Figure 6). As reported in Table 2, within the \(T_{\text{spike}}\) time interval, both BB+Band and Band+PL models marginally improve the fits of the data with respect to Compt+PL model within a confidence level of 5\%. Again, the C-STAT values of BB+Band and Band+PL models are almost the same (ΔC-STAT \(\approx 0.15\)) and they are statically equivalent in the \(T_{\text{spike}}\). For the BB+Band model, the observed temperature of the thermal component is \(kT = (515 \pm 28)\) keV and the flux ratio between the BB component and the NT component increases up to \(F_{\text{BB}}/F_{\text{NT}} \approx 0.69\).

We have performed a further analysis in the time interval from \(T_0 + 0.192\) s to \(T_0 + 0.896\) s, which we indicate as \(T_{\text{tail}}\), by considering the BB+PL, Compt, and PL models (see Figure 7 and Table 1). The comparison in Table 2 shows that the best fit is the Compt model. The BB+PL model is less preferred. From the data analysis in the \(T_{\text{tail}}\) time interval, we can conclude that a thermal component is ruled out.

In view of the above, we have focused our attention on the fit of the data of the BB+Band model within the Fireshell scenario, which is equally probable from a mere statistical point of view, with the other two choices, namely Band+PL and Compt+PL. According to the Fireshell scenario (see Section 2.1), the emission within the \(T_{\text{spike}}\) time interval is related to the P-GRB and is expected to be thermal. In addition, the transition between the transparency emission of the P-GRB and the extended afterglow is not sharp. The time separation between the P-GRB and the peak of the extended afterglow depends on the energy of the \(e^+e^-\) plasma \(E_{\text{pe}}\), the baryon load \(B\), and the CBM density \(n_{\text{CBM}}\) (see Figure 4).

### Table 1

The C-STAT Improvement with the Addition of Extra Parameters in the \(T_{90}\), \(T_{\text{spike}}\), and \(T_{\text{tail}}\) Time Intervals (see Table 1)

| Int. | Model Description | \(\Delta C\)-STAT | Significance |
|------|-------------------|-------------------|-------------|
| \(T_{90}\) | BB+Band over Compt+PL | 3.87 | 0.049 |
|      | BB+PL over Compt+PL | 2.98 | 0.084 |
| \(T_{\text{spike}}\) | BB+Band over Compt+PL | 4.02 | 0.045 |
|      | BB+PL over Compt+PL | 3.87 | 0.049 |
| \(T_{\text{tail}}\) | BB+PL over PL | 2.22 | 0.33 |
|      | BB+PL over Compt | 2.66 | 0.10 |
|      | Compt over PL | 4.88 | 0.027 |

\(^4\) ftp://legacy.gsfc.nasa.gov/fermi/data/rgb/bursts
indeed predicts a thermal component due to the transparency of the $e^+e^-$ plasma in the early part of the prompt emission of GRBs (see Section 2), while no thermal component is expected in the extended afterglow (see Section 2.1), as observed in the $T_{90}$ time interval.

Our theoretical interpretation is consistent with the observational data and the statistical analysis. From an astrophysical point of view, the BB+Band model is preferred over the other two models, and is statistically equivalent in view of the above theoretical considerations.

### 3.2. Time-resolved Spectral Analysis

We have performed a time-resolved spectral analysis on shorter selected time intervals of 32 ms in order to correctly identify the P-GRB, namely finding out in which time interval the thermal component exceeds or at least has a comparable flux with respect to the NT component due to the onset of the extended afterglow. In this way we can single out the contribution of the NT component in the spectrum of the P-GRB.

A time-resolved spectral analysis was performed by Guiriec et al. (2010) by selecting time intervals from 2 ms to 94 ms. In view of the low statistical content in some small time bins, the authors fitted the data by using simple Band functions. We have performed a time-resolved analysis on time intervals of 32 ms (see Figure 8) in order to optimize the statistical content in each time bin and to test the presence of BB plus an extra NT component. The results are summarized in Table 3, where we have compared the BB+NT with the single Band function.

