Ph.D. Thesis

A novel paradigm for energetic gamma-ray bursts associated with supernovae: towards a new standard candle

Thesis Advisor: Prof. Remo Ruffini

Ph.D. student: Giovanni Battista Pisani

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Abstract

Gamma-ray bursts (GRBs) are among the most extreme and puzzling astrophysical objects that we observe. The “fireshell” model, interpreting GRBs as the consequence of a stellar mass black hole (BH) birth, well reproduces the photometrical and spectral features observed in the bulk emission of GRBs. Recently, the induced gravitational collapse (IGC) mechanism, which includes the fireshell model, has been proposed to explain the spacial and temporal connection of some GRBs with supernovae (SNe) starting from an evolved binary system composed of a FeCO core and a neutron star (NS). The recent works on GRB 090618 and 101023, which were been found to show a multiepisodic nature, opened the way to the extension of the IGC application to GRBs with isotropic energy larger than $10^{52}$ erg.

My work during three years of Ph.D. has been, and currently is, focused on the application and development of the IGC and the fireshell model to GRB sources. My work comprehends reduction and analysis of data coming from various detectors, such as BAT, XRT and UVOT onboard Swift satellite; GBM and LAT onboard Fermi satellite; and others several space- and ground-based telescopes. My work also encompasses simulations of GRBs light curves and spectra within the fireshell model, search for correlations among different GRB observables and, in general, for analogies and differences among the multiwavelenght components of GRBs.

Together with my collaborators, I have fitted various GRB sources within the fireshell model, such as: GRB 110709B and 970828, multiepisodic GRBs analogous to GRB 090618 and 101023; and GRB 090510, a long GRB which appears short due to the peculiar surrounding conditions. The main result on my thesis work is the discovery of a striking common behaviour in the late X-ray luminosity light curve within a “golden sample” of nearby, energetic, multiepisodic GRBs associated with SNe: GRB 060729, 061007, 080319B, 090618, 091127, and 111228. This result contributed to the development of the new concept of binary-driven hypernova (BdHN), which includes the IGC and the fireshell models, whose aim is the exhaustive explanation of the GRB-SN connection. This scaling law has rapidly become a necessary criterium for the BdHN identification, allowing us to predict the SN emergence in the optical band $\sim 13$ days after the GRB 130427A explosion. We have used this scaling law as a distance indicator too, inferring the distances of GRBs fitting the BdHN paradigm as GRB 101023 and 110709B, and successfully predicting the redshift of GRB 140512 before its measurement. Finally, we have recently identified the farthest ($z = 8.2$) GRB 090423 as a BdHN thanks to the overlapping of its X-ray luminosity with the BdHNe ones at late times. This result opens the way for the late X-ray luminosity of BdHNe to be actually used in future as a standar candle to test the ΛCDM model.
Introduction

Gamma-ray bursts (GRBs) are the brightest transient astronomical events that we observe in $\gamma$-rays. They are isotropically distributed in the sky and explode at cosmological distances, with their redshifts spanning in the range $z \sim 0.0085 - 8.2$. The isotropic energy released in a GRB explosion spans several orders of magnitude: $E_{\text{iso}} \sim 10^{48} - 10^{54}$ erg. Such huge amount of energy, up to the order of one solar mass, is released within a time scale going from milliseconds to minutes. GRBs are indeed the most powerful events ever observed in the Universe. The duration $T_{90}$ of GRBs appears to be bi-modal: the GRBs with $T_{90} < 2$ s are traditionally classified as short GRBs, while the ones with $T_{90} > 2$ s are referred as long GRBs. Short GRBs are in average harder than the long ones, and are mostly observed in the halo of their host galaxies. On the other hand, long GRBs are mainly observed in the high formation rate regions of their host galaxies, and they are associated in space and time with broad lines Ib/c supernova (SN) events. These facts lead to the traditional idea that short GRBs originate in mergers of compact objects, while long ones are the result of the final explosions of very massive stars.

A variety of models have been developed to theoretically explain the observational properties of GRBs. The most popular theory of GRBs is currently the “fireball” model, which says that a large energy released around a collapsing core leads to an optically thick $e^+e^-$ plasma loaded with baryonic matter. The total annihilation of the plasma leads to a huge release of energy in form of a relativistic expanding fireball, assumed to be collimated within a jet. The conversion of the fireball energy to radiation originates by collision-less shocks, either internal ones generated by faster moving matter within the flow taking over a slower moving shell, or external ones occurring when the flow interacts with the circum-burts medium (CBM). Following the fireball model, the most likely progenitors for long GRBs are very massive stars which have lost their hydrogen envelope (“collapsar” model), while for short GRBs the candidate progenitors are the mergers of compact objects.

An alternative approach to explain the GRBs is the “fireshell” model, proposed for the first time just a few months after the presentation of the discovery of GRBs at the Meeting of American Astronomical Society in San Francisco in 1973. This model can naturally explain a GRB isotropic release of energy up to $10^{54}$ erg in a time scale of seconds or less. Such energy is extracted from the electromagnetic energy of an arising Kerr-Newman black hole (BH) through a vacuum polarization process occurring during the gravitational collapse when the electric field of the BH exceeds the critical value for the formation of $e^+e^-$ pairs. The $e^+e^-$ plasma thermalizes and self-accelerates to ultra-relativistic velocity (up to a Lorentz factor of $\Gamma \sim 100–1000$) confined in a shell. After the engulfment and the thermalization of the baryonic
matter left over by the gravitational collapse within the expanding plasma, it finally reaches the transparency, emitting the proper-GRB. The remaining baryonic matter converts its kinetic energy into multi-wavelenght radiation via inelastic collisions with the CBM, giving rise to the extended afterglow.

The fireshell model predicts a new classification scheme for GRBs with $E_{\text{iso}} > 10^{52}$ erg, which can be divided in: 1) “genuine-short GRBs”, originating in the merger of binary neutron stars (NSs); 2) “disguised-short GRBs”; and 3) “canonical long GRBs”. Last two classes both refer to GRBs associated with SNe, which originate from a new kind of progenitor recently proposed by our group, namely a tight and evolved binary system composed by an FeCO core and a NS companion. We refer to such sources as binary driven hypernovae (BdHNe). The difference between the two classes of disguised-short and canonical long GRBs relies only on the values of the $\Gamma$ factor reached by the plasma and the average density of the CBM. Particular values of these two parameters can shrink down the apparent duration of a GRB down to $T_{90} \lesssim 1$ s. In this case the GRB is then disguised as a short duration one even if it is intrinsecally long.

Regarding the physical mechanism behind the BdHNe, what happens is that the FeCO core eventually explodes as a Ib/c SN. If the binary system is tight enough, such SN explosion triggers, via hypercritical accretion, the collapse of the NS companion to a BH, with the corresponding emission of a GRB following the fireshell model. This induced gravitational collapse (IGC) mechanism naturally explains several observational features: above all, the long GRBs – SNe connection and the thermal component observed in the precursor of several nearby GRBs. On the other hand, if at the SN explosion epoch the system is too detached, the NS cannot reach its critical mass via matter accretion, and therefore no GRB is emitted. Within this scenario, we interpret the low-energy ($E_{\text{iso}} < 10^{52}$ erg) GRBs-SNe simply as hypernovae (HNe), which are basically failed BdHNe. Famous examples of this class are GRB 980425 - SN 1998bw and GRB 060218 - SN 2006aj.

One of the most exciting outcomes of this novel paradigm is the possibility to consider BdHNe as standard candles. We have found a striking common behaviour at late times in the X-ray luminosity of a “golden sample” of closeby ($z \lesssim 1$) BdHNe. Further studies revealed an even more interesting nested structure of the X-ray luminosity light curves of BdHNe. We currently use these results as criteria for the identification of a BdHN, like we have done in the case of GRB 130427A, predicting some days in advance the appearence of its associated SN. Using the X-ray late time luminosity of BdHNe as distance indicator, we successfully predicted the redshift of GRB 140512A before its measurement. An additional key step was the identification as a BdHN of GRB 090423 at $z = 8.2$, which opens the patch for this novel distance indicator to be tested at high redshifts. If confirmed, it could provide new independent challenges to the current cosmological model.

**Bibliography produced by the Ph.D. candidate**


Chapter 1

Gamma-ray bursts

1.1 Gamma-ray bursts history

Gamma-ray bursts (GRBs) are intense $\gamma$-ray explosions. Their cosmological nature is a recent breakthrough, reached after many years of continuous observations. They were discovered in a serendipitous way in the late ’60 by the Vela satellites, an US Army project launched with the only purpose of monitoring the compliance of the Nuclear Test-Ban Treaty by the Soviet Union. This treaty prohibited all kind of nuclear weapons tests in the atmosphere, in outer space and underwater, except those conducted underground. The Vela satellites were equipped with X and $\gamma$-ray detectors. The first burst, GRB 670702\(^1\), was discovered on July 2, 1967, by the Vela 3a and 3b and Vela 4a and 4b satellites. From 1969 to 1972 these satellites detected 16 GRBs, whose durations were variable from 0.1 to about 30 s (Klebesadel et al., 1973). By analyzing the differences in the arrival time of the bursts at different satellites, it was possible to deduce their sky positions with sufficient accuracy to rule out a terrestrial or solar origin. It was initially advanced the hypothesis that GRBs could originate from the outskirts of supernovae (SNe) explosion in other galaxies, not necessarily bright in the optical (Colgate, 1968).

The announcement of the discovery at the Meeting of the American Astronomical Society in 1973 alerted the astronomical community to the existence of GRBs (Strong, 1975). Since then, several missions were planned to identify their origin and to make order in the great number of theoretical models born to explain this new, intriguing phenomenon. In fact for a certain period “there were more theoretical models than events observed” (Piran, 1999), though the major question remained unanswered: were GRBs galactic or extragalactic events?

1.1.1 BATSE and the prompt emission properties

The first important step toward the comprehension of GRBs was made by the NASA satellite Compton Gamma-Ray Observer (CGRO). It was a space observatory that detected photons with energies from 20 keV to 30 GeV, the second “Great

\(^1\)GRBs are named according to the date of detection. For example, the first GRB was detected on 02 July 1967, therefore is called GRB 670702. When more GRBs are detected in the same day, their order of occurrence is labeled by capital letters, like 030405A, 030405B, etc.
Figure 1.1: Total map of 2704 GRBs detected by BATSE during the nine-year mission. The projection is in galactic coordinates. The burst locations are color-coded based on the fluence values; grey is used for GRB with incomplete data. The source distribution is isotropic, with no concentration in the galactic plane, indicating an extragalactic origin. Credit: CGRO BATSE Team.

Observatory” launched by NASA, after the Hubble Space Telescope. It carried four instruments on board: the Burst and Transient Source Experiment (BATSE), covering the 20 keV–2 MeV energy range; the Oriented Scintillation Spectrometer Experiment (OSSE), effective in the 50 keV–10 MeV range; the Imaging Compton Telescope (COMPTEL), working in the 750 keV–30 MeV energy range; the Energetic Gamma Ray Experiment Telescope (EGRET), operating in the range 2 MeV–30 GeV.

The BATSE instrument (Meegan et al., 1992) was the most important instrument of CGRO. It was an all sky monitor consisting of eight identical detector modules, one at each side of the satellite’s corners. BATSE was characterized by a great accuracy (between 2 and 3 degrees, and sometimes 20 degrees for low-luminosity signals) in the localization of the sources and provided detailed observations of the temporal and spectral characteristics of large samples of GRBs. BATSE observed, on average, at a rate of one event per day. The complete sky distribution of 2704 detected bursts (see Fig. 1.1) evidenced an isotropic sky distribution (Meegan et al., 1992), with no concentration in the galactic plane, and confirmed with high significance their extragalactic origin. This left out two possibilities: the cosmological or an extended galactic halo origin of GRBs (Fenimore et al., 1993).

Another important outcome was that the observed spectral energy distribution (SED) of GRBs is non-thermal, being best fitted by a phenomenological model composed of a smoothly joined broken power-law (Band et al., 1993), in the energy
The functional form of the Band model (see Fig. 1.2) is

\[ N(E) = K \begin{cases} \left( \frac{E}{100} \right)^{\alpha} \exp \left[ \frac{(2 + \alpha)E}{E_p} \right], & E \leq \left( \frac{\alpha - \beta}{2 + \alpha} \right) E_p \\ \left( \frac{E}{100} \right)^{\beta} \exp \left( \beta - \alpha \right) \left[ \frac{(\alpha - \beta)E_p}{(2 + \alpha)} \right]^{\alpha - \beta}, & E > \left( \frac{\alpha - \beta}{2 + \alpha} \right) E_p \end{cases} \]  

(1.1)

where typical values the power-law indexes are \(-1.5 \leq \alpha \leq 0.5\) and \(-2.5 \leq \beta \leq -2\), while for the peak energy are \(100 \text{ keV} \leq E_p \lesssim \text{few MeV}\); \(K\) is the normalization constant.

BATSE revealed also a great variety of burst profiles in the time structures: it was possible to identify single pulses, spiky or smooth in time, multiple pulses well-separated in time or chaotic bursts, very erratic (Fishman & Meegan, 1995). Examples are shown in Fig. 1.3.

But the most important result on the complete BATSE GRBs catalog was the evidence of a bimodal distribution of their \(T_{90}\) duration of the prompt emission.\(^2\)

\(^2\)The \(T_{90}\) duration is defined as the time interval over which 90% of the total background-subtracted counts are observed, with the interval starting when 5% of the total counts have been observed.
Therefore, GRBs were classified into classes: long and short bursts, being their $T_{90}$ longer or shorter than 2 s (see Fig. 1.4). The observed spectra of the short GRBs have appeared also to be systematically harder than the ones of the long ones (Klebesadel, 1992; Dezalay et al., 1992; Kouveliotou et al., 1993; Tavani, 1998). This dichotomy led to an idea of different progenitors: the explosion of very massive stars for long GRBs (the Collapsar model, see e.g. Woosley, 1993) and the merger of compact objects for short GRBs (Blinnikov et al., 1984; Paczyński, 1998).

1.1.2 Beppo-SAX and the cosmological era

BATSE observations pointed toward an extragalactic origin of GRBs, however a direct measurement of the distance was still missing. To solve this problem, faster and more precise ($\sim$ few-arcminutes of resolution) locations were needed to find...
1.1 Gamma-ray bursts history

Figure 1.4: Bimodal distribution of the $T_{90}$ of the 4BATSE catalog. Credit: CGRO BATSE Team.

the counterparts at other wavelengths of GRBs: the afterglow. This component originates from material ejected at high velocity, which interacts with the ambient medium; the heated material gives rise to a long lived emission of energy following the burst. At that time the afterglow was a mere theoretical prediction, but no observational data could confirm its existence.

This enigma was solved with the launch of the Italian-Dutch satellite *BeppoSAX* (1997-2002). *Beppo*-*SAX* was the first X-ray mission with a scientific payload covering more than three decades of energy (from 0.1 to 300 keV) with a relatively large effective area, medium energy resolution and imaging capabilities in the range of 0.1–10 keV. This satellite was equipped with the γ-ray detector *Gamma-Ray Burst Monitor* (GRBM), together with X-ray *Wide Field Cameras* (WFCs) and *Narrow Field Instruments* (NFIs).

The turning point occurred on February 28, 1997 with the detection in γ-rays of GRB 970228 by the WFCs. The *Beppo*-*SAX* capabilities allowed the NFIs to repoint the GRB field 4–6 hours after the GRB trigger (see left image in Fig. 1.5), leading to the detection of the first X-ray afterglow (Costa et al., 1997). A second follow-up with *Beppo*-*SAX* was performed after about 3 days (see right image in Fig. 1.5). The more refined location of the burst in X-rays allowed a possible optical follow-up with the Hubble Space Telescope (HST) and ground-based telescopes (Sahu et al., 1997). The measured location within arcseconds accuracy, enabled the identification of the host galaxy of GRB 970228 and the measurement of its redshift, $z = 0.695$ (Van Paradijs et al., 1997). The following measurements of the redshift of other GRB afterglows (Metzger et al., 1997) solved the debate on the origin of the GRBs in favor of the cosmological one.

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*Beppo* name is in honor of the Italian physicist Giuseppe “Beppo” Occhialini; SAX stands for *Satellite per Astronomia a raggi X* or “Satellite for X-ray Astronomy”
1.1.3 The Swift revolution

The Swift satellite (Gehrels et al., 2009) is a mission designed specifically for GRBs science, providing continuously data to the scientific community. The on board instruments, the Burst Alert Telescope (BAT, 15–150 keV), the X-Ray Telescope (XRT, 0.3–10 keV) and the Ultra-Violet/Optical Telescope (UVOT, 170–650 nm), work together to observe GRBs in all the $\gamma$, X and optical bands. The BAT instrument is responsible for the trigger in the $\gamma$-rays and within about 10 s after the trigger, it provides a burst localization (within an accuracy from 1 to 4 arcminutes) which is transmitted to ground observatories. In addition, according to the BAT position, the spacecraft can slew, bringing the GRB into the XRT and UVOT field of view. In this way Swift provides a rapid localization of GRBs and a rapid follow-up of the afterglows in different wavelengths. Within about 60 s after the trigger, the XRT refines the BAT position. The UVOT produces an even more accurate localization within about 200 s after the burst trigger. The Swift mission offers the opportunity to observe a GRB from the beginning to the end of the transient phenomenon without the gap in the data of 8 hours as in Beppo-SAX.

Swift detected more than 1000 bursts (up to November 2014). In this sample, there are $\sim$ 300 GRBs with redshift, mainly determined by the large optical telescopes on ground, and among there is the most distant burst, GRB 090423 at confirmed redshift $z = 8.2$ (Salvaterra et al., 2009; Tanvir et al., 2009). This result was mainly due to the sensitivity of the BAT instrument (Barthelmy et al., 2005a), higher than the Beppo-SAX and HETE-2$^4$ ones. On the other hand, Swift has detected a lower fraction of short GRBs ($\sim 10\%$) than BATSE did ($\sim 25\%$) because

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$^4$http://space.mit.edu/HETE/
the *Swift* energy sensitivity band (15–150 keV) is softer than the BATSE one (20–2000 keV). This is a consequence of the fact that short GRBs have harder spectra than the long ones, although this difference is less evident in the observations by HETE-2 and *Swift* (Sakamoto et al., 2006).

The optical afterglow observations (by UVOT and/or on ground) alerted by the BAT detections allowed the determination of the host galaxies of GRBs, their redshift and, in few cases, a spatial and temporal connection between long GRBs and Ib/c SNe. On the other hand, short GRBs were typically located in elliptical or early type galaxies, with little star formation, suggesting for this class of GRBs a different progenitor: the merging of two compact objects (Paczyński, 1986; Narayan et al., 1992). These results partly supported the BATSE classification of GRBs. However, another fundamental result achieved by the *Swift*/BAT instrument challenged this basic idea: the discovery of a class of short GRBs with an extended emission (Norris & Bonnell, 2006). These sources evidenced hybrid properties between short and long bursts. Their prompt emission is characterized by an initial hard/short spike-like emission lasting a few seconds, followed by a prolonged extended emission, lasting up to some hundred seconds after the trigger. This long lasting emission is softer and, more important, $10^{-3}–10^{-1}$ times less intense than the main pulse, suggesting the possibility that many short GRBs of the 4BATSE catalog could have this component with the intensity below the detector threshold. A possible explanation for these sources is that they are GRBs characterized by a low CBM density, producing a softer extended emission which sometimes is not detected by any hard X-ray instrument (see next Chapter). The existence of these short GRBs with an extended emission suggests that the usual classification in short and long bursts should be revised using a more physically motivated GRB classification.

The most important contribution of XRT (Burrows et al., 2005a) consists in the observation, $\sim 100$ s after the trigger, of complex behaviors in the X-ray afterglow light curves consisting at most of three different power-law segments (Nousek et al., 2006; Zhang et al., 2006): (1) an early steep decay (Tagliaferri et al., 2005), reasonably interpreted as the tail of the prompt emission at large angles (Kumar & Panaitescu, 2000), followed by (2) a very shallow decay, called the plateau, usually accompanied by spectral parameter variations (Butler & Kocevski, 2007), and (3) a final decay, less steep than the first one (see Fig. 1.6). Another important discovery of XRT was the detection of a flaring activity in the X-ray afterglow (Chincarini et al., 2007). The observed behavior of these flares, the rapid rise and exponential decay together with a fluence comparable in some cases to the prompt emission (Burrows et al., 2005b), points out that the same mechanism for the prompt emission is responsible for the flaring activity (Chincarini et al., 2010).

The greatest goal by the UVOT instrument (Roming et al., 2005) consists in the discovery of an early optical component within the prompt emission and correlated with it (Vestrand et al., 2006), suggesting a common origin for both components. The optical afterglows of $\sim 50\%$ of GRBs exhibit simple power-law decays but also flat or rising behaviors before the canonical power-law afterglow decays; the remaining GRBs do not show any optical emission and they are addressed as *dark* GRBs. The nature of these bursts seems to be related to their distances, although recently it was showed that the lack of an optical afterglow could be ascribed to
the presence of dust near the GRB site or in its host galaxy (Perley et al., 2009). Another interesting feature is the presence of chromatic breaks in the afterglow light curves of GRBs. This break occurs in X-ray band signing the end of the plateau phase, but not in the optical afterglow, which follows a single power-law decay. This chromaticity is not due to the jet-break transition from the relativistic expanding jet to the non-relativistic regime, since it is expected to be achromatic (see Sec. 1.3.4).

*Swift* enabled a multi-wavelength study of GRBs phenomena. However, further observational data are required to crack the mystery of their emission mechanism.

### 1.1.4 The *Fermi* satellite and the modern age

In recent years, among all of the satellites dedicated to the observations of GRBs, the *Fermi Gamma-ray Space Telescope* is the satellite that is offering the most interesting results for astronomers and astrophysicists communities. *Fermi* includes two instruments, the *Large Area Telescope* (LAT) and the *Gamma-ray Burst Monitor* (GBM). The LAT detector (Atwood et al., 2009) allows the detection of photons within the energy range 20 MeV–300 GeV, so far never explored in the GRBs case. The GBM detector (Meegan et al., 2009) consists of 14 scintillation detectors, 12 sodium iodide (NaI) crystals (8 keV–1 MeV) and two bismuth germanate (BGO) crystals (150 keV–40 MeV). In this way, it is possible to have a complete monitoring of GRB emission in a very wide range of energies.

In the first two years of observations *Fermi* obtained very remarkable results, in particular for the high-energy emission. Before LAT very high-energy emission from GRBs was detected by EGRET (Hurley et al., 1994), the high-energy $\gamma$-ray detector on-board the CGRO. LAT has observed $\sim$ 80 GRBs with GeV emission (up to November 2014), and in most of them this emission is delayed (Abdo et al., 2009) and lasts longer than the low-energy emission in the keV–MeV range.

One of the most recent outcome of the *Fermi* GBM is the detection of a thermal signature in the spectra of the prompt emission of some energetic bursts, such as
GRB 090902B (Ryde et al., 2010), GRB 100724B (Guiriec et al., 2011), GRB 090618 (Izzo et al., 2012a), and GRB 101023 (Penacchioni et al., 2012). The detection of a thermal component is in line with the results on the BATSE 4B catalog Kaneko et al. (2006), where F. Ryde found a large number of bursts showing thermal features associated to an extra non-thermal component, usually a power-law (Ryde, 2004; Ryde & Pe`er, 2009). The interpretations of the nature of this thermal component are different, as it will be clear in the following.

Other GRBs missions are currently operating in the hard X and γ-rays domain. Among them there is the Swift satellite, which has been already described. The International Gamma-Ray Astrophysics Laboratory (INTEGRAL)\(^5\), which is able to produce a complete map of the sky and it is capable of performing high spectral (20 keV–8 MeV) and spatial observations in γ-rays. The Konus\(^6\) experiment, on-board the WIND spacecraft, continues to provide omni-directional coverage of the sky of hard X and γ-ray transients (Aptekar et al., 1995). The Italian satellite, Astro-rivelatore Gamma ad Immagini LEggero (AGILE)\(^7\), which includes the Gamma Ray Imaging Detector (GRID), complementary to the LAT instrument (30 MeV–50 GeV), and the SuperAGILE wide field monitor with 18–60 keV energy range.

In the X-ray domain we have at work the X-ray Multi-Mirror (XMM-Newton)\(^8\) mission, carrying an X-ray telescopes with a very large collecting area and provide highly sensitive observations, and the Advanced X-ray Astrophysics Facility (AXAF)\(^9\), renamed Chandra in honor of Chandrasekhar, which combines high resolution, large collecting area and sensitivity to higher energy X-rays making possible to study extremely faint sources.

Other important goals in the study of the time evolution in the mildly relativistic regime of GRBs have been reached by the observations at lower frequencies. There are currently several large ground-based telescopes to follow the optical decay of the afterglow, e.g. GROND\(^10\), PROMPT\(^11\), ROTSE\(^12\), and other telescopes dedicated to the observations of the afterglow in the optical and near Infra-Red (IR) bands, e.g. the class of 8-meters telescopes, as the Very Large Telescope (VLT), the Large Binocular Telescope (LBT), and the 10-meters Keck telescope in Hawaii.

### 1.2 Long GRBs connection with SNe

The discovery and localization of the first afterglows of GRBs rapidly led to the establishment of the long-sought distance scale for the sources, which began an earnest observational hunt for the progenitors. A preponderance of evidence linked long-duration, soft-spectrum GRBs with the death of massive stars. The observations of the GRB-SN connection present the most direct evidence of this
1.2.1 GRB 980425/SN 1998bw: the first observed connection

GRB 980425 was discovered early in the afterglow era. In the error circle of GRB 980425, two X-ray sources were found, though the precise characterisation of their respective variability was uncertain. Therefore, the identification of the true X-ray counterpart to GRB 980425 was controversial (Pian et al., 2000; Kouveliotou et al., 2004); as a result, the discovery of a supernova, SN 1998bw (Fig. 1.7), coincident with one of the X-ray sources was not immediately taken as unequivocal evidence for a direct link to GRB 980425.

SN 1998bw was a spectacular event. It was a bright ($M_B = -18.7$ mag at peak), broad-lined Type Ic SN (Galama et al., 1998) suggesting a significant amount of mass with very fast (upwards of 30,000 km s$^{-1}$) photospheric expansion (Woosley & Bloom (2006) advocate for the designation as Ic-BL, for broad-lined SN without He, H or Si in the spectrum). The light curve is shown in Fig. 1.8 and its spectral evolution (Patat et al., 2001) is shown in Fig. 1.9.

Iwamoto et al. (1998) suggested that these observations can be reproduced by an extremely energetic explosion of a massive star composed mainly of carbon and oxygen (having lost its hydrogen and helium envelopes). Based upon an independent modelling effort, Woosley et al. (1999) concurred with the carbon and oxygen core hypothesis and also argued that SN 1998bw was an asymmetric explosion. Iwamoto et al. (1998) and others at the time used the term “hypernova” (Paczyński, 1998) to describe such a very energetic SN, modelled to have released roughly 10 times more energy than in a typical ($10^{51}$ erg) SN.

No traditional optical afterglow (as seen in most other GRBs) was detected. Moreover, the comparatively low energy output of GRB 980425 (see e.g., Kaneko et al., 2007) and its low redshift were considered as pointing to a different class of GRB (Kulkarni et al., 1998; Bloom et al., 1998), not necessarily of the same progenitor origin as the truly cosmological GRBs (loosely defined as having a significant redshift, a high energy output in $\gamma$ rays, $E_{\gamma} \sim 10^{52}$ erg, and an (optical) afterglow decaying as a power law) that had been detected so far.

Doubts therefore remained about the GRB-SN connection, arising from an $a$ posteriori statistical argument about the association in time and place with two X-ray sources in the $\gamma$-ray error circle, the lack of an optical afterglow, and the low implied energy output; even if the physical connection was believed, GRB 980425 was clearly set apart from the typical cosmological GRBs emitting orders of magnitude more $\gamma$-ray energy.

1.2.2 GRB 030329/SN 2003dh: the “smoking gun”

Almost 5 years after GRB 980425/SN 1998bw, GRB 030329 eliminated any doubts as to the deep GRB-SN connection. GRB 030329 was a bright burst detected by the HETE-2 satellite (Vanderspek et al., 2004; Lipkin et al., 2004). At an inferred redshift of $z = 0.1685$ (Greiner et al., 2003b), it was “truly” cosmological
Figure 1.7: Discovery of SN 1998bw associated with GRB 980425. The upper panels show the images of the host galaxy of GRB 980425, before (left) and shortly after (right) the occurrence of SN 1998bw (Galama et al., 1998). The bottom panel shows a late HST image of the host galaxy and SN 1998bw. The 3-step zoom-in shows SN 1998bw 778 days after the explosion embedded in a large star-forming region of a spiral arm (Fynbo et al., 2000).
Figure 1.8: Light curves of spectroscopic GRB-SNe contrasted with upper limits on SNe in SN-less GRBs. The red data points are the light curves of the GRB-SNe 1998bw (Galama et al., 1998), 2003dh (Hjorth et al., 2003), 2003lw (Malesani et al., 2004), 2006ap (Pian et al., 2006), and 2010bh (Bufano et al., 2011). The upper limits are from the short GRBs 050509B (Hjorth et al., 2005a) and 050709 (Hjorth et al., 2005b) (blue arrows) and two SN-less long GRBs (green arrows) (Fynbo et al., 2006). Approximate bolometric magnitudes are based on R and V band upper limits offset relative to the corresponding SN 1998bw V or R band light curves. Time is in the restframe. The $^{56}$Co decay slope is shown for reference (dashed curve).
1.2 Long GRBs connection with SNe

Figure 1.9: Spectral evolution of GRB-SNe 1998bw (Patat et al., 2001) and 2003dh (Hjorth et al., 2003). Solid lines indicate spectra of SN 2003dh obtained by subtracting a model for the afterglow and host galaxy contributions from the spectra. Dotted red lines indicate spectra of SN 1998bw taken at similar epochs. Times after the GRB are indicated in the rest frame. From Hjorth et al. (2003).
and had a total isotropic energy release $10^4$ times that of GRB 980425. Moreover, it was followed by a bright optical afterglow (Price et al., 2003), helping solidify this event as part of the cosmological GRB class. Several days after the burst, the optical spectrum started to change from a featureless power-law spectrum, characteristic of GRB afterglows, to include more and more SN features (Matheson et al., 2003a; Stanek et al., 2003; Hjorth et al., 2003; Kawabata et al., 2003; Matheson et al., 2003b). By subtracting the afterglow contribution, the SN spectrum could be isolated. It was shown to closely follow that of SN 1998w, thus conclusively showing that the GRB afterglow and SN were spatially coincident and that GRB 030329 and SN 2003dh were co-eval to within a few days (Hjorth et al., 2003) (Fig. 1.9).

The SN light curve was almost completely masked by the bright afterglow (Lipkin et al., 2004). Only by subtraction of the afterglow was it obvious that SN 2003dh peaked at about the brightness of SN 1998bw but evolved faster (see Fig. 1.8 and Hjorth et al., 2003; Matheson et al., 2003b).

In retrospect, the GRB 030329/SN 2003dh connection also eliminated any doubts about the association between GRB 980425 and SN 1998bw.

### 1.2.3 Supporting evidences for the GRB-SN connection

Further clear spectroscopic evidences of GRB-SN connection have been found in the cases of GRB 031203 (Soderberg et al., 2003; Tagliaferri et al., 2004), GRB 060218 (Campana et al., 2006; Soderberg et al., 2006a), GRB 100316D (Bufano et al., 2012; Chornock et al., 2010; Sakamoto et al., 2010), GRB 120422A (Melandri et al., 2012; Barthelmy et al., 2012), and GRB 130427A (Melandri et al., 2014; Xu et al., 2013b; Von Kienlin, 2013), all at relatively low redshifts ($z \lesssim 0.3$). It is important to consider the evidence for GRB-SNe at higher redshifts and for GRBs with $E_{\gamma,iso}$ in the range $10^{50}$–$10^{54}$ erg (Frail et al., 2001). At higher redshift secure SN identification becomes difficult because the SN appears fainter, which leads to the difficulty of obtaining a sufficient signal-to-noise ratio in the broad SN features. The signal-to-noise problem is aggravated by the contamination of the host galaxy and the afterglow, which do not necessarily get comparatively fainter with redshift (see, e.g., Woosley & Bloom, 2006).

There exists, however, substantial photometric evidence for late-time light-curve bumps. The bulk of the evidence points to Type Ic SNe and only in a few cases Type II SNe have been suggested (e.g., Garnavich et al., 2003; Gorosabel et al., 2005). To date, 35 GRB-SN associations have been confirmed on spectroscopic and/or photometric grounds, see Table 1.1 (Hjorth & Bloom, 2012; Kovacevic et al., 2014).

GRB-SNe are generally consistent with being broad-lined Type Ib/c, with a dispersion in both peak brightness, rise time, light curve width, and spectral broadness. The SN lightcurve peaks at 10–15 days after the GRB trigger (in the source rest-frame), powered by the radioactive decay of $^{56}$Ni, whose half-life time is about 6 days (Arnett, 1996).
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Table 1.1: The sample of the 35 confirmed GRB-SN connections updated to the 31 May 2014 presented in Kovacevic et al. (2014). List of references: (1) Reichart (1997); (2) Bloom et al. (1999); (3) Galama et al. (1998); (4) Frontera et al. (2009); (5) Zeh et al. (2004); (6) Lazzati et al. (2001); (7) Hurley et al. (2000); (8) Bloom et al. (2002); (9) Hurley et al. (2001); (10 Greiner et al. (2003a)); (11) Gorosabel et al. (2005); (12) Hurley et al. (2002a); (13) Masetti et al. (2003); (14) Hurley et al. (2002b); (15) Nicastro et al. (2004); (16) Levan et al. (2005); (17) Della Valle et al. (2003); (18) Vreeswijk et al. (2003); (19) Crew et al. (2002); (20) Golenetskii et al. (2003); (21) Kawabata et al. (2003); (22) Stanek et al. (2003); (23) Fynbo et al. (2003); (24) Soderberg et al. (2003); (25) Tagliaferri et al. (2004); (26) Fenimore et al. (2004); (27) Soderberg et al. (2006c); (28) Galassi et al. (2004); (29) Bikmaev et al. (2004); (30) Della Valle et al. (2006b); (31) Campaña et al. (2006); (32) Soderberg et al. (2006a); (33) Cano et al. (2011); (34) Parsons et al. (2006); (35) Hill et al. (2007); (36) Perley et al. (2008); (37) Kann et al. (2008); (38) Cummings et al. (2008); (39) Soderberg et al. (2008); (40) Markwardt et al. (2008); (41) Izzo et al. (2012a); (42) McBreen (2009); (43) Cobb et al. (2010); (44) Wilson-Hodge & Preeece (2009); (45) Bufano et al. (2012); (46) Chornock et al. (2010); (47) Sakamoto et al. (2010); (48) Sparer et al. (2011); (49) Van Der Horst (2010); (50) D’Avanzo et al. (2012); (51) Briggs & Yonessi (2011); (52) Melandri et al. (2012); (53) Barthelmy et al. (2012); (54) Cummings et al. (2012); (55) Klose et al. (2012); (56) Cano et al. (2014); (57) Ukwatta et al. (2012); (58) De Ugarte Postigo et al. (2013a); (59) Yonessi & Bhat (2013); (60) Melandri et al. (2014); (61) Xu et al. (2013b); (62) Von Kienlin (2013); (63) Cenko et al. (2013); (64) Collazzi & Connaughton (2013); (65) Singer et al. (2013); (66) Klose et al. (2013); (67) Golenetskii et al. (2013).
1.2.4 Long-duration GRBs without associated SNe

The absence of a SN signature in their light curves has been proposed as a defining characteristic of short GRBs. However, the discovery of another class of SN-less GRBs, namely long-duration GRBs like GRB 060614 (Della Valle et al., 2006a; Fynbo et al., 2006; Gal-Yam et al., 2006) and GRB 060505 (Fynbo et al., 2006) with no SNe observed to deep limits, poses a challenge to an otherwise clean classification scheme.

