Binary Progenitors of Gamma-Ray Bursts in the Fireshell Model

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Summary

The works presented in this thesis share a common scope. Each of them plays a part in the establishment of a new classification of gamma-ray bursts based on results obtained with the alternative fireshell model. Due to the extreme nature of GRBs, it is noteworthy that a better understanding of these phenomena may yield important developments in the fields of relativistic astrophysics and cosmology – we summarize the main cosmological implications in the first chapter.

According to the classification that we obtain, all GRBs – short and long, energetic and less energetic – are outcomes of binary interactions. The binary nature of short and long GRBs nevertheless differs significantly. Indeed, short GRBs are understood as binary compact object mergers while long GRBs are viewed as the products of the interactions of a neutron star and an evolved stellar core undergoing a supernova explosion.

Specifically, we report on the following results:

• The introduction of the Induced Gravitational Collapse paradigm leads to the idea of binary GRB progenitors. This paradigm applies to energetic long GRBs associated to supernovae, and stems from the identification of physically different episodes in the γ-ray observations of several GRBs. The sequence of events in an IGC event (also referred to as a binary-driven hypernova) is detailed, and we characterize each of the four episodes that we identify. In the IGC framework, the first episode is due to the onset of a supernova and to the accretion of the ejecta onto a companion neutron star. The second episode is produced by the collapse of this neutron star to a black hole. The third episode, which encompasses emission from the SN ejecta, the SN shock breakout, and the new neutron star remnant of the supernova, appears to follow a regular behavior: the lightcurves of the late X-ray emission show evidence for overlapping and nesting features. Finally, the fourth episode consists of the supernova peak optical signal. We also report on a work that aims at characterizing IGC events through an analysis of their joint X-ray and optical spectral energy distributions.

• These initial results are expanded to several remarkable GRBs to which we apply the IGC paradigm. Thus the cases of GRB 130427A – a very energetic yet relatively nearby event –, of GRB 090423 – the farthest GRB with a spectroscopic redshift to date –, and of GRB 970828 are summarized.
In addition to the study of the long GRB population, the understanding of short GRBs is improved through the analysis of energetic short events. The prototypical GRB 090227B serves as a model for the cases of GRB 140619B and GRB 090510, which are understood as binary neutron star mergers leading to the formation of black holes. In particular, GRB 090510 bears remarkable peculiarities that we interpret in the framework of the fireshell model; these peculiarities lead us to conclude that the newborn black hole may be endowed with a high spin.

An important feature of the fireshell model is its energy source: originally, electromagnetic energy extraction from a Kerr-Newman black hole was considered and found to be able to deliver up to $10^{55}$ erg in a few seconds for a $10 M_\odot$ black hole. Thus, whether gravitational collapse to a black hole occurs or not is of paramount importance regarding the energetics of a GRB. As a consequence of this dichotomy, both short and long GRBs are further divided in two families characterized by the formation – or lack thereof – of a black hole during the course of a GRB.

The classification scheme of GRBs that we obtain may be summarized by the following figure. The space-time diagrams of each family are shown in Figs. 6.2, 6.3, 6.4, 6.5.

**All GRBs are composite and originate from binary systems**

- **Short GRBs**
  - Binary progenitor: NS–NS or WD–NS
  - SN: never
  - BH: $E_{\text{iso}} < 10^{53}$ erg
  - Hard spectrum: YES ($E_{\gamma,i} < 100$ keV)
  - X-ray Afterglow: YES (without scaling)
  - GeV emission: NO
  - Outcome: massive NS
  - Rates: 1–10 (Gpc$^{-3}$y$^{-1}$)

- **Long GRBs**
  - Binary progenitor: CO core–NS
  - SN: always
  - BH: $E_{\text{iso}} > 10^{53}$ erg
  - Hard spectrum: YES ($E_{\gamma,i} > 100$ keV)
  - X-ray Afterglow: YES (without scaling)
  - GeV emission: NO
  - Outcome: NS–NS
  - Rates: 11–71 (Gpc$^{-3}$y$^{-1}$)

Résultats et perspectives

Les travaux présentés dans ce mémoire de thèse partagent un même but. Ils participent à l’établissement d’une nouvelle classification des sursauts gamma qui se fonde sur les résultats que nous avons obtenus à l’aide du modèle de la coquille de feu (fireshell model). Il est pertinent de noter qu’en raison de la nature extrême des sursauts gamma, une meilleure compréhension de ces phénomènes peut potentiellement mener à d’importants développements dans les domaines de l’astrophysique relativiste et de la cosmologie – les principales applications cosmologiques sont résumées dans le premier chapitre.

D’après cette nouvelle classification, tous les sursauts gamma – longs comme courts, les plus énergétiques comme les moins énergétiques – résultent d’interactions entre systèmes binaires. Les systèmes binaires à l’origine des sursauts longs et courts sont toutefois complètement différents : les sursauts courts sont produits par la fusion de deux objets compacts tandis que les sursauts longs ont pour origine les interactions entre une étoile à neutrons et un noyau d’étoile subissant une supernova.

Ce mémoire porte plus spécifiquement sur les résultats suivants :

- L’introduction du paradigme de l’effondrement gravitationnel provoqué (EGP) mène à l’idée de progéniteurs binaires. Ce paradigme s’applique aux sursauts longs et énergétiques associés à une supernova. Il trouve son origine dans l’identification d’épisodes d’origines physiquement distinctes dans les observations de l’émission \( \gamma \) de plusieurs sursauts. La suite d’événements qui constitue un EGP est détaillée et chacun des quatre épisodes identifiés est caractérisé. Dans le cadre de l’EGP, le premier épisode est dû aux premières phases de la supernova que subit le noyau d’étoile et à l’accrétion d’une partie de la matière éjectée sur l’étoile à neutrons qui l’accompagne. Le second épisode est quant à lui produit par l’effondrement de l’étoile à neutrons en un trou noir. Le troisième épisode, qui englobe les émissions des éjectas de la supernova, de l’onde de choc de la supernova, ainsi que de la nouvelle étoile à neutrons née de la supernova, suit un comportement régulier : l’émission rémanente dans les rayons X montre en effet des caractéristiques de superposition et d’imbrication de ses courbes de luminosité. Enfin, le quatrième épisode est constitué du pic de luminosité de la supernova dans le domaine optique. Une étude des distributions spectrales d’énergie jointes des signaux X et optiques d’une collection d’événements EGP est également présentée.
• Ces résultats sont étendus par l’application du paradigme de l’EGP à plusieurs sur-
sauts gamma remarquables. Ainsi, les cas de GRB 130427A – un sursaut gamma parti-
culièrement énergétique et relativement proche –, de GRB 090423 – le plus
lointain sursaut pour lequel on dispose d’un décalage vers le rouge mesuré de façon
spectroscopique –, et de GRB 970828 sont présentés.

• En sus du cas des sursauts longs, nous étudions également le cas des sursauts courts
travers l’analyse de sursauts courts énergétiques. Le prototype GRB 090227B sert
de modèle pour l’étude de GRB 140619B et de GRB 090510, qui sont compris comme
étant les produits de la fusion de binares d’étoiles à neutrons menant à la formation
d’un trou noir. En particulier, GRB 090510 se distingue par des particularités que
nous interprétons dans le cadre du modèle de la coquille de feu ; ces particularités
nous mènent à la conclusion que le trou noir nouveau né est sans doute doté d’un
important moment angulaire.

La source d’énergie est une caractéristique importante du modèle de la coquille de feu.
Dans les premières formulations du modèle, l’extraction de l’énergie électromagnétique
d’un trou noir de Kerr-Newman a été étudiée : ce mécanisme permet d’obtenir jusqu’à
$10^{55}$ erg en l’espace de quelques secondes pour un trou noir de $10 M_\odot$. Par conséquent,
la formation d’un trou noir, ou son absence, a d’importantes répercussions sur le budget
énergétique d’un sursaut gamma. Les sursauts gamma courts et longs sont donc séparés
en deux familles définies par la création ou la non-création d’un trou noir.

La figure suivante résume la classification des sursauts gamma que nous obtenons:

Tous les sursauts gamma sont composites et résultent de systèmes binaires

ÉN: étoile à neutrons. NB: naine blanche. $E_{p,i}$: énergie du pic du spectre dans le repère
cosmologique.
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Introduction

The transient $\gamma$-ray sky is illuminated roughly once a day for a very brief time – milliseconds to minutes – by the most luminous phenomena in the Universe. Describing these bursts of $\gamma$-rays, or gamma-ray bursts (hereafter GRBs), would require the use of many superlatives. But for now, let us just note that they are cosmological events and that they occur at least as early as $\sim 600$ Myr after the Big Bang, at redshifts $\gtrsim 9$. These enormous distances imply, if GRBs were to emit radiation isotropically, an energy release of the order of $10^{49} - 10^{55}$ erg... that is, for the most energetic of them, more than the rest-mass equivalent energy of the Sun.

What are GRBs? How are they produced? What are their progenitors? The understanding of GRBs is of great interest in itself; but its implications have the potential to lead to significant advances in cosmological studies (see Section 1.5). While many breakthroughs took place in the past two decades, there are still many unknowns and the exact processes that produce GRBs are not fully clarified. Since their discovery at the end of the 1960s by American military spacecrafts, much has been learned and much still evades understanding: they remain elusive events. However, we do know that there exist at least two types of GRBs: long/soft bursts, which are related to type Ib/c supernovae and to star formation and are thus traced back to the death of massive stars; and short/hard bursts, for which circumstantial evidence points towards an old stellar population origin – the merger of compact objects are prime candidates.

We also know from the compactness argument and from radio observations (cf. Section 2.1.1) that they are ultra-relativistic events. There exists a popular theoretical framework for GRB studies: the “fireball model”, which relies on the dynamics and interactions of an expanding, slightly baryon-contaminated photon-lepton plasma. Different emission mechanisms (such as photospheric emission, internal shocks, external shocks, inverse Compton scattering – see Section 2.1) are envisioned within this framework in order to explain the complex phenomenology of GRBs; none of them is however able to fully reproduce the unsettling diversity of GRBs in whole.

The works presented in this thesis may be considered as an effort to describe and classify GRBs using the alternative fireshell model. The foundation of this model lies in the possibility to extract electromagnetic energy from a Kerr-Newman black hole through a vacuum polarization process that occurs during the gravitational collapse of an astronom-
tical object to a black hole. This model naturally explains the release of energies up to $10^{54} - 10^{55}$ erg in a timescale of seconds.

Building upon this framework, we devised a scheme in which all GRBs may be explained by binary interactions. Both short GRBs, here explained by binary compact object mergers, and long GRBs, here explained by the interactions between a neutron star and an evolved core undergoing a supernova, are divided in two families. Indeed, since the presence of a black hole may imply the release of a fantastic amount of energy, the formation of a black hole, or lack thereof, has significant consequences. As a result, these families are defined by the absence (family 1) or presence (family 2) of black hole formation during the course of a GRB.

This thesis is divided in 6 chapters. The first chapter aims at providing a broad introduction to the world of GRBs. It does not deal with theoretical interpretations, which are summarized in chapter 2, but it includes a review of the phenomenology of GRBs, of GRB instrumentation, and of the potential use of GRBs in cosmological studies. Chapter 3 presents the Induced Gravitational Collapse paradigm, its origins and its formulation. This paradigm explains energetic long GRBs connected to supernovae. Chapter 4 summarizes several case studies of Induced Gravitational Collapse GRBs. Chapter 5 is dedicated to the study of short GRBs. Finally, in chapter 6 we summarize the works presented here and conclude the thesis.

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List of publications

Refereed journals


Proceedings


The purpose of this chapter is to provide a basic framework upon which the reader will be able to build an understanding of the gamma-ray burst (GRB) phenomenon and to fully appreciate the works summarized in this thesis. After a brief historical overview, we present a phenomenological description of GRBs, including their multi-wavelength emission, their empirical classification, their correlations, and their environments. Although this thesis focuses mainly on the understanding of the nature of GRBs themselves, we also deem relevant to expand on the possible uses of GRBs as cosmological probes, as well as on their potential impact on the development of life in the Universe. It is also important to keep in mind the properties, the peculiarities, and the shortcomings of the instruments that provide the data used in this work; a section is consequently also dedicated to this purpose.
1.1 A GRB history

As their name suggests, gamma-ray bursts are short, intense pulses of $\gamma$-ray radiation. They are the most luminous events to be observed (with $\gamma$-ray luminosities sometimes in excess of $10^{54}$ erg/s$^1$ for the brightest of them), and they may outshine all other sources of $\gamma$ radiation of the visible Universe combined for a duration varying between tens of milliseconds to thousands of seconds. With a full sky coverage, an average of about one GRB per day is detected.

In spite of these impressive properties, GRBs were first observed only during the 1960s. Indeed, the atmosphere of the Earth is opaque to X- and $\gamma$-ray radiation; the discovery of GRBs then had to rely on spacecraft-borne (or, alternatively, on balloon-borne) detectors. As it turns out, the first incentive to send $\gamma$-ray detectors out in space was a military challenge related to nuclear weapon testing. As the Cold War raged on, numerous nuclear detonations were carried underwater, on the surface of the Earth, or in the atmosphere, and concerns grew about the danger of radioactive fallout. This led to the Partial Test Ban Treaty, a treaty signed and ratified by most countries (notably by the United States and by the USSR in the fall of 1963). The essence of this treaty comes down to the strict interdiction of nuclear weapon detonations, except in the case of underground explosions whose radioactive fallout stays within the national borders of the country detonating the weapon.

Following ratification of the treaty, the US army started to send pairs of satellites equipped in particular with X-ray, $\gamma$-ray and neutron detectors in order to enforce surveillance of spatial nuclear detonations. These satellites took the name Vela, short for velador (watchman in Spanish). The first pair was launched in October 1963 and the sixth (and last) pair was launched in 1970. The last satellite to be decommissioned was in function until 1984.

No nuclear detonations were ever detected$^2$. On July 2, 1967 however, a bright flash of $\gamma$-rays was seen: this was GRB 670702$^3$, the first GRB ever to be observed. Other similar events followed, and a crude localization of sixteen of them, based on the difference in arrival time at different detectors, has been successfully performed. This allowed the Los Alamos team in charge of the investigations to rule out both a terrestrial and a solar origin; the conclusion has been drawn that these events must be of cosmic origin. The discovery was declassified and made public in 1973 at the Meeting of the American Astronomical Society (Klebesadel et al., 1973; Strong, 1975).

What have we learned in the past 40 years? Progress has been slow at first, hindered by the intrinsic brevity of GRBs and by technical difficulties in determining the incoming direction of $\gamma$-rays. In the absence of accurate celestial positions, no counterparts at longer wavelengths can be obtained. And without the latter, the distance at which GRBs explode

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$^1$Astronomers and astrophysicists tend, for historical reasons, to use cgs (centimeter gram second) units instead of SI units. The erg is to the cgs system what the joule is to the SI system – a unit of energy expressed in the system units. Hence, one erg is equal to $1 \text{ g cm}^2 \text{s}^{-2} = 10^{-7} \text{ J}$. For comparison, the equivalent rest-mass energy of the Sun is about $1.8 \times 10^{54}$ erg.

$^2$Although an incident occurring on September 22, 1979 was never clarified: a double flash signal, characteristic of nuclear detonations, was detected by a Vela satellite in the vicinity of an island between South Africa and Antarctica. Possible explanations range from nuclear detonations by various countries to a meteoroid hitting the satellite.

$^3$The GRB naming convention follows the format GRB YYMMDD. In the case of multiple detections on a single day the format GRB YYMMDDX is adopted, where X is a letter – A for the first detection, B for the second one, etc. Since 2010, all GRB names follow the YYMMDDX convention (including the final letter) even if only one GRB is detected on a given day.
cannot be determined; as a result the great debate between the tenants of a cosmological origin and the supporters of a local (galactic) origin of GRBs could not be settled. While some astrophysicists proposed cosmological models, others argued that the energy budget required to reach the observed luminosities meant that GRBs had to be local events. Many theories – of the order of several hundred – were introduced\textsuperscript{4}, most of them positing galactic sources.

The InterPlanetary Network (IPN, e.g. Cline & Desai 1976), a network of spacecrafts, was able to provide localizations of hundreds of arcminutes down to a few arcminutes, but with a delay of days to months – which is too long to detect an afterglow. Hartmann & Epstein (1989) nevertheless concluded that a sample of 88 IPN-localized GRBs had, within the statistical limits, an isotropic distribution. This result hinted towards a cosmological origin, as galactic events would be expected to concentrate in the galactic plane. Yet the galactic origin theory still had significant support: in addition to the existence of theoretical models based on neutron stars, an event detected on March 5, 1979 was traced back to a supernova remnant in the large Magellanic Cloud, which provided a link between GRBs and neutron stars\textsuperscript{5}. The high transverse velocities of neutron stars (Frail et al., 1994) mean that neutron stars could populate the galactic halo; an isotropic distribution of GRBs could therefore support the galactic neutron star origin.

A first breakthrough occurred as the NASA launched the Compton Gamma-Ray Observatory (CGRO) in 1991. Among the four instruments on-board, the Burst And Transient Source Experiment (BATSE) (Meegan et al., 1992), a sensitive $\gamma$-ray detector working in the 20 keV – 2 MeV band, proved the most fruitful in the GRB field. Its eight-module detectors covered the entire sky; as a result BATSE detected close to one GRB per day during its nine years of operations. BATSE was also able to promptly notify a crude localization (2 to 3 degrees, up to 20 degrees for low-luminosity events). A celestial distribution of 2704 GRBs was constructed from BATSE data (see Fig. 1.1): this map shows that GRBs follow an isotropic distribution. This result strongly suggested a cosmological origin for GRBs, even though galactic halo models and solar system models were not disqualified: there were still no direct measurements of distance. Other important results (detailed in the following sections) included the observation that the spectra of GRBs are non-thermal and that the durations of GRBs follow a bi-modal distribution.

The next breakthrough came from the Dutch-Italian satellite BeppoSAX\textsuperscript{6}, even though it was not specifically designed for GRB observations. Launched in 1996, in function until 2002, and deorbitted in 2003, it was able to provide faster and more precise localizations. This was an important feature as at the time, theoretical predictions suggested the existence – never confirmed to date – of a long-lived counterpart in longer wavelengths to the short $\gamma$-ray emission: the afterglow. The afterglow was thought to emerge from the interaction of high-velocity ejected material with the surrounding medium.

BeppoSAX embarked five instruments that covered a range of more than three decades in energy – from 0.1 to 300 keV – with a relatively large effective area. Four of these instruments constituted the Narrow Field Instruments (NFI), covering the full energy range and

\textsuperscript{4}Piran (1999) highlights the fact that for a while, there were more theoretical models than observed events.

\textsuperscript{5}This event turned out not to be an actual GRB. It had an unusual lightcurve and spectrum, and 16 more bursts were observed from the same source. It was later classified as a soft gamma repeater, originating in a magnetar.

\textsuperscript{6}Beppo, short for Giuseppe, is a tribute to Italian physicist Giuseppe Occhialini; SAX stands for Satellite per Astronomia a raggi X (satellite for X-ray astronomy).
pointing in the same direction. The fifth instrument was the Wide Field Camera (WFC), consisting in two coded-aperture cameras each covering a 40 × 40 degrees area in the 2 to 30 keV range. When a GRB was detected, the WFC could provide a position accurate down to the arcminute. The position would then quickly be shared, so that follow-up observations by the NFI and optical ground-based telescopes could be undertaken.

The first afterglow ever to be observed was that of GRB 970228. The WFC caught a pulse of X-rays during the GRB which allowed the position of the burst to be determined by a ground-based analysis with a 3 arcminute precision. The NFI were repointed towards the position within 8 hours, successfully leading to the detection of a fading X-ray source about 10,000 times fainter than the original signal. The refinement of the GRB position using the X-ray detection led to follow-up observations by the Hubble Space Telescope as well as by ground-based telescopes. Thus the inferred host galaxy of this GRB could be pinpointed and its redshift could be measured, at a cosmological value $z = 0.695$. It could be argued that the presence of the galaxy in the GRB error circle was merely a spatial coincidence. However, with the further detection of X-ray afterglows and multiple redshift measurements\(^7\), the issue of the cosmological-versus-galactic origin was definitely settled.

GRB science entered its modern era as two highly successful – and still operational – satellites, Swift and Fermi (formerly GLAST), were launched respectively in 2004 and 2008. The characteristics and main results of the instruments aboard are presented in Section 1.4.

\(^7\)In particular, GRB 970508 presented absorption features in its spectrum, leading to a direct redshift measurement of $z = 0.835$. 

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Figure 1.1: Galactic coordinates map of the 2704 GRBs detected by BATSE. The color code refers to the fluence of the bursts; gray dots indicate incomplete data. Credits: CGRO BATSE Team.
1.2 Phenomenology

Although GRBs do share some generic features, they are remarkable in that the diversity of their properties is astounding: no two GRBs among the thousands observed so far are alike. This section presents the phenomenology of GRBs.

1.2.1 The burst in γ-ray burst: the prompt emission

The most prominent feature of a GRB, the one that gives the phenomenon its name, is the γ-ray emission (that is, emission above energies of \( \sim 10 \) keV). Referred to as the “prompt emission” in the literature, it encompasses most of the energy released electromagnetically. The isotropic luminosity during the prompt falls in the range \( 10^{47} \) erg/s – \( 10^{54} \) erg/s, and the isotropic energy \( E_{\text{iso}} \) falls in the range \( 10^{49} \) erg – \( 10^{55} \) erg. This high-energy emission exhibits a wide range of temporal behaviors, as shown in Fig. 1.3.

Temporal behavior

The main temporal characteristics are listed below.

- The duration of a burst is generally characterized by \( T_{90} \), a quantity defined as the time between which 5% and 95% of the total fluence is registered. The use of \( T_{90} \) is adopted in order to limit the uncertainty on the entire duration, as the start and the end of a GRB cannot be determined precisely due to background fluctuations. \( T_{90} \) may be as short as a few tens of milliseconds, or as long as several thousand seconds in a handful of cases, with an average of a few tens of seconds. However, there is a number of caveats that one should keep in mind concerning \( T_{90} \). Its value is detector-dependent, since an instrument sensitive at lower energies – or simply more sensitive – would measure a larger value. Some GRBs also feature large gaps during which no emission is detected; in those cases the time during which the GRB progenitor (cf. chapter 2) is active may be over-estimated. Additionally, \( T_{90} \) may well encompass episodes of different physical origins, thereby losing any physical significance.

Keeping these caveats in mind, the \( T_{90} \) distribution is found to include two log-normal components peaking at \( 0.2 - 0.3 \) s and \( 20 - 30 \) s (see also Fig. 1.7). A trough separates these components around 2 s. Section 1.3.1 details the classification of GRBs based on their duration and hardness properties.

- The lightcurve of a GRB can be highly structured, with numerous pulses clearly separated from one another, with an erratic behavior, or it may simply consist in one single pulse (Fishman & Meegan, 1995). Pulses may be smooth or spiky; they may appear symmetric in time with a rising part similar to the decaying part, but more often they adopt a fast-rising and a slow-decaying profile. A sample of BATSE GRB lightcurves is shown in Fig. 1.3. Note that the shape of a lightcurve depends on the

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8The isotropic energy is defined as the energy emitted in the \( 1 - 10^4 \) keV range in the rest-frame of the source assuming the emission to be isotropic (spherically symmetric). The energy requirements may be relaxed if the emission is collimated, as is often assumed in the literature. For typical jet half-opening angles \( \theta_j \) of \( \sim 5^\circ \), the energy release is a factor \( (1 - \cos \theta_j)^{-1} \approx 100 \) lower than \( E_{\text{iso}} \). The GRB rate estimates, taking into account those GRBs that do not fall in the line-of-sight, get correspondingly larger.

9Interestingly, the distribution of the separation times between pulses follows a log-normal profile (Li & Fenimore, 1996).
Figure 1.2: The lightcurve of GRB 080916C in different energy bands. Figure reproduced from Abdo et al. (2009a).
adopted energy band: pulses tend to have narrower profiles in harder bands (see Fig. 1.2).

- Some events are preceded by a soft and faint precursor emission tens or hundreds of seconds before the bulk of the GRB. Estimates of the fraction of GRBs with precursors range from 3% to ~ 20% (Koshut et al., 1995; Burlon et al., 2009; Lazzati, 2005) depending on the precise definition of a precursor event. No statistical differences between GRBs with a precursor and those without one appear to exist (Lazzati, 2005; Burlon et al., 2009).

- No periodicity has been observed in GRB lightcurves. However, Beloborodov (2000) averaged the power density spectra of several bright GRBs and found a power law with index 5/3 and a break at 1 Hz.

**Spectral behavior**

In the spectral domain, GRBs almost always reveal a highly non-thermal nature. However, in sharp contrast to the seemingly chaotic temporal behavior, the spectra of a majority of GRBs can be adequately fitted by a 4-parameter empirical model that features two smoothly connected power laws (see Fig. 1.4). This model is known as the Band model, and its functional form is (Band et al., 1993)

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

where \( K \) is the normalization constant, \( \alpha \) and \( \beta \) are the photon spectra indices, \( E_p \) (sometimes written \( E_{\text{peak}} \)) is the peak energy in the spectral energy distribution (SED)\(^{10}\). \( N(E)\,dE \) corresponds to the number of photons in the energy bin \( dE \). \( E \) is expressed in units of keV. Typical values of the power law indices fall in the ranges \(-1.5 \leq \alpha \leq 0.5 \) and \(-2.5 \leq \beta \leq -2\); typical peak energies \( E_p \) range from several keV to a few MeV\(^{11}\). When performing a time-resolved analysis, all of these parameters are seen to evolve during the burst.

In the limit \( \beta \to \infty \), a cut-off power law function is recovered. Such a function is often used to fit GRB spectra; however, this is essentially a consequence of the limited bandpasses of the detectors that do not allow \( \beta \) to be constrained. In the limit \( \alpha \to \beta \) a regular power law is obtained.

It should be noted that a number of GRBs nevertheless feature strong evidence for additional components. A power law extending to high energies has been clearly observed in e.g. GRB 090510 and GRB 090902B (Ackermann et al., 2010), and a subdominant quasi-thermal component has been seen in e.g. GRB 100724B (Guiriec et al., 2011), GRB 110721A (Axelsson et al., 2012), GRB 120323A (Guiriec et al., 2013). As a result, Zhang et al. (2011) proposed that the prompt emission spectrum may include three components

\(^{10}\)The flux density spectrum \( F_E \) (or \( F_\nu \) in terms of frequency) corresponds to \( EN(E) \), while the SED \( E F_E \) (or \( \nu F_\nu \)) corresponds to \( E^2 N(E) \).

\(^{11}\)A loose classification based on \( E_p \) is sometimes used in the literature. Hard bursts with \( E_p > 50 \) keV are called GRBs; intermediate bursts with \( 30 \text{ keV} < E_p < 50 \text{ keV} \) may be called X-ray rich GRBs; soft bursts with \( E_p < 30 \) keV may be called X-ray flashes.
A practical guide to GRBs

Figure 1.3: Twelve GRB lightcurves as seen by BATSE (in units of $10^3$ counts/s) demonstrating their diversity in duration (milliseconds to tens of minutes), in temporal structure, and in pulse shape. Credits: Daniel Perley and the BATSE Archive.

Figure 1.4: Flux spectrum (top) and spectral energy distribution (bottom) of GRB 990123, fitted with a Band function. Figure reproduced from Bloom (2011).
1.2 Phenomenology

(see Fig. 1.5): a Band component, a quasi-thermal component in the tens to hundreds keV range, and a power law extending to high energies.

GRB spectra feature strong evolution more often than not. Time-integrated spectra are therefore of limited significance; but time-resolved spectroscopy is only possible with bright GRBs as there must be enough photons in each temporal bin in order to obtain a spectrum of good enough quality. Time-resolved analyses reveal that in general the Band component shows no clear trend of evolution. On the other hand, GRB pulses often exhibit a hard-to-soft evolution (meaning that $E_p$ decreases from the beginning of the pulse, Norris et al. 1986), but it may happen (sometimes in the same GRB) that $E_p$ tracks the intensity (Golenetskii et al., 1983).

Multi-wavelength prompt emission

Due to the unpredictable nature of GRBs, observations of the prompt emission in wavelengths shorter than $\gamma$-rays are sparse\(^{12}\). Early data can be acquired if a precursor emission alerts the community or in the case of an exceptionally long duration GRB. In the optical domain, two types of components are seen (both may be present in the same burst): a component for which the peak of the optical emission is offset with respect to the peak of the $\gamma$-ray emission (which points to a different physical origin), and a component that tracks the $\gamma$-ray lightcurve.

1.2.2 X-ray afterglow

The prompt emission is followed by a fading signal in longer wavelengths, called the afterglow. It is usually observable on timescales of days, depending on the observational window (the longer the wavelength, the longer the duration: a radio signal may be detected up to several months after the GRB itself).

As explained in the previous section, X-ray afterglows have not been detected before 1997. Even then, the X-ray data were sparse: they covered mainly the first hundreds of seconds and the emission several hours after trigger. The situation nevertheless dramatically improved when Swift came into operation: more than 95% of Swift GRBs are associated to an X-ray afterglow, and their lightcurves are much more complete, starting seconds after the burst and lasting for days. Thanks to this excellent coverage, a canonical picture of the X-ray afterglow emerged (cf. Fig. 1.6).

The temporal evolution of X-ray afterglows is smooth, driven by an underlying continuum that may be composed of up to four different segments superimposed by an occasional flaring activity. Afterglows follow a relatively simple pattern in comparison to the chaotic prompt emission, as five components are sufficient to characterize the data. All of them may appear in a given afterglow, but this is not necessarily the case. The five components are described hereafter (the numbering refers to that of Fig. 1.6).

I An initial steep decay phase initiates the X-ray afterglow. Typical power law indices are steeper than $-2$, often $\lesssim -3$. This steep decay can be linked to the tail of the prompt emission when BAT and XRT data are both available.

II After $10^2 - 10^3$ s the steep decay may be followed by a plateau phase (with a slope of $-0.5$ or larger) that is characterized by a shallow decay or sometimes flat profile,\(^{12}\) Remarkably, GRB 130427A is the only example to date of a GRB with observations from the optical to the GeV range during the prompt emission.
Figure 1.5: The three spectral components proposed by Zhang et al. (2011) to appear in the time-resolved GRB data. Any of these components can be suppressed in some GRBs. Figure reproduced from Zhang et al. (2011).

Figure 1.6: The five canonical components of X-ray afterglows as observed by *Swift/XRT*: an initial steep decay phase (I), a shallow decay / plateau phase (II), a normal decay phase (III), a late time steep decay phase (IV), and flares (V). Typical times and decay indices are indicated. Figure reproduced from Zhang et al. (2006).
occasionally even slightly rising in the beginning.

III A normal decay phase with index $\sim -1$ starts at typical times $10^3 - 10^4$ s. In a small fraction of GRBs, the plateau is followed by a very steep decay (index $\sim -3$ or steeper).

IV A late time steep decay (index $\sim -2$ or steeper) can occasionally follow.

V A flaring activity (consisting in one or more flares) is seen in nearly half of X-ray afterglows. The behavior of these flares may suggest that they share a common origin with the prompt emission: the fast-rise exponential-decay profile and the fluence (that can be as large as the one of the prompt emission) support this statement (Burrows et al., 2005b; Chincarini et al., 2010).

1.2.3 Broadband afterglow

GRB afterglows are multi-wavelength events. Even though the X-ray part of the emission is the easiest to detect, there may also be significant emission in ultraviolet, optical, infrared (UVOIR), and radio bands. Afterglow detection is nowadays routinely performed following a well-established strategy: the crude localization given by the $\gamma$-ray emission (with an accuracy of 1 to 4 arcminutes for the Swift/BAT) leads to a tentative detection by an X-ray instrument that, if successful, refines the position (down to a few arcseconds for the Swift/XRT). The error radius is then small enough that optical searches can be carried out, quite often successfully: more than half of GRBs with a Swift X-ray afterglow are also detected in UVOIR domains. The detection rate of radio afterglows is on the other hand lower: from 1997 up to the end of the year 2014, there were 1418 reported GRB detections, of which 945 were associated to an X-ray afterglow, 590 to an optical detection, and 108 to a radio observation. The low rate of radio detections is usually attributed to synchrotron self-absorption in the early part of the radio afterglow.

Most of the non-detections of optical afterglows result from insufficiently sensitive searches. However, there is a 10 to 15% proportion of GRBs that do not have an optical detection despite adequate follow-up. These events are termed dark bursts. Greiner et al. (2011) concluded that about three quarters of dark GRBs are due to a high extinction in the host galaxy, while one quarter of the studied events show consistency with a high redshift interpretation, according to which the faint optical flux is a consequence of intergalactic neutral hydrogen absorption.

A remarkable characteristic of multi-wavelength afterglows lies in the fact that they exhibit a chromatic behavior, meaning that the features of the lightcurve (such as bumps and variations of flux) seen in one wavelength range do not necessarily occur throughout the other wavelength domains. In contrast to the relative simplicity of X-ray afterglows, UVOIR emission can be very diverse from one event to another.

Optical afterglows may also provide photometric or spectroscopic evidence for the occurrence of supernovae in association to GRBs. The GRB – supernova connection is detailed in Section 3.1.

---

13The afterglow of one GRB, often referred to as the naked-eye burst (GRB 080319B), reached an optical magnitude of 5 that made it potentially visible to the unaided human eye for a few seconds. No actual witness of the event is known; this GRB nevertheless set a new distance record on the farthest object ($z = 0.94$) that could have been seen with the naked eye.

14These statistics are taken from Jochen Greiner’s GRB page at http://www.mpe.mpg.de/~jcg/grbgen. html.
1.2.4 GeV emission

The LAT instrument on-board Fermi routinely detects very high energy photons in the GeV range in coincidence with GRBs ($\gtrsim 8 - 10$ detections per year above a few tens of MeV, Ackermann et al. 2013). The photon statistics are however low due to the limited effective area: only a few photons above 10 GeV are detected in the best cases. Early GeV emission had already been observed in 1994 by EGRET on-board CGRO (Hurley et al., 1994), but past and ongoing efforts to detect high-energy emission with ground-based telescopes such as MAGIC, HESS, and VERITAS proved unfruitful. The upcoming CTA (Cherenkov Telescope Array) is expected to provide unprecedented sensitivity at energies starting at $\lesssim 30$ GeV, down to $\sim 15$ GeV in some cases (Inoue et al., 2013).

Since August 2008, the Fermi/LAT has seen significant emission above 0.1 GeV in about 60 GRBs. A redshift has been obtained for 16 of them, in a range $z = 0.145 - 4.35$ (Nava et al., 2014). Emission lasts for hundreds to thousands of seconds with the exception of faint events, and its flux decreases in time as a power law with index $1.2$ (Ackermann et al., 2013). In a handful of cases, an extra-component in addition to the Band function must be added to properly describe the LAT data (see Section 1.2.1). The high-energy emission starts during the prompt emission phase, often with a delay with respect to the less energetic MeV emission. It also lasts longer; its later evolution exhibits a smooth behavior similar to a regular afterglow behavior, in contrast to the prompt phase during which the GeV emission is usually highly variable (sometimes in correlation with the MeV emission). Interestingly, the time delay appears to scale with the duration of the burst. The output at GeV energies represents a small fraction of the total energy budget, although it may be more important for short GRBs.

The two highest energy photons attributed to a GRB had measured energies of 33.39 GeV, which at the redshift $z = 1.822$ of GRB 090902B corresponds to a rest-frame energy of 94.2 GeV (Ackermann et al., 2013), and 95 GeV, which at the redshift $z = 0.34$ of GRB 130427A corresponds to a rest-frame energy of 128 GeV (Ackermann et al., 2014). The detection of photons carrying this much energy implies that particle acceleration mechanisms have to be very efficient; they also provide a way to measure the opacity of the Universe, as high-energy photons (above $\sim 10$ GeV) interact with ambient optical and UV photons.

1.2.5 Polarization

There have been several claimed detections of linear polarization in the $\gamma$-ray prompt emission. Polarization measurements are however difficult; and these claims are controversial. No optical polarization measurements have been carried out during the prompt phase, but there are early measurements in a handful of cases yielding claims of positive detections. The most natural explanation for polarized emission would be that the source is endowed with coherently aligned magnetic fields. Polarization observations and their implications are reviewed in Lazzati & Begelman (2009).

1.3 GRB taxonomy and correlations

Even though GRBs span a stunningly diverse range of properties in most observational aspects, a classification scheme has been devised in which GRBs fall into just two categories which are constructed from their duration and hardness properties. Building on the
observables of these two classes and on their environments, their respective progenitors have been inferred (Sections 1.3.1 & 1.3.2). Several correlations relating temporal and spectral properties have also been found (Section 1.3.3); the most quoted of these correlations relates the peak energy of the Band function to the isotropic energy of the GRB – this is the so-called Amati correlation (Amati et al., 2002; Amati, 2006).

1.3.1 Classification: short hard vs. long soft

As exemplified by several scientific discoveries, an insightful classification work may give important clues to the true nature of a yet poorly-understood phenomenon\textsuperscript{15}. As it turns out, GRBs can be phenomenologically classified in two broad classes, which are thought to reveal profound underlying differences.

Short and long GRBs

Closely following the launch of the Compton Gamma Ray Observatory, Kouveliotou et al. (1993) evidenced a bi-modality in the distribution of the observer frame $T_{90}$ duration of GRBs\textsuperscript{16} and in the hardness distribution of GRB spectra: longer bursts tend to have a softer spectrum (see Fig. 1.7). The dividing line is usually set at $T_{90} = 2$ s.

Since no GRB redshifts were available at that time, rest-frame durations were unknown; these works are therefore based on observer-frame durations. Concerns about the validity of a result that is not based on rest-frame quantities may be alleviated by the following argument: while the duration of a GRB is stretched by a factor $(1 + z)$ between the rest-frame and the observer-frame values, it is also dependent on the fluence threshold of the detector. As a consequence, a high redshift event is, when compared to a similar low redshift event, both stretched by the cosmological time dilation and shortened by the fact that parts of the emission fall below background level; this mitigates the effects of the cosmological redshift on $T_{90}$, as suggested by simulations (e.g. L"u et al. 2014).

Since the measurement of $T_{90}$ depends on the energy band and the sensitivity of the detector, a single GRB seen by two different instruments could appear both short and long. The confusion nevertheless only arises for those GRBs which lie in-between the bulk of the short and long distributions. As summarized in Table 1.8, about 25\% of BATSE GRBs are short; this fraction is smaller for other detectors (for instance roughly 10\% for Swift).

Short GRBs and their afterglows are significantly fainter than long GRBs and span a distribution of isotropic energies $10^{49} - 10^{52}$ erg. The majority of short GRBs lies in the redshift range $0.1 - 1.3$, and their median redshift is 0.5, much smaller than that of long GRBs, at $z \sim 2$. Assuming isotropic emission, estimates of the local long GRB rate lie in

\textsuperscript{15}Examples include the work of Mendeleev, who formulated a periodic table in 1869 following early efforts in element classification. This table predicted the existence and some properties of yet unknown elements, almost 30 years before the discovery of the electron and 50 years before that of the proton. Another example lies in the classification of radioactivity: its phenomenological classification turned out to be equally relevant from a theoretical point of view, as radioactivity $\alpha$ is due to the strong force, the $\beta$ one is due to the weak force, and the $\gamma$ one is due to the electromagnetic force. One should however bear in mind that some classifications may also be misleading: such is the case of supernova classification, for which the type I / type II classification is based on the absence or presence of hydrogen spectral lines. From a theoretical point of view, it is more relevant to distinguish between type Ia (thermonuclear runaway explosions) and other supernovae (core-collapse events).

