On the Ultra-relativistic Prompt Emission, the Hard and Soft X-Ray Flares, and the Extended Thermal Emission in GRB 151027A

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Abstract

We analyze GRB 151027A within the binary-driven hypernova approach, with a progenitor of a carbon–oxygen core on the verge of a supernova (SN) explosion and a binary companion neutron star (NS). The hypercritical accretion of the SN ejecta onto the NS leads to its gravitational collapse into a black hole (BH), to the emission of the gamma-ray burst (GRB), and to a copious $e^+e^-$ plasma. The impact of this $e^+e^-$ plasma on the SN ejecta explains the early soft X-ray flare observed in long GRBs. Here, we apply this approach to the ultra-relativistic prompt emission (UPE) and to the hard X-ray flares. We use GRB 151027A as a prototype. From the time-integrated and the time-resolved analysis, we identify a double component in the UPE and confirm its ultra-relativistic nature. We confirm the mildly relativistic nature of the soft X-ray flare, of the hard X-ray flare, and of the extended thermal emission (ETE). We show that the ETE identifies the transition from an SN to a hypernova (HN). We then address the theoretical justification of these observations by integrating the hydrodynamical propagation equations of the $e^+e^-$ into the SN ejecta, with the latter independently obtained from 3D smooth particle hydrodynamics simulations. We conclude that the UPE, the hard X-ray flare, and the soft X-ray flare do not form a causally connected sequence. Within our model, they are the manifestation of the same physical process of the BH formation as seen through different viewing angles, implied by the morphology and the $\sim300$ s rotation period of the HN ejecta.

Key words: binaries: general – black hole physics – gamma-ray burst: general – hydrodynamics – stars: neutron – supernovae: general

1. Introduction

Gamma-ray bursts (GRBs) are traditionally classified in short GRBs with a total duration of $\lesssim2$ s, and as long GRBs lasting $\gtrsim2$ s (Mazets et al. 1981; Dezalay et al. 1992; Klebesadel 1992; Kouveliotou et al. 1993; Tavani 1998). A large majority of long bursts are spatially correlated with bright star-forming regions in their host galaxies (Fruchter et al. 2006; Svensson et al. 2010). For this reason, the long GRBs have been traditionally associated with the collapse of the core of a single massive star to a black hole (BH), surrounded by a thick massive accretion disk: the collapsar (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999; Piran 2004; Bromberg et al. 2013). In this traditional picture, the GRB dynamics follows the “fireball” model, which assumes the existence of a single ultra-relativistic collimated jet (see e.g., Blandford & McKee 1976; Shen & Piran 1990; Meszaros et al. 1993; Piran et al. 1993; Mao & Yi 1994). The structures of long GRBs were described either by internal or external shocks (see Rees & Meszaros 1992, 1994). The emission processes were linked to the occurrence of a synchrotron and/or inverse-Compton radiation coming from the single ultra-relativistic jetted structure, characterized by Lorentz factors $\Gamma \sim 10^2–10^3$.

Such a collapsar model does not address some observational facts: (1) most massive stars are found in binary systems (Smith 2014), (2) most SNe Ib/c occur in binary systems (Smith et al. 2011), and (3) the SNe associated with long GRBs are indeed of type Ib/c (Della Valle 2011). These facts motivated us to develop the binary-driven hypernova (BdHN) model.

Recently, we have found evidence for multiple components in long GRB emissions, indicating the presence of a sequence of astrophysical processes (Izzo et al. 2012; Penacchioni et al. 2012), which have led us to formulate, in precise terms, the sequence of events in the Induced Gravitational Collapse (IGC) paradigm (Ruffini et al. 2001a, 2007a; Rueda & Ruffini 2012; Fryer et al. 2014), making explicit the role of binary systems as progenitors of the long GRBs.

Within the IGC scenario, the long bursts originate in tight binary systems composed of a carbon–oxygen core ($CO_{\text{core}}$) undergoing an SN explosion and a companion neutron star (NS; Becerra et al. 2015, 2016, 2018). The SN explosion triggers a hypercritical accretion process on the companion NS; photons are trapped in the infalling material, and the gravitational energy gained by accretion is carried out through an efficient neutrino emission (Zeldovich et al. 1972; Ruffini & Wilson 1973; Fryer et al. 2014). Depending on the $CO_{\text{core}}$–NS binary separation period, two outcomes may occur. For widely separated ($a \gtrsim 10^{11}$ cm) $CO_{\text{core}}$–NS binaries, the hypercritical accretion rate is $<10^{-2} M_\odot \text{s}^{-1}$, and it is insufficient to induce the gravitational collapse of the NS to a BH. Instead, the NS just increases its mass, becoming a massive NS. This process leads to the emission of the so-called X-ray flashes (XRFs) with a typical X-ray emission of $\lesssim10^{32}$ erg.

For more tightly bound ($a \lesssim 10^{11}$ cm) $CO_{\text{core}}$–NS binaries, the hypercritical accretion rate of the SN ejecta can be as large as $\gtrsim10^{-2}–10^{-1} M_\odot \text{s}^{-1}$, leading the companion NS to collapse into a BH. This process leads to the occurrence of the BdHN,
which exhibits a more complex structure than XRFs and an emission of $\gtrsim 10^{52}$ erg (Ruffini et al. 2016b).

The opportunity of introducing the BdH model, based on binary progenitors, which exhibits a large number of new physical process and admits a theoretical treatment by detailed equations whose corresponding solutions are in agreement with the observations, has been presented in a large number of publications and was recently summarized in Ruffini et al. (2018c). There, we performed an extensive analysis using 421 BdH, all with measured redshift and observed until the end of 2016, and described in their cosmological rest frame (Pisani et al. 2016).

The large variety of spectra and light curves has allowed the introduction of seven different GRBs subclasses (see e.g., Ruffini et al. 2016b, 2018b).

We recalled that since 2001, we fit the ultra-relativistic prompt emission (UPE) light curve and spectra, solving the equations of the dynamics of the $e^+e^−$ baryon plasma and of its slowing down due to the interaction with the circumburst medium (CBM; see e.g., Ruffini et al. 1999, 2000, 2002). This treatment allows us to evaluate the ultra-relativistic gamma factor of the UPE exhibited in hundreds of short and long GRBs. Some underluminous GRBs may well have a non-ultra-relativistic prompt emission (J. A. Rueda et al. 2018, in preparation).

Attention was then directed to examine the flare plateau afterglow (FPA) phase following the UPE.

Among the BdHNe, we identified all of the ones with a soft X-ray flare in the $0.3$–$10$ keV rest-frame energy range in the FPA phase. In view of the excellent data and complete light curves, we could identify a thermal component in them (see Figure 32 and Table 7 in Ruffini et al. 2018c), which is essential in measuring the mildly relativistic expansion velocity of $v = c\beta \sim 0.8c$ (see Section 9 in Ruffini et al. 2018c).

In addition we then followed, through a hydrodynamical description, the propagation and the slowing down inside the SN ejecta of the $e^+e^−$ plasma generated in the BH formation, in order to explain the mildly relativistic nature of the soft X-ray flares expansion velocity (see Section 10 in Ruffini et al. 2018c).

Obviously, these considerations cannot be repeated here.

We only recall a few points of the conclusions of Ruffini et al. (2018c); e.g., (a) the data of the soft X-ray flare have determined its mildly relativistic expansion velocity already $\sim 100$ s after the UPE, in contrast to the traditional approach; (b) the role of the interaction of the $e^+e^−$ GRB emission in SN ejecta in order to explain the astrophysical origin of soft X-ray flare; (c) the determination of the density profile of the SN ejecta derived from the simulation of the IGC paradigm.