One proposed resolution was to posit the > 100 s long GRB 060614 as belonging to a short GRB population (Zhang et al., 2007). Another possibility is a chance coincidence of a GRB with a foreground galaxy at the purported redshift ($z = 0.125$, see Cobb et al., 2006; Campisi & Li, 2008), thereby giving the false impression of deep non-detections of SN light.

GRB 060505 ($z = 0.089$) was a GRB with a duration of 4–5 s (depending on bandpass) and a non-zero spectral lag (namely, the delay of arrival of low energy photons with respect to higher energy photons) of 0.36 s, inconsistent with the lags of short GRBs (McBreen et al., 2008). It has been suggested to be a member of the short GRB class, belonging to the long tail of the duration distribution (Ofek et al., 2007). This is supported by the fact that it is an outlier of the so called Amati relation (Amati et al., 2007) just like short GRBs.

1.3 The standard “fireball” model

The GRBs energy range is typically $\sim 10^{49}–10^{54}$ erg. Their observed non-thermal spectrum indicates that these sources must be optically thin. Using the Newtonian causality limit, observed variability time scales of $\delta t \approx 10$ ms imply that GRBs originate from very compact regions with size $R \leq c\delta t \approx 3000$ km. For typical values of the luminosity distance $d_l$ and fluence $S$ of GRBs the estimated average photon density is very huge (Piran, 2004)

$$\rho_\gamma \approx \frac{d_l^2 S}{E_\gamma(c\delta t)^3} ,$$

and two $\gamma$-rays can annihilate and produce $e^+e^-$ pairs if their energies are $E_\gamma \approx m_e c^2$, being $m_e$ the electron mass. The opacity for pair creation is $\tau_{\gamma\gamma} \approx f_{e^+e^-}\sigma_T\rho_\gamma c\delta t$, where $f_{e^+e^-}$ is the fraction of photons with energies sufficient to produce pairs and $\sigma_T$ is the Thomson cross-section. For typical values, this optical depth is very large, $\tau_{\gamma\gamma} \sim 10^{15}$, therefore the source must be optically thick (Piran, 2004). This is the so-called compactness problem.

As Ruderman pointed out (Ruderman, 1975), relativistic effects can solve this problem. The causality limit of a source moving relativistically with Lorentz factor $\Gamma \gg 1$ towards the observer is $R \leq \Gamma^2 c\delta t$. Consequently, the observed photons are blue-shifted and their energy at the source is lower by a factor $\approx 1/\Gamma$, which may be insufficient for pair production. This leads to a decrease in the estimated optical depth, expressed through the formula (Piran, 1999)

$$\tau_{\gamma\gamma} = \frac{1}{\Gamma^{2\beta+2}} \frac{f_{e^+e^-}\sigma_T d_l^2 S}{m_e c^2 (c\delta t)^2} ,$$

(1.3)
1.3 The standard “fireball” model

where the $\beta$ is the high-energy power-law index of photon spectrum of the burst. For $\Gamma > 100$ one obtain the optically thin condition of the source. Ultra-relativistic expansion of GRBs is unprecedented in astrophysics. There are indications that relativistic jets in active galactic nuclei have $\Gamma \sim 2–10$, but some GRBs have $\Gamma \sim 300$ and more.

A large velocity of the expansion of the outflow from GRBs finds a confirmation with the radio scintillation observed in their afterglows (Goodman, 1997), and also from the apparent observation of self-absorption in the radio spectrum of the afterglow (Katz & Piran, 1998), where it is possible to obtain independent estimates of the dimensions of the afterglow relic.

1.3.1 The concept of fireball

The release of a large quantity of $\gamma$-ray photons into a compact region can lead to an opaque photon-lepton plasma through the production of $e^+e^-$ pairs. The idea that the $e^+e^-$ plasma could play an important role as energy source of GRBs was proposed independently by Damour & Ruffini (Damour & Ruffini, 1975) and by Cavallo & Rees (Cavallo & Rees, 1978). In particular Cavallo & Rees proposed a sudden release of energy in a process of gravitational collapse leading to a large number of $e^+e^-$ pairs, whose instantaneous annihilation would lead to a vast release of energy pushing on the CBM: the concept of fireball13. Later Goodman (Goodman, 1986) quantified the dynamical effects of the expansion of the fireball computing the effect of the blue-shift due to the bulk Lorentz factor on the observed temperature.

The opaque pairs-radiation plasma behaves like a perfect fluid described by the stress-energy tensor $T_{\mu\nu}$ with pressure $p$, energy density $\epsilon$ and equation of state $p = \epsilon/3$. Shemi & Piran (Shemi & Piran, 1990) were the first to compute the dynamics of such a fireball in presence of some baryonic matter, which may be injected with the original radiation or may be present in an atmosphere surrounding the initial explosion (Piran, 1999). The presence of baryons can influence the fireball evolution in two ways: the electrons associated with this matter increase the opacity, delaying the escape of radiation; the baryons, accelerated with the rest of the fireball, convert part of the radiation energy into bulk kinetic energy.

The expansion of the plasma is ruled by the relativistic conservation equations of baryon number, energy and momentum

$$ (\rho_B U^\mu)_{;\mu} = 0 \quad , \quad (T_{\mu\nu})_{;\nu} = 0 , $$

(1.4)

where $\rho_B$ is the baryon mass density and $U^\mu$ its 4-velocity. The expanding fireball has two basic phases: a radiation dominated phase and a matter dominated phase (Piran, 1999). During the radiation dominated phase it occurs that $\gamma \ll (\epsilon_0/\rho_B^0) \gamma_0$ and the conservation equations reduce to the first order in $\gamma^{-2}$ to these simple scaling laws (Piran, 1999):

$$ \gamma \propto r \quad , \quad \rho_B \propto r^{-3} \quad , \quad \epsilon \propto r^{-4} . $$

(1.5)

13The term fireball refers to an opaque plasma with an initial energy significantly greater than its rest mass (Piran, 1999)
The matter dominated phase, under the same approximation, is characterized by (Piran, 1999):

\[ \gamma \rightarrow \text{const} , \quad \rho_B \propto r^{-2} , \quad \epsilon \propto r^{-8/3} . \]  

(1.6)

During this last stage, since \( \epsilon \ll \rho_B \), the radiation has not important dynamical effect on the motion and produces no significant radial acceleration, therefore the fluid coasts with a constant asymptotic radial velocity.

The fireball is composed of shells of particles at different velocities. At some point during the expansion, the fireball will become optically thin and the frozen pulse approximation must ultimately break. From this stage on the radiation and the baryons no longer move with the same velocity and the radiation pressure vanishes. Any remaining radiation will escape freely now and the baryon shells will coast with their own individual velocities.

1.3.2 The “internal-external” shock scenario

The energy transport occurs via kinetic energy of a shell of relativistic particle with width \( \Delta \) (Piran, 1999). The kinetic energy is converted into energy of relativistic particles via shocks (Piran, 1999). Two processes of energy conversion have been proposed: external shocks, due to interaction with an external medium (Mészáros & Rees, 1993a), or internal shocks, that arise within the flow when fast moving shells catch up with slower ones (Rees & Meszaros, 1994) (see Fig. 1.10).

In the standard model, internal shocks explain the temporal structures observed in GRBs prompt emission (Piran, 1999) (see Fig. 1.10). These shocks take place at distances of \( \sim 10^{15} \) cm and convert 2–20% of the kinetic energy of the flow to thermal energy. With this mechanism it is possible to extract at most half of the shell energy (Kobayashi et al., 1997).
1.3 The standard “fireball” model

The afterglow emission is produced when the relativistic ejecta is slowed down by the surrounding matter (Mészáros & Rees, 1997; Sari & Piran, 1997) (see Fig. 1.10). At this stage, a cold shell (with negligible internal energy, compared to its rest mass) can overtake another cold shell or move into the cold CBM, producing external shocks (Piran, 1999). Generally, two shocks form: an outgoing one propagating into the CBM or into the external shell, and a reverse one that propagates backward into the ejecta (Mészáros & Rees, 1993b; Sari & Piran, 1999). The shocks structure is described by the Lorentz factor $\gamma$ of the inner shell relative motion to the outer one or the CBM, and by the ratio $f$ between the particle number densities of the regions before and after the shock. The reverse shock emission has a much lower temperature than the forward shock one, and therefore radiates at considerably lower frequencies. For this reason the signatures from a reverse shock emission are seen in the early optical light curve of a GRB.

In the initial phases of the external shocks scenario the conversion of the energy might be radiative, namely a significant fraction of the kinetic energy is dissipated and the radiation process affects the hydrodynamics of the shock. This means that the fraction of the shock energy which goes into electron energy, $\epsilon_e$, is close to unity (Piran, 2004). Later the radiation process become less efficient and an adiabatic phase begins, therefore the radiation losses do not influence the hydrodynamics (Piran, 2004). Finally, a transition into the Newtonian regime takes place when $\gamma \sim 1.5$. The theory of a relativistic shell propagating into the CBM has been worked out in a classical paper by Blandford & McKee (Blandford & McKee, 1976). This model is a self-similar spherical solution describing an adiabatic ultra-relativistic blast wave in the limit of $\gamma \gg 1$. For this blast wave, the total energy follow a scaling law

$$\gamma \propto r^{-a}.$$  \hspace{1cm} (1.7)

with $a = 3/2$. Analogously, it is possible to find for a fully radiative regime another scaling law (Blandford & McKee, 1976), this time with $a = 3$. The simple adiabatic model assumes that the energy of the GRB is constant. However a possible energy injection at late times can occur when initially faster moving matter is slowed down by the CBM matter, which eventually catches up and produces refreshed shocks (Rees & Meszaros, 1998; Kumar & Piran, 2000). There are two implications for the refreshed shocks. First, the additional energy injection influences the dynamics of the blast wave (Rees & Meszaros, 1998), changing the canonical decay slope in the light curve and producing a slower decay (Piran, 2004). Second, a reverse shock is produced and propagates into the slower material when it catches up with the faster one (Kumar & Piran, 2000). This reverse shock could be episodal or long lasting, depending on the profile of the additional matter (Piran, 2004) and is typically observed in the radio or the far IR range.

1.3.3 The spectrum

In the Fireball model the observed Band spectrum (Band et al., 1993) has been explained as synchrotron emission of the fireball relativistic electrons (Rybicki & Lightman, 1979). The typical energy of synchrotron photons depends on the Lorentz
factor of the relativistic electron $\gamma_e$

$$h\nu_s = \gamma \gamma_e \frac{\hbar e B}{m_e c},$$  \hspace{1cm} (1.8)$$

where $\gamma$ is the Lorentz factor of the emitting material, $h$ the reduced Planck constant, $e$ the electron charge and $B$ the magnetic field. The spectral power for a single relativistic electron with initial energy $\gamma_e m_e c^2$ is approximately a power-law with $F_\nu \propto \nu^{1/3}$ up to $\nu_s(\gamma_e)$ and exponentially decays above it. The emitted power can be expressed as

$$P(\gamma_e) = \frac{4}{3} \sigma_T c \gamma^2 \gamma_e^2 \frac{B^2}{8\pi},$$  \hspace{1cm} (1.9)$$

This description is suitable for the adiabatic case, when the electron does not lose a significant fraction of its energy into radiation. This requires $\gamma_e$ to be less than a critical value $\gamma_c$ given by the condition $\gamma \gamma_e m_e c^2 \equiv P(\gamma_c) t$, namely

$$\gamma_c = \frac{6\pi m_e c}{\gamma \sigma_T B^2 t}. \hspace{1cm} (1.10)$$

An electron with $\gamma_e > \gamma_c$ cools down to $\gamma_c$ in an observer time $t$, so its synchrotron frequency varies as $\gamma_e^2$ and its energy as $\gamma_e$. It follows that the spectral power varies as $F_\nu \propto \nu^{-1/2}$ over the frequency range $\nu(\gamma_c) < \nu < \nu(\gamma_e)$.

To define the net spectrum, one needs to integrate over the Lorentz factor distribution of the electrons. The simplest distribution is $N(\gamma_e) \approx \gamma^{-p}$, with $p > 2$. The minimum Lorentz factor of the distribution $\gamma_m$ is defined as

$$\gamma_m = \gamma \epsilon_e \left( \frac{p-2}{p-1} \right) m_p m_e, \hspace{1cm} (1.11)$$

which defines the “typical” synchrotron frequency $\nu_m = \nu_s(\gamma_m)$ ($m_p$ is the proton mass). The lowest part of the overall spectrum is the sum of all emissions from each electron ($F_\nu \propto \nu^{1/3}$). The most energetic electrons, instead, will always be cooling rapidly and emit practically all their energy at their synchrotron frequency, thus $F_\nu \propto \nu^{-p/2}$. The net spectrum in the “fast cooling” regime ($\gamma_m > \gamma_c$) results to be

$$F_\nu = F_{\nu,\text{max}} \begin{cases} (\nu/\nu_m)^{1/3} & , \ \nu < \nu_m \\ (\nu/\nu_m)^{-1/2} & , \ \nu_m < \nu < \nu_c \\ (\nu/\nu_m)^{-1/2} (\nu/\nu_m)^{-p/2} & , \ \nu_c < \nu \end{cases}, \hspace{1cm} (1.12)$$

In the slow cooling “slow cooling” regime ($\gamma_m < \gamma_c$) we have instead

$$F_\nu = F_{\nu,\text{max}} \begin{cases} (\nu/\nu_m)^{1/3} & , \ \nu < \nu_m \\ (\nu/\nu_m)^{(p-1)/2} & , \ \nu_m < \nu < \nu_c \\ (\nu/\nu_m)^{(p-1)/2} (\nu/\nu_m)^{-p/2} & , \ \nu_c < \nu \end{cases}, \hspace{1cm} (1.13)$$

where the normalization is $F_{\nu,\text{max}} = N_e P_{\nu,\text{max}}/(4\pi d_l^2)$, the number of electrons in the post-shock region is $N_e = 4\pi R^3 n/3$ and the total peak spectral power is $P_{\nu,\text{max}} \approx P(\gamma_e)/\nu(\gamma_e)$. 


Fast cooling must take place during the prompt emission, where the internal shocks must be effective to avoid inefficiency problem (Piran, 2004), otherwise there would be no time variability if the cooling time is too long. The transition to the slow cooling regime occurs very likely during the early stages of an external shock (Mészáros & Rees, 1997; Waxman, 1997).

The self-absorption in general should cause a steep cut-off at lower frequencies. In the case of \( \nu_c < \nu_m \) this frequency splits in two: \( \nu_{ac} \) and \( \nu_{sa} \), where an optical depth of unity is produced by non-cooled electrons and all electrons, respectively (Granot et al., 2000; Granot & Sari, 2002). For \( \nu < \nu_{ac} \) the flux is proportional to \( \sim \nu^2 \), while in the intermediate case, \( \nu_{ac} < \nu < \nu_{sa} \), is proportional to \( \sim \nu^{11/8} \). So, ordering all of the possible combinations of the break frequencies, leads to the five spectral regimes shown in Fig. 1.11.

Inverse Compton (IC) scattering may influence the spectrum even if the system is optically thin to Compton scattering (Rybicki & Lightman, 1979). In view of the high energies involved, a photon undergo single IC scattering. The effect of IC depends on the Comptonization parameter \( Y = \gamma^2 \tau_e \) (\( \tau_e \) is the opacity of the electrons) and becomes important when \( Y > 1 \). Its effect is to add an ultrahigh-energy component to the GRB spectrum and to speed up the cooling of the emitting regions and shorten the cooling time by a factor \( Y \) (Piran, 2004).

1.3.4 Jets, collimation and jet-breaks

In the case of non-spherical ejecta, the theory of the afterglow is much more complicated. The commonly called jets correspond to relativistic matter ejected into a cone of opening angle \( \theta \). The ejecta is beamed locally into the jets, regardless to their hydrodynamic evolution, until its Lorentz factor is \( \gamma^{-1} < \theta \) (Sari et al., 1999). When the bulk Lorentz factor drops below \( \theta^{-1} \), the jet material begins to spread sideways. This fact has two effects: an on-axis observer, detects the original jet and then detects a jet-break due to the faster spreading of the emitted radiation. An off-axis observer, that could not detect the former emission, detects an orphan afterglow, namely an afterglow without a preceding GRB.

The sideways expansion causes a change in the hydrodynamic behavior and therefore a break in the light curve (Sari et al., 1999). The beaming outside of the original jet opening angle also causes a break (Panaitescu & Mészáros, 1999; Sari et al., 1999). If the sideways expansion is at the speed of light, then both transitions take place at the same time (Sari et al., 1999). Afterglow observations by Swift have shown a consistent lack of achromatic jet-breaks (i.e. breaks occurring in all energy bands) compared to the Beppo-SAX, or pre-Swift era (De Pasquale et al., 2009). An increasing sample of Swift GRBs show evidence of chromatic breaks, i.e. breaks that are present in the X-ray but not in the optical (De Pasquale et al., 2009). It has been found that jet-breaks are very late in some cases, and there is no evidence of jet-breaks to very late times in other afterglows (Burrows et al., 2009). Recent findings (Racusin et al., 2009; Burrows et al., 2009) suggest that some jet breaks occur at very late times but that the opening angles are typically of order 5–10 degrees.
Figure 1.11: The five possible spectral energy distributions from a relativistic blast-wave that accelerates the electrons to a power-law distribution of energies. In the different scenarios, are described all of the break frequencies and respective fluxes and time series. For a further explanations of each power-law feature see (Granot & Sari, 2002).
1.3.5 The photospheric scenario

In recent years, the identification of thermal components in the spectra of some GRBs detected by the Fermi satellite has led to reconsider the role of the pair breakdown and of a photospheric component immediately before the interaction of the shells.

The initial optically thick $e^+e^-$ plasma accelerates, due to its internal energy, with Lorentz factor $\gamma \propto r$ and co-moving temperature $T' \propto r^{-1}$ until the pairs drop out of equilibrium when $T' \sim 20$ keV. This occurs at the pair photosphere radius $r_p$ above which the scattering optical depth is less than unity. However, if the plasma wind carries enough baryons, described by the baryon load parameter $\dot{M}$, the photosphere occurs at radius $r_{ph} \geq r_p$. This electron scattering photosphere is defined by the transparency condition $\tau' = n'Y \sigma_T r_{ph}/(2\gamma) = 1$, where $n' = L/(4\pi r^2 c^3 \gamma \eta)$ is the co-moving baryon density, $Y$ is the number of electrons per baryon and $\eta = L/Mc^2$ is the dimensionless entropy (Mészáros & Rees, 2000). The Lorentz factor cannot exceed the entropy value $\eta$, so at the saturation radius $r_s$ the plasma continues to coast with a constant $\gamma$ value. There are two distinct cases separated by the critical value

$$\eta_* = \left(\frac{\sigma_T Y L \gamma_0}{4\pi m_p c^3 r_0}\right)^{1/4},$$

(1.14)

where $Y \geq 1$ and $\gamma_0$ and $r_0$ are the Lorentz factor and the radius at the base of the outflow. For $\eta < \eta_*$ the flow remains optically thick above the saturation radius and the photosphere arises in the coasting regime at $r_{ph} > r_s$ defined as

$$r_{ph}^> = \frac{L \sigma_T Y}{4\pi m_p c^3 \eta^{3/2}},$$

(1.15)

and most of the initial thermal energy is converted to the kinetic energy below the photosphere. For $\eta > \eta_*$ the photospheric emission should appear during the accelerating phase of the plasma, below the saturation radius, therefore

$$r_{ph}^< = \left(\frac{L \sigma_T Y r_0^2}{4\pi m_p c^3 \eta \gamma_0^2}\right)^{1/3},$$

(1.16)

For very low baryon loads it follows that $r_{ph}^< < r_p$, but this cannot be possible. In this case the photospheric emission occurs at $r_{ph} = r_p$ and most of the luminosity is radiated at the photosphere. The observed photospheric temperature is given by

$$\frac{T_{ph}}{T_0} \approx \left\{ \begin{array}{ll}
(r_{ph}/r_s)^{-2/3} = (\eta/\eta_*)^{8/3}, & r_{ph} > r_s \\
1, & r_{ph} < r_s
\end{array} \right.,$$

(1.17)

while the observed photospheric thermal luminosity $L_{ph}$ is given by

$$\frac{L_{ph}}{L_0} \approx \left\{ \begin{array}{ll}
(r_{ph}^>/r_s)^{-2/3} = (\eta/\eta_*)^{8/3}, & r_{ph} > r_s \\
1, & r_{ph} < r_s
\end{array} \right..$$

(1.18)
There is the real possibility that the black body photons emitted in the photospheric phase can scatter with relativistic electrons and pairs to higher energies (Mészáros & Rees, 2000; Rees & Mészáros, 2005). Dissipative process in the flow (e.g. magnetic reconnection (Giannios & Spruit, 2005), neutron decay and nuclear collisions between protons and neutrons (Beloborodov, 2003, 2010), internal shock waves (Rees & Meszaros, 1994) and/or jet interaction with stellar envelope (Pe’er et al., 2005; Lazzati & Begelman, 2010)), may accelerate electrons to high energies. In the case of internal shocks (Pe’er et al., 2006), a fraction $\epsilon_p \leq 1$ of these electrons is accelerated to a power-law energy distribution, while the residual electrons have a Maxwellian distribution. These relativistic electrons produce, via IC scattering, photons with energies boosted by a $\gamma^2$ factor having a power-law distribution with energies larger than 1 MeV. If their power-law distribution has a steep slope, we should see a broad thermal peak slightly boosted in energy, by a factor of $\sim 10$.

Summarizing, in the case of dissipative processes in the plasma the expected co-moving frame spectrum is characterized by an up-scattered broad-photospheric-thermal component and an additional synchrotron component originating from shocks outside the photosphere, see e.g. Fig. 1.12. The case of GRB 090902B is particularly striking (Ryde et al., 2011).

### 1.3.6 GRB progenitors

The fireball model does not address the nature of the “inner engine” of GRBs (Mészáros, 2002), but simple considerations on the energetics and time scales lead
to the idea it could be a black hole–massive accretion disk system. This could include mergers, as neutron star-neutron star (NS-NS Eichler et al., 1989; Narayan et al., 1992), neutron star-black hole (NS-BH Paczynski, 1991) or neutron star-white dwarf (NS-WD Fryer et al., 1999b) binaries, and models based on “failed SNe” or Collapsars (Woosley, 1993; Paczynski, 1998; MacFadyen & Woosley, 1999).

It has been suggested by (Narayan et al., 2001) that within the standard model among all the above scenarios Collapsars could produce long bursts and NS-NS (or NS-BH) mergers could produce short bursts. The basic idea is that the duration of the accretion depends on the size of the disks. This means that short bursts must originate from small disks which are naturally produced in mergers, while long bursts require large disks continuously fed by the stellar envelope of the massive star.

An alternative explanation pass through newly formed highly-magnetic NSs: the so-called *magnetars*.

**The Collapsar model.** The connection of some long GRBs with type Ic SNe (Della Valle, 2006), which are characterized by no hydrogen (H) and no or weak helium (He) lines, and their occurrence close to star-forming regions (Paczynski, 1998; Fruchter et al., 2006; Savaglio et al., 2009) offer very strong evidences that long GRBs could be associated with the death of massive stars. In this light, the best candidates are the Wolf-Rayet stars, very massive stars with an hydrogen envelope largely depleted, endowed with a fast rotation (Woosley, 1993). This is the main idea of the Collapsar model. Very massive stars are able to fuse material in their centers all the way to iron (Fe). At this point they cannot continue to generate energy by fusion and collapse forming a BH. Matter from the star around the core rains down towards the center and swirls into a high-density accretion disk. The core carries high angular momentum to form a pair of relativistic jets\(^\text{14}\) out along the rotational axis where the matter density is much lower than in the accretion disk. Jets propagate through the stellar envelope of the star at velocities approaching the speed of light, creating a relativistic shock wave at the front (Blandford & McKee, 1976). If the star is not surrounded by a thick, diffuse hydrogen envelope, the leading shock actually accelerates as the density of the stellar matter it travels through decreases, and by the time it reaches the surface of the star. Eventually, the energy is released in the form of $\gamma$-rays and the Lorentz factor can be $\gamma \geq 100$.

The Collapsar model attempts to explain the time structure of GRBs prompt emission, through the modulation of the jets by their interaction with the surrounding medium, which could produce the variable Lorentz factor necessary for the internal shocks occurrence (Woosley & Bloom, 2006). The relativistic jet propagation through the stellar envelope of a collapsing star is described in (MacFadyen & Woosley, 1999). The collimation of a jet by the stellar mantle was shown to occur analytically (Mészáros & Rees, 2001) and numerically (Zhang et al., 2003). Another prediction of this model is the prolonged activity of the central engine which can potentially contribute to the GRB afterglow (Burrows et al., 2005b). This occurs because the jet and the disk are inefficient at ejecting all the matter in the equa-

\(^{14}\)The progenitor should have a low metallicity, while the Wolf-Rayet stars possess typical solar metallicity. This arguments seem to be contradictory to the formation of a jet in GRBs.
torial plane of the pre-collapse star and some continues to fall back and accrete (MacFadyen et al., 2001).

**NS-NS and NS-BH mergers.** There are three arguments supporting the fact that short GRBs originate from NS-NS (Eichler et al., 1989; Narayan et al., 1992) or NS-BH binary mergers (Paczyński, 1991): (1) there are no SNe associated (Fox et al., 2005; Berger et al., 2005), (2) short GRBs usually have been found in elliptical host galaxies or early type galaxies with low star formation rate (Gehrels et al., 2005; Barthelmy et al., 2005b) and (3) are located in the galactic halos or in the intergalactic space (Watson et al., 2006), since large observed offsets from the centers of their host galaxies have been inferred (Fong et al., 2010). These mergers take place because of the binary orbits decay due to gravitational radiation emission (Taylor & Weisberg, 1989). A merger releases $5 \times 10^{53}$ erg, but most of this energy is in the form of low energy neutrinos and gravitational waves. There is still enough energy available to get a GRB, but a crucial aspect not yet understood is how a merger generates the relativistic wind required to power a burst. In (Eichler et al., 1989) it has been suggested that about one over thousand of these neutrinos annihilates and produces pairs that in turn produces $\gamma$-rays via $\nu \bar{\nu} \rightarrow e^+ e^- \rightarrow \gamma \gamma$. This idea was criticized by different authors because the main problem is that it does not produce enough energy. For example in (Jaroszynski, 1996) it has been pointed out that a large fraction of the neutrinos will be swallowed by the BH that forms.

**Magnetars.** Recently, it has been proposed as a GRB progenitor a newly formed magnetar (Metzger et al., 2007), although the mechanisms of the GRB emission are quite the same. These objects are NSs with an extremely large magnetic field, of the order of $10^{14} - 10^{15}$ G, whose decay should power the emission of very large X and $\gamma$ radiation. Up to now there are 21 possible magnetars known, most of them located in SN Remnants (SNR), suggesting that the progenitor star of this emission is a NS with a very large endowed magnetic field (Kouveliotou, 2003).
Chapter 2

Short and long GRBs within the fireshell model

2.1 A brief review of the fireshell model

2.1.1 The GRB prompt emission in the fireball scenario

A variety of models have been developed to theoretically explain the observational properties of GRBs. One of the most quoted is the fireball model, which has been briefly resumed in the previous Chapter.

An alternative approach, originating in the gravitational collapse to a BH, is the fireshell model (see for a review Ruffini et al., 2010; Ruffini, 2011). There the GRBs originate from an optically thick electron–positron plasma in thermal equilibrium, having a total energy of $E^{\pm}_{\text{tot}}$. Such plasma is initially confined between the radius of a BH $r_h$ and the dyadosphere radius

$$r_{ds} = r_h \left[ 2\alpha \frac{E^{\pm}_{\text{tot}}}{m_e c^2} \left( \frac{\hbar}{m_e c} \right) \right]^{3/4},$$

(2.1)

where, $\alpha$ is the usual fine structure constant, $\hbar$ and $c$ the Planck constant and the speed of light, and $m_e$ the mass of the electron. The lower limit of $E^{\pm}_{\text{tot}}$ coincides with $E_{\text{iso}}$. The condition of thermal equilibrium assumed in this model as shown by Aksenov et al. (2007), differentiates this approach from the alternative ones (e.g. the one by Cavallo & Rees, 1978).

In the fireshell model, the rate equation for the $e^+e^-$ pairs and its dynamics have been given by Ruffini et al. (2000) (the pair-electromagnetic pulse or PEM pulse for short). This plasma engulfs the baryonic material left over in the process of gravitational collapse having mass $M_B$, still keeping thermal equilibrium between electrons, positrons and baryons. The baryon load is measured by the dimensionless parameter $B = M_B c^2 / E^{\pm}_{\text{tot}}$. It was shown (Ruffini et al., 1999) that no relativistic expansion of the plasma can be found for $B > 10^{-2}$. The fireshell is still optically thick and self-accelerates to ultrarelativistic velocities (the pair-electromagnetic-baryonic pulse or PEMB pulse for short, Ruffini et al., 1999). Then the fireshell becomes transparent and the proper-GRB (P-GRB) is emitted (Ruffini et al., 2001b). The
final Lorentz gamma factor at transparency can vary in a vast range between $10^2$ and $10^3$ as a function of $E_{\text{tot}e^+e^-}$ and $B$, see Fig. 2.1. For the final determination it is necessary to integrate explicitly the rate equation of the $e^+e^-$ annihilation process and evaluate, for a given BH mass and a given $e^+e^-$ plasma radius, the reaching of the transparency condition (Ruffini et al., 2000), see Fig. 2.2.

The fireshell scenario does not require any prolonged activity of the inner engine. After transparency, the remaining accelerated baryonic matter still expands ballistically and starts to slow down by the collisions with the CBM, having average density $\langle n_{\text{CBM}} \rangle$. In the standard fireball scenario (Mészáros, 2006), the spiky light curve is assumed to be caused by internal shocks. In the fireshell model the entire extended afterglow emission is assumed to originate from an expanding thin shell enforcing energy and momentum conservation in the collision with the CBM. The condition of a fully radiative regime is assumed (Ruffini et al., 2001b). This, in turn, allows to estimate the characteristic inhomogeneities of the CBM, as well as its average value.

It is appropriate to recall a further difference between our treatment and the ones in the current literature. The complete analytic solution of the equations of motion of the baryonic shell has been developed (Bianco & Ruffini, 2004, 2005a), while in the current literature usually the Blandford - McKee (Blandford & McKee, 1976) self-similar solution has been uncritically adopted (e.g. Mészáros et al., 1993; Sari, 1997, 1998; Waxman, 1997; Rees & Meszaros, 1998; Granot et al., 1999; Panaitescu & Meszaros, 1998; Gruzinov & Waxman, 1999; Van Paradijs et al., 2000; Mészáros, 2002). The analogies and differences between the two approaches have been explicitly pointed out in Bianco & Ruffini (2005b).

From this general approach, a canonical GRB bolometric light curve composed of two different parts is defined: the P-GRB and the extended-afterglow. The relative energetics of these two components, the observed temporal separation between the corresponding peaks, is a function of the above three parameters $E_{\text{tot}e^+e^-}$, $B$, and the average value of the $n_{\text{CBM}}$; the first two parameters are inherent to the accelerator characterizing the GRB, i.e., the optically thick phase, while the third one is inherent to the GRB surrounding environment which gives rise to the extended-afterglow. If one goes to the observational properties of this model of a relativistic expanding shell, a crucial concept has been the introduction of the equitemporal surfaces (EQTS). In this topic, also, our model differs from the ones in the literature for deriving the analytic expression of the EQTS from the analytic solutions of the equations of motion (Bianco & Ruffini, 2005b).

When we have very accurate information on the luminosity and the spectral properties of the source, we assume $E_{\text{tot}e^+e^-} = E_{\text{iso}}$. In other cases, to take into account the observational limitations, due to detector thresholds, distance effects and lack of data, we assume $E_{\text{tot}e^+e^-} > E_{\text{iso}}$.

### 2.1.2 The emission of the P-GRB

The lower limit of $E_{\text{tot}e^+e^-}$ is given by the observed isotropic energy emitted in the GRB, $E_{\text{iso}}$. The identification of the energy of the afterglow and of the P-GRB determines the baryon load $B$ and, from these, it is possible to determine, see Fig. 2.2:
2.1 A brief review of the fireshell model

Figure 2.1: The evolution of the Lorentz $\Gamma$ factor until the transparency emission, for a GRB of a fixed $E_{e^+e^-} = 1.22 \times 10^{55}$ erg (upper panel), and $E_{e^+e^-} = 1.44 \times 10^{49}$ erg, for different values of the baryon load $B$. This computation refers to a mass of the BH of 10 M$_\odot$ and a $\tau = \int_R dr (n_{e^+} + n_{e^-}) \sigma_T = 0.67$, where $\sigma_T$ is the Thomson cross-section and the integration is over the thickness of the fireshell (Ruffini et al., 1999).

the value of the Lorentz $\Gamma$ factor at transparency, the observed temperature as well as the temperature in the comoving frame and the laboratory radius at transparency. We can determine indeed from the spectral analysis of the P-GRB candidate, the temperature $kT_{obs}$ and the energy emitted in the transparency $E_{PGRB}$. The relation between these parameters can not be expressed by an analytical formulation: they can be only obtained by a numerical integration of the entire fireshell equations of motion. In practice we need to perform a trial and error procedure to find the set of values which fit the observations.

The direct measure of the temperature of the thermal component at the transparency offers a very important new information in the determination of the GRB parameters. In the emission of the P-GRB two different phases are present: one corresponding to the emission of the photons when the transparency is reached, and the second is the early interaction of the ultra-relativistic protons and electrons with the CBM. A spectral energy distribution with a thermal component and a non-thermal one should be expected to occur.

2.1.3 The extended-afterglow

The majority of works in the current literature has addressed the analysis of the afterglow emission as due to various combinations of Synchrotron and Inverse Compton processes, see e.g. Piran (2005). It appears, however, that this description is not fully satisfactory (see e.g. Ghirlanda et al., 2003; Kumar & McMahon, 2008; Piran et al., 2009).