In our analysis we have preferred the $\chi^2$ statistic because of the high photon fluxes in the first five time intervals, $\gtrsim 100$ photons (cm$^2$ s)$^{-1}$.

Within the first time-resolved interval the BB+PL model has a thermal flux ($11.2 \pm 3.4$) times bigger than the PL flux; the fit with BB+Band provides $F_{BB} = (0.50 \pm 0.26)F_{NT}$, where the NT component is in this case the Band model. In the second and fourth intervals, the BB+Band model provides an improvement at a significance level of 5% in the fitting procedure with respect to the simple Band model (see Table 3, last column). In the third time interval as well as in the remaining time intervals up to $T_0 + 0.192$ s the Band spectral models provide better fits with respect to the BB+NT ones.

This is exactly what we expect from our theoretical understanding: from $T_0 - 0.032$ s to $T_0 + 0.096$ s we have found the edge of the P-GRB emission, in which the thermal components have fluxes higher than or comparable to the NT ones. The third interval corresponds to the peak emission of the extended afterglow (see Figure 11). The contribution of the extended afterglow in the remaining time intervals increases while the thermal flux noticeably decreases (see Table 3).

We have then explored the possibility of a further rebinning of the time interval $T_{\text{spike}}$, taking advantage of the large statistical content of each time bin. We have plotted the NaI-n2 light
curve of GRB 090227B using time bins of 16 ms (see Figure 9, left panels). The rebinned light curves show two spike-like substructures. The duration of the first spike is 96 ms and it is clearly distinct from the second spike. In this time range the observed BB temperature is \( kT = (517 \pm 28) \text{ keV} \) (see Table 4) and the ratio between the fluxes of the thermal component and the non-thermal component is \( F_{BB}/F_{NT} \approx 1.1 \). Consequently, we have interpreted the first spike as the P-GRB and the second spike as part of the extended afterglow. Their spectra are shown in Figure 9 (right panels) and the results of the spectral analysis are summarized in Table 4.

4. ANALYSIS OF GRB 090227B IN THE FIRESHELL MODEL

The identification of the P-GRB is fundamental in order to determine the baryon load and the other physical quantities characterizing the plasma at the transparency point (see Figure 2). The determination of the cosmological redshift is crucial, which can be derived combining the observed fluxes and the spectral properties of the P-GRB and of the extended afterglow with the equation of motion of our theory. From the cosmological redshift we derive \( E_{tot}e^+e^- \) and the relative energetics of the P-GRB and of the extended afterglow components (see Figure 2). Having so derived the baryon load \( B \) and the energy \( E_{tot}^e^+e^- \), we can constrain the total energy and simulate the canonical light curve of the GRBs with their characteristic pulses, modeled by a variable number density distribution of the CBM around the burst site.

4.1. Estimation of the Redshift of GRB 090227B

Having determined the redshift of the source, the analysis consists of equating \( E_{tot}^e^+e^- \equiv E_{iso} \) (namely \( E_{iso} \) is a lower limit on \( E_{tot}^e^+e^- \)) and inserting a value of the baryon load to complete the simulation. The right set of \( E_{tot}^e^+e^- \) and \( B \) is determined when the theoretical energy and temperature of the P-GRB match the observed ones of the thermal emission [namely \( E_{P-GRB} \equiv E_{BB} \) and \( kT_{obs} = kT_{blue}/(1+z) \)].

In the case of GRB 090227B, we have estimated the ratio \( E_{P-GRB}/E_{tot}^e^+e^- \) from the observed fluences:

\[
\frac{E_{P-GRB}}{E_{tot}^e^+e^-} = \frac{4\pi d_l^2 F_{BB} \Delta t_{BB}/(1+z)}{4\pi d_l^2 F_{tot} \Delta t_{tot}/(1+z)} = \frac{S_{BB}}{S_{tot}},
\]