\textsuperscript{16}Before definite proof based on large statistics was obtained by Kouveliotou et al. (1993), Cline & Desai (1976); Mazets et al. (1981) provided early hints to the existence of these classes; Norris et al. (1984) further gave stronger evidence. The works of Dezalay et al. (1992) and Klebesadel (1992) may also be cited.
the range $0.1 - 1.5 \text{ yr}^{-1} \text{ Gpc}^{-3}$, with the short GRB rate thought to be larger despite their relatively low detection rate. Note that the radio detection rate of long GRBs ($\sim 30\%$) is higher than that of short GRBs ($\sim 10\%$, Berger 2014). This difference may stem from the fact that radio detections are often limited by the detectors sensitivities – and short GRBs are in general less luminous than long GRBs.

Additional evidence for a distinction between the long and short classes came from the study of spectral lags, a delay between the arrival time of high-energy photons with respect to lower energy ones. By definition, a spectral lag is said to be positive when the high-energy photons arrive first. It has been shown that short GRBs have null spectral lags, in contrast to long GRBs which have positive lags (Norris et al., 2010).

Beyond the long/short view

The apparent simplicity of the long/short picture is however blurred by a number of troubling cases, listed hereafter.

- Among the class of long GRBs, a distinction can be made between the low-luminosity bursts with smoother lightcurves and exploding at a higher rate, and the high-luminosity “classical” GRBs. Low-luminosity bursts probably form a distinct group in the GRB luminosity function (Virgili et al., 2009), although the separation between low- and high-luminosity GRBs is not clear-cut.

- The existence of ultra-long GRBs, with durations $T_{90}$ in excess of $1,000 \text{ s}$ or even $10,000 \text{ s}$, is established. They remain rare events, as only a few candidate ultra-long bursts occurred in the Swift era – notably GRB 101225A, GRB 111209A, and GRB 130925A. Whether they form a different class of events (e.g. with a different progenitor such as the collapse of a very large star – a blue giant for instance, Gendre et al. 2013) or are part of the end-tail of the long GRB distribution is not yet clear (Zhang et al., 2014).

- GRBs with hybrid short and long properties have been observed. GRB 060614 and GRB 060605 are long duration GRBs that exploded nearby (respectively at $z = 0.125$ and $z = 0.089$); yet no associated supernovae have been found despite deep searches (Della Valle et al., 2006a; Fynbo et al., 2006; Gal-Yam et al., 2006). Except for its long duration, GRB 060614 is very similar to regular short GRBs: its lightcurve starts with a short-hard spike, it is located in a region of low specific star-formation rate, and its spectral lag is very short. It has also been realized that the highest redshift bursts often have a rest-frame duration of less than $2 \text{ s}$ (e.g. GRB 080913 at $z = 6.7$, GRB 090423 at $z = 8.2$, GRB 090429B at $z \approx 9.4$), although simulations (e.g. Lü et al. 2014) suggest that the observer-frame duration does not increase substantially with increasing redshift because part of the signal falls below the background level.

- The existence of a third (and even of a fourth) class of intermediate duration GRBs, in addition to the long and short bursts, have been claimed, but the statistical support is limited. See Ripa & Mészáros (2015) and references therein for more details.

1.3.2 GRB environments and inferred possible progenitors

The environment of GRBs, both at a large scale and at a galactic scale, provides clues to the nature of their progenitor systems. It can be inferred that short GRBs are related to
1.3 GRB taxonomy and correlations

Figure 1.7: This diagram evidences the bi-modal GRB distribution of BATSE events in terms of duration (horizontal axis) and spectral hardness (vertical axis), evaluated through the peak energy $E_{\text{peak}}$ of the spectral energy distribution. Two regions can clearly be distinguished, even if there is a significant overlap between them. Outset histograms show the number of events in appropriate time and energy bins. Figure reproduced from Bloom (2011).

<table>
<thead>
<tr>
<th>Category</th>
<th>Average $T_{90}$ (s)</th>
<th>Hardness $E_p$</th>
<th>Spectral lag</th>
<th>$%$ of BATSE GRB population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short</td>
<td>0.3 $E_p \sim 600$ keV</td>
<td>Negligible</td>
<td>$\sim 25%$</td>
<td></td>
</tr>
<tr>
<td>Long</td>
<td>30 $E_p \sim 200$ keV</td>
<td>Order of seconds</td>
<td>$\sim 75%$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1.8: Summary of the properties of the BATSE short and long GRBs.
old stellar populations, while long GRBs are good tracers of star formation and are thus related to young, massive stellar populations.

**Short GRBs**

Again, short and long GRBs differ by the specifics of their host galaxies. About half of the short GRBs detected by *Swift* are associated to a host galaxy. From this sample, it is seen that short GRBs explode in both early- (∼20% of them) and late-type galaxies, and in both field and cluster galaxies. In particular, some short GRBs have been associated to elliptical galaxies, which strongly relates them to an old stellar population (Berger, 2014). On the other hand, the occurrence of short GRBs in late-type galaxies does not necessarily imply a young progenitor: GRB 050709 exploded in a late-type galaxy but was shown not to be associated with a star-forming region (Fox et al., 2005). Old progenitors are not exclusively found in old systems, as evidenced e.g. by the occurrence of a large fraction of type Ia supernovae in spiral galaxies.

More generally, short GRBs under-represent their host light, and they are often found far from the galactic center: Fong et al. (2010) concluded that short GRBs occur on average five times farther from the center than long GRBs, consistent with compact object binaries that had enough time to travel far away before merging, due to large natal kicks following supernova explosions (Paczyński, 1998). In addition, it should be noted that the specific star-formation rate of short GRB hosts is much lower than that of long GRB hosts, at less than $1 M_\odot \text{yr}^{-1}(L/L_\odot)^{-1}$ compared to ∼10 $M_\odot \text{yr}^{-1}(L/L_\odot)^{-1}$ (here $L$ stands for the luminosity of the galaxy, $L_\odot$ being a characteristic luminosity similar to that of the Milky Way). All these elements are consistent with a merger of compact objects: double neutron star mergers and black hole – neutron star mergers are indeed generally considered as the most likely progenitors of short GRBs.

**Long GRBs**

Almost all long GRBs are found in dwarf, blue, irregular galaxies with a high star-formation rate, although a few nearby events occurred in star-forming regions of spiral galaxies. Importantly, long GRBs are seen to concentrate preferentially in the brightest regions of their hosts, suggesting a high specific star-formation rate (Graham & Fruchter, 2013). Berger (2009) underlines the following differences between long and short GRB host galaxies in the same redshift range $z \lesssim 1.1$ (note that even the star-forming hosts of short GRBs have different properties from the long GRB hosts, Fong et al. 2010):

- Long GRB hosts are subluminous with respect to short GRB hosts by a median value of $M_B \sim 1.1$ mag.
- The star-formation rate of long GRB hosts and short GRB hosts are, respectively, 0.2 − 50 $M_\odot \text{yr}^{-1}$ and 0.2 − 6 $M_\odot \text{yr}^{-1}$; and the specific star-formation rate of long hosts is 3 − 40 $M_\odot \text{yr}^{-1} L_\odot^{-1}$, one order of magnitude higher than that of short hosts.
- The metallicity of long hosts is lower than that of short hosts, with median values of respectively $12 + \log(O/H) \approx 8.3$ and $12 + \log(O/H) \approx 8.8 \approx 1 Z_\odot$.

---

17 The specific star-formation rate is defined as the star-formation rate per unit stellar mass.
• The stellar mass of long hosts is substantially lower compared to that of short hosts, with median values of respectively \(10^{9.2} \, M_\odot\) and \(10^{10.0} \, M_\odot\) (Berger 2014 and references therein). Using single stellar population models, the median values of the inferred age of the stellar populations are respectively 60 Myr and 0.25 Gyr (Leibler & Berger, 2010).

These considerations point to a progenitor of long GRBs that is related to the death of massive, short-lived stars, which die near their birth place. The most popular model is the collapsar picture (see Section 2.1.7); it features rapid accretion of \(0.01 - 0.1 \, M_\odot\) onto a black hole formed by gravitational collapse of the core of a massive star.

### 1.3.3 GRB correlations

GRBs are not quite standard candles: their luminosities, for instance, vary by a factor of up to \(10^6\). Despite this variability, a number of empirical GRB correlations have been found, linking luminosity- or energy-related quantities to temporal or spectral properties. The importance of these correlations stems from the fact that they might be used to standardize GRBs, possibly revealing e.g. their true distance without the need to assume a cosmological model, hence turning GRBs into cosmological probes (see Section 1.5.4). The exact origins of the correlations are still unclear though, and their validity is sometimes questioned: some groups claim that they arise as a by-product of detector selection effects (e.g. Nakar & Piran 2005). However, it can be argued that the existence of a given correlation in the time-resolved data disfavors this interpretation (e.g. Ghirlanda et al. 2010).

One of the most used and studied correlations involves the rest-frame peak energy in the \(\nu F_\nu\) spectrum, \(E_{\text{peak}}\), and the isotropic energy in the \(1 - 10,000\) keV rest-frame energy band, \(E_{\gamma,\text{iso}}\). This \(E_{\text{peak}} - E_{\gamma,\text{iso}}\) correlation is often referred to as the Amati correlation; its scatter is rather broad. Its validity is restricted to long GRBs, as short GRBs are found to follow a similar but different correlation (Calderone et al. 2015; Zhang et al. 2012, see also Fig. 1.9). GRB 980425, a low-luminosity long GRB, is a significant outlier. It has been argued that this correlation is a result of selection effects (Nakar & Piran, 2005), but Ghirlanda et al. (2008) showed that selection effects cannot completely cancel the correlation.

The \(E_{\text{peak}} - E_{\gamma,\text{iso}}\) correlation with 41 GRBs takes the form (Amati, 2006):

\[
\frac{E_{\text{peak}}}{1 \, \text{keV}} = (81 \pm 2) \left( \frac{E_{\gamma,\text{iso}}}{10^{52} \, \text{erg}} \right)^{0.57 \pm 0.02}.
\]  

A similar correlation between \(E_{\text{peak}}\) and the isotropic peak luminosity \(L_{\text{iso}}\) has also been reported; it is sometimes referred to as the Yonetoku correlation (Yonetoku, 2004) and features a wide scatter too. The \(E_{\text{peak}} - L_{\text{iso}}\) correlation based on 16 events takes the form (Yonetoku, 2004):

\[
10^{55} L_{\text{iso}} \, \text{erg s}^{-1} = 2.34^{+2.29}_{-1.76} \left( \frac{E_{\text{peak}}}{1 \, \text{keV}} \right)^{2.0 \pm 0.2}.
\]  

Ghirlanda et al. (2004) found a tighter correlation between \(E_{\text{peak}}\) and the collimation-corrected energy \(E_\gamma\), computed (assuming that the temporal breaks found in the pre-Swift afterglows are jet breaks) as

\[
E_\gamma = \frac{E_{\text{iso}}}{4\pi} 2 \int_0^{\theta_j} 2\pi \sin \theta d\theta = (1 - \cos \theta_j) E_{\text{iso}}
\]  

These empirical correlations can provide insights into the properties of the progenitor stars and the central engines of GRBs, and their validity remains a topic of active research.
Figure 1.9: “Amati” correlation for long GRBs (black triangles are pre-\textit{Fermi} GRBs, green circles are \textit{Fermi} GRBs; the black line represents the best fit $E_{\text{peak}} = 100 \times (E_{\text{iso}}/10^{52})^{0.51}$ and $E_{\text{peak}} - E_{\text{iso}}$ correlation for short GRBs (red squares; the blue line represents the best fit $E_{\text{peak}} = 2455 \times (E_{\text{iso}}/10^{52})^{0.59}$). The blue stars stand for two controversial GRBs, GRB 071227 and GRB 100816A. Figure reproduced from Zhang et al. (2012).

where $\theta_j$ is the jet half opening angle. The correlation reads (Ghirlanda et al., 2004):

$$\frac{E_{\text{peak}}}{100 \text{ keV}} \simeq 4.8 \left( \frac{E_\gamma}{10^{51} \text{ erg}} \right)^{0.7}.$$  (1.5)

In the \textit{Swift} era, the interpretation of the temporal breaks as jet breaks became doubtful, in particular because of the frequent absence of achromaticity.

A number of other correlations have been claimed; these include – among others – the spectral lag $\tau_{\text{lag}}$ vs. $L_{\text{iso}}$ (Norris et al., 2000); the variability $V$ vs. $L_{\text{iso}}$ (Reichart et al., 2001); the rise time $\tau_{\text{rise}}$ vs. $L_{\text{iso}}$ (Schaefer, 2007).

### 1.4 Instruments and instrumental biases

This section focuses on instrumental issues. The work presented in this thesis is mainly based on data obtained from two satellites which revolutionized GRB studies, \textit{Swift} and \textit{Fermi}. It is thus important to keep in mind the specifications and the limitations of the different instruments on-board these satellites, and to be aware of potential biases that may arise due to instrument limitations.

#### 1.4.1 On observational biases

GRBs have been, and are being, monitored by a number of different detectors. Each detector has a different sensitivity, a different bandpass, different timing and spectral capabilities, different calibrations. As a result, the properties of GRBs can differ sometimes significantly depending on the observing instrument. For instance, CGRO/BATSE had a harder energy band ($50 \text{ keV} - 2 \text{ MeV}$) than \textit{Swift}/BAT ($15 \text{ keV} - 150 \text{ keV}$); thus 25% of
BATSE GRBs are short-hard ones, while the proportion falls to $\sim 10\%$ for BAT. Furthermore, Swift is also less sensitive to short bursts because of their lowest fluences. Another illustration of instrumental bias is that pre-Swift bursts have an average redshift of 1.2, while Swift bursts have a mean redshift of 2.5 (Gehrels et al., 2009): Swift is indeed more sensitive than its predecessors BeppoSAX and HETE-2.

Fig. 1.10 shows the bi-modal distribution in the $T_{90}$ duration of GRBs with different detectors; the bi-modality appears more or less well-defined depending on the instrument. The $T_{90}$ distribution also changes radically even with a single detector, if one considers different energy bands: Qin et al. (2013) studied this effect in the case of Fermi/GBM.

The Malmquist bias (an inclination towards intrinsically bright objects, i.e. towards high luminosities) is an obvious bias that is however difficult to correct for. The luminosity function of GRBs, which is uncertain, and an estimate of the sensitivity limits of the detectors are required in order to account for this effect.

Redshifts are an absolute necessity in order to study rest-frame properties of GRBs; any bias in the obtention of redshifts may lead to subsequent biases in the conclusions inferred on those GRB populations defined by rest-frame quantities. $\sim 30\%$ of Swift-detected GRBs have a redshift (Gehrels & Razzaque, 2013), but there is a clear bias towards the brightest bursts. Moreover, $\sim 40\%$ of Swift GRBs have no optical detection at all. For many of them, this fact may be explained by insufficiently sensitive searches, but in many cases the detection of an optical observation evades deep searches. This is attributed to heavy dust extinction (see the discussion on dark GRBs in Section 1.2.3). The spectroscopic identification of absorption or emission lines is another bias: the redshifted lines may indeed fall in unfavorable observer-frame wavelength domains where observations are difficult, thus hampering their identification. In particular, the most common lines used to spectroscopically determine a redshift are hard to identify in the so-called redshift desert, in the range $1.4 \lesssim z \lesssim 2.5$.

### 1.4.2 The Swift mission and its legacy

The Swift satellite (Gehrels et al., 2009), launched in December 2004 in low Earth orbit at an altitude of $\sim 600$ km, was specifically designed for GRB science. In particular, emphasis was put on its fast repointing abilities in order to obtain a good follow-up of the afterglow of a burst, both at X-ray and optical wavelengths. Swift detects an average of two GRBs per week. When it is not engaged in GRB observations, Swift is available for other investigations. Its nominal targeted lifetime was 2 years; after 10 years, it is still in function and working flawlessly. It carries three co-aligned instruments on-board:

- the Burst Alert Telescope (BAT, Barthelmy et al. 2005a), the primary instrument, is a coded-mask detector.\(^{18}\) It has a wide field of view (1 steradian fully coded – close to $1/12^{th}$ of the sky –, 1.4 steradian half-coded, and $\sim 3$ steradians partly coded) in order to monitor a large part of the sky, and its bandpass is in the hard X-ray range ($15 – 150$ keV). When the BAT is triggered, it provides an arcminute position within 10 seconds; this position is immediately relayed to the ground. Automatic fast-slewing ground-based optical telescopes can then try to observe the GRB, and Swift itself autonomously repoints towards the direction of the burst, if deemed worthy (and provided that it is free of observing constraints, such as a GRB occurring too

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\(^{18}\)The BAT uses a coded-aperture mask, i.e. a grid of opaque material. The shadow cast by this mask forms a pattern from which a crude localization of the source can be deduced.
Figure 1.10: $T_{90}$ distributions of HETE-2/FREGATE (Plangeon et al., 2008), BeppoSAX/GRBM Frontera et al. (2009), CGRO/BATSE (Paciesas et al., 1999), Swift/BAT (Sakamoto et al., 2011), INTEGRAL/SPI-ACS (Savchenko et al., 2012). One- or two-gaussian fits to the distributions are shown, as well as the $T_{90} = 2$ s dotted line. Figure taken from Qin et al. (2013).
close to the Sun). Swift repoints for about 80% of GRB triggers. Its slewing time typically lies under one minute.

- the X-Ray Telescope (XRT, Burrows et al. 2005a), a focusing X-ray telescope with a 110 cm$^2$ effective area, operates in the 0.2 – 10 keV range and is able to refine the position of the burst to within 5 arcseconds within 10 seconds, with a typical 2 arcsec error circle. Its field of view is 23.6 arcmin. It can follow the X-ray emission from 20 to 70 seconds up to several days after trigger due to its ability to cover over 7 orders of magnitude in flux.

XRT can take data in three (originally four) different modes. The imaging mode is only used to provide rapidly the first position estimate of a GRB, with exposures of 0.1 or 2.5 s depending on the source flux. The windowed timing mode produces one-dimensional images with 1.7 millisecond time resolution and full energy resolution and is useful for fluxes of $1 – 600$ mCrab. Finally, the photon counting mode builds two-dimensional images in a 2.5 s time resolution and a full energy resolution; this mode is useful for faint fluxes below 1 mCrab. The photo-diode mode, which provided no spatial information but a 0.14 ms time-resolution, is disabled since May 2005.

- the UltraViolet and Optical Telescope (UVOT, Roming et al. 2005) is sensitive in the 170 – 650 nm band and provides 0.3 arcsec positions in a 17 arcmin field of view. It is a 30-cm Ritchey-Chrétien telescope and carries an 11-position filter wheel which allows broadband photometry as well as grism spectroscopy for bright GRBs. This instrument is important as ground-based facilities cannot observe in the UV domain and are limited by weather conditions; the UVOT is on the other hand only limited by the presence of bright sources in the field of view.

The influence of Swift on GRB science is tremendous. As of July 13, 2015, it detected 986 bursts, of which 308 (roughly one third)$^{19}$ have a measured redshift$^{20}$. A comparison with the pre-Swift era is eloquent: there were no more than 4 – 9 redshift identifications per year, amounting to a grand total of $\sim 40$ redshift determinations up to 2004. The slewing abilities of Swift play a great role in its achievements: they allow a much more responsive follow-up of GRB afterglows at longer wavelengths, as well as much better and more frequent localizations of GRBs. The latter point significantly improved e.g. the study of the host galaxies of GRBs, leading to strong arguments regarding the determination of the progenitors of the short and long GRB classes (cf. Section 1.3.1).

Notable discoveries made with Swift, inside and outside the GRB field, include (Gehrels & Cannizzo, 2015):

- the realization that X-ray afterglows follow more complex patterns (especially at early times) than the simple power law decay previously observed;
- the first observations of flares and bright afterglows in GRBs;
- the first observations of a shock breakout in a type Ib/c supernova;

$^{19}$Statistics taken from NASA’s Swift GRB Table Stats at http://swift.gsfc.nasa.gov/archive/grb_table/stats/.

$^{20}$Note that these redshifts are mostly determined by ground-based facilities and not by Swift observations.
• the discovery of a class of GRBs that challenges the simple short/long classification: 
  *Swift* indeed observed a few short GRBs with an extended emission (Norris & Boffnell, 2006) that exhibit hybrid properties mixing characteristic of both the short and long classes (cf. Section 1.3.1);

• the discovery of $z > 8$ GRBs;

• the discovery of very young supernova remnants;

• the discovery of ultra-long GRBs;

• evidence for a kilonova\footnote{It is theorized that a neutron star merger leads to a supernova-like ejection of radioactive material, dimmer than a supernova but brighter than a nova – hence the name *kilonova* (the term *macronova* can also be found).} in a short GRB.

### 1.4.3 The *Fermi* mission and its legacy

The Fermi Gamma-ray Space Telescope (formerly *GLAST* and hereafter *Fermi*) is a satellite carrying instruments designed to perform $\gamma$-ray observations in a wide bandpass. It was launched in June 2008 in low Earth orbit (at an altitude of 550 km); the time of operations goal is ten years. Its initial main objectives are numerous and ambitious: they include a better understanding of particle acceleration in active galactic nuclei, supernova remnants, and pulsars; an accurate scrutiny of potential dark matter signals; an examination of the $\gamma$-ray sky; and finally a better understanding of the high-energy behavior of GRBs and other transients. *Fermi* carries two instruments on-board that scan most of the sky about 16 times per day:

• The Large Area Telescope (LAT, Atwood et al. 2009) is a pair-conversion instrument that detects photons in the $20 \text{ MeV} - 300 \text{ GeV}$ energy range. It has a large field of view, covering $\sim 2.4$ steradians at 1 GeV, and an effective area of 6,500 cm$^2$ on-axis at $> 1 \text{ GeV}$. The LAT was designed to have a large field of view, a large effective area throughout the energy range, and also to reject most signals generated by cosmic rays. In view of the expected mission lifetime, the capacities of the LAT were also designed to avoid degradation over time.

• The Gamma-ray Burst Monitor (GBM, Meegan et al. 2009) includes 14 scintillation detectors, of which twelve cover the $8 \text{ keV} - 1 \text{ MeV}$ range with sodium iodide (NaI) crystals, and two cover the $150 \text{ keV} - 30 \text{ MeV}$ range with bismuth germanate (BGO) crystals. This configuration makes it able to detect a source in the entire sky that is not occulted by the Earth. The GBM can provide a rough localization ($10^\circ$ uncertainty) within 1 s; this ability is necessary in order to repoint the LAT in the direction of the burst.

Notable *Fermi* discoveries include:

• the first detection of a pulsar, located in the CTA-1 supernova remnant, that emits in the $\gamma$-ray band only;

• the determination of the fact that supernova remnants accelerate particles and that active galactic nuclei are only responsible for less than $\sim 30\%$ of the $\gamma$-ray background radiation;
1.4 Instruments and instrumental biases

- the discovery of the Fermi bubbles;
- the detection of the highest energy solar photons at 4 GeV, and of the highest energy photon of a GRB at 95 GeV (128 GeV in the rest-frame of the burst, GRB 130427A).

An important achievement of Fermi in GRB science consists in the detections of high-energy emission from several dozen GRBs by the LAT (Ackermann et al., 2013). The presence of a thermal signature in the prompt emission of some energetic GRBs is one of the most interesting observations drawn from GBM data.

1.4.4 Other missions

GRB studies currently benefit from the operations of a number facilities in addition to Swift and Fermi.

The Russian experiment Konus (Aptekar et al., 1995) on-board the American satellite WIND launched in November 1994 detects 100 to 150 GRBs per year\(^{22}\). It provides event lightcurves in three bands in the energy range 10 – 770 keV with a 64-ms temporal resolution, with an almost isotropic sensitivity. WIND is located in the interplanetary space; as a result, Konus is not subject to Earth occultations and to background distortions due to the South Atlantic Anomaly.

AGILE\(^{23}\), an Italian X- and γ-ray satellite launched in 2007 in low Earth orbit carries a Gamma-Ray Imaging Detector (GRID) sensitive in the 30 MeV – 50 GeV range, the wide field monitor SuperAGILE, sensitive in the 18 keV – 60 keV range, and a mini-calorimeter non-imaging scintillation detector sensitive in the 350 keV – 100 MeV range (MCAL). Its scientific objectives include the study of GRBs, active galactic nuclei, X- and γ-ray galactic sources, diffuse galactic and extra-galactic emission, and fundamental physics.

Other X- or γ-ray instruments occasionally observe GRBs or GRB afterglows. NuSTAR is an American X-ray telescope launched in 2012; it is sensitive in the 3 – 79 keV range, which makes it able to detect afterglows. INTEGRAL\(^{24}\) (International Gamma-ray Astrophysics Laboratory) is a very sensitive European γ-ray satellite-borne detector launched in 2002; it carries four co-aligned instruments (an imager observing from 15 keV to 10 MeV, a spectrometer sensitive in the 20 keV – 8 MeV range, an X-ray monitor in the 3 to 35 keV range, and an optical monitor sensitive in the 500 – 580 nm range). The European XMM-Newton\(^{25}\) mission provides highly sensitive observations with a large collective area in the X-ray domain. Launched in 1999, it carries three instruments: an X-ray imager and an X-ray spectrometer (0.15 – 12 keV), and a co-aligned optical monitor. Chandra\(^{26}\), formerly known as AXAF (Advanced X-ray Astrophysics Facility) is suited for observations of extremely faint sources in the X-rays. Cherenkov telescopes (ground-based γ-ray instruments sensitive upward of a few tens of GeV) such as MAGIC, HESS, and VERITAS have not detected any GRB signal so far.

At lower frequencies, many facilities occasionally contribute to the GRB field. These include the Hubble Space Telescope and many fast-repointing ground-based telescopes in the optical and the near-infrared frequencies, such as GROND, PROMPT, TAROT, or

\(^{23}\)Astro-rivelatore Gamma a Immagini LEggero, http://agile.asdc.asi.it/.
\(^{24}\)http://sci.esa.int/integral/.
\(^{25}\)http://sci.esa.int/xmm-newton/.
\(^{26}\)http://chandra.harvard.edu/about/axaf_mission.html.
A practical guide to GRBs

ROTSE. Large 8-meter class telescopes, such as the Very Large Telescope, the Large Binocular Array, or the 10-m Keck telescope, may also re-point to GRB afterglows. Radio facilities may additionally detect GRB afterglows.

1.5 Cosmological implications (or: what can GRBs teach us?)

The extreme $\gamma$- and X-ray luminosities of GRBs mean that they can be observed out to cosmological distances, where only few objects are bright enough to be detected even with modern telescopes. Thus GRB 090423, with a spectroscopic redshift of $\approx 8.2^{27}$ (Tanvir et al., 2009), is the farthest object with a spectroscopic redshift to date. GRB 090429B has an even larger photometric redshift$^{28}$ of 9.4, however with a large uncertainty (Cucchiara et al., 2011).

GRBs have additional properties that make them promising probes of the early Universe. Their afterglows have smooth, featureless power law spectra that make the detection of absorption or emission features much easier than in the case of e.g. quasars, whose spectra are much more convoluted. Note that interestingly, the afterglow flux at a given time after trigger (in the observer frame) is not expected to decrease significantly with increasing redshift: cosmological time dilation means that for a higher redshift, we observe the flux at earlier rest-frame times, that is when the emission is intrinsically brighter. In addition, GRB afterglows can be as much as thousands of times brighter than the brightest quasars in the optical domain. And since GRBs are of stellar origin, they do not depend on the size of the host galaxy, which means that they outshine their hosts by a larger factor at earlier times, when galaxies are smaller and fainter.

Consequently, GRBs may help to shed light on different aspects of cosmology. We summarize the most important ones in this section.

1.5.1 GRBs in context: a brief history of the Universe

GRBs occur over a wide range of redshifts that covers about 13 billion years of the history of the Universe. In order to put them in context, we offer a short reminder of the milestones of the Universe's history in the standard Big Bang scenario (see also Fig. 1.11).

A relic of the extreme conditions prevailing during the very first moments following the Big Bang, the hot ionized gas isotropically filling the Universe gradually cooled down as a consequence of the expansion of the latter. The mean free path of photons was very short as long as there were free electrons around since the interaction cross-section of photons with free electrons is very high. When the temperature became low enough (around 3,000 K), electrons and protons started to combine to form hydrogen atoms$^{29}$; the Universe thus became neutral and transparent to photons. This transition happened gradually at a redshift $z \sim 1,100$ ($\sim 380,000$ years after the Big Bang).

As clumps of the primordial gas started to collapse gravitationally to form the first pristine, metal-free stars (termed Population III stars) at redshifts $15 \sim 80$ (Yoshida et al., 2003), reionization of the intergalactic medium began, powered at least in part by the

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$^{27}$A redshift of 8.2 corresponds to a time of $\approx 630$ million years after the Big Bang in a standard flat $\Lambda$CDM cosmology.

$^{28}$The determination of a redshift is said to be spectroscopic when it is based on spectral lines, either due to absorption or emission. A photometric redshift is obtained by studying the relative brightness of a signal through various filters and is therefore less reliable in addition to being less precise.

$^{29}$Recombination of helium atoms occurred before that of hydrogen ones as helium atoms are more tightly bound.
intense UV light emitted by these stars. The then relatively simple and homogeneous Universe transitioned to a highly complex and structured one. Reionization reached completion (with a fraction of neutral hydrogen $\lesssim 10^{-3}$) at a redshift $\sim 5$, which corresponds to an age of $\sim 1.2$ billion years. Since then, galaxies kept growing, stars kept enriching the galactic medium, and environments favorable to the apparition of life appeared.

The farthest GRBs observed so far are GRB 090423 and GRB 090429B; they exploded well before the end of reionization, possibly at a time when population III stars were still constituting the bulk of the stellar population.

1.5.2 The Universe at high redshift

A small sample of GRBs at redshifts $\gtrsim 6$ has been collected during the first decade of Swift operations: it includes 5 events with a spectroscopic redshift, and 3 more with a well-constrained photometric redshift (Salvaterra, 2015). Future GRB experiments are likely to significantly enhance this sample, raising the question of the use of GRBs as probes of the high redshift Universe, independently from galaxies and quasars.

Population III stars

As population III stars are expected to be very massive, they might power extremely energetic GRBs. If these stars can indeed produce GRBs, it is expected (in the collapsar interpretation) that these GRBs would be orders of magnitude more energetic and much longer compared to population I/II GRBs, and they would also be characterized by a bright radio afterglow peaking at late times. This means that they would be detectable out to the very beginning of the star-formation epoch, although they are expected to be extremely rare and hard to distinguish from population I/II GRBs. Limits on population III GRBs can be set considering that none of the high-$z$ GRBs detected so far is likely to be a population III GRB (Salvaterra, 2015). The population III GRB rate upper limit, assuming that all population III GRBs can be seen by Swift, is estimated to be close to $0.03 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Salvaterra, 2015). In other words, population III GRBs seem to be rare events, and they would form the majority of the GRB population only at redshifts higher than $\sim 10 - 15$ (Campisi et al., 2011).

Host galaxies

The precise celestial position and distance of a high-redshift GRB also gives away the location of its host galaxy. But since the detection of a GRB is independent from its host galaxy properties, it is interesting to note that the follow-up of GRBs allows for the study of a population of galaxies that are not selected for their brightness.

Deep searches of high-redshift GRB locations with ground- and space-based facilities have been carried out (Tanvir et al., 2012; Berger et al., 2014). No detections have been made in spite of the deep limits reached; however the non-detections put upper limits on the star-formation rate. As an example, observations of the location of GRB 090423 led to the derivation of an upper limit on the unobscured star-formation rate of $0.38 \text{ } M_\odot \text{ yr}^{-1}$ (Tanvir et al., 2012) and on the obscured star-formation rate of $5 \text{ } M_\odot \text{ yr}^{-1}$ (Berger et al., 2014).

The study of GRB afterglows may also deliver information on several important quantities. Metallicity measurements can be obtained from absorption lines up to high redshifts:
thus the spectrum of GRB 130606A \((z = 5.91)\) evidences the presence of many metal elements. This allows the abundance profile and the gas kinematics of the inner region of a high-redshift galaxy to be probed (Hartoog et al., 2014).

Dust properties may be derived from extinction profiles in the UVOIR range. It is found that a small Magellanic Cloud dust profile is most often preferred over large Magellanic Cloud or Milky Way profiles; this result is not surprising since GRB hosts often share many characteristics with the small Magellanic Cloud (low mass, low luminosity, active star-formation). Interestingly, the afterglow of GRB 071025 \((z \sim 5)\) offers evidence that a theoretical dust profile produced by supernovae matches the data the best (Perley et al., 2010); this suggests that the composition of dust was different in the early Universe. Weaker evidence for supernova-synthesized dust has also been reported for GRB 050904 at \(z = 6.3\) (Stratta et al., 2011).

Additional information on the interstellar medium of the host galaxy may be probed via the study of metal absorption lines; more specifically, knowledge on the temperature, the ionization state, and the kinematics of the medium might be obtained. However, the immediate vicinity of the burst (within \(\sim 10\) pc) cannot be probed, as the X-ray and UV emission from the GRB is intense enough to fully ionize the interstellar medium within this distance.

The intergalactic medium

Quasars have been used to measure the fraction of neutral hydrogen in the intergalactic medium (IGM), thus placing constraints on the reionization history. This is done by taking advantage of the Gunn-Peterson trough, a drop in the spectrum due to the Lyman \(\alpha\) transition caused by neutral hydrogen absorption in an entire redshift range (see Fig. 1.12). GRBs have been used in a similar way, with the following advantages: they are detected at higher redshifts than quasars; they are located in cosmic regions less affected by local ionization or clustering; and as stated previously, their spectrum is much more simple than that of quasars. The main limitation for this use of GRBs is the local galactic absorption. Chen et al. (2007) concluded that 20 to 30\% of GRB afterglows have an extinction low enough to allow direct measurements of absorption from the IGM.

Bright radio signals from high-redshift afterglows could excite the spin doublet fundamental state of the neutral hydrogen atom. This would produce a characteristic forest of 21-cm absorption lines giving information on the gas distribution at the beginning of galaxy formation and on the reionization time line (Ciardi et al., 2015).

The metal enrichment of the IGM at different times may also be probed by high-redshift GRBs (see e.g. Furlanetto & Loeb 2003).

Line-of-sight objects

An intriguing feature of GRBs is that they may shed light on random galaxies located on their line-of-sight. A sample of such objects would form a random distribution of galaxies, while galaxy surveys (in particular spectroscopic ones) are heavily luminosity-biased. Invaluable knowledge on e.g. faint galaxies or the properties of gas halos may be obtained, provided that a sample large enough is built.
1.5 Cosmological implications (or: what can GRBs teach us?)

Figure 1.11: A brief history of the Universe.

<table>
<thead>
<tr>
<th>Redshift</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
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<tr>
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<td>17 Myr</td>
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<td>10</td>
<td>480 Myr</td>
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<td>1.2 Gyr</td>
</tr>
<tr>
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<td>8.7 Gyr</td>
</tr>
<tr>
<td>0</td>
<td>13.7 Gyr</td>
</tr>
</tbody>
</table>

**GRB 090423**

**8.2**

Djorgovski et al.

Figure 1.12: The Ly$_\alpha$ transition between the ground state and the first excited state of the hydrogen atom occurs at a wavelength of 1216 Å. A photon with this wavelength in the local frame has a high probability of being absorbed. As a beam of light travels towards us through a neutral medium from a high redshift origin, the cosmological redshift implies that light blueward of the Ly$_\alpha$ transition in the source frame is blocked, creating the so-called Gunn-Peterson trough. The figure shows the spectrum of a quasar located at $z = 6.28$. The signal is indeed extinguished blueward of $1216 \times (1 + z) \approx 8850$ Å.
1.5.3 The star-formation rate

The evolution of stars is a key concept in the study of the history of the Universe. Stars participate in enriching their environments in metals and are driving forces of their host galaxy evolution; moreover, the first stars likely played a central role in reionization. Consequently, it comes as no surprise that measuring the star-formation rate (SFR) is one of the main goals of observational cosmology.

The SFR is currently poorly constrained – especially at high redshifts – and the different measurement methods are sometimes in tension with one another. One possible method to estimate it is to look for specific emission lines in the optical domain, the intensity of which gives an estimate of the prevalence of hot, massive stars. This method suffers several caveats: dust may block optical light, thus a significant fraction of the light may go unnoticed (dust studies suggest that more than one third of the star formation is obscured); in addition, the ratio between massive stars and less massive ones is poorly constrained and has to be assumed. Radio emission from supernova shocks may also be used to measure the SFR. Although it is model-dependent, this method is often favored as radio emission penetrates dust effectively. However, both of these methods are biased in that they do not take into account small, faint galaxies which may be responsible for most of the star formation at high redshift.

As discussed in Section 1.3.2, long GRBs are very likely related to the demise of massive, short-lived stars. As such, GRBs trace star formation in that they mark the birthplace of massive stars. Since γ-rays and X-rays also penetrate dust, they offer a dust-unbiased view on the SFR. In addition, GRBs also have bright optical afterglows: measuring their extinction may give a measurement of the extinction of all star formation. Note that there is a potentially important bias concerning the use of GRBs as tracers of the SFR: while the measurement of a redshift is a necessity, it relies on the detection of an afterglow at optical wavelengths, especially at \( z \gtrsim 2 \) where the detection of emission lines from the host galaxy requires excessive amounts of observing time. Importantly, GRBs can in principle probe the SFR in low-to-moderate star-forming galaxies at \( z \gtrsim 5 \), a realm that is currently beyond the reach of any other SFR measurement method.

The inferred GRB rate as a function of redshift is qualitatively similar to the SFR: it features a rapid rise from \( z = 0 \) to \( z = 1 \) and a sharp drop beyond \( z = 4 \). At low redshifts, it seems that the GRB rate is suppressed compared to the SFR; this may be caused by a metallicity bias. Several authors indeed argue that GRBs preferentially explode in low metallicity environments (see e.g. Fruchter et al. 2006).

However, the link between the GRB rate and the SFR is not fully understood yet. Do GRBs relate directly to the SFR, or are they sensitive to other parameters? In short, are they good tracers of star formation? Evidence suggests the presence of an evolution of the GRB-to-star-formation rate ratio with redshift (see e.g. Salvaterra et al. 2012). The role of metallicity is often invoked; this would mean that GRBs can be good tracers of the SFR at high redshift, where the metal enrichment is low.

1.5.4 Probing cosmological models

GRBs rank among the very farthest events that can be observed – much farther than e.g. type Ia supernovae, the detection range of which is limited to \( z < 2 \). As a consequence, the lure for researchers to constrain cosmological models and parameters using GRBs is strong, although the viability of this method is sometimes disputed (see e.g. Li 2007).
1.5 Cosmological implications (or: what can GRBs teach us?)

Amati & Della Valle (2013) review the use of the $E_{\text{peak}} - E_{\text{iso}}$ correlation to give an independent estimate on $\Omega_M$; they find a value $\Omega_M \approx 0.3$, in agreement with other methods.

