Early X-Ray Flares in GRBs

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Abstract

We analyze the early X-ray flares in the GRB “flare–plateau–afterglow” (FPA) phase observed by Swift-XRT. The FPA occurs only in one of the seven GRB subclasses: the binary-driven hypernovae (BdHNe). This subclass consists of long GRBs with a carbon–oxygen core and a neutron star (NS) binary companion as progenitors. The hypercritical accretion of the supernova (SN) ejecta onto the NS can lead to the gravitational collapse of the NS into a black hole. Consequently, one can observe a GRB emission with isotropic energy $E_{\text{iso}} \gtrsim 10^{52}$ erg, as well as the associated GeV emission and the FPA phase. Previous work had shown that gamma-ray spikes in the prompt emission occur at $\sim 10^{15} - 10^{17}$ cm with Lorentz Gamma factors $\Gamma \sim 10^2 - 10^3$. Using a novel data analysis, we show that the time of occurrence, duration, luminosity, and total energy of the X-ray flares correlate with $E_{\text{iso}}$. A crucial feature is the observation of thermal emission in the X-ray flares that we show occurs at radii $\sim 10^{17}$ cm with $\Gamma \lesssim 4$. These model-independent observations cannot be explained by the “fireball” model, which postulates synchrotron and inverse-Compton radiation from a single ultrarelativistic jetted emission extending from the prompt to the late afterglow and GeV emission phases. We show that in BdHNe a collision between the GRB and the SN ejecta occurs at $\sim 10^{10}$ cm, reaching transparency at $\sim 10^{12}$ cm with $\Gamma \lesssim 4$. The agreement between the thermal emission observations and these theoretically derived values validates our model and opens the possibility of testing each BdHN with the corresponding Lorentz Gamma factor.

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

Supporting material: machine-readable table

1. Introduction

Following the discovery of the gamma-ray bursts (GRBs) by the Vela satellites (Klebesadel et al. 1973) and the observations by the BATSE detectors on board the Compton Gamma-Ray Observatory (CGRO; Gehrels et al. 1993), a theoretical framework for the interpretation of GRBs was established. This materialized into the “traditional” model of GRBs developed in a large number of papers by various groups. They all agree in their general aspects: short GRBs are assumed to originate from the merging of binary neutron stars (NSs; see, e.g., Goodman 1986; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1991, 1992; Mészáros & Rees 1997), and long GRBs are assumed to originate from a “collapsar” (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999; Bromberg et al. 2013), which, in turn, originates from the collapse of the core of a single massive star to a black hole (BH) surrounded by a thick massive accretion disk (Piran 2004). In this traditional picture, the GRB dynamics follows the “fireball” model, which assumes the existence of an ultrarelativistic collimated jet (see, e.g., Shen & Piran 1990; Mészáros et al. 1993; Piran et al. 1993; Mao & Yi 1994). The structures of long GRBs were described by either internal or external shocks (see Rees & Mészáros 1992, 1994). The emission processes were linked to the occurrence of synchrotron and/or inverse-Compton radiation coming from the jetted structure, characterized by Lorentz factors $\Gamma \sim 10^2 - 10^3$, in what later will become known as the “prompt emission” phase (see Section 3).

The joint X-ray, gamma-ray, and optical observations heralded by BeppoSAX and later extended by Swift discovered the X-ray “afterglow,” which allowed the optical identification and the determination of the GRBs’ cosmological distance. The first evidence for the coincidence of a GRB and a supernova (SN; GRB 980425/SN 1998bw) was also announced as well as the first observation of an early X-ray flare (XRT), later greatly extended in number and spectral data by the Swift satellite, the subject of this paper. The launch of the Fermi and AGILE satellites led to the equally fundamental discovery of GeV emission both in long and short GRBs (see Section 2).

The traditional model was modified in light of these new basic information by extending the description of the “collapsar” model, adopted for the prompt emission, to both the afterglow and GeV emission. This approach, based on the gravitational collapse of a single massive star, which was initially inspired by analogies with the astrophysics of active galactic nuclei, has been adopted with the aim to identify a “standard model” for all long GRBs and vastly accepted by concordance (see, e.g., Piran 1999, 2004; Mészáros 2002, 2006; Gehrels et al. 2009; Berger 2014; Kumar & Zhang 2015).
Attempts to incorporate the occurrence of an SN in the collapsar by considering nickel production in the accretion process around the BH were also proposed (MacFadyen & Woosley 1999). In 1999, a pioneering work by Fryer et al. (1999b) introduced considerations based on population synthesis computations and emphasized the possible relevance of binary progenitors in GRBs.

Since 2001, we have been developing an alternative GRB model based on the concept of induced gravitational collapse (IGC) paradigm, which involves, as progenitors, a binary system with standard components: an evolved carbon–oxygen core (CO$_{\text{core}}$) and a binary companion NS. The CO$_{\text{core}}$ undergoes a traditional SN Ic explosion, which produces a new NS (νNS) and a large amount of ejecta. There is a multitude of new physical processes, occurring in selected episodes, associated with this process. The “first episode” (see Section 3) of the binary-driven hypernova (BdHN) is dominated by the hypercritical accretion process of the SN ejecta onto the companion NS. This topic has been developed in, e.g., Ruffini et al. (2001c), Rueda & Ruffini (2012), Fryer et al. (2014), and Becerra et al. (2015, 2016). These processes are not considered in the collapsar model. Our SN is a traditional Type Ic, the creation of the νNS follows standard procedure occurring in pulsar physics (see, e.g., Negreiros et al. 2012), the companion NS is a standard one regularly observed in binaries (see, e.g., Rueda & Ruffini 2012; Rueda et al. 2017), and the physics of hypercritical accretion has been developed by us in a series of recent articles (see Section 3.4).

In a BdHN, the BH and a vast amount of $e^+e^-$ plasma are formed only after the accreting NS reaches the critical mass and the “second episode” starts (see Section 3.5). The main new aspect of our model addresses the interaction of the $e^+e^-$ plasma with the SN ejecta. We apply the fireeshell model, which makes use of a general relativistic correct spacetime parameterization of the GRBs as well as a new set of relativistic hydrodynamics equation for the dynamics of the $e^+e^-$ plasma. Selected values of the baryon loads are adopted in correspondence with the different time-varying density distributions of the SN ejecta.

In the “third episode” (see Section 3.6), we also mention the perspectives, utilizing the experience gained from both data analysis and theory for the specific understanding of X-ray flares, to further address in forthcoming publications the more comprehensive case of gamma-ray flares, the consistent treatment of the afterglow, and finally the implication of the GeV radiation.

As the model evolved, we soon realized that the discovery of new sources was not leading to a “standard model” of long GRBs but, on the contrary, they were revealing a number of new GRB subclasses with distinct properties characterizing their light curves, spectra, and energetics (see Ruffini et al. 2016b). Moreover, these seven subclasses did not necessarily contain a BH. We soon came to the conclusion that only in the subclass of BdHN, with an $E_{\text{iso}}$ larger than $10^{52}$ erg, does the hypercritical accretion from the SN onto the NS lead to the creation of a newly born BH with the associated signatures in the long GRB emission (see, e.g., Becerra et al. 2015, 2016). While our alternative model was progressing, we were supported by new astrophysical observations: the great majority of GRBs are related to SNe Ic, which have no trace of hydrogen and helium in their optical spectra and are spatially correlated with bright star-forming regions in their host galaxies (Fruchter et al. 2006; Svensson et al. 2010). Most massive stars are found in binary systems (Smith 2014) where most SNe Ic occur and which favor the deployment of hydrogen and helium from the SN progenitors (Smith et al. 2011), and the SNe associated with long GRBs are indeed of Type Ic (Della Valle 2011). In addition, these SNe associated with long bursts are broad-lined Ic SNe (hypernovae) showing the occurrence of some energy injection leading to a kinetic energy larger than that of traditional SNe Ic (Lyman et al. 2016). The present paper addresses the fundamental role of X-ray flares as a separatrix between the two alternative GRB models and leads to the following main results, two obtained by data analysis and one obtained from the comparison of the alternative models:

1. The discovery of precise correlations between the X-ray flares and the GRB $E_{\text{iso}}$.
2. The radius of the occurrence of X-ray flares ($\sim 10^{12}$ cm) and the Lorentz Gamma factor $\sim 2$.
3. The occurrence of a sharp break between the prompt emission phase and the flare–plateau–afterglow (FPA) phase, not envisaged in the current GRB literature. This transition is evidence of a contradiction in using the ultrarelativistic jetted emission to explain the X-ray flares, the plateau, and the afterglow.

In Section 2, we recall, following the gamma-ray observations by the Vela satellites and the CGRO, the essential role of BeppoSAX and the Swift satellite. These satellites provided X-ray observations specifically of the X-ray flares, to which our new data analysis techniques and paradigms have been applied. We also recall that the Fermi and AGILE satellites announced the existence of GeV emission, which has become essential for establishing the division of GRBs into different subclasses.

In Section 3, we update our classification of GRBs with known redshift into seven different subclasses (see Table 2). For each subclass, we indicate the progenitor “in-states” and the corresponding “out-states.” We update the list of BdHNs (see Appendix A): long GRBs with $E_{\text{iso}} \gtrsim 10^{52}$ erg, with an associated GeV emission and with the occurrence of the FPA phase. We also recall the role of appropriate time parametrization for GRBs, which properly distinguishes the four time variables that enter into their analysis. Finally, we recall the essential theoretical background needed for the description of the dynamics of BdHNs, the role of neutrino emission in the process of hypercritical accretion of the SN ejecta onto the binary companion NS, the description of the dynamics of the $e^+e^-$–baryon plasma, and the prompt emission phase endowed with gamma-ray spikes. We then briefly address the new perspectives opened up by the present work, to be further extended to the analysis of gamma-ray flares, to the afterglow, and the essential role of each BdHN component, including the νNS. Having established the essential observational and theoretical backgrounds in Sections 2 and 3, we proceed to the data analysis of the X-ray flares.

In Section 4, we address the procedure used to compare and contrast GRBs at different redshifts, including the description in their cosmological rest frame as well as the consequent K corrections. This procedure has been ignored in the current GRB literature (see, e.g., Chincarini et al. 2010 and references therein.
as well as Section 11 of this paper). We then identify BdHNe as the only sources where early-time X-ray flares are identifiable. We recall that X-ray flares have neither been found in X-ray flashes nor in short GRBs. We also show that a claim of the existence of X-ray flares in short bursts has been superseded. We recall our 345 classified BdHNe (through the end of 2016). Their $T_{90}$\textsuperscript{9} properly evaluated in the source rest frame, corresponds to the duration of their prompt emission phase, mostly shorter than 100 s. Particular attention has been given to distinguishing X-ray flares from gamma-ray flares and spikes, each characterized by distinct spectral distributions and specific Lorentz Gamma factors. The gamma-ray flares are generally more energetic and with specific spectral signatures (see, e.g., the significant example of GRB 140206A in Section 5 below). In this article we focus on the methodology of studying X-ray flares: we plan to apply this knowledge to the case of the early gamma-ray flares. Out of the 345 BdHNe, there are 211 that have complete Swift-XRT observations, and among them, there are 16 BdHNe with a well-determined early X-ray flare structure. They cover a wide range of redshifts as well as the typical range of BdHN isotropic energies ($\sim10^{52}$–$10^{54}$ erg). The sample includes all identifiable X-ray flares.

In Section 5, we give the X-ray luminosity light curves of the 16 BdHNe in our sample and, when available, the corresponding optical observations. As usual, these quantities have been $K$-corrected to their rest frame (see Figures 9–24 and Section 4). In order to estimate the global properties of these sources, we also examine data from the Swift, Konus-Wind, and Fermi satellites. The general results of this large statistical analysis are given in Table 3, where the cosmological redshift $z$, the GRB isotropic energy $E_{\text{iso}}$, the flare peak time $t_p$, peak luminosity $L_p$, duration $\Delta t$, and the corresponding $E_f$ are reproduced. This lengthy analysis has been carried out over the past years, and only the final results are summarized in Table 3.

In Section 6, we present the correlations between $t_p$, $L_p$, $\Delta t$, $E_f$, and $E_{\text{iso}}$ and give the corresponding parameters in Table 4. In this analysis, we applied the Markov Chain Monte Carlo (MCMC) method, and we also have made public the corresponding numerical codes in https://github.com/YWangScience/AstroNeuron and https://github.com/YWangScience/MCCC.

In Section 7, we discuss the correlations between the energy of the prompt emission, the energy of the FPA phase, and $E_{\text{iso}}$ (see Tables 5–6 and Figures 29–31).