where \( d_l \) is the luminosity distance of the source and \( S = F \Delta t \) are the fluences. The fluence of the BB component of the P-GRB (see Table 4, first interval) is \( S_{BB} = (1.54 \pm 0.45) \times 10^{-5} \text{ erg cm}^{-2} \). The total fluence of the burst is \( S_{tot} = (3.79 \pm 0.20) \times 10^{-5} \text{ erg cm}^{-2} \) and has been evaluated in the time interval from \( T_0 - 0.016 \text{ s} \) to \( T_0 + 0.896 \text{ s} \). This interval slightly differs from the \( T_0 \) because of the new time boundaries defined after the rebinning of the light curve at resolution of 16 ms. Therefore the observed energy ratio is \( E_{P-GRB}/E_{tot}^e^+e^- = (40.67 \pm 0.12)\% \).
As is clear from the bottom right diagram in Figure 2, for each value of this ratio we have a range of possible parameters $B$ and $E_{\text{tot}}^{r_e}$. In turn, for each of their values we can determine the theoretical blueshifted toward the observer temperature $kT_{\text{blue}}$ (see top right diagram in Figure 2). Correspondingly, for each couple of value of $B$ and $E_{\text{tot}}^{r_e}$, we estimate the value of $z$ by the ratio between $kT_{\text{blue}}$ and the observed temperature of the P-GRB $kT_{\text{obs}}$:

$$\frac{kT_{\text{blue}}}{kT_{\text{obs}}} = 1 + z.$$  \hspace{1cm} (3)

In order to remove the degeneracy $[E_{\text{tot}}^{r_e}(z), B(z)]$, we have made use of the isotropic energy formula

$$E_{\text{iso}} = 4\pi d_I^2 \frac{S_{\text{tot}}}{(1+z)} \int_{E_{\text{min}}/(1+z)}^{E_{\text{max}}/(1+z)} EN(E) \, dE$$  \hspace{1cm} (4)

in which $N(E)$ is the photon spectrum of the burst and the integrals are due to the bolometric correction on $S_{\text{tot}}$. The correct value is the one for which the condition $E_{\text{iso}} \equiv E_{\text{tot}}^{r_e}$ is satisfied.

We have found the equality at $z = 1.61 \pm 0.14$ for $B = (4.13 \pm 0.05) \times 10^{-5}$ and $E_{\text{tot}}^{r_e} = (2.83 \pm 0.15) \times 10^{53}$ erg. The complete quantities so determined are summarized in Table 5.

4.2. The Analysis of the Extended Afterglow and the Observed Spectrum of the P-GRB

As noted in Section 2, the arrival time separation between the P-GRB and the peak of the extended afterglow is a function of $E_{\text{tot}}^{r_e}$ and $B$ and depends on the detailed profile of the CBM density. For $B \sim 4 \times 10^{-5}$ (see Figure 3), the time separation is $\sim 10^{-3} - 10^{-2}$ s in the source cosmological rest frame. In this light, there is an interface between the reaching of transparency of the P-GRB and the early part of the extended afterglow. This connection has already been introduced in the literature (Pe’er et al. 2012; Izzo et al. 2012b; Penacchioni et al. 2012).

From the determination of the initial values of the energy, $E_{\text{tot}}^{r_e} = 2.83 \times 10^{53}$ erg, of the baryon load, $B = 4.13 \times 10^{-5}$, and of the Lorentz factor $\Gamma_{\text{tr}} = 1.44 \times 10^4$, we have simulated the light curve of the extended afterglow by deriving the radial distribution of the CBM clouds around the burst site (see Table 6 and Figure 10). In particular, each spike in Figure 10 corresponds to a CBM cloud. The error boxes on the number density on each cloud is defined as the maximum possible tolerance to ensure the agreement between the simulated light curve and the observed data. The average value of the CBM density is $\langle n \rangle = (1.90 \pm 0.20) \times 10^{-5}$ particles cm$^{-3}$ with an average density contrast $\langle \delta n / n \rangle = 0.82 \pm 0.11$ (see also Table 5). These
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Figure 8. 32 ms time-binned NaI-n2 light curve of GRB 090227B in the time interval from $T_0 - 0.032$ s to $T_0 + 0.192$ s; each time bin corresponds to the time-resolved interval considered in Section 3.2.