We have adopted in the fireshell model a pragmatic approach by making the full use of the knowledge of the equations of motion, of the EQTS formulations (Bianco & Ruffini, 2005a) as well as of the correct relativistic transformations between the comoving frame of the fireshell and the observer frame. These equations, that relate
Figure 2.2: The fireshell temperature in the comoving and observer frame and the laboratory radius at the transparency emission (panels (a) and (b)), the Lorentz $\Gamma$ factor at the transparency (panel (c)) and the energy radiated in the P-GRB and in the afterglow in units of $E_{\text{tot}}^{e^+e^-}$ (panel (d)) as a function of the baryon load $B$, for 4 different values of $E_{\text{tot}}^{e^+e^-}$. 
the four time variables, are necessary for the interpretation of the GRB data. They are: a) the comoving time, b) the laboratory time, c) the arrival time, and d) the arrival time at the detector corrected by the cosmological effects. This is the content of the Relative Space-Time Transformations paradigm, essential for the interpretation of GRBs data (Ruffini et al., 2001a). Such a paradigm made it a necessity to have a global, instead of a piecewise, description of a GRB phenomenon (Ruffini et al., 2001a). This global description led to a new interpretation of the burst structure paradigm (Ruffini et al., 2001b). A new conclusion, arising from the burst structure paradigm, has been that the emission by the accelerated baryons interacting with the CBM is indeed occurring already in the prompt emission phase, just after the P-GRB emission. This is the extended-afterglow emission, which presents in its “light curve” a rising part, a peak, and a decaying tail. Following this paradigm, the prompt emission phase is therefore composed by both the P-GRB emission and the peak of the extended-afterglow.

To evaluate the extended-afterglow spectral properties, we have adopted an ansatz on the spectral properties of the emission in the collisions between the baryons and the CBM in the comoving frame. We have then evaluate all the observational properties in the observer frame by integrating on the EQTS. The initial ansatz of thermal spectrum (Ruffini et al., 2001b), has been recently modified to

$$\frac{dN_\gamma}{dVd\epsilon} = \left(\frac{8\pi}{\hbar^3c^3}\right) \left(\frac{\epsilon}{k_B T}\right)^\alpha \frac{\epsilon^2}{\exp\left(\frac{\epsilon}{k_B T}\right) - 1},$$

where $\alpha$ is a phenomenological parameter defined in the comoving frame of the fireshell (Patricelli et al., 2011), determined by the optimization of the simulation of the observed data. It is well known that in the ultrarelativistic collision of protons and electrons with the CBM, collective processes of ultrarelativistic plasma physics are expected, not yet fully explored and understood (e.g. Weibel instability, see Medvedev & Loeb (1999)). Promising results along this line have been already obtained by Spitkovsky (2008) and Medvedev & Spitkovsky (2009), and may lead to the understanding of the physical origin of the $\alpha$ parameter in Eq. 2.2.

In order to take into due account the filamentary, clumpy and porous structure of the CBM, we have introduced the additional parameter $R$, which describes the fireshell surface filling factor. It is defined as the ratio between the effective emitting area of the fireshell $A_{eff}$ and its total visible area $A_{vis}$ (Ruffini et al., 2002, 2005).

One of the main features of the GRB afterglow has been the observation of hard to soft spectral variation, which is generally absent in the first spike-like emission, which we have identified as the P-GRB, Bernardini et al. (2007); Caito et al. (2009, 2010); De Barros et al. (2011). An explanation of the hard-to-soft spectral variation has been advanced on the ground of two different contributions: the curvature effect and the intrinsic spectral evolution. In particular, in the work of Peng et al. (2011) the authors use the model developed in Qin (2002) for the spectral lag analysis, taking into account an intrinsic Band model for the GRBs and a Gaussian profile for the GRB pulses, in order to take into account the angular effects, and they find that both causes provide a very good explanation for the observed time lags. Within the fireshell model we can indeed explain a hard-to-soft spectral variation very naturally, in the extended-afterglow emission. Since the Lorentz $\Gamma$ factor decreases with time,
the observed effective temperature of the fireshell will drop as the emission goes on, so the peak of the emission will occur at lower energies. This effect is amplified by the presence of the curvature effect, which has origin in the EQTS concept. Both these observed features are considered as the responsible for the time lag observed in GRBs.

2.1.4 The simulation of a GRB light curve and spectrum

The simulation of a GRB light curve and the respective spectrum requires also the determination of the filling factor $\mathcal{R}$ and of the CBM density $n_{\text{CBM}}$. These extra parameters are extrinsic and they are just functions of the radial coordinate from the source. The parameter $\mathcal{R}$, in particular, determines the effective temperature in the comoving frame and the corresponding peak energy of the spectrum, while $n_{\text{CBM}}$ determines the temporal behavior of the light curve. It is found that the CBM is typically formed of “clumps” of width $\sim 10^{15-16}$ cm and average density contrast $10^{-1} \lesssim \langle \delta n/n \rangle \lesssim 10$ centered on the value of 4 particles/cm$^3$ and clumps of masses $M_{\text{clump}} \approx 10^{22-24}$ g. Particularly important is the determination of the average value of $n_{\text{CBM}}$. Values of the order of 0.1-10 particles/cm$^3$ have been found for GRBs exploding inside star forming region galaxies, while values of the order of $10^{-3}$ particles/cm$^3$ have been found for GRBs exploding in galactic halos (Bernardini et al., 2007; Caito et al., 2009; De Barros et al., 2011). The presence of such a clumpy medium, already predicted in pioneering works of Fermi in the theoretical study of interstellar matter in our galaxy (Fermi, 1949, 1954), is by now well-established both from the GRB observations and by additional astrophysical observations, see e.g. the circum-burst medium observed in novae (Shara et al., 1997), or by theoretical considerations on supergiant, massive stars, clumpy wind (Ducci et al., 2009). Interesting are the considerations by Arnett and Meakin (Arnett & Meakin, 2011), who have shown how realistic 2D simulations of the late evolution of a core collapse show processes of violent emission of clouds: there the 2D simulations differ from the one in 1D, which show a much more regular and wind behavior around the collapsing core. Consequently, attention should be given also to instabilities prior to the latest phases of the evolution of the core, possibly giving origin to the cloud pattern observed in the CBM of GRB phenomenon (D. Arnett, private communication).

The determination of the $\mathcal{R}$ and $n_{\text{CBM}}$ parameters depends essentially on the reproduction of the shape of the extended-afterglow and of the respective spectral emission, in a fixed energy range. Clearly, the simulation of a source within the fireshell model is much more complex than simply fitting the $N(E)$ spectrum with phenomenological analytic formulas for a finite temporal range of the data. It is a consistent picture, which has to find the best value for the parameters of the source, the P-GRB (Ruffini et al., 2001b), its spectrum, its temporal structure, as well as its energetics. For each spike in the light curve are computed the parameters of the corresponding CBM clumps, taking into account all the thousands of convolutions of comoving spectra over each EQTS leading to the observed spectrum (Bianco & Ruffini, 2005a,b). It is clear that, since the EQTS encompass emission processes occurring at different comoving times weighted by their Lorentz and Doppler factors,
2.1 A brief review of the fireshell model

the “fitting” of a single spike is not only a function of the properties of the specific CBM clump but of the entire previous history of the source. Any mistake at any step of the simulation process affects the entire evolution that follows and, conversely, at any step a fit must be made consistently with all the previous history: due to the non-linearity of the system and to the EQTS, any change in the simulation produces observable effects up to a much later time. This brings to an extremely complex procedure by trial and error in the data simulation, in which the variation of the parameters defining the source are further and further narrowed down, reaching very quickly the uniqueness. Of course, we cannot expect the latest parts of the simulation to be very accurate, since some of the basic hypothesis on the equations of motion, and possible fragmentation of the shell, can affect the procedure.

In particular, the theoretical photon number spectrum to be compared with the observational data is obtained by an averaging procedure of instantaneous spectra. In turn, each instantaneous spectrum is linked to the simulation of the observed multiband light curves in the chosen time interval. Therefore, both the simulation of the spectrum and of the observed multiband light curves have to be performed together and simultaneously optimized.

2.1.5 The GRBs classification in the fireshell model

Within the fireshell model the presence of the intermediate class of short GRBs with an extended emission does not represent a theoretical challenge in the classification problem of GRBs. In fact it possible to classify bursts according to their values of $B$ and of $\langle n_{CBM} \rangle$.

The “canonical long GRBs”

The canonical long GRBs are characterized by a baryon load varying in the range $3.0 \times 10^{-4} \lesssim B \lesssim 10^{-2}$ and they occur in a typical galactic CBM with an average density $\langle n_{CBM} \rangle \approx 1 \text{ cm}^{-3}$. As a result the extended afterglow is predominant with respect to the P-GRB (see Fig. 2.3).

The “disguised-short GRBs”

After the observations by *Swift* of GRB 050509B (Gehrels et al., 2005), which was declared in the literature as the first short GRB with an extended emission ever observed, it has become clear that all such sources are actually disguised short GRBs (Bernardini et al., 2007). It is conceivable and probable that also a large fraction of the declared short duration GRBs in the BATSE catalog, observed before the discovery of the afterglow, are members of this class. The Baryon load for disguised short GRBs varies in the same range of the long bursts, while the CBM density is of the order of $10^{-3} \text{ cm}^{-3}$. As a consequence, the extended afterglow results in a “deflated” emission that can be exceeded in peak luminosity by the P-GRB (Bernardini et al., 2007). Indeed the integrated emission in the extended afterglow is much larger than the one of the P-GRB (see Fig. 2.14), as expected for long GRBs. With these understandings long and disguised short GRBs are interpreted
Figure 2.3: The energy emitted in the extended afterglow (solid green curve) and in the P-GRB (solid red curve) in units of $E_{\text{tot}}^{e+e-} = 1.77 \times 10^{53}$ erg (dashed horizontal line), as functions of $B$. The crossing point, corresponding to the condition $E_{\text{P-GRB}} \equiv 50\% E_{\text{tot}}^{e+e-}$, marks the division between the genuine short and disguised short and long GRBs region.
in terms of long GRBs exploding, respectively, in a typical galactic density or in a galactic halo density.

Recently, it has been proved the existence of a yet different kind of a disguised short bursts, whose prototypical source is GRB 090510 (Muccino et al., 2013b). These bursts, again, have Baryon load in the range $3 \times 10^{-4} \lesssim B \lesssim 10^{-2}$ and occur in a medium with $\langle n_{CBM} \rangle \approx 10^{3}$ cm$^{-3}$. In the case of GRB 090510 the joint effect of the very dense CBM, $\langle n_{CBM} \rangle \approx 2 \times 10^{3}$ cm$^{-3}$, and the high Lorentz factor at the transparency, $\Gamma_{tr} \sim 700$, compresses in time the emission of the extended afterglow. Therefore its light curve is shortened in time and “inflated” in intensity with respect to the canonical one for disguised short bursts, making it apparently closer to the genuine short class of GRBs (Muccino et al., 2013a). We define, indeed, these GRBs as “disguised-short burst by excess”, being their $\langle n_{CBM} \rangle$ much larger than the canonical one. Correspondingly, we indicate the disguised short with a CBM density typical of the galactic halo environments, $\langle n_{CBM} \rangle \approx 10^{-3}$ cm$^{-3}$, as “disguised-short GRBs by defect”.

The class of “genuine-short GRBs”

Genuine-short GRBs occur in the limit of very low Baryon load, e.g. $B \lesssim 10^{-5}$ with the P-GRB predominant with respect to the extended afterglow. For such small values of $B$ the afterglow peak emission shrinks over the P-GRB and its flux is lower than the P-GRB one (see Fig. 2.4). The thermalization of photon-pairs plasma is reached in a very short timescale at the beginning of the expansion phase and the thermal equilibrium is implemented during the entire phase of the expansion (Aksenov et al., 2007), therefore the spectrum of these genuine short GRBs is expected to be characterized by a significant thermal-like emission. Since the baryon load is small but not zero, in addition to the predominant role of the P-GRB, a non-thermal component originating from the extended afterglow is expected.
Figure 2.5: A space-time diagram illustrating the merger of a NS-NS binary system and the consequent different emissions in the various phases. Before the merging there is the emission of gravitational waves. In the moment of the merging the short GRB is emitted following the fireshell model: A) the overcritical electric field generated in the collapse just outside the event horizon creates a fireshell of $e^+e^-$ plasma that begins to accelerate radially under its own pressure; B) the fireshell, after catching baryons, becomes transparent and the P-GRB is emitted; C) the accelerated baryons interact with the local circum-burst medium (CBM) originating the extended afterglow. What remains after the merging is a rotating ’Kerr’ BH (BH). In such scenario no prolonged emission is expected, neither in optical, nor in X-ray, and nor in GeV energy bands, like in the case of the genuine-short GRB 090227B (Muccino et al., 2013a). This is not the case for GRB 090510, where prolonged GeV/X-ray/optical emission are observed.
2.2 GRB 970228: a disguised-short GRB by defect

The progenitor of such events are very likely binary NS mergers (Muccino et al., 2013a), leading to a ‘Kerr’ BH formation following the time sequence of events described in Figure 2.5. Two sources of this subclass has been identified so far: GRB 090227B (Muccino et al., 2013a) and GRB 140619B (Muccino et al., in preparation).

2.2 GRB 970228: a disguised-short GRB by defect

The discovery by Swift and HETE-2 of an afterglow emission associated possibly with short GRBs opened the new problematic of their nature and classification. This issue has been further enhanced by a new analysis of the BATSE catalog which led to the identification of a new class of GRBs with an occasional softer extended emission lasting tenths of seconds after an initial spikelike emission, called “short GRBs with extended emission” (sGRBs + EE). Within the fireshell model it is possible to identify such sources as disguised-short GRBs by defect. It follows a summary on the prototypical case of GRB 970228, analyzed in details by Bernardini et al. (2007).

2.2.1 Observational properties

GRB 970228 was detected by the Gamma-Ray Burst Monitor (GRBM, 40–700 keV) and Wide Field Cameras (WFC, 2–26 keV) on board BeppoSAX on February 28.123620 UT (Frontera et al., 1998). The burst prompt emission is characterized by an initial 5 s strong pulse followed, after 30 s, by a set of three additional pulses of decreasing intensity (Frontera et al., 1998). Eight hours after the initial detection, the NFIIs on board BeppoSAX were pointed at the burst location for a first target of opportunity observation and a new X-ray source was detected in the GRB error box: this is the first “afterglow” ever detected (Costa et al., 1997). A fading optical transient has been identified in a position consistent with the X-ray transient (Van Paradijs et al., 1997), coincident with a faint galaxy with redshift $z = 0.695$ (Bloom et al., 2001). Further observations by the Hubble Space Telescope clearly showed that the optical counterpart was located in the outskirts of a late-type galaxy with an irregular morphology (Sahu et al., 1997).

The BeppoSAX observations of GRB 970228 prompt emission revealed a discontinuity in the spectral index between the end of the first pulse and the beginning of the three additional ones (Costa et al., 1997; Frontera et al., 1998, 2000). The spectrum during the first 3 s of the second pulse is significantly harder than during the last part of the first pulse (Frontera et al., 1998, 2000), while the spectrum of the last three pulses appear to be consistent with the late X-ray afterglow (Frontera et al., 1998, 2000). This was soon recognized by Frontera et al. (1998, 2000) as pointing to an emission mechanism producing the X-ray afterglow already taking place after the first pulse.
Figure 2.6: BeppoSAX GRBM (40–700 keV, above) and WFC (2–26 keV, below) light curves (green points) compared with the theoretical ones (red lines). The onset of the afterglow coincides with the end of the P-GRB (represented qualitatively by the blue lines).
2.2.2 The analysis of the prompt emission

Fig. 2.6 shows the theoretical fit of *BeppoSAX* GRBM (40–700 keV) and WFC (2–26 keV) light curves of GRB 970228 prompt emission (Frontera et al., 1998). The first main pulse is identified with the P-GRB and the three additional pulses with the afterglow peak emission, consistently with the above mentioned observations by Costa et al. (1997) and Frontera et al. (1998). Such last three pulses have been reproduced assuming three overdense spherical CBM regions (see Fig. 2.7) with a very good agreement (see Fig. 2.6).

The two parameters characterizing the source in the fireshell model are therefore obtained: $E_{e^\pm}^{tot} = 1.45 \times 10^{54}$ erg, $B = 5.0 \times 10^{-3}$. This implies an initial $e^\pm$ plasma created between the radii $r_1 = 3.52 \times 10^7$ cm and $r_2 = 4.87 \times 10^8$ cm with a total number of $e^\pm$ pairs $N_{e^\pm} = 1.6 \times 10^{59}$ and an initial temperature $T = 1.7$ MeV. The theoretically estimated total isotropic energy emitted in the P-GRB is $E_{P-GRB} = 1.1\% E_{e^\pm}^{tot} = 1.54 \times 10^{52}$ erg, in excellent agreement with the one observed in the first main pulse ($E_{P-GRB}^{obs} \sim 1.5 \times 10^{52}$ erg in 2 – 700 keV energy band, see Fig. 2.6), as expected due to their identification. After the transparency point at $r_0 = 4.37 \times 10^{14}$ cm from the progenitor, the initial Lorentz gamma factor of the fireshell is $\gamma_0 = 199$. On average, during the afterglow peak emission phase the values $\langle R \rangle = 1.5 \times 10^{-7}$ and $\langle n_{CBM} \rangle = 9.5 \times 10^{-4}$ particles/cm$^3$ are obtained. This very low average value for the CBM density is compatible with the observed occurrence of GRB 970228 in its host galaxy’s halo (Sahu et al., 1997; Van Paradijs et al., 1997; Panaitescu, 2006) and it is crucial in explaining the light curve behavior.

The values of $E_{e^\pm}^{tot}$ and $B$ determined are univocally fixed by two tight constraints.
Figure 2.8: The theoretical fit of the BeppoSAX GRBM observations (red line, see Fig. 2.6) is compared with the afterglow light curve in the 40–700 keV energy band obtained rescaling the CBM density to $\langle n_{CBM}\rangle = 1$ particle/cm$^3$ keeping constant its shape and the values of the fundamental parameters of the theory $E_{tot}^{\pm}$ and $B$ (black line). The P-GRB duration and luminosity (blue line), depending only on $E_{e\pm}^{tot}$ and $B$, are not affected by this process of rescaling the CBM density (see sec. 2.1).
The first one is the total energy emitted by the source all the way up to the latest afterglow phases (i.e. up to \( \sim 10^6 \) s). The second one is the ratio between the total time-integrated luminosity of the P-GRB and the corresponding one of the whole afterglow (i.e. up to \( \sim 10^6 \) s). In particular, in GRB 970228 such a ratio results to be \( \sim 1.1\% \). However, the P-GRB peak luminosity actually results to be much more intense than the afterglow one (see Fig. 2.6). This is due to the very low average value of the CBM density \( \langle n_{CBM} \rangle = 9.5 \times 10^{-4} \) particles/cm\(^3\), which produces a less intense afterglow emission. Since the afterglow total time-integrated luminosity is fixed, such a less intense emission lasts longer than what is expected for an average density \( \langle n_{CBM} \rangle \sim 1 \) particles/cm\(^3\).

### 2.2.3 Rescaling the CBM density

Now an explicit example is presented in order to probe the crucial role of the average CBM density in explaining the relative intensities of the P-GRB and of the afterglow peak in GRB 970228. The basic parameters of the source, namely the total energy \( E_{\text{tot}} \) and the baryon loading \( B \), are kept fixed in order to fix as well the P-GRB and the afterglow total time-integrated luminosities. Then the CBM density profile given in Fig. 2.7 is rescaled by a constant numerical factor in order to raise its average value to the standard one \( \langle n_{ism} \rangle = 1 \) particle/cm\(^3\). The corresponding light curve is then computed, shown in Fig. 2.8.

There is a clear enhancement of the afterglow peak luminosity with respect to the P-GRB one in comparison with the fit of the observational data presented in Fig. 2.6. The two light curves actually crosses at \( t_d \sim 1.8 \times 10^4 \) s since their total time-integrated luminosities must be the same. The GRB “rescaled” to \( \langle n_{ism} \rangle = 1 \) particle/cm\(^3\) appears to be totally similar to a canonical long GRB.

It is appropriate to emphasize that, although the two underlying CBM density profiles differ by a constant numerical factor, the two afterglow light curves in Fig. 2.8 do not. This is because the absolute value of the CBM density at each point affects in a non-linear way all the following evolution of the fireshell due to the feedback on its dynamics (Bianco & Ruffini, 2005b). Moreover, the shape of the surfaces of equal arrival time of the photons at the detector (EQTS) is strongly elongated along the line of sight (Bianco & Ruffini, 2005a). Therefore photons coming from the same CBM density region are observed over a very long arrival time interval.

### 2.2.4 Conclusions on GRB 970228

The conclusion is that GRB 970228 is a disguised-short GRB by defect. Its baryon loading value is quite near to the maximum \( B \sim 10^{-2} \), and it is typical of the canonical long GRBs. The difference with the canonical long GRBs is the low average value of the CBM density \( \langle n_{CBM} \rangle \sim 10^{-3} \) particles/cm\(^3\) which deflates the afterglow peak luminosity. Hence, the predominance of the P-GRB, coincident with the initial spikelike emission, over the afterglow is just apparent: 98.9% of the total time-integrated luminosity is indeed in the afterglow component. Such a low average CBM density is consistent with the occurrence of GRB 970228 in the galactic halo.
of its host galaxy (Sahu et al., 1997; Van Paradijs et al., 1997), where lower CBM densities have to be expected (Panaitescu, 2006).

2.3 GRB 090227B: the first observed genuine-short GRB

The time-resolved spectral analysis of GRB 090227B, made possible by the Fermi/GBM data (Meegan et al., 2009), allows to identify in this source the missing link between the genuine-short and long GRBs. The genuine-short GRBs class of GRBs is characterized by severely small values of the Baryon load, $B \lesssim 10^{-5}$ (see Fig. 2.14). The energy emitted in the P-GRB is predominant and the characteristic duration is expected to be shorter than a fraction of a second. It follows a summary on the analysis of GRB 090227B performed by Muccino et al. (2013a).

2.3.1 Observations and data analysis in the fireshell model

At 18:31:01.41 UT on 27$^{th}$ February 2009, the Fermi/GBM detector (Guiriec, 2009) triggered and located the short and bright burst, GRB 090227B (trigger 257452263/090227772). The angle from the Fermi/LAT boresight was $72^\circ$. The burst was also located by IPN (Golenetskii et al., 2009a) and detected by Konus/WIND (Golenetskii et al., 2009b), showing a single pulse with duration $\sim 0.2$ s ($20$ keV – $10$ MeV). No X rays and optical observations were reported on the GCN Circular Archive, thus the redshift of the source is unknown. The 64 ms binned GBM light curves show one very bright spike with a short duration of 0.384 s, in the energy range $8$ keV – $40$ MeV, and a faint tail lasting up to 0.9 s after the trigtime $T_0$ in the energy range $10$ keV – $1$ MeV.

Time-resolved spectral analysis

We have performed a time-resolved spectral analysis on selected time intervals of 32 ms in order to correctly identify the P-GRB, namely finding out in which time interval the thermal component exceeds or at least has a comparable flux with respect to the non-thermal (NT) one due to the onset of the extended afterglow. In this way we can single out the contribution of the NT component in the spectrum of the P-GRB. We have performed a time-resolved analysis on time intervals of 32 ms in order to optimize the statistical content in each time bin and to test the presence of BB plus an extra NT component.

Within the first time-resolved interval the BB+PL model has a thermal flux $(11.2 \pm 3.4)$ times bigger than the PL flux; the fit with BB+Band provides $F_{BB} = (0.50 \pm 0.26)F_{NT}$, where the NT component is in this case the Band model. In the second and fourth intervals, the BB+Band model provides an improvement at a significance level of $5\%$ in the fitting procedure with respect to the simple Band model. In the third time interval as well as in the remaining time intervals up to $T_0 + 0.192$ s the Band spectral models provide better fits with respect to the BB+NT ones. This is exactly what we expect from our theoretical understanding:
2.3 GRB 090227B: the first observed genuine-short GRB

Figure 2.9: The 16 ms time-binned NaI-n2 light curves of the P-GRB (left upper panel) and the extended afterglow (left lower panel) and their NaI-n2+BGO-b0 $\nu F_{\nu}$ spectra (on the right, the upper panel for the P-GRB and the lower one for the extended afterglow). The fit of the P-GRB is composed of a BB superimposed by a Band spectrum; the extended afterglow is well fitted by a simple Band function.

from $T_0 - 0.032$ s to $T_0 + 0.096$ s we have found the edge of the P-GRB emission, in which the thermal components have fluxes higher or comparable to the NT ones. The third interval corresponds to the peak emission of the extended afterglow. The contribution of the extended afterglow in the remaining time intervals increases, while the thermal flux noticeably decreases.

We have then explored the possibility of a further rebinning of the time interval $T_{\text{spike}}$, taking advantage of the large statistical content of each time bin. We have plotted the NaI-n2 light curve of GRB 090227B using time bins of 16 ms (see Fig. 2.9, left panels). The re-binned light curves show two spike-like substructures. The duration of the first spike is 96 ms and it is clearly distinct from the second spike. In this time range the observed BB temperature is $kT = (517\pm28)$ keV (see Tab. 2.1) and the ratio between the fluxes of the thermal component and the non-thermal one is $F_{BB}/F_{NT} \approx 1.1$. Consequently, we have interpreted the first spike as the P-GRB and the second spike as part of the extended afterglow. Their spectra are shown in Fig. 2.9, right panels, and the results of the spectral analysis are summarized in Tab. 2.1.
Table 2.1: The results of the spectral analysis of the P-GRB (from \( T_0 - 0.016 \) s to \( T_0 + 0.080 \) s, best fit BB+Band model) and the extended afterglow (from \( T_0 + 0.080 \) s to \( T_0 + 0.368 \) s, best fit Band model) of GRB 090227B in the energy range 8 keV – 40 MeV.

### Estimation of the redshift

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

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

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

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

where \( d_l \) is the luminosity distance of the source and \( S = F \Delta t \) are the fluences. The fluence of the BB component of the P-GRB (see Tab 2.1, first interval) is \( S_{BB} = (1.54 \pm 0.45) \times 10^{-5} \) erg/cm\(^2\). The total fluence of the burst is \( S_{tot} = (3.79 \pm 0.20) \times 10^{-5} \) erg/cm\(^2\) and has been evaluated in the time interval from \( T_0 - 0.016 \) s to \( T_0 + 0.896 \) s. This interval slightly differs from the \( T_90 \) because of the new time boundaries defined after the rebinning of the light curve at resolution of 16 ms. Therefore the observed energy ratio is \( E_{P-GRB}/E_{tot}^{e^+e^-} = (40.67 \pm 0.12)\% \). As is clear from the lower right diagram in Fig. 2.2, for each value of this ratio we have a range of possible parameters \( B \) and \( E_{tot}^{e^+e^-} \). In turn, for each value of them we can determine the theoretical blue-shifted toward the observer temperature \( kT_{blue} \) (see upper left diagram in Fig. 2.2). Correspondingly, for each couple of value of \( B \) and \( E_{tot}^{e^+e^-} \) we estimate the value of \( z \) by the ratio between \( kT_{blue} \) and the observed temperature of the P-GRB \( kT_{obs} \),

\[
\frac{kT_{blue}}{kT_{obs}} = 1 + z .
\]

In order to remove the degeneracy \( [E_{tot}^{e^+e^-}(z), B(z)] \), we have made use of the isotropic
2.3 GRB 090227B: the first observed genuine-short GRB

Energy formula

\[ E_{\text{iso}} = 4\pi d_i^2 \frac{S_{\text{tot}}}{(1+z)} \int_{E_{\text{min}}/(1+z)}^{E_{\text{max}}/(1+z)} E N(E) \frac{dE}{E} \left( \int_{8}^{40000} E N(E) \frac{dE}{E} \right), \]  

\[ \]  

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

We have found the equality at \( z = 1.61 \pm 0.14 \) for \( B = (4.13 \pm 0.05) \times 10^{-5} \) and \( E_{\text{tot},e^+e^-} = (2.83 \pm 0.15) \times 10^{53} \) ergs.

The analysis of the extended afterglow and the observed spectrum of the P-GRB

The arrival time separation between the P-GRB and the peak of the extended afterglow is a function of \( E_{\text{tot},e^+e^-} \) and \( B \) and depends on the detailed profile of the CBM density. For \( B \sim 4 \times 10^{-5} \) the time separation is \( \sim 10^{-3}-10^{-2} \) s in the source cosmological rest frame. In this light, there is an interface between the reaching of transparency of the P-GRB and the early part of the extended afterglow. This connection has already been introduced in literature (Pe’er et al., 2010; Izzo et al., 2012a; Penacchioni et al., 2012).

From the determination of the initial values of the energy, \( E_{e^+e^-} = 2.83 \times 10^{53} \) ergs, of the Baryon load, \( B = 4.13 \times 10^{-5} \), and of the Lorentz factor \( \Gamma_{tr} = 1.44 \times 10^4 \), we have simulated the light curve of the extended afterglow by deriving the radial distribution of the CBM clouds around the burst site (see Fig. 2.10, upper right panel). In particular, each spike in Fig. 2.10 (upper right panel) corresponds to a CBM cloud. The error boxes on the number density on each cloud is defined as the maximum possible tolerance to ensure the agreement between the simulated light curve and the observed data. The average value of the CBM density is \( \langle n_{\text{CBM}} \rangle = (1.90 \pm 0.20) \times 10^{-5} \) particles/cm\(^3\) with an average density contrast \( \langle \delta n/n \rangle = 0.82 \pm 0.11 \). These values are typical of the galactic halos environment. In Fig. 2.10 (upper left panel) we show the NaI-n2 simulated light curve (8–1000 keV) of GRB 090227B and in Fig. 2.10 (lower left panel) the corresponding spectrum in the early \( \sim 0.4 \) s of the emission. The simulation of the extended afterglow starts \( T_a - T_0 \sim 0.017 \) s after the Trigtime \( T_0 \). Without changing the parameters used in the theoretical simulation of the NaI-n2 data, we have extended the simulation up to 40 MeV and we compared the results with the BGO-b0 data (see Fig. 2.10, lower right panel). The theoretical simulation we performed, optimized on the NaI-n2 data alone, is perfectly consistent with the observed data all over the entire range of energies covered by the Fermi/GBM detector, both NaI and BGO.

We turn now to the emission of the early 96 ms. We have studied the interface between the P-GRB emission and the on-set of the extended afterglow emission. In Fig. 2.11 we have plotted the thermal spectrum of the P-GRB and the fireshell simulation (from \( T_0 + 0.015 \) s to \( T_0 + 0.080 \) s) of the early interaction of the extended afterglow. The sum of these two components is compared with the observed spectrum from the NaI-n2 detector in the energy range 8–1000 keV (see Fig. 2.11, left panel). Then, again, from the theoretical simulation in the energy range of the NaI-n2 data, we have verified the consistency of the simulation extended up to 40 MeV.
Figure 2.10: Left upper panel: the NaI-n2 simulated light curve of the extended-afterglow of GRB 090227B; each spike corresponds to the CBM density profile described in the right panel. The zero of the lower x-axis corresponds to the trigger time $T_0$; the zero of the upper x-axis is the time from which we have started the simulation of the extended afterglow, $T_a$, namely 0.017 s after $T_0$. Right upper panel: the radial CBM density distribution of GRB 090227B (black line) and its range of validity (red shaded region). Left lower panel: the simulated photon number spectrum of the extended-afterglow of GRB 090227B (from $T_0 + 0.015$ s to $T_0 + 0.385$ s) in the energy band 8–1000 keV, compared to the NaI-n2 data in the same time interval. Right lower panel: the same simulated spectrum, with the same parameters, extended up to 40 MeV and compared to the NaI-n2 and the BGO-b0 data in the same time interval.
2.3 GRB 090227B: the first observed genuine-short GRB

Figure 2.11: Left panel: the time-integrated (from $T_0 + 0.015$ s to $T_0 + 0.080$ s) fireshell simulation in the energy band 8–1000 keV, dashed blue line, and the BB emission, dashed-dotted green line; the sum of the two components, the solid red line, is compared to the observed P-GRB emission. Right panel: the same considerations including the BGO data up to 40 MeV.

with the observed data all over the range of energies covered by the Fermi/GBM detector, both NaI and BGO. The result is shown in Fig. 2.11 (right panel).

2.3.2 Conclusions on GRB 090227B

GRB 090227B is the missing link between the genuine short GRBs, with the Baryon load $B \lesssim 5 \times 10^{-5}$ theoretically predicted by the fireshell model (Ruffini et al., 2001c,b,a), and the long bursts. Thanks to the excellent data available from Fermi/GBM (Meegan et al., 2009), it has been possible to determine the cosmological redshift, $z = 1.61 \pm 0.14$, as well as the Baryon load, $B = (4.13 \pm 0.05) \times 10^{-5}$, its energetics, $E_{e^+e^-}^{tot} = (2.83 \pm 0.15) \times 10^{53}$ ergs, and the extremely high Lorentz $\Gamma$ factor at the transparency, $\Gamma_{tr} = (1.44 \pm 0.01) \times 10^4$.

We are led to the conclusion (see also Rueda & Ruffini, 2012) that the progenitor of this GRB is a binary NS, which for simplicity we assume to have the same mass, by the following considerations: 1) the very low average number density of the CBM, $\langle n_{CBM} \rangle \sim 10^{-5}$ particles/cm$^3$; this fact points to two compact objects in a binary system that have spiraled out in the halo of their host galaxy; 2) the large total energy, $E_{e^+e^-}^{tot} = 2.83 \times 10^{53}$ ergs, which we can indeed infer in view of the absence of beaming, and the very short time scale of emission point again to two NSs. We are led to a binary NS with total mass $m_1 + m_2$ larger than the NS critical mass, $M_{\text{cr}}$.

In light of the recent NS theory in which all the fundamental interactions are taken into account (Belvedere et al., 2012), we obtain for simplicity in the case of equal NS masses, $m_1 = m_2 = 1.34M_\odot$, radii $R_1 = R_2 = 12.24$ km, where we have used the NL3 nuclear model parameters for which $M_{\text{cr}} = 2.67M_\odot$; 3) the very small value of the baryon load, $B = 4.13 \times 10^{-5}$, is consistent with the above two NSs which have crusts $\sim 0.47$ km thick. The new theory of the NSs, developed in Belvedere et al. (2012), leads to the prediction of GRBs with still smaller baryon load and, consequently, shorter periods. An absolute upper limit on the energy emitted via gravitational waves, $\sim 9.6 \times 10^{52}$ ergs has been inferred in Rueda & Ruffini (2012),
while the explicit calculation has been later performed by Oliveira et al. (2014).

2.4 GRB 090510

GRB 090510, observed both by Fermi and AGILE satellites, is the first bright short-hard Gamma-Ray Burst (GRB) with an emission from the keV up to the GeV energy range. Within the fireshell model, it has been possible to identify such source as a disguised-short GRB by excess, thanks to the joint effect of the very dense CBM and the high Lorentz factor at the transparency, $\Gamma_{tr} \sim 700$, which lead to an extended afterglow with $T_{90} < 2$ s (Muccino et al., 2013b).

2.4.1 Observations and Data Analysis

At 00:22:59.97 UT on 10th May 2009, the Fermi/GBM detector (Guiriec et al., 2009) triggered and located the short and bright burst, GRB 090510, which was also detected by Swift/BAT (Hoversten et al., 2009), Fermi/LAT (Ohno & Pelassa, 2009; Omodei et al., 2009), AGILE (Longo et al., 2009), Konus/WIND (Golenetskii et al., 2009c), and Suzaku-WAM (Ohmori et al., 2009). Optical observations by VLT/FORS2 located the host galaxy of GRB 090510 at the redshift of $z = 0.903 \pm 0.003$ (Rau et al., 2009). The offset with respect to the Nordic Optical Telescope refined afterglow position (Olofsson et al., 2009) corresponds to 5.5 kpc.

We have analyzed the Fermi/GBM data from NaI-n6 (8 – 900 keV) and BGO-b1 (260 keV – 40 MeV) detectors and the LAT data in the energy range 100 MeV – 30 GeV.