In Section 8, we analyze the thermal emission observed during the X-ray flares (see Table 7). We derive, in an appropriate relativistic formalism, the relations between the observed temperature and flux and the corresponding temperature and radius of the thermal emitter in its comoving frame.

In Section 9, we use the results of Section 8 to infer the expansion speed of the thermal emitter associated with the thermal components observed during the flares (see Figure 32 and Table 8). We find that the observational data imply a Lorentz factor $\Gamma \lesssim 4$ and a radius of $\approx 10^{12}$ cm for such a thermal emitter.

In Section 10, we present a theoretical treatment using a new relativistic hydrodynamical code to simulate the interaction of the $e^+e^-$-baryon plasma with the high-density regions of the SN ejecta. We first test the code in the same low-density domain of validity describing the prompt emission phase, and then we apply it in the high-density regime of the propagation of the plasma inside the SN ejecta, which we use for the theoretical interpretation of the X-ray flares. Most remarkably, the theoretical code leads to a thermal emitter with a Lorentz factor $\Gamma \lesssim 4$ and a radius of $\approx 10^{12}$ cm at transparency. The agreement between these theoretically derived values and the ones obtained from the observed thermal emission validates the model and the binary nature of the BdHN progenitors, in clear contrast with the traditional ultrarelativistic jetted models.

In Section 11, we present our conclusions. We first show how the traditional model, describing GRBs as a single system with ultrarelativistic jetted emission extending from the prompt emission all the way to the final phases of the afterglow and of the GeV emission, is in conflict with the X-ray flare observations. We also present three new main results that illustrate the new perspectives opened up by our alternative approach based on BdHNe.

A standard flat $\Lambda$CDM cosmological model with $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s$^-1$ Mpc$^-1$ is adopted throughout the paper, while Table 1 summarizes the acronyms we have used.

### 2. Background for the Observational Identification of the X-Ray Flares

The discovery of GRBs by the Vela satellites (Klebesadel et al. 1973) was presented at the AAAS meeting in February 1974 in San Francisco (Gursky & Ruffini 1975). The Vela satellites were operating in gamma-rays in the 150–750 keV energy range and only marginally in X-rays (3–12 keV; Cline et al. 1979). Soon after it was hypothesized from first principles that GRBs may originate from an $e^+e^-$ plasma in the gravitational collapse to a Kerr–Newman BH, implying an energy $\sim 10^{54} M_{\odot} / M_5$ erg (Damour & Ruffini 1975; see also Ruffini 1998).

Since 1991, the BATSE detectors on the CGRO (see Gehrels et al. 1993) have been leading to the classification of GRBs on the basis of their spectral hardness and of their observed $T_{90}$ duration in the 50–300 keV energy band into short/hard bursts ($T_{90} < 2$ s) and long/soft bursts ($T_{90} > 2$ s) (Mazets et al. 1981; Dezalay et al. 1992; Klebesadel 1992; Kouveliotou et al. 1993; Tavani 1998). Such an emission was later called the GRB

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\textsuperscript{9} $T_{90}$ is the duration of the interval starting (ending) when 5% (95%) of the total energy of the event in gamma-rays has been emitted.
“prompt emission.” In a first attempt, it was proposed that short GRBs originate from merging binary NSs (see, e.g., Goodman 1986; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1991, 1992; Mészáros & Rees 1997) and long GRBs originate from a single source with ultrarelativistic jetted emission (Woosley 1993; Paczynski 1998; MacFadyen & Woosley 1999; Bromberg et al. 2013).

The BeppoSAX satellite, operating since 1996, joined the expertise of the X-ray and gamma-ray communities. Its gamma-ray burst monitor (GRBM) operating in the 40–700 keV energy band determined the trigger of the GRB, and two wide-field cameras operating in the 2–30 keV X-ray energy band allowed the localization of the source within an arcminute resolution. This enabled a follow-up with the narrow-field instruments (NFI), transmitted to the optical field instruments (see Figure 3). Within 90 s, Swift can re-point the narrow-field X-ray telescope (XRT), operating in the 0.3–10 keV energy range, and relay the burst position to the ground. This overcomes the “8 hr gap” in the BeppoSAX data.

Thanks to the Swift satellite, the number of detected GRBs increased rapidly to 480 sources with known redshifts. By analyzing the light curve of some long GRBs, including the data in the “8 hr gap” of BeppoSAX, Nousek et al. (2006) and Zhang et al. (2006) discovered three power-law segments in the XRT flux light curves of some long GRBs. We refer to these as the “Nousek–Zhang power laws” (see Figure 2). The nature of this feature has been the subject of a long debates, still ongoing, and is finally resolved in this article.

We have used Swift-XRT data in differentiating two distinct subclasses of long GRBs: XRfs with $E_{iso} \lesssim 10^{52}$ erg and BdHNe with $E_{iso} \gtrsim 10^{52}$ erg (see Section 3). An additional striking difference appears between the XRT luminosities of these two subclasses when measured in their cosmological rest frames: in the case of BdHNe, the light curves follow a specific behavior that conforms to the Nousek–Zhang power law (see, e.g., Penacchioni et al. 2012, 2013; Pisani et al. 2013, 2016; Ruffini et al. 2014). None of these features are present in the case of XRfs (see Figure 3).

Finally, the Fermi satellite (Atwood et al. 2009), launched in 2008, detects ultrahigh energy photons from 20 MeV to 300 GeV with the Large Area Telescope (LAT) and detects photons from 8 keV to 30 MeV with the Gamma-ray Burst Monitor (GBM). For the purposes of this article addressing long GRBs, the Fermi observations have been prominent in further distinguishing between XRfs and BdHNe: the Fermi-LAT GeV emission has been observed only in BdHNe and never in XRfs.

3. Background for the Theoretical Interpretation of X-Ray Flares and Their Dynamics

3.1. The Classification of GRBs

The very extensive set of observations carried out by the above satellites in coordination with the largest optical and radio telescopes over a period of almost 40 years has led to an impressive set of data on 480 GRBs, all characterized by spectral, luminosity, and time variability information, and each one with a well-established cosmological redshift. By understanding the astrophysical nature of the GRB–SN connection.

The Swift Burst Alert Telescope (BAT), operating in the 15–150 keV energy band, can detect GRB prompt emissions and accurately determine their position in the sky within 3 arcmin. Within 90 s, Swift can re-point the narrow-field X-ray telescope (XRT), operating in the 0.3–10 keV energy range, and relay the burst position to the ground. This overcomes the “8 hr gap” in the BeppoSAX data.

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classifying both the commonalities and the differences among all GRBs, it has been possible to create “equivalence relations” and divide GRBs into a number of subclasses, each one identified by a necessary and sufficient number of observables. We recall in Table 2 and Figure 4 the binary nature of all GRB progenitors and their classification into seven different subclasses (see, e.g., Ruffini et al. 2016b). In Table 2, we indicate the number of sources in each subclass, the nature of their progenitors and final outcomes of their evolution, their rest-frame $t_{0b}$, their rest-frame spectral peak energy $E_{p,1}$ and $E_{iso}$ as well as the isotropic energy in X-rays $E_{iso,X}$ and in GeV emission $E_{iso,GeV}$, and finally their local observed number density rate. In Figure 4, we mention the $E_{p,1}$–$E_{iso}$ relations for these sources, including the Amati one for BdHNe and the MuRuWaZha one for the short bursts (see Ruffini et al. 2016a, 2016b), comprising short gamma-ray flashes (S-GRFs) with $E_{iso} \lesssim 10^{52}$ erg, authentic short GRBs (S-GRBs) with $E_{iso} \gtrsim 10^{52}$ erg, and gamma-ray flashes (GRFs), sources with hybrid short/long burst properties in their gamma-ray light curves, i.e., an initial spike-like harder emission followed by a prolonged softer emission observed up to $\sim 100$ s, originating from NS–white dwarf binaries (Caito et al. 2009, 2010; Ruffini et al. 2016b). We have no evidence for an $E_{p,1}$ and $E_{iso}$ relation in the XRFs (see Figure 4). The Amati and the MuRuWaZha relations have not yet been theoretically understood, and as such they have no predictive power.

3.2. The Role of Time Parametrization in GRBs

Precise general relativistic rules in the spacetime parameterization of GBRs are needed (Ruffini et al. 2001a). Indeed, there are four time variables entering this discussion, which have to be properly distinguished one from another: (1) the comoving time $t_{com}$, which is the time used to compute the evolution of the thermodynamical quantities (density, pressure, temperature); (2) the laboratory time $t = \Gamma t_{com}$, where as usual the Lorentz Gamma factor is $\Gamma = (1 - \beta^2)^{-1/2}$ and $\beta = v/c$ is the expansion velocity of the source; (3) the arrival time $t_a$ at which each photon emitted by the source reaches an observer in the cosmological rest frame of the source, given by (see also Bianco et al. 2001; Ruffini et al. 2002; Bianco & Ruffini 2005a)

$$t_a = t - \frac{r(t)}{c}\cos \vartheta,$$

where $r(t)$ is the radius of the expanding source in the laboratory frame and $\vartheta$ is the displacement angle of the normal to the emission surface from the line of sight; and (4) the arrival time at the detector on the Earth, $t_a^d = t_a(1+\gamma)$, corrected for cosmological effects, where $\gamma$ is the source redshift needed in order to compare GRBs at different redshifts $z$. As emphasized in Ruffini et al. (2001a, p. L108), “the bookkeeping of these four different times and the corresponding space variables must be done carefully in order to keep the correct causal relation in the time sequence of the events involved.” The chain of relations between these four times is given by (see e.g., Bianco et al. 2001; Ruffini et al. 2001a, 2002; Bianco & Ruffini 2005a, and see also Sections 8 and 9 for the dynamics of the flares)

$$t_a^d = (1+z)t_a = (1+z)\left(t - \frac{r(t)}{c}\cos \vartheta\right)$$

$$= (1+z)\left(\Gamma t_{com} - \frac{\Gamma t_{com}}{c}\cos \vartheta\right).$$

The proper use of these four time variables is mandatory in modeling GRB sources, especially when we are dealing with a model not based on a single component but on multiple components, each characterized by a different world line and a different Lorentz Gamma factor, as is the case for BdHNe (see Sections 4 and 5).

3.3. The Role of the GRBs’ Cosmological Rest Frame

In addition to all of the above, in order to compare the luminosities of different GRBs at different redshifts we need to express the observational data in the cosmological rest frames of each source (where the arrival time is $t_a$), and correspondingly apply the $K$ correction to luminosities and spectra (see Section 4). This formalism is at the very foundation of the treatment presented in this paper and has been systematically neglected in the great majority of current GRB models.

3.4. Episode 1: The Hypercritical Accretion Process

In order to describe the dynamics of BdHNe, a number of different episodes involving different physical conditions have
Ruffini et al. (2016a, 2016b), and Becerra et al. (2016).

Figure 4. Updated $E_{\gamma, p}-E_{\gamma, X}$ plane for the subclasses defined in Ruffini et al. (2016b): XRF (red triangles) cluster in the region defined by $E_{\gamma, p} \lesssim 200$ keV and $E_{\gamma, X} \lesssim 10^{52}$ erg. BdHN (black squares) cluster in the region defined by $E_{\gamma, p} \gtrsim 200$ keV and $E_{\gamma, X} \gtrsim 10^{52}$ erg and fulfilling the Amati relation (solid magenta line with slope $\alpha = 0.57 \pm 0.06$ and extra scatter $\sigma = 0.25$; see, e.g., Amati & Della Valle 2013; Calderone et al. 2015). S-GRFs (green circles) and the initial spike-like emission of the GRFs (orange reverse triangles) are concentrated in the region defined by $E_{\gamma, p} \lesssim 2$ MeV and $E_{\gamma, X} \lesssim 10^{52}$ erg, while S-GRBs (blue diamonds) are concentrated in the region defined by $E_{\gamma, p} \gtrsim 2$ MeV and $E_{\gamma, X} \gtrsim 10^{52}$ erg. Short bursts and GRFs fulfill the $\mu$RuWazha relation (blue solid line with slope $\alpha = 0.53 \pm 0.07$ and extra scatter $\sigma = 0.24$; see, e.g., Zhang et al. 2012; Calderone et al. 2015; Ruffini et al. 2015b, 2016a). The BH-SN and U-GRB subclasses (see Table 2 in Ruffini et al. 2016b for details) are not in the plot since their observational identifications are still pending. The crucial difference between BdHN and XRFs, and S-GRBs and S-GRFs, is that BdHN and S-GRBs form a BH, their energy is $\gtrsim 10^{52}$ erg, and they exhibit GeV emission.