In this article, we apply our model to study a multiple component in the UPE phase observed in the range of $10$–$1000$ keV as well as the hard X-ray flares observed in the range of $0.3$–$150$ keV, the extended thermal emission (ETE), and finally the soft X-ray flare observed in the range of $0.3$–$10$ keV using GRB 151027A as a prototype. The aim is to identify the crucial role of the SN and of its binary NS companion in the BdH model, to analyze the interaction of the $e^+e^−$ plasma generating the GRB with the SN ejecta via 3D simulations, and to compare and contrast the observational support of the BdH model with the other traditional approaches. To facilitate the reader, we have made a special effort in referencing to the current works, in indicating new developments and their observational verifications, and finally in giving references for the technical details in the text.

In Section 2, we outline the new results motivating our paper: (1) three thermal emissions in GRBs, compared and contrasted. The relativistic treatment that relates the velocity of expansion of the hard X-ray flare, of the soft X-ray flare and of the ETE to the observed fluxes and temperatures is particularly relevant for our work. (2) The 3D simulations of the hypercritical accretion in a BdH, which are essential for obtaining the density profiles of the SN ejecta recently submitted for publication in Becerra et al. (2018). (3) The generalization of the spacetime representation of the BdH. These are some useful conceptual tools needed to create a viable GRB model.

In Section 3, we refer to GRB 151027A as a prototype example of high-quality data, enabling the detailed time-resolved analysis for the UPE phase, with its thermal component, as well as the first high-quality data for studying the hard X-ray flare and especially for the clear evolution of the ETE. We perform the time-integrated analysis for the UPE, further analyze the two ultra-relativistic gamma-ray spikes in the UPE, and apply the fireshell model to the first spike. We identify the proper GRB (P-GRB), the baryon load $B = (1.92 \pm 0.35) \times 10^{-2}$, and an average CBM density of $(7.46 \pm 1.2) \text{cm}^{-3}$, which are consistent with our numerical simulation presented in Section 6. We determine an initial Lorentz factor of the UPE $\Gamma_0 = 503 \pm 76$, confirming the clearly observed ultra-relativistic nature of the UPE.

In Section 4, we perform the time-resolved analysis for the hard X-ray flare and the soft X-ray flare, comparing and contrasting our results with the ones in the literature by Nappo et al. (2017). The hard X-ray flare is divided into eight time intervals, and we find a high significant thermal component existing in all time intervals (see Figure 8). We report the results of our time-resolved spectral analysis in the first five columns of Table 2. Using the best-fit model for a nonthermal component in the time interval 95–130 s, we determine a Lorentz factor $\Gamma = 3.28 \pm 0.84$ for the hard X-ray flare duration. The soft X-ray flare is analyzed in 4 time intervals, in which spectra are best fitted by a single power-law (PL).

In Section 5, we turn to the thermal component evolving across the hard X-ray flare by adopting the description in the GRB laboratory frame. Following our recent works (Ruffini et al. 2018c), we determine the expansion velocity evidencing the transition from an initial velocity $\approx 0.38c$ and increasing up to 0.98c in the late part; see column 6 of Table 2. This is the first relativistic treatment of the hard X-ray flare and its associated thermal emission clearly evidences the transition from an SN to an HN, which was first identified in GRB 151027A. We compare and contrast our results with the current ones in the literature.

In Section 6, we proceed to the hard X-ray flare and the soft X-ray flare theoretical explanation from the analysis of the $e^+e^−$ plasma propagating and slowing down within the SN ejecta. The simulated velocity and radius of the hard X-ray flare and the soft X-ray flare are consistent with the observations. We visualize all these results by direct comparison of the observational data by Swift, the International Gamma-ray Astrophysics Laboratory (INTEGRAL), Fermi, and Agile, in addition to the optical observations, with the theoretical understanding of the 3D dynamics of the SN recently jointly performed by our group in collaboration with the Los Alamos National Laboratory (Becerra et al. 2018). This visualization is
particularly helpful in order to appreciate the novel results made possible by the BdHN paradigm and also by allowing the visualization of a phenomena observed today but occurred 10 billion light years away in our past light cone. The impact of the $e^+e^-$ plasma on the entire SN ejecta gives origin to the thermal emission from the external surface of the SN ejecta and, equally, we can therefore conclude that the UPE, the hard X-ray flare, and the soft X-ray flare are not a causally connected sequence (see Figures 14–17 and Table 2). Within our model, they are the manifestation of the same physical process of the BH formation as seen through different viewing angles, implied by the morphology and by the $\sim$300 s rotation period of the HN ejecta.

In Section 7, we proceed to the summary, discussion, and conclusions:

1. In the summary, we have recalled the derived Lorentz gamma factor and the detailed time-resolved analysis of the light curves and spectra of UPE, hard X-ray flare, ETE, and soft X-ray flare. We mention a double spike structure in the UPE and in the FPA, which promises to be directly linked to the process of the BH formation. We have equally recalled our relativistic treatment of the ETE, which, for the first time, has allowed us to observe the transition of an SN into an HN—the main result of this paper.

2. We have recalled in the discussions, using specific examples in this article, that our data analysis is performed within a consistent relativistic field-theoretical treatment. In order to be astrophysically significant, it needs the identification of the observed astrophysical components, including: the binary nature of the progenitor system, the presence of an SN component, and it also needs a 3D simulation of the process of hypercritical accretion in the binary progenitors. We have also recalled the special role of the rotation by which phenomena, traditionally considered different, are actually the same phenomenon as seen from different viewing angles.

3. Looking forward in the conclusions, three main implications follow from the BdHN model, which are now open to further scrutiny: (1) only 10% of the BdHNe whose line of sight lies in the equatorial plane of the progenitor binary system are actually detectable; in the other 90%, the UPE is not detectable due to the morphology of the SN ejecta (see Figure 2) and therefore the Fermi and Swift instruments are not triggered; (2) the $E_{\text{iso}}$, traditionally based on a spherically symmetric equivalent emission, has to be replaced by an $E_{\text{iso}}$, duly taking into account the contributions of the UPE, hard X-ray flare, ETE, and soft X-ray flare; (3) when the BdHNe are observed normally to the orbital plane, the GeV emission from the newly formed BH becomes observable, and this additional energy should also be accounted for.

We summarize in Table 1 the list of acronyms introduced in the present paper.

### Table 1

Alphabetic Ordered List of the Acronyms Used in This Work

| Extended Wording                      | Acronym |
|---------------------------------------|---------|
| Binary-driven hypernova               | BdHN    |
| Black hole                            | BH      |
| Carbon–oxygen core                    | CO$_{\text{core}}$ |
| Circumburst medium                    | CBM     |
| Extended thermal emission             | ETE     |
| Flare plateau afterglow               | FPA     |
| Gamma-ray burst                       | GRB     |
| Gamma-ray flash                       | GRF     |
| Induced gravitational collapse        | IGC     |
| Massive neutron star                  | MNS     |
| Neutron star                          | NS      |
| New neutron star                      | $\nu$NS  |
| Ultra-relativistic prompt emission    | UPE     |
| Proper gamma-ray burst                | P-GRB   |
| Short gamma-ray burst                 | S-GRB   |
| Short gamma-ray flash                 | S-GRF   |
| Supernova                             | SN      |
| Ultrashort gamma-ray burst            | U-GRB   |
| White dwarf                           | WD      |
| X-ray flash                           | XRF     |

2. Recent Progress on BdHNe

We address three progresses obtained in the last year in the theory of BdHNe: (1) the identification of three different thermal emission processes, (2) the visualization of the IGC paradigm, and (3) an extended spacetime diagram of the BdHN with a viewing angle in the equatorial plane of the binary progenitors.

One of the first examples of a thermal emission has been identified in the early seconds after the trigger of some long GRBs (Ryde 2004; Ryde et al. 2006; Ryde & Pe’er 2009). This emission has been later identified in the BdHN model with the soft X-ray emission occurring in the photosphere of convective outflows in the hypercritical accretion process from the newly born SN into the NS binary companion. Additional examples have been given in BdHNe (Fryer et al. 2014) and in XRFs (Becerra et al. 2016). These process are practically Newtonian in character with the velocity of expansions of the order of $10^8–10^9$ cm s$^{-1}$ (see e.g., Izzo et al. 2012, for the case of GRB 090618).