The light curve of GRB 090510 is composed of two different episodes, 0.5 s apart. The first episode, from $T_0 - 0.064$ s to $T_0 + 0.016$ s (in the following $\Delta T_1$; $T_0$ is the trigger time), has not been considered by Ackermann et al. (2010), Giuliani et al. (2010) and Guiriec et al. (2010) because of the small content of detected photons. Even though the statistical content of this first episode is very poor, we show its great relevance for the theoretical analysis, since it can be identified with the P-GRB. The second episode can be interpreted as the extended afterglow. In the statistical analysis of the first episode, we have considered power-law (PL), black body (BB) plus PL, Band (Band et al., 1993), Comptonized (Compt), Band+BB and Compt+BB models. Following the statistical analysis for nested models by Guiriec et al. (2010), models more complicated than the simplest Band and Compt are singled out. The direct statistical comparison between BB+PL and PL models gives a significance level of 3%. This means that the BB+PL model improves the fit of the data of the first episode with respect to the PL model, which is excluded at 97% confidence level. The simple Band model has an unconstrained $\alpha$ index and a large error on the energy peak $E_p$, as well as in the case of the Compt model, for which the total flux is underestimated with respect to the Band and BB+PL models. The quality of data does not allow us to favor the BB+PL model versus the Compt one from a pure statistical analysis. In order to clarify such a fundamental issue, it is appropriate that future space missions with larger collecting area and X/γ-rays timing be flown in the near future. From our theoretical interpretation the BB+PL, being equally probable than the Compt model, is adopted for its physical
2.4 GRB 090510

Figure 2.12: Upper panels: on the left, the 16 ms time-binned NaI-n6 light curve and, on the right, the NaI-n6+BGO-b1 νFν spectrum (best fit BB+PL) in the ΔT1 time interval. Lower panels: on the left, the 16 ms time-binned NaI-n6 light curve and, on the right, the NaI-n6+BGO-b1 νFν spectrum (best fit Band+PL) in the ΔT2 time interval.

meaning and because it is not ruled out by the data. The BB observed temperature is $kT_{\text{obs}} = (34.2 \pm 7.5) \text{ keV}$ (see Fig. 2.12, upper right panel) and the total energy of the first episode is $E_1 = (2.28 \pm 0.39) \times 10^{51} \text{ erg}$.

We have then analyzed the second episode in the time interval from $T_0 + 0.400 \text{ s}$ to $T_0 + 1.024 \text{ s}$ (in the following ΔT2). The best fit in the energy range 8 keV – 40 MeV is Band+PL (Ackermann et al., 2010) or, alternatively Compt+PL (Giuliani et al., 2010; Guiriec et al., 2010). The results are shown in Fig. 2.12, and more details are in Muccino et al. (2013b). Including the LAT data, the spectrum is again best fitted by Band+PL, with the PL observed up to 30 GeV (Ackermann et al., 2010). The total energy is $E_2 = (1.08 \pm 0.06) \times 10^{53} \text{ erg}$.

2.4.2 Theoretical interpretation

In the fireshell model (Ruffini et al., 2001c,b,a) GRBs originate from an optically thick $e^+e^-$ plasma created by vacuum polarization processes in the gravitational collapse to a BH (Damour & Ruffini, 1975; Ruffini et al., 2010). The dynamics of such an expanding plasma in the optically thick phase is described by its total energy $E_{e^+e^-}^{\text{tot}}$ and by the amount of the engulfed baryons $B$. The spherical symmetry of
the system is assumed. The canonical GRBs light curve is then characterized by a first emission due to the transparency of the $e^+e^-$-photon-baryon plasma, the P-GRB, followed by a multi-wavelength emission, the extended afterglow, due to the collisions, in a fully radiative regime, between the accelerated baryons and the CBM. The radius at which the transparency occurs, $r_{tr}$, the theoretical temperature blue-shifted toward the observer $kT_{blue}$ and the Lorentz factor $\Gamma_{tr}$ as well as the amount of the energy emitted in the P-GRB are functions of $E_{e^+e^-}^{tot}$ and $B$ (Ruffini et al., 2001b, 2009). The structures observed in the extended afterglow of a GRB are described by two quantities associated with the environment: the CBM density profile $n_{CBM}$, which determines the temporal behavior of the light curve, and the filling factor $R$, which assumes spherically distributed clouds and the value of the filling factor $F$, determined by matching the theoretically simulated energy $E_{tr}$ and temperature $kT_{th} = kT_{blue}/(1+z)$ of the P-GRB with the ones observed in the faint pulse, $E_1$ and $kT_{obs}$. The results of our simulation are the following:

$$\Gamma_{tr} = (6.7 \pm 1.6) \times 10^2 \ , \ r_{tr} = (6.51 \pm 0.92) \times 10^{13} \text{ cm} \ ,$$

$$E_{tr} = (2.94 \pm 0.50)\% E_{e^+e^-}^{tot} \ , \ kT_{th} = (34.2 \pm 7.5) \text{ keV}. \tag{2.6}$$

The theoretically predicted P-GRB energy slightly differs from the observed $E_1 = (2.28 \pm 0.39) \times 10^{51} \text{ erg} = (2.08 \pm 0.35)\% E_{iso}$, since emission below the threshold is expected between the small precursor and the main emission (see light curves in Fig. 2.12), thus the value of $E_1$ is certainly underestimated.

In the following analysis we focus our attention on the main emission. Since in $\Delta T_2$ no evidence of a thermal component has been found (see Fig. 2.12, lower right panel), we have interpreted this emission as the extended afterglow. Using the above values of $E_{e^+e^-}^{tot}$ and $B$, we have simulated the light curve of the extended afterglow by defining the radial number density distribution of the CBM (assuming spherically distributed clouds) and the value of the filling factor $R$, following a trial and error procedure to reproduce the pulses observed in the light curve and the corresponding spectrum. The errors on the densities and the filling factors are obtained varying them within the observational errors; typically the errors are about 10% of the value. The average value is indeed very high, $\langle n_{CBM} \rangle = (1.85\pm0.14) \times 10^3$ particles/cm$^3$, assuming spherically distributed clouds (see Fig. 2.13, upper plot). Basically this high average density is due to the second and the third brightest spikes of the light curve (see Fig. 2.13, middle panel), where the density of the clouds is $\sim 2 \times 10^4$ particles/cm$^3$ (see Muccino et al., 2013b). The filling factor assumes values $1.5 \times 10^{-10} \leq R \leq 3.8 \times 10^{-8}$ (see Muccino et al., 2013b). Correspondingly, the values of the densities of the filaments $n_{fil}$ are estimated (see Muccino et al.,
Figure 2.13: In the upper panel the radial CBM density distribution of GRB 090510 (red solid line) with its uncertainty (light red shaded region) and the mean value (black dashed line) are shown. The simulated NaI-n6 light curve (8–1000 keV) of the extended afterglow (middle panel) and the corresponding spectrum of the early $\sim 0.4$ s of the emission in the energy range 8 keV – 40 MeV (lower panel) are consequently obtained.
Figure 2.14: **Left panel:** the energy emitted in the extended afterglow (green curve) and in the P-GRB (red curve) in units of $E_{\text{tot}}^{\text{ext}}$ are plotted as functions of $B$. The values of $B$ of GRB 090510 (in blue) and of the genuinely short GRB 090227B (in black) are compared. **Right panel:** the 50 ms time-binned NaI-n6 light curve (green data) and the extended afterglow simulations corresponding to CBM average densities of a “disguised short GRB by excess” with $\langle n_{\text{CBM}} \rangle \approx 10^3$ particles/cm$^3$ (red curve), of a canonical long GRB with $\langle n_{\text{CBM}} \rangle = 1$ particle/cm$^3$ (blue curve), and of a “disguised short GRB by defect” with $\langle n_{\text{CBM}} \rangle = 10^{-2}$ particles/cm$^3$ (purple curve). For larger densities the extended afterglow compresses in time and “inflates” in intensity.

2013b). In Fig. 2.13 we show also the simulated extended afterglow light curve from the NaI-n6 detector (middle panel) and the corresponding spectrum of the early $\sim 0.4$ s of the emission (lower panel) in the energy range 8 keV – 40 MeV. The last part of the simulation requires a more detailed 3-dimensional code to take into due account the distribution of the CBM.

### 2.4.3 Conclusions on GRB 090510

We list our conclusions. 1) The simulated spectrum of the extended afterglow in the time interval $\Delta T_2$, considered in the analysis by Ackermann et al. (2010), is in excellent agreement with the one in Fig. 2.12 in the sub-MeV and in the MeV region. The baryon load $B = (1.45 \pm 0.28) \times 10^{-3}$ used in this simulation has been determined from the analysis of the first episode, which has been identified with the P-GRB. The current quality of the data does not allow us to properly distinguish between BB+PL and Compt spectral models. From our theoretical interpretation, BB+PL model was adopted, since it is not ruled out by the data. Such a fundamental issue will be further clarified by future space missions with larger collecting area and X/$\gamma$-rays timing. 2) We have found that GRB 090510 occurs in an over-dense medium with an average value of $\langle n_{\text{CBM}} \rangle \approx 10^3$ particles/cm$^3$ (for spherically symmetric distributed clouds). This high CBM density and the small value of the filling factor, $1.5 \times 10^{-10} \leq \mathcal{R} \leq 3.8 \times 10^{-8}$, leads to local over-dense CBM clouds, in the form of filaments, bubbles and clumps, with a range of densities $n_{\text{fil}} = n_{\text{CBM}}/\mathcal{R} \approx (10^6 - 10^{14})$ particles/cm$^3$. 3) The joint effect of the high value...
of the Lorentz factor, $\Gamma_{tr} = (6.7 \pm 1.6) \times 10^2$, and the high density compresses in time the emission of the extended afterglow. Therefore its light curve is shortened in time and “inflated” in intensity with respect to the canonical one for disguised short bursts (see Fig. 2.14, lower panel), making it apparently closer to the genuine short class of GRBs (Muccino et al., 2013a).
Short and long GRBs within the fireshell model
Chapter 3

Evidence for multi-components and a new distance indicator in GRBs

3.1 GRB 090618

3.1.1 Observations and data analysis

On 18th of June 2009, the Burst Alert Telescope (BAT) on board the Swift satellite (Gehrels et al., 2009) triggered on GRB 090618 (Schady et al., 2009). After 120 s the X-Ray Telescope (XRT) (Burrows et al., 2005a) and the UltraViolet Optical Telescope (UVOT) (Roming et al., 2005) on board the same satellite, started the observations of the afterglow of GRB 090618. GRB 090618 was observed also by the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite (Meegan et al., 2009). The redshift of the source is $z = 0.54$ and it was determined at the Lick observatory (Cenko et al., 2009). Given the redshift, and the distance of the source, the emitted isotropic energy in the 8 - 10000 keV energy range is computed using the Schaefer formula (Schaefer, 2007): using the fluence in the (8-1000 keV) as observed by Fermi/GBM, $S_{\text{obs}} = 2.7 \times 10^{-4}$ (McBreen, 2009), and the ΛCDM cosmological standard model $H_0 = 70 \text{ km/s/Mpc}, \Omega_m = 0.27, \Omega_\Lambda = 0.73$, for the isotropic energy emitted the value of $E_{\text{iso}} = 2.90 \times 10^{53}$ erg is obtained. Thanks to the complete data coverage of the optical afterglow of GRB 090618, the possible presence of a SN underlying the emission of the GRB 090618 optical afterglow (Cano et al., 2011) was reported.

Izzo et al. (2012a) divide the entire GRB in two main episodes: one, named Episode 1, lasting the first 50 s; and the other, named Episode 2, lasting from 50 to 151 s after the GRB trigger time, see Fig. 3.1. They show that the first 50 s of emission, corresponding to the first episode, are well fitted by a Band model as well as a black-body with an extra power-law model. The same happens for the first 9 s of the second episode (from 50 to 59 s after the trigger time). For the subsequent time interval corresponding to the three main peaks in the light curve, only the Band model fits the spectrum with good accuracy, with the exception of the first main spike (compare the values of $\chi^2$ in the table).
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Figure 3.1: The two episode nature of GRB 090618.

The result of this analysis points to a different emission mechanism in the first 50 s of GRB 090618 and in the following 9 s. A sequence of very large pulses follow, which spectral energy distribution is not attributable either to a blackbody or a blackbody and an extra power-law component.

3.1.2 Analysis in the fireshell scenario: a multi-component GRB

Izzo et al. (2012a) proceeded to identify the P-GRB within the emission between 50 and 59 s, since they found a clear blackbody component in this early second-episode emission. The isotropic energy of the Episode 2 is $E_{\text{iso}} = (2.49 \pm 0.02) \times 10^{53}$ ergs. The simulation within the fireshell scenario is done assuming $E_{\text{tot}}^{+e-} \equiv E_{\text{iso}}$. Within the fireshell model, from and the observed temperature $kT = 29.22 \pm 2.21$ the value of the baryon load is then derived: $B = 1.98 \pm 0.15 \times 10^{-3}$. The bulk Lorentz factor at the transparency results $\Gamma_{tr} = 495$.

The extended-afterglow starts at the above given radius of the transparency, with an initial value of the Lorentz $\Gamma$ factor of $\Gamma_0 = 495$. In order to simulate the extended-afterglow emission, the determination of the radial distribution of the CBM around the burst site is needed, which results characterized by a mean value of $\langle n_{\text{CBM}} \rangle > = 0.6$ part/cm$^3$. Fig. 3.2 shows the simulated light curve (8-1000 keV) of GRB and the corresponding spectrum. The second episode, lasting from 50 to 151 s, agrees with a canonical GRB in the fireshell scenario.

3.1.3 A different emission process in the first episode

Izzo et al. (2012a) have performed a detailed time-resolved analysis of the first episode, considering different time bin durations in order to have a good statistic in the spectra and to take into account the sub-structures in the light curve. The best
Figure 3.2: Simulated light curve (left panel) and time integrated spectrum (right panel) of the extended-afterglow of GRB 090618.

Figure 3.3: Left panel: Evolution of the $kT$ observed temperature of the blackbody component. The blue line corresponds to the fit of the time evolution of the temperature with a broken power-law function. It is evident a break time $t_b$ around 11 s after the trigger time, as obtained from the fitting procedure. Right panel: Evolution of the radius of the first episode emitter.

fit of the data results a blackbody plus a power-law component. The analysis has been summarized in Figs. 3.3.

Particularly interesting is the clear evolution in the time-resolved spectra, corresponding to the blackbody and power-law component. In particular the $kT$ parameter of the blackbody presents a strong decay, with a temporal behavior well described by a double broken power-law function, see Fig. 3.3. The results presented in Figs. 3.3 point to a rapid cooling of the thermal emission with time of the Episode 1.

We turn now to the estimate of an additional crucial parameter for the identification of the nature of the black-body component: the radius of the emitter $r_{em}$. The first episode has been proven to be not an independent GRB, not a part of a GRB. It is therefore possible to provide the estimate of the radius of the emitter from non-relativistic considerations, just corrected for the cosmological redshift $z$. Assuming a standard cosmological model ($H_0 = 70$ km/s/Mpc, $\Omega_m = 0.27$ and
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\( \Omega_\Lambda = 0.73 \) for the estimate of the luminosity distance \( D \), the evolution of the radius of the surface emitting the black-body \( r_{\text{em}} \) as a function of time is computed and then given in Fig. 3.3. An average velocity of \( \bar{v} = 4067 \pm 918 \text{ km/s} \), \( R^2 = 0.91 \) is estimated in these first 10 s of emission. In Episode 1 the observations lead to a core of an initial radius of \( \sim 12000 \text{ km} \) expanding in the early phase with a sharper initial velocity of \( \sim 4000 \text{ km/s} \). The effective Lorentz \( \Gamma \) factor is very low, \( \Gamma - 1 \sim 10^{-5} \).

3.1.4 Conclusions on GRB 090618

GRB 090618 is one of the closest \((z = 0.54)\) and most energetic \((E_{\text{iso}} = 2.9 \times 10^{53} \text{ ergs})\) GRBs up to date. These circumstances have produced an unprecedented set of high quality data as well as the coverage of the instantaneous spectral properties and of the time variability in luminosity of selected bandwidth of the source. In addition there is also the possibility of identifying an underlying SN event from the optical observations (Cano et al., 2011).

The application of the fireshell scenario to GRB 090618 supports the hypothesis that it is actually composed of two different episodes is supported: Episode 1, lasting from 0 to 50 s, and Episode 2, from 50 s to 151 s after the trigger time. While Episode 2 can be interpreted as a canonical GRB, Episode 1 cannot be either a GRB nor a part of a GRB. By a time-resolved spectral analysis of Episode 1 the instantaneous spectra by a blackbody plus an extra power-law component have been fitted. The temperature of the blackbody appears to have a regular dependence with time, described by two power-law functions: a first power-law with decay index \( a_{kT} = -0.33 \pm 0.07 \) and the second one with \( b_{kT} = -0.57 \pm 0.11 \). All these features follow precisely some of the results obtained by Felix Ryde and his collaborators (Ryde & Pe'er, 2009), where the authors analyzed selected temporal episodes in some GRBs observed by BATSE. Assuming a standard cosmological model the evolution of the radius of the surface emitting the blackbody \( r_{\text{em}} \) as a function of time has been computed, which results expanding with non-relativistic velocity \((\Gamma - 1 \sim 10^{-5})\).

3.2 GRB 101023

3.2.1 Observations

On 23 October 2010 the Fermi/GBM (Briggs, 2010) detector was triggered by a source quite similar to GRB 090618 (Izzo et al., 2012a), with a trigger time of 309567006.726968 (in MET seconds). The burst was also detected by BAT (Saxton et al., 2010), onboard the Swift satellite, with a trigger time of 436981 (in MET seconds) and the following location coordinates: \( RA(J2000) = 21h11m49s, \ Dec(J2000) = -65^\circ23'37'' \) with an uncertainty of 3 arcmin. The Swift/XRT detector (Page & Saxton, 2010) has also observed this source from 88 s to 6.0 ks after the BAT trigger. Moreover, there have been detections in the optical band by the Gemini telescope (Levan et al., 2010).

The GBM light curve (Fig. 3.4) shows two major pulses. The first one starts at the trigger time and lasts 45 s. It consists of a small peak that lasts about 10 s,
followed by a higher emission that decays slowly with time. The duration, as well as the topology of this curve, leads to think that this may not be a canonical GRB, in analogy with the Episode 1 of GRB 090618 (Izzo et al., 2012a). The second pulse starts at 45 s after the trigger time and lasts 44 s. It presents a peaky structure, composed of a short and weak peak at the beginning, followed by several bumps, big not only in magnitude but also in duration. This second phase is identified as a canonical GRB, namely the Episode 2 of GRB 101023 (Penacchioni et al., 2012).

### 3.2.2 Pseudo-redshift determination

The redshift of this source is unknown, owing to the lack of data in the optical band. However, to constrain it, Penacchioni et al. (2012) employed three different methods, mentioned below.

**Method 1: nH column density**

A first estimate of the redshift has been made using the method developed in Grupe et al. (2007b) work, where the authors comment on the possible relation between the absorption column density in excess of the galactic absorption column density $\Delta N_H = N_{H,fit} - N_{H,gal}$ and the redshift $z$. An upper limit for the redshift of 3.8 is obtained.
Evidence for multi-components and a new distance indicator in GRBs

Method 2: Amati relation

Another method of constraining the redshift is the Amati relation, which relates the isotropic energy $E_{\text{iso}}$ emitted by a GRB to the peak energy in the rest frame $E_{p,i}$ of its $\nu F_\nu$ electromagnetic spectrum (see Amati et al., 2009, and references therein). The analysis started up under the hypothesis that Episode 2 is a long GRB. The values of $E_{p,i}$ and $E_{\text{iso}}$ for different given values of $z$ have been computed. The Amati relation is fulfilled by Episode 2 for $0.3 < z < 1.0$.

Method 3: Empirical method for the pseudo-redshift

An empirical method following Atteia (2003) and Pelangeon et al. (2006), which can be used as a redshift indicator, has been also tried. This method consists in determining a pseudo-redshift from the GRB spectral properties. The application of this treatment to Episode 2 of GRB 101023 gives a value for the redshift of $z = 0.9^{+0.45}_{-0.3}$. This result agrees with the redshift range found from the Amati relation for Episode 2 and is also consistent with the upper limit determined with method 1.

3.2.3 Analysis of the Episode 1

The temperature of the black-body component is plotted in Fig. 3.5 as a function of time, for the first 20 s of emission. Its evolution in the first 20 s of emission, in agreement with Ryde (2004), can be reproduced by a broken power-law behavior, with $\alpha = -0.47 \pm 0.34$ and $\beta = -1.48 \pm 1.13$ being the indices of the first and second power law, respectively. The radius of the most external shell with time is also plotted in Fig. 3.5, right panel. The radius remains almost constant (in fact it increases, but only slightly). From this it is possible to see that the plasma is expanding at non-relativistic velocities. This fact confirms the non-GRB nature for the first episode (Penacchioni et al., 2012).
3.2 GRB 101023

Figure 3.6: Simulation within the fireshell model of the light curve (left panel) and the spectrum (right panel) of the extended afterglow of GRB 101023.

3.2.4 Analysis of the Episode 2 as a canonical GRB

To identify the P-GRB, (Penacchioni et al., 2012) performed the following procedure: knowing that the P-GRB consists of a black-body emission, a detailed spectral analysis has been performed every 1 s with the black-body model to see the behavior of the black body component, i.e where the black body component dominates. That will indicate more precisely the time range and duration of the P-GRB. In fact, only the first 5 s of emission have a marked black body component, with a typical pulse shape. The emission that follows seems not to be related to the P-GRB, but to the extended afterglow. So the conclusion is that Episode 2 is indeed a GRB and the first 5 s of emission are the P-GRB.

From the simulation for Episode 2 it was found, at the transparency point, a value of the laboratory radius of \(1.34 \times 10^{14}\) cm, a theoretically predicted temperature that after cosmological correction gives \(kT_{th} = 13.26\) keV, a Lorentz Gamma factor of \(\Gamma = 260.48\), a P-GRB laboratory energy of \(2.51 \times 10^{51}\) erg and a P-GRB observed temperature of \(28.43\) keV. A value for the dyadosphere energy of \(E_{\text{dyad}}^{\pm} = 1.8 \times 10^{53}\) erg and a baryon loading of \(B = 3.8 \times 10^{-3}\) have been adopted. The simulated light curve and spectrum of Episode 2 are shown in Fig. 3.6.

The X-ray afterglow as a possible redshift estimate

We have seen that GRB 090618 and GRB 101023 share similar properties. They seem to be composed of two different emission episodes, the first being connected to a quasi-thermal process, while the second is the canonical GRB.

Anyway, if both GRBs were created originated by the same physical mechanism and since the energetics are very similar, considering the value \(z = 0.9\) for GRB 101023, we can expect similar luminosity behavior for the X-ray afterglow. Penacchioni et al. (2012) attempted a simple test that compared the observed X-ray afterglow of both GRBs as if they were located at the same redshift. Since there are different spectral components in the GRB X-ray afterglow, pseudo-redshift light curves have been built for both these different emissions. Thanks to the Swift/XRT observations, it is known that the early X-ray afterglow of both GRBs shows a canon-
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An X-ray light curve of GRB 090618 has been built as if it was observed at redshift $z = 0.9$, which is the estimate for the redshift of GRB 101023. The Swift/XRT (which operates in the 0.3–10 keV energy range) light curve of GRB 090618 (Evans et al., 2007a, 2009b) corresponds to the emission in the rest frame at $z = 0.54$ in the energy range 0.462–15.4 keV, while for GRB 101023 the XRT window corresponds to the range 0.57–19 keV. The emission of GRB 090618 must be obtained in this last energy range, in order to compare the two light curves. At first it has been assumed that the spectrum of each time interval is best fitted by a simple power-law model. Then, the emission of the afterglow of GRB 090618 has been extrapolated in the 0.57–19 keV energy range by considering the ratio between the number of photon counts in both energy ranges. This value corresponds to a conversion factor, which has been considered for scaling the intensity of the light curve. Finally, the time interval of emission of GRB 090618 has been amplified by a term $(1 + z_{101023})/(1 + z_{090618})$, obtaining as a final result the afterglow light curve of GRB 090618 as if it was observed by XRT at redshift 0.9, see Fig. 3.7. It is, most remarkably, a perfect superposition of the light curve emission of both GRBs. This evidence delineates three important aspects:

- the X-ray afterglow of both GRBs clearly confirms a common physical mechanism for these GRBs;

- there is ample convergence and redundancy with different methods of determining a value of redshift $z = 0.9$ for GRB 101023. There has also been the unexpected result pointing to the late afterglow as a possibly independent redshift estimator;

- the redshift of GRB 101023 derived by the superposition of the two afterglow curves is consistent with the value of $z = 0.9$, which was found before.

This last point led to another analysis consisting in the redshift-translation of the X-ray afterglow of GRB 090618 considering different values for the redshift. Following the same procedure and considering five different values for the redshift, $z = (0.4, 0.6, 1.2, 2, 3)$, the X-ray emission of GRB 101023 is compatible with the X-ray afterglow of GRB 090618 as if it bursted between $z = 0.6$ and $z = 1.2$, see Fig. 3.7. Then the conclusion is that the previous estimate for the redshift of GRB 101023 of $z = 0.9$ is very reliable (Penacchioni et al., 2012).

3.2.5 Conclusions on GRB 101023

1) A striking similarity between GRB 101023 and GRB 090618 has been found, as can be seen from the light curves. Following the study of GRB 090618, the emission is divided into two episodes: Episode 1, which lasts 45 s, presents a smooth emission without spikes that decays slowly with time. Episode 2, of 44 s of duration, presents a spiky structure, composed of a short and faint peak at the beginning, followed by
3.2 GRB 101023

Figure 3.7: Left panel: The X-ray afterglow of GRB 090618 (blue data) as if it was observed at redshift \( z = 0.9 \) (see text). The X-ray afterglow of GRB 101023 is also shown as comparison (red data). Data on GRB 101023 are missing between \( \sim 200 \) s and 3550 s. Where data are present, the superposition is striking. Right panel: The X-ray afterglow of GRB 090618 as if it was observed at different redshifts \( z = (0.4, 0.6, 1.2, 2, 3) \), where each color corresponds to a different redshift. The X-ray afterglow of GRB 101023 is also shown for comparison (red data).

several intense bumps, after which there is a fast decay with time. Episode 2 has all the characteristics of a canonical long GRB.

2) In the absence of a direct measurement of the redshift to the source, it has been inferred from several empirical methods. First, following the work of Grupe et al. (2007b), which considers the hydrogen equivalent column density in the direction of the source, an upper limit of \( z < 3.8 \) is obtained. Then, from the peak energy \( E_{\text{peak}} \) and using the Amati relation under the hypothesis that Episode 2 is a canonical long GRB, the value of the redshift is constrained to be between 0.3 and 1.0. Finally, using the parameters of the Band model and following the work of Atteia (2003), a value of the redshift of \( z = 0.9 \pm 0.084(\text{stat.}) \pm 0.2(\text{sys.}) \) is determined. The three methods are consistent, so the assumed redshift of GRB 101023 is \( z = 0.9 \).

3) Episode 1 is fitted with a black-body plus a power-law model and the evolution of the black-body component with time is computed. The observed temperature decreases during the first 20 s following a broken power law: the first with index \( \alpha = -0.47 \pm 0.34 \) and the second with index \( \beta = -1.48 \pm 1.13 \). From the knowledge of the redshift, the flux emitted by Episode 1 can be evaluated, and from the observed black-body temperature, the radius of the black-body emitter and its variation with time can be inferred. The radius increases during the first 20 s of emission, with a non-relativistic velocity \( \sim 1.5 \times 10^4 \) km/s, in analogy with GRB 090618.

4) From the knowledge of the redshift of the source, Episode 2 is analyzed within the fireshell model. A total energy \( E_{\text{iso}} = 1.79 \times 10^{53} \) erg and a P-GRB energy of \( 2.51 \times 10^{54} \) erg are determined and then used to simulate the light curve and spectrum with the numerical code GRBsim. The simulation gives a baryon load \( B = 3.8 \times 10^{-3} \) and, at the transparency point, a value of the laboratory radius of \( 1.34 \times 10^{14} \) cm, a theoretically predicted temperature of \( kT_{\text{th}} = 13.26 \) keV (after cosmological correction) and a Lorentz gamma factor of \( \Gamma = 260.48 \), confirming that Episode 2 is indeed a canonical GRB.

5) Finally, the following test is performed. Owing to the similarities between
GRB 101023 and GRB 090618 regarding morphology and energetics, they are expected to be created by the same physical mechanism, so the late observed X-ray afterglow of both GRBs are compared as if they were located at the same redshift; i.e., a light curve of the X-ray afterglow of GRB 090618 (of $z = 0.54$) is built as if it had redshift $z = 0.9$ extrapolating it to the XRT energy window of GRB 101023. A surprising perfect superposition of the light curves is found for $z = 0.9$, receiving a further confirmation of the correctness of the cosmological redshift determination. This result points to a possible use of the late afterglow as a distance indicator.

The conclusion is that GRB 101023 and GRB 090618 have striking analogies and are members of a specific new family of GRBs. The existence of precise scaling laws between these two sources opens a new window on the use of GRBs as distance indicators.

### 3.3 GRB 110709B

#### 3.3.1 Observations

GRB 110709B has been detected by Suzaku (Ohmori et al., 2011) and Swift (Cummings et al., 2011) satellites, and by ground-based telescopes like GROND (Updike et al., 2011) and Gemini (Berger, 2011). The Burst Alert Telescope (BAT) on board Swift triggered a first time at 21:32:39 UT (trigger N° = 456967). The light curve is composed of multiple peaks, with the whole emission extending up to 60 s after the trigger (see Fig. 3.8). What is most interesting is that there was another trigger at 21:43:25 UT (trigger N°=456969), $\sim 11$ minutes after the first trigger. This time Swift did not need to slew, because it was already pointing to that position. This second emission shows a bump that begins 100 s before the second trigger and lasts around 50 s, followed by several overlapping peaks with a total duration of about 40 s, and another isolated peak of 10 s of duration, 200 s after the second trigger. Fig. 3.8 shows the complete BAT light curve. There have not been detections in the optical band by Swift/UVOT, which started to observe 70 s after the first BAT trigger (Holland, 2011). The observations with GROND at La Silla Observatory (Updike et al., 2011) simultaneously in the g’ r’ i’ z’ JHK, reveal two point sources within the 5”.3 XRT error circle reported by Cummings et al. (2011). They suggest that one of them could be an afterglow candidate for GRB 110709B, although it is very faint. It has been suggested by Zauderer et al. (2012) that this source is an “optically dark” GRB. The possible reasons for this are: 1) dust obscuration, 2) intrinsically dim event, and/or 3) high redshift (optical emission suppressed by Ly$\alpha$ absorption at $\lambda_{\text{obs}} \leq 1216\text{Å} (1+z)$).

In the following we refer to the emission that goes from 40 s before the first BAT trigger to 60 s after it as Episode 1. We call the emission going from 35 s before the second BAT trigger to 100 s after it as Episode 2.

#### 3.3.2 Cosmological redshift determination

We used four phenomenological methods to constrain the redshift of the source, based on different relations, detailed below.
Figure 3.8: BAT light curve of GRB 110709B, including both triggers. Here we can appreciate the time separation (about 10 minutes) between the first and the second trigger. The light curve is in the (15-150 keV) energy band. The time is relative to the first trigger, of 331939966 s (in MET seconds). The second trigger was at 331940612 s in MET seconds.

$N_H$ column density

We first tried to get an upper limit for $z$ following the work of Grupe et al. (2007b). They consider a relation between the absorption column density in excess of the galactic column density, given by $\Delta N_H = N_{H, \text{fit}} - N_{H, \text{gal}}$ and the redshift $z$. We obtained an upper limit for the redshift of $z < 1.35$.

Amati Relation

We also tried to determine the redshift of Episode 2 through the Amati relation, that relates the isotropic energy $E_{\text{iso}}$ of the GRB to the peak Energy in the rest frame $E_{p,i}$ of the $\nu F_\nu$ spectrum (Amati et al., 2009). Following the same procedure as described in (Penacchioni et al., 2012, 2013), we calculated $E_{\text{iso}}$ and $E_{p,i}$ for different values of $z$, from 0.1 to 3, at steps of 0.1. The relation is satisfied for values of $z > 0.4$. This puts a lower limit to the estimation of the redshift.

Yonetoku Relation

We finally obtained a range of possible redshifts by using the Yonetoku relation (Yonetoku, 2004). This relation, also known as the $E_p -$ Luminosity relation ($E_p - L$), connects the observed isotropic luminosity $L$ in units of $10^{52}$ erg s$^{-1}$ with the peak energy $E_p(1 + z)$ in the rest frame of the GRB. We see that the Yonetoku relation is satisfied within 1$\sigma$ for values of the redshift $> 0.7$, consistent with the
results obtained with the Amati relation.

In conclusion, if we put together the three methods, we have a range of possible redshifts of $0.7 < z < 1.35$.

**Estimate of the redshift using the X-ray afterglow**

We already presented in (Penacchioni et al., 2012) a method to estimate the redshift of GRB 101023 by comparing its X-ray light curve to the one of GRB 090618, of known redshift ($z = 0.54$). Here we rescale the X-ray light curve of GRB 090618 as if it was seen at different redshifts and plot it together with GRB 110709B light curve, looking for the values of $z$ for which these light curves overlap at late times. We find a remarkable consistency between this method and the phenomenological methods already mentioned.

In order to compare in a common rest frame the two emissions from the GRBs, we apply the following operations only to GRB 090618: 1) determination of the starting time $T_{\text{start}}$ of the late decay emission, 2) spectral analysis of this emission with an absorbed power-law model, 3) extrapolation of this spectral model in a common cosmological rest-frame energy range and, consequently, rescaling of GRB 090618 light curve for the different energy ranges, 4) cosmological correction for the arrival time by taking into due account the different scaling due to cosmological redshift, and 5) correction of the observed flux by changing the redshift of GRB 090618. A detailed description of the method has been given in Pisani et al. (2013) and will be described in Section 3.5. In this way we compare directly both light curves for different redshifts of GRB 090618. Fig. 3.9 shows GRB 090618 light curve seen as if the source was located at different redshifts: 0.2 (blue), 0.4 (green), 0.7 (grey), 1.0 (orange) and 2.0 (purple). The red light curve corresponds to GRB 110709B.

We can see that it lies between the green and the orange ones. A more accurate scaling of the late X-ray afterglow suggests a redshift of $z = 0.75$ for this source.

Fig. 3.9 shows the superposition of GRB 110709B and GRB 090618 light curves in the observer frame, as if they were located at a redshift $z = 0.75$.

There is however a second aspect which is due to the peculiarity of the turn-on $T_0$ of the XRT detector. At the time BAT triggered for the second time, XRT was already pointing at the source and was able to detect the emission at very early times, making this GRB probably the first for which XRT has the earliest detection up to date. We need to shift GRB 110709B light curve in order to make the early steep decays (originating in the prompt in our interpretation) coincide. This is done by adding a time $T_s = +800$ s to GRB 090618 light curve. The superposition is very good. In this way we also make the early decays coincide. This factor is arbitrary, but we need to include it because GRB 110709B XRT light curve presents many spikes at the beginning, which according to our interpretation correspond not to the steep decay of the X-ray light curve but to the prompt emission.