to be described. Episode 1 is dominated by the IGC paradigm: the hypercritical accretion of an SN ejecta onto the companion binary NS (see, e.g., Fryer et al. 2014, 2015; Becerra et al. 2015, 2016). Weak interactions and neutrinos (see, e.g., Fermi 1934), which play a fundamental role in SNe through the URCA process (Gamow & Schoenberg 1940, 1941), are also needed in the case of hyperecritical accretion processes onto an NS in an SN fallback (Colgate 1971; Zel’ dovich et al. 1972; Ruffini & Wilson 1973). They are especially relevant in the case of BdHN where the accretion rate onto the NS companion from $C_{\text{core}}$ can reach up to $M = 0.1 M_\odot$ s$^{-1}$ (Rueda & Ruffini 2012; Fryer et al. 2014; Becerra et al. 2015, 2016). Due to weak interactions, $e^+e^-$ pairs annihilate to $\nu\bar{\nu}$ pairs with a cross-section $\sigma \sim G_F^2 \langle E_e \rangle^3$ (Munakata et al. 1985; Itoh et al. 1989). In the thermal system of $e^+e^-$ pairs at large temperature $kT > m_e c^2$ and density $n_e \sim T^3$, the neutrino emissivity of the $e^+e^-$ annihilation is $\epsilon_{e^+e^-} \sim n_e^2 \langle e^{-}\rangle \langle E_e \rangle \sim 10^{39} (kT/\text{MeV})^3 \text{erg s}^{-1} \text{cm}^{-3}$, leading to neutrino luminosities $L_\nu \sim 10^{52} \text{erg s}^{-1} \text{cm}^{-2}$, which dominate over other microphysical processes for cooling (Becerra et al. 2016). Thus, $e^+e^-$ pair annihilation to $\nu\bar{\nu}$ is the main process for cooling, allowing the process of hypercritical accretion to convert gravitational energy into thermal energy, to build up high temperature, and consequently to form an $e^+e^-$ plasma. Only at the end of Episode 1, as the critical mass of the companion NS is reached, is a BH formed with the additional $e^+e^-$ pairs linked to the BH electrodynamical process (Damour & Ruffini 1975; Cherubini et al. 2009).

3.5. Episode 2: $e^+e^-$ Pairs Colliding with the SN Ejecta

Episode 2 is dominated by the new phenomenon of the impact of $e^+e^-$ pairs generated in the GRB on the SN ejecta. We describe this process within the fireball model. Two main differences exist between the fireshell and the fireball models. In the fireshell model, the $e^+e^-$ plasma is initially in thermal equilibrium and undergoes ultrarelativistic expansion, keeping this condition of thermal equilibrium all the way to reaching transparency (Ruffini 1998; see also Aksenov et al. 2007; Ruffini et al. 2010 and references therein), while in the fireball model (Cavallo & Rees 1978), the $e^+e^-$ pairs undergo an initial annihilation process that produces the photons driving the fireball. An additional basic difference is that the evolution of the $e^+e^-$ plasma is not imposed by a given asymptotic solution but integrated following the relativistic fluid dynamics equations. The plasma, with energy $E_{e^+e^-}$, first goes through an initial acceleration phase (Ruffini et al. 1999). After colliding with the baryons (of total mass $M_B$), characterized by the baryon load parameter $B = M_B c^2 / E_{e^+e^-}$, the optically thick plasma keeps accelerating until it reaches transparency and emits a proper gamma-ray burst (P-GRB; see Ruffini et al. 2000). The accelerated baryons then interact with the circumburst medium (CBM) clouds (Ruffini et al. 2001b); the equation of motion of the plasma has been integrated, leading to results that differ from
the ones in Blandford & McKee’s (1976) self-similar solution (see Bianco & Ruffini 2004, 2005a, 2005b, 2006). By using Equation (2), which defines “equitemporal surfaces” (see Bianco et al. 2001; Bianco & Ruffini 2004, 2005a, 2005b, 2006), it has been possible to infer the structure of the gamma-ray spikes in the prompt emission, which for the most part has been applied to the case of BdHNe (see, e.g., Ruffini et al. 2002, 2016a; Bernardini et al. 2005; Izzo et al. 2012; Patricelli et al. 2012; Penacchioni et al. 2012, 2013). For typical baryon loads of \(10^{-4} \lesssim B \lesssim 10^{-2}\) leading to Lorentz Gamma factors \(\Gamma \approx 10^2-10^3\) at transparency for the \(e^+e^-\)-baryon plasma, characteristic distances from the BH of \(\approx 10^{15}-10^{17}\) cm have been derived (see, e.g., Ruffini et al. 2016b and references therein). Those procedures are further generalized in this paper to compute the propagation of \(e^+e^-\) through the SN ejecta (see Section 10), after computing their density profiles (see Figure 35) and the corresponding baryon load (see Figure 34), and the equations have been integrated all the way up to the condition of transparency (see Figures 36 and 37).

3.6. Episode 3: Ongoing Research on the Gamma-Ray Flares, Afterglow, and GeV Emission

We have exemplified the necessary steps in the analysis of each episode, which include determining the physical nature of each episode and the corresponding world line with the specific time-dependent Lorentz Gamma factor and so determining, using Equation (2), the arrival time at the detector, which has to agree, for consistency, with the one obtained from the observations. This program is applied in this article specifically for the analysis of early X-ray flares (see Sections 8 and 9). We will follow the same procedures for (1) the more complex analysis of gamma-ray flares, (2) the analysis of the afterglow consistent with the constraints on the X-ray flares observations, and (3) the properties of the GeV emission, common to BdHNe and S-GRBs (Ruffini et al. 2015c, 2016a). Having established the essential observational and theoretical background in Sections 2 and 3, we proceed to the data analysis of the early X-ray flares (see Sections 4–10).

4. The Early Flares and Sample Selection

With the increase in the number of observed GRBs, an attempt was made to analyze the X-ray flares and other processes considered to be similar in the observer reference frame, independent of the nature of the GRB type and of the value of their cosmological redshift or the absence of such a value. The goal of this attempt was to identify their “standard” properties, following a statistical analysis methodology often applied in classical astronomy (see Chincarini et al. 2007; Falcone et al. 2007; Margutti et al. 2010). Similarly, for the flux observed by the above satellites in Section 2, each instrument is characterized by its fixed energy window \([\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}]\). The observed flux \(f_{\text{obs}}\) defined as the energy per unit area and time in a fixed instrumental energy window \([\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}]\), is expressed in terms of the observed photon number spectrum \(n_{\text{obs}}\) (i.e., the number of observed photons per unit energy, area, and time) as

\[
f_{\text{obs}}(\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}) = \int_{\epsilon_{\text{obs},1}}^{\epsilon_{\text{obs},2}} \epsilon n_{\text{obs}}(\epsilon) d\epsilon.
\]

(3)

It then follows that the luminosity \(L\) of the source (i.e., the total emitted energy per unit time in a given bandwidth), expressed by definition in the source cosmological rest frame, is related to \(f_{\text{obs}}\) through the luminosity distance \(D_L(z)\):

\[
L(\epsilon_{\text{obs},1}(1+z); \epsilon_{\text{obs},2}(1+z)) = 4\pi D_L^2(z) f_{\text{obs}}(\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}).
\]

(4)

The above Equation (4) gives the luminosities in different cosmological rest-frame energy bands, depending on the source determining such a correlation. We have analyzed all X-ray flares and found, a posteriori, that X-ray flares only occur in BdHNe. No X-ray flare has been identified in any other GRB subclass, either long or short. A claim of their existence in short bursts (Barthelmy et al. 2005; Fan et al. 2005; Dai et al. 2006) has been superseded: GRB 050724 with \(T_{90} \sim 100\) s is not a short GRB, but actually a GRF, expected to originate in the merging of an NS and a white dwarf (see Figure 4); the X-ray data for this source from XRT are sufficient to assert that there is no evidence of an X-ray flare as defined in this section. GRB 050709 is indeed a short burst. It has been classified as an S-GRF (Aimuratov et al. 2017) and has been observed by HETE with very sparse X-ray data (Butler et al. 2005), and no presence of an X-ray flare can be inferred; the Swift satellite pointed at this source too late, 38.5 hr after the HETE trigger (Morgan et al. 2005).

As a second step, since all GRBs have a different redshift \(z\), in order to compare them we need a description of each of them in its own cosmological rest frame. The luminosities have to be estimated after doing the necessary \(K\) corrections and the time coordinate in the observer frame has to be corrected by the cosmological redshift \(t^\text{fl} \approx (1+z)t^\text{obs}\). This also affects the determination of the \(T_{90}\) of each source (see, e.g., Figure 38 in Section 11 where the traditional approach by Kouveliotou et al. 1993 and Bromberg et al. 2013 has been superseded by ours).

As a third step, we recall an equally important distinction from the traditional fireball approach with a single ultrarelativistic jetted emission. Our GRB analysis envisages the existence of different episodes within each GRB, each one characterized by a different physical process and needing the definition of its own world line and corresponding Gamma factors, essential for estimating the time parametrization in the rest frame of the observer (see Section 2).

These three steps are applied in the present article, which specifically addresses the study of early X-ray flares and their fundamental role in establishing the physical and astrophysical nature of BdHNe and in distinguishing our binary model from the traditional one.

Before proceeding, let us recall the basic point of the \(K\) correction. All of the observed GRBs have a different redshift. In order to compare them, it is necessary to refer to each of them in its cosmological rest frame. This step has often been ignored in the current literature (Chincarini et al. 2007; Falcone et al. 2007; Margutti et al. 2010). Similarly, for the flux observed by the above satellites in Section 2, each instrument is characterized by its fixed energy window \([\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}]\). The observed flux \(f_{\text{obs}}\), defined as the energy per unit area and time in a fixed instrumental energy window \([\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}]\), is expressed in terms of the observed photon number spectrum \(n_{\text{obs}}\) (i.e., the number of observed photons per unit energy, area, and time) as

\[
f_{\text{obs}}(\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}) = \int_{\epsilon_{\text{obs},1}}^{\epsilon_{\text{obs},2}} \epsilon n_{\text{obs}}(\epsilon) d\epsilon.
\]

(3)

It then follows that the luminosity \(L\) of the source (i.e., the total emitted energy per unit time in a given bandwidth), expressed by definition in the source cosmological rest frame, is related to \(f_{\text{obs}}\) through the luminosity distance \(D_L(z)\):

\[
L(\epsilon_{\text{obs},1}(1+z); \epsilon_{\text{obs},2}(1+z)) = 4\pi D_L^2(z) f_{\text{obs}}(\epsilon_{\text{obs},1}; \epsilon_{\text{obs},2}).
\]

(4)
redshift. To express the luminosity $L$ in a fixed cosmological rest-frame energy band, e.g., $[E_1, E_2]$, common to all sources, we can rewrite Equation (4) as

$$ L_{[E_1; E_2]} = 4\pi D_L^2 \int_{E_{\text{obs,1}}}^{E_{\text{obs,2}}} \int_{E_1}^{E_2} \frac{\epsilon n_{\text{obs}}(\epsilon)}{\epsilon^{2+\alpha}} \, d\epsilon \, dE_f $$

where we have defined the $K$-correction factor:

$$ k[\epsilon_{\text{obs,1}; \epsilon_{\text{obs,2}}; E_1; E_2; \epsilon] = \frac{\int_{E_{\text{obs,1}}}^{E_{\text{obs,2}}} \int_{E_1}^{E_2} \epsilon n_{\text{obs}}(\epsilon)}{\int_{E_{\text{obs,1}}}^{E_{\text{obs,2}}} \int_{E_1}^{E_2} \epsilon n_{\text{obs}}(\epsilon)} $$

If the energy range $[E_{\text{obs,1}}; E_{\text{obs,2}}]$ is not fully inside the instrumental energy band $[E_1; E_2]$, it may well happen that we will need to extrapolate $n_{\text{obs}}$ within the integration boundaries $[E_{\text{obs,1}}; E_{\text{obs,2}}]$.

Finally, we express each luminosity in a rest-frame energy band that coincides with the energy window of each specific instrument.

We turn now to the selection procedure for early X-ray flares. We take the soft X-ray flux light curves of each source with known redshift from the Swift-XRT repository (Evans et al. 2007, 2009). We then apply the above $K$ correction to obtain the corresponding luminosity light curves in the rest frame 0.3–10 keV energy band. Starting from 421 Swift-XRT light curves, we found 50 sources X-ray flare structures in the early 200 s. Remarkably, all of them are in BdHNe. We further filter our sample by applying the following criteria:

1. We exclude GRBs with flares having a low ($<20$) signal-to-noise ratio or with an incomplete data coverage of the early X-ray light curve—14 GRBs are excluded (see e.g., Figure 5).
2. We consider only X-ray flares and do not address here the gamma-ray flares, which will be studied in a forthcoming article—eight GRBs having only gamma-ray flares are temporarily excluded (see, e.g., Figure 6). In Figure 7, we show an illustrative example of the possible co-existence of an X-ray flare and a gamma-ray flare, and a way to distinguish them.
3. We also ignore here the late X-ray flare, including the ultralong GRB, which will be discussed in a forthcoming paper—six GRBs are consequently excluded.
4. We ignore the GRBs for which the soft X-ray energy observed by Swift-XRT (0.3–10 keV) before the plateau phase is higher than the gamma-ray energy observed by Swift-BAT (15–150 keV) during the entire valid Swift-BAT observation. This Swift-BAT anomaly points to an incomplete coverage of the prompt emission—six GRBs are excluded (see, e.g., Figure 8).