(A color version of this figure is available in the online journal.)

Table 3

| Interval (s) | Models       | $kT$ (keV) | $E_\nu$ (keV) | $\alpha$     | $\beta$     | $F_{\text{int}} \times 10^{-5}$ (erg cm$^{-2}$ s$^{-1}$) | $\chi^2$/dof | $F_{\text{BB/NT}}$ BB+Band over Band |
|--------------|--------------|------------|---------------|--------------|-------------|----------------------------------------------------------|--------------|--------------------------------------|
| $-0.032 \to 0.000$ | BB+PL | 274 ± 17   | 1703 ± 407   | $-1.75 \pm 0.29$ | 0.50 ± 0.25 | 7.03 ± 0.76  | 196.85/241 = 0.82 | 11.2 ± 3.4 |
|               | BB+Band     | 280 ± 66   | 1493 ± 155   | $-0.21 \pm 0.11$ | 0.50 ± 0.25 | 8.22 ± 0.99  | 180.23/239 = 0.75 | 0.50 ± 0.26 | 0.051 |
| $0.000 \to 0.032$ | BB+PL | 377 ± 12   | 858 ± 214    | $-1.20 \pm 0.03$ | 0.15 ± 0.17 | 62.2 ± 3.6   | 308.97/241 = 1.28 | 1.04 ± 0.11 | 0.041 |
|               | BB+Band     | 571 ± 44   | 2140 ± 102   | $-0.10 \pm 0.06$ | 0.15 ± 0.17 | 46.2 ± 2.3   | 222.54/239 = 0.93 | 1.41 ± 0.38 | 0.081 |
| $0.032 \to 0.064$ | BB+PL | 437 ± 20   | 1713 ± 1045  | $-1.21 \pm 0.03$ | 0.42 ± 0.14 | 43.4 ± 3.1   | 247.41/241 = 1.03 | 1.00 ± 0.24 | 0.020 |
|               | BB+Band     | 572 ± 65   | 2439 ± 257   | $-0.29 \pm 0.07$ | 0.42 ± 0.14 | 35.0 ± 2.6   | 222.18/239 = 0.93 | 0.55 ± 0.35 | 0.081 |
| $0.064 \to 0.096$ | BB+PL | 329 ± 21   | 435 ± 297    | $-1.41 \pm 0.04$ | 0.48 ± 0.09 | 17.8 ± 1.9   | 241.91/241 = 1.00 | 0.92 ± 0.27 | 0.020 |
|               | BB+Band     | 373 ± 34   | 1586 ± 281   | $-0.48 \pm 0.29$ | 0.48 ± 0.09 | 17.5 ± 1.9   | 221.50/239 = 0.93 | 0.85 ± 0.28 | 0.020 |
| $0.096 \to 0.128$ | BB+PL | 124.9 ± 8.4 | 454 ± 162    | $-1.27 \pm 0.04$ | 0.11 ± 0.30 | 18.9 ± 0.23  | 258.17/241 = 1.07 | 0.21 ± 0.08 | 0.061 |
|               | BB+Band     | 144 ± 84   | 622 ± 112    | $-0.11 \pm 0.17$ | 0.11 ± 0.30 | 16.1 ± 1.1   | 262.61/239 = 0.95 | 0.13 ± 0.06 | 0.067 |
| $0.128 \to 0.160$ | BB+PL | 35.5 ± 4.8  | unc          | $-1.52 \pm 0.08$ | 0.12 ± 1.4  | 8.27 ± 0.95  | 202.44/241 = 0.84 | 0.13 ± 0.06 | 0.045 |
|               | BB+Band     | 39.6 ± 6.8 | 193 ± 124    | $-0.75 \pm 0.40$ | 0.12 ± 1.4  | 2.8 ± 1.2    | 198.00/239 = 0.83 | 0.14 ± 0.08 | 0.067 |
| $0.160 \to 0.192$ | BB+PL | 30.2 ± 7.7  | unc          | $-1.19 \pm 0.10$ | 0.12 ± 1.4  | 5.7 ± 1.4    | 237.82/241 = 0.99 | 0.020 ± 0.019 | 0.0045 |

Notes. In the first column we have indicated the time bin; in the following five columns we have indicated the spectral models and their parameters. In the next three columns we have listed, respectively, the total flux, the $\chi^2$, and the ratio between the thermal (where considered) and the non-thermal fluxes. The last column reports the significance in the addition of the BB with respect the sole Band model.