In the case of GRB 110709B, thanks to the fact that XRT was already active and collecting data at the time of the second BAT trigger, we were able to follow the behavior of the whole GRB emission of Episode 2. This is a key point to our understanding of GRB 110709B, since only in very few cases XRT had a response during the early emission. In the big flare at $\sim 1000$ s after the first BAT trigger we notice a strong correlation between the emission in X-rays and in $\gamma$-rays. We
identify this emission as the prompt emission of Episode 2. After this prompt phase the traditional plateau phase is observed. After the plateau phase, there is the late decay phase in the X-ray light curve following a power-law behavior which has already been observed in other sources (i.e., GRB 101023, GRB 090618, GRB 111228).

### 3.3.3 Analysis of the Episode 1

We perform a time-integrated analysis to the whole Episode 1, using five different spectral models, namely BB, Band (Band et al., 1993), BB+PL, PL and CutoffPL. Statistical tests show that BB+PL ($\chi^2 = 56.65$) and CutoffPL ($\chi^2 = 54.45$) models are the best ones and statistically equivalent. We obtain a BB temperature $kT = (22 \pm 5)$ keV, a PL index $\gamma = 1.4 \pm 0.1$ and a $\chi^2 = 56.65$ (54 DOF). The flux of the BB component is $\sim 12\%$ of the total flux. The total energy of Episode 1 is $E_{\text{iso}}^{\text{Ep1}} = 1.42 \times 10^{53}$ erg. Then we perform a time-resolved spectral analysis with a binning of 5 s fitting the same model and find that the temperature of the BB component follows a broken power-law, as mentioned in Ryde (2004), from 5 s before the trigger to 55 s after it (see Fig. 3.10). The broken power-law is indeed a constant function plus a simple power-law function. This is the same behavior as for the previously analyzed GRB 090618 (Izzo et al., 2012a) and GRB 101023 (Penacchioni et al., 2012). However, we notice that the temperatures for this GRB are lower. Nevertheless, the simultaneous presence of a BB and PL component is necessary in order to obtain an acceptable fit of the data.

With the knowledge of the redshift and the parameters of the fit with a BB + PL model, we computed the isotropic energy of the whole Episode 1, $E_{\text{iso}}^{(1)} = 1.42 \times 10^{53}$ erg. With the energy flux of the BB component $\phi_{BB}$ as a function of time from the
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Figure 3.10: **Left panel**: Evolution of the kT component of the BB+PL model during Episode 1. The first data point corresponds to 5 s before the first BAT trigger. The vertical line corresponds to the trigger time. The time is in the observer frame. The temperature evolves in time following a broken power-law fit. There is a break at $t = 41.21$ s. The indices of the PL are $\alpha = 0$ (consistent with a constant function) and $\beta = -4 \pm 2$, respectively. The presence of the BB, although smaller than in previous cases, is essential to have an acceptable fit. **Right panel**: Radius of the emitting region as a function of time (in the cosmological rest frame), corresponding to Episode 1. The radius increases non-relativistically with time following a power-law $a t^b$, with $a = (1.5 \pm 1.2) \times 10^4$ and $b = 0.32 \pm 0.27$.

3.3.4 Analysis of the Episode 2

We also performed a time-integrated spectral analysis of Episode 2. This episode starts 35 s before the second trigger and last 135 s, until 100 s after the second trigger. We tried to fit the spectrum with the following spectral models: BB, PL, BB+PL, cutoffPL and Band. We concluded that the model that best fits Episode 2 is the cutoffPL model. It is clear from the analogies with GRB 090618 and GRB 101023 that Episode 2 has all the characteristics of a canonical GRB. A difference between GRB 110790B and the already analyzed ones is that the separation between Episode 1 and Episode 2, $\sim 10$ min, is much bigger than previously, $\sim 50$ s. This remarkable time separation between the two episodes is an additional new fact to propose a different astrophysical origin of these two components.

Having fixed the value of the redshift to $z = 0.75$, we started the analysis of Episode 2 within the fireshell model. We selected the P-GRB as the 9 s from 35 to 26 s before the second trigger, and the following emission from -26 to 100 s as the afterglow. We calculated a P-GRB energy of $E_{\text{P-GRB}} = 3.44 \times 10^{50}$ erg and an isotropic energy of $E_{\text{iso}} = 2.43 \times 10^{52}$ erg. Thanks to these values, we calculated the value of the baryon load, $B = 5.7 \times 10^{-3}$ and we simulated the light curve and the spectrum, obtaining, at the transparency point, a Laboratory Radius $r_{\text{tr}} = 6.04 \times 10^{13}$ cm, a gamma Lorentz factor $\Gamma = 1.73 \times 10^2$ and a P-GRB observed temperature (after cosmological correction) $kT = 12.36$ keV.
3.3 GRB 110709B

Figure 3.11: Simulation of the BAT light curve (left panel) and spectrum (right panel) of Episode 2 of GRB 110709B. We included XRT data in the fit of the spectrum to show that the slope predicted in the fireshell model is in agreement with the slope of the X-ray spectrum.

Figs. 3.11 shows the simulation of the light curve and the spectrum of Episode 2. The photon index of the XRT and BAT spectra are in agreement with that predicted by the simulation. Details of this calculation and the density mask of the CBM are in Penacchioni et al. (2013).

3.3.5 Conclusions on GRB 110709B

GRB 110709B is a very peculiar source, since it is the first for which Swift/BAT has triggered twice. Its Swift/BAT light curve presents two well defined episodes, Episode 1 and Episode 2. Episode 1 lasts 100 s and Episode 2 lasts 135 s. The light curve and spectrum of this source share similar characteristics with GRB 090618 (Izzo et al., 2012a), GRB 101023 (Penacchioni et al., 2012).

The redshift of GRB 110709B is unknown, so in Section 3.3.2 we used four phenomenological methods to constrain it; i.e., Grupe (Grupe et al., 2007b), Amati (Amati et al., 2009), Yonetoku (Yonetoku, 2004) and the scaling of the X-Ray afterglow (Penacchioni et al., 2012; Pisani et al., 2013). The first method gives an upper limit of $z < 1.35$. The second and third methods give a lower limit of $z > 0.6$ and $z > 0.7$, respectively. The last method gives a precise value of $z = 0.75$, which lies within the range determined by three the above mentioned methods. We then fixed this last value as the redshift of GRB 110709B.

We find a value of the isotropic energy for Episode 1 of $E^{(1)}_{iso} = 1.42 \times 10^{53}$ erg. We fit the spectrum with a BB+PL model. The temperature of the BB component evolves with time following a broken power-law (see Fig. 3.10). The corresponding radius of the BB emitter evolves in time following a power-law, in analogy with the Episode 1 of GRB 090618 and GRB 101023.

We find an isotropic energy for Episode 2 of $E^{(2)}_{iso} = 2.43 \times 10^{52}$ erg. We interpret this episode as a canonical GRB and simulated its light curve and spectrum within the Fireshell model. We find at transparency a Lorentz factor $\Gamma \sim 1.73 \times 10^2$, laboratory radius of $6.04 \times 10^{13}$ cm, P-GRB observed temperature $kT_{P-GRB} = 12.36$...
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keV, baryon load $B = 5.7 \times 10^{-3}$, P-GRB energy of $E_{P-GRB} = 3.44 \times 10^{50}$ erg, and a CBM mean density 76 part cm$^{-3}$. This value is consistent with a “dark GRB”, as cited in Zauderer et al. (2012). The lack of detection of a SN emission for this particular GRB could be due to obscuration by the circumstellar dust in the host galaxy.

3.4 GRB 970828

3.4.1 Observations

GRB 970828 is one of the first GRBs with a determined redshift of $z=0.9578$ from the identification of its host galaxy (Djorgovski et al., 2001). It was detected by the All Sky Monitor (ASM) detector on board the Rossi X-ray Timing Explorer (RXTE) spacecraft (Remillard et al., 1997), and then observed also by the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (Smith et al., 1997). The crucial data on the afterglow of GRB 970828 were collected by the Advanced Satellite for Cosmology and Astrophysics (ASCA) in the (2 - 10) keV energy range, one day after the RXTE detection (Filippenko et al., 1997), and by ROSAT (Greiner et al., 1997) in the (0.1 - 2.4) keV, one week later. Observations on optical wavelengths failed to detect the optical afterglow (Odewahn et al., 1997; Groot et al., 1998). The fluence measured by BATSE implies an isotropic energy for the total emission of $E_{iso} = 4.2 \times 10^{53}$ erg. The BATSE-LAD light curve is characterized by two main emission phenomena, see Fig.3.12: the first lasts about 40 s and is well described by two main pulses, the second one is more irregular, being composed by several sharp pulses, lasting other 40 s. The optical observations, which started about 4 hr after the burst, did not report any possible optical afterglow for GRB 970828 up to $R=23.8$ (Groot et al., 1998). However, the observations at radio wavelengths of the burst position, 3.5 hrs after the initial burst, succeeded in identifying a source at a good significance level of 4.5 $\sigma$ (Djorgovski et al., 2001) inside the ROSAT error circle (10$''$). The following deep searches for a possible optical counterpart of this radio source led to the identification of an interacting system of faint galaxies, successively recognized as the host galaxy of GRB 970828. The spectroscopic observations of the brightest of this system of galaxies led to the identification of their redshift, being $z=0.9578$. The lack of an optical transient associated with the afterglow of GRB 970828 can be explained as due to the presence of strong absorption, due to dusty clouds in the burst site environment, whose presence does not affect the X-ray and the radio observations of the GRB afterglow. The absence of an optical afterglow (Groot et al., 1998), together with the large intrinsic absorption column detected in the ASCA X-ray data (Yoshida et al., 2001) and the contemporary detection in radio-wavelengths of the GRB afterglow, imply a very large value for the circum-burst medium (CBM); the variable absorption might be an indication of a strong inhomogeneous CBM distribution.
3.4.2 Analysis of the Episode 1

In analogy to the cases of GRB 090618, GRB 101023, and GRB 110709B (Izzo et al., 2012a; Penacchioni et al., 2012, 2013), in Ruffini et al. (in press) we analyzed the first emission episode in GRB 970828 to seek for a thermal signature. As often done in GRB analysis, we first perform a time-integrated spectral analysis of the first 40 s of emission, which corresponds to the Episode 1, to identify the best-fit model and the possible presence of thermal features. We make use of different spectral models to determine the best-fit function. We also check if nested models really improve the best-fit, as in the case of models with an extra power-law component. We find that the best-fit corresponds to a double blackbody model with an extra power-law component. We perform then a time-resolved spectral analysis to determine the existence and the evolution of a thermal component. We find that the double blackbody model observed in the time-integrated spectrum can be explained by the presence of an instantaneous single blackbody with a temperature $kT$ varying in intensity and time, showing a double decay trend. We have then analyzed this characteristic evolution of the blackbody in both time intervals, corresponding each one to an observed decay trend of the temperature. From the observed flux of the blackbody component $\phi_{BB,\text{obs}}$ for each interval, we obtain the evolution of the emitter radius in the rest-frame:

\[
    r_{em} = \left( \frac{\phi_{BB,\text{obs}}}{\sigma T_{\text{obs}}^4} \right)^{1/2} \frac{D}{(1 + z)^2}
\]

(3.1)

whose evolution is shown in Fig. 3.13. It is very interesting that the radius monotonically increases, with a non-relativistic velocity, without showing an analog double trend which is observed for the temperature, see Fig. 3.13. The global evolution of the emitter radius is well-described with a power-law function $r = \alpha t^\delta$ and a best fit of the data provides for the $\delta = 0.41 \pm 0.04$ and $\alpha = (5.38 \pm 0.52) \times 10^3$, with an $R^2$ statistic value of 0.98, see Fig. 3.13.
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Figure 3.13: (Left panel) The evolution of the temperature $kT$ (red crosses) as obtained from a time-resolved spectral analysis of the first 40 s of emission of GRB 970828. The light curve of the first episode (blue dots) is shown in background. (Right panel) Evolution of the rest-frame radius of the first episode of GRB 970828. The solid line corresponds to the best fit of this dataset with a power-law function $r \propto t^\delta$, with $\delta = 0.41 \pm 0.04$.

### 3.4.3 The Episode 2: the GRB emission

Turning now to the second emission episode, we have computed the isotropic energies emitted in this episode, by considering a Band model as the best fit for the observed integrated spectra: $E_{iso,2nd} = 1.6 \times 10^{53}$ erg. We explain this second emission episode of GRB 970828 as a single canonical GRB emission in the context of the fireshell scenario (Ruffini et al., in press). To simulate the second episode of GRB 970828 we need to identify the P-GRB signature in the early second episode light curve. We have then started to seek for a possible thermal signature attributable to the P-GRB emission in the early emission of the Episode 2. Our search for the P-GRB emission is concentrated in the 9 s time interval anticipating the first intense spike, since from the fireshell model the expected luminosity of the P-GRB emission is of the order of $10^{-2}$ of the prompt emission. The observed fluence (10-1000 keV) in the P-GRB emission, computed from the fit with the power-law function is $S_{obs} = (1.54 \pm 0.10) \times 10^{-6}$ erg/cm$^2$, which corresponds to an isotropic energy of the P-GRB of $E_{iso,PGRB} = 1.46 \times 10^{51}$ erg, which is quantitatively in agreement with the energetic of the P-GRB for this GRB (it is $\approx 0.01 \%$ the total energy of the Episode 2). However, due to the paucity of photons in this time interval, we are not able to put tight constraints, e.g. about a possible observed temperature of the P-GRB. With these results, we can estimate the value of the baryon load from the numerical solutions of the fireshell equations of motion. We find that the baryon load is $B = 7 \times 10^{-3}$, which corresponds to a Lorentz gamma factor at transparency $\Gamma = 142.5$. The GRB emission was simulated with very good approximation by using a density mask characterized by an irregular behavior: all the spikes correspond to spherical clouds with a large particle density $\langle n_{CBM} \rangle \sim 10^3$ part/cm$^3$, and with radius of the order of $(4 - 8) \times 10^{14}$ cm. Considering all the clouds found in our analysis, the average density of the CBM medium is $\langle n_{CBM} \rangle = 3.4 \times 10^3$
3.4 GRB 970828

Figure 3.14: Light curve (top panel) and spectrum (lower panel) with the simulation of the second episode emission in GRB 970828, in the context of the fireshell scenario. In the simulation we have assumed for simplicity a purely radial 1-dimensional distribution of the CBM, which leads at late times (when $\Gamma \approx 10$), to broader structures than the observed ones. This difficulty can be overcome by a much more time-consuming 3-dimensional description of the CBM, but without any conceptual additional contribution (Izzo et al., 2010).

particles/cm$^3$. The corresponding masses of the blobs are of the order of $10^{24}$ g, in agreement with the clumps found in GRB 090618. The simulated light curve and spectrum are shown in Fig. 3.14.

3.4.4 The Episode 3: the late X-ray afterglow

As shown in Penacchioni et al. (2012, 2013); Pisani et al. (2013), from the knowledge of the redshift of the source, we can compute the X-ray luminosity light curve in the common rest frame energy range 0.3–10 keV after $\approx 10^4$ s from the initial GRB emission. However, while such analysis is based on the available X-ray data (0.3–10 keV) from the Swift/XRT detector, GRB 970828 occurred in the pre-Swift era. Its observational X-ray data are available in the energy range 2–10 keV, since the data were collected by three different satellites: RXTE, ASCA and ROSAT. We verify the overlapping of the late X-ray data with the one of GRB 090618 (Ruffini et al., in press). To this aim, we have computed its luminosity light curve $L_{rf}$ in a common rest-frame energy range 0.3–10 keV. Since the observed energy band is different (2–10 keV), the expression for the flux light curve $f_{rf}$ in the 0.3–10 keV rest-frame energy range is

$$f_{rf} = f_{obs} \left( \frac{10}{1+z} \right)^{2-\gamma} \left( \frac{0.3}{1+z} \right)^{2-\gamma} \frac{10^{2-\gamma} - 2^{-\gamma}}{10^{2-\gamma} - 2^{-\gamma}}, \quad (3.2)$$

where $\gamma$ is the photon index of the power-law spectral energy distribution of the X-ray data. All the other data transformations, reported in Pisani et al. (2013), remain unchanged.

We made use in particular of the RXTE-PCA observations and ASCA data
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Figure 3.15: The X-ray afterglows luminosity in the rest-frame (0.3 - 10 keV) energy range of GRB 090618 (gray data) and GRB 970828 (blue data). The data overlapping at late times (t > 10^4 s) is clearly evident.

presented in Yoshida et al. (2001); the averaged photon indexes are taken from the text, for RXTE-PCA (γ ∼ 2), and from Tab. 1, for the ASCA data, of the same paper. The last data-point by ROSAT is taken from Fig. 7 in Djorgovski et al. (2001), with a corresponding photon index ∼ 2. We show in Fig. 3.15 the late X-ray (0.3 - 10 keV) light curve of GRB 970828 and we compare it with some GRBs of GRB 090618.

3.4.5 Limits on the SN optical bump observations

The analysis of GRB 090618 (Izzo et al., 2012a) represents an authentic “Rosetta Stone” for the understanding of the GRB-SN phenomenon. The presence of a SN emission, observed ten days after the burst in the cosmological rest-frame of GRB 090618, was found to have the same luminosity of SN 1998bw (Cano et al., 2011), the SN related to GRB 980425 and which is the prototype of SNe connected with GRBs (Della Valle, 2011). We have transposed the data of the “bump” Rc-band light curve observed in the optical afterglow of GRB 090618, associated to the presence of an underlying SN (Cano et al., 2011), to the redshift of GRB 970828. This simple operation concerns only the transformation of the flux observed, under the assumption that the SN has the same intrinsic luminosity. Moreover, we have also transposed the U and R−band light curves of SN 1998bw (Galama et al., 1998), which is the prototype of a SN associated to a GRB. From the K−correction transformation formula, the U−band light curve, transposed at z=0.9578, corresponds approximately to the observed R−band light curve, so in principle we should consider the U = 365 nm transposed light curve as the actual one observed with the Rc = 647 nm optical filter. These transposed light curves are shown in Fig. 3.16. We conclude that the
SN emission could have been seen between 20 and 40 days after the GRB trigger, neglecting any possible intrinsic extinction. The optical observations were made up to 7 days from the GRB trigger, reaching a limit of $R \sim 23.8$ (Groot et al., 1998) and subsequent deeper images after $\sim 60$ days (Djorgovski et al., 2001), so there are no observations in this time interval. It is appropriate to notice that the $R$-band extinction value should be large since the observed column density from the X-ray observations of the GRB afterglow is large as well (Yoshida et al., 2001): the computed light curve for the possible SN of GRB 970828 should be lowered by more than 1 magnitude, leading to a SN bump below the $R = 25.2$ limit, see Fig. 3.16. The presence of very dense clouds of matter near the burst site might have darkened both the SN emission and the GRB optical afterglow. Indeed we find the presence of clouds in our simulation at the average distances of $\sim 10^{15-16}$ cm from the GRB progenitor, with average density of $\langle n_{CBM} \rangle \approx 10^3$ part/cm$^3$ and typical dimensions of $(4-8) \times 10^{14}$ cm (Ruffini et al., in press).

3.4.6 Conclusions on GRB 970828

In Episode 1, we determine the evolution of the thermal component and of the radius of the blackbody emitter, which increases in time with a non-relativistic velocity. In Episode 2, the GRB, we give the details of the simulation of the light curve and the spectrum of the real GRB emission. We have also shown the total
energy of the $e^+e^-$ plasma, the baryon load $B$, the temperature of the P-GRB $kT_{th}$
and the Lorentz Gamma factor at transparency $\Gamma$, as well the average value of the
CBM density $\langle n_{CBM} \rangle$. In Episode 3, we have shown that the late afterglow emission
observed by ASCA and ROSAT, although limited to few data points, when consid-
ered in the cosmological rest-frame of the emitter, presents a successful overlap with
the standard luminosity behavior of GRB 090618, GRB 101023, and GRB 110709B.
Finally, from this latter analogy, we have given reasons why a SN associated to GRB
970828 was not observable due to the large interstellar local absorption, in agree-
ment with the large column density observed in the ASCA X-ray data Yoshida et al.
(2001) and with the large value we have inferred for the CBM density distribution,
$\langle n_{CBM} \rangle \approx 10^3$ particles/cm$^3$.

3.5 A common behavior in the late X-rays

3.5.1 The four Episodes

The analysis summarized in the previous Sections point to a new subclass of long
GRBs sharing different common features. The prototype is GRB 090618 (Ruffini
et al., 2011; Izzo et al., 2012a,b) at redshift $z = 0.54$, where four different emission
episodes have been identified.

**Episode 1** has been observed to have thermal as well as power-law emission.
The thermal emission changes in time following a precise power-law behavior (Izzo
et al., 2012a; Penacchioni et al., 2012, 2013; Ruffini et al., in press).

**Episode 2** follows and corresponds to the GRB emission coincident with the
BH formation. The characteristic parameters of the GRB, including baryon load,
the Lorentz factor, and the nature of the circumburst medium (CBM), have been
computed (Izzo et al., 2012a; Penacchioni et al., 2012, 2013; Ruffini et al., in press).

**Episode 3** is characterized in the X-ray light curve by a shallow phase (a plateau)
followed by a final steeper decay. Typically, it is observed in the range $10^2 - 10^6$ s
after the GRB trigger.

**Episode 4** occurs after a time of about ten days in the cosmological rest-frame,
corresponding to the SN emission due to the Ni decay (see Arnett, 1996, for a
complete review). This emission is clearly observed in GRB 090618, emerging from
the late optical GRB afterglow emission.

3.5.2 The Golden Sample

Here we present our analysis (see Pisani et al., 2013) of the X-ray emissions seen
by Swift/XRT of a sample of eight nearby ($z \lesssim 1$) GRBs with $E_{iso} \geq 10^{52}$ erg that
satisfy at least two of the following three requirements:

- there is a double emission episode in the prompt emission: Episode 1, with a
decaying thermal feature, and Episode 2, a canonical GRB, as in GRB 090618
(Izzo et al., 2012a), GRB 101023 (Penacchioni et al., 2012), and in GRB
110709B (Penacchioni et al., 2013);
Table 3.1: GRB sample considered in Pisani et al. (2013), from now on Golden Sample (GS). The redshifts of GRB 101023 and GRB 110709B, which are marked with an asterisk, were deduced theoretically by using the method outlined here (Penacchioni et al., 2012, 2013) and the corresponding isotropic energy computed by assuming these redshifts. Pisani et al. (2013) work is previous to GRB 130427A event, which will be included in the GS in the later work of Ruffini et al. (in press), see Chapter 4.

<table>
<thead>
<tr>
<th>GRB</th>
<th>$z$</th>
<th>$E_{\text{iso}}$ (erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 060729</td>
<td>0.54</td>
<td>$1.6 \times 10^{52}$</td>
</tr>
<tr>
<td>GRB 061007</td>
<td>1.261</td>
<td>$1.0 \times 10^{54}$</td>
</tr>
<tr>
<td>GRB 080319B</td>
<td>0.937</td>
<td>$1.3 \times 10^{54}$</td>
</tr>
<tr>
<td>GRB 090618</td>
<td>0.54</td>
<td>$2.9 \times 10^{53}$</td>
</tr>
<tr>
<td>GRB 091127</td>
<td>0.49</td>
<td>$1.1 \times 10^{52}$</td>
</tr>
<tr>
<td>GRB 111228</td>
<td>0.713</td>
<td>$2.4 \times 10^{52}$</td>
</tr>
<tr>
<td>GRB 101023</td>
<td>0.9*</td>
<td>$1.8 \times 10^{53}$</td>
</tr>
<tr>
<td>GRB 110709B</td>
<td>0.75*</td>
<td>$1.7 \times 10^{53}$</td>
</tr>
</tbody>
</table>

- there is a shallow phase followed by a final steeper decay in the X-ray light curve: Episode 3;

- there is a clear or partial evidence of an associated SN emergent in the optical observations after about ten days from the GRB trigger in the rest-frame: Episode 4.

We found eight GRBs that satisfy our requirements (from now on Golden Sample (GS), see Table 3.1).

**GRB 060729.** In this source a SN bump was observed in the optical GRB afterglow (Cano et al., 2011). It is at the same redshift $z = 0.54$ as GRB 090618 and shows a small precursor plus a main event in the prompt light curve and a peculiar prolonged duration for the X-ray afterglow. The isotropic energy emitted in this burst is $E_{\text{iso}} = 1.6 \times 10^{52}$ erg (Grupe et al., 2007a).

**GRB 061007.** This GRB has no associated SN but is characterized by a precursor with a clear evolving thermal emission (Larsson et al., 2011). With an energetic $E_{\text{iso}}$ of $1.0 \times 10^{54}$ erg (Golenetskii et al., 2006) at $z = 1.261$, it is the farthest GRB in our sample. The large distance makes the detection of a SN from this GRB difficult.

**GRB 080319B.** A tentative SN was reported also for GRB 080319B, well-known as the naked-eye GRB, whose prompt emission also shows a possible double-emission episode (Kann et al., 2008). Its measured redshift is $z = 0.937$. This is one of the most energetic GRB, with $E_{\text{iso}} = 1.3 \times 10^{54}$ erg (Golenetskii et al., 2008), and its X-ray light curve is well fit by a simple decaying power-law.

**GRB 090618.** This GRB is the prototype of this new family of GRBs. Its prompt emission shows a clear Episode 1 plus Episode 2 structure in light curve and spectrum. The measured redshift is $z = 0.54$ and the $E_{\text{iso}} = 2.9 \times 10^{53}$ erg (Izzo et al., 2012a). There is a clear optical bump, about ten days of rest-frame
Evidence for multi-components and a new distance indicator in GRBs

time after the GRB trigger, in the afterglow light curve of GRB 090618 that is associated with the SN emission (Cano et al., 2011). The characteristic parameters of this GRB, including the baryon load \( (B = 1.98 \times 10^{-3}) \), the Lorentz factor at the transparency \( (\Gamma_{tr} = 495) \), and the nature of the CBM \( (\langle n_{CBM} \rangle = 0.6 \text{ part/cm}^3) \), have been estimated previously (Izzo et al., 2012a).

GRB 091127. GRB 091127 is associated with SN 2009nz at a redshift of \( z = 0.49 \) (Cobb et al., 2010). The \( E_{iso} \) for this burst is \( 1.1 \times 10^{52} \) erg (Wilson-Hodge & Preece, 2009).

GRB 111228. A SN feature was also reported in the literature for GRB 111228 (D’Avanzo et al., 2012), which shows a multiply peaked prompt light curve in the Fermi/GBM data. The measured redshift of this GRB is \( z = 0.713 \), its \( E_{iso} = 2.4 \times 10^{52} \) erg (Briggs & Younes, 2011), and a dedicated analysis of this GRB will be presented elsewhere. The detection of a SN in GRB 111228 is debated, since the subsequent optical bump has the same flux as the host galaxy of the source, but SN features were observed in the differential photometry between the last epochs of observations, where a transient component was detected that was unrelated to the afterglow, and was consequently attributed to the SN.

GRB 101023. This GRB shows clear Episode 1 and Episode 2 emissions in the prompt light curve and spectrum, but there is no detection of a SN and no measured redshift because of the lack of optical observations at late times. We estimated the redshift of this source at \( z = 0.9 \) by analogy to the late X-ray afterglow decay observed in the six GRBs with a measured redshift. This leads to an estimate of \( E_{iso} = 1.8 \times 10^{53} \) erg, a baryon load of \( B = 3.8 \times 10^{-3} \), a Lorentz factor at transparency of \( \Gamma_{tr} = 260 \), and an average density for the CBM of \( \langle n_{CBM} \rangle \approx 16 \text{ part/cm}^3 \) (Penacchioni et al., 2012).

GRB 110709B. Like GRB 101023, this GRB shows clear Episode 1 plus Episode 2 emission in the prompt light curve and spectrum, but there is no detection of a SN. This can be explained by the fact that it is a dark GRB, whose emission is strongly influenced by absorption. Particularly interesting is the detection of clear radio emission (Zauderer et al., 2012). There is no measurement for the redshift but, as for GRB 101023, we estimated it to be \( z = 0.75 \) by analogy to the late X-ray afterglow decay observed in the six GRBs with measured redshifts. This leads to an estimate of an isotropic energy of \( E_{iso} = 1.7 \times 10^{53} \) erg, a baryon load of \( B = 5.7 \times 10^{-3} \), a Lorentz factor at the transparency of \( \Gamma_{tr} = 174 \), and an average density of the CBM of \( \langle n_{CBM} \rangle \approx 76 \text{ part/cm}^3 \) (Penacchioni et al., 2013).

3.5.3 X-ray Luminosity in a common rest-frame

We focused the analysis of all available XRT data of these sources. Characteristically, XRT follow-up starts only about 100 seconds after the BAT trigger (typical repointing time of Swift after the BAT trigger). Because the behavior was similar in all sources, we compared the analyzed XRT luminosity light curve \( L_{rf} \) for the six GRBs with measured redshifts in the common rest-frame energy range 0.3–10 keV. As a first step we converted the observed XRT flux \( f_{obs} \) to one in the 0.3–10 keV rest-frame energy range. In the detector frame, the 0.3–10 keV rest-frame energy range becomes \( [0.3/(1+z)] - [10/(1+z)] \) keV, where \( z \) is the redshift of the GRB.
3.5 A common behavior in the late X-rays

We assumed a simple power-law function as the best fit for the spectral energy distribution of the XRT data\(^1\):

\[
\frac{dN}{dA dt dE} \propto E^{-\gamma}.
\]

We can then write the flux light curve, \(f_{rf}\), in the 0.3–10 keV rest-frame energy range as

\[
f_{rf} = f_{obs} \frac{\int_{0.3 \text{keV}}^{10 \text{keV}} E^{1-\gamma} dE}{\int_{0.3 \text{keV}}^{10 \text{keV}} E^{1-\gamma} dE} = f_{obs} (1 + z)^{\gamma - 2}.
\]

Then, we have to multiply \(f_{rf}\) by the luminosity distance to derive \(L_{rf}\):

\[
L_{rf} = 4 \pi d_L^2 (z) f_{rf},
\]

where we assume a standard cosmological \(\Lambda\)CDM model with \(\Omega_m = 0.27\) and \(\Omega_L = 0.73\). Clearly, this luminosity must be plotted as a function of the rest-frame time \(t_{rf}\), namely

\[
t_{rf} = \frac{t_{obs}}{1 + z}.
\]

The X-ray luminosity light curves of the six GRBs with measured redshifts in the 0.3–10 keV rest-frame energy band are plotted in Fig. 3.17. What is most striking is that these six GRBs, with redshifts in the range 0.49–1.261, show a remarkably common behavior of the late X-ray afterglow luminosity light curves (Episode 3), despite their very different prompt emissions (Episode 1 and 2) and energetics spanning more than two orders of magnitude. The common behavior starts between \(10^4–10^5\) s after the trigger and continues until the emission falls below the XRT threshold. This standard behavior of Episode 3 represents a strong evidence of very low or even absent beaming in this particular phase of the X-ray afterglow emission process. This scaling law, when confirmed in sources with Episode 1 plus Episode 2 emissions, offers a powerful tool for estimating the redshift of GRBs that belong to this subclass of events, as we have done in the cases of GRB 101023 (Penacchioni et al., 2012) and GRB 110709B (Penacchioni et al., 2013). This is an important independent validity confirmation for this new redshift estimator we are proposing for this new family of energetic GRBs-SNe. We stress, however, that the redshift was determined assuming the validity of the standard \(\Lambda\)CDM cosmological model for sources with redshift in the range \(z = 0.49–1.216\). We are currently testing the validity of this assumption for sources at higher cosmological redshifts.

In all the above examples we have considered very energetic sources (\(E_{iso} \geq 10^{52}\) erg). Less energetic GRB-SN sources, e.g. GRB 980425 (Pian et al., 2000), also show a late X-ray emission different from the typical emission of energetic GRB-SN sources, and we will discuss this matter later, in Chapter 4.

3.5.4 Predictive power

We presented a sample of energetic (\(E_{iso} \geq 10^{52}\) erg) GRB-SN systems with a standard late-time (\(10^4–10^5\) s after the trigger) X-ray luminosity light curve in the

\(^1\)http://www.swift.ac.uk/
Evidence for multi-components and a new distance indicator in GRBs

Figure 3.17: X-ray luminosity light curves of the six GRBs with measured redshift in the 0.3–10 keV rest-frame energy range: in pink GRB 060729, $z = 0.54$; black GRB 061007, $z = 1.261$; blue GRB 080319B, $z = 0.937$; green GRB 090618, $z = 0.54$, red GRB 091127, $z = 0.49$, and in cyan GRB 111228, $z = 0.713$. 
0.3–10 keV rest-frame energy band. This standard behavior points to a common physical origin of this emission. This scaling law can provide a new distance indicator for this subclass of GRBs, allowing one to predict the redshift of the source as well as the presence of an associated SN.

It is possible to test the predictive power of this result on three different observational scenarios for GRBs with \( E_{\text{iso}} \gtrsim 10^{52} \) erg:

- GRBs at high redshift. We are able to predict the existence of a SN in these systems, which is expected to emerge after \( t \sim 10 (1 + z) \) days, the canonical time sequence of a SN explosion. This offers a new challenge to detect SNe at high redshift;

- for GRBs with \( z \leq 1 \) we can indicate in advance from the X-ray luminosity light curve observed by XRT the expected time for the observations of a SN and alert direct observations from ground- and space-based telescopes;

- as we showed here, we can infer the redshift of GRBs in the same way we did for GRB 110709B and GRB 101023A.

We are currently expanding the GS to increase the statistical validity of our approach and its cosmological implications. Two examples in this direction are the pre-Swift/XRT cases of GRB 970228 and GRB 030329.

GRB 970228 \((z = 0.695, E_{\text{iso}} = 1.86 \times 10^{52})\) is interpreted as a disguised short GRB by defect within the fireshell model (see Chapter 2, Section 2.2) and it appears to be connected with a SN (see Table 1.1 and Reichart, 1997). The X-ray afterglow data of GRB 970228, the first one ever observed, were collected by BeppoSAX (Costa et al., 1997), ASCA (Cline et al., 1997), and ROSAT (Frontera et al., 1997). Fig. 3.18 (upper panel) shows the X-ray luminosity light curve of GRB 970228 in comparison with the one of GRB 090618 in the 0.3–10 keV rest-frame energy range. The overlap between the X-ray luminosity light curve of GRB 970228 with the one of GRB 090618 results clear.

GRB 030329 \((z = 0.168, E_{\text{iso}} = 1.70 \times 10^{52})\) is the smoking gun evidence for the GRB-SN connection. It is the only pre-Swift GRB having \( E_{\text{iso}} > 10^{52} \) with a clear associated SN. The X-ray afterglow data of GRB 030329 were collected by Rossi-XTE and XMM-Newton (see Tiengo et al., 2003, 2004, and references therein). Fig. 3.18 (lower panel) shows the X-ray luminosity light curve of GRB 030329 in comparison with the one of GRB 090618 in the 0.3–10 keV rest-frame energy range. Analogously to the previous case, the overlap between the X-ray luminosity light curve of GRB 030329 with the one of GRB 090618 results clear.
Figure 3.18: *Upper panel*: X-ray luminosity light curves of GRB 090618 (green) and GRB 970228 (red) in the 0.3–10 keV rest-frame energy range. *Lower panel*: X-ray luminosity light curves of GRB 090618 (green) and GRB 030329 (red) in the 0.3–10 keV rest-frame energy range.
Chapter 4

A new paradigm for energetic GRBs-SNe: binary-driven hypernovae

4.1 The induced gravitational collapse and the new concept of binary-driven hypernova

4.1.1 Summary of the four observational Episodes

In the previous Chapter it has been shown that energetic ($E_{\text{iso}} \gtrsim 10^{52}$ erg) GRBs connected with SNe are composed by four distinct observational Episodes:

**Episode 1:** when detected, shows the presence of a characteristic power-law component extended up to the MeV region with a thermal component with temperature of the order of $kT \lesssim 10$ keV. From the variation of the temperature of the thermal component and the observed flux, it is possible to infer the radius of the emitting region being of the order of $\sim 10^9$–$10^{10}$ cm, expanding in time with an average non-relativistic velocity of $\sim 10^8$ cm s$^{-1}$ (see Izzo et al., 2012a; Penacchioni et al., 2012, 2013; Ruffini et al., in press). In some cases this signal is not observable since it is under the threshold of the instrumental detectability (Ruffini et al., 2014b).