The equation of state of dark energy may also be constrained using GRBs. Much interest goes into models of dark energy density varying with time, for which the equation of state is usually parametrized as $P = w(z) \rho$ with $w(z) = w_0 + w_a (1 + z)$ where $P$ is the dark energy pressure and $\rho$ is the dark energy density (e.g. Chevallier & Polarski 2001). A constant dark energy ($w_0 = -1, w_a = 0$), or “cosmological constant”, is currently favored by observations. However, a slow variation of $w(z)$ is not ruled out. In particular, extending the type Ia supernovae Hubble diagram with GRBs through calibration of the $E_{\text{peak}} - E_{\text{iso}}$ correlation would allow to probe a redshift range in which the luminosity distance is more sensitive to the properties and the evolution of dark energy (Demianski et al., 2012).

1.5.5 Ultra-high energy cosmic rays

The origin of ultra-high energy cosmic rays (UHECRs), with energies $> 10^{19}$ eV, remains puzzling, as it challenges models of particle acceleration. In particular, supernova remnants – which produce high-energy cosmic-rays – do not seem to be able to produce the very highest energy cosmic rays. There are few (known) astrophysical objects that might allow the production of these ultra-high energy particles; besides active galactic nuclei, GRBs are promising candidates (Waxman, 2006). Indeed, they make ideal particle accelerators (since they are highly energetic and non-thermal emitters), and the detected rate of UHECRs is roughly consistent with the rate at which GRBs could produce them.

If GRBs do play this role in the production of UHECRs, there should be observable consequences in the high-energy neutrino flux from GRBs (see next subsection). Non-detections by IceCube start to put serious constraints on theoretical models (Abbasi et al. 2012, see also next subsection).

1.5.6 Prospects for neutrino and gravitational wave astronomy

Neutrinos and gravitational waves promise to open new windows of observations of the Universe via non-electromagnetic channels, allowing optically opaque environments such as the heart of a supernova to be probed.

Neutrinos from GRBs

Neutrino astronomy is still in its infancy, as very few neutrinos originating outside the solar system have been observed\footnote{Noteworthy are the twenty-four events registered by Kamiokande and a few other neutrino detectors, signaling the nearby supernova SN 1987A that exploded in the large Magellanic cloud.}. The south pole neutrino Cherenkov detector IceCube, designed to observe neutrinos at TeV – PeV energies, began full-scale operations in May 2011 and observed thirty-seven very high energy neutrino events (cf. Fig. 1.13) in the full 988-day sample (up to 2013). However, none of these events were coincidental with a GRB, which puts stringent upper limits on the GRB neutrino production: earlier models based on the fireball model and the GRB origin of ultra-high energy cosmic rays (see previous subsection) predicted around 10 GRB neutrino detections during this period.

Indeed, neutrinos in the $10^{14}$ eV energy range are expected if GRBs produce UHECRs. It is believed that only active galactic nuclei and GRBs are capable of accelerating cosmic
rays to the highest observed energies (\( > 10^{19} \text{ eV} \), Wick et al. 2004). GRBs are believed to be efficient cosmic ray accelerators, as they are highly energetic and non-thermal emitters. If protons reach an energy \( E_p \) and interact with a photon of observer-frame energy \( E_\gamma \) such that the following condition is satisfied:

\[
E_p E_\gamma \gtrsim \frac{m_\Delta^2 - m_p^2}{2} \left( \frac{\Gamma}{1+z} \right)^2 = \left( \frac{\Gamma}{1+z} \right)^2 0.147 \text{ GeV}^2
\]  

then PeV neutrinos can be produced via the \( \Delta \)-resonance in the \( p\gamma \) mechanism:

\[
p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu, & 1/3 \text{ probability} \\
p + \pi^0 \rightarrow p + \gamma + \gamma, & 2/3 \text{ probability.}
\end{cases}
\]

where \( m_\Delta \) and \( m_p \) are the rest masses of \( \Delta^+ \) and the proton and \( \Gamma \) is the bulk Lorentz factor.

Each of the four leptons is produced with an overall energy around 0.05\( E_p \). For typical \( E_\gamma \) of the order of hundreds of keV, \( E_p \) should be in the PeV range and neutrinos reach sub-PeV energies (Waxman & Bahcall, 1997).

\( pn \) processes, whose optical depth can become large in dense environments, also generate pions and ultimately neutrinos. In addition, neutrinos may be generated at different sites where the photon energies and the Lorentz factor can differ. As a result, GRB neutrinos may reach down to GeV energies and up to the EeV regime. The “central engine” in the fireball model (see Section 2.1.7) is also expected to copiously emit MeV neutrinos (as in core-collapse events). However, detection of MeV neutrinos would require a GRB to explode exceedingly close to the Earth (\( \approx 100 \text{ kpc} \)), which is unlikely to happen.

Waxman & Bahcall (1997); Guetta et al. (2004); Murase (2008) among others have computed PeV neutrino GRB production both analytically and numerically. Current limits from IceCube challenge the role of GRBs as sources of UHECRs (Abbasi et al., 2012).
Future detections or non-detections will help constraint the progenitor models of GRBs. In particular, the nearby bright GRB 130427A puts tight constraints on the photospheric model and on the internal shock model (Gao et al., 2013) (see chapter 2 for a description of theoretical GRB models).

**Gravitational waves from GRBs**

While no gravitational waves have been directly detected so far, it is expected that Advanced LIGO (Abbott et al., 2009) and Advanced Virgo (Acernese et al., 2008) will be sensitive enough to bring the first direct detections in the next few years. Binary neutron star mergers emit enormous amounts of energy in the form of a characteristic chirp signal of gravitational waves in the last milliseconds before the merger; thus they should be detectable out to a distance of $\sim 300$ Mpc. Several tens of detections per year are expected with these characteristics. And since short GRBs are likely produced by neutron star mergers, it is expected that coincidental electromagnetic and gravitational wave events be detected. Such detections can potentially deliver information about the mass, the size, and maybe the internal structure of the merging neutron stars. The post-merger object can also be deduced: in the case of a black hole, a ring-down signal is expected after the merger phase (Baiotti et al., 2008) while a supra-massive neutron star would produce extended gravitational wave emission due to secular bar-mode instabilities (Baiotti et al., 2008).

The amount of gravitational waves produced by core-collapse events, which are leading candidates for long GRB progenitors, is on the other hand highly uncertain; if the collapse is asymmetric, the accretion disk may be subject to bar-mode instabilities so that strong gravitational wave signals may be released (Ott et al., 2012). Furthermore, the local rate of long GRBs is smaller than that of short GRBs.

**1.5.7 Lorentz-invariance violation**

Lorentz invariance is one of the founding principles of modern physics, and no departure from it has been observed so far. There are however theoretical motivations to look for violations of Lorentz invariance. From a quantum mechanical point of view, vacuum (i.e. the lowest energy state of a medium) may be endowed with a virtual structure even if it is devoid of particles. This in turn may mean that the structure of space-time near the Planck scale $E_{Pl} = \sqrt{\hbar c/G} \simeq 10^{19}$ GeV, where gravitational effects are expected to become as strong as those of other forces, may become non-trivial. High-energy particle propagation may be affected by this effect, and distant, rapidly-variable sources of high-energy photons could provide sensitive probes of some models (Amelino-Camelia et al., 1998). Candidate sources include pulsars, GRBs, and AGNs.

There exist several theoretical models in which Lorentz-invariance violation arises. These include models based on features of string theory, on some models of loop quantum gravity, on spontaneous Lorentz-invariance violation, on Lifshitz-type quantum field theories, on purely phenomenological models, or on deformation – rather than violation – of Lorentz invariance (this the case of e.g. doubly special relativity). See Ellis & Mavromatos (2013) and references therein for more details.

Note that Lorentz-violating effects are expected to depend on the particle species. Constraints on electron, proton, neutrino, and photon Lorentz invariance are thus of independent interest. GRB constraints are restricted to the case of photon Lorentz invariance.
Amelino-Camelia et al. (1998) proposed that the energy-dependence of the speed of light in the vacuum can be parameterized as a Taylor expansion of the dispersion relation:

\[ c^2 p^2 = E^2 \left[ 1 \pm \xi_1 \left( \frac{E}{E_{Pl}} \right) \pm \xi_2 \left( \frac{E}{E_{Pl}} \right)^2 \pm \ldots \right] \]

(1.8)

where the coefficients \( \xi_n \) are specified by a given theory of quantum gravity and could be equal to 0. Two scenarios are usually considered, one in which the linear term is dominant and the other in which the quadratic term dominates.

A major difficulty in probing the effects of Lorentz-invariance violation on the arrival time of photons of different energies emerges from the nature of GRB emission. Spectral evolution and other features typical of GRBs (such as the delay between the onset of the \( \gamma \)-ray emission and the GeV emission) pollute the search for effects of Lorentz-invariance violation. Nevertheless, the best limit on the linear term thus far has been placed by Fermi/LAT observations of GRB 090510, which require \( M_1 = E_{Pl}/\xi_1 > 1.5 \times 10^{19} \) GeV (Abdo et al., 2009b).

1.5.8 GRBs and life in the Universe

A number of authors have pondered the question of the potential effects that GRBs may have on life on Earth and in the Universe. Asserting the lethality of a GRB requires a number of hypotheses, such as the reaction of the atmosphere to a deluge of \( \gamma \)-rays and the consequences of increased exposure to UV light. Nevertheless, it appears that the main hazard concerns the ozone layer that shields terrestrial life as well as shallow marine life (Thomas et al., 2005) – including planktons that are at the basis of the marine food chain – from DNA-damaging solar ultraviolet radiation (Ruderman, 1974): about 98% of biologically harmful solar UV light is blocked by ozone. However, \( \text{N}_2 \) molecules in the upper atmosphere are susceptible to dissociation by \( \gamma \)-ray photons. Dissociated isolated nitrogen atoms are highly prone to bonding with oxygen atoms, thus forming nitrogen oxides (NO, \( \text{NO}_2 \)) that catalyze conversion of ozone molecules \( \text{O}_3 \) to oxygen molecules (Gehrels et al., 2003). Nitrogen oxides persist for several years in the atmosphere (Jackman et al., 2000), but \( \text{NO}_2 \) is opaque: this would further block solar light, leading to a long-lasting ice age.

Piran & Jimenez (2014) estimate the probability of a life-threatening GRB event to occur in the vicinity of the Earth and in different galactic environments, based on their rate, their luminosity function, and the properties of their host galaxies. They conclude that a life-threatening GRB likely occurred close enough to Earth to harm life at least once in the past 5 Gyr, and that there is a 50% chance that one occurred in the past 500 Myr – eventually producing a mass extinction event. They also find that a lethal GRB is much more likely to happen in the inner part of the Milky Way, making it a dangerous environment for life to develop. In a broader analysis, they consider that the low-density outer parts of large galaxies are the most hospitable environments for life, and that a life similar to the terrestrial one could not have existed at \( z > 0.5 \) because of the larger GRB rate and the smaller size of galaxies.

In Li & Zhang (2015), the authors attempt to answer the question of the possibility for life to survive GRBs in the high-redshift Universe. They estimate that a lethal GRB on Earth should occur roughly every 500 Myr (consistent with the timescale of the Ordovician-Silurian mass extinction, see next paragraph). This timescale is suggested to be long enough for advanced life to develop, leading to the definition of a benign environment. Making use of observational data, they also investigate the lethal GRB rate in other galaxies, finding that as many as 99% of local galaxies may be benign and that \( \sim 50\% \) of
galaxies are still benign at $z = 1.5$. Even at $z = 3$, they find a benign galaxy fraction of $\sim 10\%$, reaching a different conclusion than Piran & Jimenez (2014) who conclude that life could not exist at $z > 0.5$.

The Ordovician-Silurian mass extinction event, one of the largest to ever take place, is generally consistent with a GRB origin (Melott et al., 2004), although it is by no means the favored explanation. This event occurred some 445 million years ago in two steps separated by $0.5 - 2$ Myr; all known complex organisms lived in the seas and the oceans at that time. The extinction has been linked to a fast global cooling followed by a fast global warming (Melott et al. 2004 and references therein), as well as to a fall of the sea level. Although it is difficult to evaluate them properly, the patterns of species extinction are compatible with surface marine life being hit much harder than organisms dwelling in deeper waters. This is consistent with an increased UV exposure due to ozone depletion, while the global cooling is consistent with the creation of opaque NO$_2$ in the atmosphere.

Chen & Ruffini (2014) discuss the possible role of a GRB event in the Cambrian explosion, a sudden increase in the rate of diversification of species that occurred 542 Myr ago and lasted 20 – 25 Myr. They conclude that it might have been triggered by a GRB exploding 500 pc from the Earth, as a significant fraction of (Compton-scattered) GRB photons could have reached sea level and induced DNA mutations in organisms protected by a shallow layer of either water or soil.

1.6 Going further: a selection of books and reviews

There exists a great wealth of review material on GRBs, both in the form of books and review articles. An inexhaustive selection is presented here for the interested reader.

- Recent reviews on GRBs and the fireball model include Piran (2005) and Gehrels et al. (2009). Kumar & Zhang (2015) offer a broad review entitled *The Physics of Gamma-Ray Bursts and Relativistic Jets* that covers the major developments in the understanding of GRBs. Special attention is given to the magnetic jet model. A review of the alternative fireshell model, upon which this thesis relies, may be found in Ruffini (2011).


While the previous chapter focused on historical, experimental, and empirical considerations, the present chapter is devoted to the theoretical understanding of gamma-ray bursts. There exists a standard framework which is used by a majority of the community in order to describe GRBs and infer their physical signification, the so-called fireball model. We will present this theory, its successes, and its limitations. We will then move on to the description of an alternative model upon which this thesis relies heavily: the fireshell model. Lastly, for the sake of completeness, we shall take a quick glimpse at other alternative models.
2.1 The fireball model

The fireball model may arguably be considered as a standard model, since it is widely adopted by the GRB community. This model provides the basic ingredients to explain GRB observations, although precise quantitative predictions are still lacking and some observations challenge some of its expectations. The model is reviewed e.g. by Piran (1999) or Mészáros (2006).

2.1.1 On compactness and ultra-relativistic motion

As we have seen in the previous chapter, making sense of the diversity encountered in GRB observations is not an easy task. Fortunately there exist several strong arguments that reveal the ultra-relativistic nature of GRBs. First of all, the observed variability $\delta t$ of the $\gamma$-ray lightcurves, down to tens of milliseconds, sets tight constraints on the size of the emitting region. Indeed, the time that sound waves need to cross an object forms a natural timescale for the observed variability of its lightcurve. The speed of sound $c_s$ can be very large in compact objects, reaching a significant fraction of the speed of light; hence from $\delta t \approx l/c_s$ one obtains an estimate of the size $l$ of the emitting region of GRBs as $l \lesssim c\delta t \approx 3000$ km.

Such a compact source implies that the optical depth for high-energy photons must be very large – this is often referred to as the compactness problem. The optical depth $\tau_{\gamma\gamma}$ is equal to $\sigma_T n_\gamma$, where $\sigma_T$ is the cross-section for photon-photon interaction producing $e^+/e^-$ pairs, $l$ is the distance traveled by the high-energy photon to escape, and $n_\gamma$ is the density of photons for which the pair creation threshold $2m_e c^2$ is reached ($m_e$ being the electron mass). $n_\gamma$ may be approximated by the energy of a typical burst ($E = 4\pi S d_l^2$ where $d_l$ is the luminosity distance to the source and $S$ is the fluence of the burst) divided by a typical photon energy $E_\gamma \approx m_e c^2$, over the volume of the source $4/3\pi l^3$. One then obtains:

$$\tau_{\gamma\gamma} \approx \frac{3\sigma_T S d_l^2}{m_e c^2 l^2}.$$  (2.1)

For values typical of a GRB, $\tau_{\gamma\gamma} \sim 10^{15}$. With such a high optical depth, the source should be optically thick (Piran, 2005) and no high-energy photons should be able to escape and reach the Earth. Ruderman (1975) nevertheless pointed out that a relativistic motion of the source towards the observer with Lorentz factor $\gamma \gg 1$ relaxes the requirements on $\tau_{\gamma\gamma}$. Two effects come into play: first, a relativistically expanding source can appear much smaller than what is inferred from the variability timescale, because the emitting material closely follows the light it just emitted, so that successive photons are squeezed for the observer. The variability timescale is then $\delta t = \delta t'/(2\gamma^2)$ where $\delta t'$ is the variability timescale in the source rest-frame. The second effect is a Doppler-Fizeau blueshift: a photon observed at energy $E$ was emitted in the source rest-frame at an energy $\sim E/\gamma$. This reduces $\tau_{\gamma\gamma}$ by a factor $\sim \gamma^{-2\beta}$ (Piran, 1999), where $\beta$ is the high energy spectral index of the Band function, because of the reduction in the number of photons that carry enough energy to enable pair creation. Overall, ultra-relativistic motion implies:

$$\tau_{\gamma\gamma} \approx \frac{1}{2\gamma^{4-2\beta}} \frac{3\sigma_T S d_l^2}{m_e c^2 l^2}.$$  (2.2)
2.1 The fireball model

The source becomes optically thin for typical Lorentz factors $\gamma \gtrsim 50$. This ultra-relativistic motion makes GRBs very unique sources: if relativistic motions e.g. in active galactic nuclei jets are observed, their Lorentz factor is typically $\sim 2 - 20$; GRBs on the other hand may reach up to $\gamma \gtrsim 1000$.

An independent and more direct confirmation of the relativistic nature of the expansion stems from radio observations. Knowing the distribution of electrons in the galaxy, scintillation (i.e. erratic variations of the flux by a factor $\sim 2$) in radio observations allows for the size of the source to be inferred. In particular, observations of GRB 970508 – the distance to which is known – shows that the source is expanding relativistically, as can be determined from the gradual suppression of scintillation when the angular size of the source becomes larger than the electron fluctuation scale in the interstellar medium (Frail et al., 1997). The analysis of GRB 030329, a nearby burst observed with a high resolution using VLBI maps, also led to the conclusion that the blast wave was still expanding at $\gamma = 7$ one month after the GRB (Taylor et al., 2004).

Before the high-energy photons can escape however, the emitting material must reach these extreme velocities. The release of a large quantity of energy into a small, compact region implies an energy density so high that collisions of high-energy photons creating $e^+e^-$ pairs (that in turn annihilate in $\gamma$-rays) are common. This may lead to an expanding opaque photon-lepton plasma, commonly referred to as a fireball. Opacity implies that the energy is trapped until transparency is reached.

2.1.2 Evolution of the fireball

Cavallo & Rees (1978) built a model in which a sudden release of energy during a gravitational collapse process leads to the creation of a large number of pairs, the annihilation of which releases a large amount of energy in the close environment – a photon-lepton fireball. Goodman (1986) later quantified the dynamics of the expansion of such a fireball.

Let us consider an outflow with total energy $E_0$ and mass $M_0 \ll E_0/c^2$ enclosed within a radius $r_0$. Due to the high optical depth the expansion may be considered adiabatic. In the comoving frame, $TV^{1-\gamma_a}$ is constant, where $T$ is the temperature of the fireball, $V$ its volume, and $\gamma_a$ is the adiabatic index (equal to $4/3$ here since the pressure is dominated by radiation). It follows that $T \propto V^{\gamma_a-1}$. Since $V \propto r^3$, the temperature evolves as $T \propto r^{-1}$.

This pure lepton-photon fireball model however does not pass observational scrutiny. As it turned out, a baryon-loaded fireball is a much more interesting GRB candidate. Shemi & Piran (1990) computed the dynamics of a fireball in the presence of baryonic matter. The presence of baryons has two major influences: the accelerated baryons carry bulk kinetic energy converted from the initial radiation energy (implying that the coasting Lorentz factor will be smaller and that the presence of too many baryons kills the ultra-relativistic motion, as occurs in a supernova where the ejecta expands at a velocity $< 0.1c$), and the electrons associated to the baryons increase opacity. At first, the fireball is radiation-dominated, as most of the energy is carried by photons; but eventually the matter entrained in the fireball will hold most of the energy in the form of kinetic energy – this is referred to as the matter-dominated phase. In this phase, matter essentially coasts with a constant radial velocity.

The quantity of entrained mass can be constrained using the Lorentz factor. During the matter-dominated phase, most of the initial fireball energy $E_f$ has been transferred to a mass $M_0$ with total energy $\gamma M_0 c^2$: it follows that $M_0 = E_f/(\gamma c^2)$. A typical value for $M_0$ is of the order of $10^{-5} M_\odot$. 


2.1.3 Photospheric emission

It is expected that a fraction of the initial thermal energy of the fireball is radiated at the photosphere, where the plasma becomes optically thin. The predicted spectrum of this photospheric emission is thermal; however, a blackbody component cannot fit the Band-like spectra of GRBs: its low-energy spectral index is +1 while it is −1 for a typical GRB, and its high-energy part includes an exponential fall-off while a typical GRB exhibits a power law with index \( \sim -2.5 \). Geometric broadening of the blackbody as a result of the finite size of the photosphere (e.g. Goodman 1986) cannot account for the diversity of GRB spectra.

More recently, modified photospheric emission has received significant interest since blackbody components have been identified in several GRBs (Ryde, 2004). In particular, a blackbody component appears in time-resolved spectra (Ryde, 2005), the temperature evolution of which follows the predictions of the fireball model. Sub-photospheric dissipative processes – such as magnetic reconnection (Giannios & Spruit, 2005), internal shock waves (Rees & Mészáros, 1994), neutron decay and proton-neutron collisions (Beloborodov, 2003, 2010), or interactions of the jet with the stellar envelope (Pe’er et al., 2006; Lazzati & Begelman, 2010) – may lead to a spectrum characterized by an up-scattered and broadened blackbody component, in addition to a synchrotron component originating in shocks outside the photosphere. The case of GRB 090902B is particularly interesting in light of this photospheric theory (Ryde et al., 2011).

2.1.4 Internal and external shocks

Once the fireball accelerates to relativistic velocities, an efficient way to convert the kinetic energy of the baryons back to radiation is needed. The particles’ trajectories must be perturbed in order to release energy, and shocks are natural and simple candidates to do so. Shocks may be thought of sharp discontinuities in the properties of a region (such as density, temperature, pressure) compared to those of a neighbouring one. Two categories of shocks are envisioned in the fireball model: internal shocks and external shocks.

Internal shocks

In the internal shock scenario, several shells of relativistic particles are emitted with slightly different Lorentz factors. When a fast-moving shell catches up with another slower one, a shock occurs (Rees & Mészáros, 1994). The density of matter is not high enough that there can be a significant number of direct collisions; instead, interactions mediated by long-range forces (magnetic fields are thought to play this role) enable energy and momentum transfer. Internal shocks typically take place at radial distances \( \sim 10^{14} - 10^{15} \) cm from the emitting region. This scenario can easily explain the strong variability of the \( \gamma \)-ray lightcurves as the result of the emission of shells of different energies and Lorentz factors. On the other hand, the kinetic-to-radiation energy conversion efficiency is rather low, because the relative velocity between the shells is limited: at most half of the shell energy may be extracted (Kobayashi et al., 1997). In spite of this efficiency issue, the expected properties of internal shocks have promoted the internal shock theory to the rank of most likely explanation for the prompt emission in the fireball model.
External shocks

The external shock scenario studies the consequences of a shock between a fast-moving shell and the circumburst medium (CBM), which slows down the shell. This shock takes place from the beginning of the expansion of the outflow, but it becomes efficient only when the swept mass is large enough to significantly reduce the kinetic energy of the shell. This mechanism is somewhat similar to supernova remnants interacting with the surrounding interstellar matter, but the collected mass has to remain at low levels so as not to kill relativistic motion. External shocks provide an efficient way to convert bulk energy to radiation; however, they cannot produce variable bursts with typical pulse durations much smaller than the burst duration (which is the case during the prompt emission). This is why external shocks are thought to produce the afterglows of GRBs.

The deceleration of the shell creates a forward shock propagating in the CBM as well as a reverse shock propagating back into the ejecta (Mészáros & Rees, 1993). The reverse shocks, being much less energetic, are thought to radiate at longer wavelengths. In particular, they are thought to cause the optical flashes that can be seen in the afterglow of several GRBs (Sari & Piran, 1999).

The density profile of the CBM is important, as it affects the evolution of external shocks. The CBM may have a constant profile with a density of particles $n$ usually of the order of $1 \text{ cm}^{-3}$ (typical of the interstellar medium), or it may have a stellar wind-like profile where $n \propto r^{-2}$, where $r$ is the radial distance to the center of explosion.

2.1.5 Spectral predictions

In the context of the internal-external shock model, the spectrum of GRBs is generally thought to be mainly produced by synchrotron emission of relativistic electrons gyrating in local magnetic fields (Piran, 1999). The electrons are accelerated by the Fermi mechanism, which implies a power law distribution in terms of energy. The electron energy distribution is then given by

$$N(\gamma_e) = \gamma_e^{-p} ; \gamma_e > \gamma_m = \gamma_e \left( \frac{p - 2}{p - 1} \right) \frac{m_p}{m_e}$$

(2.3)

where $\gamma_e$ is the electron Lorentz factor, $\gamma_m$ is the minimum electron Lorentz factor, $\gamma$ is the bulk Lorentz factor, $p > 2$ is the electron energy distribution power law index, $\epsilon_e$ is the fraction of energy contained in the random motion of electrons, $m_e$ is the electron mass, and $m_p$ is the proton mass. The typical synchrotron frequency of a relativistic electron is dependent on its Lorentz factor and reads in the fluid frame

$$\nu_{\text{syn}}(\gamma_e) = \frac{\gamma_e^2 q_e B}{2\pi m_e c}$$

(2.4)

where $q_e$ is the electron charge and $B$ is the magnetic field. The spectral power of a relativistic electron with initial energy $\gamma_e m_e c^2$ is approximately a power law of index 1/3 (i.e. $F_\nu \propto \nu^{1/3}$) that decays exponentially above $\nu_{\text{syn}}$. The total emitted power can be expressed (again, in the fluid frame) as

$$P_{\text{syn}} = \frac{4}{3} \sigma_T c \gamma_e^2 B^2 \frac{B}{8\pi}.$$  

(2.5)

However, this is only valid as long as the electron loses a negligible fraction of its energy to radiation (adiabatic condition).
This translates into a critical upper Lorentz factor \( \gamma_c \) such that \( \gamma \gamma_c m_e c^2 = P_{\text{syn}}(\gamma_c) t \), or

\[
\gamma_c = \frac{6 \pi m_e c}{\gamma \sigma_T B^2 t}.
\]

(2.6)

Here, \( t \) is the timescale (in observer time) within which the electron cools down from \( \gamma > \gamma_c \) down to \( \gamma_c \). The spectral power varies as \( F_\nu \propto \nu^{-1/2} \) between \( \nu_{\text{syn}}(\gamma_c) \) and \( \nu_{\text{syn}}(\gamma_e) \). The most energetic electrons, on the other hand, are cooling rapidly and emit almost all their energy at their synchrotron frequency, so that \( F_\nu \propto \nu^{-p/2} \).

Let us define \( \nu_m = \nu_{\text{syn}}(\gamma_m) \) and \( \nu_c = \nu_{\text{syn}}(\gamma_c) \). If \( \nu_m > \nu_c \) (or \( \gamma_m > \gamma_c \)) the integrated spectrum of the total electron distribution is in the fast-cooling regime (all electrons with Lorentz factors above \( \gamma_c \) cool rapidly) and is characterized by

\[
F_\nu = F_{\nu,\text{max}} \begin{cases} 
(\nu/\nu_c)^{1/3}, & \nu < \nu_c \\
(\nu/\nu_c)^{-1/2}, & \nu_c < \nu < \nu_m \\
(\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2}, & \nu_m < \nu.
\end{cases}
\]

(2.7)

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

In the slow-cooling regime \( \nu_m < \nu_c \) (where only the highest energy electrons cool rapidly), the spectrum is given by

\[
F_\nu = F_{\nu,\text{max}} \begin{cases} 
(\nu/\nu_m)^{1/3}, & \nu < \nu_m \\
(\nu/\nu_m)^{-p/2}, & \nu_m < \nu < \nu_c \\
(\nu_c/\nu_m)^{-(p-1)/2}(\nu/\nu_c)^{-p/2}, & \nu_c < \nu.
\end{cases}
\]

(2.8)

The prompt phase of GRBs is expected to be in the fast-cooling regime in order to achieve a high variability (the cooling time must indeed be short) as well as a high efficiency in the internal shocks (Piran, 1999). Transition to the slow-cooling regime is expected to take place during the early stages of external shocks (Mészáros & Rees, 1997a; Waxman, 1997).

Additional processes are expected to alter this pure synchrotron spectrum. Thus synchrotron self-absorption causes a cut-off at lower frequencies, when the optical depth reaches unity for non-cooled electrons (this frequency is termed \( \nu_{\text{ac}} \)) and when it reaches unity for all electrons (at frequency \( \nu_{\text{sa}} \)). Fig. 2.1 shows the five possible spectral configurations, depending on the respective order of the characteristic frequencies \( \nu_m, \nu_c, \nu_{\text{ac}}, \) and \( \nu_{\text{sa}} \).

Inverse Compton (IC) scattering is also believed to play a role in spite of the fact that the outflow is optically thin to Compton scattering (Rybicki & Lightman, 1979). However, the energies involved are very large, which sets the outflow in a regime in which the IC cross-section decreases rapidly; as a result, a photon undergoes only a single scattering. The effects of IC depend on the comptonization parameter \( Y \) defined as \( Y = \gamma^2 \tau_e \) with \( \tau_e \) being the electron opacity. They can be neglected for \( Y < 1 \); otherwise a high-energy component (of the order of 10 MeV) appears in the spectrum and the cooling timescale is shortened by a factor \( Y \) (Piran, 2005).

In addition, the detection of thermal components due to photospheric emission at early times has been claimed (see Section 2.1.3).
Figure 2.1: The five possible spectral energy distributions of a relativistic blast-wave that accelerates the electrons to a power-law energy distribution. Each panel gives all of the break frequencies, and respective fluxes and time series. For further details see Granot & Sari (2002).
2.1.6 On jets

In order to relax the energy requirements (remember that the isotropic energy of some GRBs can reach up to $\sim 10^{55}$ erg), it has been suggested and widely accepted that the emission is collimated into jets, i.e. the outflows are ejected into a cone of half-opening angle $\theta_j$. From the point of view of the observer, two effects discriminate a jetted outflow from an isotropic outflow. First, relativistic motion due to the velocity of the ejecta beams the radiation into a cone of half-opening angle $\sim \gamma^{-1}$ which is initially smaller than the jet half-opening angle $\theta_j$. As the outflow slows down, the visibility cone gets progressively larger, until its half-opening angle equals $\theta_j$ at which point a break in the lightcurve occurs.

Second, the ejecta is only contained into the jet as long as its Lorentz factor is large enough that $1/\gamma \lesssim \theta_j$ (Sari et al., 1999). After this, the ejecta starts to expand sideways. For an on-axis observer, this causes a break in the lightcurve; for an off-axis observer who is not in the line-of-sight of the jet and therefore could not observe the GRB, an orphan afterglow (i.e. an afterglow without the $\gamma$-ray emission) could in principle be observed.

Since these two effects are purely relativistic and hydrodynamic, they should affect the lightcurve at every wavelength in the same way: this means that the expected break in the lightcurve of the afterglow caused by the collimated geometry – the so-called jet break – is achromatic.

$\theta_j$ may be computed from the jet break time $t_j$ following Sari et al. (1999) as

$$
\theta_j \approx 0.1 \left( \frac{t_j/1 \text{ hour}}{6.2(1+z)} \right)^{3/8} \left( \frac{n_0}{E_{\text{iso}}/10^{52} \text{ erg}} \right)^{1/8}
$$

$$
= 0.13 \left( \frac{t_j/1 \text{ day}}{1+z} \right)^{3/8} \left( \frac{n_0}{E_{\text{iso}}/10^{52} \text{ erg}} \right)^{1/8}
$$

(2.9)

where $n_0$ is the CBM density in cm$^{-3}$. It is found that for long GRBs, the typical half-opening angle lies in the range $3^\circ \lesssim \theta_j \lesssim 10^\circ$ (e.g. Berger 2014 and references therein). These values imply a beaming correction factor $f_b = 1 - \cos(\theta_j) \approx 10^{-2}$, meaning that the true energy release is two orders of magnitude lower than the measured $E_{\text{iso}}$ (with a typical value of a few $10^{51}$ erg) and that the long GRB rate is correspondingly larger.

Sparser measurements are available for short GRBs mainly due to the faintness of their afterglows. The average $\theta_j$ of short GRBs nevertheless seems to be larger than that of long GRBs (Berger, 2014). Beaming-corrected energies usually fall under $10^{50}$ erg. Under the hypothesis that short GRBs are caused by binary neutron star mergers, the detection rate of Advanced LIGO and VIRGO will be able to set constraints on the jet opening angle of short GRBs (Berger, 2014).

In the pre-Swift era, observational support for jetted emissions came from the detection of achromatic breaks in the afterglow lightcurves of several GRBs (e.g. Bloom et al. 2001). However, it should be noted that afterglow observations in the Swift era have shown a lack of achromatic breaks compared to the pre-Swift era (De Pasquale et al., 2009): the X-ray breaks compatible with a jet interpretation either are not present in the XRT observations (Racusin et al., 2009) or occur before the optical jet-like breaks (Kocevski & Butler, 2008). Missing breaks are attributed to far off-axis observations (van Eerten et al., 2011), to bad quality of data (Curran et al., 2008), or to the break time falling beyond the end of XRT follow-up. Another possible interpretation is that the X-ray afterglow of many GRBs is not due to external shocks but to a long-lasting central engine (Metzger et al., 2011), so that only the optical lightcurve may be suitable to identify jet breaks.
2.1 The fireball model

As explained above, orphan afterglows detected without a $\gamma$-ray counterpart are another predicted effect of jetted emission. The possibility of detecting orphan afterglows has been discussed by several authors. Thus Nakar et al. (2002) find that at most 15 orphan afterglows should be present in the Sloan Digital Sky Survey, while Totani & Panaitescu (2002) find a rate 10 times higher. However the issue of identifying the candidate events remains. To date, no positive detection has been successfully carried out.

2.1.7 Central engines

The fireball model does not assume a specific progenitor: it assumes a large quantity of energy being released in a small spatial volume but stays silent on the energy source. Given the characteristics of GRB emission\(^1\), rapid accretion onto a black hole is a natural candidate. As detailed in Section 1.3.2, observations are consistent with short GRBs being produced by binary neutron star mergers, and long GRBs being produced by collapsars – the difference in duration being related to the size of the accretion disk in each case. Accretion disks in collapsars can be fed by the stellar envelope, while compact object mergers produce smaller accretion disks. An alternative possibility is that the central engine consists of a highly magnetized neutron star, a so-called magnetar.

Collapsars

The collapsar model (Woosley, 1993; Popham et al., 1999) posits a massive star origin of long GRBs. When a massive star (i.e. with a mass in excess of about 20 $M_\odot$) fuses material to iron and forms an iron core, nuclear fusion does not generate energy any more. It is expected that in some cases gravitational pressure may directly lead to a catastrophic collapse to a black hole. Surrounding stellar matter then falls towards the black hole by forming an accretion disk. The accretion rate must be of the order of hundredths up to several solar masses per second for a typical GRB. A pair of relativistic jets that take angular momentum away along the rotational axis can be created by three possible mechanisms:

- neutrino/anti-neutrino annihilation along the rotational axis may drive a jet endowed with the expected properties;
- the Blandford-Znajek mechanism\(^2\) can produce a Poynting-flux dominated jet;
- the accretion disk may be highly magnetized, in which case differential rotation leads to an eruption of magnetic blobs. The jets propagate through the stellar envelope, which creates a relativistic shock wave. If the envelope is thin enough, the jets can pierce through it and exit with Lorentz factors $\gamma \geq 100$.

Wolf-Rayet (WR) stars are prime candidates to form collapsar events. WR stars are massive stars that lost most of their hydrogen envelopes. Spectral characteristics include very high surface temperatures (in excess of 30,000 K), strong stellar winds, and a high surface metallicity. Evidence in favor of WR progenitors include the connection of GRBs

---

\(^1\)In particular: the energy budget and the luminosity; the erratic behavior evidenced by the rapidly varying lightcurve; the low amount of baryons necessary to achieve ultra-relativistic motion; the spatial compactness.

\(^2\)The Blandford-Znajek mechanism is a way to extract energy from a rotating black hole (Blandford & Znajek, 1977). In addition to a spinning black hole, it requires an accretion disk endowed with a strong poloidal magnetic field that extracts the rotational energy.
to type Ib/c supernovae that lack hydrogen lines in their spectra and exhibit little-to-no helium; the localization of long GRBs in star-forming regions thus linking their progenitors to a massive star origin. However, contradicting additional properties are required: WR stars typically have a high metal abundance which results in angular momentum loss\footnote{Metals are efficient at tapping radiation pressure. This explains the strong stellar winds, which efficiently carry away angular momentum.}, but long GRB progenitors must have low metallicity levels in order to retain enough angular momentum to form the accretion disk.

**Magnetars**

Rapidly spinning magnetars (with period $P \sim 1$ ms and surface magnetic field $B_s \sim 10^{15}$ G) have been proposed as alternative central engines. They have been shown to be able to power a GRB through spin-down (Usov, 1992; Wheeler et al., 2000): the total rotational energy of a millisecond magnetar of initial period $P_0$ can be written as

$$E_{\text{rot}} \approx \frac{1}{2} I \Omega^2 \approx 1.5 \times 10^{52} \frac{M}{M_\odot} \left( \frac{R}{10^6 \text{ cm}} \right)^2 \left( \frac{P_0}{10^{-3} \text{ ms}} \right)^{-2}$$

(2.10)

where $R$ stands for the radius of the magnetar and the energy is given in erg. Only GRBs with energy below the value given by Eq. 2.10 may be powered by magnetars. Note that most GRBs fall below the critical value when their energy is collimation-corrected. Typical luminosities and durations can be reproduced.

The detailed mechanism of emission has been studied e.g. in Bucciantini et al. (2008, 2009); Metzger et al. (2011). The newborn magnetar is initially very hot; neutrinos then drive a significant wind. This wind carries away too many baryons to achieve relativistic motion. However, after $\sim 10$ s this baryonic wind weakens as the NS cools down, and a jet may be produced for about half a minute until the neutrino emission suddenly drops. Continuous spin-down may further inject energy in the form of Poynting flux.

**Compact object mergers**

Independently of the environment of short GRBs – which are consistent with evolved stellar objects –, the progenitors of short GRBs can be traced back to systems with a dynamical timescale of the order of milliseconds because of their short durations. As a consequence, the merging of compact binaries – double neutron stars or neutron star/black hole systems are considered (Eichler et al., 1989; Narayan et al., 1992) – is the most popular scenario to explain short GRBs.

Binary orbits decay at an increasing pace set by the loss of energy and angular momentum in the form of gravitational radiation. The end result of a NS-NS merger is expected to be a hyperaccreting black hole; a similar configuration may be expected from BH-NS mergers if the tidal disruption of the NS occurs outside the horizon of the BH. Energy is extracted in a similar way as in the collapsar case: a fast rotation and a high accretion rate may drive neutrino-anti-neutrino annihilation or magneto-hydrodynamic processes that produce collimated outflows.
2.2 The fireshell model (or: another take on the GRB experience)

Building upon the idea of black hole energy extraction, the fireshell model was formulated in its early form soon after the announcement of the discovery of GRBs at the 1973 AAS meeting. While the source of energy that powers a GRB in the fireball model is thought to be related to black hole (or magnetar) formation, the exact mechanism of energy extraction is still unclear. On the other hand, the fireshell model was built starting from the energy extraction mechanism. This section deals with the fundamentals of the fireshell model: central engine, dynamics of the fireshell, observational signatures, lightcurves, and spectra. Lately, the model has evolved to account for binary interactions: this will be the subject of the following chapters.