Finally, we have found 16 BdHNe satisfying all of the criteria to be included in our sample. Among them, seven
BdHNe show a single flare. The other nine BdHNe contain two flares: generally, we exclude the first one, which appears to be a component from the gamma-ray spike or gamma-ray flare, and therefore select the second one for analysis (see, e.g., Figure 7).

These 16 selected BdHNe cover a wide range of redshifts. The closest one is GRB 070318 with redshift $z = 0.84$, and the farthest one is GRB 090516A with redshift $z = 4.11$. Their isotropic energy is also distributed over a large range: five GRBs have energies of the order of $10^{52}$ erg, nine GRBs of the order of $10^{53}$ erg, and two GRBs have extremely high isotropic energies $E_{\text{iso}} > 10^{54}$ erg. Therefore, this sample is well-constructed although the total number is limited.

5. The XRT Luminosity Light Curves of the 16 BdHN Sample

We now turn to the light curves of each of these 16 GRBs composing our sample (see Figures 9–24). The blue curves represent the X-rays observed by Swift-XRT, and the green curves are the corresponding optical observations when available. All of the values are in the rest frame and the X-ray luminosities have been $K$-corrected. The red vertical lines indicate the peak time of the X-ray flares. The rest-frame luminosity light curves of some GRBs show different flare structures compared to the observed count flux light curves. An obvious example is GRB 090516A, which follows from comparing Figure 18 in this paper with Figure 1 in Troja et al. (2015). The details of the FPA, as well as their correlations or the absence of correlation with $E_{\text{iso}}$, are given in the next section.

We then conclude that in our sample, there are Swift data for all GRBs: Konus-Wind observed GRBs 080607, 080810, 090516A, 131030A, 140419A, 141221A, and 151027A, while Fermi detected GRBs 090516A, 140206, 141221A, and 151027A. The energy coverage of the available satellites is limited, as mentioned in Section 2: Fermi detects the widest photon energy band, from 8 keV to 300 GeV, Konus-Wind observes from 20 keV to 15 MeV, and Swift-BAT has a narrow coverage from 15 keV to 150 keV. No GeV photons were observed, though GRB 090516A and 151027 were in the Fermi-LAT field of view. This contrasts with the observations of S-GRBs for which, in all of the sources so far identified and within the Fermi-LAT field of view, GeV photons were always observed (Ruffini et al. 2016a, 2016b) and can always freely reach a distant observer. These observational facts suggest that NS–NS (or NS–BH) mergers leading to the formation of a BH leave the surrounding environment poorly contaminated with the material ejected in the merging process ($\lesssim 10^{-2} - 10^{-3} M_\odot$) and therefore the GeV emission, originating from the accretion on the BH formed in the merger process (Ruffini et al. 2016a) can be observed. On the other hand, BdHNe originate in CO-core–NS binaries in which the material ejected from the CO-core explosion ($\approx M_\odot$) greatly pollutes the environment where the GeV emission has to propagate to reach the observer (see Section 3). This, together with the asymmetries of the SN
ejecta (see Section 3 and Becerra et al. 2016), lead to the possibility that the GeV emission in BdHNe can be “obscured” by the material of the SN ejecta, explaining the absence of GeV photons in the above cases of GRBs 090516A and 151027.

We derive the isotropic energy $E_{\text{iso}}$ by assuming the prompt emission to be isotropic and by integrating the prompt photons in the rest-frame energy range from 1 keV to 10 MeV (Bloom et al. 2001). None of the satellites is able to cover the entire energy band of $E_{\text{iso}}$, so we need to fit the spectrum and find the best-fit function, then extrapolate the integration of energy by using this function. This method is relatively safe for GRBs observed by Fermi and Konus-Wind, but six GRBs in our

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Figure 16. 081210: this GRB was detected by Swift-BAT (Krimm et al. 2008). Swift-XRT began observing 23.49 s after the BAT trigger. The BAT light curve begins with two spikes with a total duration of about 10 s and an additional spike at 45.75 s. There is no observation from the Fermi satellite. X-shooter found its redshift to be 2.0631 (Perley et al. 2016). The isotropic energy of this GRB is $1.56 \times 10^{53}$ erg.

Figure 17. 090516A: this source was detected by Swift (Rowlinson et al. 2009), Konus-Wind, and Fermi/GBM (McBreen 2009). The BAT prompt light curve is composed of two episodes, the first starting 2 s before the trigger and lasting up to 10 s after the trigger, while the second episode starts at 17 s and lasts approximately 2 s. The GBM light curve consists of about five overlapping pulses from $T_{D,0} = 10$ s to $T_{D,0} + 21$ s (where $T_{D,0}$ is the trigger time of the Fermi/GBM). Konus-Wind observed this GRB in the waiting mode. VLT identified the redshift of the afterglow as $z = 4.109$ (de Ugarte Postigo et al. 2012), in agreement with the photometric redshift obtained with GROND (Rossi et al. 2009). Fermi-LAT was inside the field of view, following the standard Fermi-LAT likelihood analysis in https://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/likelihood_tutorial.html, the upper limit of the observed count flux is $4.76 \times 10^{-6}$ photons cm$^{-2}$ s$^{-1}$, and no GeV photon was found for this high redshift and low observed fluence GRB. The isotropic energy is $E_{\text{iso}} = 6.5 \times 10^{53}$ erg.

Figure 18. 090812: this source was detected by Swift (Stamatikos et al. 2009). It has a redshift $z = 2.452$ as confirmed by VLT (de Ugarte Postigo et al. 2012) and an isotropic energy $E_{\text{iso}} = 4.75 \times 10^{53}$ erg. The BAT light curve shows three successive bumps lasting $\sim 20$ s in total. XRT began observing the field 22 s after the BAT trigger (Stamatikos et al. 2009). The BAT light curve shows a simple power-law behavior.

Figure 19. 131030A: this source was observed by Swift (Troja et al. 2013) and Konus-Wind (Golenetskii et al. 2013). The BAT light curve shows two overlapping peaks starting, with respect to the Swift-BAT trigger $T_{D,0}$, at $\sim T_{D,0} - 3.5$ s and peaking at $\sim T_{D,0} + 4.4$ s (Barthelmy et al. 2013). The duration is 18 s in the 15–350 keV band. The Konus-Wind light curve shows a multipeaked pulse from $\sim T_{D,0} - 1.3$ s until $\sim T_{D,0} + 11$ s (where $T_{D,0}$ is the Konus-Wind trigger time). The redshift of this source is $z = 1.293$, as determined by NOT (Xu et al. 2013). The isotropic energy is $E_{\text{iso}} = 3 \times 10^{53}$ erg.

which provides a sequence of power-law functions. The corresponding energy in a fixed time interval is obtained by summing up all of the integrals of the power laws within it. This method is applied to estimate the energy of the flare $E_{\text{f}}$ as well as the energy of the FPA phase up to $10^{53}$ s, $E_{\text{FPA}}$. An interesting alternative procedure was used in Swenson & Roming (2014) to fit the light curve and determine the flaring structure with a Bayesian Information method. On this specific aspect, the two treatments are equally valid and give compatible results.

Table 3 contains the relevant energy and time information of the 16 BdHNe of the sample: the cosmological redshift $z$, $E_{\text{iso}}$, the flare peak time $t_{\text{fp}}$, the corresponding peak luminosity $L_{\text{fp}}$, the flare duration $\Delta t$, and the energy of the flare $E_{\text{f}}$. To determine $t_{\text{fp}}$, we apply a locally weighted regression, which results in a

sample have been observed only by Swift, so we uniformly fit and extrapolate these six GRBs by power laws and cutoff power laws; we then take the average value as $E_{\text{iso}}$. In general, our priority in computing $E_{\text{iso}}$ is Fermi, Konus-Wind, then Swift. In order to take into account the expansion of the universe, all of our computations consider the $K$ correction. The formula of $K$ correction for $E_{\text{iso}}$ varies depending on the best-fit function. The energy in the X-ray afterglow is computed in the cosmological rest-frame energy band from 0.3 to 10 keV. We smoothly fit the luminosity light curve using an algorithm named locally weighted regression (Cleveland & Devlin 1988),
smoothed light curve composed of power-law functions: the flare peak is localized where the power-law index is zero. Therefore, $t_p$ is defined as the time interval between the flare peak and the trigger time of Swift-BAT.\(^{10}\) Correspondingly, we find the peak luminosity $L_p$ at $t_p$ and its duration $\Delta t$, which is defined as the time interval between a start time and an end time where the luminosity is half of $L_p$. We have made public the entire details including the codes online.\(^{11}\)

\(^{10}\) In reality, the GRB occurs earlier than the trigger time, since there is a short period when the flux intensity is lower than the satellite trigger threshold (Fenimore et al. 2003).

\(^{11}\) https://github.com/YWangScience/AstroNeuron

6. Statistical Correlation

We then establish correlations between the above quantities characterizing each luminosity light curve of the sample with the $E_{iso}$ of the corresponding BdHN. We have relied heavily on the MCMC method and iterated $10^5$ times to obtain the best fit of the power law and their correlation coefficient. The main results are summarized in Figures 25–28. All of the codes are publicly available online.\(^{12}\) We conclude that the peak time and

\(^{12}\) https://github.com/YWangScience/MCCC
the duration of the flare, as well as the peak luminosity and the total energy of flare, are highly correlated with $E_{\text{iso}}$, with correlation coefficients larger than 0.6 (or smaller than $-0.6$). The average values and the 1σ uncertainties are shown in Table 4.

7. The Partition of the Electron–Positron Plasma Energy Between the Prompt Emission and the FPA

The energy of the prompt emission is proportional to $E_{\text{iso}}$, if and only if spherical symmetry is assumed: this clearly follows from the prompt emission time-integrated luminosity. We are now confronted with a new situation: the total energy of the FPA emission up to $10^{15}$ s ($E_{\text{FPA}}$) is also proportional to $E_{\text{iso}}$, following the correlation given in Tables 5 and 6, and Figure 29. What is clear is that there are two very different components where the energy of the dyadosphere $E_{e^-e^+}$ is utilized: the energy $E_{\text{prompt}}$ of the prompt emission and the energy $E_{\text{FPA}}$ of the FPA, i.e., $E_{e^-e^+} = E_{\text{iso}} = E_{\text{prompt}} + E_{\text{FPA}}$. Figures 30 and 31 show the distribution of $E_{e^-e^+} = E_{\text{iso}}$ between these two components.

As a consequence of the above, in view of the presence of the companion SN remnant ejecta (see Becerra et al. 2016 for more details), we assume here that the spherical symmetry of the prompt emission is broken. Part of the energy due to the impact of the $e^-e^+$ plasma on the SN is captured by the SN ejecta, and gives rise to the FPA emission as originally proposed by Ruffini (2015). We shall return to the study of the impact between the plasma and the SN ejecta in Section 10 after studying the motion of the matter composing the FPA in the next few sections.

It can also be seen that the relative partition between $E_{\text{prompt}}$ and $E_{\text{FPA}}$ strongly depends on the value of $E_{e^-e^+}$: the lower the GRB energy, the higher the FPA energy percentage, and consequently the lower the prompt energy percentage (see Figure 31).

In Becerra et al. (2016), we indicate that both the value of $E_{e^-e^+}$ and the relative ratio of the above two components can in principle be explained in terms of the geometry of the binary nature of the system: the smaller the distance is between the COcore and the companion NS, the shorter the binary period of the system, and the larger the value of $E_{e^-e^+}$.

8. On the Flare Thermal Emission, Its Temperature, and Dynamics

We discuss now the profound difference between the prompt emission, which we recall is emitted at distances of the order of $10^{16}$ cm away from the newly born BH with $\Gamma \approx 10^{2–3}$, and the FPA phase. We focus on a further fundamental set of data, which originates from a thermal emission associated with the flares. Only in some cases is this emission so clear and prominent that it allows the estimation of the flare expansion speed and the determination of its mildly relativistic Lorentz factor $\Gamma \lesssim 4$, which creates a drastic separatrix both in the energy and in the Gamma factor between the astrophysical nature of the prompt emission and of the flares.