A second thermal emission process has been identified in the acceleration process of GRBs, when the self-accelerating optically thick $e^+e^-$ plasma reaches transparency and a thermal emission with very high Lorentz factor $\Gamma \sim 10^3–10^4$ is observed. This has been computed both in the fireball model (Piran 1999; Daigne & Mochkovitch 2002; Pe’er et al. 2007) and in the fireshell model (Ruffini 1999; Ruffini et al. 2000). The difference consists in the description of the equations of motion of the fireball assumed in the literature and instead is explicitly evaluated in the fireshell model from the integration of classical and quantum magnetohydrodynamic process (see also Ruffini et al. 2007b, and references therein). The moment of transparency leads to a thermal emission whose relativistic effect has been evaluated, leading to the concept of the equitemporal surface (EQTS; Bianco & Ruffini 2005a). This derivation has also been successfully applied to short GRBs (Ruffini et al. 2015, 2016a; Aimuratov et al. 2017) and is here applied in Section 3 to the UPE.

There is finally a third additional ETE observed in BdHNe and in the X-ray flares (Ruffini et al. 2018c). This ETE has allowed the determination of the velocity of expansion and the Lorentz gamma factor of the thermal emission based on the variation in time of the observed radius and temperature of the thermal emission (see the equation in Figure 1) under the assumption of uncollimated emission and considering only the radiation coming...
from the line of sight. The left-hand side term is only a function of the velocity, $\beta$, the right-hand side term is only function of the observables, and $D_L(z)$ is the luminosity distance for redshift $z$. Therefore, from the observed thermal flux, $F_{bb,obs}$ and the temperature, $T_{obs}$, at arrival times of the detector $t_{a,1}^d$ and $t_{a,2}^d$, the velocity and the corresponding Lorentz factor can be computed. This equation assumes uncollimated emission and considers only the radiation coming from the line of sight. The computed velocity is instantaneous, and there is no reliance on the expansion history.

The second progress has been presented in Becerra et al. (2016) and more recently in Becerra et al. (2018). The first 3D smoothed particle hydrodynamics (SPH) simulations of the IGC leading to a BdHN are there presented. We simulate the SN explosion of a CO$_{core}$ forming a binary system with a NS companion. We follow the evolution of the SN ejecta, including their morphological structure, subjected to the gravitational field of both the new NS ($\nu$NS), formed at the center of the SN, and the one of the NS companion. We compute the accretion rate of the SN ejecta onto the NS companion as well as onto the $\nu$NS from SN matter fallback. We determine the fate of the binary system for a wide parameter space, including different CO$_{core}$ masses, orbital periods ($\sim 300$ s), and SN explosion geometry and energies. We evaluate, for selected NS equations of state, if the accretion process leads the NS either to the mass-shedding limit or to the secular asymmetric instability for the gravitational collapse to a BH or to a more massive, fast rotating but stable NS. We also assess whether the binary keeps or is not gravitationally bound after the SN explosion, hence exploring the space of the binary and SN explosion parameters leading to the formation of $\nu$NS–NS or $\nu$NS–BH binaries. The consequences of our results for the modeling of GRBs via the IGC scenario are discussed in Becerra et al. (2018). The relevance of these simulations for GRB 151027A, which is subject of this paper, will be illustrated below (see Figure 2).

Finally, we present an update of the BdHN spacetime diagram (see Figure 3) that clearly evidences the large number of episodes and physical processes, each with observationally computed time-varying Lorentz $\Gamma$ factors, which require the systematic use of the four different time coordinates, as already indicated in Ruffini et al. (2001a). The diagram illustrates departures from the traditional collapsar-fireball description of a GRB. The diagram shows how the sequence of events of the UPE, of the hard X-ray flare, and of the soft X-ray flare occur in a sequence only when parameterized in the arrival time and when they are not, in fact, causally related.

We recall that, within our model, the line of sight of the prototypical GRB 151027A lies in the equatorial plane of the progenitor binary system. The more general case of an arbitrary viewing angle has been explored in Ruffini et al. (2018a), and some specific additional characteristic features common to the collapsar model have been manifested in this more general case.

Figure 1. Equation to compute the velocity from the thermal component. This equation is summarized from Ruffini et al. (2018c). The left-hand side term is only a function of velocity $\beta$, and the right-hand side term is only of the observables. $D_L(z)$ is the luminosity distance for redshift $z$. From the observed thermal flux, $F_{bb,obs}$ and the temperature, $T_{obs}$ at arrival times of the detector $t_{a,1}^d$ and $t_{a,2}^d$, the velocity and the corresponding Lorentz factor can be computed. This equation assumes uncollimated emission and considers only the radiation coming from the line of sight. The computed velocity is instantaneous, and there is no reliance on the expansion history.

Figure 2. A 3D, half-hemisphere view of the density distribution of the SN ejecta at the moment of BH formation in a BdHN. The simulation is performed with an SPH code that follows the SN ejecta expansion under the influence of the gravitational field of both the new NS formed at the center of the SN and of the NS companion. It includes the effects of the orbital motion and the changes in the NS gravitational mass by the hypercritical accretion process (see Becerra et al. 2016, for additional details). The binary parameters of this simulation are: the NS companion has an initial mass of 2.0 $M_\odot$, the CO$_{core}$ obtained from a progenitor with ZAMS mass, $M_{30ZAMS} = 30 M_\odot$, which leads to a total ejecta mass of 7.94 $M_\odot$ and to a 1.5 $M_\odot$ $\nu$NS, and the orbital period is $P \approx 5$ min (binary separation $a \approx 1.5 \times 10^{10}$ cm). Only the sources, whose ultra-relativistic emission lies within the allowed cone of $\sim 10^\circ$ with low baryon contamination, will trigger the gamma-ray instrument (e.g., Fermi/GBM or Swift/BAT).

3. UPE

GRB 151027A was detected and located by the Swift Burst Alert Telescope (BAT; Maselli et al. 2015). It was also detected by the Fermi Gamma-ray Burst Monitor (GBM; Toelge et al. 2015), Monitor of All-sky X-ray Image (MAXI; Masumitsu et al. 2015), and by Konus-Wind (Golenetskii et al. 2015). The Swift X-Ray Telescope (XRT) started its observation 87 s after the burst trigger (Goad et al. 2015). The redshift of the source, measured through the Mg II doublet in absorption from the Keck/High Resolution Echelle Spectrometer (HIRES) spectrum, is $z = 0.81$ (Perley et al. 2015). The Large Area Telescope (LAT) boresight of the source was 10° at the time of the trigger, there are no associated high-energy photons; an upper limit of observed count flux is computed as $9.24 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$ following the standard Fermi-LAT likelihood analysis. The BAT light curve shows a complex peaked structure lasting at least 83 s. XRT began observing the field 48 s after the BAT trigger. The GBM light curve consists of various pulses with a duration of about 68 s in the 50–300 keV range.
band. The *Konus*-Wind light curve consists of various pulses with a total duration of \( \sim 66 \) s. The MAXI detection is not significant, but the flux is consistent with the interpolation from the *Swift*-XRT light curve. The first 25 s (rest frame 14 s) corresponds to the UPE. It encompasses two spikes of duration of \( \approx 8.5 \) s and \( \approx 7.5 \) s, respectively, with a separation between two peaks of \( \approx 17 \) s (see Figure 4(a)). The rest-frame 1–10\(^{\text{keV}}\) isotropic equivalent energies computed from the time-integrated spectra of these two spikes (see Figures 4(b) and (c)) are \( E_{\text{iso},1} = (7.26 \pm 0.36) \times 10^{51} \) erg and \( E_{\text{iso},2} = (4.99 \pm 0.60) \times 10^{51} \) erg, respectively.