2.2.1 Fireshell and fireball: differences and similarities

The fireshell model represents an attempt to analyze the GRB phenomenon as a whole, starting from the energy source – the central engine. It has been shown (Damour & Ruffini, 1975) that the formation of a Kerr-Newman black hole may deliver as much as

$$E_{\text{max}} = 1.1 \times 10^{54} \frac{M_{\text{BH}}}{M_{\odot}} \text{ erg.}$$

(2.11)

It is interesting to note that this energy budget is large enough that it does not require a collimated emission (a jet), which is necessary in the fireball approach, to account for the isotropic energy of GRBs.

This approach is in sharp contrast with that of the fireball picture, which has been developed in a piecewise way: the deduction of the presence of ultra-relativistic motion led to the idea of a (initially spherically symmetric) photon-lepton fireball, later modified to be collimated and to include a small amount of baryons (cf. Section 2.1.1).

The fireball and the fireshell models have in common the idea that a good fraction of the $\gamma$ radiation is produced by plasma interactions at a distance $\sim 10^{14} - 15$ cm from the central engine. However, in the case of the fireshell model the equations of motion of the baryonic shell are integrated exactly in a self-consistent way once the initial conditions are set (Bianco & Ruffini, 2004, 2005a). The fireball approach uses the result of Blandford & McKee (1976) that describes the propagation of a relativistic shell in the circumburst medium: this model introduces the self-similar spherical solution of an adiabatic ultra-relativistic blastwave. The differences between these two approaches are outlined in Section 2.2.3 (see also Bianco & Ruffini 2005b for more details).

While the collapsar model does not consider binary interactions, the latest developments of the fireshell model provide a picture in which all GRBs (the long ones as well as the short ones) may originate in binary systems. The effects of binarity on long GRBs are largely overlooked in the fireball model: binarity is mostly invoked to build a possible formation channel of rapidly rotating stellar cores that are stripped of their hydrogen envelopes, which may produce collapsar events (see e.g. Fryer et al. 1999c). However, most type Ib/c supernovae – the type of supernovae that are connected to GRBs – are found to occur in binary systems (Smith et al., 2011), and most massive stars – which are related to the progenitors of long GRBs – are found in binary systems (Smith et al., 2014): it is therefore a natural idea to study the consequences of binary interactions in the framework of GRB science.
Central engine and energy budget

The foundations of the fireshell model lie in the mass-energy formula of a charged rotating (Kerr-Newman) black hole (KN-BH), the most general solution of the Einstein-Maxwell equations completely characterized by the mass \( M \), the charge \( Q \), and the angular momentum \( L \). The formula reads (Christodolou & Ruffini, 1971):

\[
E_{\text{BH}}^2 = M^2 c^4 = \left( M_{\text{ir}} c^2 + \frac{Q^2}{2 \rho^2_+} \right)^2 + \frac{L^2 c^2}{\rho^2_+} \tag{2.12}
\]

where \( M_{\text{ir}} \) is the irreducible mass of the BH\(^4\) (Christodolou & Ruffini, 1971) and \( \rho_+ \) is the horizon radius, such that the horizon surface \( S \) is

\[
S = 4\pi \rho^2_+ = 16\pi \left( \frac{G^2}{c^4} \right) M^2_{\text{ir}} . \tag{2.13}
\]

In addition, the following condition applies:

\[
\frac{1}{\rho^4_+} \left( \frac{G^2}{c^8} \right) (Q^4 + 4L^2 c^2) \leq 1 . \tag{2.14}
\]

It can be deduced from Eq. 2.14 that the extractable rotational energy has an upper limit value of 29% of the total mass-energy, while the extractable Coulomb energy may reach a maximum of 50% of the total mass-energy.

We restrict hereafter to the case of a charged, non-rotating black hole (a Reissner-Nordström black hole, RN-BH). Damour & Ruffini (1975) demonstrated that vacuum polarization leading to the creation of electron-positron pairs (Schwinger, 1951) can occur around a RN-BH if the electrical field exceeds the critical value

\[
E_c = \frac{m^2 e^3}{\hbar c} . \tag{2.15}
\]

Damour & Ruffini (1975) also found that the pair creation process is fully reversible: this makes it an extremely efficient mechanism of energy extraction, with a maximum extractable energy given by Eq. 2.11. In the spherically symmetric case of a RN-BH, the region of pair creation (termed dyadosphere) is bounded by the horizon radius \( r_+ \) and the dyadosphere radius \( r_{ds} \) where the electric field is equal to \( E_c \) (Preparata et al., 1998):

\[
r_+ = 1.47 \times 10^5 \mu \left( 1 + \sqrt{1 - \xi^2} \right) \text{ cm} ; \quad r_{ds} = 1.12 \times 10^8 \sqrt{\mu \xi} \text{ cm} . \tag{2.16}
\]

Here, \( \mu = M_{\text{BH}}/M_\odot \) is the mass and \( \xi = Q/(M_{\text{BH}} \sqrt{G}) \) is the charge parameter. The total energy stored in the dyadosphere \( E_{e^+e^-}^{\text{tot}} \) can be computed from the number of \( e^+e^- \) pairs \( N_{e^+e^-} \). The latter is derived by modeling the dyadosphere as a set of concentric shells of capacitors of thickness \( \sim \hbar/(m_e c) \) each producing a number of pairs \( \sim Q/e \) (Preparata et al., 1998, 2002). We obtain

\[
N_{e^+e^-} \simeq \frac{Q - Q_e}{e} \left[ 1 + \frac{r_{ds} - r_+}{\hbar/(m_e c)} \right] , \tag{2.17}
\]

with \( Q_e = E_c r^2_+ \). We have then (Preparata et al., 1998)

\[
E_{e^+e^-}^{\text{tot}} = \frac{Q^2}{2r_+} \left( 1 - \frac{r_+}{r_{ds}} \right) \left[ 1 - \left( \frac{r_+}{r_{ds}} \right)^4 \right] . \tag{2.18}
\]

\(^4\)The irreducible mass is the minimal value of the mass left after the energy extraction process.
In the case of a KN-BH, the system loses spherical symmetry and becomes axially symmetric. The geometry of the pair creation region becomes a torus, termed dyadotorus (Cherubini et al., 2009). The detailed consequences of this change have not been worked out yet.

### 2.2.3 Overview of the dynamics

The pair plasma that we obtained in the previous section is optically thick and has $E_{e^+e^-}^{\text{tot}}$ in the range $10^{49} - 10^{54}$ erg. On a timescale of $\sim 10^{-13}$ s, the plasma reaches thermal equilibrium (Aksenov et al., 2007) and starts to expand and accelerate under its own internal radiation pressure. Initially, baryon contamination is limited since the local environment has been depleted by the gravitational collapse that formed the BH; but baryon contamination becomes significant as the pair plasma encounters and engulfs the remnant of the BH progenitor.

**Free expansion**

The dynamics can be described starting from energy conservation. Both a numerical approach based on the analytic equations of the system (Wilson et al., 1998) and a simplified approach leading to ordinary differential equations have been carried out and have been shown to be in agreement (Wilson et al., 1998; Ruffini et al., 1999, 2000).

The plasma is described by the stress-energy tensor

$$ T^{\mu\nu} = p g^{\mu\nu} + (p + \rho) U^\mu U^\nu $$

where $\rho$ is the total proper energy density in the comoving frame of the plasma fluid, $p$ is the pressure in the same frame, and $U^\mu$ is the 4-velocity of the plasma. $p$ and $\rho$ are connected through the equation of state

$$ \Gamma_T = 1 + \frac{p}{\rho} $$

where $\Gamma_T$ is a thermal index. The energy-momentum conservation of the plasma along a flow line is given by

$$ U_\mu (T^{\mu\nu})_{,\nu} = \left( \rho U^t \right)_t + \frac{1}{r^2} \left( r^2 \rho U^r \right)_r + p \left[ \left( U^t \right)_t + \frac{1}{r^2} \left( r^2 U^r \right)_r \right] = 0. $$

The baryon number conservation law can be expressed as

$$ (n_B U^\mu)_{,\mu} = (n_B U^t)_t + \frac{1}{r^2} \left( r^2 n_B U^r \right)_r = 0 $$

where $n_B$ is the proper baryon number density. The pair rate equation is given by

$$ (n_{e^\pm} U^\mu)_{,\mu} = \frac{\sigma_c}{\pi} \left[ n_{e^-} (T) n_{e^+} (T) - n_{e^-}^0 n_{e^+}^0 \right] $$

where $n_{e^\pm} (T)$ and $n_{e^-} (T)$ are the proper number densities of $e^+$ and $e^-$ given by appropriate Fermi integrals with zero chemical potential, and $n_{e^\pm}^0$ and $n_{e^-}^0$ are the proper number densities at the initial time of the expansion. $T$ is the equilibrium temperature, determined by thermalization processes occurring in the expanding plasma. The average value $\sigma_c$ is such that the cross-section of pair creation or annihilation $\sigma$ is approximated by the Thomson cross-section $\sigma_T$ and the speed of sound $c_s$ is given by $c_s \sqrt{p/\rho}$. 
Wilson et al. (1998) numerically computed the (spherically symmetric) solutions of these equations. A simplified set of equations has also been derived. In the latter case, the main assumptions are the following:

- Gravitational interactions are considered a perturbation of the total energy, so that the plasma evolves in a flat space-time.
- Energy losses of the pair plasma are negligible until transparency.
- The plasma shell has a constant laboratory frame width throughout the expansion.

The adiabatic condition $d(\epsilon V) + pdV = 0$ (where $\epsilon$ is the internal energy density and $V$ the pulse volume in the comoving frame) is imposed, and using Eq. 2.20 it leads to

$$\epsilon = \epsilon_0 \left( \frac{V_0}{V} \right)^{\Gamma_T}.$$

(2.24)

From Eq. 2.21 the stress-energy tensor flux through the space-like hypersurface $\Sigma_t$ orthogonal to the static vector field $\xi^\mu$ normalized at infinity can be expressed as

$$E = \int_{\Sigma_t} \xi_\mu T^{\mu\nu} d\Sigma_\nu = (\Gamma_T \rho \gamma^2 + p) V$$

(2.25)

where $V$ is the laboratory frame volume of the pulse and, as defined above, $V = \gamma V$ in the comoving frame volume. Since the Lorentz factor at this stage is $\sim 50$, the pressure term in Eq. 2.25 can be neglected. The evolution of the pulse Lorentz factor is then

$$\Gamma_{T,0} \rho_0 \gamma_0^2 V_0 = \Gamma_T \rho \gamma^2 V \implies \gamma = \gamma_0 \sqrt{\frac{\rho_0 V_0}{\rho V}},$$

(2.26)

where the subscript “0" refers to quantities evaluated at initial time. Eqs. 2.26 and 2.24 provide a complete set of equations for the numerical integration together with the $e^+e^-$ pair rate equation.

Fig. 2.2 shows the evolution of the Lorentz factor with the radius. The assumption of a constant shell thickness in the laboratory frame (Slab 1 curve) is strengthened by the results, while the Lorentz factor at this stage is $\sim 50$, the pressure term in Eq. 2.25 can be neglected. The evolution of the pulse Lorentz factor is then

where the subscript “0" refers to quantities evaluated at initial time. Eqs. 2.26 and 2.24 provide a complete set of equations for the numerical integration together with the $e^+e^-$ pair rate equation.

Baryon contamination

Up to now, a baryon-free plasma has been considered. This assumption is valid until the plasma shell engulfs the baryonic remnant of the progenitor; the remnant is assumed to form a spherical shell outside the dyadosphere, but close enough that the plasma reaches it before it achieves transparency. Numerical simulations have shown that the dynamics of the pulse after baryon contamination is little sensitive to the location of the remnant (Ruffini et al., 2003). The mass of the baryonic remnant $M_B = N_B m_p$ (where $N_B$ is the number of baryons and $m_p$ the proton mass) can be expressed relative to the total pair energy $E_{e^+e^-}^\text{tot}$ as a dimensionless parameter termed baryon load

$$B = \frac{M_B c^2}{E_{e^+e^-}^\text{tot}}.$$

(2.27)

The following assumptions are made in order to model the interaction of the plasma with the remnant:
2.2 The fireshell model (or: another take on the GRB experience)

Figure 2.2: Comparison between the 1-dimensional numerical solution to the exact equations (squares) and three simplified solutions described in the text: Slab 1 (solid line), Slab 2 (dashed line) and Sphere (dotted-dashed line). Slab 1, that corresponds to a constant width in the laboratory frame, provides the best match to the analytical solution. Figure reproduced from Ruffini et al. (1999).

Figure 2.3: Evolution of the Lorentz factor of the plasma with the radial coordinate, assuming $B = 10^{-4}$. After the initial free expansion, the plasma impacts with the baryonic remnant. The Lorentz factor abruptly decreases and then accelerates again. The agreement between the assumption of constant width in the laboratory frame (dot-dashed line) and the exact equations (squares) is shown. Figure reproduced from Ruffini et al. (1999).
• The geometry of the plasma does not change during the interaction.
• The interaction is completely inelastic.
• The baryons thermally equilibrate with the plasma.

These assumptions are valid under the following conditions (Ruffini et al., 2000):

- $E_{e^+e^-}^{\text{tot}}$ is much larger than $M_B c^2$ ($B < 10^{-2}$);
- the ratio $n_{e^\pm} / n_B$ between the comoving number density of pairs and that of baryons is greater than $10^{56}$; the plasma has a high Lorentz factor $\gtrsim 100$.

The consequences of the interaction between the plasma and the baryons are (Ruffini et al., 2000, 2003):

• The Lorentz factor of the system abruptly decreases.
• The comoving internal energy increases, leading to significant heating of the plasma, to an increase in the number of pairs, and consequently to an increase of the opacity.
• The pairs and the baryons thermalize in a timescale $\sim 10^{-13}$ s (Aksenov et al., 2007), independently of the baryon load if $B < 10^{-2}$ (Aksenov et al., 2008).

Fig. 2.3 shows the evolution of the Lorentz factor starting from the initial free expansion of the plasma. The sudden drop in the Lorentz factor can be clearly seen, as can be the re-acceleration following the drop.

2.2.4 P-GRB and prompt emission

The next cornerstone in this scenario occurs when the opacity decreases enough that photons can escape. Following transparency, interactions between the ultra-relativistic shell of accelerated baryons left over after transparency and the CBM produce the prompt emission.

Transparency emission: P-GRB

The transparency condition is

$$\int_R dr (n_{e^\pm} + \bar{Z} n_B) \sigma_T \approx 1 \quad (2.28)$$

where $\bar{Z}$ is the average number of electrons per baryon and the integration is done in the comoving frame radial direction. Once this condition is fulfilled, all the photons trapped in the (thermalized) plasma escape in a flash of thermal radiation, called the proper GRB (P-GRB, Ruffini et al. 1999, 2000, 2001a, 2003). The P-GRB has a blackbody spectrum with temperature $T$ of the order of 15 keV, at which the pairs annihilate. The baryons on the other hand will continue to expand ballistically and collide with the CBM. As can be seen in Fig. 2.3, the constant width approximation loses accuracy after transparency as the difference between the exact equations and the approximated ones increases.

The Lorentz factor at transparency has an asymptotic value

$$\gamma_{\text{asym}} = \frac{E_{e^+e^-}^{\text{tot}}}{M_B c^2} = \frac{1}{B} \quad (2.29)$$

$\gamma_{\text{asym}}$ is reached in the limiting case where all the plasma energy is converted to baryon kinetic energy (Ruffini et al., 2000). Fig. 2.4 shows the evolution of the Lorentz factor of
2.2 The fireshell model (or: another take on the GRB experience)

Figure 2.4: Lorentz factor plotted against the radial coordinate for $E_{e^+e^-}^{\text{tot}} = 1.22 \times 10^{55}$ erg and selected values of $B$.

Figure 2.5: Lorentz factor of the fireshell of GRB 991216 plotted against the radial coordinate, assuming $E_{e^+e^-}^{\text{tot}} = 9.57 \times 10^{52}$ erg, $B = 4 \times 10^{-3}$ and $n_{\text{CBM}} = 1 \text{ cm}^{-3}$. The plasma expands freely (I) until it collides with the baryonic remnant (II). The baryonic shell keeps on expanding (III) until it reaches transparency and the prompt emission phase begins (IV). Being slowed down by the CBM, it finally reaches the non-relativistic regime (V). Figure reproduced from Ruffini et al. (2001a).
the fireshell until transparency. As $B$ tends towards its limiting value\(^5\), the Lorentz factor at transparency tends towards $\gamma_{\text{asym}}$. This means that as $B$ increases, the fraction of the total energy $E_{e^+e^-}^{\text{tot}}$ converted to baryonic kinetic energy increases and the energy going to the P-GRB decreases (Ruffini et al., 2000, 2003).

**Prompt emission**

The accelerated baryons and the remaining leptons follow a ballistic path after the emission of the P-GRB, until they run into the circumburst medium. This (inelastic) interaction produces a multi-wavelength emission and slows down the shell. In order to model this interaction, the relativistic conservation laws of energy and momentum have to be used. In the literature, and in particular in the framework of the fireball model, the Blandford-McKee self-similar solution (Blandford & McKee, 1976) that makes an ultra-relativistic approximation is widely adopted; however, in the fireshell model, the exact solutions of the equations of motion are used. The following assumptions are made:

- The width of the baryonic shell remains constant in the laboratory frame.
- The interaction between the baryons and the CBM is modeled as a sequence of inelastic collisions of the baryonic shell with several cold and thin spherical shells of matter that are at rest in the laboratory frame.
- The energy is emitted instantaneously (fully radiative scenario, Ruffini et al. 2003).

In the limit of infinitely thin CBM shells, one obtains the following set of equations (Bianco & Ruffini, 2005b):

\[
\begin{align*}
\frac{dE_{\text{int}}}{c^2} &= (\gamma - 1) dM_{\text{CBM}}, \\
\frac{d\gamma}{M} &= -\frac{\gamma^2 - 1}{M} dM_{\text{CBM}}, \\
\frac{dM}{c^2} &= \frac{1 - \epsilon}{\epsilon^2} dE_{\text{int}} + dM_{\text{CBM}}, \\
dM_{\text{CBM}} &= 4\pi m_p n_{\text{CBM}} r^2 dr.
\end{align*}
\]  

$E_{\text{int}}$ is the internal energy of the shell, $\epsilon$ is the fraction of the energy emitted in the collision, $M_B$ is the mass of the baryons, $M_{\text{CBM}}$ is the swept-up mass and is equal to $\frac{4}{3} \pi m_p n_{\text{CBM}} (r^3 - r_0^3)$ where $n_{\text{CBM}}$ is the CBM particle number density in the laboratory frame, $r$ is the radial distance in the laboratory frame, and $r_0$ is the radius at which the shock front develops.

One then obtains the following equation for the evolution of the Lorentz factor (Piran, 1999; Ruffini et al., 2003; Bianco & Ruffini, 2005a). In the fully radiative regime ($\epsilon = 1$),

\[
\gamma = \frac{1 + (M_{\text{CBM}}/M_B)(1 + \gamma_0^{-1})[1 + (1/2)(M_{\text{CBM}}/M_B)]}{\gamma_0^{-1} + (M_{\text{CBM}}/M_B)(1 + \gamma_0^{-1})[1 + (1/2)(M_{\text{CBM}}/M_B)]}.
\]  

(2.31)

Fig. 2.5 shows as an example the evolution of the Lorentz factor during the entire course of GRB 991216 (Ruffini et al., 2001c).

\(^5B = 10^{-2}\) represents a limiting value, as the approximation of constant comoving width of the fireshell breaks down: turbulent motion inside the shell can occur and stop the expansion of the pulse, preventing the GRB to be emitted.
2.2 The fireshell model (or: another take on the GRB experience)

2.2.5 Obtaining GRB lightcurves and spectra

The foundations of the GRB emission mechanism in the fireshell model are now laid down. However, in order to explain the observed lightcurves and spectra, important additional effects still have to be taken into account. Relativistic effects affect the observer lightcurve; spectra are also affected. Once these effects are properly taken into account, the fitting of GRB lightcurves and spectra can be performed; the fitting process in turn reveals the characteristics of the CBM.

Lightcurves: arrival times and equitemporal surfaces (EQTS)

Relativistic motion implies a beaming of the emitted radiation: only photons emitted from a limited area centered on the line-of-sight can be seen by the observer. The angle $\theta$ between the line-of-sight and elements of the visible area, measured from the center of explosion, must satisfy (Bianco et al., 2001; Ruffini et al., 2002, 2003)

\[ \cos \theta \geq \frac{v(t)}{c} \]  

(2.32)

where $v(t)$ is the velocity of the emitting region. In the early phases of a GRB, ultra-relativistic motion implies $v \approx c$ and $\theta_{\text{max}} \approx 0$. In the late phases, $\theta_{\text{max}}$ tends towards $\pi/2$ (Ruffini et al., 2002, 2003). $\theta$ allows us to relate the time interval between the arrival of two photons from the point of view of a local observer with respect to the observer $t_d$, and in the laboratory time $t$. Due to cosmological time dilation, one has $t_d = t_a(1 + z)$ (with $z$ being the redshift of the GRB). Ruffini et al. (2001a, 2003) give the relation between $t_a$ and $t$ as

\[ t_a = t - \int_0^t \frac{v(t')dt'}{c} \cos \theta + r_{ds} \cos \theta \]  

(2.33)

where $r_{ds}$ is the dyadosphere radius. Computing this expression requires the knowledge of the entire world line of the source. Eq. 2.33 is often approximated as $t_a = t/(2\gamma^2)$ (Rees & Mészáros, 1998; Piran, 1999; Mészáros, 2002). This approximation uses the assumption that $v$ is constant throughout the motion and is a first order expansion in the case of $\gamma \gg 1$ and $\cos \theta = 1$, which is not valid at every stage of a GRB (Ruffini et al., 2001c).

Two photons arriving at the same time in the observer’s detector generally have not been emitted at the same comoving time. In the case of a spherically symmetric relativistic source, the surfaces of equal arrival time at the observer (equitemporal surfaces, EQTSs) are surfaces of revolution around the line-of-sight (Bianco & Ruffini, 2005a) and are consequently characterized by the quantity $\theta(r)$. Ruffini et al. (2003); Bianco & Ruffini (2004, 2005a) give the following expression for the arrival time:

\[ c t_a = c t(r) - r \cos \theta + r^* \]  

(2.34)

where $r^*$ corresponds to the initial size of the expanding source. $t(r)$ is obtained from the expression of the Lorentz factor $\gamma = [1 - (v/c)^2]^{-1/2}$ as

\[ c t(r) = \int_0^r \frac{dr'}{\sqrt{1 - \gamma^{-2}(r')}} \]  

(2.35)

\(^6\)That is, an observer located in the vicinity of the GRB (at the same redshift).
In the fully radiative regime, one obtains (using Eq. 2.31):

\[
t(r) = \frac{M_B - m_i^0}{2c\sqrt{C}} (r - r_0) + \frac{m_i^0 r_0}{8r\sqrt{C}} \left( \frac{r}{r_0} \right)^4 - 1 + \frac{r_0\sqrt{C}}{12cm_i^0A^2} \ln \left\{ \frac{[A + (r/r_0)]^3(A^3 + 1)}{[A^3 + (r/r_0)^3](A + 1)^3} \right\} \\
\quad + t_0 + \frac{r_0\sqrt{3C}}{6cm_i^0A^2} \left[ \arctan \frac{2(r/r_0) - A}{a\sqrt{3}} - \arctan \frac{2 - A}{a\sqrt{3}} \right],
\]

where \( A = [(M_B - m_i^0)/m_i^0]^{1/3} \) and \( C = M_B^2(\gamma_0 - 1)/(\gamma_0 + 1) \). The corresponding EQTSs are then characterized by

\[
\cos \theta = \frac{M_B - m_i^0}{2r\sqrt{C}} (r - r_0) + \frac{m_i^0 r_0}{8r\sqrt{C}} \left( \frac{r}{r_0} \right)^4 - 1 + \frac{r_0\sqrt{C}}{12cm_i^0A^2} \ln \left\{ \frac{[A + (r/r_0)]^3(A^3 + 1)}{[A^3 + (r/r_0)^3](A + 1)^3} \right\} \\
\quad + \frac{c(t_0 - t_a)}{r} + \frac{r^*}{r} + \frac{r_0\sqrt{3C}}{6cm_i^0A^2} \left[ \arctan \frac{2(r/r_0) - A}{a\sqrt{3}} - \arctan \frac{2 - A}{a\sqrt{3}} \right].
\]

As previously noted, Eqs. 2.30 are usually solved using an ultra-relativistic approximation following Blandford & McKee (1976). This approximation leads to the relation \( \gamma \propto r^{-a} \) where \( a = 3 \) in the fully radiative regime. This leads to significantly different expressions of \( t(r) \), which has non-negligible consequences (Bianco & Ruffini, 2004, 2005a,b).

**Spectra: convolution and modified thermal spectrum**

In the fireshell model, the radiation produced by the interaction of the shell with the CBM is assumed to be thermal in the comoving spectrum. Another assumption states that the increase in internal energy due to the collision is radiated away instantly and isotropically (Ruffini et al., 2004). The observed spectra of GRBs are however highly non-thermal in general. But as the temperature of the fireshell evolves with the comoving time (Ruffini et al., 2004), the observed spectrum at any given time is the convolution of spectra of different temperatures originating in the entire corresponding EQTS. This produces a non-thermal spectrum (Bernardini et al., 2005). In a time-integrated spectrum, this convolution of spectra has to be itself convoluted over the observing time, giving the following final observed spectrum as

\[
\frac{dE_{[\nu_1,\nu_2]}^{\Delta t}}{dt \, d\Omega} = \int_{EQTS} \frac{\Delta \epsilon}{4\pi} \nu \cos \theta A^4 \frac{dt}{d\Omega} W(\nu_1, \nu_2, T_a) d\Sigma.
\]

where \( \Delta \epsilon \) is the energy density released in the interaction and \( d\Sigma \) is the EQTS surface element at detector arrival time \( t_\Delta \) (Ruffini et al., 2002). The observed temperature of \( d\Sigma \) is \( T_a = \Delta T/(1 + z) \) where \( T \) is the comoving temperature. \( W \) is an effective weight required to evaluate the contribution in the energy band \( [\nu_1, \nu_2] \) and is defined as

\[
W(\nu_1, \nu_2, T_a) = \frac{h}{\int_0^{\nu_2} \left( \frac{dN_\gamma}{d\nu} \right) \nu d\nu} = \frac{\int_0^{\nu_2} \left( \frac{dN_\gamma}{d\nu} \right) \nu d\nu}{\int_0^{\nu_2} \left( \frac{dN_\gamma}{d\nu} \right) \nu d\nu} aT^4_a
\]

where \( h \) is the Planck constant, \( \alpha = 4\sigma/c \) is the radiation constant (\( \sigma \) being the Stefan-Boltzmann constant), and \( N_\gamma \) is the photon number density per unit energy, assumed to follow a thermal distribution

\[
\frac{1}{h} \frac{dN_\gamma}{dV d\nu} = \left( \frac{8\pi}{\hbar^3} \right) \frac{\nu^2}{\exp \left( \frac{\hbar \nu}{kT} \right) - 1}
\]
2.2 The fireshell model (or: another take on the GRB experience)

Figure 2.6: Instantaneous photon spectra with different values of the $\alpha$ parameter. The curve with $\alpha = 0$ corresponds to the pure thermal spectrum.

Figure 2.7: Main quantities of the fireshell model at transparency for selected values of $E_{e+e-}^{\text{tot}}$: the radius in the laboratory frame; the comoving frame and blue-shifted temperatures of the plasma; the Lorentz factor; and the fraction of energy radiated in the P-GRB and in the extended afterglow as functions of $B$. A sudden transition between the optically thick adiabatic phase and the fully radiative condition at the transparency has been assumed.
where \( k \) is the Boltzmann constant.

The assumption of a pure thermal comoving frame emission is however not able to reproduce the spectra of high-energy GRBs, which emit most of their radiation at higher energies. A modified blackbody spectrum with a different power law index in the low energy part \( \alpha \) was consequently introduced (Patricelli et al., 2012):

\[
\frac{1}{\hbar} \frac{dN_\gamma}{dV d\nu} = \left( \frac{8 \pi}{h c^3} \right) \left( \frac{h \nu}{kT} \right)^\alpha \frac{\nu^2}{\exp \left( \frac{h \nu}{kT} \right) - 1}.
\]

(2.41)

The pure thermal case corresponds to the case \( \alpha = 0 \). Fig. 2.6 shows photon spectra with different \( \alpha \) values.

### 2.2.6 Fitting a GRB in the fireshell scenario (or: a summary)

In the previous subsections the conceptual basis of the fireshell model was introduced, and the subsequent conclusions regarding the dynamics of the fireshell were developed. Important additional effects concerning the lightcurves and spectra of GRBs have been explained, so that a consistent picture can be drawn.

The fireshell model requires only two parameters to determine the physics of the dyadosphere. The first one, the total energy of the pair plasma \( E_{e^+e^-}^{\text{tot}} \), is obtained by equating it to the isotropic energy \( E_{\text{iso}} \) of the GRB. \( E_{\text{iso}} \) is however a lower limit in the case that a significant part of the GRB emission falls below the sensitivity limits – or outside the bandpass – of the detector. The second fundamental parameter is the baryon load \( B \) that is uniquely characterized by the ratio of the energy of the P-GRB \( E_{P,\text{GRB}} \) to \( E_{e^+e^-}^{\text{tot}} \). The lower right panel of Fig. 2.7 depicts how the ratio of \( E_{P,\text{GRB}} \) to the total energy leads to the determination of \( B \). In order to determine \( E_{P,\text{GRB}} \), the P-GRB has to be correctly identified through a spectral analysis. Two components can usually be seen in a P-GRB spectrum: the thermal component from transparency emission, as well as a non-thermal component which may be due to the early onset of the extended afterglow. \( E_{P,\text{GRB}} \) is determined solely from the thermal component.

Fig. 2.7 also shows that the knowledge of \( B \) gives the radius and the temperature of the fireshell, and the Lorentz factor at transparency. \( B \) is also uniquely determined from these quantities. This means that an observational cross-check is possible: from the observed temperature of the thermal component \( kT_{\text{obs}} = kT_{\text{blue-shifted}}/(1 + z) \), one can verify that the value of \( B \) obtained in this way is consistent with that obtained from \( E_{P,\text{GRB}} \).

Once \( E_{e^+e^-}^{\text{tot}} \) and \( B \) are determined, three extra quantities are needed to reproduce the lightcurve and spectrum of a GRB:

- The CBM density profile \( n_{\text{CBM}} \), which is dependent on the radius. It determines the temporal behavior of the lightcurve.

- The filling factor \( R = A_{\text{eff}}/A_{\text{vis}} \), a quantity dependent on the radius that accounts for the size of the effective emitting area of the shell \( A_{\text{eff}} \) compared to the total visible area of the shell \( A_{\text{vis}} \) (Ruffini et al., 2002, 2004, 2005). This factor takes into account the filamentary, clumpy structure of the CBM. Results from fireshell simulations imply that the CBM clumps have a typical width of the order of \( 10^{15} \) – \( 10^{16} \) cm, a typical mass in the range \( 10^{-11} – 10^{-8} \text{ M}_\odot \), and a density contrast \( \delta n/n \sim 0.1 – 10 \). This CBM profile is consistent with that deduced e.g. from the study of the interstellar medium in novae (Shara et al., 1997) or from theoretical considerations of supergiant stars and clumpy winds (Ducci et al., 2009).
2.3 Alternative theories

• The $\alpha$ index that modifies the low-energy part of the thermal spectrum. Note that $\alpha$ differs from GRB to GRB.

These quantities can be determined by running a trial-and-error simulation. This simulation makes the shell of ultra-relativistic baryons evolve starting from the fireshell transparency. It is expected that each pulse in the lightcurve corresponds to a CBM cloud, the parameters of which can be determined by fitting the lightcurve. However, fitting a pulse also depends on the entire previous history of the GRB because of the EQTS effect, and it affects the entire future evolution of the lightcurve. As a result, fitting the lightcurve and the spectrum of a GRB proves to be a complex procedure. It is important to note that the latest sections of a fit will not be accurate, as some of the hypotheses made on the equations of motion may break down, and the fireshell may fragment (Dainotti et al., 2007). An example of fitting result is shown in Fig. 2.8.

2.3 Alternative theories

There exist a number of alternative theories to the internal-external shock model and to the fireshell model. This section introduces some of them, but does not aim at an exhaustive census.

Perhaps the most extensively studied alternative theory considers the prompt emission to arise from magnetic reconnection or dissipative processes, assuming that the ejecta are highly magnetized or Poynting dominated (Usov, 1994; Thompson, 1994; Mészáros & Rees, 1997b). As a result, a very high degree of polarization is expected. It is not clear whether baryonic outflows (i.e. outflows not dominated by magnetic energy) can achieve such high degrees of polarization or not. Typical emission radii and spectral evolutions would also be different from those of the internal shock model, but the afterglow is likely to be similar to the one expected from external shocks. The main difference is that no reverse shock (or only a weak one) is expected because of the high Alfvén speed of the ejecta. Kumar & Zhang (2015) extensively review magnetic jet models.

Several models (e.g. Lazzati et al. 2000; Broderick 2005) consider the idea of converting the kinetic energy of the jet to $\gamma$ radiation via inverse Compton scattering of photons coming either from the progenitor star, from the supernova, or from the ambient photon field. Titarchuk et al. (2012) consider in addition IC scattering by electrons in the radiation-dominated subrelativistic phase of the outflow.

The “cannonball” model (Dado et al., 2002, 2007) builds upon the assumption that the outflow is composed of discrete, non-fluids cannonball-like packets of plasma that interact through particle-particle interactions (instead of collisionless shocks). In this model, the prompt emission arises from blue-shifted bremsstrahlung and the afterglow is produced by IC scattering of ambient or progenitor photons.
Figure 2.8: Upper panel: lightcurve of GRB 090510 as observed by Fermi/GBM and its simulated counterpart. Lower panel: spectrum of GRB 090510 and its simulated counterpart. Figures reproduced from Muccino et al. (2013b).
Towards the Induced Gravitational Collapse paradigm

It is now an established fact that at least a fraction of long GRBs occur (almost) simultaneously with supernovae. This GRB – SN connection, together with the premises of the fireshell model, led to the development of the Induced Gravitational Collapse (IGC) paradigm. This framework explains the connection between SNe and energetic long GRBs (with $E_{\text{iso}} \gtrsim 10^{52}$ erg) in terms of the interactions between an evolved stellar core on the verge of undergoing a SN explosion and its companion neutron star. Hypercritical accretion of the SN ejecta onto the NS drives its subsequent collapse to a black hole.

In this chapter, we will detail the GRB – SN connection and summarize a work that aimed at finding previously undetected GRB – SN events using Fermi data (Kovacevic et al., 2014). We will then present the evidence for the presence of multiple episodes in several energetic GRBs, including GRB 090618 which has become a prototypical IGC event. This multi-episode structure led to a physical picture of the IGC paradigm. Additional properties of IGC systems, including a joint optical/X-ray analysis of their spectra and the nesting features (Ruffini et al., 2014a) of their X-ray afterglows, will also be presented.
3.1 The GRB – SN connection

The idea that GRBs could be related to SNe is an old one. Early works – anterior even to the detection of GRBs – suggested that SN shock breakouts may generate an observable signature in $\gamma$-rays (Colgate, 1968), which led to the first – albeit unsuccessful – searches for a SN counterpart (Klebesadel et al., 1973). Further efforts were carried out during the 1970s and 1980s, without any more luck. However, Paczyński (1986) noted that if GRBs were to be cosmological in origin, the energy released in $\gamma$-rays would be of the order of that released by a typical SN. In addition, the collapsar model (Woosley, 1993) naturally connected GRBs to the death of massive stars, so that concurrent SNe could be expected\(^1\). Another clue that linked GRBs and SNe lied in the fact that even early afterglow localizations of long GRBs pinpointed them in the vicinity of star-forming regions (Bloom et al., 2002b).

3.1.1 Supernova taxonomy

Supernovae are believed to originate in two types of events: first, the thermonuclear runaway of an accreting white dwarf or that of two merging white dwarfs (this latter formation channel may be the dominant mechanism, see e.g. the review by Maoz et al. 2014); second, the explosive deaths of massive stars (see e.g. Woosley & Heger 2014 for a review on the deaths of massive stars).

The classification of supernovae does not follow this progenitor distinction, as early classification efforts relied on observational constraints. Two main groups were defined based on the absence (type I SNe) or the presence (type II) of hydrogen spectral lines. Type II SNe are further categorized in several subgroups depending on the aspect of their lightcurves. Type I SNe are subdivided in type Ic (absence of helium lines), type Ib (presence of helium lines, absence of silicon lines), and type Ia (presence of helium and silicon lines). White dwarf-related SNe appear as type Ia events while all other types are caused by core-collapse events.

GRB – SNe are generally consistent with being of type Ib/c, although type II events have been occasionally suggested (Garnavich et al., 2003; Gorosabel et al., 2005). They fall on the luminous end tail of the distribution of type Ib/c SNe and their spectral lines are broad, indicating a high ejecta velocity. Other features of this population of SNe however do not appear to follow common trends: thus the distributions of peak brightnesses, rise times, or broadness of the spectral lines for instance experience a large dispersion.

3.1.2 Observational evidence

One of the first detections of a SN contemporaneous with a GRB occured in 1998: when BeppoSAX detected GRB 980425 (Pian et al., 2000), optical follow-up showed that instead of fading, the optical afterglow was getting brighter. This signal was identified as the bright and peculiar SN 1998bw (Galama et al., 1998), a type Ic supernova with broad spectral lines, indicating that the photosphere was expanding at high velocity (> 0.1 c). But at a redshift $z = 0.0085$, the very nearby GRB 980425 turned out to be an unusual event with an extremely low energy output (Kaneko et al., 2007). The possibility that

\(^1\)The early formulation of the collapsar model by Woosley (1993) did not accommodate for a simultaneous SN, but the model was later refined.
3.1 The GRB – SN connection

this GRB had a different progenitor as cosmological “classical” GRBs do cast doubts on the possibility of extending the GRB – SN connection to cosmological GRBs\(^2\).

Direct evidence for a SN connection to a cosmological GRB nevertheless already existed, with the earliest ones being related to the observation of a supernova-like bump in the optical afterglow of GRB 980326 (Bloom et al., 1999) and GRB 970228 (Reichart, 1997). Definitive proof came with the spectroscopic identification of SN 2003dh following GRB 030329. GRB 030329 was a bright burst detected by HETE-2 (Vanderspek et al., 2004; Lipkin et al., 2004) that exploded at \(z = 0.1685\) (Greiner et al., 2003b). Its optical afterglow first appeared as a typical, featureless GRB afterglow, but after a few days SN characteristics began to emerge (e.g. Hjorth et al. 2003). Subtracting the contribution of the GRB afterglow, it turned out that SN 2003dh was very similar to SN 1998bw, as illustrated in Fig. 3.1.

Up to May 31, 2014 a total of 35 photometric and spectroscopic identifications of SNe connected to GRBs (listed in Table 3.1) have been performed. Note that observational constraints restrict most spectroscopic identifications to \(z \lesssim 0.3 – 0.6\), while photometric identification is reasonably probable up to \(z \sim 1\).