Values are typical of the galactic halos environment. The filling factor varies in the range $9.1 \times 10^{-12} \lesssim R \lesssim 5 \times 10^{-11}$, up to $2.38 \times 10^{17}$ cm away from the burst site, and then drops to the value $R = 1.0 \times 10^{-15}$. The value of the $\alpha$ parameter has been found to be $-1.99$ along the total duration of the GRB. In Figure 11 we show the NaI-n2 simulated light curve.
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Figure 9. 16 ms time-binned NaI-n2 light curves of the P-GRB (left upper panel) and the extended afterglow (left lower panel) and their NaI-n2+BGO-b0 νFν spectra (on the right, the upper panel for the P-GRB and the lower one for the extended afterglow). The fit of the P-GRB is composed of a BB superimposed by a Band spectrum; the extended afterglow is well fitted by a simple Band function.

(A color version of this figure is available in the online journal.)

Table 4
The Results of the Spectral Analysis of the P-GRB (from \( T_0 - 0.016 \) s to \( T_0 + 0.080 \) s, Best-fit BB+Band Model) and the Extended Afterglow (from \( T_0 + 0.080 \) s to \( T_0 + 0.368 \) s, Best-fit Band Model) of GRB 090227B in the Energy Range 8 keV–40 MeV

| Model   | \( kT \) (keV) | \( \alpha \) | \( \beta \) | \( E_{\text{peak}} \) (keV) | \( F_{\text{tot}} \) (erg cm\(^{-2}\) s\(^{-1}\)) | \( F_{\text{BB}} \) (erg cm\(^{-2}\) s\(^{-1}\)) | C-STAT/dof |
|---------|---------------|-------------|-------------|-----------------|-----------------|-----------------|-------------|
| P-GRB   | 517 ± 28      | -0.80 ± 0.05| -2.14 ± 0.17| 952 ± 251       | \((3.13 \pm 0.13) \times 10^{-4}\) | \((1.61 \pm 0.47) \times 10^{-4}\) | 263.51/239  |
| Ext. Aft.| -0.79 ± 0.06  | -2.01 ± 0.10| 1048 ± 178   | \((2.66 \pm 0.26) \times 10^{-5}\) |                |            | 276.50/241  |

Table 5
The Results of the Simulation of GRB 090227B in the Fireshell Model

| Fireshell Parameter | Value                   |
|--------------------|-------------------------|
| \( E_{\text{tot}}^{\text{nu}} \) (erg) | \((2.83 \pm 0.15) \times 10^{37}\) |
| \( B \)            | \((4.13 \pm 0.05) \times 10^{-5}\) |
| \( \Gamma_{\text{tr}} \) | \((1.44 \pm 0.01) \times 10^{4}\) |
| \( r_{\text{tr}} \) (cm) | \((1.76 \pm 0.05) \times 10^{13}\) |
| \( k_{\text{blue}} \) (keV) | \((1.34 \pm 0.01) \times 10^{3}\) |
| \( z \)            | 1.61 ± 0.14             |
| \( \langle n \rangle \) (particles cm\(^{-3}\)) | \((1.90 \pm 0.20) \times 10^{-5}\) |
| \( \langle n/n \rangle \) | 0.82 ± 0.11             |