**Episode 2:** it is the second part of X and $\gamma$-ray emission: it has an isotropic energy $E_{\text{iso}} \gtrsim 10^{52}$ erg and it is emitted after the collapse of a NS to a BH, following the fireshell model. The characteristic spatial extension goes all the way up to $\sim 10^{16}$–$10^{17}$ cm, reached at its end (see Fig. 10 in Izzo et al., 2012a). It shows a typical baryon load in the range $10^{-4} \lesssim B \lesssim 10^{-2}$ and its $T_{90}$ is a strong function of the gamma Lorentz factor and of the circum-burst medium (CBM) density. Typically for an average density $\langle n_{\text{CBM}} \rangle \sim 1$ cm$^{-3}$ and $\Gamma \sim 200$–500 the duration is of the order of $T_{90} \gtrsim 10$ s, typical of the long GRBs. These conditions define what we call the canonical long GRB. Under the special circumstances of $\langle n_{\text{CBM}} \rangle \sim 10^{-3}$ cm$^{-3}$ and $\Gamma \sim 200$, the prompt of the GRB appears like a short-like spike followed by a softer tail having duration of the order of $10^3$ s (Bernardini et al., 2007). This defines a disguised-short GRB by defect. Viceversa, in the case $\langle n_{\text{CBM}} \rangle \sim 10^3$ cm$^{-3}$
Figure 4.1: Radii (open blue circles) of the emitting regions of thermal components observed in GRB 090618, measured in the cosmological rest frame. Episode 1 radius ranges from $\sim 10^9$ cm to $\sim 10^{10}$ and expands at $\Gamma \approx 1$ (Izzo et al., 2012a). The Episode 3 radius, in the early phases of the steep decay, starts from a value of $\sim 7 \times 10^{12}$ cm and expands at $\Gamma \approx 2$. The Episode 2 rest-frame duration is indicated by the shaded purple region. The expansion velocity at late times is expected to approach the asymptotic value of $0.1c$ observed in the optical spectra (Della Valle, 2011), in the absence of any further acceleration process.

and $\Gamma \sim 1000$, the $T_{90}$ can be less than one second. This is called disguised-short GRB by excess (Muccino et al., 2013b).

**Episode 3:** includes the X-ray emission seen by *Swift*/XRT (0.3—10 keV) also observed by other X-ray detectors as well as optical observations. In the traditional fireball jetted model (see e.g. Piran, 2005; Mészáros, 2006; Gehrels et al., 2009, and references therein) it is interpreted as part of the GRB emission and indicated as "GRB afterglow emission". It has an isotropic energy of $\approx 6 \times 10^{51}$ erg. The X-ray flux light curve shows a typical shape composed by an initial steep decay, followed by a plateau phase, going to a late power-law decay. A striking feature occurs at late times, namely all the X-ray luminosity light-curves of the GS have the same behaviour at late times, independently from the initial steep decay and plateau shapes, and from the different $E_{iso}$ of the GRBs (Pisani et al., 2013). Another striking feature occurs during its steep decay phase: in the early observed 150 s of the X-ray emission of GRB 090618 Page et al. (2011) have found a thermal component with a decreasing temperature from $\sim 0.97$ keV to $\sim 0.29$ keV. The surface radius of the emitter can be inferred from the observed temperature $T_o$ and flux $F_{BB}$ of the thermal component. We have, in fact (Izzo et al., 2012a),
4.1 The induced gravitational collapse and the new concept of binary-driven hypernova

\[ r \approx \Gamma d_l (1 + z)^{-2} \sqrt{F_{BB}/(\sigma T_o^4)} , \]  

(4.1)

where \( d_l \) is the luminosity distance in the ΛCDM cosmological model and \( \sigma \) the Stefan-Boltzmann constant. As usual, \( \Gamma = 1/\sqrt{1 - \beta^2} \), where \( \beta = v/c \) is the expansion velocity in units of the speed of light \( c \). In parallel, the relation between the detector arrival time \( t_{da} \), the cosmological rest-frame arrival time \( t_a \) and the laboratory time \( t \), is given by \( t_{da} \equiv t_a (1 + z) = t(1 - \beta \cos \theta)(1 + z) \), where \( \theta \) is the displacement angle of the considered photon emission point from the line of sight (see, e.g., Bianco et al., 2001). We can then deduce the expansion velocity \( \beta \), assumed to be constant, from the ratio between the variation of the emitter radius \( \Delta r \) and the emission duration in laboratory frame \( \Delta t \), i.e. \( \beta = \Delta r/(c \Delta t) \). Using the condition \( \beta \leq \cos \theta \leq 1 \) (Bianco et al., 2001), we obtain \( 0.75 \leq \beta \leq 0.89 \) and, correspondingly, \( 1.50 \leq \Gamma \leq 2.19 \) and radii \( r \sim 10^{13} \) cm (see Fig. 4.1). This confirms that the X-ray emission is not a prolonged part of the GRB but comes from the SN ejecta which are expected to expand with a mildly relativistic velocity. A similar behaviour has been found also in GRB 060729 by Grupe et al. (2007a), who have found a thermal component in the early X-ray afterglow between 85 and 160 s with temperature cooling from 0.6 to 0.1 keV, and possibly in other GRBs-SNe (Starling et al., 2012).

**Episode 4:** it includes the so called ”optical SN event”, visible after \( t_{rf} \sim 10–15 \) days from the burst. It is usually well identifiable if the source has a redshift \( z \lesssim 0.3 \) all the way up to \( z \lesssim 1 \).

4.1.2 The binary-driven hypernova time sequence

The induced gravitational collapse (IGC, Ruffini et al., 2008; Rueda & Ruffini, 2012) model requires a tight binary (produced in a common envelope phase) between a massive FeCO star (a star that has lost its hydrogen envelope and helium shell) and a NS companion. In this scenario, the SN explosion and the GRB occur following a precise time sequence (see Figg. 4.2 and 4.3): explosion of the FeCO core \( \rightarrow \) hypercritical accretion onto the NS \( \rightarrow \) the critical mass is reached \( \rightarrow \) gravitational collapse to a BH is induced \( \rightarrow \) emission of the GRB.

It has been clear since the analysis of GRB 090618 by Izzo et al. (2012a) that the entire emission of what has been traditionally called a GRB, instead of being a single event, is actually a multiepisodic source whose understanding needs a time-resolved data scrutiny data (see Chapter 3). The IGC has been successfully applied to a class of energetic (\( E_{iso} \sim 10^{52}–10^{54} \) erg) GRB-SNe. These systems, recently named binary-driven hypernovae (BdHNe, Ruffini et al., 2014a), evolve in a rapid sequence lasting a few hundreds of seconds in their rest-frame. Up to now, the IGC has been verified in a dozen of GRBs, all with cosmological redshift \( z \leq 1 \) (see Pisani et al., 2013, and references therein), and very recently in one of the farthest observed sources, GRB 090423 at \( z = 8.2 \) (Ruffini et al., 2014b). These systems are characterized by four distinct Episodes, each with specific signatures in its spectrum and luminosity evolution summarized in the previous Section.

**Episode 1** is characterized by the explosion of the FeCO core, followed by the hypercritical accretion onto the NS which leads to the reaching of the critical mass of the NS and consequently to its IGC to a BH. The hypercritical accretion of the SN
ejecta onto the NS has been estimated using the Bondi-Hoyle-Lyttleton formalism (Bondi & Hoyle, 1944; Bondi, 1952) to be $10^{-2} M_\odot \, s^{-1}$, here $M_\odot$ is the solar mass (see e.g., in Rueda & Ruffini, 2012). The inflowing material shocks as it piles up onto the NS, producing a compressed layer on top of the NS (see e.g., Fryer et al., 1996). As this compressed layer becomes sufficiently hot, it triggers the emission of neutrinos which cool the in-falling material, allowing it to be accreted into the NS (Zel’dovich et al., 1972; Ruffini & Wilson, 1975; Ruffini et al., 1999, 2000; Fryer et al., 1996, 1999c). Recently Fryer et al. (2014) have presented a significant progress in understanding the underlying physical phenomena in the aforementioned hypercritical accretion process of the SN ejecta into the binary companion NS (Ruffini et al., 2008; Rueda & Ruffini, 2012). The new treatment, based on the two-dimensional cylindrical geometry smooth particle hydrodynamics code, has simulated numerically the process of hypercritical accretion, the classical Bondi-Hoyle regimes, in the specific case of the IGC paradigm and leading to the first astrophysical application of the neutrino production process considered in Zel’dovich et al. (1972) and in Ruffini & Wilson (1975). Indeed the fundamental role of neutrinos emission allows the accretion rate process to increase the mass of the binary companion star to its critical value and lead to the BH formation giving origin to the GRB in Episode 2. This results confirm and quantifies the general considerations presented in Rueda & Ruffini (2012).

**Episode 2** is emitted after the collapse of the NS to a BH. All technical, numerical and basic physical processes have been tested in the literature, and the fireshell model is now routinely applied to all GRBs, see e.g., GRB 101023 in Penacchioni et al. (2012) and GRB 110709B in Penacchioni et al. (2013).

**Episode 3** is the emission of the SN ejecta. The concurrence of the above well-defined scaling laws and power law of the observed luminosities in the X-rays of the BdHNe have been considered arguments in favor for looking to the $r$-process and to heavy nuclei radioactive decay as the energy sources (Ruffini et al., 2014a; Li & Paczynski, 1998). The extended interaction of the $\nu$-NS and its binary NS companion in the SN ejecta (see Fig. 4.3) provides environment for $r$-processes to create the needed neutron rich very heavy elements to attribute some of the electromagnetic energy in Episode 3 to nuclear decay, $\approx 10^{52}$ erg. Alternatively, we are considering emission originating from type-I and type-II Fermi acceleration mechanisms, introduced by Fermi precisely to explain the radiation process in the SN remnants (Fermi, 1949). Also these processes can lead to a power law spectrum (Aharonian, 2004), similar to the one presented in Section 4.4 and in our recent letter (Ruffini et al., 2014a). The GRB emission of Episode 2 interacting with the SNe ejecta could represent that energy injection long sought by Fermi for the onset of his acceleration mechanism (Fermi, 1949). Both of the above processes can indeed operate as energy sources for the mildly relativistic X-ray component.

**Episode 4**: emergence of the SN emission after $\sim 10–15$ days from the occurrence of the GRB, in the source rest-frame. It has been observed for almost all the sources fulfilling the IGC paradigm with $z \lesssim 1$, for which current optical instrumentation allows their identification.
4.1 The induced gravitational collapse and the new concept of binary-driven hypernova

Figure 4.2: Sketch of the accretion induced collapse scenario. An evolved star in close binary with a NS explodes as a SN Ib/c. The NS rapidly accretes a part of the SN ejecta and reaches in a few seconds the critical mass undergoing gravitational collapse to a BH, emitting the GRB.
Figure 4.3: IGC spacetime diagram (not in scale) illustrates 4 episodes of IGC paradigm: the non-relativistic Episode 1 ($\Gamma \simeq 1$), the relativistic motion of Episode 2 ($\Gamma \simeq 10^2 \sim 10^3$), the mildly relativistic Episode 3 ($\Gamma \simeq 2$), and non-relativistic Episode 4 ($\Gamma \simeq 1$). Initially there is a binary system composed by a massive star (yellow thick line) and a NS (blue line). The massive star evolves and explodes as a SN at point A, forms a $\nu$NS (red line). The companion NS accretes the SN ejecta starting from point B, interacts with the $\nu$NS starting from point C, and collapses into a BH (black line) at point D, this period from point B to point D we define as Episode 1. Point D is the starting of Episode 2, due to the collision of GRB outflow and interstellar filaments. At point E, Episode 2 ends and Episode 3 starts. Episode 3 lasts till the optical signal of SN emerges at point F, where the Episode 4 starts.
4.1 The induced gravitational collapse and the new concept of binary-driven hypernova

4.1.3 BdHN progenitor and low-energy GRBs-SNe

The occurrence of a BdHN event in the scenario presented above is subjected to some specific conditions of the NS-FeCO binary progenitor system, such as a short binary separation and orbital period $P < 1 \text{ h}$. This is indeed the case of GRB 970828, which has been analyzed in Ruffini et al. (in press) and will be exposed in Section 4.2. It is also worth noticing that the condition $B \lesssim 10^{-2}$ on the baryon load parameter of a GRB (Ruffini et al., 2000) might constrain on the binary separation $a$ for the occurrence a GRB-SN event. When the NS reaches the critical mass, the distance between the location of the front of the undisturbed SN ejecta and the NS center should be $<< a$, otherwise the emitted $e^+e^-$ plasma in the GRB might engulf a large amount of baryonic matter from the SN ejecta, reaching or even overcoming the critical value $B \sim 10^{-2}$.

It is appropriate now to discuss the possible progenitors of such binary systems. A viable progenitor is represented by X-Ray Binaries such as Cen X-3 and Her X-1 (Schreier et al., 1972; Wilson, 1972; Tananbaum et al., 1972; Leach & Ruffini, 1973; Gursky & Ruffini, 1975; Rawls et al., 2011). The binary system is expected to follow an evolutionary track (see Nomoto & Hashimoto, 1988; Iwamoto et al., 1994, ...
for details): the initial binary system is composed of main-sequence stars 1 and 2 with a mass ratio $M_2/M_1 \gtrsim 0.4$. The initial mass of the star 1 is likely $M_1 \gtrsim 11M_\odot$, leaving a NS through a core-collapse event. The star 2, now with $M_2 \gtrsim 11M_\odot$ after some almost conservative mass transfer, evolves filling its Roche lobe. It then starts a spiral in of the NS into the envelope of the star 2. If the binary system does not merge, it will be composed of a Helium star and a NS in close orbit. The Helium star expands filling its Roche Lobe and a non-conservative mass transfer to the NS, takes place. This scenario naturally leads to a binary system composed of a FeCO star and a massive NS, as the one considered in the IGC scenario. If after the BdHN event the $\nu$-NS and the BH are still gravitationally bound they give origin to a new kind of binary system, which can lead itself to the merging of the NS and the BH and consequently to a new process of gravitational collapse of the NS into a final single BH. In this case the system could originate an additional process of GRB emission, eventually emitting a genuine-short GRB, and possibly a predominant emission in gravitational waves.

It is important to recall that the association of a long GRB and a SN occurs most commonly in a family of less energetic long GRBs (see e.g. Maselli et al., 2013b) with the following characteristics: 1) isotropic energies $E_{iso}$ in the range of $10^{49}$–$10^{52}$ erg (Guetta & Della Valle, 2007); 2) a soft spectrum with rest-frame peak energy $E_{p,i} < 100$ keV, although the instruments are sensitive up to GeV; 3) a X-ray emission far weaker than canonical ones observed in the GS (see Figure 4.4 and Pisani et al., 2013); 4) SN emissions are observable up to a cosmological distance $z < 1$. We shall refer to this family in the following as family 1. On the other hand we have the energetic GRBs-SNe systems, namely the BdHNe, with their characteristics: 1) $E_{iso}$ is in the range $10^{52}$–$10^{54}$ erg; 2) they present multiple components in their spectra and in their overall luminosity distribution, ranging from X-ray, $\gamma$-ray all the way to GeV emission. They have peak energies from 100 keV to some MeV; 3) they presents a striking common behaviour in the late X-rays (Pisani et al., 2013); 4) in view of their large energetics, their observation extends to the entire universe all the way up to $z = 8.2$ (Ruffini et al., 2014b). We shall refer to the BdHN family as family 2.

As first pointed out in Rueda & Ruffini (2012) and Ruffini et al. (2014a), further evidenced in Fryer et al. (2014), the crucial factor which may explain the difference between the family 1 and family 2 of GRBs is the initial distance between the FeCO core and its binary NS companion. The accretion from the SN ejecta onto the companion NS and the consequent emission process decrease by increasing this distance: consequently is hampered the possibility for the binary companion NS to reach its critical mass (see Fig. 3 and Fig. 4 in Izzo et al., 2012b, and the discuss therein). Unlike family 2, in family 1 no BH is formed, no GRB is emitted, and no Episode 2 nor Episode 3 exist, only a softer and less energetic radiation from the accretion onto the NS will be observed in these sources. The problem of explaining the coincidence between the GRB and SN in the case of the family 1 is just a tautology: no GRB in this family exist but only a hypernova (Ruffini et al., 2014a).
4.2 The origin of Episode 1: hypercritical accretion onto a NS

4.2.1 The Bondi-Hoyle-Lyttleton accretion framework

We turn now to the details of the accretion process of the SN material onto the NS. In a spherically symmetric accretion process, the magnetospheric radius is given by (see e.g. Toropina et al., 2012) \( R_m = B^2 R^6 / (\dot{M} \sqrt{2GM_{\text{NS}}})^{2/7} \), where \( B, M_{\text{NS}}, R \) are the NS magnetic field, mass, radius, and \( \dot{M} \equiv dM/dt \) is the mass-accretion rate onto the NS. We now estimate the relative importance of the NS magnetic field on the accretion process. At the beginning of a SN explosion, the ejecta moves at high velocities \( v \sim 10^9 \) cm s\(^{-1}\), and the NS will capture matter at a radius approximately given by \( R_{\text{cap}}^{\text{sph}} \sim 2GM/v^2 \). For \( R_m << R_{\text{cap}}^{\text{sph}} \), we can neglect the effects of the magnetic field. In Fig. 4.5 we have plotted the ratio between the magnetospheric radius and the gravitational capture radius as a function of the mass accretion rate onto a NS of \( B = 10^{12} \) Gauss, \( M_{\text{NS}} = 1.4M_\odot \), \( R = 10^6 \) cm, and for a flow with velocity \( v = 10^9 \) cm s\(^{-1}\). It can be seen how for high accretion rates the influence of the magnetosphere is negligible.

We therefore assume hereafter, for simplicity, that the NS is non-rotating and neglect the effects of the magnetosphere. The NS captures the material ejected from the core collapse of the companion star in a region delimited by the radius \( R_{\text{cap}} \) from

![Figure 4.5: Magnetospheric to gravitational capture radius ratio of a NS of \( B = 10^{12} \) Gauss, \( M_{\text{NS}} = 1.4M_\odot \), \( R = 10^6 \) cm, in the spherically symmetric case. The flow velocity has been assumed as \( v = 10^9 \) cm s\(^{-1}\).](image-url)
the NS center

\[ R_{\text{cap}} = \frac{2GM_{\text{NS}}}{v_{\text{rel},e}^2}, \]  

(4.2)

where \( v_{\text{rel},e} \) is the ejecta velocity relative to the orbital motion of the NS

\[ v_{\text{rel},e} = \sqrt{v_{\text{orb}}^2 + v_{ej}^2}, \quad v_{\text{orb}} = \sqrt{\frac{G(M_{\text{SN-prog}} + M_{\text{NS}})}{a}}, \]  

(4.3)

with \( v_{ej} \) the velocity of the ejecta and \( v_{\text{orb}} \) the orbital velocity of the NS, where \( a \) is the binary separation. Here we have assumed that the velocity of the SN ejecta \( v_{ej} \) is much larger than the sound speed \( c_s \) of the material, namely that the Mach number of the SN ejecta satisfies \( \mathcal{M} = v_{ej}/c_s >> 1 \), which is a reasonable approximation in the present case. The orbital period of the binary system is

\[ P = \sqrt{\frac{4\pi^2a^4}{G(M_{\text{SN-prog}} + M_{\text{NS}})}}, \]  

(4.4)

where \( M_{\text{SN-prog}} \) is the mass of the SN core progenitor.

The NS accretes the material that enters into its capture region defined by Eq. (4.2). The mass-accretion rate is given by (see Bondi & Hoyle, 1944, for details)

\[ \dot{M} = \xi\pi\rho_{ej}R_{\text{cap}}^2v_{ej} = \xi\pi\rho_{ej}\frac{(2GM_{\text{NS}})^2}{(v_{\text{orb}}^2 + v_{ej}^2)^{3/2}}, \]  

(4.5)

where the parameter \( \xi \) is comprised in the range \( 1/2 \leq \xi \leq 1 \), \( \rho_{ej} \) is the density of the accreted material, and in the last equality we have used Eqs. (4.2) and (4.3). The upper value \( \xi = 1 \) corresponds to the Hoyle-Lyttleton accretion rate (Hoyle & Lyttleton, 1939). The actual value of \( \xi \) depends on the properties of the medium on which the accretion process occurs, e.g. vacuum, wind. In Fig. 4.2 we have sketched the accreting process of the SN ejected material onto the NS.

The high and rapid accretion rate of the SN material can lead the NS mass to reach the critical value \( M_{\text{crit}} \). This system will undergo gravitational collapse to a BH, producing a GRB. The initial NS mass is likely to be rather high due to the highly non-conservative mass transfer during the previous history of the evolution of the binary system (see e.g. Nomoto & Hashimoto, 1988; Iwamoto et al., 1994, for details). Thus, the NS could reach the critical mass in just a few seconds. Indeed, Eq. (4.6) shows that for an ejecta density \( 10^6 \, \text{g cm}^{-3} \) and ejecta velocity \( 10^9 \, \text{cm s}^{-1} \), the accretion rate might be as large as \( \dot{M} \sim 0.1M_{\odot}\text{s}^{-1} \). This first estimate of the IGC process was based on a simplified model of the binary parameters and the Bondi-Hoyle-Lyttleton accretion rate. Fryer et al. (2014) present the first full numerical simulations of the IGC phenomenon. The authors simulate the core-collapse and SN explosion of FeCO stars to obtain the density and ejection velocity of the SN ejecta. The hydrodynamic evolution of the accreting material falling into the Bondi-Hoyle surface of the NS is followed all the way up to its incorporation to the NS surface. The simulations go up to BH formation when the NS reaches the critical mass. For appropriate binary parameters the IGC occurs in short timescales \( \sim 10^2 - 10^3 \, \text{s} \) owing to the combined effective action of the photon trapping and the
neutrino cooling near the NS surface. Fryer et al. (2014) also show that the IGC scenario leads to a natural explanation for why GRBs are associated only to SN Ic with totally absent or very little helium.

4.2.2 The origin of the thermal component

The first estimate of the IGC process (Rueda & Ruffini, 2012) was based on a simplified model of the binary parameters and the Bondi-Hoyle-Lyttleton accretion formalism (Hoyle & Lyttleton, 1939; Bondi & Hoyle, 1944; Bondi, 1952). The following discussion is based on the more recent and accurate results presented in Fryer et al. (2014) (see Figure 4.6), in which the collapsing FeCO cores leading to SN Ic are simulated to calculate realistic profiles for the density and ejection velocity of the SN outer layers. The hydrodynamic evolution of the accreting material falling into the Bondi-Hoyle accretion region is also computed from numerical simulations all the way up to its incorporation onto the NS surface.

The hypercritical accretion onto the NS from the SN ejecta can be estimated from the Bondi-Hoyle-Lyttleton formula

\[ \dot{M}_{BHL} = 4\pi r_{BHL}^2 \rho (v^2 + c_s^2)^{1/2}, \]

where \( \rho \) is the SN ejecta density, \( v \) is the ejecta velocity in the rest-frame of the NS, which includes a component from the ejecta velocity, \( v_{ej} \), and another component from the orbital velocity of the NS, \( v_{orb} \); \( c_s \) is the SN ejecta sound speed, and \( r_{BHL} \) is the Bondi radius

\[ r_{BHL} = \frac{GM_{NS}}{v^2 + c_s^2}, \]

being \( G \) the gravitational constant and \( M_{NS} \) is the NS mass. The conditions of the binary system are such that both the velocity components, \( v_{orb}, v_{ej} \), are typically
much larger than the sound speed. The ejecta velocity as a function of time is

determined by the explosion energy and the nature of the SN explosion. The orbital
velocity depends upon the orbital separation, which in turn depends upon the radius
of the FeCO core and the binary interactions prior to the explosion of the FeCO
core. The effect of the NS magnetic field is negligible in this process (Fryer et al.,
1996; Rueda & Ruffini, 2012): for a NS with surface magnetic field \( B = 10^{12} \) G,

mass \( M_{NS} = 1.4 M_\odot \), and radius \( r_{NS} = 10^6 \) cm, one has that for accretion
rates \( \dot{M} > 2.6 \times 10^{-8} M_\odot \) yr\(^{-1} \), the Alfvén magnetospheric radius satisfies

\[
R_A = \left[ \frac{B^2 R_6^2}{(\dot{M}\sqrt{2GM_{NS}})^{2/7}} \right] < r_{NS}.
\]

The evolution of the SN ejecta density near the NS companion depends on the SN
explosion and the structure of the progenitor just prior to collapse. The compactness
of the FeCO core is such that there is no Roche lobe overflow prior to the SN
explosion. The Roche lobe radius can be computed from Eggleton (1983),

\[
R_{L,CO}/a \approx 0.49q^{2/3}/[0.6q^{2/3} + \ln(1 + q^{1/3})],
\]

where \( q = M_{CO}/M_{NS} \). For a FeCO core progenitor

\( M_{CO} \approx 5 M_\odot \), \( R_{CO} \approx 3 \times 10^9 \) cm, no Roche lobe
overflow occurs for binary periods \( P \geq 2 \) min, or binary separations \( a \geq 6 \times 10^9 \) cm, assuming a NS companion mass

\( M_{NS} \geq 1.4 M_\odot \).

In order to derive the accretion onto the NS, the explosion has to be modeled.
Fryer et al. (2014) have recently performed the numerical simulations following two
different approaches: the first assuming a homologous outflow with a set explosion
energy and a second approach following the collapse, bounce, and explosion of a

\( 20 M_\odot \) zero-age main sequence (ZAMS) mass progenitor. The calculation uses a 1D
core-collapse code (Fryer et al., 1999a) to follow the collapse and bounce and then
injects energy just above the proto-NS to drive different SN explosions mimicking
the convective-engine paradigm. With this progenitor and explosion, we produce
the density and velocity evolution history at the position of the Bondi-Hoyle surface
of the NS companion.

Under the above conditions, we have found from our numerical simulations in
Fryer et al. (2014) that hypercritical accretion rates of up to \( 10^{-2} M_\odot/s \) occur in these
systems. This infall rate is well above the critical Eddington rate. The Eddington
accretion limit, or critical accretion rate makes a series of assumptions: 1) the
potential energy gained by the accreting material is released in the form of photons
which exert pressure finally reducing the accretion rate, 2) the inflowing material
and outflowing radiation is spherically symmetric, 3) the photons are not trapped
in the flow and can deposit momentum to the inflowing material, and 4) the opacity
is dominated by electron scattering. However, many of these assumptions break down
in the IGC scenario, allowing hypercritical accretion rates.

It can be shown that the photons for the hypercritical accretion rates in the IGC
are trapped in the flow. Chevalier (1989) derived the trapping radius where photons
emitted diffuse outward at a slower velocity than infalling material flows inward:

\[
r_{trapping} = \min\left(\frac{M_{BH,\kappa}}{4\pi c}, r_{BHL}\right)
\]

where \( \kappa \) is the opacity (in \( \text{cm}^2 \) \( \text{g}^{-1} \)) and \( c \) is the speed of light. If the trapping radius
is near or equal to the Bondi radius, the photons are trapped in the flow and the
Eddington limit does not apply. We estimate for our FeCO core a Rosseland mean
opacity roughly \( 5 \times 10^3 \) \( \text{cm}^2 \) \( \text{g}^{-1} \), a factor \( \sim 10^4 \) higher than electron scattering.
4.2 The origin of Episode 1: hypercritical accretion onto a NS

Combined with our high accretion rates, it is clear that the Eddington limit does not apply in this scenario and hypercritical accretion must occur.

The inflowing material shocks as it piles up onto the NS producing an atmosphere on top of the NS which, by compression, becomes sufficiently hot to emit neutrinos (Zel’dovich et al., 1972; Chevalier, 1989; Houck & Chevalier, 1991; Fryer et al., 1996). The neutrinos have become then crucial in cooling the infalling material, allowing its incorporation into the NS (Ruffini & Wilson, 1973; Fryer et al., 1996; Fryer, 2009). We compute the neutrino emission following (Fryer et al., 1996; Fryer, 2009). We thus take into account $\nu_e$ and $\nu^+$ capture by free protons and neutrons, and pair and plasma $\nu\bar{\nu}$ creation; $\nu$ absorption processes include $\nu_e$ capture by free neutrons, $\bar{\nu}_e$ by free protons, and $\nu\bar{\nu}$ annihilation. $\nu$ scattering includes $\nu^-$ and $\nu^+$ scattering off $\nu$ and neutral current opacities by nuclei. The three species $\nu_{e,\mu,\tau}$ are tracked separately by the transport algorithm.

As material piles up, the accretion shock moves outward. The accretion shock weakens as it moves out and the entropy jump becomes smaller, producing an unstable atmosphere with respect to Rayleigh-Taylor convection. Previous simulations (Fryer et al., 2006; Fryer, 2009) of such instabilities accretion process have shown that they can accelerate above the escape velocity driving outflows from the accreting NS with final velocities approaching the speed of light, causing the ejection of up to 25% of the accreting material. The entropy of the material at the base of our atmosphere, $S_{\text{bubble}}$, is given by (Fryer et al., 1996):

$$S_{\text{bubble}} = 38.7 \left( \frac{M_{\text{NS}}}{2M_{\odot}} \right)^{7/8} \left( \frac{\dot{M}_{\text{BHL}}}{0.1 M_{\odot} \text{s}^{-1}} \right)^{-1/4} \left( \frac{r_{\text{NS}}}{10^6 \text{ cm}} \right)^{-3/8}$$

$k_B$ per nucleon, where $r_{\text{NS}}$ is the radius of the NS. The corresponding temperature of the bubble, $T_{\text{bubble}}$, is:

$$T_{\text{bubble}} = 195 S_{\text{bubble}}^{-1} \left( \frac{r_{\text{NS}}}{10^6 \text{ cm}} \right)^{-1}.$$  

Under the hypercritical accretion of the IGC, the temperature of the bubble when it begins to rise is $T_{\text{bubble}} \sim 5 \text{ MeV}$. If it rises adiabatically, expanding in all dimensions, it drops to $5 \text{ keV}$ at a radius of $10^9 \text{ cm}$, far too cool to observe. However, if it is ejected in a jet, as simulated in Fryer (2009), it expands laterally but not radially, so we have roughly $\rho \propto r^2$ and $T \propto r^{-2/3}$. In that simplified bubble evolution, the outflow would have a temperature $T_{\text{bubble}} \sim 50 \text{ keV}$ at $10^9 \text{ cm}$ and $T_{\text{bubble}} \sim 15 \text{ keV}$ at $6 \times 10^9 \text{ cm}$. This could explain the temperature and size evolution of the blackbody observed in the Episode 1 of BdHNe. For example, the blackbody observed in Episode 1 of GRB 090618 (Izzo et al., 2012a) evolves as $T \propto r^{-m}$ with $m = 0.75 \pm 0.09$, in agreement with this simplified theoretical estimate. For the case of GRB 970828, the fully lateral bubble evolution do not match perfectly, implying that the above simplified picture needs further refinement and/or the presence of other mechanisms. We are currently deepening our analysis of the possible explanation of the thermal emission observed in Episode 1 of BdHNe as based on convective instabilities in the hypercritical accretion process, and the results will be presented elsewhere.
4.2.3 A possible explanation for the non-thermal component

Concerning the power-law component observed in the luminosity of Episode 1 in addition to the blackbody one, we advance the possibility that such a high-energy emission could come from the angular momentum of the binary system as follows. The angular momentum per unit mass accreting by the NS can be estimated as

\[ j_{\text{acc}} \approx \frac{1}{2} \omega_{\text{orb}} r_B^2, \]  

where \( \omega_{\text{orb}} = v_{\text{orb}} / a \) is the orbital angular velocity, \( v_{\text{orb}} = (GM_T / a)^{1/2} \) is the orbital velocity, \( a \) the separation distance of the binary components, \( M_T = M_{\text{CO}} + M_{\text{NS}} \) is the total mass of the binary. \( r_B \) is the Bondi capture radius. From our numerical simulations, we know that when the NS reaches the critical mass, the inequality \( v_{\text{ej}} \ll v_{\text{orb}} \) is satisfied, so we can approximate Eq. (4.7) as

\[ r_{\text{BHL}} \approx \frac{2GM_{\text{NS}}}{v_{\text{orb}}^2} \rightarrow \frac{2GM_{\text{crit}}}{v_{\text{orb}}^2} = \frac{2GM_{\text{BH}}}{v_{\text{orb}}^2}, \]  

where \( M_{\text{BH}} = M_{\text{crit}} \), is the mass of the newly-formed BH, so it equals \( M_{\text{crit}} \), the critical mass of the NS. The BH can gain angular momentum up to it reaches the maximal value allowed by the Kerr solution

\[ j_{\text{maxBH}} = \frac{GM_{\text{BH}}}{c}. \]  

Therefore we have (see Fig. 4.7)

\[ \frac{j_{\text{maxBH}}}{j_{\text{acc}}} = \frac{1}{2} \frac{M_T}{M_{\text{BH}}} \sqrt{\frac{GM_T}{c^2 a}} = \frac{1}{2} \left( 1 + \frac{M_{\text{CO}}}{M_{\text{BH}}} \right) \sqrt{\frac{G(M_{\text{CO}} + M_{\text{BH}})}{c^2 a}}. \]  

Figure 4.7: Maximal BH to accretion angular momentum ratio, \( j_{\text{maxBH}} / j_{\text{acc}} \), as a function of the binary separation in units of solar radius. Here for simplicity we have used \( M_{\text{CO}} \approx 6 M_\odot \) and \( M_{\text{BH}} \approx 3 M_\odot \).
4.2 The origin of Episode 1: hypercritical accretion onto a NS

It becomes then clear from the above first simplified estimate that the angular momentum carried out by the accreted material highly exceed the maximal angular momentum that the newly-born BH can support, and therefore angular momentum dissipation, very likely in form of collimated emission, is likely to occur. We are currently performing numerical simulations of this process in order to assess the validity and accuracy of these first order of magnitude estimates.