A similar analysis was performed by Nappo et al. (2017). They describe the two spikes of the UPE by a single light curve with a “Fast Rise and Exponential Decay” (FRED) shape.

We analyze the first spike (see Figure 5) as the traditional UPE of a long GRB within the fireshell model (see, e.g., Ruffini et al. 2003, for a review).

Thanks to the wide energy range of the *Fermi*-GBM instrument (8–1000 keV), it has been possible to perform a time-resolved analysis within the UPE phase to search for the typical P-GRB emission at the transparency of the \( e^+e^-\)–baryon plasma (Ruffini 1999; Ruffini et al. 2000, 2001b). Indeed, we find this thermal spectral feature in the time interval \( t_0 - 0.1 - t_0 + 0.9 \) s (with respect to the *Fermi*-GBM trigger time \( t_0 \)). The best-fit model of this emission is a composition of a blackbody (BB) spectrum and a cutoff power-law model (CPL, see Figure 5(a)). The BB component has an observed temperature \( \nu_0 = 3.66 \pm 0.51 \) keV and an energy of \( E_{\text{BB}} = (0.074 \pm 0.038) \times E_{\text{iso},1} = (5.3 \pm 2.7) \times 10^{50} \) erg. These values are in agreement with an initial \( e^+e^-\) plasma of energy, \( E_{\text{iso},1} \), with a baryon load of \( B = (1.92 \pm 0.35) \times 10^{-3} \), and a Lorentz factor.

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**Figure 3.** Spacetime diagram (not in scale) of BdHNe. The CO\textsubscript{core} explodes as an SN at point A and forms a vNS. The companion NS (bottom right line) accretes the SN ejecta starting from point B, giving rise to the nonrelativistic Episode 1 emission (with Lorentz factor \( \Gamma \approx 1 \)). At point C, the NS companion collapses into a BH, and an \( e^+e^-\)–plasma—the dyadosphere—is formed (Ruffini 1999). The following self-acceleration process occurs in a spherically symmetric manner (thick black lines). A large portion of plasma propagates in the direction of the line of sight, where the environment is cleaned up by the previous accretion into the NS companion, the direction of the line of sight, where the environment is cleaned up by the symmetric manner \( \sim \). The remaining part of the plasma impacts with the high-density portion of the SN ejecta (point E), propagates inside the ejecta encountering a baryon load of \( B = 10^{-5} \), and finally reaches transparency, leading to the hard X-ray flare emission (point F) in gamma-rays with an effective Lorentz factor of \( \Gamma \approx 10 \) and to soft X-ray flare emission (point G) with an effective \( \Gamma \approx 4 \), which are then followed by the late afterglow phases (point H). For simplicity, this diagram is 2D and static and does not attempt to show the 3D rotation of the ejecta.

**Figure 4.** (a) *Fermi*-GBM light curve from the NaI-n0 detector (<8–800 keV) of the UPE of GRB 151027A. The dotted horizontal line corresponds to the \( \gamma\)-ray background. (b) Time-integrated \( \nu F_{\nu} \) spectrum of the first spike. (c) Time-integrated \( \nu F_{\nu} \) spectrum of the second spike.
and a radius at the transparency condition of $\Gamma_0 = 503 \pm 76$ and $r_t = (1.92 \pm 0.17) \times 10^{13}$ cm, respectively.

We turn now to the simulation of the remaining part of the first spike of the UPE (from $T_0 + 0.9$ s to $T_0 + 9.6$ s). In the fireshell model, this emission occurs after the P-GRB, and results from the slowing down of the accelerated baryons due to their interaction with the CBM (Ruffini et al. 2002, 2006; Patricelli et al. 2012). To simulate the UPE light curve and its corresponding spectrum, we need to derive the number density of the CBM clouds surrounding the burst site. The agreement between the observations and the simulated light curve and its corresponding spectrum, we need to derive the number density of the CBM clouds used for the above UPE light curve and spectrum simulations.

The general conclusion of the UPE is the following: from the morphological 3D simulation, the SN ejecta is distorted by the binary accretion. A cone of very low baryon contamination is formed along the direction from the SN center pointing to the newly born BH (see Figure 2). A portion of $e^+e^-$ plasma generated from the BH formation propagates through this cone and engulfs a low baryon load of $B = (1.92 \pm 0.35) \times 10^{-3}$ and reaches a Lorentz gamma factor of $\Gamma_0 = 503 \pm 76$. The $e^+e^-$ plasma self-accelerates and expands ultra-relativistically until reaching transparency (Ruffini 1998; Aksenov et al. 2007; Ruffini et al. 2010), when a short-duration (<1 s) thermal emission occurs: the P-GRB. The ultra-relativistic associated baryons then interact with the CBM clouds. The dynamics of the plasma has been integrated by the classical hydrodynamics equations and by the equation of annihilation-creation rate (Bianco et al. 2001; Izzo et al. 2004, 2005a, 2005b; Bianco & Ruffini 2006). It enables us to simulate the structure of spikes in the prompt emission, and it has been applied to the case of BdHNe (see, e.g., Ruffini et al. 2002, 2016a; Bernardini et al. 2005; Izzo et al. 2012; Penacchioni et al. 2012, 2013). For a typical baryon load for the cone direction, $10^{-4} \lesssim B \lesssim 10^{-2}$, a Lorentz factor of $\Gamma \approx 10^2$–$10^3$, characteristic of the prompt emission occurs in a distance $\approx 10^{15}$–$10^{17}$ cm from the BH (Ruffini et al. 2016b).

1. A double emission is clearly manifested by presence of the two spikes at the time interval of the 17 s (rest frame 9 s). We are currently examining the possibility that this double emission is an imprinting of the process of the BH formation.

2. When we take into account the rotation period of the binary $\sim 300$ s, we see that UPE occurs in a cone centered in the BH of $10^\circ$. 

**Figure 5.** Ultra-relativistic prompt emission (UPE). (a) The combined Na i n0, n3+BGO-b0 $\nu F_\nu$, spectrum of the P-GRB in the time interval $T_0 = 0.1$–$T_0 + 0.9$ s. The best-fit model is CPL+BB. (b) The comparison between the background subtracted 10–1000 keV Fermi–GBM light curve (green) and the simulation with the fireshell model (red curve) in the time interval $T_0 + 0.9$–$T_0 + 9.6$ s. (c) The comparison between the Na i n0 (purple squares), n3 (blue diamonds), and the BGO-b0 (green circles) $\nu F_\nu$ data in the time interval, $T_0 + 0.9$–$T_0 + 9.6$ s, and the simulated fireshell spectrum (red curve). (d) The radial density of the CBM clouds used for the above UPE light curve and spectrum simulations.
3. This conical region is endowed with a very low density determined by the P-GRB and the inferred CBM medium density of \((7.46 \pm 1.2) \text{ cm}^{-3}\) up to \(10^{16} \text{ cm}\) from BH along the cone (see Figure 5(d)).

This conceptual framework can, in principle, explain the featureless nature of the second spike, which propagates along the region that has already been swept by the first spike (see Figure 6).

4. Hard and Soft X-Ray Flare

4.1. Hard X-Ray Flare

We turn now to the hard X-ray flare and the soft X-ray flare. The hard X-ray flare is observed in the time interval 94–180 s (corresponding to the rest-frame time interval 52–99 s; see Figure 7(a)). The luminosity light curves in the rest-frame energy bands of 10–1000 keV for Fermi-GBM (green), 15–150 keV for Swift-BAT (red), and 0.3–10 keV for Swift-XRT (blue) are displayed. The total isotropic energy of the hard X-ray flare is \(E_\gamma = (3.28 \pm 0.13) \times 10^{52} \text{ erg}\). The overall spectrum is best fit by a superposition of a PL function with an index of \(-1.69 \pm 0.01\) and a BB model with a temperature of \(kT = 1.13 \pm 0.08 \text{ keV}\) (see Figure 7(b)).