\((8–1000 \) keV) of GRB 090227B and in Figure 12 (left panel) we show the corresponding spectrum in the early \( \sim 0.4 \) s of the emission, using the spectral model described by Equation (1) (Patricelli et al. 2012). The simulation of the extended afterglow starts \( T_a - T_0 \sim 0.017 \) s after the Trigtime \( T_0 \). After the submission of this manuscript, at the 13th Marcel Grossmann meeting Dr. G. Vianello suggested to extend our simulations from 1 MeV all the way to 40 MeV, since significant data are available from the BGO detector. Without changing the parameters used in the theoretical simulation of the NaI-n2 data, we have extended the simulation up to 40 MeV and we compared the results with the BGO-b0 data (see Figure 12, right panel). The theoretical simulation we performed, optimized on the NaI-n2 data alone, is perfectly consistent with the observed data all over the entire range of energies covered by the Fermi-GBM detector, both NaI and BGO.

We turn now to the emission of the early 96 ms. We have studied the interface between the P-GRB emission and the onset of the extended afterglow emission. In Figure 13 we have
plotted the thermal spectrum of the P-GRB and the Fireshell simulation (from $T_0 + 0.015 \text{ s}$ to $T_0 + 0.080 \text{ s}$) of the early interaction of the extended afterglow. The sum of these two components is compared with the observed spectrum from the NaI-n2 detector in the energy range 8–1000 keV (see Figure 13, left panel). Then again, from the theoretical simulation in the energy range of the NaI-n2 data we have verified the consistency of the simulation extended up to 40 MeV with the observed data all over the range of energies covered by the Fermi-GBM detector, both NaI and BGO. The result is shown in Figure 13 (right panel).

5. CONSISTENCY WITH THE OPACITY DUE TO PAIR PRODUCTION

It is interesting to compare the Lorentz $\Gamma$ factor theoretically determined from the P-GRB analysis with the lower limit coming from the opacity argument applied to the afterglow emission.

An estimate on this lower limit comes from the solution of the classical compactness problem for GRBs which arises from the combination of their large energy released, $\sim 10^{51} \text{ erg}$, the short variability timescale $\delta t$ of a few milliseconds and
As Ruderman (1975) pointed out, relativistic effects can solve this problem. The causality limit of a source moving relativistically with Lorentz factor $\Gamma \gg 1$ toward us is $R \leq c\delta t/\Gamma^2$. Additionally, the observed photons have been blueshifted. At the source they have lower energy, by a factor $\approx 1/\Gamma$, which may be insufficient for pair production. Together this leads to a decrease in the estimated optical depth by a factor of $\Gamma^{2+2\beta}$ (Piran 2012), where $\beta$ is the high energy spectral index of the photon number distribution. Thus, the average optical depth, up to a factor due to the cosmological effects, is

$$\tau_{\gamma\gamma} = \frac{f_p}{\Gamma^{2+2\beta}} \frac{\sigma_T S d_l^2}{c^2 \delta t^2 m_e c^2}, \quad (5)$$

where $f_p$ is the fraction of photon pairs at the source that can effectively produce pairs, $\sigma_T$ is the Thompson cross-section and $S$ is the observed fluence. From the condition $\tau_{\gamma\gamma} < 1$, Equation (5) becomes

$$\Gamma > \left( \frac{f_p \sigma_T S d_l^2}{c^2 \delta t^2 m_e c^2} \right)^{\frac{1}{\beta + 2}}. \quad (6)$$

By setting $\delta t$ equal to the minimum variability timescale observed for GRB 090227B, $\sim 2$ ms (Guiriec et al. 2010), and

the observed hard non-thermal spectrum. Using the usual (Newtonian) causality limit on the size $R \leq c\delta t$ to estimate the density of photons, one finds that the optical depth for pair production at the source $\gamma\gamma \rightarrow e^+e^-$ would be $\sim 10^{15}$ (see Piran 1999). Such an optically thick source could not emit the observed non-thermal spectrum.
using the observed total fluence, $S_{\text{tot}} = 3.79 \times 10^{-5}$ erg cm$^{-2}$, the high energy spectral index, $\beta = 2.90$, and the theoretically inferred redshift, $z = 1.61$, we obtain a lower limit $\Gamma > 594$.