4.2.4 The compactness problem in the non-thermal component

It is well known (see Piran, 1999) that most of GRBs emit a large fraction of observed high-energy photons ($E \gg 1$ MeV) which can interact with low-energy photons to produce electron-positron pairs via $\gamma \gamma \rightarrow e^+ e^-$ in a compact region with radius $R$ that, with a naive estimate, can be considered $R < ct \approx 3000$ km. This would imply an optical depth $\tau \gg 1$, but we know that GRB spectra are non-thermal, so we are in presence of a paradox. This issue can be solved assuming a relativistic expansion of the emitting source, with Lorentz factor $\Gamma \gg 1$ (Ruderman, 1975; Piran, 1999). In this case, in fact, we would have $R < 2c^2 \gamma^2 dt$ and consequently a decrease of the estimated optical depth (Woods & Loeb, 1995; Lithwick & Sari, 2001; Zhang & Pe`er, 2009). The observed high-energy photon spectrum is often modeled by a single power-law $KE^{-\gamma}$, with $E_{\min} < E < E_{\max}$ and power-law index $\gamma$. The energy $E_{\max}$ is the highest observed photon energy. In the frame of the emitting material, where the photons are assumed to be isotropic, a photon with energy $E'$ can annihilate a second photon with energy $E_{\text{th}}$, yielding an electron-positron pair. The threshold for this process is described by

$$E' E_{\text{th}} \geq (m_e c^2)^2 ,$$

where $m_e$ is the electron mass. If the source is moving toward the observer with a Lorentz factor $\Gamma$, then the photons previously analyzed have detected energy of $E = \Gamma E'/(1+z)$ and $E_{\text{th}} \geq \Gamma E_{\text{th}}/(1+z)$, respectively. Therefore in the observer frame photons with energy $E_{\max}$ annihilate only with other photons having energy $E_{\max,\text{th}} = [\Gamma m_e c^2/(1+z)]^2 E_{\max}$. Although the observed high-energy photon spectrum is a power-law up to 4 MeV in the rest frame of the burst, there is no observational evidence for the presence of a cut-off due to the $e^+e^-$-pair creation. Therefore we can estimate the minimum Lorentz factor of the non-thermal component allowed by the observations from the maximum energy observed in the first episode $E_{\max} \sim 2$ MeV. From this assumption, it is straightforward to impose that the threshold energy $E_{\max,\text{th}}$ for the pair creation process has to be $E_{\max,\text{th}} < E_{\max}$ (see e.g. case (III) in Gupta & Zhang, 2008). It follows then a lower limit on the Lorentz factor from the observed energy $E_{\max}$

$$\Gamma_{\min} \geq \frac{E_{\max}}{m_e c^2} (1+z) .$$

We can identify $E_{\max}$ with the cut-off energy of the spectrum $E_c$, but for the moment we treat them as different energies. Following the considerations in Gupta & Zhang
(2008), we have calculated the averaged number of photons interacting with $E_{\text{max}}$ from $E_{\text{max},\text{th}}$ to $E_{c} \geq E_{\text{max}}$ on the cross-section of the process integrated over all the angles $\theta$

\[
\langle \sigma N_{\text{max},\text{th}} \rangle = 4\pi d_{z}^{2} \Delta t \int_{E_{\text{max},\text{th}}}^{+\infty} K E^{-\gamma} dE \int_{1}^{E_{\text{max}} \gamma E_{\text{max}} \sigma_{T}} \frac{3}{16} \sigma_{T} ds = \frac{2E_{\text{max},\text{th}}^{1-\gamma}}{\xi} \tag{4.17}
\]

and we have correspondingly evaluated the optical depth

\[
\tau_{\gamma\gamma} = \frac{\langle \sigma N_{\text{max},\text{th}} \rangle}{4\pi (\Gamma^{2} c \Delta t)^{2}} , \tag{4.18}
\]

by defining the following quantities

\[
d_{z} = \frac{D}{1+z} , \quad s = \frac{E_{\text{max}} \gamma E(1 - \cos \theta)}{2(m_{e} c^{2})^{2}} , \quad \xi \equiv \left[ \frac{3\pi \sigma_{T} d_{z}^{2} K \Delta t}{4(\gamma^{2} - 1)} \right]^{-1} ,
\]

and using the Thomson cross-section $\sigma_{T}$. The condition $\tau_{\gamma\gamma} < 1$ yields to a lower limit on the Lorentz $\Gamma$ factor. We have applied these considerations to non-thermal spectrum of the first episode of GRB 970828, and considered for $\Delta \tau$ in Eq. 4.18 the whole duration of the first episode in GRB 970828. Therefore we have calculated an averaged lower limit on the Lorentz factor, i.e. $\Gamma_{\text{min}} = 77$ for the whole first episode. Therefore, a relativistic outflow of the accretion process of the SN onto the companion NS, can explain the origin of the power-law high energy component observed in Episode 1.

### 4.3 Prediction of a SN: GRB 130427A / SN 2013cq

We are going to show, in what follows, how GRB 130427A, associated with SN 2013cq and being the most luminous GRB ever observed in the past 40 years, offers the longest multi-wavelength observations of Episode 3 so far. It confirms and extends all the above understanding and the corresponding scaling laws already observed in X-ray to lower and higher energies. It allows the exploration of the occurrence of similar constant power-law emission in the high energy emission (GeV) and in the optical domain. We proceed with our data analysis of the ultra high GeV energy observations (Fermi/LAT), those in soft and hard X-rays (Swift/XRT and NuStar, respectively) as well as of optical observations (Swift/UVOT and ground based satellites). These observational facts set very specific limits: a) on the Lorentz $\Gamma$ factor of each component; b) on the corresponding mechanism of emission; c) on the clear independence of any prolongation of the GRB emission of Episode 2 to the emission process of Episode 3.

The observation of the scaling law in the first $2 \times 10^{4}$ s alone has allowed us to verify the BdHN nature of this source which necessarily implies the presence of a SN.
Figure 4.8: Overlapping of GRB 130427A and GRB 060729. Green cross is the light curve of GRB 060729. Red triangle and orange dots represent the light curve of GRB 130427A respectively before and after May 2, 2013. The vertical line marks the time of $2 \times 10^4$ s which is the lower limit for the domain of validity of the Pisani relation prior to GRB 130427A.
4.3.1 Identification and prediction

With the appearance of GRB 130427A, we decided to explore the applicability of the IGC paradigm in the “terra incognita” of GRB energies up to $\sim 10^{54}$ erg. In fact, prior to GRB 130427A, the only known case of an equally energetic source, GRB 080319B, gave some evidence of an optical bump (Bloom et al., 2009; Tanvir et al., 2010), but in no way a detailed knowledge of the SN spectrum or type. We soon noticed in GRB 130427A the characteristic overlapping of the late X-ray decay in the cosmological rest frame of the source with that of GRB 060729, a member of the GS (in red in Fig. 4.8), and from the overlapping we deduced a redshift which was consistent with the observational value $z = 0.34$ (Levan et al., 2013a).

Therefore from the observations of the first $2 \times 10^4$ s, GRB 130427A has been confirmed to fulfill the IGC paradigm, and we conclude, solely on this ground, that a SN should necessarily be observed under these circumstances. We sent the GCN circular 14526\(^1\) (Ruffini et al., 2013) on May 2, 2013 predicting that the optical R-band of a SN will reach its peak magnitude in about 10 days in the cosmological rest-frame on the basis of the IGC paradigm, and we encouraged observations. Indeed, starting from May 13, 2013, the telescopes GTC, Skynet and HST discovered the signals from the type Ic SN SN 2013cq (De Ugarte Postigo et al., 2013b; Trotter et al., 2013; Levan et al., 2013b,c; Xu et al., 2013b). We kept updating the X-ray Swift data for weeks and we confirmed the complete overlapping of the late X-ray luminosities, in the respective cosmological rest frames, of GRB 130427A and GRB 060729 (in orange in Fig. 4.8).

4.3.2 Data analysis of Episode 3

GRB 130427A was first observed by the Fermi/GBM at 07:47:06.42 UT on April 27 2013 (Von Kienlin, 2013), which we set as the starting time $t_0$ throughout the entire analysis. After 51.1 s, the Burst Alert Telescope (BAT) onboard Swift was triggered. The Swift Ultra Violet Optical Telescope (UVOT) and the Swift X-ray Telescope (XRT) began observing at 181 s and 195 s after the GBM trigger respectively (Maselli et al., 2013a). Since this was an extremely bright burst, successively more telescopes pointed at the source: the Gemini North telescope at Hawaii (Levan et al., 2013a), the Nordic Optical Telescope (NOT) (Xu et al., 2013a) and the VLT/X-shooter (Flores et al., 2013) which confirmed the redshift $z = 0.34$.

GRB 130427A is one of the few GRBs with an observed adequate fluence in the optical, X-ray and GeV bands simultaneously for hundreds of seconds. In particular it remained continuously in the LAT field of view until 750 s after the trigger of

\(^{1}\text{GCN 14526: The late X-ray observations of GRB 130427A by Swift/XRT clearly evidence a pattern typical of a family of GRBs associated to SNe following the Induce Gravitational Collapse (IGC) paradigm (Rueda & Ruffini 2012; Pisani et al. 2013). We assume that the luminosity of the possible SN associated to GRB 130427A would be the one of 1998bw, as found in the IGC sample described in Pisani et al. 2013. Assuming the intergalactic absorption in the I-band (which corresponds to the R-band rest-frame) and the intrinsic one, assuming a Milky Way type for the host galaxy, we obtain a magnitude expected for the peak of the SN of $I = 22 - 23$ occurring 13-15 days after the GRB trigger, namely between the 10th and the 12th of May 2013. Further optical and radio observations are encouraged.}
4.3 Prediction of a SN: GRB 130427A / SN 2013cq

Fermi/GBM (Ackermann et al., 2013), which gives us the best opportunity so far to compare the light curves and spectra in different energy bands, and to verify our IGC paradigm. In Ruffini et al. (in press) we did the data reduction of Fermi and Swift satellites by the following methods.

**Fermi:** Data were obtained from the Fermi Science Support Center\(^2\), and were analyzed using an unbinned likelihood method with Fermi Science Tools v9r27p1\(^3\). Event selections \texttt{P7SOURCE.V6} and \texttt{P7CLEAN.V6} were used, depending on which one gave more stable results. Recommended data cuts were used (e.g., \(z_{\text{max}} = 100\) degree). The background is composed of the galactic diffuse emission template and the isotropic emission template as well as about 60 point sources which are within the 15 degree radius of the GRB (however, their contribution was found to be negligible). The parameters for the background templates were held fixed during the fit. Luminosity light curve in Figure 4.9 corresponds to the energy range of 100 MeV to 100 GeV, circle radius of 15 degrees, with a power law spectra assumption. Since the data points up to the last two give a photon index of \(\approx 2.1\) with small errors, we set the photon index for the last two points to the value 2.1 during the fitting procedure in order to obtain more stable results. The light curve can be obtained with great temporal detail before 750 s. However, since we are interested in the general behavior of Episode 3, for simplicity we neglected such a fine temporal structure and we rebinned the light curve. Therefore there are only 3 data points up to 750 s. The spectrum is plotted in Figure 4.10.

**Swift:** XRT data were retrieved from UKSSDC\(^4\) and were analyzed by the standard Swift analysis software included in the NASA’s Heasoft 6.14 with relevant calibration files\(^5\). In the first 750 s only Windows Timing (WT) data exists and the average count rate exceeds 300 counts/s: the highest count rate even reaches up to 1000 counts/s, far beyond the value of 150 counts/s which is suggested for the WT mode as a threshold of considering pile-up effects (Evans et al., 2007a). Pile-up effects cause the detector to misrecognize two or more low energy photons as a single high energy photon, which softens the spectrum. We adopted the method proposed by Romano et al. (2006), fitting dozens of spectra from different inner sizes of box annulus selections in order to determine the extent of the distorted region. Taking the time interval 461 s to 750 s as an example, the deviation comes from where the inner size is smaller than 6 pixels, shown in Figure 4.10. Then we applied the standard XRT data analyzing process (Evans et al., 2007a, 2009b) to obtain the spectrum, plotted in Figure 4.10. For the luminosity light curve, we split XRT observations in the nominal 0.3–10 keV energy range to several slices with a fixed count number, and we followed the standard procedure (Evans et al., 2007a, 2009b) and considered the pile-up correction.

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\(^2\)http://Fermi.gsfc.nasa.gov

\(^3\)http://Fermi.gsfc.nasa.gov/ssc/data/analysis/software/

\(^4\)http://www.Swift.ac.uk

\(^5\)http://heasarc.gsfc.nasa.gov/lheasoft/
A new paradigm for energetic GRBs-SNe: binary-driven hypernovae

Figure 4.9: The multi-wavelength light curve of GRB 130427A. The high energy (100 MeV–100 GeV) emission detected by Fermi/LAT marked with red and soft X-ray (0.3–10 keV) data from Swift/XRT marked with blue are deduced from the original data. NuStar data (3 – 79 keV) marked with orange comes from (Kouveliotou et al., 2013). The optical (R band, center at 629 nm) data marked with green comes from ground based satellites (Perley et al., 2013). The error bars are too small with respect to the data points except for Fermi/LAT data. The horizontal error bars of Fermi/LAT represent the time bin in which the flux is calculated and vertical bars are statistical $1 - \sigma$ errors on the flux (the systematic error of 10% is ignored). The details in the first tens of seconds are ignored as we are interested in the behavior of the high energy light curve on a longer time scale. The vertical gray dashed line at ($\sim$ 400s) indicates when the constant decaying slope starts. It is clear that all the energy bands have almost the same slope after 400 s in Episode 3.
Figure 4.10: Top: Data from the \textit{Swift}/XRT (0.3–10 keV) in the time range of 461–750 s for GRB 130427A. The data shows the photon index for different region selections after considering the pile up effect. After 6 inner pixels the photon index approaches an almost constant value of 1.52. Bottom: Spectra of GRB 130427A in the time range of 461–750 s. The green data points are from \textit{Swift}/UVOT (Perley et al., 2013), the blue and gray points come from \textit{Swift}/XRT and red data correspond to \textit{Fermi}/LAT. The horizontal error bars are energy bins in which the flux is integrated and the vertical ones are $1 - \sigma$ statistical errors on the count rate. The gray data points correspond to unabsorbed \textit{Swift}/XRT data while the blue ones are obtained with the assumption of absorption.
4.3.3 The qualifying features for the identification of Episode 3

As presented in Ruffini et al. (in press), we first focus on the extended X-ray emission of Episode 3 which, as we have shown above, gives the qualifying features for the identification of GRB 130427A as a BdHN. We first proceed to identify the power law component of the light curve after the steep decay and the end of the plateau. This power law component, in the present case of this most energetic source GRB 130427A, has a power law index $\alpha = -(1.31 \pm 0.01)$ and it extends all the way from 400 s to $\sim 10^7$ s without jet breaks. These results are consistent with some previous papers (see e.g. in Perley et al., 2013; Laskar et al., 2013) which find no jet break, but differs from (Maselli et al., 2013b) in which a break of the later time light curve is claimed.

We turn now to an additional crucial point: to confirm that the X-ray emission of Episode 3 belongs to the SN ejecta and not to the GRB. To do this it is crucial, as already done for other sources (Ruffini et al., 2014a), to determine the presence of a thermal component in the early time of Episode 3 and infer its temperature and the size of its emitter. Indeed, by analyzing the XRT data, we find that adding a
blackbody component efficiently improves the fit with respect to a single power law from 196 s to 461 s. The corresponding blackbody temperature decreases in that time duration from 0.5 keV to 0.1 keV, in the observed frame. Figure 4.11 shows the evolution of the power law plus blackbody spectra in three time intervals, clearly the flux of thermal component drops along the time, as well as the temperature corresponding to the peak flux energy decreases. Kouveliotou et al. (2013) find that a single power law is enough to fit the NuStar data in the NuStar epochs, the reason could be that the thermal component has faded away or exceeded the observational capacity of the Swift satellite in the NuStar epochs, which start later than $10^5$ s.

By assuming that the blackbody radiation is isotropic in the rest frame, the emitter radius along the light of sight increases from $\sim 0.7 \times 10^{13}$ cm at 196 s to $\sim 2.8 \times 10^{13}$ cm at 461 s in the observed frame, orders of magnitude smaller than the emission radius of the GRB, which is larger than $10^{15}$ cm in the traditional GRB collapsar afterglow model. The size of $10^{13}$ cm at hundreds of seconds is consistent with the observation of SN ejecta. After considering the cosmological and the relativistic corrections, $t_a^d \simeq t(1+z)/(2\Gamma^2)$, where $t$ and $t_a^d$ are the time in the laboratory and observed frame respectively, and $\Gamma$ is the Lorentz factor of the emitter, we get an expansion speed of $\sim 0.8c$, corresponding to Lorentz factor $\Gamma = 1.67$. These results contradict the considerations inferred in (Maselli et al., 2013b) $\Gamma \sim 500$, which invoke a value of the Lorentz factor in the traditional collapsar afterglow model (see e.g. Mészáros, 2006). Again in the prototypical GRB 090618, the Lorentz factors ($1.5 \leq \Gamma \leq 2.19$) and emission radii ($\sim 10^{13}$ cm) are very similar to the ones of GRB 130427A presented in Ruffini et al. (2014a). It is interesting that such a thermal component has been also found in the early parts of Episode 3 of GRB 060729 and some other GRBs-SNe (see Ruffini et al., 2014a; Grupe et al., 2007a; Starling et al., 2012).

### 4.3.4 Discussion of multi-wavelength observations in Episode 3

Now we turn to the most unexpected feature in the analysis of the optical, X-ray, γ-ray and very high energy emission in Episode 3 of GRB 130427A (Ruffini et al., in press). The optical emission was observed by Swift/UVOT and many ground-based telescopes (R band as an example for the optical observation). The soft X-ray radiation was observed by Swift/XRT (0.3–10 keV). Similarly the hard X-ray radiation was observed by Swift/BAT (15–150 keV) and by NuStar (3–79 keV). The gamma ray radiation was observed by Fermi/GBM (8 KeV –40 MeV), and the high energy radiation by Fermi/LAT (100 MeV – 100 GeV). The main result is that strong analogies are found in the late emission at all wavelengths in Episode 3: after 400s, these luminosities show a common power law behavior with the same constant index as in the X-ray (and clearly with different normalizations), by fitting multi-wavelength light curves together we have a power law index $\alpha = -(1.3 \pm 0.1)$.

Turning now to the spectrum, integrated between 461 s and 750 s, the energy range covers 10 orders of magnitude, and the best fit is a broken power law (see Fig. 4.10). In addition to the traditional requirements for the optical SN emission in Episode 4, the much more energetically demanding requirement for the general
multi-wavelength emission of Episode 3 has to be addressed.

4.3.5 The onset of Episode 3

In the previous subsection we have emphasized the clear evidence of GeV emission and its analogy in the late power law luminosities as functions of the arrival time for the X-ray, optical and GeV emissions. Equally important in this section is to emphasize some differences between the X-, γ-ray, and the high energy GeV emission, especially with respect to the onset of Episode 3 at the end of prompt emission in Episode 2 (see Fig. 4.12). We observe:

1) The γ-ray light curves, observed by Fermi/GBM and hard X-ray observed by Swift/BAT, have similar shapes. They reach the highest luminosity between 4 s to 10 s during the prompt emission phase of Episode 2.

2) The high energy (> 100 MeV) GeV emission gradually rises up, just after the gamma and X-ray prompt emissions drop down at the end of Episode 2: the high energy GeV emission raises to its peak luminosity at about 20 s. The turn on of the GeV emission coincides, therefore, with the onset of our Episode 3. These considerations have been recently confirmed and extended by the earliest high energy observations in GRB 090510 (Pisani et al., in preparation).

3) At about 100 s, the Swift/XRT starts to observe the soft X-ray and a sharp spike appears in the hard X-ray and gamma ray bands (see Fig. 4.12). Only at this point the Swift/XRT started to observe soft X-ray. We are currently addressing the occurrence of the spike to the thermal emission observed to follow in the sharp decay of the X-ray luminosity prior to the plateau and the above mentioned common power law decay (Ruffini et al., in preparation).

The detailed analysis of the prolonged emission observed by Fermi/LAT in GeV enables us to set specific limits on the Lorentz factor of this high energy emission. We have analyzed the GeV emission from ∼300 s to 2.5 × 10^4 s, dividing this time interval into seven sub-intervals and in each of them collecting the corresponding maximum photon energy and photon index of the spectral energy distribution, as shown in Ackermann et al. (2013, Fig. 2). We have focused our attention on the estimate on the Lorentz factor for this high energy component from the usual optical depth formula for pair creation τ_{γγ} (see, e.g., Lithwick & Sari, 2001; Gupta & Zhang, 2008). We have computed for different values of radii of the emitter, the corresponding Lorentz factors at the transparency condition, i.e., τ_{γγ} = 1, see the solid curves in Figure 4.13. The constraints on the size of the emitting regions come from causality in the ultra-relativistic regime, i.e., R_{em} = 2Γ^2cΔt, where Δt corresponds to the duration of the time intervals under consideration (see the dot-dashed curves in Figure 4.13). The values of the Lorentz factor ranges between ∼10 and ∼40 and correspondingly, the radii of the emitting region at the transparency point are located between ∼10^{16} cm and ∼2 × 10^{17} cm (see the filled circles in Figure 4.13).
Figure 4.12: Flux of first 700 s. Blue points are the Fermi/LAT high energy emission from 100 MeV till 100 GeV (Ackermann et al., 2013), grey dotted line represents the Fermi/GBM, from 10 keV to 900 keV, green dashed line represents the photons detected by Swift/BAT from 10 keV to 50 keV, and red solid line is the soft X-ray Swift/XRT detection, in the range of 0.3 KeV to 10 KeV. From this figure, clearly the Fermi/LAT emission reaches highest fluence at about 20 s while the gamma-ray detected by Fermi/GBM releases most of the energy within the first 10 s.
Figure 4.13: Constraints on the Lorentz factors and on the size of the GeV emitting region at the transparency point. Solid curves represent the curves defined by varying the emitting region size from the $\tau_{\gamma\gamma} = 1$ condition; dot-dashed curves represent the radius of the emitter obtained from causality in the ultra-relativistic regime, i.e., $R_{em} = 2\Gamma^2 c \Delta t$. Filled circles correspond to the solutions of both the limits. The different colors refer to the time intervals from $\sim 273$ s to 24887 s, in the order: cyan, green, blue, purple, red, orange, and pink.
4.3 Prediction of a SN: GRB 130427A / SN 2013cq

4.3.6 Conclusions on GRB 130427A

We have recalled that GRB 130427A is one of the most energetic GRBs ever observed ($E_{\text{iso}} \simeq 10^{54}$ ergs), with the largest $\gamma$-ray fluence and the longest lasting simultaneous optical, X-ray, $\gamma$-ray and GeV observations of the past 40 years. For this reason in Ruffini et al. (in press) we have performed our own data analysis of the Swift and Fermi satellites in order to probe the BdHN nature of this source and infer new perspectives for the IGC paradigm and the physical and astrophysical understanding of GRBs.

We summarize the main results in the following.

- Following the work on the GS (Pisani et al., 2013) we have first verified that the soft X-ray emission of GRB 130427A follows for time $t \simeq 10^4$ s the power-law decay described in Pisani et al. (2013). Surprisingly in this most energetic GRB unveils such power-law behavior already exists at the early time as $t \sim 100$ s (details in Ruffini et al., in press, 2014a). From the X-ray thermal component observed at the beginning of Episode 3 following a spiked emission at $\sim 100$ s, a small Lorentz factor of the emitter is inferred ($\Gamma < 2$): this X-ray emission appear to originate in a mildly relativistic regime with a velocity $v \sim 0.8c$, in addition it does not appear to have substantial beaming and appears to be relatively symmetric and with no jet break, see Figure 4.9.

- Although the light curves of X-ray and GeV emission appear to be very similar, sharing similar power-law decay index, their Lorentz $\Gamma$ factors appear to be very different, and their physical origin are necessarily different. Within the IGC model the X-ray and the high energy can originate from the interaction of some of the physical components (e.g., NS and BH) newly created in IGC process: the interaction of the GRBs with the SN ejecta (Ruffini et al., in preparation) may well generate the X-ray emission and the associated thermal component. The high energy should be related to the novel three components, the BH, the $\nu$NS and the SN ejecta. From the dynamics it is likely that the $\nu$NS and the BH form a binary system (see e.g. Rueda & Ruffini, 2012).

- The verification of the BdHN paradigm in GRB 130427A has confirmed that for sources with isotropic energy approximately $10^{54}$ erg, the common power law behavior is attained at earlier times, i.e., $\sim 10^3$ s, and higher X-ray luminosities than the characteristic time scale indicated in (Pisani et al., 2013). From the observation of the constant-index power law behavior in the first $2 \times 10^4$ s of the X-ray luminosity light curve, overlapping with the known BdHNs, it is possible to have an estimate of: 1) the redshift of the source, 2) the isotropic energy of the GRB and 3) the fulfillment of the necessary and sufficient condition for predicting the occurrence of the SN after $\sim 10$ days in the rest frame of the source, see e.g., GCN 14526. This procedure has been successfully applied to GRB 140512A (Ruffini et al., in preparation).
4.4 Unveiling the nature of Episode 3

In Chapter 3 it has been showed that Episodes 1 and 2 can differ greatly in luminosity and timescale from source to source, while we confirm that in Episode 3, the late X-ray luminosities overlap: they follow a common power-law behavior with a constant slope in the source rest frame (Pisani et al., 2013). In a later work, Ruffini et al. (2014a) point out that the starting point of this power-law component is a function of the GRB isotropic energy $E_{\text{iso}}$. The main goals of Ruffini et al. (2014a) consisted in comparing and contrasting the steep decay, the plateau, and the power-law decay of the X-ray luminosities as functions of $E_{\text{iso}}$ by considering three selected GRBs (060729, 061121, and 130427A).

4.4.1 Nested structure

We now turn to show the “nested” structure of the late X-ray luminosity (see Ruffini et al., 2014a). Pisani et al. (2013) have shown that the X-ray rest-frame 0.3–10 keV luminosity light curves present a constant decreasing power-law behavior, at $t_a \gtrsim 10^4$ s, with typical slopes of $-1.7 \lesssim \alpha_X \lesssim -1.3$. This has been proven in the GS composed of six BdHNe: GRBs 060729, 061007, 080319B, 090618, 091127, and 111228 (GS, see, e.g., Pisani et al., 2013).

We compare and contrast GRB 130427A X-ray data with GRB 060729, a member of the GS, and GRB 061121, which shows the general behavior of BdHNe. GRB 060729, at $z = 0.54$, has $E_{\text{iso}} = 1.6 \times 10^{52}$ erg (Grupe et al., 2007a) and a SN bump in its optical afterglow (Cano et al., 2011). GRB 061121, at $z = 1.314$ (Bloom et al., 2006), has $E_{\text{iso}} = 3.0 \times 10^{53}$ erg, and its Episode 4 is clearly missing in view of the high cosmological redshift. In Fig. 4.14 we have plotted the rebinned rest-frame 0.3–10 keV luminosity light curves of GRBs 130427A, 060729, and 061121. Their steep decay is modeled by a power-law function, i.e. $L_p(t_a/100)^{-\alpha_p}$, where $L_p$ and $\alpha_p$ are the power-law parameters. The plateau and the late power-law decay are instead modeled by using the following phenomenological function

$$L(t_a) = L_X (1 + t_a/\tau)^{\alpha_X},$$

(4.19)

where $L_X$, $\alpha_X$, and $\tau$, respectively, are the plateau luminosity, the late power-law decay index, and the characteristic timescale of the end of the plateau. From Eq. (4.19), we have defined the end of the plateau at the rest-frame time $t_\ast_a = \tau[(1/2)^{1/\alpha_X} - 1]$, when the luminosity of the plateau is half of the initial one, $L_a(t_\ast_a) = L_X/2$.

From this fitting procedure, we can conclude that the three BdHNe systems considered here share the following properties:

a) the power-law decay for the more energetic sources starts directly from the steep decay, well before the $t_a \approx 2 \times 10^4$ s, as indicated in Pisani et al. (2013). Consequently, the plateau shrinks as a function of the increasing $E_{\text{iso}}$ (see Fig. 4.14);

b) the luminosities in the power-law decay are uniquely functions of the cosmological rest-frame arrival time $t_a$ independently on the $E_{\text{iso}}$ of each source (see Fig. 4.14);

c) most remarkably, the overlapping of the X-ray light curves reveals a “nested” structure of BdHNe Episodes 3.
4.4 Unveiling the nature of Episode 3

Figure 4.14: Rest-frame 0.3–10 keV re-binned luminosity light curves of GRB 130427A (purple), GRB 061121 (red, shifted by 50s in rest frame), and GRB 060729 (pink). The light curves are fitted by using a power-law for the steep decay phase (dashed lines) and the function in Eq. (4.19) for the plateau and the late decay phases (dot-dashed curves).
Table 4.1: List of the quantities of the considered sources and best fit parameters of the correlations in Fig. 4.15.

<table>
<thead>
<tr>
<th>GRB</th>
<th>(\langle L_{iso}\rangle) ((10^{50}\text{erg/s}))</th>
<th>(t_a^*) (ks)</th>
<th>(L_a) ((10^{47}\text{erg/s}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>060729</td>
<td>1.25 ± 0.08</td>
<td>27.4 ± 1.4</td>
<td>0.20 ± 0.01</td>
</tr>
<tr>
<td>061007</td>
<td>267 ± 18</td>
<td>0.041 ± 0.036</td>
<td>521 ± unc</td>
</tr>
<tr>
<td>080319B</td>
<td>279 ± 7</td>
<td>0.12 ± 0.03</td>
<td>430 ± 170</td>
</tr>
<tr>
<td>090618</td>
<td>34.7 ± 0.3</td>
<td>0.74 ± 0.03</td>
<td>7.81 ± 0.17</td>
</tr>
<tr>
<td>091127</td>
<td>26.8 ± 0.3</td>
<td>1.31 ± 0.10</td>
<td>4.39 ± 0.26</td>
</tr>
<tr>
<td>111228A</td>
<td>4.79 ± 0.24</td>
<td>2.17 ± 0.27</td>
<td>1.38 ± 0.10</td>
</tr>
<tr>
<td>130427A</td>
<td>98 ± 15</td>
<td>0.16 ± 0.03</td>
<td>121 ± 21</td>
</tr>
</tbody>
</table>

4.4.2 Correlations

In our sample of BdHNe, composed by the GS plus GRB 130427A (see Tab. 4.15), we verify the applicability of the Dainotti-Willingale relations \(\langle L_{iso}\rangle \sim t_a^*\) and \(L_a \sim t_a^*\) (Dainotti et al., 2008, 2011; Willingale et al., 2007), where \(\langle L_{iso}\rangle = E_{iso}/t_a\), \(90\) is the averaged luminosity of the prompt and \(t_a,90\) is the rest-frame \(t_{90}\) duration of the burst (see Ruffini et al., 2014a). The resulting correlations, \(\log_{10} Y_i = m_i \log_{10} X_i + q_i\), are shown in Fig. 4.15. The parameters of each BdHN and the best fit parameters, \(m_i\) and \(q_i\) (where \(i = 1,2\)), are summarized in Table 4.1. As is clear from the extra scatter values \(\sigma_i\), our total BdHN sample provides tighter correlations. The extra scatter of the \(L_a \sim t_a^*\), \(\sigma = 0.26\), is less than the Dainotti et al. (2011) ones, i.e., \(\sigma = 0.76\) for the whole sample of 62 bursts and \(\sigma = 0.40\) for the best subsample of eight bursts \((U0095)\). The Dainotti-Willingale correlations consider X-ray afterglows characterized by a steep decay, a plateau phase, and a late power-law decay (Nousek et al., 2006; Zhang et al., 2006), independently of their energetics. In our BdHN sample we limit the attention to a) the most energetic sources, \(10^{52}-10^{54}\) erg, b) the presence of four emission episodes (neglecting Episode 4 for \(z > 1\)), and c) sources with determined redshift and complete data at \(t_a = 10^4-10^6\) s. All these conditions appear to be necessary to fulfill the nested structure in Fig. 4.14 and the tighter correlations between the astrophysical parameters \(\langle L_{iso}\rangle, L_a,\) and \(t_a^*\) in Fig. 4.15.

4.4.3 The origin of Episode 3

To summarize:

a) the X-ray luminosity of Episode 3 in all BdHN sources presents precise scaling laws (see, e.g., Fig. 4.14);

b) the very high energy emission all the way, up to 100 GeV, in GRB 130427A, as well as the optical one, follows a power-law behavior in time similar to the one in the X-ray emission described above. The corresponding spectral energy
4.4 Unveiling the nature of Episode 3

Figure 4.15: The \(\langle L_{\text{iso}}\rangle-t_a^*\) (upper panel) and the \(L_a-t_a^*\) (lower panel) correlations (solid black lines) and the corresponding 1\(\sigma\) confidence levels (dashed black lines). The considered sources are GRB 060729 (pink), GRB 061007 (black), GRB 080319B (blue), GRB 090618 (green), GRB 091127 (red), GRB 111228A (cyan), and GRB 130427A (purple). The tighter BdHNe \(L_a-t_a^*\) correlation is compared to the one in Dainotti et al. (2011), corresponding to \(m = -1.04\) and \(q = 51.30\) (solid gray line) and \(\sigma = 0.76\) (dotted-dashed gray lines).
distribution is also described by a power-law function (Kouveliotou et al., 2013; Ruffini et al., in press);

c) an X-ray thermal component has been observed in the early phases of Episode 3 of several GRBs (Page et al., 2011; Starling et al., 2012). In particular, this feature has been clearly observed in GRB 090618 (Ruffini et al., 2014a) and GRB 130427A (Ruffini et al., in press). This implies an emission region size of \(10^{12} - 10^{13}\) cm in these early phases of Episode 3, with an expansion velocity of \(0.1 < v/c < 0.9\), with a bulk Lorentz \(\Gamma\) factor \(\lesssim 2\).

The simultaneous occurrence of these three features imposes very stringent constraints on any possible theoretical models. In particular, the traditional synchrotron ultra-relativistic scenario of the Collapsar jet model (Woosley, 1993; Mészáros & Rees, 2000) does not appear suitable for explaining these observational facts.

In Ruffini et al. (2014b,a, in press), we have recently pointed out the possibility of using the nuclear decay of ultra-heavy nuclei originally produced in the close binary phase of Episode 1 by \(r\)-process as an energy source of Episode 3. There is the remarkable coincidence that this set of processes leads to the value of the power-law emission with decay index \(\alpha\), similar to the one observed and reported in Metzger et al. (2010). The total energy emitted in the decay of these ultra-heavy elements agrees with the observations in Episode 3 of BdHN sources (Ruffini et al., 2014a). An additional possibility of process-generating a scale-invariant power law in the luminosity evolution and spectrum are the ones expected from type-I and type-II Fermi acceleration mechanisms (Fermi, 1949). The application of these acceleration mechanisms to the BdHN remnant has two clear advantages: 1) for us, to fulfill the above-mentioned power laws, both for the luminosity and the spectrum; and 2) for Fermi, to solve the longstanding problem, formulated by Fermi in his classic paper, of identifying the injection source to make his acceleration mechanism operational on an astrophysical level.
Chapter 5

Applications of the new distance indicator

5.1 Prediction of the redshift of GRB 140512

5.1.1 Observations

GRB 140512A was discovered on 12 May 2014, at 19:31 UT, by the Swift/BAT detector (Pagani et al., 2014). The BAT light curve showed a double emission episodes, characterized by a total duration of \( \sim \) 170 s. GRB 140512A was detected also by the Fermi/GBM (Stanbro, 2014) and by Konus/WIND (Golenetskii et al., 2014). The Swift/XRT and UVOT slewed immediately to point and observe the afterglow, finding a bright optical counterpart. Optical follow-up made with Master, Mondy, GROND and Xinlong TNT telescopes reported the evolution of the fading afterglow up to 11 hours from the initial outburst. Particularly interesting are the second set of the Master observations (Gorbovskoy et al., 2014), in which it is reported the results of observations in polarization mode up to 25 minutes from the initial outburst. The redshift of the GRB was determined by the NOT (De Ugarte Postigo et al., 2014) to be \( z = 0.725 \).