Following the standard data reduction procedure of Swift-XRT (Romano et al. 2006; Evans et al. 2007, 2009), X-ray data within the duration of flare are retrieved from the United Kingdom Swift Science Data Centre (UKSSDC) and analyzed by Heasoft. Table 7 shows the fit of the spectrum within the duration $\Delta t$ of the flare for each BdHN of the sample. As a first approximation, in computing the radius, we have assumed a constant expansion velocity of 0.8c indicated for some BdHNe, such as GRB 090618 (Ruffini et al. 2014) and GRB 130427A (Ruffini et al. 2015c). Out of 16 sources, seven BdHNe have highly confident thermal components (significance $>0.95$; see boldfaced entries in Table 7), which means that the addition of a blackbody spectrum improves a single power-law fit (which is, conversely, excluded at the 2σ confidence level). These blackbodies have fluxes in a range from 1% to 30% of the total flux and share a similar order of magnitude radii, i.e., $\sim 10^{11–12}$ cm. In order to have a highly significant thermal component, the blackbody radiation itself should be prominent as well as its ratio to the nonthermal part. Another critical reason is that the observable temperature must be compatible with the satellite bandpass. For example, Swift-XRT observes in the 0.3–10 keV photon energy band, but the hydrogen absorption affects the lower energy part ($\sim 0.5$ keV), and data are not always adequate beyond 5 keV, due to the low effective area of satellite for high-energy photons. The reliable temperature only ranges from 1.5 keV to 1.5 keV (since the peak photon energy is equal to the temperature times 2.82), so the remaining nine GRBs may contain a thermal component in the flare but outside the satellite bandpass.

We now attempt to perform a more refined analysis to infer the value of $\beta$ from the observations. We assume that during the flare, the blackbody emitter has spherical symmetry and expands with a constant Lorentz Gamma factor. Therefore, the expansion velocity $\beta$ is also constant during the flare. The relations between the comoving time $t_{\text{com}}$, the laboratory time $t$,

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13 The late afterglow phases have been already discussed in Pisani et al. (2013, 2016).
14 http://www.swift.ac.uk
15 http://heasarc.gsfc.nasa.gov/heasoft/
Table 3
GRB Sample Properties of the Prompt and Flare Phases

| GRB    | $z$   | $T_{90}$ (s) | $E_{iso}$ (erg) | $t_p$ (s) | $L_p$ (erg s$^{-1}$) | $\Delta t$ (s) | $E_f$ (erg) | $\alpha_f$ |
|--------|-------|--------------|-----------------|-----------|----------------------|----------------|------------|-----------|
| 060204B| 2.393 | 40.12        | 2.93(±0.60) × 10$^{53}$ | 100.72 ± 6.31 | 7.35(±2.05) × 10$^{49}$ | 17.34 ± 6.83 | 8.56(±0.82) × 10$^{50}$ | 2.73     |
| 060607A| 3.082 | 24.49        | 2.14(±1.19) × 10$^{53}$ | 66.04 ± 4.98 | 2.28(±0.48) × 10$^{50}$ | 18.91 ± 3.84 | 3.33(±0.32) × 10$^{51}$ | 1.72     |
| 070318  | 0.84  | 28.80        | 3.41(±2.14) × 10$^{52}$ | 154.7 ± 12.80 | 6.28(±1.30) × 10$^{48}$ | 63.80 ± 19.82 | 3.17(±0.37) × 10$^{58}$ | 1.84     |
| 080607  | 3.04  | 21.04        | 1.87(±0.11) × 10$^{54}$ | 37.48 ± 3.60 | 1.14(±0.27) × 10$^{51}$ | 15.63 ± 4.32 | 1.54(±0.24) × 10$^{52}$ | 2.08     |
| 080805  | 1.51  | 31.08        | 7.16(±1.90) × 10$^{52}$ | 48.41 ± 5.46 | 4.66(±0.59) × 10$^{49}$ | 27.56 ± 9.33 | 9.68(±1.24) × 10$^{50}$ | 1.25     |
| 080810  | 3.35  | 18.25        | 5.00(±0.44) × 10$^{53}$ | 51.03 ± 6.49 | 1.85(±0.53) × 10$^{50}$ | 12.38 ± 4.00 | 1.80(±0.17) × 10$^{51}$ | 2.37     |
| 081008  | 1.967 | 62.52        | 1.35(±0.66) × 10$^{53}$ | 102.24 ± 5.66 | 1.36(±0.33) × 10$^{50}$ | 18.24 ± 3.63 | 1.93(±0.16) × 10$^{51}$ | 2.46     |
| 081210  | 2.063 | 47.66        | 1.56(±1.54) × 10$^{53}$ | 127.59 ± 13.68 | 2.23(±0.21) × 10$^{49}$ | 49.05 ± 6.49 | 8.86(±0.54) × 10$^{50}$ | 2.28     |
| 090516A | 4.109 | 68.51        | 9.96(±1.67) × 10$^{53}$ | 80.75 ± 2.20 | 9.10(±2.26) × 10$^{50}$ | 10.43 ± 2.44 | 7.74(±0.63) × 10$^{51}$ | 3.66     |
| 090812  | 2.452 | 18.77        | 4.40(±0.65) × 10$^{53}$ | 77.43 ± 16.6 | 3.13(±1.38) × 10$^{50}$ | 17.98 ± 4.51 | 5.18(±0.61) × 10$^{51}$ | 2.20     |
| 131030A | 1.293 | 12.21        | 3.00(±0.20) × 10$^{53}$ | 49.55 ± 7.88 | 6.63(±1.12) × 10$^{50}$ | 33.73 ± 6.55 | 3.15(±0.57) × 10$^{51}$ | 2.22     |
| 140206A | 2.73  | 7.24         | 3.58(±0.79) × 10$^{53}$ | 62.11 ± 12.26 | 4.62(±0.99) × 10$^{50}$ | 26.54 ± 4.31 | 1.04(±0.59) × 10$^{51}$ | 1.73     |
| 140301A | 1.416 | 12.83        | 9.50(±1.75) × 10$^{51}$ | 276.56 ± 15.5 | 5.14(±1.84) × 10$^{48}$ | 64.52 ± 10.94 | 3.08(±0.22) × 10$^{50}$ | 2.30     |
| 140419A | 3.956 | 16.14        | 1.85(±0.77) × 10$^{54}$ | 41.00 ± 4.68 | 6.23(±1.45) × 10$^{50}$ | 14.03 ± 5.74 | 7.22(±0.88) × 10$^{51}$ | 2.32     |
| 141221A | 1.47  | 9.64         | 6.99(±1.98) × 10$^{52}$ | 140.38 ± 5.64 | 2.60(±0.64) × 10$^{49}$ | 38.34 ± 9.26 | 7.70(±0.78) × 10$^{50}$ | 1.79     |
| 151027A | 0.81  | 68.51        | 3.94(±1.33) × 10$^{52}$ | 183.79 ± 16.43 | 7.10(±1.75) × 10$^{48}$ | 163.5 ± 30.39 | 4.39(±2.91) × 10$^{51}$ | 2.26     |

Note. This table contains the redshift $z$, the $T_{90}$ in the rest frame, the isotropic energy $E_{iso}$, the flare peak time $t_p$ in the rest frame, the flare peak luminosity $L_p$, the flare duration where the starting and ending time correspond to half of the peak luminosity $\Delta t$, the flare energy $E_f$ within the time interval $\Delta t$, and $\alpha_f$ the power-law index from the fitting of the flare’s spectrum.

Figure 25. Relation between $E_{iso}$ and $t_p$ fit by a power law. The shaded area indicates the 95% confidence level.

Figure 27. Relation between $E_{iso}$ and $L_p$ fit by a power law. The shaded area indicates the 95% confidence level.

Figure 26. Relation between $E_{iso}$ and $\Delta t$ fit by a power law. The shaded area indicates the 95% confidence level.

Figure 28. Relation between $E_{iso}$ and $E_f$ by a power law. The shaded area indicates the 95% confidence level.
Figure 29. Relation between $E_{\text{iso}}$ and $E_{\text{FPA}}$ fit by a power law. The shaded area indicates the 95% confidence level.

Table 4

| Correlation                  | Power-law Index | Coefficient |
|-----------------------------|-----------------|-------------|
| $E_{\text{iso}} - L_p$      | $-0.290(0.010)$ | $-0.764(0.123)$ |
| $E_{\text{iso}} - \Delta t$ | $-0.461(0.042)$ | $-0.760(0.138)$ |
| $E_{\text{iso}} - L_p$      | $1.186(0.037)$  | $0.883(0.070)$  |
| $E_{\text{iso}} - E_f$      | $0.631(0.117)$  | $0.699(0.145)$  |

Note. The values and uncertainties (at the 1σ confidence level) of the power-law index and of the correlation coefficient are obtained from 105 MCMC iterations. All relations are highly correlated.

Table 5

| GRB    | $z$  | $E_{\text{iso}}$ (erg) | $E_{\text{FPA}}$ (erg) |
|--------|-----|------------------------|------------------------|
| 060204B| 2.339| $2.93(0.60) \times 10^{51}$ | $6.02(0.20) \times 10^{51}$ |
| 060607A| 3.682| $2.14(1.19) \times 10^{53}$ | $2.39(0.12) \times 10^{53}$ |
| 070318 | 0.84 | $3.41(2.14) \times 10^{52}$ | $4.76(0.21) \times 10^{52}$ |
| 080607 | 3.04 | $1.87(0.11) \times 10^{54}$ | $4.32(0.96) \times 10^{52}$ |
| 080805 | 1.51 | $7.16(1.90) \times 10^{52}$ | $6.65(0.42) \times 10^{51}$ |
| 080810 | 3.35 | $5.00(0.44) \times 10^{53}$ | $1.67(0.14) \times 10^{52}$ |
| 081008 | 1.967| $1.35(0.66) \times 10^{53}$ | $6.56(0.74) \times 10^{51}$ |
| 081210 | 2.063| $1.56(0.54) \times 10^{53}$ | $6.59(0.70) \times 10^{51}$ |
| 090516A| 4.109| $9.96(1.67) \times 10^{53}$ | $3.34(0.22) \times 10^{52}$ |
| 090812 | 2.452| $4.40(0.65) \times 10^{53}$ | $3.19(0.36) \times 10^{52}$ |
| 131030A| 1.293| $3.00(0.40) \times 10^{53}$ | $4.12(0.23) \times 10^{52}$ |
| 140206A| 2.73 | $3.58(0.79) \times 10^{52}$ | $5.98(0.69) \times 10^{52}$ |
| 140301A| 1.416| $9.50(1.75) \times 10^{51}$ | $1.42(0.14) \times 10^{50}$ |
| 140419A| 3.956| $1.85(0.77) \times 10^{54}$ | $6.84(0.82) \times 10^{52}$ |
| 141221A| 1.47 | $6.99(1.98) \times 10^{52}$ | $5.31(1.21) \times 10^{51}$ |
| 151027A| 0.81 | $3.94(1.33) \times 10^{52}$ | $1.19(0.18) \times 10^{52}$ |

Note. This table lists $z$, $E_{\text{iso}}$, and the FPA energy $E_{\text{FPA}}$ from the flare until $10^5$ s.

Figure 30. Relation between the percentage of $E_{\gamma}$ going to the SN ejecta and the energy in FPA, i.e., $E_{\text{FPA}}/E_{\text{iso}} \times 100\%$, and $E_{\text{iso}}$ fit by a power law. The shaded area indicates the 95% confidence level.

Table 6

| Correlation                  | Power-law Index | Coefficient |
|-----------------------------|-----------------|-------------|
| $E_{\text{iso}} - E_{\text{FPA}}$ | $0.613(0.041)$ | $0.791(0.103)$ |
| $E_{\text{iso}} - E_{\text{FPA}}/E_{\text{cos}}$ | $-0.005(0.002)$ | $0.572(0.178)$ |

Note. The statistical considerations of Table 4 are valid here as well.