We perform a more detailed analysis by dividing the whole hard X-ray flare duration (94–180 s) into eight intervals (indicated with \(\Delta t_{\text{int}}^f\) in Table 2). Among these time intervals, the first six have both BAT and XRT data (total energy range 0.3–150 keV), while the last two fits involve XRT data only (an energy range of 0.3–10 keV). The XRT data were extremely piled up, and corrections have been performed in a conservative way to ascertain that the BB is not due to pileup effects (Romano et al. 2006). The absorption of the spectrum below 2 keV has been also taken into due account. Here, we use the following spectral energy distributions to fit the data: power law (PL), cutoff power law (CPL), PL+BB, and CPL+BB. An extra BB component is always preferred to the simple PL models and, only in the sixth interval, to the CPL model whose cutoff energy may be constrained within a 90% significance. The results of the time-resolved analysis are shown in Figure 8 and summarized in Table 2. The BB parameters and errors in Table 2 correspond, respectively, to the main values and the 90\% probability interval errors with respect to the central values, both obtained from the Markov Chain-Monte Carlo method applied in XSpec with 10^5 steps (excluding first 10^5). The values in line with the ones corresponding to minimum \(\chi^2\) and with errors to the ones corresponding to intervals obtained from the difference \(\Delta \chi^2 = 2.706\) from the minimum \(\chi^2\) value. The only exception is the first time bin where \(\chi^2_{\text{min}}\) value is almost two times lower than the main value. It is useful to infer the bulk Lorentz factor of the hard X-ray flare emission.
from the nonthermal component of the spectrum. Using the Fermi data, the best-fit model for this nonthermal component in the time interval 95–130 s is a CPL with a spectral cutoff energy, $E_c = 926 \pm 238$ keV. Such a cutoff can be caused by $\gamma\gamma$ absorption, for which the target photon's energy is comparable to $E_c$, i.e., $E_c \geq \Gamma \frac{m_e c^2}{(1+z)^2}/E_c$ and, therefore, the Lorentz factor can be deduced by
\[
\Gamma \approx \frac{E_c}{m_e c^2} (1+z),
\]
where $m_e$ is the electron mass. From the above value of $E_c$, we infer $\Gamma \approx 3.28 \pm 0.84$, which represents an average over the hard X-ray flare duration. It is in the range of the ones observed in thermal component (see the first five columns of the Table 2), coinciding in turn with the numerical simulation of the interaction of the $e^+e^-$ plasma with the SN ejecta described in the Section 6.

4.2. Soft X-Ray Flare

The soft X-ray flare, which has been discussed in Ruffini et al. (2018c), peaks at a rest-frame time of $t_p = (184 \pm 16)$ s, has a duration of $\Delta t = (164 \pm 30)$ s, a peak luminosity of $L_p = (7.1 \pm 1.8) \times 10^{48}$ erg s$^{-1}$, and a total energy in the rest-frame 0.3–10 keV energy range of $E_X = (4.4 \pm 2.9) \times 10^{53}$ erg. The overall spectrum within its duration, $\Delta t$, is best-fit by a PL model with a PL index of $-2.24 \pm 0.03$ (see Figure 9).

Here, we also perform a time-resolved analysis of the soft X-ray flare. We divide the total interval $\Delta t$ into four subintervals, i.e., 235–300 s, 300–365 s, 365–435 s, and 435–500 s in the observer frame (see Figure 10). The best-fits of each of these four time intervals are PL models with indexes ranging from $-2.3$ to $-2.1$, which are consistent with the typical values inferred in Ruffini et al. (2018c).

The complete spacetime diagram, showing UPE, hard X-ray flare, and soft X-ray flare, is represented in Figure 11.

5. Evolution of Thermal Component around the Hard X-Ray Flare

Following Figure 1, it is possible to infer the expansion velocity $\beta$ (i.e., the velocity in units of the velocity of light $c$). We assume that the blackbody emitter has spherical symmetry and expands with a constant Lorentz gamma factor. Therefore, the expansion velocity $\beta$ is also constant during the emission. The relations between the comoving time, $t_{\text{com}}$; the laboratory time, $t$; the arrival time, $t_{\text{arr}}$; and the detector time, $t_{\text{det}}$, are duration. It is in the range of the ones observed for the Hard X-Ray Flare: Parameters of the Time-resolved Spectral Analysis

| $\Delta t$ (s) | Model | $\alpha$ | $E_p$ (keV) | $kT_{bb}$ (keV) | $\frac{A_{bb}}{\phi_0}$ (ph cm$^{-2}$s$^{-1}$) | $\phi_0$ (10$^{15}$ cm$^{-2}$) | $\beta$ | $\Gamma$ | $R$ (10$^{12}$ cm) |
|---------------|-------|---------|-------------|----------------|---------------------------------|----------------------------|-------|------|-------------|
| 94–100        | BB+PL | 1.349   | 0.024       | 2.3 ± 0.11    | 0.502 ± 0.043                 | 0.065 ± 0.070              | 0.38 ± 0.19 | 1.079 ± 0.18 | 0.10 ± 0.21 |
| 100–110       | BB+PL | 1.293   | 0.030       | 2.57 ± 0.43   | 0.206 ± 0.083                 | 0.094 ± 0.041              | 0.606 ± 0.042 | 1.257 ± 0.057 | 0.194 ± 0.076 |
| 110–120       | BB+PL | 1.392   | 0.028       | 2.17 ± 0.22   | 0.062 ± 0.14                 | 0.229 ± 0.053              | 0.852 ± 0.035 | 0.519 ± 0.024 | 0.80 ± 0.25 |
| 120–130       | BB+PL | 1.732   | 0.037       | 1.10 ± 0.12   | 0.592 ± 0.077                 | 0.87 ± 0.23                | 0.957 ± 0.014 | 3.46 ± 0.76 | 5.7 ± 2.3 |
| 130–140       | BB+PL | 1.82    | 0.13       | 0.617 ± 0.043 | 0.247 ± 0.038                | 1.79 ± 0.28                | 0.983 ± 0.079 | 5.6 ± 1.0 | 19.1 ± 5.6 |
| 140–150       | CPL+PL | 1.66    | 0.45       | 0.469 ± 0.064 | 0.102 ± 0.028                | 0.29 ± 0.041               | 0.983 ± 0.054 | 0.25 ± 0.18 | 9.5 ± 9.5 |
| 150–160       | BB+PL | 2.40    | 0.34       | 0.386 ± 0.061 | 0.046 ± 0.015                | 1.97 ± 0.70                | 0.935 ± 0.054 | 2.8 ± 0.18 | 10.5 ± 10.5 |
| 160–180       | BB+PL | 2.15    | 0.34       | 0.193 ± 0.050 | 0.020 ± 0.013                | 5.2 ± 0.23                 | 0.953 ± 0.052 | 3.3 ± 2.3 | 32 ± 32 |

Note. Columns list, respectively, the time interval of the spectral analysis; the PL or CPL Index $\alpha$; the CPL energy $E_p$ when present; the BB observed temperature, $kT_{bb}$; and normalization $A_{bb}$, fitted from Section 4. The quantity, $\phi_0$, expansion velocity, $\beta$, the Lorentz factor, $\Gamma$; and the effective thermal emitter radius in the laboratory frame, $R$, inferred from Section 5.
where we have defined the Doppler factor $\mathcal{D}(\cos \vartheta)$ as

$$\mathcal{D}(\cos \vartheta) \equiv \frac{1}{\Gamma(1 - \beta \cos \vartheta)}. \quad (7)$$