5.1.2 The early redshift estimate

The presence in the light curve of a long precursor, followed by a brighter event, qualitatively indicates the presence of Episodes 1 and 2 of a typical BdHN. On the other hand, the most important observational feature to scrutiny the membership of a GRB to the BdHNe sources consists in the overlapping of the X-ray afterglow luminosity light curve of the source (Episode 3), with the one of the prototypical BdHN, GRB 090618, when computed in a rest-frame energy band 0.3–10 keV (see, e.g., Pisani et al., 2013). To this aim, we have started to collect all the X-ray data observed by the Swift/XRT (Evans & Racusin, 2014). About one day after the GRB trigger in \( \gamma \)-rays, we were ready to compare the Episode 3 of this source with ones of the other best sample of BdHNe (the GS in Pisani et al., 2013 and GRB 130427A, for which the prediction of the occurrence of the associated SN (Ruffini et al., 2013) within the IGC paradigm was observationally confirmed by De Ugarte Postigo et al.,
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Figure 5.1: Fermi/GBM light curve from the NaI-n1 detector of GRB 140512A. The double emission episode nature is evident.

(2013b). On the ground of this fitting, we were able to predict a possible range of cosmological redshift of \(0.6 \lesssim z \lesssim 1.1\), defined within the scatter of the overlapping of all the BdHNe (see Fig. 5.2, left panel).

Observations from the NOT telescope provided the actual cosmological redshift to be \(z = 0.725\) (De Ugarte Postigo et al., 2014), within the range of our theoretical prediction, implying an isotropic energy \(E_{\text{iso}} = (7.67 \pm 0.11) \times 10^{52}\) erg. The agreement between the theoretical prediction and the observations, the overlapping of the Episode 3 at the actual redshift with the best sample of BdHNe (see Fig. 5.2, right panel), and the overall energetic \(> 10^{52}\) erg are sufficient to identify GRB 140512A as a BdHN source as well.

After having proved the membership of GRB 140512A to the class of BdHN sources, we started to analyse into details its Episodes.

5.1.3 Episode 1

Episode 1 of GRB 140512A occurs between \(T_0 - 10\) s and \(T_0 + 20\) s, where \(T_0\) is the Fermi trigger time, with a total duration of \(\sim 30\) s (see Fig. 5.3). The overall spectrum is well fit by a comptonised (Compt) spectral model (see Fig. 5.3). No evidence of a thermal component has been found, both in the time-integrated and the time-resolved analyses. On the other hand, there is an overall agreement in the energetic of its Episode 1, which is \(E^{(1)}_{\text{140512A}} = (1.68 \pm 0.06) \times 10^{52}\) erg, and the one of the prototype GRB 090618, i.e. \(E^{(1)}_{\text{090618}} = (4.09 \pm 0.07) \times 10^{52}\) erg (Izzo et al.,
5.1 Prediction of the redshift of GRB 140512

Figure 5.2: Upper panel: comparison between the Episode 3 of our best sample of BdHNe (gray data in background) to the one of GRB 140512A at $z = 0.6$ (blue lower data) and at $z = 1.1$ (green upper data), during the Les Houches meeting. Lower panel: the updated version of the overlapping of GRB 140512A at the measured redshift $z = 0.725$ (red data) with the best sample of BdHNe (gray data in background).
It is important to remark that in the case of GRB 090618, the thermal component in Episode 1 spectrum contributed at most at 10% of the total energy. We can conclude that the spectrum of Episode 1 of GRB 140512A is dominated by the non-thermal component, originating in the accretion process of the SN ejecta onto the companion NS, before the collapse into a BH.

5.1.4 Episode 2

Episode 1 of GRB 140512A, occurring between $T_0 + 100$ s and $T_0 + 160$ s, lasts $\sim 60$ s (see Fig. 5.3). Its isotropic energy is $E_{iso}^{(2)} = (5.99 \pm 0.09) \times 10^{52}$ erg. This emission has been also observed by the Swift/XRT. To better identify the transparency emission, the proper GRB (P-GRB) of Episode 2 within the Fireshell model (Ruffini et al., 2010), and to constrain its parameters, we have performed a joint GBM-XRT spectral analysis. We have found in the early 6 s of Episode 2 the best fit is Compt plus a black body (BB) component with a temperature $kT = (7.4 \pm 2.2)$ keV and, correspondingly, an energy $E_{BB} = (6.9 \pm 3.9) \times 10^{50}$ erg (see Fig. 5.4).

From these observed constraints we have derived the Baryon load $B = 3.25 \times 10^{-3}$, the laboratory radius at transparency $r_{tr} = 7.16 \times 10^{13}$ cm, and the corresponding Lorentz factor $\Gamma_{tr} = 303$.

Within the Fireshell model, the observed spikes in the prompt emission light curve after the P-GRB are due to the interaction of the Fireshell in optically thin regime with the circumburst medium (CBM). The fitting procedure requires an average CBM density of $\langle n \rangle = 1.4$ cm$^{-3}$ (see Fig. 5.5, left plot). The right plot in Fig. 5.5, shows the simulation of the GRB spectrum after the P-GRB, computed using the fireshell model.
5.1 Prediction of the redshift of GRB 140512

Figure 5.4: Fermi/GBM and Swift/XRT joint spectrum of the early 6 s of Episode 2 of GRB 140512A in the energy band 0.3–5000 keV. The best fit is Compt+BB.

Figure 5.5: Fermi/GBM NaI-n1 light curve (left) and NaI-n1+BGO-b0 spectrum (right) of GRB 140512A, compared to the Fireshell simulations (red lines).
5.1.5 Expectations on the Episode 4

The location of the GRB afterglow implies a value of the Galactic column density absorption of $N_{H,\text{gal}} = 1.47 \times 10^{21} \text{ cm}^{-2}$ (Kalberla et al., 2005). From the late time (PC mode) *Swift*/XRT observations, we have an intrinsic column density of the afterglow of $N_{H,\text{int}} = 9 \times 10^{20} \text{ cm}^{-2}$. Assuming a Milky Way type for the GRB host-galaxy, we compute, using standard procedures described in Predehl & Schmitt (1995); Cardelli et al. (1989); Schlegel et al. (1998), a Galactic and host galaxy extinction of $A(V)_{\text{MW}} = 0.54$, and $A(V)_{\text{host}} = 0.45$ respectively. Consequently, a possible emerging SN 1998bw-like (Clocchiatti et al., 2011) associated with this GRB would have peaked at an approximate observed magnitude $V \sim 24.5 - 25$ after 25-30 days from the GRB emission. If we consider the case of lower-energetic SNe, as the case of SN 2010bh (Bufano et al., 2012) we would have an approximate magnitude $V \sim 25.3 - 25.8$ after 17-22 days from the GRB emission. Unfortunately, the follow-up of the optical emission extended up to few days from the GRB trigger, so we do not have until now confirmation of the presence of Episode 4 of GRB 140512A.

5.1.6 Conclusions on GRB 140512A

From the analysis of the *Swift* and *Fermi* data, we have confirmed the BdHN nature of GRB 140512A. The presence in the $\gamma$-ray light curves of a long precursor, followed by a brighter event, qualitatively indicated the presence of Episodes 1 and 2 of a typical BdHN.

Episode 1 does not evidence the characteristic expanding thermal component in the spectrum of typical BdHNe (see, e.g., GRB 090618 in Izzo et al., 2012a). On the other hand, the energetic of the non-thermal part of the spectrum of GRB 140512A, $E_{\gamma,\text{140512A}}^{(1)} = (1.68 \pm 0.06) \times 10^{52} \text{ erg}$, is consistent with the one of the prototype GRB 090618, i.e. $E_{\gamma,\text{090618}}^{(1)} = (4.09 \pm 0.07) \times 10^{52} \text{ erg}$ (Izzo et al., 2012a). This led us to conclude that Episode 1 of GRB 140512A is dominated by the non-thermal component, originating in the accretion process of the SN ejecta onto the companion NS, before the collapse into a BH.

A detailed spectral analysis, performed by a joint GBM-XRT fitting procedure, allowed us to find the P-GRB emission in the early 6 s of Episode 2 and to constrain the basic parameters of the GRB emission in the fireshell model. GRB 140512A is, indeed, a canonical long GRB with an overall energetic $E_{\gamma,\text{iso}}^{(2)} = (5.99 \pm 0.09) \times 10^{52} \text{ erg}$, a baryon load $B = 3.25 \times 10^{-3}$, a laboratory radius at transparency $r_{tr} = 7.16 \times 10^{13} \text{ cm}$, and a corresponding Lorentz factor $\Gamma_{tr} = 303$. The joint simulation of the prompt emission light curve after the P-GRB, and of the corresponding spectrum (see Fig. 5.5) allowed us to infer the that GRB 140512A occurred in a CBM with an average number density of $\langle n_{\text{CBM}} \rangle = 1.4 \text{ cm}^{-3}$, typical, again, of canonical long GRBs.

The most important observational feature of GRB 140512A consists in the overlapping of its Episode 3 with the ones of our sample of BdHNe, when computed in a rest-frame energy band 0.3–10 keV (see, e.g., Pisani et al., 2013). Before the redshift determination by the NOT telescope of $z = 0.725$ (De Ugarte Postigo et al., 2013).
5.2 Pushing the distance indicator at high redshift: GRB 090423

In 2014, the working hypothesis that GRB 140512A could represent a new member of the BdHN sources, allowed us to predict a possible range of cosmological redshift of $0.6 \lesssim z \lesssim 1.1$, defined within the scatter of the overlapping of all the BdHNe (see Fig. 5.2, left panel). The agreement between the theoretical prediction and the observations, and the perfect overlap of the Episode 3 at the actual redshift by the NOT telescope with the best sample of BdHNe (see Fig. 5.2, right panel), allowed us to definitively conclude that GRB 140512A is a BdHN.

Unfortunately, the prediction of a possible emerging associated SN, with an expected peak magnitude $V \sim 24.5–25$ after 25–30 days from the GRB emission (for a SN 1998bw-like event), or with an approximate magnitude $V \sim 25.3–25.8$ after 17–22 days (for a SN 2010dh-like event), cannot be confirmed due to the limited in time the follow-up of the optical emission.

5.2 Pushing the distance indicator at high redshift: GRB 090423

5.2.1 Observations

GRB 090423 was discovered on 23 April 2009, 07:55:19 UT, $T_0$ from here, by the Swift Burst Alert Telescope (BAT) (Krimm et al., 2009), at coordinates R.A. = 09$^h$ 55$^m$ 35$^s$, Dec = +18$^\circ$ 09$'$ 37$''$ (J2000.0; 3$'$ at 90 % containment radius). The Swift/BAT light curve showed a double-peaked structure with a duration of about 20 s. The X-ray Telescope (XRT) on board the same spacecraft started to observe GRB 090423 72.5 s after the initial trigger, finding a fading source and providing enhanced coordinates for the follow-up by on-ground telescopes that have allowed the discovery of its redshift ($z = 8.2$, Salvaterra et al., 2009; Tanvir et al., 2009). The light curve is characterized by an intense and long flare peaking at about $T_0 + 180$, followed by a power-law decay, observed from the second orbit of Swift (Stratta & Perri, 2009). The prompt emission from GRB 090423 was also detected by the Fermi GBM (trigger 262166127 / 090423330), (Von Kienlin, 2009a), whose on-ground location was consistent with the Swift position. The Large Area Telescope (LAT) on-board the Fermi satellite did not detect any signal from GRB 090423. The GBM light curve showed a single-structured peak with a duration of about 12 s, whose spectral energy distribution was best fit with a power law with an exponential cut-off energy, parameterized as $E_{\text{peak}} = (82 \pm 15)$ keV. The observed fluence was computed from Fermi data to be $S_\gamma = 1.1 \times 10^{-6}$ ergs/cm$^2$ that, considering the standard ΛCDM cosmological model, corresponds to an isotropic energy emitted of $E_{\text{iso}} = 1.1 \times 10^{53}$ ergs for the spectroscopic redshift $z = 8.2$ (Von Kienlin, 2009b).

With these values for $E_{\text{peak}}$ and $E_{\text{iso}}$, GRB 090423 satisfies the Amati relation, which is only valid for long GRBs (Amati et al., 2002).

5.2.2 The impossibility of detecting Episode 1

It has become natural to ask if observations of Episodes 1 and 2 in the hard X-ray energy range could be addressed for the case of GRB 090423. In Ruffini et al.
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(2014b) we have analyzed a possible signature of Episode 1 in GRB 090423. Since the Swift/BAT, 15–150 keV, light curve is a single-structured peak with duration of $\sim 19$ s, as detected by Swift/BAT, with no thermal emission in its spectrum and no detection of any emission from a precursor in the Swift and Fermi data, we have considered the definite possibility that Episode 1 was not observed at all. In this light, the best way to check this possibility consists in verifying that the Episode 1 emission is below the threshold of the Swift/BAT detector, consequently, it could have not triggered the Swift/BAT. We have considered the prototype of Episode 1 as the one observed in GRB 090618 (Izzo et al., 2012a), which is at redshift $z = 0.54$, and then we transposed it at redshift $z = 8.2$, simulating the observed emission of GRB 090618 as if it had been observed at this large distance. Then, we performed a time-resolved spectral analysis of Episode 1 in GRB 090618, using a Band function as spectral model, and finally we translated the specific photon spectra obtained from the analysis at the redshift of GRB 090423. This last operation consists in two transformations, concerning the peak energy $E_{\text{peak}}$ of the Band function and the normalization value $K_{\text{Band}}$. The new value of the peak energy is simply given by $E_{\text{peak,8}} = E_{\text{peak}} (1 + 0.54) / (1 + 8.2)$, while the normalization, which corresponds to the specific photon flux at 1keV, requires knowledge of the luminosity distances of the two bursts, $d_l(z)$:

$$K_{\text{Band,8}} = K_{\text{Band}} \left( \frac{1 + 8.2}{1 + 0.54} \right)^2 \left( \frac{d_l(0.54)}{d_l(8.2)} \right)^2. \quad (5.1)$$

Another transformation concerns the observational time of Episode 1 of GRB 090618 at redshift $z = 8.2$. At large distances, any astrophysical event will be dilated in time by the cosmological redshift effect, which in the current case modifies the time interval by a quantity $(1 + 8.2) / (1 + 0.54) = 5.97$. The knowledge of this time interval is fundamental since it represents the exposure of a simulated spectrum translated at $z = 8.2$. We considered Fermi/GBM data for analyzing the time-resolved spectra of GRB 090618, as described by Izzo et al. (2012a). The wide energy range of Fermi/GBM NaI detectors, (8 - 1000) keV, allows a more accurate determination of the Band parameters, which are used as input values for the simulated spectra. We also rebinned the Fermi data considering a signal-to-noise ratio (SNR) = 10, and finally performed our spectral analysis. The next step consisted in transforming the peak energy of the Band function and of the normalization of all these time-resolved photon spectra $N(E)$, as described above.

Following the work of Band (2003), the sensitivity of an instrument to detect a burst depends on its burst trigger algorithm. The Swift/BAT trigger algorithm, in particular, looks for excesses in the detector count rate above expected background and constant sources. There are several criteria for determining the correct BAT threshold significance $\sigma_0$ for a single GRB (Barthelmy et al., 2005a), but in this work we have considered the treatment given in Band (2003). Recently, the threshold of Swift/BAT has been modified to allow detecting of subthreshold events, but since GRB 090423 was detected before, the Band (2003) analysis is still valid for our purposes. The preset threshold significance for Swift/BAT can be expressed by the following formula:
5.2 Pushing the distance indicator at high redshift: GRB 090423

<table>
<thead>
<tr>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_{p,i}$</th>
<th>norm. $\tilde{\chi}^2$</th>
<th>$\Delta t_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>090618</td>
<td>-0.66 ± 0.57</td>
<td>-1.99 ± 0.05</td>
<td>284.57 ± 172.10</td>
<td>0.3566 ± 0.16</td>
</tr>
<tr>
<td>090423</td>
<td>-0.78 ± 0.34</td>
<td>-3.5 ± 0.5</td>
<td>433.6 ± 133.5</td>
<td>0.015 ± 0.010</td>
</tr>
</tbody>
</table>

Table 5.1: Results of the spectral fits of the T90 duration of GRB 090423 and of the $\Delta t_{A,\text{obs}}$ time interval for GRB 090618. The latter is computed in a time interval corresponding to the one expected to be observed if GRB 090618 is transposed at the redshift $z = 8.2$, and in the observed energy range (89.6 - 896) keV.

\[
\sigma_0 = \frac{A_{\text{eff}} f_{\text{det}} f_{\text{mask}} \Delta t \int_{15}^{150} \epsilon(E) N(E) dE}{\sqrt{A_{\text{eff}} f_{\text{det}} \Delta t \int_{15}^{150} B(E) dE}}, \quad (5.2)
\]

where $A_{\text{eff}}$ is the effective area of the detector, $f_{\text{det}}$ the fraction of the detector plane that is active, $f_{\text{mask}}$ the fraction of the coded mask that is open, $\Delta t$ the exposure of the photon spectrum $N(E)$, $\epsilon(E)$ the efficiency of the detector, and $B(E)$ the background. We considered the values for these parameters as the ones given in the Band work (with the exception of the detecting area, assumed to be $A_{\text{eff}} = 5200$ cm$^2$), while the efficiency and the background were obtained from the Swift/BAT integrated spectrum of GRB 090423 using the XSPEC fitting package. Then we considered as input photon spectra $N(E)$ the ones obtained from the Fermi/GBM analysis of Episode 1 of GRB 090618 and translated for the redshift $z = 8.2$. It is appropriate to note that the transformations of spectra presented above are the correct ones: since the sensitivity of Swift/BAT strongly depends on the peak energy of the photon flux of the single spectra of the GRB (for the Swift/BAT case, see e.g. Fig. 7 of Band, 2003), we find that at $z = 8.2$ the observed peak energies of any spectrum will be lowered by a factor $(1 + 0.54)/(1 + 8.2)$. Our procedure takes this further effect of to the cosmological redshift into account also.

Since the threshold significance of Swift/BAT is variable from a minimum value of $\sigma_0 = 5.5$ up to a maximum value of 11\(^1\), with an average value of $\sigma_0 = 6.7$, the results of this first analysis suggest that an Episode 1 similar to the one of GRB 090618 would not have been detected in GRB 090423 (see Fig. 5.6).

5.2.3 Detection of Episode 2 and its analysis

Episode 2 emission of GRB 090423, detected by Swift/BAT, was examined in the context of the fireshell scenario (Ruffini et al., 2014b). A Lorentz Gamma factor of $\Gamma \sim 1100$ and a baryon load $B = 8 \times 10^{-4}$ were obtained. The simulations of the observed spikes in the observed time interval (0 - 440) s lead to homogeneous circumburst medium ($R = 10^{-8}$, see Bianco & Ruffini, 2005a for a complete description), and an average density of $10^{-1}$ particles cm$^{-3}$. The simulation of the GRB 090423 emission is shown in Fig. 5.7.

\(^1http://swift.gsfc.nasa.gov/about_swift/bat_desc.html\)
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Figure 5.6: Threshold significance $\sigma_0$ computed using the treatment of Band (2003) for any single time-resolved spectra of the first emission episode in GRB 090618, as if they were emitted at redshift 8.2. The dashed lines correspond to the values for the threshold significance of $\sigma_0 = 5.5$ and $\sigma_0 = 6.7$.

We can now compare and contrast the emission observed in GRB 090423, expressed at $z = 8.2$ (see Fig. 5.7, Izzo et al., 2010), and the portion of the emission of GRB 090618 if observed at $z = 8.2$ (see Fig. 5.8, Ruffini et al., in press). In view of the Swift/BAT threshold, only the dashed region in Fig. 5.9, lasting 6 s, would be detectable. The observed flux in Fig. 5.7 and the one of the dashed region in Fig. 5.9 will be similar when compared in a common frame.

For the above considerations, the analysis presented in the previous section can be applied to Episode 2 of GRB 090618. Assuming a detector threshold for Swift/BAT of $\sigma_0 = 6.7$, see Eq. 5.2, only the dashed region in Fig. 5.8 is detectable when transposing GRB 090618 at $z = 8.2$. In the observer frame, this emission corresponds to the time interval $(T_{0,G} + 63.0, T_{0,G} + 69.1)$ s, with $T_{0,G}$ the trigger time of Fermi/GBM data of GRB 090618. This time interval, at $z = 8.2$, has a duration $\Delta t_{A,\text{obs}} = \Delta t_{\text{obs}} \times 5.97 = 36.4$ s, owing to the time dilation by the cosmological redshift $z$ (see Fig. 5.7). The remaining emission of GRB 090618 is unobservable, since below the threshold of the Swift/BAT detector. We note that $\Delta t_{A,\text{obs}}$ is quite comparable to the observed duration of GRB 090423 (see Fig. 5.7).

We turn now to comparing and contrasting the spectral energy distributions in the rest frame of the two GRBs. We consider the spectrum of GRB 090618 in the energy range (89.6 - 896) keV, which corresponds to the Swift/BAT band (15 - 150) keV in the rest frame of GRB 090423. As for the time interval in GRB 090423, we consider the observational time interval (63.0 - 69.1) s, determined from applying Eq. 5.2 to the entire Episode 2 of GRB 090618 (see the dashed region in Fig. 5.8).
5.2 Pushing the distance indicator at high redshift: GRB 090423

Figure 5.7: *Swift/BAT* (15-150 keV) light curve emission of GRB 090423. The red line corresponds to the simulation of the GRB emission in the fireshell scenario (Izzo et al., 2010).
Figure 5.8: Light curve of Episode 2 in GRB 090618, ranging from 50 to 150 s. The dashed region represents the portion which would have triggered the Swift/BAT if this GRB had been at the redshift $z = 8.2$. The observed duration of that interval is approximately $\Delta t \simeq 6$ s. The results obtained in Fig. 5.7, when scaled to $z = 0.54$, provide $\Delta T \simeq 3$ s.
5.2 Pushing the distance indicator at high redshift: GRB 090423

We fitted the spectral emission observed in GRB 090423 with a Band function (Band et al., 1993), and the results provide an intrinsic peak energy \( E_{p,i} = (284.57 \pm 172.10) \) keV (see Table 5.1). The same model provides for the spectral emission of GRB 090423, in the \( T_{90} \) time duration, an intrinsic peak energy of \( E_{p,i} = (433.6 \pm 133.5) \) keV. However, the break in GRB 090423 is steeper, while in GRB 090618 it is more shallow. This is clear in Fig. 5.9, where we show the spectra of both GRBs that are transformed to a common frame, which is the one at redshift \( z = 8.2 \). Very likely, the difference in the steepening at high energies is related to the structure of the circumburst medium (CBM): the more fragmented the CBM, the larger the cutoff energy of the fireshell spectrum (Bianco & Ruffini, 2005a). Another important result is that the low energy index \( \alpha \) is quite similar in both GRBs. This agrees with the expectation from the fireshell scenario, where a photon index of \( \approx -0.8 \) is expected in the early emission of a GRB (Patricelli et al., 2011).

The isotropic energy emitted in the time interval delineated by the dashed region in Fig. 5.8 has been computed to be \( E_{iso} = 3.49 \times 10^{52} \) erg, which is very similar to the one computed for the \( T_{90} \) duration, in the same energy range, for GRB 090423, \( E_{iso} = 4.99 \times 10^{52} \) erg.

5.2.4 Striking observations of Episode 3

That in long GRBs the X-ray emission, observed by Swift/XRT in energy range 0.3–10 keV, presents a typical structure composed of a steep decay, a plateau phase and a late power-law decay, was clearly expressed by Nousek, Zhang and their
collaborators (Nousek et al., 2006; Zhang et al., 2006). This structure acquires a special meaning when examined in the most energetic sources, $E_{\text{iso}} = 10^{52} - 10^{54}$ erg, and leads to the fundamental proof that GRB 090423 is a BdHN source.

It has only been after applying the BdHN paradigm to the most energetic long GRBs associated to SNe that we noticed the most unique characterizing property of the BdHN sources: while the steep decay and the plateau phase can be very different from source to source, the late X-ray power-law component overlaps, when computed in the cosmological rest-frame (see Pisani et al., 2013 and Fig. 3.17). This has become the crucial criterion for asserting membership of a GRB in the BdHN family. Indeed, when we report the late X-ray emission of Episode 3 in GRB 090423 at $z = 8.2$, and GRB 090618 at $z = 0.54$, we observe a complete overlapping at times longer than $10^4$ s, see Fig. 5.10 and Ruffini et al. (2014b).

5.2.5 Conclusions on GRB 090423

The ansatz that GRB 090423 is the transposed of GRB 090618 at $z = 8.2$ has passed scrutiny. It is viable with respect to Episodes 1 and 4 and has obtained important positive results from the analysis of Episodes 2 and 3:

- Episodes 1 and 4 have not been detected in GRB 090423. This is consistent with the fact that the flux of Episodes 1 and 4 of GRB 090618 should not be observed by the Swift/BAT detector or by the optical telescopes, owing to
the very high redshift of the source and the current sensitivities of X-ray and optical detectors;

- Episode 2 of GRB 090423 has definitely been observed by Swift/BAT: its observed emission is comparable 1) to energy emitted \(3.49 \times 10^{52} \text{ erg for GRB 090618 and } 4.99 \times 10^{52} \text{ erg for GRB 090423}\), 2) to the observed time duration (34 s for the observable part of GRB 090618 when transposed to \(z = 8.2\) and 19 s for GRB 090423), and 3) to the spectral energy distribution: the low energy part of the spectra of both GRBs is consistent with the expectation of the fireshell model (Patricelli et al., 2011). There is a significant difference only in the high energy part of the spectrum of GRB 090423, where a cutoff is observed at lower energy than the one in GRB 090618. This can be explained, in the fireshell scenario, by the existence of a dense and homogeneous CBM (Bianco & Ruffini, 2005a), which is expected for bursts at high redshifts;

- Episode 3 shows the striking feature of the overlapping of the late X-ray luminosities of Episode 3 in GRB 090618 and GRB 090423, when compared in their cosmological rest frames (see Fig. 5.10). This result confirms the extension of the relation presented in Pisani et al. (2013) for \(z \leq 1\), all the way up to \(z = 8.2\).

From an astrophysical point of view, all the above results clearly indicate that

a) GRB 090423 is fully consistent with being a member of the BdHN family, and the associated SN did occur already at \(z = 8.2\): the possibility of having an evolved binary system about 650 Myr after the Big Bang is not surprising, since the lifetime of massive stars with a mass up to 30 \(M_\odot\) is \(~ 10 \text{ Myr} \) (Woosley et al., 2002), which is similar to expectations from normal Population II binary stars also at \(z = 8.2\), as pointed out by Belczynski et al. (2010);

b) the FeCO core and the NS companion occurring at \(z = 8.2\) also implies the existence, as the progenitor, of a massive binary \(~ 40 - 60 \, M_\odot\)^2. Such massive binaries have recently been identified in Eta Carinae (Damineli et al., 2000). The very rapid evolution of such very massive stars will lead first to a binary X-ray source, like Cen-X3 Gursky & Ruffini (see, e.g., 1975) and Giacconi & Ruffini (1978), which will further evolve in the FeCO with the binary NS companion. A similar evolution starting from a progenitor of two very massive stars was considered by Fryer et al. (1999b) and by Bethe & Brown (1998), leading to the formation of binary NSs or postulating the occurrence of GRBs. They significantly differ from the IGC model and also differ in their final outcomes;

c) the results presented in this Section open the way to considering the late X-ray power-law behavior in Episode 3 as a distance indicator and represents a significant step toward formulating a cosmological standard candle based on Episode 3 of these BdHN sources.

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\[^2\text{http://nsm.utdallas.edu/texas2013/proceedings/3/1/Ruffini.pdf}\]
Applications of the new distance indicator
Conclusions and perspectives

Since their first detection by the Vela satellites in the late 1960s, GRBs do not cease to puzzle the astronomers and astrophysicists communities, even after more than fifty years of observational and theoretical efforts dedicated on the understanding of their nature.

The fireshell model, a promising alternative scenario respect to the traditional fireball model, predicts a new classification for energetic ($E_{iso} > 10^{52}$ erg) GRBs, which can be divided into three classes.

- **Genuine-short GRBs**: they occur in the limit of very low baryon load, e.g. $B \lesssim 10^{-5}$ with the P-GRB predominant with respect to the extended afterglow. For such small values of $B$ the afterglow peak emission shrinks over the P-GRB and its flux is lower than the P-GRB one. The progenitor of such events are very likely binary NS mergers, leading to a Kerr BH formation. Two sources of this subclass have been recently identified: GRB 090227B and GRB 140619B.

- **Canonical long GRBs**: they are characterized by a baryon load varying in the range $3.0 \times 10^{-4} \lesssim B \leq 10^{-2}$ and they occur in a typical galactic CBM with an average density $\langle n_{CBM} \rangle \approx 1$ cm$^{-3}$.

- **Disguised-short GRBs**: the baryon load for disguised-short GRBs varies in the same range of the long bursts, but such GRBs appear as short ones because of their particular conditions of $\Gamma$ and $\langle n_{CBM} \rangle$. When the CBM density is of the order of $10^{-3}$ cm$^{-3}$, typical of a galactic halo, like in the case of GRB 970228, the extended afterglow results in a “deflated” emission that can be exceeded in peak luminosity by the P-GRB. We indicate such disguised-short GRBs as “disguised-short GRBs by defect”. If the GRB explodes in a medium with $\langle n_{CBM} \rangle \approx 10^3$ cm$^{-3}$, we refer to it as a “disguised-short GRB by excess”. In the case of GRB 090510 the joint effect of the $\langle n_{CBM} \rangle \approx 2 \times 10^3$ cm$^{-3}$, and the $\Gamma_{tr} \sim 700$, compresses in time the emission of the extended afterglow. The result is that the GRB, even being intrinsically long, appears as a short one.

Analyzing several candidates of the last two classes of energetic GRBs, which are associated to SNe, we have found a set of common observational features.

- The presence of a precursor having a spectrum with a non-relativistically expanding thermal component plus an extra power-law. Examples of sources showing this feature are GRB 090618, 101023, 110709B, and 970828.
The striking overlapping at late times of the X-ray luminosity light curves, firstly found in the GS: GRB 060729, 061007, 080319B, 090618, 091127, 111228. It has been verified also for GRB 970228, 970828, 030329, 130427A, 090423.

The fact that the typical shape of the X-ray luminosity light curve, consisting of a steep decay, then a plateau phase, followed by a late power-law decay, hides a nested structure. Precise anticorrelations have been found between the $\gamma$-ray $E_{\text{iso}}/T_{90}$ and the X-ray plateau luminosity respect to the end time of the X-ray plateau.

In the initial steep decay phase of the X-ray emission of GRB 060729, 090618, 130427A, and other GRBs-SNe a thermal component has been identified. It shows a temperature decreasing from $kT \sim 1$ keV to $kT \sim 0.1$ keV, and an inferred radius expanding at $\Gamma \sim 2$.

The GeV component associated to GRB 130427A, the only one in our sample due to Fermi/LAT absence or missing follow up in the other cases, shows a remarkable luminosity power-law behaviour in time from the end of the respective prompt emission. Its slope at late times is compatible with the one of the corresponding X-ray emission. For this GeV emission, the expansion $\Gamma$ of the emitting region has been constrained within the range $\Gamma \sim 10–40$.

Thanks to these observational results, we have been recently addressed the nature of energetic long and disguised GRBs and their connection with SNe in terms of the BdHN paradigm. A tight evolved binary system composed of a FeCO-core and a NS is assumed as progenitor. As the FeCO-core undergoes SN explosion, the accretion of a part of its ejecta on the companion NS induces the gravitational collapse of the NS to a BH and concurrently the GRB emission occurs. Four distinct emission processes characterize such a system and give reasons for the above mentioned observations.

**Episode 1**: corresponds to the onset of the FeCO-core SN explosion, creating a $\nu$NS. Part of the SN ejecta triggers an hypercritical accretion process onto the NS companion. This leads to an emission, visible in $\gamma$-rays, preceding the GRB and presenting a spectrum with a non-relativistically expanding thermal component plus an extra power-law.

**Episode 2**: occurs when the companion NS reaches its critical mass and collapses to a BH, emitting a GRB with $\Gamma \approx 10^2–10^3$, following the fireshell model.

**Episode 3**: it encompasses both X-ray and GeV prolonged emissions, coming from the interaction between the expanding SN remnant, the $\nu$NS and the BH. We have recently pointed out the possibility of using as an energy source of Episode 3 the nuclear decay of ultra-heavy nuclei produced by $\tau$-processes in the $\nu$NS-NS binary phase of Episode 1. An additional possibility of process-generating for Episode 3 is represented by type-I and type-II Fermi acceleration mechanisms.
• **Episode 4**: corresponds to the optical SN emission due to the $^{56}$Ni decay occurring $\sim 10–15$ days after the GRB explosion in the cosmological rest-frame. It is only detectable for sources at $z \lesssim 1$, in view of the limitations of the current optical telescopes.

One of the most exciting outcomes of the discovery of the late time common behaviour of the X-ray luminosity of the BdHNe is the possibility to use this scaling law as a distance indicator, allowing one to predict the redshift of the source as well as the presence of an associated SN just few hours after the GRB explosion. It is possible to test the predictive power of this result on three different observational scenarios for BdHNe.

- $z \gtrsim 1$: we are able to predict the existence of a SN associated, which is expected to emerge in the optical follow-up observations after $t \sim 10(1 + z)$ days. This offers a new challenge to detect SNe at high redshift.

- $z \lesssim 1$: we can indicate in advance the expected time for the observations of a SN and alert direct observations from ground- and space-based telescopes, like we have done for GRB 130427A.

- Unknown $z$: we can infer the redshift of GRBs like we have done for the cases of GRB 101023 and 110709B, whose $z$ has not been measured due to their poor optical data, and the case of GRB 140512, whose observed redshift matched our prediction.

The identification of a BdHN at the highest observed redshift (GRB 090423 at $z \sim 8.2$) strongly suggests that our scaling law could be valid independently from the space-time distance of the source. If confirmed, this novel standard candle could be used to test the $\Lambda$CDM cosmological parameters back to $\sim 600$ millions years after the Big-Bang. Our current work is indeed focused on enlarging the GS, looking for BdHN candidates among all the GRBs with measured redshift, a consequent isotropic energy $E_{\text{iso}} > 10^{52}$ erg, and good quality X-ray data mostly provided by the Swift/XRT detector. Increasing the BdHN statistics is equally fundamental to deepen our theoretical understanding of the physics behind the Episode 3 as well as strengthen the BdHN paradigm. Indeed, more BdHN candidates are needed to find out the all the analogies and differencies between the X-ray and the high energy emissions of the BdHNe.

From the experimental point of view, we strongly encourage more observations with the current instrumentation as well as improvements within the next generations of detectors. An increased sensitivity and enlarged energy bands coverage are needed in order to clearly identify and distinguish different spectral components of the multiwavelenght emissions of GRBs. A better time resolution is required to follow the evolution of different spectral components over time, down to the ms scale or below. Indeed, it is by now clear how important a good time-resolved data analysis is in astrophysics, especially to unveil the nature of ultra-relativistic phenomena as GRBs.
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