We now need the relation between $T_{\text{com}}$ and the observed blackbody temperature $T_{\text{obs}}$. Considering both the cosmological redshift and the Doppler effect due to the velocity of the

\[ F_{\text{bb,obs}} = \frac{L}{4\pi D_{\text{L}}(z)^2}, \]

where $D_{\text{L}}(z)$ is the luminosity distance of the source, which in turn is a function of the cosmological redshift $z$ and $L$ is the source bolometric luminosity (i.e., the total emitted energy per unit time). $L$ is Lorentz invariant, so we can compute it in the comoving frame of the emitter using the usual blackbody expression,

\[ L = 4\pi R_{\text{com}}^2 \sigma T_{\text{com}}^4, \]
emitting surface, we have
\[
T_{\text{obs}}(T_{\text{com}}, z, \Gamma, \cos \vartheta) = \frac{T_{\text{com}}}{(1 + z)(1 - \beta \cos \vartheta)} = \frac{T_{\text{com}} D(\cos \vartheta)}{1 + z},
\]
(11)
where we have defined the Doppler factor \( D(\cos \vartheta) \) as
\[
D(\cos \vartheta) = \frac{1}{\Gamma(1 - \beta \cos \vartheta)}.
\]
(12)
Equation (11) 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 (11) computed over the emitter surface.\(^{16}\)
\[
T_{\text{obs}}(T_{\text{com}}, z, \Gamma) = \frac{1}{1 + z} \int_{\beta}^{1} D(\cos \vartheta) T_{\text{com}} \cos \vartheta d \cos \vartheta
= \frac{2}{1 + z} \frac{\beta(\beta - 1) + \ln(1 + \beta)}{\Gamma \beta^2 (1 - \beta^2)} T_{\text{com}}
= \frac{\Theta(\beta)}{1 + z} T_{\text{com}},
\]
(13)
where we defined
\[
\Theta(\beta) \equiv 2 \frac{\beta(\beta - 1) + \ln(1 + \beta)}{\beta^2}.
\]
(14)
\(^{16}\)From the point of view of the observer, the spectrum is not a perfect blackbody, coming from a convolution of blackbody spectra at different temperatures. The blackbody component we obtain from the spectral fit of the observed data is an effective blackbody of temperature \( T_{\text{com}} \), analogous to other cases of effective temperatures in cosmology (see, e.g., Ruffini et al. 1983).

![Figure 31](image)

**Figure 31.** Distribution of the GRB total energy \( E_{\nu_{\gamma}} \) into prompt and FPA energies. The percentage of \( E_{\nu_{\gamma}} \) going to the SN ejecta accounting for the energy in the FPA phase appears in red, i.e., \( E_{\nu_{\gamma}} / E_{\text{iso}} \times 100\% \). The green part is therefore the percentage of \( E_{\nu_{\gamma}} \) used in the prompt emission, i.e., \( E_{\text{prompt}} / E_{\text{iso}} \times 100\% \). It can be seen that the lower the GRB energy \( E_{\nu_{\gamma}} = E_{\text{iso}} \), the higher the FPA energy percentage, and consequently the lower the prompt energy percentage.

| GRB       | Radius (cm)       | \( kT_{\text{obs}} \) (keV) | Significance |
|-----------|-------------------|-----------------------------|-------------|
| 060204B  | 1.80 (±1.11) \times 10^{11} | 0.60 (±0.15)               | 0.986       |
| 060607A  | 1.67 (±1.01) \times 10^{11} | 0.92 (±0.24)               | 0.991       |
| 090318A  | unconstrained     | 1.79 (±1.14)               | 0.651       |
| 080607A  | 1.52 (±0.72) \times 10^{12} | 0.49 (±0.10)               | 0.998       |
| 080805   | 1.12 (±1.34) \times 10^{11} | 1.31 (±0.59)               | 0.809       |
| 080810A  | 2.34 (±0.84) \times 10^{12} | 0.61 (±0.57)               | 0.999       |
| 091008A  | 1.84 (±0.68) \times 10^{12} | 0.32 (±0.03)               | 0.999       |
| 081210A  | unconstrained     | 0.80 (±0.51)               | 0.295       |
| 090516A  | unconstrained     | 1.30 (±1.30)               | 0.663       |
| 090812A  | 1.66 (±1.84) \times 10^{12} | 0.24 (±0.12)               | 0.503       |
| 131003A  | 3.67 (±1.02) \times 10^{12} | 0.55 (±0.06)               | 0.999       |
| 140206A  | 9.02 (±2.84) \times 10^{11} | 0.54 (±0.07)               | 0.999       |
| 140301A  | unconstrained     | unconstrained              | 0.00        |
| 140419A  | 1.85 (±1.17) \times 10^{12} | 0.23 (±0.05)               | 0.88        |
| 141221A  | 1.34 (±2.82) \times 10^{11} | 0.24 (±0.24)               | 0.141       |
| 151027A  | 1.18 (±0.67) \times 10^{12} | 0.29 (±0.06)               | 0.941       |

**Note.** The observed temperatures \( kT_{\text{obs}} \) are inferred from fitting with a power-law plus blackbody spectral model. The significance of a blackbody is computed by the maximum likelihood ratio for comparing nested models and its addition improves a fit when the significance is \( > 0.95 \). The radii are calculated assuming mildly relativistic motion (\( \beta = 0.8 \)) and isotropic radiation. The GRBs listed in boldface have prominent blackbodies, with radii of the order of \( \sim 10^{11} \)–\( 10^{12} \) cm. Uncertainties are given at the 1\( \sigma \) confidence level.

We have used the fact that due to relativistic beaming, we observe only a portion of the surface of the emitter defined by
\[
\beta \leq \cos \vartheta \leq 1,
\]
and we used the definition of \( \Gamma \) given in Section 3. Therefore, inverting Equation (13), 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 as follows:
\[
T_{\text{com}}(T_{\text{obs}}, z, \Gamma) = \frac{1 + z}{\Theta(\beta) \Gamma} T_{\text{obs}}.
\]
(16)
We can now insert Equation (16) into Equation (10) to obtain

\[ F_{bb,obs} = \frac{R_{\text{com}}}{D_L(z)^2} \sigma T_{\text{com}}^4 \theta/ \sigma T_{\text{obs}}^4 \left[ \frac{1 + \bar{z}}{\Theta(\beta) \Gamma} \right]^4. \]  

(17)

Since the radius \( R_{\text{lab}} \) of the emitter in the laboratory frame is related to \( R_{\text{com}} \) by

\[ R_{\text{com}} = \Gamma R_{\text{lab}}, \]

we can insert Equation (18) into Equation (17) and obtain

\[ F_{bb,obs} = \frac{(1 + \bar{z})^4}{\Gamma^2} \frac{R_{\text{lab}}}{D_L(z)^2} \sigma \left[ \frac{T_{\text{obs}}}{\Theta(\beta)} \right]^4. \]  

(19)

Solving Equation (19) for \( R_{\text{lab}} \), we finally obtain the thermal emitter’s effective radius in the laboratory frame:

\[ R_{\text{lab}} = \Theta(\beta)^2 \Gamma \frac{D_L(z)}{(1 + \bar{z})^2} \frac{F_{bb,obs}}{\sigma T_{\text{obs}}^4} = \Theta(\beta)^2 \Gamma \phi_0, \]

(20)

where we have defined \( \phi_0 \):

\[ \phi_0 \equiv \frac{D_L(z)}{(1 + \bar{z})^2} \frac{F_{bb,obs}}{\sigma T_{\text{obs}}^4}. \]  

(21)

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 \( R_{\text{lab}} \) in Equation (20) crucially depends on the knowledge of its expansion velocity \( \beta \) (and, correspondingly, of \( \Gamma \)).

It must be noted that Equation (20) above gives the correct value of \( R_{\text{lab}} \) for all values of \( 0 \leq \beta \leq 1 \) by taking all of the relativistic transformations properly into account. In the non-relativistic limit (\( \beta \to 0, \Gamma \to 1 \)), we have, respectively:

\[ \Theta \to 1, \quad \Theta^2 \to 1, \quad T_{\text{com}} \to T_{\text{obs}}(1 + \bar{z}), \quad R_{\text{lab}} \to \phi_0, \]

(22)

as expected.

9. Implications on the Dynamics of the Flares from Their Thermal Emission

An estimate of the expansion velocity \( \beta \) can be deduced from the ratio between the variation of the emitter effective radius \( \Delta R_{\text{lab}} \) and the emission duration in laboratory frame \( \Delta t \), i.e.,

\[ \beta = \frac{\Delta R_{\text{lab}}}{c \Delta t} = \Theta(\beta)^2 \Gamma (1 - \beta \cos \vartheta)(1 + \bar{z}) \frac{\Delta \phi_0}{c \Delta t_a}, \]

(24)

where we have used Equation (20) and the relation between \( \Delta t \) and \( \Delta t_a \) given in Equation (7). We then have

\[ \beta = \Theta(\beta)^2 \frac{1 - \beta \cos \vartheta}{\sqrt{1 - \beta^2}} (1 + \bar{z}) \frac{\Delta \phi_0}{c \Delta t_a}, \]

(25)

where we used the definition of \( \Gamma \) given in Section 3.

For example, in GRB 081008, we observe a temperature of \( T_{\text{obs}} = (0.44 \pm 0.12) \) keV between \( t_a^d = 280 \) s and \( t_a^e = 300 \) s (i.e., \( 20 \) s before the flare peak time), and a temperature of \( T_{\text{obs}} = (0.31 \pm 0.05) \) keV between \( t_a^d = 300 \) s and \( t_a^e = 320 \) s (i.e., \( 20 \) s after the flare peak time, see the corresponding spectra in Figure 32). In these two time intervals, we can infer \( \phi_0 \), and by solving Equation (25) and taking the errors of the parameters properly into account, get the value of \( \langle \beta \rangle \) corresponding to the average expansion speed of the emitter from the beginning of its expansion up to the upper bound of the time interval considered. The results so obtained are listed in Table 8. Moreover, we can also compute the value of \( \langle \beta \rangle \) between the two time intervals considered above. For \( \cos \vartheta = 1 \), namely along the line of sight, we obtain \( \langle \beta \rangle = 0.90^{+0.06}_{-0.31} \) and \( \langle \Gamma \rangle = 2.34^{+1.29}_{-1.10} \). In conclusion, no matter what the details of the approximation adopted, the Lorentz Gamma factor is always moderate, i.e., \( \Gamma \lesssim 4 \).

![Figure 32. Thermal evolution of GRB 081008 (\( l = 1.967 \)) in the observer frame. The X-ray flare of this GRB peaks at 304±17 s. Upper panel: Swift-XRT spectrum from 280 s to 300 s. Lower panel: Swift-XRT spectrum from 300 to 320 s. The gray points are the observed data markedly absorbed at low energies, while the blue points are absorption-corrected ones. The data are fit with a combination of power-law (dotted-dashed lines) and blackbody (dotted lines) spectra. The power-law + blackbody spectra are shown as solid curves. Clearly, the temperature decreases with time from ∼0.44 keV to ∼0.31 keV, but the ratio of the thermal component goes up from ∼20% to ∼30%. This is a remarkably high percentage of our sample.](image)
10. The Electron–Positron Plasma as the Common Origin of the Prompt Emission and the X-Ray Flares

10.1. Necessity for a New Hydrodynamic Code for $10^{-2} \leq B \leq 10^2$

As stated above, there are many different components of BdHNe: following episode 1 of the hypercritical accretion of the SN ejecta onto the NS, the prompt emission occurs with $\Gamma \approx 10^2\mathrm{--}10^3$, which represents the most energetic component accelerated by the $\varepsilon^+\varepsilon^-$ plasma; a third component, which encompasses the X-ray flare with $\Gamma \lesssim 4$ and represents only a fraction of $E_{\varepsilon^+\varepsilon^-}$ ranging from 2% to 20% (see Figure 31); finally, there are in addition the gamma-ray flare and the late X-ray flares, which will be addressed in a forthcoming publication, as well as the late afterglow phases, which have already been addressed in Pisani et al. (2013, 2016) but whose dynamics will be discussed elsewhere. As already mentioned, for definiteness, we address here the case of X-ray flares.

In Section 3.5, we showed that our model successfully explains the entire prompt emission as originating from the transparency of an initially optically thick $\varepsilon^+\varepsilon^-$ plasma with a baryon load $B < 10^{-2}$ reaching $\Gamma \approx 10^2\mathrm{--}10^3$ and the accelerated baryons interacting with the clouds of the CBM. The fundamental equations describing the dynamics of the optically thick plasma, its self-acceleration to ultrarelativistic velocities, and its interaction with the baryon load have been described in Ruffini et al. (1999, 2000). A semi-analytic approximate numerical code was developed, which assumed that the plasma expanded as a shell with a constant thickness in the laboratory frame (the so-called “slab” approximation; see Ruffini et al. 1999). This semi-analytic approximate code was validated by comparing its results with the ones obtained by numerically integrating the complete system of equations for selected values of the initial conditions. It turns out that the semi-analytic code is an excellent approximation to the complete system of equations for $B < 10^{-2}$, which is the relevant regime for the prompt emission, but this approximation is not valid beyond this limit (see Ruffini et al. 1999, 2000 for details).