Equation (6) gives us the observed blackbody temperature of the radiation coming from different points of the emitter surface, corresponding to different values of $\cos \vartheta$. However, since the emitter is at a cosmological distance, we are not able to resolve spatially the source with our detectors. Therefore, the temperature that we actually observe corresponds to an average of Equation (6) computed over the emitter surface:

$$T_{\text{obs}}(T_{\text{com}}, z, \Gamma) = \frac{1}{1 + z} \int_1^\infty \mathcal{D}(\cos \vartheta) T_{\text{com}} \cos \vartheta d \cos \vartheta$$

$$= \frac{2}{1 + z} \frac{\beta(\beta - 1) + \ln(1 + \beta)}{\Gamma \beta^2 (1 - \beta^2)} T_{\text{com}}$$

$$= \Theta(\beta) \frac{\Gamma}{1 + z} T_{\text{com}}, \quad (8)$$

where we defined

$$\Theta(\beta) \equiv \frac{2}{\beta^2} \frac{\beta(\beta - 1) + \ln(1 + \beta)}{1 + z}. \quad (9)$$

We have used the fact that due to relativistic beaming, we observe only a portion of the surface of the emitter defined by

$$\beta \leq \cos \vartheta \leq 1, \quad (10)$$

and we used the definition of $\Gamma$ given above. Therefore, inverting Equation (8), the comoving blackbody temperature, $T_{\text{com}}$, can be computed from the observed blackbody temperature, $T_{\text{obs}}$, the source cosmological redshift, $z$, and the emitter Lorentz gamma factor in the following way:

$$T_{\text{com}}(T_{\text{obs}}, z, \Gamma) = \frac{1 + z}{\Theta(\beta) \Gamma} T_{\text{obs}}. \quad (11)$$
We can now insert Equation (11) into Equation (5) to obtain
\[
F_{bb,obs} = \frac{R_{com}^2}{D_L(z)^2} \sigma T_{com}^4 = \frac{R_{com}^2}{D_L(z)^2} \left[ \frac{1 + z}{\Theta(\beta)\Gamma} \sigma T_{obs}^4 \right].
\]
(12)

Since the radius, \( R \), of the emitter in the laboratory frame is related to \( R_{com} \) by
\[
R_{com} = \Gamma R,
\]
(13)
we can insert Equation (13) into Equation (12) and obtain
\[
F_{bb,obs} = \frac{(1 + z)^4}{\Gamma^2} \frac{R}{D_L(z)^2} \sigma \left[ \frac{T_{obs}^4}{\Theta(\beta)} \right].
\]
(14)

Solving Equation (14) for \( R \), we finally obtain the thermal emitter effective radius in the laboratory frame:
\[
R = \Theta(\beta)^2 \Gamma \frac{D_L(z)}{(1 + z)^2} \sqrt{\frac{F_{bb,obs}}{\sigma T_{obs}^4}} = \Theta(\beta)^2 \Gamma \phi_0,
\]
(15)
where we have defined \( \phi_0 \) as
\[
\phi_0 = \frac{D_L(z)}{(1 + z)^2} \sqrt{\frac{F_{bb,obs}}{\sigma T_{obs}^4}}.
\]
(16)

The evolutions of the rest-frame temperature and \( \phi_0 \) are shown in Figure 12. In astronomy, the quantity \( \phi_0 \) is usually identified with the radius of the emitter. However, in relativistic astrophysics, this identity cannot be straightforwardly applied, because the estimate of the effective emitter radius \( R \) in Equation (15) crucially depends on the knowledge of its expansion velocity \( \beta \) (and, correspondingly, of \( \Gamma \)).

It must be noted that Equation (15) above gives the correct value of \( R \) for all values of \( 0 \leq \beta \leq 1 \) by taking all of the relativistic transformations properly into account. In the nonrelativistic limit (\( \beta \to 0 \)), we have, respectively:
\[
\Theta \to 1, \Theta^2 \to 1,
\]
(17)
\[
T_{com} \to T_{obs}(1 + z), R \to \phi_0.
\]
(18)
as expected. Analogously, in the ultra-relativistic limit \((\beta \rightarrow 1)\), we have
\[
\Theta \rightarrow 1.39, \quad \Theta^2 \rightarrow 1.92, \quad \Gamma \rightarrow 1.92 \phi_0. \tag{19}
\]
\[
T_{\text{com}} \rightarrow 0.72 T_{\text{obs}}(1 + z), \quad R \rightarrow 1.92 \Gamma \phi_0. \tag{20}
\]
It must also be noted that the numerical coefficient in Equation (15) is computed as a function of \(\beta\) using Equation (9) above, and it is different from the constant values proposed by Pe’er et al. (2007) and by Ghirlanda et al. (2013).

An estimate of the expansion velocity, \(\beta\), can be deduced from the ratio between the variation of the emitter effective radius, \(\Delta R\), and the emission duration in laboratory frame, \(\Delta t\), i.e.,
\[
\beta = \frac{\Delta R}{c \Delta t} = \Theta(\beta^2 \Gamma(1 - \beta \cos \vartheta))(1 + z) \frac{\Delta \phi_0}{c \Delta t_0}. \tag{21}
\]
where we used Equation (15), the relation between \(\Delta \Gamma\) and \(\Delta t_0\) given in Equation (2), we used the definition of \(\Gamma\) given above, and \(\vartheta\) is the displacement angle of the considered photon emission point on the surface from the line of sight. In the following, we only consider the case \(\cos \vartheta = 1\). In this case, using Equation (9), Equation (21) assumes the form presented in Figure 1. It allows us to estimate the expansion velocity, \(\beta\), of the emitter using only the observed blackbody flux, temperature, photon arrival time, and cosmological redshift, assuming uncollimated emission and only considering the radiation coming from the line of sight. We can explain the observed blackbody emission in GRB 151027A without introducing the “reborn fireball” scenario (see Ghisellini et al. 2007; Nappo et al. 2017).

To infer \(\beta\), we fit the evolution of \(\phi_0\) (see Figure 12 and Table 2) using two smoothly joined PL segments. It allows us to estimate the ratio \(\Delta \phi_0/(c \Delta t_0)\) in Equation (21) and, therefore, the values of \(\beta\) and \(\Gamma\), assuming that they are constant in each time interval (see Figure 13, top and middle panels). Consequently, we can estimate the evolution of the radius, \(R\), of the emitter in the laboratory frame by taking into account the relativistic transformations described in Equations (2), (15), and (16) (see bottom panel of Figure 13). The results are also summarized in Table 2.

6. On the Nature of the Hard X-Ray Flare and the Soft X-Ray Flare

Following the procedure described in Section 10 of Ruffini et al. (2018c), we interpret the thermal emission observed in the hard X-ray flare as the observational feature arising from the early interaction between the expanding SN ejecta and the \(e^+e^-\) plasma. In order to test the consistency of this model with the data, we have performed a series of numerical simulations, whose details we summarize as follows.

(a) Our treatment of the problem is based on an implementation of the 1D relativistic hydrodynamical module included in the PLUTO code\(^5\) (Mignone et al. 2011). In the spherically symmetric case considered, only the radial coordinate is used, and consequently the code integrates a system of partial differential equations in only two coordinates:

\[\frac{\partial(\rho \Gamma)}{\partial t} + \nabla \cdot (\rho \Gamma \mathbf{v}) = 0,\]
\[\frac{\partial m_r}{\partial t} + \nabla \cdot (m_r \mathbf{v}) + \rho \frac{\partial \rho}{\partial r} = 0,\]
\[\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot (\mathbf{m} - \rho \Gamma \mathbf{v}) = 0,\]

where \(\rho\) and \(p\) are the comoving fluid density and pressure, \(\mathbf{v}\) is the coordinate velocity in natural units \((c = 1)\), \(\Gamma = (1 - v^2)^{-1/2}\) is the Lorentz gamma factor, \(\mathbf{m} = h \Gamma^2 \mathbf{v}\) is the fluid momentum, \(m_r\) is the radial component, \(\mathcal{E}\) is the internal energy density measured in the comoving frame, and \(h\) is the comoving enthalpy density, which is defined by \(h = \rho + \epsilon + p\). We define \(\epsilon\) as follows:

\[\mathcal{E} = h \Gamma^2 - p - \rho \Gamma.\]

The last two terms on the right-hand side of this equation coincide with the \(T^{\alpha\beta}\) component of the fluid energy-momentum, and the last one is the mass density in the laboratory frame.