3.1.3 Are all long GRBs associated to SNe?

Along with the association of long GRBs with star-forming environments (see Section 1.3.2) and the first observations of GRB – SNe came the idea that all long GRBs could be connected to SNe. This situation finds a natural explanation in the collapsar model, and it was suggested that the absence of a SN counterpart was a defining feature of short GRBs. It turned out, however, that GRBs would once more defy predictions as 2006 saw the detection of two low-redshift, long events that did not have a concurrent SN down to very deep limits: 6 to 7 magnitudes fainter than usual GRB – SNe, e.g. Della Valle et al. (2006a); Gehrels et al. (2006). See also Fig. 3.2.

With \(T_{90}\) durations of respectively 4 s and 102 s at respective redshifts 0.089 and 0.125, GRB 060505 and GRB 060614 do not fit into the short/long classification scheme. Intriguingly, even though they do exhibit characteristic features of long GRBs, they also have typical short GRB features. Thus GRB 060505 had a significant spectral lag, as long GRBs do, and exploded in a low-metallicity star forming region of its host galaxy, which was a late-type one (Ofek et al., 2007; Thöne et al., 2004) – yet another long GRB characteristic. It is however an outlier to the Amati correlation satisfied by long GRBs. Another GRB detected during the same year, GRB 060614, had an initial 5 s spike with no spectral lag (a typical feature of short GRBs), followed by a softer emission. Its host galaxy is underluminous but undergoes relatively little star formation, and the GRB occurred in a region with probable little UV emission (Gal-Yam et al., 2006) and consequently a low star-forming rate. It has been suggested that GRB 060614 may have suffered from a chance superposition with a foreground galaxy, which would justify the non-detection of a SN (Cobb et al., 2006; Campisi & Li, 2008).

\(^{2}\)In addition, two X-ray sources were found in the error circle of GRB 980425. The identification of its X-ray counterpart was therefore controversial (Pian et al., 2000; Kouveliotou et al., 2004), as was the association with SN 1998bw.
Towards the IGC paradigm

Figure 3.1: Evolution of the spectra of SN 1998bw (Patat et al., 2001) and SN 2003dh (Hjorth et al., 2003). The GRB afterglows and the contribution of the host galaxies have been taken into account. The times indicated are rest-frame times. Figure reproduced from Hjorth et al. (2003).

Figure 3.2: Lightcurves of four GRB-SNe compared to upper limits in SN-less GRBs. The red data points correspond to GRB-SNe, the blue upper limit arrows correspond to two short GRBs, the green ones correspond to the long duration GRB 060614 and GRB 060505. Approximate bolometric magnitudes are based on $R$ and $V$ band upper limits offset relative to the corresponding SN 1998bw $R$ or $V$ band light curves. Time is in rest-frame units. For comparison, the dashed line represents the $^{56}$Co decay slope.
Table 3.1: The 35 confirmed GRB-SN connections up to the May 31, 2014. Reproduced from Kovac'evic 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. et al. (2000); (8) Bloom et al. (2002a); (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. (2003a); (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) Campana 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 & Preece (2009); (45) Bufano et al. (2012); (46) Chornock et al. (2010); (47) Sakamoto et al. (2010); (48) Sparre et al. (2011); (49) van der Horst (2010); (50) D’Avanzo et al. (2012); (51) Briggs & Younes (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) Ukawa et al. (2012); (58) De Ugarte Postigo et al. (2013a); (59) Younes & 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).
3.1.4 A search for GRB – SN events with Fermi

The search for a SN signal following the detection of a GRB relies on optical observations. The decay of heavy unstable elements forged in the harsh environment of an exploding star indeed powers tremendous luminosities: at their peak luminosities, SNe can shine brighter than their entire host galaxies.

In stripped-envelopes SNe (type Ib/c), the shock breakout is short, hard, and relatively faint. The lightcurve is entirely powered by the decay of $^{56}$Ni (half-life of 6.1 days) to $^{56}$Co and of $^{56}$Co (half-life of 77.3 days) to $^{56}$Fe. As a result, the lightcurve peaks 10 to 15 rest-frame days following the star’s demise (Arnett, 1996).

The X-ray and optical follow-up abilities of Swift have made the localization of a great number of GRBs easier. This in turn increased the number of optical afterglow detections, which are essential to the detection of a SN. However, the field of view of the Swift/BAT instrument is 6.5 times smaller than that of the GBM instrument onboard Fermi (Meegan et al., 2009), which unfortunately does not offer comparable localization and follow-up abilities. As a result there may exist GRB – SNe, detected by Fermi but not by Swift, that were not accurately localized and hence lacked optical follow-up and SN detection.

In Kovacevic et al. (2014) we performed a statistical analysis on Fermi GRBs with the purpose to check whether such events can be uncovered or not, cross-checking with the Harvard catalog of SNe and the Asiago SN catalog (Barbon et al., 2010). Only SNe at redshifts $z < 0.2$ have been considered in order to ensure that SN detections would be secure enough.

The positions of 1147 long GRBs reported in the Fermi/GBM catalog up to May 31, 2014 have been compared to the SN positions (taking error boxes into due account). When a match occurred, the additional requirement that the GRB exploded within a time $\Delta t$ before the SN detection was imposed: assuming that the GRB and the SN should occur concurrently, the rise time of the SN lightcurve implies that the SN detection happens several days later.

The numbers of SNe of each type $N_{\text{Ib}/c}(\Delta t)$, $N_{\text{Ia}}(\Delta t)$, $N_{\text{IIp}}(\Delta t)$, $N_{\text{IIn}}(\Delta t)$ that satisfy these conditions of temporal and spatial coincidences are shown in Table 3.2 for several temporal windows $\Delta t$. The statistical significance of the association of type Ib/c SNe with GRBs, as well as the significance of the association of other SN types with GRBs, is investigated as follows.

The distribution of SNe is assumed to be random over the entire sky; the spatial association of GRBs and SNe then follows Poisson statistics. The significance of the deviation of $N_x$ (where $x = \{\text{Ib}/c, \text{Ia}, \text{IIp}, \text{IIn}\}$) from the expected number of associations – which is inferred from the relative proportion of each SN type in the total SN sample – can be expressed as

$$S = e^{-\lambda} \frac{\lambda^n}{n!}$$

where $\lambda$ is the expected number of events and $n = N_x(\Delta t)$ is the number of observed associations. $\lambda$ is evaluated as follows: $\lambda = N_{\text{tot}}(\Delta t) r_x$ where $r_x$ is the proportion of each SN type compared to the whole SN sample. The resulting significance as a function of $\Delta t$ is shown in Fig. 3.3: as one may expect, a significant association is only obtained for type Ib/c SNe detected within 20 days of the GRB trigger time.

Restricting now only to GRB – SN associations within $\Delta t = 20$ days and type Ib/c SNe,

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3 http://www.cbat.eps.harvard.edu/lists/Supernovae.html
3.1 The GRB – SN connection

Figure 3.3: Evolution of the statistical significance of GRB – SN associations for each SN type with $\Delta t$. Figure reproduced from Kovacevic et al. (2014).

<table>
<thead>
<tr>
<th>$\Delta t$ (days)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
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<th>$r_x$ (%)</th>
</tr>
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<td>9</td>
<td>9</td>
<td>13</td>
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<td>26</td>
<td>30</td>
<td>42</td>
<td>68</td>
<td>96</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>$N_{Ia}$</td>
<td>10</td>
<td>23</td>
<td>30</td>
<td>42</td>
<td>51</td>
<td>64</td>
<td>77</td>
<td>85</td>
<td>108</td>
<td>131</td>
<td>164</td>
<td>213</td>
<td>338</td>
<td>519</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>$N_{IIp}$</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>14</td>
<td>16</td>
<td>19</td>
<td>19</td>
<td>21</td>
<td>26</td>
<td>30</td>
<td>39</td>
<td>54</td>
<td>82</td>
<td>124</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>$N_{IIn}$</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>9</td>
<td>11</td>
<td>11</td>
<td>14</td>
<td>21</td>
<td>30</td>
<td>51</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$N_{tot}$</td>
<td>31</td>
<td>67</td>
<td>98</td>
<td>136</td>
<td>166</td>
<td>209</td>
<td>240</td>
<td>260</td>
<td>314</td>
<td>378</td>
<td>471</td>
<td>627</td>
<td>893</td>
<td>1399</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: Cumulative number of supernovae observed in spatial coincidence within the error radius and in temporal coincidence within $\Delta t$ (expressed in days) with Fermi GRBs depending on SN type. For comparison, $r_x$ is the proportion of each SN type compared to the whole SN sample.
Towards the IGC paradigm

<table>
<thead>
<tr>
<th>GRB</th>
<th>RA</th>
<th>DEC</th>
<th>Error radius</th>
<th>$T_{90}$</th>
<th>Fluence (0.01 – 1) MeV</th>
<th>Peak flux (0.01 – 1) MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>090320B</td>
<td>183.4</td>
<td>49.8</td>
<td>9.5</td>
<td>29.2</td>
<td>$1.67 \times 10^{-6}$</td>
<td>4.35 ± 0.25</td>
</tr>
<tr>
<td>090426B</td>
<td>17.6</td>
<td>-19.2</td>
<td>18.1</td>
<td>16.1</td>
<td>$6.77 \times 10^{-7}$</td>
<td>2.03 ± 0.18</td>
</tr>
<tr>
<td>110911A</td>
<td>258.58</td>
<td>-66.98</td>
<td>50.0*</td>
<td>8.96</td>
<td>$5.94 \times 10^{-7}$</td>
<td>2.38 ± 0.41</td>
</tr>
<tr>
<td>120121B</td>
<td>235.67</td>
<td>-39.34</td>
<td>7.9</td>
<td>18.4</td>
<td>$1.95 \times 10^{-6}$</td>
<td>2.66 ± 0.21</td>
</tr>
<tr>
<td>130702A</td>
<td>228.15</td>
<td>16.58</td>
<td>13.02</td>
<td>59</td>
<td>$6.3 \times 10^{-6}$</td>
<td>7.03 ± 0.86</td>
</tr>
</tbody>
</table>

Table 3.3: Properties of the sample of the five Fermi GRBs possibly associated to type Ib/c SNe. The last row, GRB 130702A, is an already established connection. * Nominal maximum value for the error radius of bursts detected by a single GBM detector.

<table>
<thead>
<tr>
<th>SN date</th>
<th>RA SN (deg)</th>
<th>DEC SN (deg)</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009di</td>
<td>2009 03 21</td>
<td>174.2411</td>
<td>0.13</td>
</tr>
<tr>
<td>2009em</td>
<td>2009 05 05</td>
<td>8.6855</td>
<td>-8.3993</td>
</tr>
<tr>
<td>2011gw</td>
<td>2011 09 15</td>
<td>112.0709</td>
<td>-62.3552</td>
</tr>
<tr>
<td>2012ba</td>
<td>2012 01 21</td>
<td>230.6047</td>
<td>-38.2012</td>
</tr>
<tr>
<td>2013dx</td>
<td>2013 07 08</td>
<td>217.3116</td>
<td>15.7740</td>
</tr>
</tbody>
</table>

Table 3.4: Properties of the sample of the five SNe possibly associated to GRBs. The last row, GRB 130702A, is an already established connection.

<table>
<thead>
<tr>
<th>GRB</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_{\text{peak}}$ (keV)</th>
<th>$E_{\text{iso}}$ (erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>090320B</td>
<td>-0.65 ± 0.35</td>
<td>-2.42 ± 0.30</td>
<td>62.6 ± 12.0</td>
<td>9.13 \times 10^{49}</td>
</tr>
<tr>
<td>090426B</td>
<td>-0.50 ± 3.12</td>
<td>-1.65 ± 0.15</td>
<td>39.9 ± 76.9</td>
<td>1.94 \times 10^{47}</td>
</tr>
<tr>
<td>110911A</td>
<td>-0.47 ± 0.50</td>
<td>-1.36 ± 0.18</td>
<td>44.8 ± 20.1</td>
<td>6.22 \times 10^{47}</td>
</tr>
<tr>
<td>120121B</td>
<td>-0.73 ± 0.21</td>
<td>-2.95 ± 0.89</td>
<td>92.2 ± 12.2</td>
<td>1.39 \times 10^{48}</td>
</tr>
</tbody>
</table>

Table 3.5: Results of the Band model spectral fits of the Fermi GRBs and their derived isotropic energies.
3.2 GRBs as composite events

one is left with five cases\(^4\). One of them is an already known and documented association (GRB 130702A – SN 2013dx, Singer et al. 2013). Tables 3.3 and 3.4 summarize the properties of these five cases. Using the redshifts derived from the spectral observation of the SNe host galaxies (see Table 3.4) and fitting the GRB spectra with a Band model, the GRB isotropic energies are derived (cf. Table 3.5).

A more detailed analysis of the data suggests that out of the four candidates left, only GRB 120121B – SN 2012ba is a good candidate for a genuine GRB – SN event. SN 2012ba, a type Ic SN, indeed reached a bright peak absolute magnitude \(R_{\text{abs}} \approx -19\) about 11 days after the GRB trigger (Kryachko et al., 2012) which is a typical rising time for GRB – SNe (Bufano et al., 2012). It is however not classified as a broad-lined SN – only two other GRB – SNe are classified as Ic rather than broad-lined Ic, SN 2002lt (Della Valle et al., 2003) and SN 2013ez (Cano et al., 2014). Note that in all three cases, the spectra were secured 20 to 40 days after the peak, which leaves open the possibility that broader lines would have been seen earlier.

First-order estimates of the number of GRB – SN connections with redshifts \(z < 0.2\) in the Fermi/GBM catalog lie in the range of one to seven (Kovacevic et al., 2014) during 6 years of observations. As reported previously, out of the 5 possible connections that a cross-check of SN surveys and the Fermi catalog delivers, one was an already known association and another one was found to be a likely genuine GRB – SN association: this result is consistent with the initial estimate. Given the Fermi annual rate detection of 238 events/year and the estimated number of GRBs associated with low-z SNe (again, one to seven in 6 years of operation), it is estimated that Fermi could detect 1 to 4 GRB – SNe within the next four years.

3.2 GRBs as composite events

The bright GRB 090618 turned out to be a key event in the evolution of the fireshell model: its analysis helped to formulate the Induced Gravitational Collapse paradigm. Indeed, distinct episodes were found in its high-energy emission; this result pointed to different physical origins for these episodes. In this section, we will summarize the analysis of GRB 090618 as well as additional evidence observed in two other GRBs, namely GRB 101023 and GRB 110709B.

3.2.1 Evidence for distinct episodes: the case of GRB 090618

GRB 090618 was a nearby \((z = 0.54\), Cenko et al. 2009\) and energetic \((E_{\text{iso}} = 2.9 \times 10^{53} \text{ erg, Izzo et al. 2012a})\) event, photometrically connected to a SN. It also benefited from a thorough instrumental coverage in the X- and \(\gamma\)-ray bands as Fermi, Swift, AGILE, Suzaku, Konus-WIND, and Coronas PHOTON all detected it – these observations encompass an energy range 0.3 keV – 40 MeV. Its duration of \(\sim 150\) s catalogs it in the “long GRB” category and its high-energy emission is characterized by four prominent pulses. In addition, many optical observatories, including the Hubble space telescope, covered the optical afterglow up to 100 days post-trigger.

Izzo et al. (2012a) found that GRB 090618 is composed of two sharply different emission episodes (see Fig. 3.4). The time-integrated spectrum from \(T_0 - 4.4\) s to \(T_0 + 213.6\) s

\(^4\)The constraint \(z < 0.2\) still applies here. Should it be relaxed, three more cases are detected (GRB130427A – SN 2013cq, GRB 101219B – SN 2010ma, GRB 091127 – SN 2009nz); all of which are already known GRB – SNe.
Figure 3.4: Fermi/GBM (NaI-n4 detector, 8 – 440 keV) lightcurve of GRB 090618. The two episodes are clearly separated. Figure reproduced from Izzo et al. (2012b).

Figure 3.5: Time-integrated spectrum of the first episode of GRB 090618 with NaI-n4 and BGO-b0 data. The left panel shows a Band fit, the right panel shows a blackbody + power law fit. Figure reproduced from Izzo et al. (2012a).

Figure 3.6: Fireshell simulation of the Fermi lightcurve (left panel) and time-integrated spectrum (right panel) of GRB 090618. Figure reproduced from Izzo et al. (2012a).
3.2 GRBs as composite events

Figure 3.7: Left panel: evolution of the $\nu F_\nu$ spectra (BB and PL components are dashed, their sum is in solid lines) during the first episode of GRB 090618. Right panel: evolution of the radius of the thermal emitter of the first episode of GRB 090618 with time.

s (where $T_0$ is the trigger time) is best fit by a cutoff power law with photon index $\gamma = 1.42 \pm 0.08$ and peak energy $E_p = 134 \pm 19$ keV (Sakamoto et al., 2009). However the first episode, lasting $\sim 50$ s in the observer frame (or $\sim 32$ s in the rest-frame) is well-fitted both by a Band model and by the sum of a blackbody and a power law (see Fig. 3.5). The first 7 s of the second episode also face this situation; but the remainder of the second episode cannot be well-fitted by the combination of a blackbody and a power law.

The analysis within the fireshell scenario leads to the conclusion that the first episode cannot be the P-GRB, because the inferred temperature of the thermal emission $\sim 52$ keV deviates from the observed temperature of $32.07$ keV. On the other hand, considering the second episode as a canonical GRB and its first 7 s of emission as the P-GRB delivers consistent results. Assuming $E^{\text{tot}}_{\gamma+e^{-}} = E_{\text{iso}}$, with an isotropic energy of the second episode of $E_{\text{iso}} = (2.49 \pm 0.02) \times 10^{54}$ erg, one obtains a baryon load $B = (1.09 \pm 0.1) \times 10^{-3}$ and a P-GRB energy $4.33^{\pm 0.25}_{-0.28} \times 10^{51}$ erg. Fig. 3.6 shows the results of the numerical simulation. This simulation leads to an estimate of the CBM average density $\langle n_{\text{CBM}} \rangle = 0.6$ part/cm$^3$ (Izzo et al., 2012a).

A time-resolved analysis of the first episode with a blackbody and power law model reveals that both components evolve significantly with time. In particular, the temperature of the blackbody component decreases following a broken power law. Considering the blackbody luminosity $L = 4\pi r^2_{\text{em}} \sigma T^4_{\text{em}} = 4\pi r^2_{\text{em}} \sigma T^4_{\text{obs}} (1 + z)^4$ and given the observed flux $\phi_{\text{obs}}$

$$\phi_{\text{obs}} = \frac{L}{4\pi d_l^2} = \frac{r^2_{\text{em}} \sigma T^4_{\text{obs}} (1 + z)^4}{d_l^2},$$

one can compute (non-relativistically) the radius of the thermal signal emitter $r_{\text{em}}$ as

$$r_{\text{em}} = \left( \frac{\phi_{\text{obs}}}{\sigma T^4_{\text{obs}}} \right)^{1/2} \frac{d_l}{(1 + z)^2},$$

where $\sigma$ is the Stefan-Boltzmann constant, $z$ is the redshift of the source, $d_l$ is the luminosity distance, $T_{\text{em}}$ and $T_{\text{obs}}$ are respectively the rest-frame and observed blackbody temperatures. As shown in Fig. 3.7, the surface radius expands at non-relativistic velocities of the order of 4000 km/s from 12,000 km to 70,000 km.
3.2.2 Additional evidence: GRB 101023, GRB 110709B

Two additional GRBs that exhibit a clear resemblance with GRB 090618 were analyzed; they were shown to have a similar multi-episode structure: the cases of GRB 101023 (Penacchioni et al., 2012) and GRB 110709B (Penacchioni et al., 2013) are summarized below.

GRB 101023

GRB 101023, a burst seen by Fermi, Swift, and Konus-WIND, shares many similarities with GRB 090618 – most notably an apparent double episode structure (see Fig. 3.8). The first 45 s are identified with an first episode similar as that of GRB 090618, and the remaining 44 s are identified with a similar second episode (Penacchioni et al., 2012).

Note that despite optical follow-up by the Gemini telescope, no redshift has been measured for this source. Using different methods, a redshift $z = 0.9$ has been inferred by Penacchioni et al. (2012): the Amati correlation applied to the second episode gives $0.3 < z < 10$ at the 1σ level; the $N_{\text{H}}$ column density method discussed in Grupe et al. (2007b) that relates the absorption column density in excess of the Galactic one and the redshift gives an upper limit $z < 3.8$; the empirical method of Atteia (2003) and Pelangeon et al. (2006) that derives a redshift value from GRB spectral properties gives $z = 0.9^{+0.45}_{-0.3}$. Interestingly, the X-ray afterglow of GRB 101023 overlaps with that of GRB 090618 if its redshift is $z = 0.9$.

Using data from the Fermi/GBM NaI-n2 and NaI-nS detectors and assuming $z = 0.9$, it has been shown that the first episode cannot be interpreted as a canonical GRB in the fireshell model (Penacchioni et al., 2012): from the isotropic energy $E_{\text{iso}} = 4.03 \times 10^{53}$ erg and the P-GRB energy $E_{\text{P-GRB}} = 1.6 \times 10^{52}$ erg, a blackbody temperature $kT_{\text{th}} = 110.6$ keV is inferred – much larger than the observed one. On the other hand, and just as in the case of GRB 090618, the second episode is a consistent GRB in the framework of the fireshell model. Its parameters are then $E_{\text{iso}} = 1.8 \times 10^{53}$ erg, $E_{\text{P-GRB}} = 2.51 \times 10^{51}$ erg, a baryon load $B = 3.8 \times 10^{-3}$, a blackbody temperature $kT_{\text{obs}} = 13.26$ keV in agreement with the observed one $-$, and an average CBM density $\langle n_{\text{CBM}} \rangle \approx 16$ cm$^{-3}$. The lightcurve and spectrum simulations are shown in Fig. 3.9.

GRB 110709B

GRB 110709B was observed by Suzaku (Ohmori et al., 2011) and Swift (Cummings et al., 2011). It is another GRB that exhibits an apparent double episode structure in its high-energy emission lightcurve (see Fig. 3.10), although in a peculiar way: a first multi-peaked emission period lasting $\sim 1$ min was followed by a second trigger $\sim 11$ min later. This first emission period has been identified with a first episode similar to the one of GRB 090618, and the second emission period has been identified with a similar second episode (Penacchioni et al., 2013).

The UVOT did not detect any signal; GROND observations detected only a faint afterglow candidate: this GRB may be considered a dark GRB (see Section 1.2.3). Thus no redshift has been measured for this burst. However, a redshift of $z = 0.75$ has been inferred following the same methods as in the case of GRB 101023. Subsequent analysis in the fireshell model gave the following parameters for the second episode: an isotropic energy $E_{\text{iso}} = 2.43 \times 10^{52}$ erg, $E_{\text{P-GRB}} = 3.44 \times 10^{50}$ erg, a baryon load $B = 5.7 \times 10^{-3}$, a blackbody temperature $kT_{\text{obs}} = 12.36$ keV in agreement with the observed one, and an
3.2 GRBs as composite events

Figure 3.8: Left panel: counts lightcurve of GRB 101023 as seen by Fermi/GBM NaI-n2 detector with 1 s time bins. Right panel: flux lightcurve of the X-ray afterglow of GRB 101023 as seen by Swift/XRT.

Figure 3.9: Simulation of the Fermi/GBM lightcurve (left panel) and spectrum in the energy range 8–440 keV (right panel) of GRB 101023.
Figure 3.10: Left panel: BAT 15–150 keV lightcurve of GRB 110709B. Note the large delay between the first and the second trigger. Right panel: X-ray lightcurve of GRB 110709B (red) assuming $z = 0.75$. The overlap with GRB 090618 (blue) is clear, provided a 800 s shift of GRB 090618 is performed in order to make the steep decay of the lightcurves coincide.

Figure 3.11: Simulation of the BAT lightcurve (left panel) and spectrum (right panel) of the second episode of GRB 110709B. XRT data were included in the spectrum fit to make it explicit that the predicted slope matches with that of the X-ray spectrum.
average CBM density \( \langle n_{\text{CBM}} \rangle \approx 76 \, \text{cm}^{-3} \) – a large value consistent with the lack of a bright optical afterglow. The lightcurve and spectrum simulations are shown in Fig. 3.11.

### 3.3 A physical picture: the Induced Gravitational Collapse paradigm

An early theory using the concept of induced collapse was formulated in Ruffini et al. (2001c) and further developed in Ruffini et al. (2008). However, the current Induced Gravitational Collapse (IGC) paradigm is based on the evidence for distinct episodes presented in the previous section. The IGC model involves an evolved (likely carbon-oxygen) stellar core undergoing a SN and its companion NS going through hypercritical accretion and gravitational collapse to a BH (Ruffini et al., 2015a). It concerns energetic GRB – SN events, with an isotropic energy \( 10^{52} \lesssim E_{\text{iso}} \lesssim 10^{54} \, \text{erg} \). The outcome system consists in a newborn NS and a BH. Pisani et al. (2013) built a sample of 8 GRBs that follow the IGC framework; additional examples of IGC events will be detailed in the next chapter. The present section is devoted to detailing the four characteristic episodes of an IGC event, which are depicted and summarized in Fig. 6.2.

#### 3.3.1 Overview: the IGC time sequence

An IGC event may be divided in four episodes. This partition follows from the distinct physical origins of these episodes. Thus Episode 1 (which is the first episode of GRB 090618, GRB 101023, and GRB 110709B) is related to the supernova onset and to the accretion of the SN ejecta onto the companion NS, while Episode 2 (the second episode of these three GRBs) is a canonical fireshell GRB as described in Section 2.2. Episode 3 is notably characterized by the late X-ray emission; Episode 4 marks the optical peak of the SN emission.

**Episode 1**

This episode is related to the onset of the SN that occurs as the initial evolved stellar core reaches the end of its life. As the SN ejecta reach the companion NS, hypercritical accretion in the Bondi-Hoyle regime begins (on the order of \( 10^{-2} M_\odot/\text{s} \), see Section 3.3.2) and eventually leads the companion NS to gravitationally collapse.

The incoming material piles up on the NS surface and shocks, producing a compressed layer on top (Fryer et al., 1996). Heating up, the latter starts to emit neutrinos, subsequently cooling down enough to allow for incoming material to accrete (Fryer et al., 1996; Fryer, 2009) which eventually induces the NS collapse.

Observationally, Episode 1 is characterized by the presence of an evolving thermal component with decreasing temperature \( kT \lesssim 10 \, \text{keV} \). If detected, it is possible to infer from this thermal component the size of the emitting region and its (non-relativistic) expansion speed (as done in Section 3.2.1). Typical values reach respectively \( 10^8 - 10^{10} \, \text{cm} \) and a few \( 10^3 \, \text{km/s} \). An additional power law component is seen accompanying the thermal one; it extends to the MeV region and is due to the accretion process (Izzo et al., 2012a; Penacchioni et al., 2012). The energetics of Episode 1 may reach up to \( \sim 10^{52} \, \text{erg} \), but this episode is not always observed as it may fall below detector threshold.
Towards the IGC paradigm

Figure 3.12: X-ray lightcurves of the GRBs with redshift presented in Pisani et al. (2013). The vertical line at a rest-frame time $2 \times 10^4$ s marks the beginning of the overlapping behavior.

**Episode 2**

Episode 2 is due to the gravitational collapse of the NS; it is a canonical fireshell GRB as described in Section 2.2, a result of the BH formation.

The observational signatures of Episode 2 include in particular the thermal component of the P-GRB. An analysis of an Episode 2 typically yields a baryon load in the range $10^{-4} - 10^{-2}$. The CBM average density usually lies around $1$ part cm$^{-3}$ and the Lorentz factor at transparency falls in the range $200 - 500$; this implies $T_{90}$ durations in excess of $10$ s.

Episode 1 and Episode 2 may both be visible in the $\gamma$-ray prompt emission, but as stated previously, Episode 1 may also be below detector threshold since it is less energetic than Episode 2.

**Episode 3**

Episode 3 is most clearly visible in X-ray observations. It comes after the steep decay of the prompt emission; it may include a plateau phase followed by a late decay. This last part has been observed to follow a standard behavior in Pisani et al. (2013); the lightcurves cluster at late rest-frame times $t \gtrsim 2 \times 10^4$ s and they undergo a decay with similar power law indices, as can be seen in Fig. 3.12. This overlapping behavior is independent of the characteristics of the steep decay and plateau phases, and of the isotropic energy of the GRB.

Episode 3 encompasses emission from the SN shock breakout, from the SN ejecta, and from the newborn NS (Negreiros et al., 2012). Its energetics reach up to a few $10^{51}$ erg, but its Lorentz factor is low at $\gamma \sim 1 - 2$.

Pisani et al. (2013) built a GRB sample with redshifts $0.49 \lesssim z \lesssim 1.261$, the available data of which verify every IGC criterion. 6 GRBs with measured redshifts are identified; two additional GRBs that lack a redshift are included since their redshifts are estimated.
using the late X-ray overlap of IGC systems.

**Episode 4**

After about 10 to 15 rest-frame days, the signal from the SN peaks in optical wavelengths due to \(^{56}\text{Ni}\) decay (Arnett, 1996). If the IGC event occurs at a redshift \(z \lesssim 1\), this signal (that we refer to as Episode 4) may be observed, at least photometrically.

### 3.3.2 On hypercritical accretion

A first approach to the hypercritical accretion regime invoked by the IGC paradigm has been detailed in Rueda & Ruffini (2012). Fryer et al. (2014) further presented numerical simulations that confirm the general results obtained in Rueda & Ruffini (2012).

Rueda & Ruffini (2012) rely on the Bondi-Hoyle-Littleton formalism for their estimates. The effects of the magnetosphere can be neglected for high accretion rates; the treatment presented hereafter thus assumes a non-rotating NS and disregards the effects of the magnetosphere.

The NS captures material from the ejecta within a radius from the NS center

\[
R_{\text{cap}} = \frac{2GM_{\text{NS}}}{v_{\text{rel,ej}}^2} \quad (3.4)
\]

where \(M_{\text{NS}}\) is the NS mass, \(G\) is the gravitational constant, and \(v_{\text{rel,ej}}\) is the velocity of the ejecta relative to the orbital motion of the NS and is given by

\[
v_{\text{rel,ej}} = \sqrt{v_{\text{orb}}^2 + v_{\text{ej}}^2} \quad \text{and} \quad v_{\text{orb}} = \sqrt{\frac{G(M_{\text{SN-prog}} + M_{\text{SN}})}{a}}. \quad (3.5)
\]

Here, \(v_{\text{ej}}\) is the velocity of the ejecta; \(v_{\text{orb}}\) is the orbital velocity of the NS; \(a\) is the binary separation. \(v_{\text{ej}}\) is assumed to be much larger than the speed of sound of the material.

The accretion rate is then (Bondi & Hoyle, 1944): \[
\dot{M} = \xi \pi \rho_{\text{ej}} R_{\text{cap}}^2 v_{\text{ej}} = \xi \pi \rho_{\text{ej}} \left(\frac{2GM_{\text{NS}}}{v_{\text{orb}}^2 + v_{\text{ej}}^2}\right)^{3/2}. \quad (3.6)
\]

Use of Eqs. 3.4 and 3.5 has been made in the last equality. \(\rho_{\text{ej}}\) is the density of the accreted material; \(\xi\) is a parameter in the range \(1/2 - 1\) depending on the properties of the medium on which the accretion occurs. The upper value corresponds to the Hoyle-Littleton accretion rate (Hoyle & Lyttleton, 1939). The density of the accreted material can be expressed as

\[
\rho_{\text{ej}} = \frac{3M_{\text{ej}}(t)}{4\pi r_{\text{ej}}^3(t)}. \quad (3.7)
\]

The accretion rate may be as high as \(0.01 \, M_{\odot} \, \text{s}^{-1}\) for \(\rho_{\text{ej}} = 10^6 \, \text{g cm}^{-3}\) and \(v_{\text{ej}} = 10^9 \, \text{cm s}^{-1}\). This can be enough for the NS to reach its critical mass in a few seconds if its initial mass is high.

Fryer et al. (2014) introduced a simulation of the IGC accretion mechanism. Core-collapses of FeCO stars are simulated in order to obtain the density and velocity of the SN ejecta; the hydrodynamic evolution of the material entering the Bondi-Hoyle trapping radius is computed until it reaches the NS surface, and the simulation is run until the NS
reaches its critical mass. It is found that for appropriate binary parameters, an induced collapse happens under short timescales of the order of $10^2 - 10^3$ s.

Becerra et al. (2015) study the role of angular momentum in the hypercritical accretion of IGC systems. The angular momentum transported by the SN ejecta is estimated, and the momentum transferred to the NS is numerically simulated in full general relativity. It is found that the NS reaches in a few seconds either the mass-shedding limit or secular axisymmetric instability, depending on its initial mass. The maximum dimensionless angular momentum is found to be $\sim 0.7$. It is also shown that the NS cannot support all the angular momentum transported by the ejecta, leading to an angular momentum excess that implies jetted emission.

Fryer et al. (2015) investigate the NS-BH binaries left as an IGC outcome. They conclude that the systems remain bound even if a large fraction of the mass is lost during the explosion: since the binary orbit is tight and the orbital velocity high, even large kicks are found to be unlikely to be able to unbind the binary. Fryer et al. (2015) also argue that the fact that almost all of these systems remain bound may play a significant role in the compact object merger rate.

### 3.3.3 IGC candidate systems

An IGC progenitor system is composed of an evolved FeCO stellar core and its companion NS. The typical orbital separation between the two bodies should be of the order of $10^{11}$ cm. The nearby binary stellar system Eta Carinae, 2300 pc away, might evolve to fulfill the conditions necessary to produce an IGC event. The primary star of this system is a luminous blue variable of initial mass $\sim 150$ $M_\odot$ of which a high fraction was lost; the secondary star is a hot supergiant of mass $30$ $M_\odot$. The primary star is expected to undergo a SN within the next million years, possibly leaving a NS remnant behind. The configuration of the system might then be suitable for the production of an IGC event.

High-mass X-ray binaries might also evolve to favorable configurations. Cen X-3 and Her X-1 (Schreier et al., 1972; Gursky & Ruffini, 1975; Rawls et al., 2011) are two examples of possible IGC candidate systems.

### 3.4 An optical/X-ray joint analysis of IGC systems

It is an important step when introducing a new concept to provide testable, characteristic observational properties that strengthen it, such as – in the present case – the late-time X-ray overlap of IGC Episodes 3 or the evolving thermal component of Episode 1. In this section, we report a work in which we analyze the afterglow optical and X-ray spectral energy distributions of the IGC sample of Pisani et al. (2013), as well as that of GRB 130427A. As a foreword, let us note that in general the optical and X-ray properties of GRBs differ at early times but after $\sim 2000$ s, the lightcurves in both wavelength ranges follow a decay with a similar slope.

#### 3.4.1 X-ray and optical extinction

The construction of the spectral energy distributions (SEDs) of astronomical events in the optical and low-energy X-ray bands requires the effects of extinction to be taken into account. While extinction is negligible at higher energies, it can indeed be significant at these wavelengths.
Optical extinction: dust

Dust is the main cause of extinction of light in the optical/UV domain. Dust may be thought of as carbon- and silicon-based molecules with sizes ranging from a few micrometers to a few millimeters. Its effect is to attenuate the luminosity along the line-of-sight.

Pei (1992) introduced an empirical graphite-silicate model that describes well the extinction from the far infrared ($\lambda \gtrsim 30,000 \text{ nm}$) to the UV domain ($\lambda \lesssim 40 \text{ nm}$). This model is based on the analytical fit of the extinction profiles of the Milky Way (MW), of the Large Magellanic Cloud (LMC), and of the Small Magellanic Cloud (SMC). The three curves are given in a dimensionless form as

$$\xi(\lambda) = \frac{E_{\lambda-V}}{E_{B-V}} + R_V$$

(3.8)

where $A_\lambda$ is the extinction (in magnitudes) at wavelength $\lambda$ and $A_B$ is the extinction in the blue photometric band. $E_{\lambda-V} = A_\lambda - A_V$ is the color excess, and $R_V = A_V/E_{B-V}$ is the ratio of total-to-selective extinction\(^5\). The subscript $V$ refers to the visual photometric band.

The analytic formulas of the curves are given as

$$\xi(\lambda) = \sum_{i=1}^{6} \frac{a_i}{(\lambda/\lambda_i)^{n_i} + (\lambda/\lambda_i)^{n_i} + b_i}$$

(3.9)

where each galaxy type (MW, LMC, SMC) has its own set of 18 parameters $a_i, b_i, \lambda_i$ (see Table 3.6). The most prominent differences between the three profiles are found in the relative importance of the two features referred to as the 2175 Å and the FUV features (see a comparison of the three extinction profiles in Fig. 3.13).

Since $A_\lambda$ is the extinction in magnitudes at wavelength $\lambda$, the unabsorbed flux density $F_\nu$ is related to the absorbed (i.e. observed) flux density $F_\nu^{\text{abs}}$ as

$$F_\nu^{\text{abs}}(\lambda) = F_\nu(\lambda) 10^{-0.4 A_\lambda} = F_\nu(\lambda) 10^{-0.4 E_{B-V} \xi(\lambda)/(1+R_V)}$$

(3.10)

where we have made use of Eq. 3.8 in the last equality. Knowing $\xi(\lambda)$ and $R_V$, the parameter $E_{B-V}$ remains to be determined through observations. Maps of dust extinction for the MW lines-of-sight exist\(^6\) (Schlegel et al., 1998; Schlafly & Finkbeiner, 2011); on the other hand the extinction in the GRB host galaxy has to be determined by fitting the SED.

X-ray extinction: photoelectric absorption

In order to take into account the X-ray extinction, we use a model for photoelectric cross-section per HI atom units, at solar metallicity\(^7\) (Morrison & McCammon, 1983). This model covers the 0.03 – 10 keV range and converts the entire set of cross-sections of all the relevant elements to the single cross-section $\sigma$ of an equivalent hydrogen column density $N_H$ (see Fig. 3.14). Analytically, it is expressed as 14 consecutive segments each taking the form:

$$(c_0 + c_1 E + c_2 E^2) E^{-3} \times 10^{-24} \text{ cm}^2$$

(3.11)

\(^5\)We adopt the following values of $R_V$ for, respectively, the MW, the LMC, and the SMC: 3.08, 3.16, 2.93.