We examine here the possibility that the energy of the X-ray flare component also originates from a fraction of the $\varepsilon^+\varepsilon^-$ plasma energy (see Figure 31) interacting with the much denser medium of the SN ejecta with $10 \lesssim B \lesssim 10^2$. The above-mentioned semi-analytic approximate code cannot be used for this purpose, since it is valid only for $B < 10^{-2}$, and therefore, thanks to the more powerful computers we have at present, we move on here to a new numerical code to integrate the complete system of equations.

We investigate if indeed the dynamics to be expected from an initially pure $\varepsilon^+\varepsilon^-$ plasma with a negligible baryon load relativistically expanding in the fireshell model, with an initial Lorentz factor $\Gamma \approx 100$, and then impacting such an SN ejecta can lead, reaching transparency, to the Lorentz factor $\Gamma \lesssim 4$ inferred from the thermal emission observed in the flares (see Tables 7 and 8, and Figure 32).

We have performed hydrodynamical simulations of such a process using the one-dimensional relativistic hydrodynamical (RHD) module included in the freely available PLUTO\footnote{http://plutocode.ph.unito.it/} code (Mignone et al. 2011). In the spherically symmetric case considered here, only the radial coordinate is used and the code integrates partial differential equations with two variables:

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

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

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

The first two terms on the right-hand side of this equation coincide with the $\gamma^{00}$ component of the fluid energy–momentum tensor $T^{\mu\nu}$, and the last one is the mass density in the laboratory frame.

Under the conditions discussed in Appendix B, the plasma satisfies the equation of state of an ideal relativistic gas, which can be expressed in terms of its enthalpy as

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

with $\gamma = 4/3$. Fixing this equation of state completely defines the system, leaving the choice of the boundary conditions as the only remaining freedom. To compute the evolution of these quantities in the chosen setup, the code uses the Harten–Lax–van Leer-contact Riemann solver. Time integration is performed by means of a second-order Runge–Kutta algorithm, and a second-order total variation diminishing scheme is used for spatial reconstruction (Mignone et al. 2011). Before each integration step, the grid is updated according to an adaptive mesh refinement algorithm, provided by the CHOMBO library (Colella et al. 2003).

It must be emphasized that the above equations are equivalent (although written in a different form) to the complete system of equations used in Ruffini et al. (1999, 2000). To validate this new numerical code, we compare its results with the ones obtained with the old semi-analytic “slab” approximate code in the domain of its validity (i.e., for $B < 10^{-2}$), finding excellent agreement. As an example, in Figure 33 we show the comparison between the Lorentz Gamma factors computed with the two codes for one particular value of $E_{\varepsilon^+\varepsilon^-}$ and $B$.

We can then conclude that for $B < 10^{-2}$, the new RHD code is consistent with the old semi-analytic “slab” approximate one, which in turn is consistent with the treatment done in Ruffini et al. (1999, 2000). This is not surprising, since we already stated that the above system of equations is equivalent to the one considered in Ruffini et al. (1999, 2000).

Having validated the new RHD code in the region of parameter space where the old semi-analytic one can also be
used, we now explore the region of $B > 10^{-2}$, which is relevant for the interaction of the plasma with the SN ejecta.

### 10.2. Inference from the IGC Scenario for the Ejecta Mass Profile

We start with the shape of the SN ejecta, following the results of the numerical simulations in Becerra et al. (2016).

The first simulations of the IGC process were presented in Fryer et al. (2014) including (1) detailed SN explosions of the CO$_\text{core}$ obtained from a 1D core-collapse SN code code of Los Alamos (Fryer et al. 1999a); (2) the hydrodynamic details of the hypercritical accretion process; and (3) the evolution of the SN ejecta material entering the Bondi–Hoyle region all the way up to its incorporation into the NS in a spherically symmetric approximation.

Then, in Becerra et al. (2015), estimates of the angular momentum carried by the SN ejecta and transferred to the NS via accretion were presented. The effects of such angular momentum transfer on the evolution and fate of the system were examined there. These calculations followed the following procedure: first, the accretion rate onto the NS is computed by adopting a homologous expansion of the SN ejecta and introducing the pre-SN density profile of the CO$_\text{core}$ envelope from numerical simulations. Then, the angular momentum that the SN material might transfer to the NS is estimated: it turns out that the ejecta have enough angular momentum to circularize for a short time and form a disk-like structure around the NS. Then, the evolution of the NS central density and rotation angular velocity is followed by computing the equilibrium configurations from the numerical solution of the axisymmetric Einstein equations in full rotation, until the critical point of collapse of the NS to a BH is reached, accounting for the stability limits given by mass shedding and the secular axisymmetric instability. In Becerra et al. (2016), an improved simulation of all of the above processes leading to a BdHN was recently presented. In particular:

1. The accretion rate estimate includes the effects of the finite size/thickness of the ejecta density profile.
2. Different CO$_\text{core}$ progenitors leading to different SN ejecta masses were also considered.
3. The maximum orbital period, $P_{\text{max}}$, up to which the accretion onto the NS companion is high enough to bring it to the critical mass for gravitational collapse to a BH, first estimated in Becerra et al. (2015), was computed for all possible initial values of the mass of the NS companion. Various values of the angular momentum transfer efficiency parameter were also explored there.
4. It was shown there how the presence of the NS companion gives rise to large asymmetries in the SN ejecta. As we show here, such a density of the SN ejecta modified by the presence of the NS companion plays a crucial role in the physical explanation for the occurrence of X-ray flares.
5. The evolution of the SN material and its consequent accretion onto the NS companion is followed via a smoothed-particle-hydrodynamic-like code in which point-like particles describe the SN ejecta. The trajectory of each particle is computed by solving the Newtonian equations of motion including the effects of the gravitational field of the NS on the SN ejecta, including the orbital motion as well as the changes in the NS gravitational mass owing to the accretion process via the Bondi–Hoyle formalism. The initial conditions of the SN are obtained from the Los Alamos core-collapse SN code (Fryer et al. 1999a). The initial power-law density profile of the CO envelope is simulated by populating the inner layers with more particles. The particles crossing the Bondi–Hoyle radius are captured and accreted by the NS so we remove them from the system. We adopted a total number of 16 million particles in this simulation.

For further details, we refer the reader to Becerra et al. (2016) and references therein.

### 10.3. The Density Profile of the Ejecta and the Reaching of Transparency

We now use the results of a simulation with the following binary parameters: the NS has an initial mass of 2.0 $M_\odot$; the CO$_\text{core}$ obtained from a progenitor with a zero-age main-sequence mass $M_{\text{ZAMS}} = 30 M_\odot$ leads to a total ejecta mass of 7.94 $M_\odot$ and follows an approximate power-law profile $\rho_{\text{ej}} \approx 3.1 \times 10^4 (8.3 \times 10^7/r)^{2.8}$ g cm$^{-3}$. The orbital period is $P \approx 5$ minutes, i.e., a binary separation $a \approx 1.5 \times 10^{10}$ cm. For these parameters, the NS reaches the critical mass and collapses to form a BH.

Figure 34 shows the SN ejecta mass that is enclosed within a cone of $5^\circ$ of the semi-aperture angle, whose vertex is at the position of the BH at the moment of its formation (see the lower-left panel of Figure 6 in Becerra et al. 2016), and whose axis is along various directions measured counterclockwise with respect to the line of sight. Figure 35 shows instead the cumulative radial mass profiles within a selected number of the aforementioned cones. We can see from these plots how the $e^+e^-$ plasma engulfs different amounts of baryonic mass.
along different directions due to the asymmetry of the SN ejecta created by the presence of the NS binary companion and the accretion process onto it (see Becerra et al. 2016).

In these calculations, we have chosen initial conditions consistent with those of the BdHNe. At the initial time, the e+e− plasma has $E_{e^+e^-} = 3.16 \times 10^{53}$ erg, a negligible baryon load, and is distributed homogeneously within a region of radii on the order of $10^8-10^9$ cm. The surrounding SN ejecta, whose pressure has been assumed to be negligible, has a mass density

\[ \rho \propto (R_0 - r)^\alpha, \]

where the parameters $R_0$ and $\alpha$, with $2 < \alpha < 3$, as well as the normalization constant, are chosen to fit the profiles obtained in

\[ t_1, t_2 \]

\[ B=18.5 \quad B=55 \quad B=110 \quad B=200 \]

\[ t_{LAB}[s] \]

\[ \text{Density [g/cm]} \]

\[ r \text{ [10^{11} cm]} \]

\[ \text{B} \]

\[ \varnothing \]

\[ M_{\odot} \]

\[ \theta/\pi \]

\[ 10^{-1} \]

\[ 10^{-2} \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ r/a \]

\[ \varnothing \]

\[ \pi \]

\[ \pi/4 \]

\[ 5\pi/4 \]

\[ \pi/2 \]

\[ 3\pi/4 \]

\[ 7\pi/4 \]
with the above-described induced asymmetries (see Figures 39–40), leads to the formation of a shock that reaches the outermost part of the ejecta with Lorentz Gamma factors at the transparency radius $\Gamma(R_{ph}) \lesssim 4$. This is in striking agreement with the one inferred from the thermal component observed in the flares (see Section 9). The spacetime diagram of the global scenario is represented in Figure 39. Clearly in this approach neither ultrarelativistic jetted emission nor synchrotron or inverse-Compton processes play any role.

11. Summary, Conclusions and Perspectives

11.1. Summary

In the last 25 years, the number of observed GRBs has exponentially increased, thanks to unprecedented technological developments in all ranges of wavelengths, going from the X-ray to the gamma-ray, to GeV radiation as well as to the radio and the optical. In spite of this progress, the traditional GRB approach has continued to follow the paradigm of a single system (the “collapsar” paradigm; see Woosley 1993), where accretion onto an already formed BH occurs (see, e.g., Piran 2004 and references therein). Following the fireball model, synchrotron and inverse-Compton emission processes, related to an ultrarelativistic jetted emission described by the Blandford & McKee (1976) solution, have been assumed to occur (see, e.g., Troja et al. 2015 for one of the latest example where this approach is further extended to the GeV emission component). The quest for a “standard” GRB model has been pursued even recently (see, e.g., Chincarini et al. 2007; Margutti et al. 2010), ignoring differences among GRB subclasses and/or neglecting all relativistic corrections in the time parameterizations presented in Section 3. Under these conditions, it is not surprising that the correlations we have found here have been missed.

It is appropriate to recall that a “standard” GRB energy of $10^{51}$ erg (Frail et al. 2001) was considered, assuming the collimation of GRBs and the existence of a light-curve break in
the GRB afterglows. This possibility followed from the traditional approach expecting the ultrarelativistic component to extend all the way from the prompt emission to the last phases of the afterglow (Mao & Yi 1994; Panaiteșcu & Mészáros 1999; Sari et al. 1999). This “traditional” approach to GRBs has appeared in a large number of papers over recent decades and is well summarized in review papers (see, e.g., Piran 1999, 2004; Mészáros 2002, 2006; Berger 2014; Kumar & Zhang 2015), which are disproved by the data presented here in which the upper limit for the Lorentz factor $\Gamma \lesssim 4$ is established in the FPA phase.

Since 2001, we have followed an alternative approach, introducing three paradigms: the spacetime parametrization of GRBs (Ruffini et al. 2001a), the field equations of the prompt emission phase (Ruffini et al. 2002), and the IGC paradigm (Rueda & Ruffini 2012; Penacchioni et al. 2013; Ruffini et al. 2015c); see Section 3. Since then,

(a) we have demonstrated that all GRBs originate in binary systems: the short GRBs in binary NSs or in binaries composed of an NS and a BH (Fryer et al. 2015; Ruffini et al. 2016b); the long GRBs in binary systems composed of CO$_{\text{core}}$ and a NS, or alternatively a BH and a CO$_{\text{core}}$, or also a white dwarf and an NS;

(b) we have divided GRBs into seven different subclasses (Ruffini et al. 2016b), each characterized by specific signatures in their spectra and luminosities in the various energy bands;

(c) we have addressed the new physical and astrophysical processes in the ultrarelativistic regimes made possible by the vast amount of gravitational and rotational energies in such binaries.

As we recalled in Sections 1–3, we have confirmed the binary nature of the GRB progenitors (see, e.g., Fryer et al. 2014, 2015; Becerra et al. 2015, 2016; Ruffini et al. 2016a; Aimeratov et al. 2017). We have obtained the first evidence of the formation of a BH in the hypercritical accretion process of the SN ejecta onto the binary NS companion: the BdHN (Ruffini et al. 2014, 2015c, 2016b), which is clearly different from the single-star collapsar model. Finally, in this paper, we have addressed the interaction that occurs in a BdHN of the GRB on the SN ejecta considered as the origin of the X-ray flares. We use this process and the mildly relativistic region in which it occurs as a discriminant between the traditional approach and our binary system approach: we use the X-ray flare properties as a discriminant between our BdHN and the “fireball” GRB models.