Under the conditions discussed in Ruffini et al. (2018c), the plasma satisfies the equation of state of an ideal relativistic gas, which can be expressed in terms of its enthalpy as

\[h = \rho + \frac{\gamma p}{\gamma - 1},\]

with \(\gamma = 4/3\). Imposing this equation of state closes and completely defines the system of equations, leaving as the only remaining freedom the choice as the matter density profile and the boundary conditions. To compute the evolution of these

\[http://plutocode.ph.unito.it/\]

![Figure 13. Evolution in the laboratory frame of \(\beta\), \(\Gamma\), and \(R\) of the thermal emitter from the time intervals in Table 2.](image-url)
quantities in the chosen setup, the code uses the HLLC Riemann solver for relativistic fluids (see Mignone et al. 2011). The time evolution is performed by means of a second-order Runge–Kutta integration, and a second-order total variation diminishing scheme is used for the spatial interpolation. An adaptive mesh refinement algorithm is implemented as well, provided by the CHOMBO library (Colella et al. 2003). We turn now to the determination of the SN ejecta.

(b) The initially ultra-relativistic $e^+e^-$ plasma expands through the SN ejecta matter, slowing down to mildly relativistic velocities. The SN density and velocity profiles are taken from the 3D SPH simulation of the SN ejecta expansion under the influence of the iNS and the NS companion gravitational field. In our simulations, we include the NS orbital motion and the NS gravitational-mass changes due to the accretion process modeled with the Bondi–Hoyle formalism (see Becerra et al. 2016, for more details). We set the SN ejecta initial conditions, adopting a homologous velocity distribution in free expansion, and the SN matter was modeled with 16 million point-like particles. Each SN layer is initially populated following a PL density profile of the CO$_{\text{core}}$, as obtained from low-metallicity progenitors evolved with the Kepler stellar evolution code (Woosley et al. 2002). Here, we take the simulation of an initial binary system formed by a 2.0 $M_\odot$ NS and a CO$_{\text{core}}$ produced by an $M_{\text{ZAMS}} = 30 M_\odot$ progenitor as a reference model. This leads to a total ejecta with a mass of $7.94 M_\odot$ and a iNS of $1.5 M_\odot$. The orbital period of the binary is $P \approx 5$ minutes, i.e., a binary separation of $a \approx 1.5 \times 10^{10}$ cm. The density profile exhibiting the evolution of the SN ejecta and the companion star is shown in Figure 14. Figure 15 shows the SN ejecta mass enclosed within a cone of 5° of the semi-aperture angle with the vertex at the position of the BH at the moment of its formation. The cone axis stands along the $\theta$ direction measured counterclockwise with respect to the line of sight. We simulate the interaction of the $e^+e^-$ plasma with such ejecta from a radius $\approx 10^{10}$ cm all the way to $\approx 10^{12}$ cm where transparency is reached. We have recently run new 3D SPH simulations of this process in Becerra et al. (2018) using the SNSPH code (Fryer et al. 2006). These new simulations have allowed for a wide exploration of the binary parameter space and have confirmed the results and the physical picture presented in Becerra et al. (2016). On the basis of these new simulations, we have determined the value of the baryon loads both for the hard X-ray flares and the soft X-ray flares.

(c) For the simulation of the hard X-ray flare, we set a total energy of the plasma equal to that of the hard X-ray flare, i.e., $E_\gamma = 3.28 \times 10^{52}$ erg, and a baryon load of $B = 79$, corresponding to a baryonic mass of $M_B = 1.45 M_\odot$. We obtain a radius of the transparency $R_{\text{ph}} = 4.26 \times 10^{11}$ cm, a Lorentz factor at transparency $\Gamma = 2.86$, and an arrival time of the corresponding radiation in the cosmological rest frame $t_a = 56.7$ s (see Figure 16). This time is in agreement with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure14}
\caption{Three snapshots of the density distribution of the SN ejecta in the equatorial plane of the progenitor binary system. The time $t = 0$ indicates the instant when the NS companion reaches, by accretion, the critical mass and leads to the formation of a BH (black dot). As evidenced in panel (a), the location of the black hole formation is widely separated from the central position represented by the SN explosion, it is actually located in the white conical region in Figure 2. The binary parameters of these simulations are: the NS companion has an initial mass of 2.0 $M_\odot$; the CO$_{\text{core}}$ obtained from a progenitor with a ZAMS mass of $M_{\text{ZAMS}} = 30 M_\odot$, leads to a total ejecta mass of $7.94 M_\odot$ and to a 1.5 $M_\odot$ iNS (white dot); and the orbital period is $P \approx 5$ minutes, i.e., a binary separation of $a \approx 1.5 \times 10^{10}$ cm.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure15}
\caption{SN ejecta mass enclosed within a cone of 5° of semi-aperture angle and vertex centered on the SN and positioned to an angle $\theta$, measured counterclockwise, with respect to the line of sight (which passes through the iNS and BH at the moment of its formation; see Conclusions). The binary parameters of these simulations are: the NS has an initial mass of 2.0 $M_\odot$; the CO$_{\text{core}}$ obtained from a progenitor with a ZAMS mass $M_{\text{ZAMS}} = 30 M_\odot$, leads to a total ejecta mass $7.94 M_\odot$, the orbital period is $P \approx 5$ min, i.e., a binary separation $a \approx 1.5 \times 10^{10}$ cm. The right-side vertical axis gives, as an example, the corresponding value of the baryon load, $B$, assuming a plasma energy of $E_{\gamma,\gamma} = 1 \times 10^{53}$ erg. It is appropriate to mention that the above values of the baryon load are computed using an averaging procedure, which is performed centered on the SN explosion and produces larger values than the one centered around the BH with a specific value of the baryon load $B \sim 1.9 \times 10^{-3}$ (see Figure 14(a)).}
\end{figure}
the starting time of the hard X-ray flare in the source rest frame (see Section 3).

For the simulation of the soft X-ray flare, we set the energy \( E_X = 4.39 \times 10^{51} \text{erg} \) as the total energy of the plasma and a baryon load as \( B = 207 \), which corresponds to a baryonic mass of \( M_B = 0.51 M_\odot \). We obtain a radius of the transparency of \( R_{\text{ph}} = 1.01 \times 10^{12} \text{cm} \), a Lorentz gamma factor at transparency \( \Gamma = 1.15 \), and an arrival time of the corresponding radiation in the cosmological rest frame of \( t_p = 236.8 \text{s} \) (see Figure 17). This time is in agreement with the above time \( t_p \) at which the soft X-ray flare peaks in the rest frame.

7. Summary, Discussion, and Conclusions

7.1. Summary

It is by now clear that seven different subclass of GRBs with different progenitors exist (Ruffini et al. 2016b). Each GRB subclass is itself composed of different episodes, each one characterized by specific observational data that make their firm identification possible (see e.g., Ruffini et al. 2018c, and references therein). Here, we evidence how, within the BdHN subclass, a further differentiation follows by selecting special viewing angles. We have applied our recent treatment (Ruffini et al. 2018c) to the UPE phase and the hard X-ray flare using the specific case of GRB 151027A as a prototype in view of the excellent available data.