\(^6\)http://ned.ipac.caltech.edu/forms/calculator.html

\(^7\)The metallicity inferred from observations of GRB afterglows is usually sub-solar, but the model is rather weakly dependent on it.
Figure 3.13: Power law fit of the SED of GRB 060729. The unabsorbed power law is plotted in dot-dashed green, the absorbed power law is plotted in orange. We illustrate the influence of the host galaxy profile on the optical absorption; the host profile is indeed the only difference between the three panels. Upper panel: the host galaxy profile is a MW type. The 2175 Å feature (at $8.95 \times 10^{14}$ Hz taking a redshift $z = 0.54$ into account) is clearly present, but the FUV feature (at $4.14 \times 10^{15}$ Hz) is less prominent compared to the other galaxy profiles. Middle panel: LMC host galaxy type. The 2175 Å component is milder, the FUV one is wider. Lower panel: SMC host galaxy type. The 2175 Å feature is almost absent, the FUV feature drop is even larger.
### 3.4 An optical/X-ray joint analysis of IGC systems

#### Table 3.6: Extinction curve parameters used in Eq. 3.9. The first column identifies each of the 6 components of the analytical function.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( a_i )</th>
<th>( \lambda_i ) (( \mu )m)</th>
<th>( b_i )</th>
<th>( n_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milky Way</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKG</td>
<td>165.</td>
<td>0.047</td>
<td>90.0</td>
<td>2.0</td>
</tr>
<tr>
<td>FUV</td>
<td>14.</td>
<td>0.08</td>
<td>4.0</td>
<td>6.5</td>
</tr>
<tr>
<td>2175 Å</td>
<td>0.045</td>
<td>0.22</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>9.7 ( \mu )m</td>
<td>0.002</td>
<td>9.7</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>18 ( \mu )m</td>
<td>0.002</td>
<td>18.0</td>
<td>-1.80</td>
<td>2.0</td>
</tr>
<tr>
<td>FIR</td>
<td>0.012</td>
<td>25.0</td>
<td>0.00</td>
<td>2.0</td>
</tr>
<tr>
<td>Large Magellanic Cloud</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKG</td>
<td>175.</td>
<td>0.046</td>
<td>90.0</td>
<td>2.0</td>
</tr>
<tr>
<td>FUV</td>
<td>19.</td>
<td>0.08</td>
<td>5.50</td>
<td>4.5</td>
</tr>
<tr>
<td>2175 Å</td>
<td>0.023</td>
<td>0.22</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>9.7 ( \mu )m</td>
<td>0.005</td>
<td>9.7</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>18 ( \mu )m</td>
<td>0.006</td>
<td>18.0</td>
<td>-1.80</td>
<td>2.0</td>
</tr>
<tr>
<td>FIR</td>
<td>0.020</td>
<td>25.0</td>
<td>0.00</td>
<td>2.0</td>
</tr>
<tr>
<td>Small Magellanic Cloud</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKG</td>
<td>185.</td>
<td>0.042</td>
<td>90.0</td>
<td>2.0</td>
</tr>
<tr>
<td>FUV</td>
<td>27.</td>
<td>0.08</td>
<td>55.50</td>
<td>4.0</td>
</tr>
<tr>
<td>2175 Å</td>
<td>0.005</td>
<td>0.22</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>9.7 ( \mu )m</td>
<td>0.010</td>
<td>9.7</td>
<td>-1.95</td>
<td>2.0</td>
</tr>
<tr>
<td>18 ( \mu )m</td>
<td>0.012</td>
<td>18.0</td>
<td>-1.80</td>
<td>2.0</td>
</tr>
<tr>
<td>FIR</td>
<td>0.030</td>
<td>25.0</td>
<td>0.00</td>
<td>2.0</td>
</tr>
</tbody>
</table>

#### Table 3.7: Coefficients used in the analytical expression Eq. 3.11 for X-ray extinction.

<table>
<thead>
<tr>
<th>Energy range (keV)</th>
<th>( c_0 )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.030 - 0.100</td>
<td>17.3</td>
<td>608.1</td>
<td>-2150.</td>
</tr>
<tr>
<td>0.100 - 0.284</td>
<td>34.6</td>
<td>267.9</td>
<td>-476.1</td>
</tr>
<tr>
<td>0.284 - 0.400</td>
<td>78.1</td>
<td>18.8</td>
<td>4.3</td>
</tr>
<tr>
<td>0.400 - 0.532</td>
<td>71.4</td>
<td>66.8</td>
<td>-51.4</td>
</tr>
<tr>
<td>0.532 - 0.707</td>
<td>95.5</td>
<td>145.8</td>
<td>-61.1</td>
</tr>
<tr>
<td>0.707 - 0.867</td>
<td>308.9</td>
<td>-380.6</td>
<td>294.0</td>
</tr>
<tr>
<td>0.867 - 1.303</td>
<td>120.6</td>
<td>169.3</td>
<td>-47.7</td>
</tr>
<tr>
<td>1.303 - 1.840</td>
<td>141.3</td>
<td>146.8</td>
<td>-31.5</td>
</tr>
<tr>
<td>1.840 - 2.471</td>
<td>202.7</td>
<td>104.7</td>
<td>-17.0</td>
</tr>
<tr>
<td>2.471 - 3.210</td>
<td>342.7</td>
<td>18.7</td>
<td>0.0</td>
</tr>
<tr>
<td>3.2110 - 4.038</td>
<td>352.2</td>
<td>18.7</td>
<td>0.0</td>
</tr>
<tr>
<td>4.038 - 7.111</td>
<td>433.9</td>
<td>-2.4</td>
<td>0.75</td>
</tr>
<tr>
<td>7.111 - 8.331</td>
<td>629.0</td>
<td>30.9</td>
<td>0.0</td>
</tr>
<tr>
<td>8.331 - 10.000</td>
<td>701.2</td>
<td>25.2</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Towards the IGC paradigm

Figure 3.14: Net photoelectric absorption cross-section per H atom as a function of energy. The cross-section is scaled by $E^3$ (with $E$ in keV) for clarity. The solid line considers a given relative abundance with all elements in gas phase and neutral atomic form. The dotted line shows the effects of condensing elements in 0.3 $\mu$m grains. Figure reproduced from Morrison & McCammon (1983).

where the photon energy $E$ is expressed in keV. Table 3.7 lists these parameters.

The unabsorbed flux density $F\nu$ is related to the absorbed one $F_{\nu}^{abs}$ as

$$F_{\nu}^{abs} = F_{\nu} \times e^{-\sigma N_H}$$  \hspace{1cm} (3.12)$$

where $N_H$ is the equivalent hydrogen column density and $\sigma$ is the cross-section. $N_H$ in the host galaxy is to be determined by observations; the MW value is derived from existing maps.\(^8\) (Kalberla et al., 2005; Dickey & Lockman, 1990).

3.4.2 Constructing and fitting SEDs

The methodology used to build the SEDs is outlined in this subsection; it largely follows the methodology presented in Zaninoni et al. (2013).

Building SEDs

The X-ray (0.3–10 keV) part of the SEDs is built using Swift/XRT data that are analyzed and fitted with XSPEC.

Optical data is taken from Zaninoni et al. (2013) who gathered all optical data from refereed papers for a sample of 68 GRBs with secure redshifts and with more than 5 data points per filter. This sample include 5 GRBs of the Pisani et al. (2013) sample as well as GRB 130427A; these 6 GRBs thus form the sample that we study.

\(^8\)Using the nh tool in XSPEC or the online equivalent http://heasarc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl.
3.4 An optical/X-ray joint analysis of IGC systems

<table>
<thead>
<tr>
<th>GRB</th>
<th>Host $E_{B-V}$ (mag)</th>
<th>Host $N_H$ (cm$^{-2}$)</th>
<th>Photon index</th>
<th>$z$</th>
<th>Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>060729</td>
<td>0.18 ± 0.04</td>
<td>9.4 ± 1.8 × 10$^{20}$</td>
<td>1.96 ± 0.024</td>
<td>0.54</td>
<td>MW</td>
</tr>
<tr>
<td>061007</td>
<td>0.18 ± 0.12</td>
<td>3.9 ± 2.3 × 10$^{21}$</td>
<td>1.99 ± 0.11</td>
<td>1.26</td>
<td>SMC</td>
</tr>
<tr>
<td>080319B</td>
<td>0.10 ± 0.07</td>
<td>8.14 ± 7.9 × 10$^{20}$</td>
<td>1.84 ± 0.053</td>
<td>0.94</td>
<td>SMC</td>
</tr>
<tr>
<td>090618</td>
<td>0.15 ± 0.05</td>
<td>1.56 ± 0.40 × 10$^{21}$</td>
<td>1.86 ± 0.074</td>
<td>0.54</td>
<td>LMC</td>
</tr>
<tr>
<td>091127</td>
<td>0.01 ± 0.01</td>
<td>6.7 ± 3.3 × 10$^{20}$</td>
<td>1.82 ± 0.076</td>
<td>0.49</td>
<td>-</td>
</tr>
<tr>
<td>130427A</td>
<td>0.08 ± 0.03</td>
<td>9.4 ± 2.2 × 10$^{20}$</td>
<td>1.65 ± 0.062</td>
<td>0.34</td>
<td>LMC</td>
</tr>
</tbody>
</table>

Table 3.8: Best-fit parameters obtained by fitting the SEDs. In the case of GRB 091127, the optical extinction is too weak to decide on a galaxy profile over another.

For each GRB, the flux lightcurve $\phi(t)$ (in erg s$^{-1}$ cm$^{-2}$) in every filter is phenomenologically fitted by a power law, a sum of a power law and a smoothly broken power law, or a sum of several smoothly broken power laws. The fit is integrated during the time interval of interest $[t_{\text{init}}, t_{\text{end}}]$; the value obtained is then converted to $f_\nu$ in jansky:

$$f_\nu(\lambda) = \frac{\lambda \int_{t_{\text{init}}}^{t_{\text{end}}} \phi(t) dt}{c(t_{\text{end}} - t_{\text{init}})}.$$  \hspace{1cm} (3.13)

Fitting

Joining X-ray and optical data, the end result of the process described above is a SED from the optical to the soft X-ray range. Extinction both in the MW (which is known through the existing maps, see previous section) and in the host galaxy has to be considered in order to properly fit the SEDs. The intrinsic shape of the SEDs (i.e. the unabsorbed SED) is assumed to be a power law, since a broken power law does not provide acceptable fits for the 6 GRBs that are under scrutiny. The index of this power law is obtained through the fit of XRT data in XSPEC. The optical data are then fitted with this power law. Extinction profiles from the three host galaxy types are considered; the galaxy profile that provides the best fit is adopted.

3.4.3 Results

In order to standardize the results as much as possible, data in the late decay phase (during which the GRB afterglows overlap) and in similar rest-frame time intervals have been considered. The data selection stops before $\sim 10^6$ s, when the associated SN becomes noticeable in the optical. Fig. 3.15 shows the lightcurves and SEDs of the 6 GRBs, and Table 3.8 lists the quantities obtained through the fitting process – namely the host galaxy optical extinction quantified by $E_{B-V}$, the X-ray extinction characterized by $N_H$, and the photon index of the power law.

Special care shall be taken when interpreting these results. The degeneracy between the photon index and $E_{B-V}$ is indeed large: a small variation of the photon index may still lead to an acceptable fit of the data, however at the expense of a significant change in the value of $E_{B-V}$. The values reported in Table 3.8 have been manually inspected to check their relevance. An additional verification can be performed using the relation between optical extinction and the hydrogen column density (Predehl & Schmitt, 1995; Güver & Özel, 2009). Thus in the MW, Güver & Özel (2009) find the following relation:

$^9$Two types of indices are used; the photon index $\Gamma$ is related to the spectral index $\beta$ by $\Gamma = \beta + 1$. 
Figure 3.15: Final lightcurves (left column) and SEDs (right column) of our IGC sample.
Figure 3.15 (Continued): Final lightcurves (left column) and SEDs (right column) of our IGC sample.
Towards the IGC paradigm

\[ N_H = (2.21 \pm 0.09) \times 10^{21} A_V \] with \( N_H \) in cm\(^{-2} \) and \( A_V \) in mag. Since \( A_V = R_V E_{B-V} \), one can estimate \( E_{B-V} \) from \( N_H \) with this method. Interestingly, the derived value is consistent with the values derived from the fitting process only for GRB 060729 – this is the single GRB that is best-fitted with a host MW galactic profile.

Thus there is only one Milky Way galaxy profile among the host galaxy types of our sample; this is not surprising as the host galaxies of long GRBs in general are known to be preferentially blue, dwarf, irregular galaxies, more akin to the Small Magellanic Cloud. This result therefore does not discriminate between IGC hosts and the hosts of the general long GRB population.

It is also compelling to compare these results to a similar analysis performed over a larger sample of GRBs. Zaninoni et al. (2013) studied the SEDs of 68 GRBs (however taken at different time intervals); Fig. 3.16 shows the distributions of \( E_{B-V} \), \( N_H \), and the photon indices of their sample. The subsample of IGC GRBs systematically lies in the lower half of these distributions. In particular, the optical extinction is weak across the whole subsample.

### 3.5 Additional properties of Episode 3

In Section 3.3.1, the overlap of the late X-ray emission of IGC systems after rest-frame times \( \sim 2 \times 10^4 \) s has been introduced. On the contrary to Episode 1 and Episode 2 that can vary dramatically from event to event, Episode 3 exhibits a much more regular nature. In this section, we summarize the additional properties of Episode 3 that have been studied in Ruffini et al. (2014a).

#### 3.5.1 A nested structure

As detailed in Pisani et al. (2013), the late X-ray emission of IGC events tends to overlap, with similar temporal decays that follow a power law with index \( -1.7 \lesssim \alpha \lesssim -1.3 \), after rest-frame times \( \gtrsim 2 \times 10^4 \) s. In addition to this property, the X-ray afterglows also follow a nesting pattern, as shown in Fig. 3.17. To evidence this behavior, the 0.3 – 10 keV rest-frame luminosity lightcurves are fitted with a power law during the steep decay phase and with the following phenomenological function during the plateau and late decay phases:

\[ L(t) = L_X (1 + t/\tau)^{\alpha_X} \quad (3.14) \]

where \( L_X \) is the plateau luminosity, \( \tau \) is the characteristic timescale of the plateau end, and \( \alpha_X \) is the late decay power law index. This function allows us to define a time for the end of the plateau phase

\[ t_{\text{end}} = \tau [(1/2)^{1/\alpha_X} - 1]. \quad (3.15) \]

Here, \( t_{\text{end}} \) is the time at which the luminosity of the plateau is \( L_{\text{end}} = L_X/2 \), i.e. half the initial plateau luminosity. Fitting three GRBs from the sample in Pisani et al. (2013), namely GRB 130427A, GRB 061121, and GRB 060729, one can note that the plateau shrinks as \( E_{\text{iso}} \) gets larger. In the case of the very energetic GRB 130427A (\( E_{\text{iso}} = 1.1 \times 10^{54} \) erg), the plateau phase is almost non-existent. This reveals a nested structure followed by Episodes 3.

The decay of heavy r-process elements has been considered as the energy source powering the nesting behavior. Li & Paczynski (1998) have shown that the surface emission of an optically thick expanding ejecta in an adiabatic regime produces a flat lightcurve
3.5 Additional properties of Episode 3

Figure 3.16: Spectral indices, optical and X-ray extinctions derived for a sample of 68 GRBs. The color codes correspond to different cases introduced in Zaninoni et al. (2013). The 6 GRBs of our sample systematically lie in the lower half of these distributions; the ranges they span are indicated by the vertical black lines. Figures reproduced from Zaninoni et al. (2013).
bution with index $-\alpha$ implies an energy release per unit mass and per unit time that follows a power law distribution. Interestingly, the avalanche of decays of elements with different lifetimes and plateau phases. After transparency, the nuclear decay of heavy nuclei becomes visible (see also Arnett 1982). In principle, this can provide an explanation for the steep decay and plateau phases. After transparency, the nuclear decay of heavy nuclei becomes visible (see also Arnett 1982). In principle, this can provide an explanation for the steep decay and plateau phases. After transparency, the nuclear decay of heavy nuclei becomes visible (see also Arnett 1982).

Table 3.9: Relevant quantities of our sources and best-fit parameters of the two correlations plotted in Fig. 3.18.

<table>
<thead>
<tr>
<th>GRB</th>
<th>$\langle L_{iso}\rangle$ (10$^{54}$ erg/s)</th>
<th>$t_{end}$ (ks)</th>
<th>$L_{end}$ (10$^{54}$ 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>

Correlation

<table>
<thead>
<tr>
<th>Correlation</th>
<th>$m_i$</th>
<th>$q_i$</th>
<th>$\sigma_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle L_{iso}\rangle$–$t_{end}$</td>
<td>$-(0.90 \pm 0.09)$</td>
<td>$54.0 \pm 0.3$</td>
<td>$0.20 \pm 0.05$</td>
</tr>
<tr>
<td>$L_a$–$t_{end}$</td>
<td>$-(1.34 \pm 0.14)$</td>
<td>$52.0 \pm 0.4$</td>
<td>$0.26 \pm 0.08$</td>
</tr>
</tbody>
</table>

(see also Arnett 1982). In principle, this can provide an explanation for the steep decay and plateau phases. After transparency, the nuclear decay of heavy nuclei becomes visible and dominant. Interestingly, the avalanche of decays of elements with different lifetimes implies an energy release per unit mass and per unit time that follows a power law distribution with index $-1.4 \lesssim \alpha \lesssim -1.1$ (Metzger et al., 2010). This index is similar to that of the late power law decay of our IGC sample.

3.5.2 Correlations

The $\langle L_{iso}\rangle$–$t_{end}$ and $L_{end}$–$t_{end}$ correlations (Dainotti et al., 2008, 2011; Willingale et al., 2007), where $\langle L_{iso}\rangle = E_{iso}/t_{90}$ is the average luminosity of the prompt emission and $t_{90}$ is the rest-frame $T_{90}$ duration, have been verified with our IGC sample. Fig. 3.18 shows the resulting correlations under the form $\log_{10} Y_i = m_i \log_{10} X_i + q_i$. The correlation parameters and the data values are listed in Table 3.9. It is interesting to note that the sample of IGC events provides tighter correlations than the ones presented in Dainotti et al. (2011): the extra scatter of the $L_{end}$–$t_{end}$ correlation is $\sigma = 0.26$, compared to $\sigma = 0.76$ for the 62 burst sample of Dainotti et al. (2011) and $\sigma = 0.40$ for the best subsample of 8 bursts. This may be explained by the fact that the IGC sample is restricted to energetic sources (with $E_{iso} \approx 10^{52} - 10^{54}$ erg).

3.6 On low-energy GRB – SN events

The IGC paradigm, as introduced in this chapter, only applies to the class of energetic GRB – SN events (with $10^{52}$ erg $\lesssim E_{iso} \lesssim 10^{54}$ erg). It is worth recalling that the majority of GRB – SN associations take place in under-energetic GRBs (e.g. Maselli et al. 2013b). In addition to their lower $E_{iso}$, these systems also have a softer spectrum with a rest-frame peak energy $E_p \lesssim 100$ keV, and a much weaker X-ray afterglow that does not show any evidence for a standard behavior.

The IGC time sequence needs specific initial conditions in order to be successfully implemented. The companion NS may form a BH only if it is already relatively massive and if the binary orbit separation is small enough that the NS can accrete enough matter from the SN ejecta. As explained in Rueda & Ruffini (2012); Ruffini et al. (2014a); Fryer et al. (2014), the initial distance between the stellar core and the NS is a critical factor.
3.6 On low-energy GRB – SN events

Figure 3.17: The nesting pattern of IGC X-ray afterglows is evidenced by fitting the lightcurves with a power law during the steep decay phase, and with Eq. 3.14 during the plateau and late decay phases. The rest-frame 0.3 – 10 keV luminosity lightcurves of GRB 130427A (purple), GRB 061121 (red, shifted by 50 s), and GRB 060729 (pink) are plotted. Figure reproduced from Ruffini et al. (2014a).

Figure 3.18: Upper panel: $\langle L_{\text{iso}} \rangle - t_{\text{end}}$ correlation (solid black line) and $1\sigma$ confidence levels (dashed black lines). Lower panel: $L_{\text{end}} - t_{\text{end}}$ correlation (solid black line) and $1\sigma$ confidence levels (dashed black lines). The following sources are included: GRB 060729 (pink), GRB 061007 (black), GRB 080319B (blue), GRB 090618 (green), GRB 091127 (red), GRB 111228A (cyan), and GRB 130427A (purple). The $L_{\text{end}} - t_{\text{end}}$ correlation with our IGC sample is tighter than the one of Dainotti et al. (2011), with $m = -1.04$, $q = 51.30$ (solid gray line), and $\sigma = 0.76$ (dash-dotted gray lines). Figures reproduced from Ruffini et al. (2014a).
Towards the IGC paradigm

and is estimated to be around $10^{11}$ cm. In the absence of BH formation, no fireshell and hence no canonical GRB (Episode 2) is emitted, although Episode 1 is still present: Fig. 6.3 presents the space-time diagram of such a system.

The picture that emerges from these considerations consequently gives two possible outcomes for this kind of stellar core-NS binary systems. If the configuration of the system does not allow for the companion NS to collapse to a BH, the resulting event is low-energetic with a weaker X-ray afterglow: we call this family of events family 1 long GRBs (Ruffini et al., 2014a), or X-ray flashes (XRFs). On the other hand, BH formation leads to the presence of an energetically dominant Episode 2 and of a scaled late X-ray emission: we refer to these events as binary-driven hypernovae (BdHNe), or family 2 long GRBs (Ruffini et al., 2014a). The space-time diagrams of these two families are depicted in Figs. 6.2 and 6.3.
Extending the IGC paradigm

Following early efforts in the study of the Induced Gravitational Collapse mechanism, additional GRB – SN systems have been investigated and interpreted within this framework. The study of these systems led us to extend the validity of the IGC paradigm to previously unexplored realms. Thus GRB 130427A (Ruffini et al., 2015a), a cosmological GRB occurring relatively nearby ($z = 0.34$), is the most luminous and energetic IGC event analyzed so far. GRB 090423 (Ruffini et al., 2014b) is the farthest one at a redshift $z = 8.2$ – this redshift corresponds to a time $\sim 630$ million years after the Big Bang, suggesting that the IGC mechanism was already at work at early times. The IGC paradigm has also been successfully applied to GRB 970828 (Ruffini et al., 2015b), a GRB detected in the pre-Swift and Fermi era.
4.1 GRB 130427A: an extremely luminous GRB

The very energetic GRB 130427A, which is associated to SN 2013cq, is the most luminous GRB observed in the past 40 years (Ruffini et al., 2015a). In particular, this GRB provided the longest multi-wavelength observations obtained so far. This kind of GRB – SNe occurs rather rarely, as GRB – SN connections are much more common in a class of less energetic long GRBs with $10^{49} \text{ erg} \lesssim E_{\text{iso}} \lesssim 10^{52} \text{ erg}$ (Guetta & Della Valle, 2007) and with a soft spectrum characterized by a rest-frame peak energy $E_{p,i} < 100 \text{ keV}$. As explained in the previous chapter, this family of long GRBs is referred to as family 1 (or X-ray flash events) and the detection horizon of its members is limited to $z \sim 1$.

Family 2 GRBs (or binary-driven hypernovae) encompass energetic GRB – SNe that exhibit a much more complex structure. They are characterized by an isotropic energy $10^{52} \text{ erg} \lesssim E_{\text{iso}} \lesssim 10^{54} \text{ erg}$, by the presence of multiple components in their spectra and lightcurves, and by a high rest-frame peak energy spanning the energy range from $\sim 100 \text{ keV}$ to several MeV. Given their energetics, family 2 GRBs may be detected out to very high redshifts – indeed, Section 4.2 presents the case of GRB 090423 that exploded at $z = 8.2$.

As they are rarer events, energetic GRB – SNe form a lesser known category of bursts. Thus, naive energetic arguments may suggest that a SN could not take place together with a powerful GRB in the collapsar model (Maselli et al., 2013b). The Induced Gravitational Collapse paradigm, on the other hand, has been introduced with the purpose of explaining energetic GRB – SNe: according to the IGC model, all long GRBs are connected to SNe. The approach adopted by the collapsar model and the approach followed in the IGC framework differ on three major points. First, while the progenitor of a collapsar is a single star\(^1\), the IGC model considers a binary progenitor constituted by an evolved stellar core and a neutron star. Second, both the spectral and temporal analyses are typically performed over the entire duration of the burst (see e.g. Tavani 1998); on the contrary, in the IGC model special attention is given to the analysis of instantaneous spectra in all wavelength ranges. Finally, the afterglow in the collapsar picture is explained by a single ultra-relativistic jetted emission (e.g. Rhoads 1999; van Eerten et al. 2010; Nava et al. 2013). In the IGC model, the afterglow results from different phenomena occurring at different Lorentz factors.

This section summarizes the information on the IGC mechanism that has been deduced from the analysis of Episode 3 in GRB 130427A.

4.1.1 Observations and data analysis

Observations

Fermi/GBM first detected GRB 130427A at 07:47:06.42 UT on April 27, 2013 (von Kienlin, 2013). Hereafter, this time will be taken as the reference time $T_0$, and the times expressed with reference to $T_0$ will be observer frame times. 51.1 s after $T_0$, Swift/BAT triggered; the XRT and UVOT instruments started collecting observations respectively 195 s and 181 s after $T_0$ (Maselli et al., 2013a). Due to the extreme brightness of this GRB, several ground telescopes pointed towards the source including the Gemini North telescope (Levan et al., 2013b), the Nordic Optical Telescope (Xu et al., 2013a), and the VLT/X-shooter (Flores et al., 2013). A spectroscopic redshift $z = 0.34$ was measured and

\(^1\)Fryer et al. (1999c) and Broderick (2005) considered binary progenitors; in their works, the binary companion is however simply a trigger to the collapsar event.
4.1 GRB 130427A: an extremely luminous GRB

independently confirmed.

GRB 130427A is a peculiar source in that its relative proximity and its high energetics ($E_{\text{iso}} = 8.1 \times 10^{53}$ erg, Maselli et al. 2013b) resulted in a very high fluence across the observable wavelength range, from the optical to the GeV bands. Remarkably, it stayed in the Fermi/LAT field of view until $T_0 + 750$ s (Ackermann et al., 2013), and was seen by the LAT until $\sim 70,000$ s post-trigger: this provides a unique opportunity to compare the lightcurves and spectra in different energy bands during a wide temporal period.

Data analysis

Fermi/LAT data were retrieved from the Fermi Science Support Center$^2$, and were processed and analyzed using an unbinned likelihood method with the Fermi Science Tools v9r27p1$^3$. P7SOURCE_V6 and P7CLEAN_V6 event selections were used, depending on which one would give the most stable result. Usual recommended data cuts were applied. The background is composed of the galactic diffuse emission template, the isotropic emission template, and about 60 sources within a $15^\circ$ radius of the GRB position, the contribution of which was found to be negligible. The background parameters were held fixed during the fit.

Fig. 4.1 shows the luminosity lightcurve of GRB 130427A until $T_0 + 750$ s in the energy range $100$ MeV to $100$ GeV for a circle of radius $15^\circ$ (assuming a power law spectral distribution). The lightcurve has been rebinned, neglecting for the sake of simplicity the fine temporal structures. A photon index of 2.1 was assumed for the fitting of the last two points, as this is the value derived from all the other data points. Fig. 4.6 shows the spectrum during this time interval.

Swift/XRT data were obtained from the UK Swift Science Data Centre (UKSSDC$^4$) and analyzed using the standard Swift analysis software in Heasoft v6.14, together with the relevant calibration files$^5$. Only Window Timing (WT) mode data are available before $T_0 + 750$ s.

The average count rate reaches 300 count s$^{-1}$ with a maximum value at 1000 count s$^{-1}$: this goes far beyond the pile-up threshold for the WT mode, which lies at around 150 count s$^{-1}$ (Evans et al., 2007). As a consequence, pile-up effects (i.e. two or more photons being mistakingly identified as a single higher energy photon) cannot be neglected. The method suggested in Romano et al. (2006) has been followed to deal with this pile-up effect: it consists in fitting dozens of spectra from annulus selections of different radii in order to determine the extent of the affected region. As an example, the distorted region in the $461-750$ s time interval is the inner circle of 6 pixel radius (see Fig. 4.2). Standard XRT analysis was then performed to obtain the spectra (Evans et al., 2007, 2009). The lightcurves were obtained by splitting XRT observations in the $0.3-10$ keV range into several slices with a fixed count number (taking into account pile-up corrections), following standard practice (Evans et al., 2007, 2009).

4.1.2 On Episode 3

We recall that in the IGC paradigm, an Episode 3 is characterized by a seemingly regular behavior that consists in an overlapping feature (Pisani et al., 2013) and a nesting

$^2$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/
Figure 4.1: Multi-wavelength lightcurve of GRB 130427A. *Fermi*/LAT data (100 MeV – 100 GeV) are plotted in red; *Swift*/XRT data (0.3 – 10 keV) are plotted in blue; *NuStar* data (3 – 79 keV) are plotted in orange and are reproduced from Kouveliotou et al. (2013); optical data (*R* band centered at 629 nm) are plotted in green and are reproduced from Perley et al. (2013). The vertical dashed gray line marks the start of the constant decay slope region. Figure reproduced from Ruffini et al. (2015a).

Figure 4.2: Photon index derived from XRT data of GRB 130427A in the time interval $T_0 + 461$ s to $T_0 + 750$ s. The extent of the region affected by pile-up can be determined by looking at the evolution of the photon index as the inner radius of the source annulus selection increases. The photon index becomes approximately constant once the inner 6 pixels are discarded: thus this is the radius of the distorted region. Figure reproduced from Ruffini et al. (2015a).
4.1 GRB 130427A: an extremely luminous GRB

Figure 4.3: X-ray afterglow of GRB 130427A compared to the one of GRB 060729. The data points of GRB 130427A switch from red to orange at the moment of the supernova prediction. Figure reproduced from Ruffini et al. (2015a).

feature (Ruffini et al., 2014a). The study of the Episode 3 of GRB 130427A gave a confirmation of this picture, and allowed for improvements of the understanding of the Episode 3 phenomenology, owing in particular to the unprecedented multi-wavelength coverage of this exceptional GRB.

Supernova prediction

Until the detection of GRB 130427A, GRB 080319B was the only observed occurrence of an equally energetic GRB – SN (with $E_{\text{iso}} \approx 10^{54}$ erg). However, as GRB 080319B lied significantly further, at $z = 0.94$, only a SN bump in the optical lightcurve was detected (Bloom et al., 2009): no spectral information – such as the SN type – could be deduced.

It was quickly realized that the X-ray afterglow of GRB 130427A followed closely the typical IGC decay pattern (see Fig. 4.3). After $\sim 3 \times 10^5$ seconds in the rest-frame, the overlapping feature led us to estimate a redshift consistent with the measured one, and to expect a detectable SN signal$^6$. The SN signal began to be observed on May 13, 2013, by telescopes such as GTC, Skynet, and HST (De Ugarte Postigo et al., 2013b; Trotter et al., 2013; Levan et al., 2013b, 2014). The supernova, named SN 2013cq, was determined to be of type Ic.

X-ray afterglow

In addition to the X-ray afterglow overlap (with a power law of index $\alpha = -1.31 \pm 0.01$ extending from $\sim T_0 + 400$ s to $\sim T_0 + 10^7$ s without any break$^7$), an early thermal component has been detected. Indeed, from $T_0 + 196$ s to $T_0 + 461$ s, we find that the addition of a thermal component significantly improves the fit of XRT data with respect to

$^6$A GCN circular (Ruffini et al., 2013) was sent on May 2, 2013, to alert the community.

$^7$Perley et al. (2013); Laskar et al. (2013) agree with the absence of a jet break (or of any break); Maselli et al. (2013b) on the other hand claim the detection of a break at later times.
a simple power law, as illustrated in Fig. 4.4. Both the flux and the temperature decrease with time (from 0.5 keV to 0.1 keV in the observer frame in the case of the latter).

Assuming the blackbody radiation to be isotropic, the application of the method used in Section 3.2.1 leads to an estimation of the emitter radius along the line-of-sight; it is found to grow from $7.0 \times 10^{12}$ cm at $T_0 + 196$ s to $2.8 \times 10^{13}$ cm at $T_0 + 461$ s. These radii are to be compared to the emission radius in the collapsar afterglow model, which is typically of the order of $10^{15}$ cm. They are on the other hand consistent with the size of SN ejecta a few hundreds seconds after explosion.

Taking into account the cosmological and relativistic time corrections an expansion speed of $\sim 0.8 \, c$ is deduced. This corresponds to a Lorentz factor $\gamma = 1.67$, in agreement with the values obtained in the prototypical GRB 090618 ($1.5 \lesssim \gamma \lesssim 2.2$ and an emitter radius $\sim 10^{13}$ cm, cf. Section 3.2.1) but in disagreement with the Lorentz factor deduced in the framework of the collapsar model by Maselli et al. (2013b), $\gamma \sim 500$.

Interestingly, similar early thermal components have been found in several GRBs such as GRB 060729 and other GRB – SN events (Ruffini et al., 2014b; Grupe et al., 2007a; Starling et al., 2012).

A simple power law was found to be an adequate fit by Kouveliotou et al. (2013) in NuStar data. NuStar however observed GRB 130427A much later, after $T_0 + 10^5$ s, and it is likely that by then the thermal component had faded away.

**Multi-wavelength observations**

GRB 130427A benefited from an excellent instrumental coverage. Fig. 4.5 illustrates this fact: it shows the flux lightcurves in soft X-ray (Swift/XRT, 0.3 – 10 keV), in hard X-ray (Swift/BAT, 15 – 150 keV and NuStar, 3 – 79 keV), in $\gamma$-rays (Fermi/GBM, 8 keV – 40 MeV), and in high-energy bands (Fermi/LAT, 100 MeV – 100 GeV). These observations reveal strong analogies in the late emission of Episode 3 at all wavelengths. In particular, after $T_0 + 4400$ s all lightcurves follow a common power law decay behavior with an index similar to the X-ray power law $\alpha = -1.3 \pm 0.1$.

The time-integrated multi-wavelength spectrum (from $T_0 + 461$ s to $T_0 + 750$ s) covers 10 orders of magnitude in energy and is best fitted by a broken power law (see Fig. 4.6).

**The onset of Episode 3**

While the analogies between the late behavior of the lightcurves in all energy bands are intriguing, the differences between them at the onset of Episode 3 should be emphasized. As can be seen in Fig. 4.5, the GBM and BAT lightcurves are similar in shape and reach their highest luminosities between $T_0 + 4$ s and $T_0 + 10$ s, that is, during the prompt phase of Episode 2. On the other hand, the high-energy ($> 100$ MeV) emission becomes gradually more intense and reaches its peak luminosity after the $\gamma$-ray emission drops, around $T_0 + 20$ s. The peak time of the high-energy emission corresponds to the onset of Episode 3. Soft X-rays observations start later but seem to catch the end of a sharp spike clearly visible in the $\gamma$-ray band.

A detailed analysis of the prolonged high-energy emission leads to specific constraints on the Lorentz factor of the emitter. The high-energy emission has been analyzed from $T_0 + 300$ s up to $2.5 \times 10^4$ s after trigger in seven time intervals. In each of them, the

\[ t_{\text{eff}} \sim t(1 + z)/(2\gamma^2) \]

where $t_{\text{eff}}$ is the observer frame time, $t$ is the laboratory time, and $\gamma$ is the Lorentz factor of the emitter.
4.1 GRB 130427A: an extremely luminous GRB

Figure 4.4: Fit of the XRT X-ray afterglow of GRB 130427A in three time intervals, during which a blackbody component notably improves the fit. The (absorbed) thermal component is plotted in dashed green, the (absorbed) power law component is plotted in dashed blue, and the red line is the sum of these two components. The time evolution of the blackbody is evident. Figure reproduced from Ruffini et al. (2015a).

Figure 4.5: Flux lightcurves of GRB 130427A during the first 700 s following trigger. It clearly appears that the highest fluence is reached by the Fermi/LAT about 20 s after trigger while most of the $\gamma$-ray energy is released within the first 10 s. Figure reproduced from Ruffini et al. (2015a).
100 Extending the IGC paradigm

Figure 4.6: Time-integrated spectrum of GRB 130427A in the time range $T_0 + 461$ s to $T_0 + 750$ s. Swift/UVOT data points are plotted in green (Perley et al., 2013); Swift/XRT data is plotted in blue (absorbed) and gray (unabsorbed); Fermi/LAT data is plotted in red. Horizontal error bars correspond to the energy bins in which the flux is integrated, vertical error bars are $1\sigma$ statistical errors on the count rate. Figure reproduced from Ruffini et al. (2015a).

Figure 4.7: Representation of the constraints on the Lorentz factor and the size of the high energy emitting region at transparency. The solid curves are obtained by varying the radius of the emitting region. The dash-dotted curves are obtained from causality conditions in the ultra-relativistic regime. The symbols mark the points where both constraints are fulfilled. The color code differentiates the seven time intervals. Figure reproduced from Ruffini et al. (2015a).
4.2 GRB 090423: the farthest GRB with a spectroscopic redshift

The farthest GRB with a spectroscopic redshift is GRB 090423, with a redshift of $z = 8.2$ (Salvaterra et al., 2009; Tanvir et al., 2009). This redshift corresponds to a mere $\sim 630$ million years after the Big Bang. In Ruffini et al. (2014b), we have investigated whether GRB 090423 is an IGC event or not, in particular by comparing it to the prototypical GRB 090618 (the analysis of which is summarized in Section 3.2.1). We verify that both GRBs do indeed share similar intrinsic features.

The maximum photon energy and the photon index of the spectral energy distribution have been determined (as shown in Ackermann et al. 2013, Fig. 2). An estimate of the Lorentz factor was computed from the optical depth formula for pair creation $\tau_{\gamma\gamma}$ (Lithwick & Sari, 2001; Gupta & Zhang, 2008). Assuming different radii for the emitter, the corresponding Lorentz factor at transparency $\tau_{\gamma\gamma}$ was computed (see Fig. 4.7). The radius of the emitting region $R_{em}$ is constrained by causality conditions in the ultra-relativistic regime (i.e. $R_{em} = 2\gamma^2 c \Delta t$, where $\Delta t$ is the duration of a time interval, see Fig. 4.7). The Lorentz factor verifies $10 \lesssim \gamma \lesssim 40$, which corresponds to transparency radii ranging from $\sim 10^{16}$ cm to $2 \times 10^{17}$ cm.

4.1.3 Conclusions

GRB 130427A ranks amongst the most energetic GRBs ever observed, with an isotropic energy close to $10^{54}$ erg. Its instrumental coverage has been one of the most complete for a GRB event, which allowed us to probe its conformity to the IGC paradigm and to infer new properties of Episodes 3. The main results of this analysis may be summarized as follows:

- The soft X-ray lightcurve of GRB 130427A has been shown to follow the standard power law decay of IGC afterglows. In this case, the power law decay started as early as 100 s post-trigger. An early thermal component has also been observed at the beginning of Episode 3, following a pulse visible in particular in the $\gamma$-ray lightcurve. A modest Lorentz factor has been derived from this thermal component ($\gamma < 2$): the X-ray emission appears to be produced in a mildly relativistic regime. No evidence for substantial beaming is present; in particular no jet break is detected.

- A multi-wavelength analysis of Episode 3 covering 10 orders of magnitude in energy has been performed. The high-energy emission peaks at the end of Episode 2, when the $\gamma$-ray fluence drops, fulfilling transparency condition for the high-energy photons. A Lorentz factor of $10 \ldots 40$ is deduced for the high energy emitter.

- The Lorentz factors of the X-ray emitter and the high-energy emitter are very different, but in both energy ranges a similar decay is observed. Within the IGC framework, the X-ray component may be produced by the interaction of the GRB with the SN ejecta while the high-energy emission may be related to the newborn BH, the new NS, and the SN ejecta.

4.2 GRB 090423: the farthest GRB with a spectroscopic redshift

GRB 090423 is the farthest GRB with a spectroscopic redshift to date, at $z = 8.2$ (Salvaterra et al., 2009; Tanvir et al., 2009): this redshift corresponds to a mere $\sim 630$ million years after the Big Bang. In Ruffini et al. (2014b), we have investigated whether GRB 090423 is an IGC event or not, in particular by comparing it to the prototypical GRB 090618 (the analysis of which is summarized in Section 3.2.1). We verify that both GRBs do indeed share similar intrinsic features.
4.2.1 Observations

GRB 090423 triggered the Swift/BAT on April 23, 2009 at 07:55:19 UT (Krimm et al., 2009) (this time will hereafter be taken as the reference time $T_0$ and any time expressed with reference to $T_0$ will be an observer-frame time). The Swift/XRT started observations 72.5 s after trigger and detected a fading source. The enhanced localization obtained by the XRT enabled on-ground telescopes to determine the very high redshift of this source, $z = 8.2$. The prompt emission was also seen by the Fermi/GBM (trigger 262166127/090423330, von Kienlin 2009), but the Fermi/LAT instrument did not detect any signal from this GRB.