The large quantitative difference between our theoretically estimated Lorentz factor from the P-GRB and the one derived from the opacity argument is not surprising in view of the very different approximations adopted. While the determination from the P-GRB consists of a precise analysis at the instant of transparency, the determination of the lower limit from the Equation (6) is based on an estimate taking a time-averaged value on the entire extended afterglow.

It is important, of course, that the precise value determined from the P-GRB does fulfill the inequality given in Equation (6).

6. CONCLUSIONS

The comprehension of this short GRB has been improved by analyzing the different spectra in the $T_{90}$, $T_{\text{spike}}$, and $T_{\text{tail}}$ time intervals. We have shown that within the $T_{90}$ and the $T_{\text{spike}}$ all the considered models (BB+Band, Band+PL, Compt+PL) are viable, while in the $T_{\text{tail}}$ time interval the presence of a thermal component is ruled out. The result of the analysis in the $T_{\text{tail}}$ time interval gives an additional correspondence between the Fireshell model (see Section 2.1) and the observational data. According to this picture, the emission within the $T_{\text{spike}}$ time interval is related to the P-GRB, and it is expected to have a thermal spectrum with an additional extra NT component due to an early onset of the extended afterglow. In this time interval a BB with an additional Band component has been observed and we have shown that it is statistically equivalent to the Compt+PL and the Band+PL models. Our theoretical interpretation is consistent with the observational data and statistical analysis. From an astrophysical point of view, the BB+Band model is preferred over the Compt+PL and the Band+PL models, which has been described by a consistent theoretical model.

GRB 090227B is the missing link between the genuine short GRBs, with the baryon load $B \lesssim 5 \times 10^{-5}$ and theoretically predicted by the Fireshell model (Ruffini et al. 2001a, 2001b, 2001c), and the long bursts.

From the observations, GRB 090227B has an overall emission lasting $\sim 0.9$ s with a fluence of $3.79 \times 10^{-5}$ erg cm$^{-2}$ in the energy range 8 keV–40 MeV. In the absence of optical identification, no determination of its cosmological redshift and of its energetics was possible.

Thanks to the excellent data available from Fermi-GBM (Meegan et al. 2009), it has been possible to probe the comparison between the observation and the theoretical model. In this sense, we have then performed a more detailed spectral analysis on the timescale as short as 16 ms of the time interval $T_{\text{spike}}$. As a result we have found a thermal emission in the early 96 ms which we have identified with the theoretically expected P-GRB component. The subsequent emission of the time interval $T_{\text{spike}}$ has been interpreted as part the extended afterglow. Consequently, we have determined the cosmological redshift, $z = 1.61 \pm 0.14$, as well as the baryon load, $B = (4.13 \pm 0.05) \times 10^{-5}$ erg, its energetics, $E^{\text{tot}}_{\Gamma \Gamma} = (2.83 \pm 0.15) \times 10^{53}$ erg, and the extremely high Lorentz $\Gamma$ factor at the transparency, $\Gamma_T = (1.44 \pm 0.01) \times 10^4$.

We are led to the conclusion (see also Rueda & Ruffini 2012) that the progenitor of this GRB is a binary neutron star, which, for simplicity, we assume to have the same mass, by the following considerations:

1. the very low average number density of the CBM, $\langle n_{\text{CBM}} \rangle \sim 10^{-3}$ particles cm$^{-3}$; this fact points to two compact objects

in a binary system that have spiraled out in the halo of their host galaxy (see Bernardini et al. 2007, 2008; Bianco et al. 2008; Caiuto et al. 2009, 2010; de Barros et al. 2011); 2. the large total energy, $E^{\text{tot}}_{\Gamma} = 2.83 \times 10^{53}$ erg, which we can indeed infer in view of the absence of beaming, and the very short timescale of emission point again to two neutron stars. We are led to a binary neutron star with a total mass $m_1 + m_2$ larger than the neutron star critical mass, $M_{\text{cr}}$. In light of the recent neutron star theory in which all the fundamental interactions are taken into account (Belvedere et al. 2012), we obtain for simplicity in the case of equal neutron star masses, $m_1 = m_2 = 1.34 M_\odot$, radii $R_1 = R_2 = 12.24$ km, where we have used the NL3 nuclear model parameters for which $M_{\text{cr}} = 2.67 M_\odot$;