### 11.2. Conclusions

We have reached three major results.

1. We have searched X-ray flares in all GRBs and identified 16 of them with excellent data. After examining the seven GRB subclasses (Ruffini et al. 2016b), we conclude that they all occur in BdHNs, and no X-ray flares are observed in other GRB sources. This indicates a link between the occurrence of the flare and the formation of a black hole in long GRBs. In Section 4, we have shown how the previously proposed association of X-ray flares with the short GRBs 050724 and 050709 has been superseded.

By a statistical analysis, we correlate the time of occurrence of their peak luminosity in the cosmological rest frame, their duration, their energy, and their X-ray luminosity to the corresponding GRB $E_{\text{iso}}$. We also correlate the energy of the FPA phase, $E_{\text{FPA}}$, as well as the relative ratio $E_{\text{FPA}}/E_{\text{iso}}$ to $E_{\text{iso}}$.

2. Using the data from the associated thermal emission, the relativistic relation between the comoving time, the arrival time at the detector, and the cosmological and Doppler corrections, we determine the thermal emitter effective radii as a function of the rest-frame time. We determine the expansion velocity of the emitter $\beta$ as the ratio between the variation of the emitter effective radius $\Delta r_{\text{em}}$ and the emission duration in laboratory time; see Equation (25). We obtain a radius of $10^{12}$ cm for the effective radius of the emitter, moving with $\Gamma \leq 4$ at a time $\sim 100$ s in the rest frame (see Table 8). These results show the clear rupture between the processes in the prompt emission phase, occurring prior to the flares at radii of the order of $10^{16}$ cm and $\Gamma = 10^{2} - 10^{3}$, and the ones in the X-ray flares.

3. We have modeled the X-ray flares by considering the impact of the GRB on the SN ejecta, introducing a new set of...
relativistic hydrodynamic equations for the expansion of the optically thick $e^+e^-$ plasma into a medium with baryon load in the range $10^{10}$–$10^{12}$. The matter density and velocity profiles of the ejecta are obtained from the 1D core-collapse code developed at Los Alamos (Fryer et al. 1999a). With this we generate the initial conditions for our smoothed-particle-hydrodynamics-like simulation (Becerra et al. 2016), which follows the evolution of the ejecta matter and the accretion rate at the position of the Bondi–Hoyle surface of the NS binary companion. In our simulations, we have adopted 16 million particles (see Section 10 for further details). We start the simulation of the interaction of the $e^+e^-$ plasma with such ejecta at $10^{10}$ cm and continue all the way to $10^{12}$ cm, where transparency is reached. We found full agreement between the radius of the emitter at transparency and the one derived from the observations, as well as between the time of the peak energy emission and the observed time of arrival of the flare, derived following Equation (2) using the computed Lorentz $\Gamma$ factor of the world line of the process.

We can now conclude the following.

The existence of such mildly relativistic Lorentz Gamma factors in the FPA phase rules out the traditional GRB model, including the claims of the existence of GRB beaming, collimation, and break in the luminosity (see, e.g., Piran 1999, 2004; Frail et al. 2001; Mészáros 2002, 2006; Berger 2014; Kumar & Zhang 2015). In these models, the common underlying assumption is the existence of a single ultrarelativistic component extending from the prompt radiation, through the FPA phase, all the way to the late afterglow and to the GeV emission, assuming a common dynamics solely described by the Blandford & McKee (1976) solution; see, however, Bianco & Ruffini (2005b, 2006). These assumptions were made without ever looking for observational support. It is not surprising that all GRB models in the current literature purport the existence of an ultrarelativistic Lorentz Gamma factor extending into the afterglow, among many others; see, e.g., Jin et al. (2010) and Yi et al. (2015). All these claims have been disproven by the present article, where a drastic break from ultrarelativistic physics with $\Gamma \sim 10^2$–$10^3$, occurring in the prompt emission, is already indicated at times $\sim 100$ s, when the Lorentz Gamma factor is limited to $\Gamma \leq 4$.

In our approach, a multi-episode structure for each GRB is necessary. Each episode, being characterized by a different physical process, leads to a different world line with a specific Lorentz Gamma factor at each event. The knowledge of the world line is essential, following Equation (2) in Section 3, to compute the arrival time of the signals in the observer frame and to compare it with the observations. This procedure, previously routinely adopted in the prompt emission phase of a BdHN, has for the first time been introduced here for X-ray flares. As a byproduct, we have confirmed both the binarity and the nature of the progenitors of the BdHNe, composed of a CO$_{\text{core}}$ undergoing an SN explosion and accreting onto a close-by binary NS, and the impact of the GRB on the hypernova ejecta.

11.3. Perspectives

Far from representing solely a criticism of the traditional approach, in this paper, (1) we exemplify new procedures in data analysis—see Sections 4 to 7, (2) we open up the topic to an alternative style of conceptual analysis which adopts procedures well-tested in high-energy physics and not yet appreciated in the astrophysical community—see Sections 8–10, and (3) we introduce new tools for simulation techniques affordable with present-day large computer facilities—see figures in Section 11, which, if properly guided by a correct theoretical understanding, can be particularly helpful in the visualization of these phenomena. We give three specific examples of our new approach and indicate as well, when necessary, some disagreements with current approaches:

(A) The first step in any research on GRBs is to represent the histogram of $T_{90}$ for the GRB subclasses. We report in
Figure 38 the $T_{90}$ values for all of the GRB subclasses we have introduced (see Ruffini et al. 2016b). The values reported are both in the observer frame (left panel; see, e.g., Kouveliotou et al. 1993; Bromberg et al. 2013) and properly converted to the cosmological rest frame of the sources (right panel). The large majority of papers on GRBs have been neglecting the cosmological corrections and subdivision in the subclasses, making impossible the comparison of $T_{90}$ among different GRBs (see, e.g., Falcone et al. 2007; Chincarini et al. 2010).

(B) For the first time, we present a simplified spacetime diagram of BdHNe (see Figure 39). This spacetime diagram emphasizes the many different emission episodes, each one with distinct corresponding Lorentz Gamma factors and consequently leading through Equation (2) to a specific value of their distinct times of occurrence in the cosmological rest frame of the GRB (see Figure 39). In all episodes we analyzed for the X-ray flares, and more generally for the entire FPA phase, there is no need for collapsar-related concepts. Nevertheless, in view of the richness of the new scenario in Figure 39, we have been examining the possibility that such concepts can play a role in additional episodes, either in BdHNe or in any of the additional six GRB subclasses, e.g., in S-GRBs. These results are being submitted for publication. The use of spacetime diagrams in the description of GRBs is indeed essential in order to illustrate the causal relation between the source in each episode, the place of occurrence, and the time at detection. Those procedures have been introduced long ago in the study of high-energy particle physics processes and codified in textbooks. Our group, since the basic papers (Ruffini et al. 2001a, 2001b, 2001c), has widely shared these spacetime formulations (see, e.g., in Taylor & Wheeler 1992) and also extended the concept of the quantum S-Matrix (Wheeler 1937; Heisenberg 1943) to the classic astrophysical regime of the many components of a BdHN, introducing the concept of the cosmic matrix (Ruffini et al. 2015c). The majority of astrophysicists today make wide use of the results of nuclear physics in the study of stellar evolution (Bethe 1991) and also of Fermi statistics in general relativity (Oppenheimer & Volkoff 1939). They have not yet been ready, however, to approach these additional concepts more typical of relativistic astrophysics and relativistic field theories, which are necessary for the study of GRBs and active galactic nuclei.

(C) The visual representation of our result (see Figure 40) has been made possible thanks to the simulations of SN explosions with the core-collapse SN code developed at Los Alamos (see, e.g., Fryer et al. 1999a, 2014; Frey et al. 2013), the smoothed-particle-hydrodynamics-like simulations of the evolution of the SN ejecta accounting for the presence of an NS companion (Ruffini et al. 2016b), and the possibility of varying the parameters of the NS, of the SN, and of the distance between the two to explore all possibilities (Becerra et al. 2015; Ruffini et al. 2016b). We recall that these signals occur in each galaxy every ~hundred million years, but with their luminosity of $\sim 10^{52}$ erg, they can be detected in all $10^9$ galaxies. The product of these two factors gives the “once per day” rate. They are not visualizable in any other way, but analyzing the spectra and time of arrival of the photons now, and simulating these data on the computer, we see that they indeed already occurred billions of years ago in our past light cone, and they are revived by scientific procedures today.

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Appendix A

The Complete List of BdHNe

We present here in Table 9 the complete list of the 345 BdHNe observed through the end of 2016, which includes the 161 BdHNe already presented in Pisani et al. (2016).

Appendix B

Parameters of the Equation of State

We give here details concerning the determination of the value of the index $\gamma$ and verify the accuracy of our assumption $\gamma = 4/3$ adopted in the equation of state of the plasma (30). This index is defined as

$$\gamma = 1 + \frac{\rho}{\epsilon}. \quad (33)$$

The total internal energy density and pressure are computed as

$$\epsilon = \epsilon_e + \epsilon_{e^+} + \epsilon_{\gamma} + \epsilon_B \quad (34)$$

$$\rho = p_{e^{-}} + p_{e^+} + p_{\gamma} + p_B. \quad (35)$$

where the subscript $B$ indicates the contributions of the baryons in the fluid. The number and energy densities, as well as the pressure of the different particles, can be computed in natural units ($\epsilon = \hbar = k_B = 1$) using the following expressions (see, e.g., Landau & Lifshitz 1980):

$$n_{e^-} = A T^3 \int_0^{\infty} f(z, T, m_e, \mu_{e^-})z^2 \, dz \quad (36)$$

$$n_{e^+} = A T^3 \int_0^{\infty} f(z, T, m_e, \mu_{e^+})z^2 \, dz \quad (37)$$

$$\epsilon_{e^-} = A T^4 \int_0^{\infty} f(z, T, m_e, \mu_{e^-}) \times \sqrt{z^2 + (m_e / T)^2} \, z^2 \, dz - m_e n_{e^-} \quad (38)$$

$$\epsilon_{e^+} = A T^4 \int_0^{\infty} f(z, T, m_e, \mu_{e^+}) \times \sqrt{z^2 + (m_e / T)^2} \, z^2 \, dz - m_e n_{e^+} \quad (39)$$
$p_e = A T^4 \frac{4}{3} \int_0^\infty f(z, T, m_e, \mu_e) \frac{\mu^4}{\sqrt{\mu^2 + (m_e/T)^2}} d\mu \quad (40)$

$p_e = A T^4 \frac{4}{3} \int_0^\infty f(z, T, m_e, \mu_e) \frac{\mu^4}{\sqrt{\mu^2 + (m_e/T)^2}} d\mu \quad (41)$

$\epsilon_\gamma = a T^4 \quad (42)$

$\rho = a T^4 \quad (43)$

$\epsilon_B = \frac{3}{2} n_N T \quad (44)$

$p_B = n_N T \quad (45)$

where

$f(z, T, m, \mu) = \frac{1}{e^{\sqrt{z^2 + (m/T)^2} - \mu/T} + 1} \quad (46)$

is the Fermi–Dirac distribution, $m_e$ is the electron mass, $n_N$ the nuclei number density, $a = 8\pi^3 k_B^2 / 15 h c^5 = 7.5657 \times 10^{-15}$ erg cm$^{-3}$ K$^{-4}$ the radiation constant, and $A = 15 a / \pi^4$. If the pair annihilation rate is zero, i.e., if the reaction $e^- + e^+ \rightarrow 2\gamma$ is in equilibrium, then the equality $\mu_e = -\mu_e \equiv \mu$ holds, since the equilibrium photons have zero chemical potential. Besides, charge neutrality implies that the difference in the number of electrons and positrons is equal to the number of protons in the baryonic matter, which can be expressed as

$n_e(\mu, T) - n_e(\mu, T) = Z n_B, \quad (47)$

where $n_B$ is the baryon number density and $1/2 < Z < 1$ is the average number of electrons per nucleon. The number density $n_B$ is related to the other quantities as

$\rho = m_p n_B + m_e (n_e - n_e), \quad (48)$

where $m_p$ is the proton mass. If the baryons are only protons, then $Z = 1$ and $n_N = n_B$. Together with Equation (47), this completely defines the mass density as a function of $(\mu, T)$. The equation of state that relates the pressure with the mass and internal energy densities is thus defined implicitly as the parametric surface

$\{(\rho(\mu, T), \epsilon(\mu, T), p(\mu, T)): T > 0, \mu \geq 0\} \quad (49)$

that satisfies all of the above relations.

In the cases relevant for the simulations performed in Section 10, we indeed have that the index $\gamma$ in the equation of state of the plasma, Equation (30), satisfies $\gamma = 4/3$ with a maximum error of 0.2%.

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