The BAT lightcurve is composed of a single-peak structure of duration $\sim 20$ s. The XRT lightcurve consists of a long, intense flare that peaks at $\sim T_0 + 180$ s followed by a power law decay. The GBM lightcurve exhibits a single-peak structure of duration $\sim 12$ s, the spectral energy distribution of which is best fitted by a power law with exponential cut-off. The peak energy is $E_{\text{peak}} = (82 \pm 15)$ keV. Considering the observed GBM fluence $S_\gamma = 1.1 \times 10^{-6}$ erg cm$^{-2}$, the isotropic energy of GRB 090423 reaches $E_{\text{iso}} = 1.1 \times 10^{53}$ erg. These values of $E_{\text{peak}}$ and $E_{\text{iso}}$ satisfy the $E_{\text{peak}} - E_{\text{iso}}$ correlation for long GRBs (Amati et al., 2002).

4.2.2 On the absence of an Episode 1

Four episodes have been identified in GRB 090618. Episode 1 is less energetic and less luminous than Episode 2, and includes a thermal component. In the case of GRB 090423, a possible signature of Episode 1 has been searched for. No thermal component can be evidenced in the BAT data ($15 - 150$ keV), and no precursor emission can be seen either in the BAT or in the GBM data. As a result, the possibility of a non-detection of an Episode 1 has been investigated.

To do so, the Episode 1 of GRB 090618 ($z = 0.54$) has been transposed to $z = 8.2$ and compared to the BAT threshold. More specifically, a time-resolved analysis of the Episode 1 of GRB 090618 has been performed in order to transpose its specific photon spectra to the redshift of GRB 090423. Fermi/GBM data ($8 - 1000$ keV range) have been used for the spectral analysis, as they allow a more precise determination of the fit parameters compared to BAT data. Data have been rebinned with a signal-to-noise ratio of 10.

Transposing the photon spectra at a different redshift

In the time-resolved analysis, a Band spectral model has been used to fit the spectra for simplicity. Transposing the photon spectra implies the application of two transformations. The first one concerns the peak energy of the spectrum $E_{\text{peak}}$ and the normalization quantity $K_{\text{Band}}$. The transposed value of $E_{\text{peak}}$ from $z_1 = 0.54$ to $z_2 = 8.2$ is simply $E_{\text{peak,}\text{tr}} = E_{\text{peak}}(1 + z_1)/(1 + z_2)$. Transposing the normalization (i.e. the specific photon flux at 1 keV) requires the knowledge of the luminosity distance $d_1(z)$:

$$K_{\text{Band,}\text{tr}} = K_{\text{Band}} \left( \frac{1 + z_2}{1 + z_1} \right)^2 \left( \frac{d_l(z_1)}{d_l(z_2)} \right)^2.$$  (4.1)

The second transformation takes into account the cosmological time dilation, which is equal to $(1 + z_2)/(1 + z_1) = 5.97$. 
4.2 GRB 090423: the farthest GRB with a spectroscopic redshift

Figure 4.8: Swift/BAT threshold significance of time-resolved spectra of Episode 1 in GRB 090618 transposed at $z = 8.2$, computed following Band (2003). The dashed lines show the lowest and average values of the BAT threshold significance. Figure reproduced from Ruffini et al. (2014b).

Figure 4.9: Swift/BAT lightcurve (15 – 150 keV) of GRB 090423 and its simulation within the fireshell model. Figure reproduced from Ruffini et al. (2014b).
Table 4.1: Band function fit parameters of the spectra of GRB 090423 and of the selected time interval of GRB 090618.

<table>
<thead>
<tr>
<th>GRB</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$E_{p,i}$ (keV)</th>
<th>Norm. (ph/cm/s/keV)</th>
<th>$\chi^2$</th>
<th>$\Delta t$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>090618</td>
<td>$-0.66 \pm 0.57$</td>
<td>$-1.99 \pm 0.05$</td>
<td>$284.6 \pm 172.1$</td>
<td>$0.357 \pm 0.16$</td>
<td>0.924</td>
<td>6.1</td>
</tr>
<tr>
<td>090423</td>
<td>$-0.78 \pm 0.34$</td>
<td>$-3.5 \pm 0.5$</td>
<td>$433.6 \pm 133.5$</td>
<td>$0.015 \pm 0.010$</td>
<td>0.856</td>
<td>10.4</td>
</tr>
</tbody>
</table>

BAT threshold

The sensitivity of an instrument depends on its burst trigger algorithm, which may be complicated. The BAT trigger algorithm focuses on excesses above expected background and constant sources in the detector count rate. Several criteria may be used to determine the BAT threshold significance $\sigma_0$ (Barthelmy et al., 2005a); the treatment of Band (2003) is followed hereafter. Note that the BAT threshold has been modified recently to allow for the detection of sub-threshold events, but GRB 090423 was detected before this modification so that the treatment of Band (2003) is still valid.

The preset threshold significance of BAT can be expressed as

$$\sigma_0 = \frac{A \epsilon \Delta t \int_{E_{\min}}^{E_{\max}} E \epsilon(E) N(E) dE}{\sqrt{A \epsilon \Delta t \int_{E_{\min}}^{E_{\max}} B(E) dE}}$$

(4.2)

where $A$ is the effective area of the detector, $f_{\text{det}}$ is the active fraction of the detector plane, $f_{\text{mask}}$ is the open fraction of the coded mask, $\Delta t$ is the exposure of the photon spectrum $N(E)$, $\epsilon(E)$ is the efficiency of the detector, $E_{\min} = 15$ keV and $E_{\max} = 150$ keV are the boundaries of the detector’s bandpass, and $B(E)$ is the background. The values from Band (2003) were adopted, with the exception of the effective area, taken to be $A = 5200$ cm$^2$. $\epsilon(E)$ and $B(E)$ were obtained from the time-integrated BAT spectrum using XSPEC. The photon spectra $N(E)$ are the ones of GRB 090618 transposed at $z = 8.2$.

The threshold significance of BAT is variable between $\sigma_{0,\text{min}} = 5.5$ and $\sigma_{0,\text{max}} = 11$. The average value is $\sigma_{0,\text{av}} = 6.7$. We find that an Episode 1 similar to the one of GRB 090618 occurring at $z = 8.2$ could not have been detected (see Fig. 4.8). This result is consistent with the non-detection of an Episode 1 in GRB 090423.

4.2.3 Analysis of Episode 2

The prompt emission of GRB 090423 has been analyzed as an Episode 2 in the fireshell model. We find that the Lorentz factor at transparency is $\sim 1100$, and the baryon load $B$ is estimated to be $8 \times 10^{-4}$. Numerical simulations suggest a homogeneous circumburst medium with a filling factor $R = 10^{-8}$ and a mean CBM density $\langle n_{\text{CBM}} \rangle \approx 10^{-1}$ part cm$^{-3}$. The simulated lightcurve is plotted in Fig. 4.9.

Following the analysis presented in the previous subsection and assuming a detector threshold significance $\sigma_0 = 6.7$, it has been determined that only a section of the lightcurve of GRB 090618 lasting for an observer-frame duration of 6 s would be detectable at the redshift of GRB 090423 (see Fig. 4.10). Considering cosmological time

\[\text{Cf. http://swift.gsfc.nasa.gov/about_swift/bat_desc.html}\]
4.2 GRB 090423: the farthest GRB with a spectroscopic redshift

Figure 4.10: Lightcurve of the Episode 2 of GRB 090618, which takes place between 50 s and 150 s post-trigger. The dashed region highlights the part that would have triggered the Swift/BAT at $z = 8.2$. Its observer frame duration is $\sim 6$ s. The duration of GRB 090423 transposed at $z = 0.54$ is $\sim 3$ s. Figure reproduced from Ruffini et al. (2014b).

Figure 4.11: Spectra of GRB 090423 (in blue) and of the dashed part of the lightcurve of GRB 090618 in Fig. 4.10 (in red). The low-energy index is $\sim -0.8$, which is expected in the fireshell scenario (Ruffini, 2011; Patricelli et al., 2012). Figure reproduced from Ruffini et al. (2014b).
dilation, this episode would last $\sim 36$ s in the observer frame if it occurred at the redshift of 8.2 – a duration similar to that of GRB 090423.

The spectral energy distributions of both GRBs may also be compared. The energy range $89.6 \, \text{–} \, 896$ keV was considered for GRB 090618 to account for the cosmological redshift, while the chosen time interval runs from $T_0 + 63.0$ s to $T_0 + 69.1$ s. This corresponds to the dashed region in Fig. 4.10. A Band function fit to this time and energy ranges provides an intrinsic (rest-frame) peak energy $E_{\text{peak},i} = (248.57 \pm 172.10)$ keV. Fitting a Band function to the $T_{90}$ interval of GRB 090423 gives $E_{\text{peak},i} = (433.6 \pm 133.5)$ keV. Table 4.1 summarizes the fitting parameters of both GRBs and Fig. 4.11 shows both spectra in a common frame at $z = 8.2$. It can be seen that the break in GRB 090423 is shallower. This difference in the steepening at high energies may be related to the structure of the CBM. Indeed, the more fragmented the CBM is, the larger the cut-off energy of the fireshell spectrum is (Bianco & Ruffini, 2005b). Interestingly, the low-energy index is similar in both GRBs at $\alpha \sim -0.8$. This is in agreement with the expectations of the fireshell model in the early emission of a GRB (Patricelli et al., 2012).

The isotropic energy of the selected part of GRB 090618 is equal to $E_{\text{iso}} = 3.49 \times 10^{52}$ erg, a value close to the one computed for GRB 090423 $E_{\text{iso}} = 4.99 \times 10^{52}$ erg.

### 4.2.4 Analysis of Episode 3

The typical X-ray afterglow structure of long GRBs, composed of a steep decay, a plateau phase, and a shallow decay, is well-known (e.g. Nousek et al. 2006; Zhang et al. 2006, see also Section 1.2.2). This standard structure acquires an additional meaning in the IGC paradigm, in which the late shallow decay has been shown to follow a standard power law behavior (Pisani et al., 2013). In this light, it is remarkable that the late X-ray emission of GRB 090423 also overlaps with that of GRB 090618 at rest-frame times $t > 10^4$ s, as shown in Fig. 4.12.

![Figure 4.12: X-ray afterglow of GRB 090423 (in black) and GRB 090618 (in green) in a rest-frame energy range $0.3 \, \text{–} \, 10$ keV. The overlapping at times $t > 10^4$ s is clear. Figure reproduced from Ruffini et al. (2014b).](image-url)
This late scale-invariant power law has been suggested to be powered by the decay of ultra-heavy nuclei produced by r-process during Episode 1 (Ruffini et al., 2015a). This mechanism leads to an emission whose luminosity evolves as a power law in time, with a decay index similar to the one observed and reported in Metzger et al. (2010). The energy budget of this decay process is in line with that of Episodes 3 (Ruffini et al., 2014a). Another possible energy source generating an adequate power law behavior both in the spectral and the luminosity domains lies in type-I and type-II Fermi acceleration mechanisms (Fermi, 1949).

An episode 4 is not expected – and not detected – since a SN would not be detectable at such a large redshift.

### 4.2.5 Conclusions

Comparing GRB 090423 to the prototypical IGC event GRB 090618 has shown that GRB 090423 is fully compatible with being a member of the IGC family. The non-detection of Episodes 1 and 4 is no surprise due to the distance and the sensitivity limits of current detectors, while the analysis of Episode 2 and Episode 3 yielded important positive results:

- The observed prompt emission of GRB 090423 is comparable to an extrapolation of GRB 090618 at \( z = 8.2 \). Be it in terms of the emitted energy (with isotropic energies of respectively \( 4.99 \times 10^{52} \) erg and \( 3.49 \times 10^{52} \) erg), of the observed duration (respectively 19 s and 34 s), or of the spectral energy distributions, the similarities between the two GRBs are evident. Only the high-energy part of the spectrum, where a cut-off is observed at lower energies in GRB 090423, shows a discrepancy. This may however be explained by the existence of a dense, homogeneous CBM. Such environments may indeed be expected for GRBs at high redshifts.

- The analysis of Episode 3 shows a clear overlap of the X-ray afterglows of both GRBs. This result extends the findings of Pisani et al. (2013), in which the GRB sample is limited to \( z < 1 \), to \( z = 8.2 \).

This suggests that GRB 090423 is very possibly a member of the IGC family. An IGC event requires a binary system composed of an evolved core undergoing a SN and a companion NS: it is expected that at 630 million years after the Big Bang, such an evolved system can already exist. Massive stars (\( M \lesssim 30 M_\odot \)) indeed have a lifetime shorter than 10 Myr (Woosley et al., 2002). This lifetime is what is also expected from normal Population II binary stars at \( z = 8.2 \) (Belczynski et al., 2010).

### 4.3 GRB 970828: a GRB of the BATSE era

Observed well before the advent of the Swift and Fermi era, GRB 970828 was one of the first GRBs for which an afterglow was successfully detected – at least in the X-ray and radio domains; however no optical signal was found despite searches starting already 4 hours after initial detection (Groot et al., 1998). The host galaxy of GRB 970828 has been identified as being a member of a system of faint galaxies lying at a redshift \( z = 0.9578 \) (Djorgovski et al., 2001).

In this section, we revisit an event detected more than 15 years ago in light of the recent progress made in the understanding of the IGC paradigm. We find that GRB 970828 is fully consistent with being an IGC event.
4.3.1 Observations and data analysis

GRB 970828 was first detected by the All-Sky Monitor instrument (sensitive in the 2 – 12 keV energy range) on-board the Rossi X-ray Timing Explorer (RXTE) spacecraft on August 28, 1997 (Smith et al., 1997). The Proportional Counter Array instrument (sensitive in the 2 – 60 keV range), also on-board RXTE, scanned the error box region within 3.6 hours; a weak X-ray source was detected (Filippenko et al., 1997). This GRB was also seen by the CGRO and Ulysses satellites (Djorgovski et al., 2001). The lightcurve obtained by CGRO/BATSE exhibits two main emission episodes (see Fig. 4.13). The first episode, lasting about 40 s, is characterized by two main pulses; the second episode also lasts $\sim 40$ s but is more irregular, being composed of several sharp pulses.

Data from the X-ray afterglow were collected by the Advanced Satellite for Cosmology and Astrophysics (ASCA; 2 – 10 keV) 1.17 day following RXTE detection (Murakami et al.,
4.3 GRB 970828: a GRB of the BATSE era

<table>
<thead>
<tr>
<th>Spectral model</th>
<th>$\chi^2$/DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power law</td>
<td>6228.1/115</td>
</tr>
<tr>
<td>Cut-off power law</td>
<td>203.83/114</td>
</tr>
<tr>
<td>Band</td>
<td>106.48/113</td>
</tr>
<tr>
<td>Band + power law</td>
<td>104.12/111</td>
</tr>
<tr>
<td>Cut-off power law + power law</td>
<td>104.28/112</td>
</tr>
<tr>
<td>Blackbody + power law</td>
<td>228.09/113</td>
</tr>
<tr>
<td>Double blackbody + power law</td>
<td>101.78/111</td>
</tr>
</tbody>
</table>

Table 4.2: Statistical comparison of a set of common GRB spectral models fitting the first 40 s of GRB 970828 in the 25 – 1900 keV range.

1997). Observations continued up to 10 days after trigger. The ROSAT spacecraft (in the 0.1 – 2.4 keV range) also observed the afterglow, one week after trigger (Greiner et al., 1997).

Optical observations started about 4 hours after trigger; but no candidate afterglow was detected down to $R = 23.8$ mag (Groot et al., 1998). However, successful radio observations starting 3.5 hours after trigger detected a source at a significance level of 4.5$\sigma$ (Djorgovski et al., 2001). These observations led to the identification of the host system. Deep optical searches at the position of the radio afterglow indeed discovered a system of interacting faint galaxies. Spectroscopic measurements led to the determination of a redshift for GRB 970828, $z = 0.9578$.

The characteristics of the prompt emission are studied through the analysis of BATSE-LAD data, covering the 25 – 1900 keV energy range. The data have been reduced with the rmfit package. Spectral analysis made use of the High Energy Resolution Burst (HERB) data; they consist of 128 separate high energy-resolution spectra.

4.3.2 Episode 1: an evolving thermal component

The lightcurve of GRB 970828 is composed of two clearly separated episodes, reminiscent of the cases of GRB 090618, GRB 101023, and GRB 110709B (cf. Section 3.2). Following an analog approach, the first emission episode has been searched for a thermal component. For the purpose of a time-resolved analysis, the lightcurve has been rebinned imposing a signal-to-noise ratio of 20 for each time bin. This allows us to consider a gaussian distribution of the photons in each bin; $\chi^2$ statistics are therefore adequate in this context.

A time-integrated analysis of the entire first episode (that is, the first 40 s after trigger) shows that the best-fit model is a double blackbody + power law model (see the comparison between different models in Table 4.2). The statistical difference with a Band model is low ($p$-value of 0.09), but the high-energy data are better fitted.

Since a time-integrated analysis may wash out the evolution of physical components, a time-resolved analysis has been performed. This analysis reveals that the double blackbody component of the time-integrated spectrum can be resolved as a single blackbody component varying in time and intensity over a power law component. In order to evaluate the evolution of the blackbody, we have made use of Eq. 3.3 that gives the radius of the emitter as a function of the observed flux and temperature of the thermal component. The evolution of the temperature and of the rest-frame radius of the emitter is shown in Fig. 4.14. Interestingly, the temperature follows a double decay pattern and the
radius follows a power law expansion $r = \alpha t^\delta$ where $\alpha = (5.38 \pm 0.52) \times 10^8$ cm and $\delta = 0.41 \pm 0.04$. The power law component has been discussed previously; its origin may lie in the hypercritical accretion of the SN ejecta onto the NS companion.

**4.3.3 Episode 2: the GRB emission**

In an analogous manner to the cases of GRB 090618, GRB 101023, and GRB 110709B, the second emission episode of GRB 970828 is interpreted as a canonical GRB in the framework of the fireshell model. This episode is characterized by an isotropic energy $E_{\text{iso}} = (1.60 \pm 0.03) \times 10^{54}$ erg.

A fundamental step in the fireshell analysis is the identification of the P-GRB, the emission at the fireshell transparency. The energy contained in the P-GRB is indeed at the basis of the determination of all the other parameters. The P-GRB is characterized by a thermal signature and has to occur in the beginning of the episode – since it marks the transparency of the fireshell, no significant emission is expected prior to it. Fig. 4.15 details the second episode of the lightcurve of GRB 970828. The early emission of Episode 2 can be described as an intense pulse preceded by a weak emission lasting about 9 s. Identifying this episode with the P-GRB, the observed fluence in the $10 - 1000$ keV range is...
range is $S_{\text{obs}} = (1.54 \pm 0.10) \times 10^{-6}$ erg/cm$^2$. This leads to a P-GRB isotropic energy $E_{\text{iso,P-GRB}} = (1.46 \pm 0.43) \times 10^{51}$ erg, which is about 1% of $E_{\text{iso}}$. This ratio between the P-GRB energy and the total energy fulfills the expectations for a long GRB endowed with a baryon load $B = 10^{-3} - 10^{-2}$ in the fireshell theory. However, since the signal during this time interval is too faint for a detailed spectral analysis, we cannot put tight constraints on e.g. the temperature of the expected P-GRB thermal component.

With the P-GRB identified, the fireshell theory gives the following results: the baryon load reaches $B = (7.00 \pm 0.55) \times 10^{-3}$, the Lorentz factor at transparency is $\gamma = 142.5 \pm 57$. A simulation starting at the transparency of the fireshell with these parameters allows for the determination of the density profile of the circumburst medium, which is obtained through the requirement of fitting the observed lightcurve. Fig. 4.15 shows the results of the simulation, namely the density profile, the simulated lightcurve, as well as the simulated spectrum. Characteristic clouds in the circumburst medium have an average density $n \approx 10^3$ part/cm$^3$, a radius $r = (4 - 8) \times 10^{14}$ cm, and a mass $m \approx 10^{22}$ g. The average density of the CBM is $\langle n \rangle = 3.4 \times 10^3$ part/cm$^3$.

4.3.4 Episode 3: late X-ray emission

As presented in Pisani et al. (2013), IGC events have been observed to follow a common behavior during the late X-ray emission. It is therefore satisfying that GRB 970828 follows this trend too.

In Pisani et al. (2013), the luminosity of the X-ray afterglow is computed in the 0.3 – 10 keV rest-frame. This is a consequence of the characteristics of the Swift/XRT instrument. GRB 970828, however, is anterior to the launch of Swift. Coverage of the X-ray afterglow by RXTE, ASCA, and ROSAT nevertheless provided observations in the 2 – 10 keV band. In particular, ASCA and RXTE data presented in Yoshida et al. (2001) have been used, together with the photon indices specified there. The luminosity lightcurve has been computed in the 0.3 – 10 keV rest-frame energy range, expressing the flux lightcurve as

$$f_{\text{rt}} = f_{\text{obs}} \left( \frac{E_{\text{max}}}{1+z} \right)^{2-\gamma} - \left( \frac{E_{\text{min}}}{1+z} \right)^{2-\gamma}$$

where $\gamma$ is the photon index of the spectral energy distribution, $E_{\text{min}} = 0.3$ keV and $E_{\text{max}} = 10$ keV are the boundaries of the bandpass we compute the rest-frame luminosity in, and $E_{\text{min,obs}} = 2$ keV and $E_{\text{max,obs}} = 10$ keV are the boundaries of the bandpass of the observed luminosity. The other corrections applied to the data follow those introduced in Pisani et al. (2013). The resulting lightcurve is shown in Fig. 4.16, together with that of other IGC GRBs (GRB 061007, GRB 080319B, GRB 090618, GRB 091127, GRB 111228A) for comparison. The overlap of GRB 970828 with these other GRBs is indeed good. Note that the last data point is obtained from ROSAT data, taken from Djorgovski et al. (2001) with a corresponding photon index $\gamma \sim 2$.

4.3.5 Episode 4: limits on a supernova signal

It is interesting to note that the supernova that occurred contemporaneously to GRB 090618 – the IGC prototypical event – had a similar luminosity as SN 1998bw, the prototype of GRB supernovae. In order to check whether a supernova associated to GRB 970828 should, or could, have been observed, we have transposed the $R_{\text{C}}$-band lightcurve of the optical afterglow of GRB 090618 to the redshift of GRB 970828. This is done
simply by transforming the observed flux. In addition, we also transposed the $U$- and $R$-band lightcurves of SN 1998bw. Taking into account the cosmological redshift, the $U$-band lightcurve of SN 1998bw approximately corresponds to the observed $R$-band for an event occurring at the redshift of GRB 970828. These transposed lightcurves are shown in Fig. 4.17.

As it turns out, the supernova emission – assuming a similar luminosity as SN 1998bw – could have been seen between 20 and 40 days after trigger (neglecting however any intrinsic extinction). Optical observations of GRB 970828 stopped after 7 days and reached a limit of $R \sim 23.8$ mag (Groot et al., 1998). Deeper images were obtained after 60 days (Djorgovski et al., 2001). There were unfortunately no observations in the favorable time range 20 – 40 days.

Note that a likely cause for the non-detection of an optical afterglow is a strong extinction along the line-of-sight. X-ray and radio signals were normally bright; the absence of an optical transient together with the large intrinsic absorption reported in the ASCA X-ray data (Yoshida et al., 2001) imply a large extinction at optical wavelengths. Taking this additional effect into account, the observed lightcurve of a SN associated with GRB 970828 should lower by at least one magnitude, making the SN bump fall below the limit of $R = 25.2$ (see Fig. 4.17). The large extinction in the optical is additionally consistent with the large circumburst average density inferred from the fireshell analysis.

4.3.6 Conclusions

The understanding of the IGC paradigm developed with the use of data gathered by many modern spacecrafts (in particular Swift and Fermi) allowed us to revisit the case of GRB 970828. It has been verified that GRB 970828 is fully compatible with being a member of the class of IGC events. An Episode 1 with an evolving thermal component is clearly observed. An Episode 2, or a canonical fireshell GRB, is also identified; this led to the determination of important quantities, such as the circumburst medium structure. A simulation of the lightcurve and spectrum of the second episode of GRB 970828 has been performed. An analysis of X-ray data of the late afterglow has shown that GRB 970828 follows the typical pattern of IGC late X-ray emissions: the overlap in Fig. 4.16 is evident. Finally, we have given an explanation as to why no supernova was observed: parts of the reason lie in the large extinction at optical wavelengths, which is consistent with the large CBM density inferred from the fireshell analysis.
4.3 GRB 970828: a GRB of the BATSE era

Figure 4.16: Luminosity lightcurve of the late X-ray emission of GRB 970828 in the 0.3 – 10 keV rest-frame energy range (in black). The lightcurves of IGC GRBs are shown for comparison: the overlapping pattern is clear. Figure reproduced from Ruffini et al. (2015b).

Figure 4.17: Lightcurve of the SN associated with GRB 090618 (in green), the $U-$ (in blue) and $R-$band (in red) lightcurve of SN 1998bw transposed at the redshift of GRB 970828 (uncorrected for intrinsic host galaxy absorption). The purple and cyan lines represent the limits obtained in Djorgovski et al. (2001) and Groot et al. (1998) respectively. Figure reproduced from Ruffini et al. (2015b).
The previous chapters highlighted the role that binaries composed of an evolved stellar core and a neutron star play in energetic long GRBs, which occur concurrently with supernovae. Energetic long GRBs (“binary-driven hypernovae” or “family 2 long GRBs”) form the Induced Gravitational Collapse class, while less energetic long GRBs (“X-ray flashes” or “family 1 long GRBs”) are characterized by the absence of black hole formation, although they are produced by similar systems as energetic long GRBs are. Short GRBs, however, have different progenitors.

In this chapter, the case is made that short GRBs also originate in binary systems, and that they can also be categorized in two families, depending on the presence or absence of black hole formation. In the first section we recapitulate the evidence accumulated in favor of the compact object merger origin. The prototypical case of an energetic genuine short event, GRB 090227B, is summarized before we describe in more details the most recent advances in the understanding of short GRBs. We will do so by introducing the cases of GRB 140619B (Ruffini et al., 2015c) and GRB 090510 (Enderli et al., 2015).
5.1 Short GRBs as binary mergers

The phenomenological distinction that is made between long and short GRBs (see Section 1.3.1) is believed to mark a physical hiatus between these two classes of events. After a short recapitulation of the relevant distinctive properties of short GRBs, we summarize the important case of GRB 090227B. In the framework of the fireshell model, this GRB may indeed be viewed as a prototypical short event and provides important hints that point towards a binary neutron star merger leading to black hole formation as the origin of energetic short GRBs.

5.1.1 Circumstantial evidence for a binary merger origin

The characteristics of the host galaxies and the local environments of the short GRB population are outlined in Section 1.3.2. We recapitulate the main points here.

The absence of concurrent supernovae is an important clue that suggests that short GRBs are not related to the deaths of massive stars.

In addition, short GRBs are observed to occur in elliptical, spiral, and irregular galaxies. In particular, only about 20% of them occur in early-type galaxies (Fong et al., 2013). Long GRBs explode almost exclusively in (late-type) dwarf, blue, irregular galaxies. On the other hand, observing short GRBs in late-type galaxies does not provide an argument against the compact object merger hypothesis, since late-type galaxies are known to host old stellar objects as well – as exemplified by the fact that type Ia SNe are commonly found in this kind of hosts. But the association of a large fraction of the short GRB population with early-type galaxies clearly relates short GRBs to old stellar progenitors. The stellar mass of short GRB hosts is also generally larger than that of long GRBs, even when considering only the star-forming galaxies. This may indicate that stellar mass plays a more important role in short GRBs than in long GRBs. Furthermore the stellar population is found to be older in short GRB hosts relative to long GRB hosts.

At galactic scales, short GRBs are located much farther away from the center of their hosts than long GRBs – which is consistent with the natal kicks of NSs – and they do not track stellar light. This means that short GRBs explode in locations which are different from their birth sites, which in turn implies that they need kicks to migrate.

5.1.2 GRB 090227B: a prototypical genuine short

GRB 090227B has been analyzed in Muccino et al. (2013a). It is a bright short burst of observer-frame duration $\sim 0.9$ s with a fluence of $3.79 \times 10^{-5}$ erg/cm$^2$ in the $8$ keV – $40$ MeV range. It triggered the Fermi/GBM instrument on February 27, 2009 and was also detected by Konus-WIND. No X-ray or optical detection has been reported; its redshift is consequently unknown. Only low-energy (LLE) data has been significantly detected by the Fermi/LAT, since GRB 090227B was outside the nominal LAT field of view (Ackermann et al., 2013): indeed, just one transient-class event above $100$ MeV was associated to this GRB.

The GBM lightcurve of GRB 090227B is characterized by a pulse of duration $\sim 0.4$ s (seen in the $8$ – $40$ keV range) followed by a faint tail detected up to $\sim 0.9$ s after trigger (in the $10$ keV – $1$ MeV range). This pulse appears as a single structure at a temporal resolution of 64 ms but can be resolved with a higher resolution as two different pulses. Identifying the first pulse as the P-GRB (see Fig. 5.1), the analysis of GRB 090227B can be
5.1 Short GRBs as binary mergers

Figure 5.1: NaI-n2 lightcurve of GRB 090227B with a temporal resolution of 16 ms. The dashed area corresponds to the P-GRB emission. Figure reproduced from Muccino et al. (2013a).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Baryon load $B$</td>
<td>$(4.13 \pm 0.05) \times 10^{-5}$</td>
</tr>
<tr>
<td>Lorentz factor at transparency $\gamma_{tr}$</td>
<td>$(1.44 \pm 0.01) \times 10^{4}$</td>
</tr>
<tr>
<td>Fireshell radius at transparency</td>
<td>$(1.76 \pm 0.05) \times 10^{13}$ cm</td>
</tr>
<tr>
<td>Theoretical redshift $z$</td>
<td>$1.61 \pm 0.14$</td>
</tr>
<tr>
<td>Total energy $E_{e^+e^-}^{\text{tot}}$ (erg)</td>
<td>$(2.83 \pm 0.15) \times 10^{53}$ erg</td>
</tr>
<tr>
<td>Fireshell temperature at transparency $kT_{\text{blue}}$</td>
<td>$(1.34 \pm 0.01) \times 10^{3}$ keV</td>
</tr>
<tr>
<td>Average CBM density $\langle n \rangle$</td>
<td>$(1.90 \pm 0.20) \times 10^{-5}$ part/cm$^3$</td>
</tr>
</tbody>
</table>

Table 5.1: Parameters derived from the fireshell analysis of GRB 090227B. The redshift and the quantities that depend on it (in particular the total energy) are determined theoretically.
performed and leads to the determination of the burst parameters summarized in Table 5.1. The observed temperature of the thermal component of the P-GRB is $517 \pm 28$ keV. A theoretical redshift $z = 1.61$ has also been derived from this analysis\(^1\), leading to an isotropic energy $E_{\text{iso}} = 2.83 \times 10^{53}$ erg.

The results of the analysis point towards a NS merger origin for GRB 090227B. Indeed, the very low average density of the circumburst medium, of the order of $10^{-5}$ part cm$^{-3}$, is typical of a galactic halo environment\(^2\); the energy budget and the timescale also suggest a NS merger; and the small value of the baryon load $B = 4.13 \times 10^{-5}$ is consistent with these neutron stars having a crust $\sim 0.5$ km thick. An estimation of the energy emitted in the form of gravitational waves has been made and found to be $\sim 9.7 \times 10^{52}$ erg.

### 5.2 GRB 140619B: a family 2 short GRB

Following and building on the early results of Muccino et al. (2013a) on GRB 090227B, we focused in Ruffini et al. (2015c) on the analysis of another short GRB, GRB 140619B, and inferred from this analysis several generic results concerning the nature of short GRBs.

The class of short GRBs with a measured redshift, an isotropic energy $E_{\text{iso}} < 10^{52}$ erg, and a rest-frame peak energy $E_{p,i} < 2$ MeV is well covered in the literature (e.g. Berger 2014 and references therein). Their long-lasting X-ray afterglow gives away the location of their host galaxies, the identification of which leads to a redshift determination. Note that among this class of events, none of the afterglows appears to follow the characteristic power law behavior identified in energetic long GRBs (see Ruffini et al. 2014a and previous chapters).

Progress in the theoretical understanding of the equilibrium configuration of neutron stars and in the determination of the masses of galactic pulsars led us to propose in Ruffini et al. (2015c) the existence of two families of short GRBs. The members of both these families originate in NS mergers, but the total mass of the merged object determines the outcome of the merger. If this mass exceeds the critical NS mass, a BH forms and the fireshell model can be applied. If this mass does not exceed the critical mass, the merger results in a massive NS and a less energetic short GRB as described in the previous paragraph. We show that GRB 140619B can instead be interpreted as a binary NS merger leading to BH formation.

### 5.2.1 Motivations from neutron star theory

The analysis of GRB 140619B is largely motivated by recent progress in neutron star theory. Indeed, Rotondo et al. (2011) showed that in the framework of relativistic quantum statistics and the Einstein-Maxwell equations, the local charge neutrality condition cannot be imposed on a self-gravitating system of degenerate neutrons, protons, and electrons in $\beta$-equilibrium. Rueda et al. (2011) and Belvedere et al. (2012) introduced the equilibrium equations of NSs taking into account weak, strong, EM, and gravitational interactions in general relativity, the equilibrium conditions obtained from the Einstein-Maxwell-Thomas-Fermi equations, as well as the constancy of the general relativistic particle Fermi energies – the Klein potentials. A theoretical estimate of the critical mass of

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\(^1\)The method used to derive the redshift, based on the fireshell theory, is described in details in the next section.

\(^2\)Where NS binaries are expected to migrate due to high velocity kicks following SN explosions – see e.g. Berger (2014); Bloom et al. (1999); Fryer et al. (1999c).
Figure 5.2: Mass-radius relation obtained from the local and global charge neutrality conditions applying the NL3 nuclear model. Figure reproduced from Belvedere et al. (2012).

Figure 5.3: Galactic binary NSs with known total mass. The horizontal dashed line represents the critical mass $M_{\text{crit}} = 2.67 M_\odot$. Figure reproduced from Ruffini et al. (2015c).
On short GRBs

$M_{\text{crit}} \approx 2.67 \, M_\odot$ for a non-rotating configuration has been obtained. Slowly rotating NSs have been studied using the Hartle formalism in Belvedere et al. (2014a). Further progress has been achieved by Rueda et al. (2014) who studied the transition layer between the core and the crust of NSs at nuclear saturation density. The surface tension and the Coulomb energy have been computed. Belvedere et al. (2014b) summarized these results, and Cipolletta et al. (2015) obtained the absolute upper limit on the angular momentum of a rotating NS fulfilling the microscopic conditions detailed here. Fig. 5.2 shows the mass-radius relation obtained from the local and global charge neutrality conditions applying the NL3 nuclear model.

Observational data from galactic pulsars allow precision tests (see e.g. Lattimer 2012; Kramer 2014). In particular, Antoniadis et al. (2013) found a large value for the mass $M = 2.01 \pm 0.04 \, M_\odot$ of PSR J0348+0432. This result favors stiff NS equations of state. Another important observational result deals with galactic binary NSs. Considering the sample of binary NSs with a measured total mass, one can note that only in a subset of them the combined mass exceeds the critical mass derived in Belvedere et al. (2012), as shown in Fig. 5.3. The implication is that only a fraction of binary NS mergers would lead to black hole formation; most would result in a massive NS.

5.2.2 Observations and data analysis

Observations

GRB 140619B triggered the Fermi/GBM instrument (Connaughton et al. 2014, trigger 424869883/140619475) at 11:24:40.52 UT on June 19, 2014 (hereafter $T_0$). The burst location was $32^\circ$ away from the LAT boresight at $T_0$, and consequently in the LAT field of view. LAT data evidenced a significant increase in the event rate (Kocevski et al., 2014). Suzaku-WAM also triggered on this GRB; its lightcurve in the $50 \, \text{keV} – 5 \, \text{MeV}$ range shows a single pulse of duration $\sim 0.7$ s. Swift/XRT coverage of the LAT error circle from $48.7 \, \text{ks}$ to $71.6 \, \text{ks}$ after trigger did not prove successful (Maselli & D’Avanzo, 2014), setting an upper limit on the $0.3 – 10 \, \text{keV}$ flux of $\sim 9.24 \times 10^{-14} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ assuming a photon index $\gamma \approx 2.2$. Without an X-ray localization, no optical follow-up was carried out, and no redshift was obtained.

Data analysis

We focused on Fermi/LAT and GBM data, respectively in the $20 \, \text{MeV} – 100 \, \text{GeV}$ range and in the $8 \, \text{keV} – 40 \, \text{MeV}$ range. Time-tagged data, suitable for short events, have been analyzed using the rmfit package. The LAT low-energy (LLE, $20 – 100 \, \text{MeV}$) and high-energy ($100 \, \text{MeV} – 100 \, \text{GeV}$) data have been analyzed with the Fermi science tools.

The GBM-NaI signal is strongest in the NaI-n6 detector. Its lightcurve nevertheless only contains a weak signal just above background level. On the other hand, the BGO-b1 signal is stronger and may be described as a short hard pulse possibly containing two substructures with a duration $\sim 0.9$ s. LAT emission starts with a delay of approximately $0.2$ s. Fig. 5.4 shows the lightcurves of the Fermi instruments.

Both a time-integrated and a time-resolved analysis have been performed on GBM data ($8 \, \text{keV} – 40 \, \text{MeV}$).

- The time-integrated spectrum, from $T_0 - 0.064 \, \text{s}$ to $T_0 + 0.640 \, \text{s}$ (which is the $T_{90}$
duration of the burst), is best fit by a Compt model, preferred over a Band model. The Band model improves the fit by $\Delta C - \text{STAT} = 2.53$ but requires an additional parameter. Considering $\Delta C - \text{STAT}$ as a $\chi^2$ variable in the change of the number of model parameters (here $\Delta n = 1$) and since the Compt model is nested in the Band model, the Band model improves the fit only at the 89% level – not enough to reject the Compt fit. The low-energy index of the Compt fit is consistent with $\alpha \approx 0$. Both spectral model fits are shown in Fig. 5.5.

- For the time-resolved analysis, the time intervals were selected with the requirement that the fluence in each bin should be larger than $\sim 10^{-6}$ erg cm$^{-2}$, in order to ensure that enough photons are detected. Two time intervals are thus selected: the main spike ($T_0$ to $T_0 + 0.192$ s), and a fainter structure ($T_0 + 0.192$ s to $T_0 + 0.640$ s).

In the first time interval, we aim at identifying the P-GRB. We consider a Compt model and a blackbody model. Both are viable; in particular, the low-energy index of the Compt model is $\alpha = 0.26 \pm 0.32$, consistent within 3$\sigma$ with $\alpha = 1$, that is, the low-energy index of a blackbody. Therefore, a blackbody model (with an observed temperature $kT = 324 \pm 33$ keV) provides an acceptable fit to the data and is the best physical model; as a result, we identify it with the P-GRB. The Compt and blackbody fits are shown in Fig. 5.6.