We recall three results:

1. We have confirmed the ultra-relativistic nature of the UPE, which appears to be composed of a double spike (see Figures 4(a) and 5(b)). This double spike structure appears to be also present in other systems, such as GRB 140206A and GRB 160509A (R. Ruffini et al. 2018, in preparation). From the analysis of the P-GRB of the first spike, we derived an ultra-relativistic Lorentz factor of \( \Gamma_0 = 503 \pm 76 \), a baryon load of \( B = (1.92 \pm 0.35) \times 10^{-3} \), and a structure in the CBM with the density \((7.46 \pm 1.2) \times 10^{-5} \text{cm}^{-3} \) extending to dimensions of \(10^{16} \text{cm} \) (see Figure 5(d)). The second spike of energy, \( E_{\text{iso},2} = (4.99 \pm 0.60) \times 10^{51} \text{erg} \), after a cosmological rest-frame time of 9 s following the first spike of energy, \( E_{\text{iso},1} = (7.26 \pm 0.36) \times 10^{51} \text{erg} \) (see Figures 4(b) and (c)), appear to be featureless. We are currently examining the possibility that the nature of these two spikes and their morphology could be directly connected to the formation process of the BH.

2. A double spikes appears to occur also in the FPA phase (see Figure 7(a)); the first component is the hard X-ray flare, and the second is the soft X-ray flare. The energy of the hard X-ray flare is \( E_X = (3.28 \pm 0.13) \times 10^{52} \text{erg} \) (Figure 7), and the energy of the soft X-ray flare is \( E_X = (4.4 \pm 2.9) \times 10^{51} \text{erg} \) (Figure 9). We have analyzed both flares with our usual approach of the hydrodynamical equations describing the interaction of the electron-positron plasma with the SN ejecta (see Figure 16 for the hard X-ray flare and Figure 17 for the soft X-ray flare). The baryon loads of the two flares are different: \( B = 79 \) for the hard X-ray flare, and \( B = 207 \) for the soft X-ray flare. This is visualized in Figure 11 as well as in our 3D simulations (see the three snapshots shown in Figure 14). Both the hard X-ray flare and the soft X-ray flare show mildly relativistic regimes, as already observed in Ruffini et al. (2018c), namely a Lorentz factor at transparency of \( \Gamma \sim 5 \) for the hard X-ray flare and a Lorentz factor of \( \Gamma \sim 2 \) for the soft X-ray flare.

3. We studied the ETE associated to the hard X-ray flare. We have measured its expansion velocity derived from the relativistic treatment described in Section 5, following the formula in Figure 1 (see also Ruffini et al. 2018c). We have identified the transition from an SN, with an initial computed velocity of 0.38c, to an HN, with a computed velocity of 0.98c (see Figure 13 and Table 2). These results are in good agreement with observations of both SNe and HNe (see e.g., Table 3 and Figure 20 in Nicholl et al. 2015).
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Table 3
Parameters of the Sequence of Astrophysical Processes that Characterize the BdHNe: The Columns List, Respectively, the Name of Each Process, the Radius of Transparency, the Lorentz Gamma Factor ($\Gamma$) and the Baryon Load, Starting Time of the Process, the Duration, and, Finally, the Best-fit Model of the Spectrum

| Name & Description | Radius(cm) | $\Gamma$ | Baryon Load | $t_{\text{start}}$(s) | Duration(s) | Spectrum |
|--------------------|------------|----------|-------------|---------------------|-------------|----------|
| UPE First spike (P-GRB) | $\sim 10^{15}$ | $\sim 10^{2}$-$10^{3}$ | $\sim 10^4$-$10^5$ | $\sim T_0$ | $\sim 1$ | CPL+BB |
| UPE First spike (rest) | $\sim 10^{15}$-$10^{17}$ | $\sim 10^{2}$-$10^{3}$ | $\sim 10^4$-$10^5$ | $\sim T_0+1$ | $\sim 5$ | Band |
| UPE Second spike | $\sim 10^{15}$-$10^{17}$ | $\geq 10^3$ | $\lesssim 10^4$ | $\sim T_0+15$ | $\sim 5$ | Band |
| Hard X-ray flare | $\sim 10^{11}$-$10^{12}$ | $\lesssim 10$ | $\sim 10^2$ | $\sim T_0+5$ | $\sim 10^2$ | PL+BB |
| Soft X-ray flare | $\sim 10^{10}$-$10^{11}$ | $\lesssim 4$ | $\sim 10^1$ | $\sim T_0+10^3$ | $\sim 150$ | PL(+BB) |
| Late afterglow | $\geq 10^{11}$ | $\lesssim 2$ | $\sim T_0+10^2$ | $\sim 10^6$ | $\sim 10^6$ | PL |
| SN optical emission | $\sim 10^{15}$ | $\sim 1$ | $\sim T_0+10^6$ | $\sim 10^6$ | $\sim 10^6$ | PL |
| GeV emission | $\sim 10^{15}$ | $\sim 1$ | $\sim T_0+10^6$ | $\sim 10^4$ | $\sim 10^4$ | PL |

Note. $T_0$ is the Fermi-GBM trigger time.

The above observational analysis, as already presented in Pisani et al. (2013, 2016), set the ensemble of the data that any viable model of GRBs has to conform. In the last 30 years, the enormous number of high-quality data obtained (e.g., by Beppo-SAX, Swift, Agile, and Fermi) further extended by specific optical, radio, and ultrahigh-energy data offered the possibility to test the viable models that conform to these data. We have shown that the BdHN model can explain the above observational features.

7.2. Discussion

1. By adopting the BdHN approach, we discovered the existence of four different processes: a double feature in the UPE phase, the hard X-ray flares, the soft X-ray flares, and the ETE phase. Each one of these processes is generated by a different $e^+e^-$ injection occurring in a different baryon load medium. Using the binary nature of the progenitor system in BDH, especially the presence of an incipient SN and a companion NS, together with an appropriate theoretical treatment and an ample program of numerical simulations (Becerra et al. 2018), we have been able to determine the nature of these processes. Clear observational predictions have followed, including (the major one) the coincidence of the numerical value of the velocity of expansion at the end of the ETE phase with the observed expansion velocity of the HN, confirmed in additional BdHN and currently being observationally addressed in additional cases. A clear temporal sequence in the occurrence of these processes, as well as the specific sequence in the values of the Lorentz gamma factors, has been established.

2. For the first time, the rotation of the binary system, of the order of 400 s, has been essential in order to untangle the sequence of events discovered and explained in this article, recognizing their a-causal nature and their modulation by the rotation of the progenitor binary system.

3. The above different processes, including the double spiky structure of the UPE phase, the hard and soft X-ray flares, and the ETE phase are actually different appearances of the same physical process: the black hole formation, as seen from different viewing angles due to the rotation of the SN ejecta in the binary system (see Figure 14) and the consequent angular dependence of the baryon load (see Figure 15).

7.3. Conclusions

1. A clear prediction that will soon be submitted, following our paper, is that of all of the BdHNe occurring with a line of sight in the orbital plane of the binary, with only a fraction of approximately 10% being actually detectable. They correspond to the sources whose ultra-relativistic emission lies within the allowed cone of $\sim 10^2$ of low baryon contamination (see Figure 2 and Figure 15). They are the only ones able to trigger the gamma-ray instruments (e.g., the Fermi/GBM or Swift/BAT detectors). The remaining 90% will not be detectable by current satellites and will possibly need a new mission operating in soft X-rays (like e.g., THESEUS; see Amati et al. 2018).

2. The $E_{\text{iso}}$ traditionally defined using an underlying assumption of isotropy of the BH emission, has to be modified by considering an anisotropic emission process. A total energy, $E_{\text{iso}}$, summing the energies of the UPE, of the hard X-ray flare, of the ETE, and of the soft X-ray flare, has to be considered for sources seen in the equatorial plane. It is not surprising that the energy of the hard X-ray flare in GRB 151027A is larger than the one of the UPE, pointing to an anisotropic emission from the BH.

3. When the inclination of the viewing angle is less that 60° from the normal to the plane of the binary system, the GeV radiation becomes detectable, and its energy, which has been related to the BH rotational energy, will need to be taken into account (Ruffini et al. 2018a).

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Software: PLUTO (Mignone et al. 2011), CHOMBO (Colella et al. 2003), SNSPH (Fryer et al. 2006).

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