3. the very small value of the baryon load, $B = 4.13 \times 10^{-5}$, is consistent with the above two neutron stars that have crusts $\sim 0.47$ km thick. The new theory of the neutron stars, developed in Belvedere et al. (2012), leads to the prediction of GRBs with still smaller baryon load and, consequently, shorter periods. We indeed infer an absolute upper limit on the energy emitted via gravitational waves, $\sim 9.6 \times 10^{52}$ erg (see Rueda & Ruffini 2012).

We can then generally conclude on the existence of three different possible structures of the canonical GRBs (see Figure 14 and Table 7):

1. long GRB with baryon load $3.0 \times 10^{-4} \lesssim B \lesssim 10^{-2}$, exploding in a CBM with average density of $\langle n_{\text{CBM}} \rangle \approx 1$ particle cm$^{-3}$, typical of the inner galactic regions;

2. disguised short GRBs with the same baryon load as the previous class, but occurring in a CBM with $\langle n_{\text{CBM}} \rangle \approx 10^{-3}$ particle cm$^{-3}$, typical of galactic halos (Bernardini et al. 2007, 2008; Bianco et al. 2008; Caiuto et al. 2009, 2010; de Barros et al. 2011);

3. genuine short GRBs which occur for $B \lesssim 10^{-5}$ with the P-GRB predominant with respect to the extended afterglow and exploding in a CBM with $\langle n_{\text{CBM}} \rangle \approx 10^{-5}$ particle cm$^{-3}$, typical again of galactic halos, being GRB 090227B the first example.
Table 7
List of the Long and Disguised Short GRBs Labeled in Figure 14
compared with GRB 090227B

| label | GRB | $E_{pe}^{90\%}$ (erg) | $B$ | $\theta_{CBM}$ (cm$^{-3}$) |
|-------|-----|----------------------|-----|--------------------------|
| (a)   | 090618 | 2.49 x 10$^{53}$ | 1.98 x 10$^{-3}$ | 1.0 |
| (b)   | 080319B | 1.32 x 10$^{54}$ | 2.50 x 10$^{-3}$ | 6.0 |
| (c)   | 991216 | 4.83 x 10$^{53}$ | 3.00 x 10$^{-3}$ | 1.0 |
| (d)   | 030329 | 2.12 x 10$^{52}$ | 4.80 x 10$^{-3}$ | 2.0 |
| (e)   | 031203 | 1.85 x 10$^{50}$ | 7.40 x 10$^{-3}$ | 0.3 |
| (f)   | 050509B | 5.52 x 10$^{48}$ | 6.00 x 10$^{-4}$ | 1.0 x 10$^{-3}$ |
| (g)   | 060614 | 2.94 x 10$^{54}$ | 2.80 x 10$^{-3}$ | 1.0 x 10$^{-3}$ |
| (h)   | 970228 | 1.45 x 10$^{54}$ | 5.00 x 10$^{-3}$ | 9.5 x 10$^{-4}$ |
| 090227B | 2.83 x 10$^{53}$ | 4.13 x 10$^{-5}$ | 1.9 x 10$^{-5}$ |

Note. For each burst the total energy of the plasma, the baryon load, and the average CBM density are indicated.

Both classes of GRBs occurring in galactic halos originate from binary mergers.

Finally, if we turn to the theoretical model within a general relativistic description of the gravitational collapse to a 10 M$_\odot$ black hole (see e.g., Ruffini et al. 2003, 2005c and Figure 2 in Fraschetti et al. 2006), we find the necessity of time resolutions of the order of the mass of a ms, possibly down to $\mu$s, in order to follow such a process. One would need new space missions larger collecting area to prove with great accuracy the identification of a thermal component. It is likely that an improved data acquisition with high signal to noise on shorter timescale would evidence more clearly the thermal component as well as distinguish more effectively different fitting procedures.

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