The second time interval is not adequately fitted by a blackbody component, especially at energies larger than 1 MeV. Thus the Compt model is favored, and consistent

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3We recall that a Comp model (short for Comptonized) is an exponentially attenuated power law.

4The Compt model may be viewed as a Band model with $\beta \rightarrow -\infty$. 
Figure 5.5: NaI-n6, NaI-n9, and BGO-b1 spectrum of GRB 140619B in the $T_{90}$ time interval. Left panel: Compt model fit of the data. Right panel: blackbody fit of the data. Figures reproduced from Ruffini et al. (2015c).
Figure 5.6: NaI-n6, NaI-n9, and BGO-b1 spectrum of GRB 140619B in the first time interval ($T_0$ to $T_0 + 0.192$ s). Left panel: Compt model fit of the data. Right panel: blackbbody fit of the data. Figures reproduced from Ruffini et al. (2015c).
with the prompt emission spectral model expected in the fireshell model as described by Patricelli et al. (2012).

5.2.3 Theoretical analysis

Once the P-GRB is identified, the fireshell theory can be applied: the baryon load and all other physical quantities that characterize the fireshell at the transparency point can be determined, and a redshift can be estimated. Note that a fundamental difference between short and long GRBs stems from the energy embedded in the P-GRB emission: on average, the latter makes up for 1 to 5% of the overall emission in long GRBs, while it represents about 40% in the cases of GRB 090227B and GRB 140619B.

Redshift estimate

The fireshell model features a valuable tool: the possibility to infer a theoretical redshift from the observations of the P-GRB and the prompt emission. This stems from the relations, engraved in the fireshell theory, between different quantities; these relations are summarized in Fig. 2.7. Thus, the ratio \( \frac{E_{P,GRB}}{E_{e^+e^-}^{\text{tot}}} \) implies a finite range for the possible values of the coupled parameters \( E_{e^+e^-}^{\text{tot}} \) and \( B \). This ratio is known, since it is equal to the ratio between the observed fluences of the respective quantities:

\[
\frac{E_{P,GRB}}{E_{e^+e^-}^{\text{tot}}} \approx \frac{4\pi d_l^2 S_{P,GRB}/(1+z)}{4\pi d_l^2 S_{\text{tot}}/(1+z)} = \frac{S_{P,GRB}}{S_{\text{tot}}} = (40.4 \pm 7.8)\% \tag{5.1}
\]

where the fluence \( S \) is equal to the flux multiplied by the duration of the time interval considered, \( E_{P,GRB} \) is given by the energy contained in the observed thermal component, and \( E_{e^+e^-}^{\text{tot}} \) is set equal to \( E_{\text{iso}} \).

In addition, the knowledge of the couple \( [E_{e^+e^-}^{\text{tot}}, B] \) implies the knowledge of the fireshell temperature at transparency blue-shifted towards the observer \( kT_{\text{blue}} \) (again, this is shown in Fig. 2.7). But we also have the following relation between \( kT_{\text{blue}} \) and the observed temperature at transparency \( kT_{\text{obs}} \), linking their ratio to the redshift:

\[
\frac{kT_{\text{blue}}}{kT_{\text{obs}}} = 1 + z . \tag{5.2}
\]

Finally, since we assume that \( E_{e^+e^-}^{\text{tot}} = E_{\text{iso}} \), we can also express \( E_{e^+e^-}^{\text{tot}} \) as a function of \( z \) using the formula of the isotropic energy:

\[
E_{\text{iso}} = 4\pi d_l^2 \frac{S_{\text{tot}}}{1+z} \int_{E_{\text{GBM},\min}}^{E_{\text{GBM},\max}} EN(E)dE = \int_{E_{\text{min}}/(1+z)}^{E_{\text{max}}/(1+z)} EN(E)dE \tag{5.3}
\]

where \( N(E) \) is the photon spectrum, \( E_{\text{min}} = 1 \text{ keV} \) and \( E_{\text{max}} = 10000 \text{ keV} \) are the boundaries of the rest-frame energy range in which \( E_{\text{iso}} \) is computed, and \( E_{\text{GBM},\min} = 8 \text{ keV} \) and \( E_{\text{GBM},\max} = 40000 \text{ keV} \) are the boundaries of the GBM bandpass.

The use of all these relations allows for the determination of a redshift through an iterative procedure, testing at every step the consistency of the values of the parameters \( E_{e^+e^-}^{\text{tot}} \) and \( kT_{\text{blue}} \). The procedure successfully ends when both values verify the relations described above.

We find \( z = 2.67 \pm 0.37 \). This corresponds to an isotropic energy \( E_{\text{iso}} = (6.03 \pm 0.79) \times 10^{52} \text{ erg} \) and a baryon load \( B = (5.52 \pm 0.73) \times 10^{-5} \).
All the quantities derived from the fireshell analysis are summarized in Table 5.2. Once the initial conditions (i.e. the total energy and the baryon load) of the fireshell are established, the dynamics of the system are uniquely determined. Thus, the Lorentz factor at transparency is obtained, $\gamma_{tr} = 1.08 \times 10^4$, and a numerical simulation can be performed in order to simulate the lightcurve and spectrum of the prompt emission of GRB 140619B. The radial profile of the circumburst medium density and of the filling factor $R$ are obtained as products of the simulation. Note that the errors concerning these two parameters are defined as their maximum variation within which the simulation of the lightcurve is consistent with the data.

Figs. 5.7 and 5.8 show the CBM density profile that is obtained, as well as the simulated lightcurve and spectrum. The similarity with the properties of GRB 090227B is striking. In particular, the average CBM number densities are very similar in both cases, at low values of the order of a few $10^{-5}$ part/cm$^3$.

The spectrum of the prompt emission is obtained using the spectral model introduced in Patricelli et al. (2012) with a phenomenological parameter $\alpha = -1.11$. The fit of the lightcurve is done in the 260 keV – 4 MeV range, but the simulation of the spectrum has been extended down to 8 keV in order to check the agreement with the data. As can be seen in Fig. 5.8, the residuals between the data and the simulated spectrum are low.

The time variability of the prompt emission in the fireshell model stems from the interaction of the accelerated baryons of the fireshell with the CBM clumps. Time variability in GRB lightcurves is subject to intense debates; in the fireball approach, it originates in the prolonged activity of the central engine (e.g. Ramirez-Ruiz & Fenimore 2000; Piran 2005). Zhang et al. (2006) and Nakar & Granot (2007) underlined difficulties in producing short time variability from CBM inhomogeneities, but Dermer & Mitman (1999) and Dermer (2006, 2008) defend the opposite view.

Within the framework of the fireshell model, Bianco & Ruffini (2005a,b) have shown that the short-time variability occurs in regimes of high Lorentz factors, in which the total visible area of the emitter is small and the dispersion in arrival time of the luminosity peaks is negligible. The CBM inhomogeneities may therefore be considered as the reason behind the time variability. It is relevant to note that the case of GRB 140619B confirms these remarks. The visible area of the emitter $d_v$ at the radius of each encounter with a CBM clump is indicated in Table 5.3. It can be seen that the values of $d_v$ are smaller than the inhomogeneities thickness ($\Delta r \approx 10^{16} - 10^{17}$ cm), which justifies the adopted spherical symmetry approximation (Patricelli et al., 2012). As a result, a finer description of the pulse substructures is not necessary and does not change the agreement of the model with...
Figure 5.7: Density profile of the circumburst medium around GRB 140619B obtained through the fireshell simulation. Figure reproduced from Ruffini et al. (2015c).

Figure 5.8: Top panel: BGO-b1 lightcurve (260 keV – 40 MeV) of GRB 140619B (in green) and simulation of the prompt emission (in red). Each pulse corresponds to a change in the CBM density. The blue dash-dotted line marks the end of the P-GRB emission; the purple long-dashed and black dashed lines indicate, respectively, the start and the end of the $T_{90}$ time interval. Bottom panel: NaI-n6 (purple squares), NaI-n9 (blue diamonds), and BGO-b1 (green circles) data of the second time interval ($T_0 + 0.192$ s to $T_0 + 0.640$ s) corresponding to the prompt emission, compared to the fireshell simulated spectrum (red curve). Figures reproduced from Ruffini et al. (2015c).
5.2 GRB 140619B: a family 2 short GRB

<table>
<thead>
<tr>
<th>Clump</th>
<th>Distance (cm)</th>
<th>( n_{\text{CBM}} ) (cm(^{-3}))</th>
<th>( R )</th>
<th>( \gamma )</th>
<th>( d_v ) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 1.50 \times 10^{13} )</td>
<td>( 1.2 \times 10^{-3} )</td>
<td>( 2.8 \times 10^{-11} )</td>
<td>( 1.08 \times 10^4 )</td>
<td>( 2.76 \times 10^{11} )</td>
</tr>
<tr>
<td>2</td>
<td>( 1.20 \times 10^{17} )</td>
<td>( 9.2 \times 10^{-6} )</td>
<td>( 2.07 \times 10^3 )</td>
<td>( 1.16 \times 10^{14} )</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( 1.70 \times 10^{17} )</td>
<td>( 2.5 \times 10^{-4} )</td>
<td>( 3.5 \times 10^{-10} )</td>
<td>( 1.84 \times 10^3 )</td>
<td>( 1.85 \times 10^{14} )</td>
</tr>
</tbody>
</table>

Table 5.3: Density, filling factor, Lorentz factor and total transversal size of the fireshell visible area of GRB 140619B.

the data.

Progenitor

Following the conclusions on GRB 090227B, we infer that GRB 140619B was produced by a binary NS merger. Considering the simple case of two NSs of equal mass \( M_{\text{NS}} \), a lower limit for the conditions necessary to the formation of a BH and the application of the fireshell model is \( 2M_{\text{NS}} \gtrsim M_{\text{crit}} \), where \( M_{\text{crit}} \) is the NS critical mass. Referring to the critical mass of Belvedere et al. (2012), we have considered \( M_{\text{NS}} = 0.5 \ M_{\text{crit}} = 1.34 \ M_{\odot} \). The corresponding radius is \( R = 12.24 \) km.

Making the further working assumption that the crustal material of both NSs contributes to the baryon load of the fireshell, we find that only a small fraction \( \sim 2.5\% \) of the crustal mass is engulfed in the fireshell. Indeed, the crustal mass deduced from the NL3 nuclear model is \( M_c = 3.63 \times 10^{-5} \ M_{\odot} \) for each NS. But the engulfed baryonic mass is \( M_B = E_{\text{tot}}^\text{LIGO}/c^2 = (1.86 \pm 0.35) \times 10^{-6} \ M_{\odot} \). This small fraction is consistent with the global charge neutrality condition; the local charge neutrality condition leads to \( M_c \approx 0.2 \ M_{\odot} \), a result that is not consistent with the small baryon load of GRB 140619B.

5.2.4 On the gravitational wave emission

Oliveira et al. (2014) estimated the gravitational wave emission of GRB 090227B. Following this work, we use the effective one body (EOB) formalism (Buonanno & Damour, 1999, 2000; Damour et al., 2000; Damour, 2001; Damour & Nagar, 2010) to estimate the gravitational wave emission of GRB 140619B, and assess its detectability by the Advanced LIGO interferometer\(^5\). This formalism maps the conservative dynamics of a binary system of non-rotating objects onto the geodesic dynamics of a single body of reduced mass \( \mu = M_1 M_2/M \), where \( M = M_1 + M_2 \) is the total binary mass. The effective metric is a modified Schwarzschild metric with rescaled radial coordinate \( r = c^2 r_{12}/(GM) \) where \( r_{12} \) is the distance between the two objects.

The binding energy as a function of the orbital frequency \( \Omega \) is given by

\[
E_b(\Omega) = M c^2 \sqrt{1 + 2\nu(\dot{H}_{\text{eff}} \Omega - 1)} - 1
\]

(5.4)

where the effective Hamiltonian \( \dot{H}_{\text{eff}}^2 = 1(u) + p_{\phi}^2 B(u) \) depends on the radial potential \( A(u) \) and \( u = 1/r \), and \( B(u) = u^2 A(u) \). The angular momentum for a circular orbit is \( p_{\phi}^2 = -A'(u)/[u^2 A(u)]' \), where a prime stands for the derivative with respect to \( u \). To obtain the derivative of \( \dot{H}_{\text{eff}} \) as a function of \( \Omega \), the chain rule together with the relation \( \Omega = \Omega(u) \) following from the angular Hamiltonian equation of motion in the circular case must be used. The rate of orbital energy loss through gravitational wave emission is then

\(^5\)http://www.advancedligo.mit.edu
obtained from the related derivative \(dE_b/d\Omega\). In the case of GRB 140619B, a total energy \(E_{GW}^T = 7.42 \times 10^{52}\) erg is emitted in the form of gravitational radiation during the in-spiral phase up to the merger.

The signal-to-noise ratio (SNR) is computed using the matched filtering technique from the Fourier transform of the signal \(h(t) = h_+ F_+ + h_\times F_\times\) where \(h_+, h_\times\) are functions that depend on the direction and polarization of the source, and \(F_+, F_\times\) depend on the orientation of the detector. Making a rms average over all possible source directions and wave polarizations \(\langle F_+^2 \rangle = \langle F_\times^2 \rangle = 1/5\), one obtains (Flanagan & Hughes, 1998):

\[
\langle \text{SNR} \rangle^2 = \int_{f_{\text{min}}}^{f_{\text{max}}} df_d \frac{h_c^2(f_d)}{5 f_d S_h^2(f_d)}
\]

(5.5)

where \(S_h(f)\) is the strain noise spectral density in Hz\(^{-1/2}\) of the interferometer and \(h_c\) is the characteristic wave amplitude defined using the Fourier transform of the wave form \(h(t)\): \(h_c(f_d) = f\hat{h}(f_d)\). We have

\[
h_c^2(f) = \frac{2(1+z)^2 dE_b}{\pi^2 f_d^2} \frac{df}{[(1+z)f_d]}
\]

(5.6)

where \(f_d = f/(1+z)\) is the wave frequency at the detector, \(f = \Omega/\pi\) is the frequency in the source frame, \(f_{\text{min}}\) is the minimal bandwidth frequency of the detector, \(f_{\text{max}} = f_c/(1+z)\) is the maximal bandwidth frequency with \(f_c = \Omega_c/\pi\) being the binary contact frequency. The strain-noise sensitivity of Advanced LIGO \(S_h(f)\) and the characteristic gravitational amplitude per square root frequency \(h_c(f_d)/\sqrt{f_d}\) are plotted as functions of the frequency at the detector in Fig. 5.9.

In the case of GRB 140619B, a very low \(\langle \text{SNR} \rangle \approx 0.21\) is obtained, far from the SNR = 8 required for an optimal positive detection. This low value of the SNR is due to the large distance of the source \(d_l \approx 21\) Gpc. An optimally located and polarized source would still lead to a low SNR of the order of 0.5.

5.2.5 On the high-energy emission

GRB 140619B is characterized by a short-lived (~ 4 s) emission at energies above 100 MeV. The lightcurve at these energies (see Fig. 5.10) shows a rising part, a peak at \(T_0 + 2\) s, and a decaying part lasting another 2 s (in the observer frame). Four intervals of 1 s each have been analyzed; the corresponding spectra are best fit by a power law function. The energy emitted in the 0.1 – 100 GeV range is \(E_{\text{LAT}} = (2.34 \pm 0.91) \times 10^{52}\) erg.

In analogy with our findings on energetic long GRBs, we attribute the GeV emission to the newborn BH. This implies that high-energy emission is a common feature among family 2 short GRBs – recall that GRB 090227B was outside the nominal LAT field of view, which gives an explanation to the lack of GeV detection for this burst. However, significant detection in the LLE data suggests that in optimal conditions, a GeV emission would also have been seen in GRB 090227B. GRB 090510, the analysis of which is summarized in the next section, and GRB 0811024B are other examples of family 2 short GRBs with an associated GeV emission.
Figure 5.9: Sensitivity curve of Advanced LIGO (in dashed black) and characteristic gravitational amplitude of the binary NS progenitor of GRB 140619B (in solid black), as functions of the frequency at the detector. $A(u)$ was computed using values for the coefficients in the 4th order post-Newtonian (PN) approximation. $P^1_{15}$ is the Padé approximant of order (1,5). Figure reproduced from Ruffini et al. (2015c).

Figure 5.10: Rest-frame isotropic luminosity of GRB 140619B in the $0.1 - 100$ GeV range (purple squares), and upper limit on the rest-frame $0.3 - 10$ keV emission (green circle). Figure reproduced from Ruffini et al. (2015c).
Table 5.4: 1 s peak photon flux $f_p$, threshold peak flux $f_T$, and maximum redshift at which each source would have been detected $z_{\text{max}}$ for GRB 090227B, GRB 090510, and GRB 140619B.

<table>
<thead>
<tr>
<th>GRB</th>
<th>$f_p$ (photons cm$^{-2}$ s$^{-1}$)</th>
<th>$f_T$ (photons cm$^{-2}$ s$^{-1}$)</th>
<th>$z_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 090227B</td>
<td>16.98</td>
<td>1.68</td>
<td>5.78</td>
</tr>
<tr>
<td>GRB 090510</td>
<td>9.10</td>
<td>1.96</td>
<td>2.25</td>
</tr>
<tr>
<td>GRB 140619B</td>
<td>4.97</td>
<td>1.03</td>
<td>5.49</td>
</tr>
</tbody>
</table>

5.2.6 The family 2 short GRB rate

Using the three family 2 short GRB with redshift (obtained either theoretically or observationally) that we identified$^6$, it is possible to infer the expected rate $\rho_0$ of family 2 short GRBs. Note that all of these bursts have been detected by the Fermi satellite. Following Soderberg et al. (2006b) and Guetta & Della Valle (2007), we have computed the 1 s peak photon flux $f_p$ in the $1 - 1000$ keV energy range. These values are reported for each of the three GRBs in Table 5.4.

Then, $f_p$ is computed for different redshift values using each source’s spectral parameters, until it coincides with the threshold peak flux $f_T$ – i.e. the lowest peak photon flux allowing detection, see Band (2003) for details. Thus the maximum redshift $z_{\text{max}}$ at which each source would have been detected is obtained and the corresponding co-moving volume $V_{\text{max}}$ can be obtained. The values of $f_T$ and $z_{\text{max}}$ for each source are reported in Table 5.4.

The empirical rate of this class of events is then given by

$$\rho_0 = \left( \frac{\Omega_F}{4\pi} \right)^{-1} \frac{N}{V_{\text{max}} T_F}$$

(5.7)

where $N = 3$ is the number of identified energetic short bursts, $\Omega_F \approx 9.6$ sr is the average solid angle field of view of Fermi, and $T = 6$ yr is the observing time of Fermi. A local rate $\rho_0 = (2.6^{+4.1}_{-1.9}) \times 10^{-4}$ Gpc$^{-3}$ yr$^{-1}$ is obtained. The errors are computed at the 95% confidence level of the Poisson statistics (Gehrels, 1986).

This rate implies an expected number of events at $z \geq 0.9$ of $N = 4^{+6}_{-3}$, consistent with the three events observed by Fermi. At $z \leq 0.9$, the expected number of events $N = 0.2^{+0.31}_{-0.4}$ is consistent with the absence of detected family 2 short bursts.

The inclusion of GRB 081024B with its constrained redshift does not change significantly the values obtained previously, but puts more constraints on the error. A rate $\rho_0 = (2.1^{+2.8}_{-0.14}) \times 10^{-4}$ Gpc$^{-3}$ yr$^{-1}$ is then obtained. Both rates are much smaller than that of the long GRBs, estimated by Wanderman & Piran (2010) to be $\rho_{\text{L-GRB}} = 1.3^{+0.7}_{-0.6}$ Gpc$^{-3}$ yr$^{-1}$. They are also much smaller than the rate of family 1 short GRBs (assuming no beaming correction), given as $\rho_{\text{short}} = 1 - 10$ Gpc$^{-3}$ yr$^{-1}$ (e.g. Berger 2014; Clark et al. 2014). These low rates may be understood in light of the data on galactic binary NS masses; as recalled in Section 5.2.1, only a subset of binary NS have a combined mass above the critical mass and may form a BH in the merging process.

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$^6$Namely GRB 090227B, GRB 140619B, and GRB 090510. GRB 081024B is not included since its redshift is only constrained, with $z > 3.0$. 
5.3 GRB 090510: merging NSs coalescing into a Kerr-Newman BH

5.2.7 Conclusions

An important prediction presented in Ruffini et al. (2015c) postulates the existence of two different families of short GRBs originating in binary NS mergers. This prediction relies on three elements:

- the analysis of GRB 090227B, viewed as a prototype event of family 2 short GRBs;
- the theoretical progress accomplished in neutron star equations of state, leading in particular to the determination of a critical mass $M_{\text{crit}} \approx 2.67 M_\odot$;
- the observations of a pulsar yielding a mass $(2.01 \pm 0.04) M_\odot$, favoring stiff equations of state, and the observations of galactic binary NSs in general.

The class of short GRBs that we refer to as “family 1” (or alternatively $\gamma$-ray flashes, GRFs) is characterized by an isotropic energy $E_{\text{iso}} < 10^{52}$ erg and a rest-frame peak energy $E_{p,i} < 2$ MeV. Family 1 short GRBs are by far the most common events among short GRBs, and in our understanding they originate in merging NSs whose combined mass does not exceed the critical mass. On the other hand, family 2 short GRBs (or S-GRBs), with an isotropic energy $E_{\text{iso}} > 10^{52}$ erg and a rest-frame peak energy $E_{p,i} > 2$ MeV, are believed to originate in NS mergers forming a BH.

The physical parameters characterizing GRB 140619B have been obtained by applying the fireshell model. Identifying the early 0.2 s with the P-GRB, the quantities summarized in Table 5.2 are obtained. In particular, a theoretical redshift $z = 2.67 \pm 0.37$ is obtained, and the average circumburst density is found to be low at values consistent with galactic halo environments, where binary NSs are expected to migrate due to natal kicks. An intense, short-lived GeV emission starting right after the end of the P-GRB has been detected in this GRB; this led us to the conclusion that this high-energy emission originates in the BH.

Finally, in view of the elements presented in this section, a number of predictions have been made.

- All family 1 short GRBs have an extended X-ray afterglow (see e.g. Berger 2014), but this afterglow does not exhibit specific behaviors as energetic long GRBs do (Pisani et al., 2013; Ruffini et al., 2014a). However, we expect that no high-energy emission be present in family 1 short GRBs. The boundary value of $10^{52}$ erg separating family 1 and 2 events may be understood in terms of the energy budget of a NS merger leading to a massive NS.

- All family 2 short GRBs observed so far have no significant X-ray or optical afterglows. However, they have an observed short-lived but intense GeV emission when LAT observations are available.

- The high-energy emission of family 2 short GRBs starts at the end of the P-GRB emission. This points to the role of the newborn BH in the production of the high-energy emission.

5.3 GRB 090510: merging NSs coalescing into a Kerr-Newman BH

The study of family 2 short GRBs (S-GRBs) has been extended in Enderli et al. (2015) with the case of GRB 090510. This GRB was previously analyzed within the fireshell model.
(Muccino et al., 2013a); it was then proposed to be a regular long GRB event exploding in an overdense CBM, making GRB 090510 appear short. This analysis was later updated as it lacks consistency with further developments of the IGC picture. In particular, the late X-ray emission of GRB 090510 does not follow the expected behavior of an Episode 3.

On the ground of theoretical developments in the study of binary neutron star mergers (see Section 5.2.1), GRB 090510 has consequently been reanalyzed. We show that this GRB may be interpreted as a binary neutron star merger that leads to the formation of a fast rotating BH. We obtain the first evidence for the formation of a Kerr-Newman BH: the P-GRB of GRB 090510 can indeed be fitted by a convolution of thermal spectra, which are understood to originate in an axially symmetric configuration of the pair-creation region—a dyadotorus—, instead of the spherically symmetric dyadosphere that is usually assumed. The GeV emission, which is conjectured to originate from the newborn BH, is one of the most energetic ever observed in short GRBs. In addition, the theoretical redshift derived from the fireshell analysis, \( z_{th} = 0.75 \pm 0.17 \) is consistent with the measured value \( z = 0.903 \pm 0.003 \).

### 5.3.1 Observations and data analysis

#### Observations

The short and bright burst GRB 090510 triggered the Fermi/GBM instrument at \( T_0 = 00:22:59.97 \) UT on May 10, 2009 (trigger 263607781/090510016, Guiriec et al. 2009). The lightcurve consists of a precursor emission that set off the trigger and lasted 30 ms, followed \( \sim 0.4 \) s later by a hard episode lasting \( \sim 1 \) s. GRB 090510 was also detected by Swift (Hoversten et al., 2009), Fermi/LAT (Ohno & Pelassa, 2009), AGILE (Longo et al., 2009), Konus-WIND (Golenetskii et al., 2009), and Suzaku-WAM (Ohmori et al., 2009).

GRB 090510 was the first bright short GRB to be observed from the keV to the GeV range. In particular, during the first second after its trigger (at 00:23:01.22 UT), the Fermi/LAT detected over 50 events (respectively over 10) with an energy above 100 MeV (respectively above 1 GeV). Within the first minute, it detected more than 150 events (respectively more than 20 events, Omodei et al. 2009).

A host galaxy was located by VLT/FORS2. It is a late-type galaxy of stellar mass \( 5 \times 10^9 M_\odot \) with a rather low star-forming rate \( \text{SFR} = 0.3 M_\odot \text{yr}^{-1} \) (Berger 2014 and references therein). Spectral emission lines from the host provided a redshift \( z = 0.903 \pm 0.003 \) (Rau et al., 2009). The refined position of GRB 090510 obtained by the Nordic Optical Telescope is offset by \( 0.7'' \) relative to the center of the host in the VLT/FORS2 image (Olofsson et al., 2009). This offset corresponds to a projected distance of 5.5 kpc at the redshift of GRB 090510.

#### Data analysis

We focused on Fermi (both GBM and LAT) and Swift/XRT data for the purposes of this analysis. The GBM signal is the most luminous in the NaI-n6 detector (\( 8 \rightarrow 900 \) keV, dropping the overflow high-energy channels and the cutting out the K-edge from \( \sim 30 \) to \( \sim 40 \) keV\(^7\)) and in the BGO-b1 detector (\( 260 \) keV \( \rightarrow 40 \) MeV, again dropping the overflow high-energy channels). We considered in addition LAT data in the \( 100 \) MeV \( \rightarrow 100 \) GeV

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\(^7\)The iodine K-edge at 33.14 keV induces a discontinuity in the response of the NaI detectors. Above the K-edge, an incident photon causes the release of an X-ray photon from the K-shell transitions.
5.3 GRB 090510: merging NSs coalescing into a Kerr-Newman BH

<table>
<thead>
<tr>
<th>Model</th>
<th>C-STAT/DOF</th>
<th>$E_{\text{peak}}$ (keV)</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$kT$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>221.46/237</td>
<td>2987 ± 343</td>
<td>-0.64 ± 0.05</td>
<td>-3.13 ± 0.42</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Comp</td>
<td>392.65/238</td>
<td>3020 ± 246</td>
<td>-0.64 ± 0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Comp + PL</td>
<td>209.26/236</td>
<td>2552 ± 233</td>
<td>-0.26 ± 0.14</td>
<td>-1.45 ± 0.07</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PL</td>
<td>492.83/239</td>
<td>-</td>
<td>-</td>
<td>-1.20 ± 0.02</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BB + PL</td>
<td>250.09/237</td>
<td>-</td>
<td>-</td>
<td>-1.38 ± 0.04</td>
<td>477.5 ± 24.9</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.5: Fitting parameters of the time interval $T_0 + 0.528$ s to $T_0 + 640$ s identified with the P-GRB, where $\alpha$ is the low-energy index of the Comp or Band component, $\beta$ is the high-energy index of the Band component, $E_{\text{peak}}$ is the peak energy of the Comp or Band component, $\gamma$ is the power law index, and $kT$ is the temperature of the blackbody component.

range. The data were retrieved from the Fermi Science Support Center\(^8\). We used standard software in our analysis: GBM time-tagged data, suitable in particular for short and highly structured events, were analyzed with the \textit{rmfit} package\(^9\); LAT data were analyzed with the Fermi Science tools\(^10\). \textit{Swift}/XRT data were retrieved from the UK Swift Data Centre at the University of Leicester\(^11\); they have been reduced and analyzed with XSPEC.

The time interval $T_0 + 0.528$ s to $T_0 + 1.024$ s (see Fig. 5.11), which will be taken in the following as the main GRB emission, is best fit by a Comptonized + power law model (using GBM time-tagged data binned in 16 ms intervals). With this spectral model, we obtain an isotropic energy $E_{\text{iso}} = (3.95 \pm 0.21) \times 10^{52}$ erg. The peak energy of the best-fit Band model of the time-integrated GBM data is $4.1 \pm 0.4$ MeV in the observer frame, or $7.89 \pm 0.76$ MeV in the rest-frame.

The first pulse ($T_0 + 0.528$ s to $T_0 + 0.640$ s), which will be identified with the P-GRB in the following, is best fitted in the $8$ keV – $40$ MeV range by a Comptonized + power law model, preferred over a power law (PL, $\Delta$C-STAT = 100), a blackbody plus PL (BB + PL, $\Delta$C-STAT = 41), or a Band model ($\Delta$C-STAT = 12). The fitting statistics are summarized in Table 5.5. The peak energy $E_{\text{peak}}$ of the Comptonized component is $2.6$ MeV and the total isotropic energy contained in this time interval is $\sim 1.77 \times 10^{52}$ erg, while the isotropic energy contained in the Comptonized part alone reaches $\sim 1.66 \times 10^{52}$ erg.

5.3.2 GRB 090510 as a family 2 short GRB

The reinterpretation of GRB 090510 as a family 2 short GRB is justified by several arguments that are based on the late X-ray emission, the $E_{\text{peak}}$ – $E_{\text{iso}}$ correlation, and the galactic environment. Theoretical results presented in the next subsection also strengthen this view.

Late X-ray emission

As explained in chapter 3, an important feature of energetic long GRBs is the existence of an overlapping and nesting behavior of the late X-ray emission – the Episode 3. If GRB 090510 were to be an IGC event as hypothesized in Muccino et al. (2013a), this characteristic behavior should be observed. However, its X-ray lightcurve has been well sampled by the \textit{Swift}/XRT. Fig. 5.12 shows a comparison between the X-ray lightcurve of

\(^{8}\)http://fermi.gsfc.nasa.gov/ssc/data/access/
\(^{9}\)http://fermi.gsfc.nasa.gov/ssc/data/analysis/rmfit/vc_rmfit_tutorial.pdf
\(^{10}\)http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone
\(^{11}\)http://www.swift.ac.uk/archive/index.php
Figure 5.11: Upper panel: GBM NaI-n6 lightcurve of GRB 090510. The hatched area marks the interval considered to compute $E_{\text{iso}}$, $T_0 + 0.528$ s to $T_0 + 1.024$ s. Lower panel: Comptonized + power law best fit of the corresponding spectrum. Figures reproduced from Enderli et al. (2015).
GRB 090510 in the rest-frame 0.3 – 10 keV range and that of the IGC prototype event GRB 090618. The late X-ray emission of GRB 090510 appears much weaker than that of IGC GRBs and does not follow the typical power law behavior as a function of time (with index $-1.7 \lesssim \alpha \lesssim -1.3$). This result is therefore inconsistent with the hypothesis of GRB 090510 being a long, energetic GRB disguised as a short one. Instead, the interpretation as a genuine short GRB is in full agreement with the theory and the data, as shown below.

$E_{\text{peak}} - E_{\text{iso}}$ correlation

Although the sample of short GRBs that benefit from redshift measurements is of modest size compared to that of long GRBs, it has been noted that a correlation similar to the Amati one exists for short GRBs (e.g. Zhang et al. 2012; Calderone et al. 2015). As can be seen in Fig. 5.13, this $E_{\text{peak}} - E_{\text{iso}}$ correlation lies above the Amati correlation – but almost parallel to it.

While Zhang et al. (2012) extended this analysis to the previously defined GRFs (or family 1 short GRBs), we have recently added four S-GRBs in this $E_{\text{peak}} - E_{\text{iso}}$ correlation. With the parameters $E_{\text{peak}} = 7.89 \pm 0.76$ MeV and $E_{\text{iso}} = (3.95 \pm 0.21) \times 10^{52}$ erg obtained in the previous sections, GRB 090510 falls right on the relation fulfilled by short GRBs (see Fig. 5.13). Note that the Amati correlation does not suffer from a significant number of outliers, which strengthens the point.

Offset from the host galaxy

Long GRBs are known to trace star formation, and they explode mainly in low-mass galaxies with high specific star-formation rates. Short GRBs, on the other hand, occur in a wider range of host galaxies, including old elliptical ones with little star formation. The median projected offset of short GRBs from the center of their hosts is about 5 kpc, four times larger than that of long GRBs (Bloom et al., 2002b). With a projected offset of 5.5 kpc, as detailed previously, GRB 090510 falls in the typical short GRB range.

As stated in Section 5.3.1, the host of GRB 090510 is a late-type galaxy with a low star-formation rate. In addition, the results of the fireshell analysis summarized in the next section also support the view that GRB 090510 is an offset event; its low average CBM density is indeed found to be similar to that of galactic halos, with $\langle n_{\text{CBM}} \rangle = 8.7 \times 10^{-6} \text{ cm}^{-3}$.

5.3.3 Interpretation

Several peculiar features are found in GRB 090510: its P-GRB spectrum is not purely thermal; a weak precursor emission is clearly seen; a high-energy emission is present – which never occurs in GRFs (family 1 short GRBs) but appears to be a general property of S-GRBs. We summarize in this subsection the analysis of these features as well as their interpretation.

Ruffini et al. (2015c) establish theoretical predictions concerning short GRBs that originate in a binary NS merger, with and without BH formation. We find that these predictions are fulfilled and that all the features of GRB 090510 can be explained by the scenario of a NS merger leading to the formation of a Kerr-Newman BH.
Figure 5.12: Rest-frame $0.3 - 10$ keV luminosity lightcurves of GRB 090510 (in orange) and GRB 090618 (in blue). Figure reproduced from Enderli et al. (2015).

Figure 5.13: $E_{\text{peak}} - E_{\text{iso}}$ correlation of all short GRBs with redshift. The black line marks the correlation for short GRBs, including the four S-GRBs with a theoretical redshift that we obtained. The correlation takes the form $\log E_{\text{peak}} = A + \gamma (\log E_{\text{iso}})$ where $A = -22.0 \pm 3.2$, $\gamma = 0.49 \pm 0.06$, and $E_{\text{peak}}$ and $E_{\text{iso}}$ are respectively given in keV and erg. The dotted and dashed lines represent respectively the $1\sigma$ and $3\sigma$ scatter of the correlation ($\sigma_{\text{sc}} = 0.17 \pm 0.04$ dex). Green boxes indicate short GRBs with a measured redshift; only lower limits are available for the two GRBs single out by an arrow. GRB 090510 is marked by the pink square. The other four symbols indicate GRBs with a theoretical redshift: the black diamond indicates GRB 081024B, the red inverted triangle GRB 140402A, the blue square GRB 140619B, and the purple triangle GRB 090227B. For comparison, the blue line marks the correlation for long GRBs as given in Calderone et al. (2015), $\log E_{\text{peak}} = A + \gamma (\log E_{\text{iso}} - B)$ where $A = 2.73$, $B = 53.21$, $\gamma = 0.57 \pm 0.06$. The dotted lines represent the $1\sigma$ scatter of the correlation ($\sigma_{\text{sc}} = 0.25$ dex). Figure reproduced from Enderli et al. (2015).
5.3 GRB 090510: merging NSs coalescing into a Kerr-Newman BH

The identification of the P-GRB is an important step of the fireshell analysis. Here, we identify the first main spike (from $T_0 + 0.528$ s to $T_0 + 0.644$ s, see Fig. 5.14) with the P-GRB. Indeed, since it marks the transparency of the fireshell, the P-GRB cannot occur after a significant fraction of the signal has been emitted. Furthermore, the GeV emission starts with a delay with respect to the main emission: it is detected only after the first main pulse (excepting two photons which are detected during the precursor emission). It is suggested in Ruffini et al. (2015c) that the GeV emission is produced by the newborn BH and starts only after the P-GRB is emitted, which is indeed the case here. The results of the analysis within the fireshell model (presented hereafter) also offer an a posteriori confirmation of this P-GRB identification.

The best-fit model of the P-GRB spectrum consists of a Comptonized + power law model. We note that a Comptonized component may be viewed as a convolution of black-bodies, as shown in Fig. 5.15.

The geometry of the fireshell is dictated by the geometry of the pair-creation region. It is in general assumed to be a spherically symmetric dyadosphere: such a configuration leads to a P-GRB spectrum described by a single thermal component, which is in general in good agreement with the spectral data. However, Cherubini et al. (2009) found that the region of pair-creation in a Kerr-Newman geometry becomes axially symmetric, thus effectively becoming a dyadotorus. Qualitatively, one expects a pure thermal spectrum from the dyadosphere configuration, while a convolution of thermal spectra of different temperatures is expected for a dyadotorus configuration.

In the case of GRB 090510, the P-GRB is best fitted by a convolution of thermal spectra.
Figure 5.15: Upper panel: The power law (dot-dashed line) and Comptonized (solid line) components of the time-integrated best fit of GRB 090510. A convolution of blackbodies (dashed red lines) produces the result plotted in the lower panel: a Comptonized component may be viewed as a convolution of thermal components. Figures reproduced from Enderli et al. (2015).
5.3 GRB 090510: merging NSs coalescing into a Kerr-Newman BH

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>$(5.54 \pm 0.70) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\gamma_{\text{tr}}$</td>
<td>$(1.04 \pm 0.07) \times 10^4$</td>
</tr>
<tr>
<td>$r_{\text{tr}}$</td>
<td>$(7.60 \pm 0.50) \times 10^{12}$ cm</td>
</tr>
<tr>
<td>$E_{e^+e^-}^{\text{tot}}$</td>
<td>$(3.95 \pm 0.21) \times 10^{52}$ erg</td>
</tr>
<tr>
<td>$kT_{\text{blue}}$</td>
<td>$(1.20 \pm 0.11) \times 10^3$ keV</td>
</tr>
<tr>
<td>$\langle n \rangle$</td>
<td>$(8.7 \pm 2.1) \times 10^{-6}$ part/cm$^3$</td>
</tr>
</tbody>
</table>

Table 5.6: Parameters derived from the fireshell analysis of GRB 090510: the baryon load $B$, the Lorentz factor at transparency $\gamma_{\text{tr}}$, the fireshell radius at transparency $r_{\text{tr}}$, the total energy of the electron-pair plasma $E_{e^+e^-}^{\text{tot}}$, the blue-shifted temperature of the fireshell at transparency $kT_{\text{blue}}$, and the CBM average density $\langle n \rangle$.

This provides the first evidence that the angular momentum can play a major role in the merging of two NS and that a dyadotorus is formed, as theoretically predicted in e.g. Cherubini et al. (2009). Previous identifications of pure thermal components in the P-GRB of other GRBs (e.g. Izzo et al. 2012a; Ruffini et al. 2015c) nevertheless evidence that the angular momentum of the BH formed by GRB 090510 must be exceptionally large in order to affect the P-GRB spectrum.

**Prompt emission**

In order to simulate the lightcurve and spectrum of the prompt emission of GRB 090510, we assume that the initial fireshell energy $E_{e^+e^-}^{\text{tot}}$ is equal to $E_{\text{iso}}$. Since the P-GRB spectrum is not purely thermal, we derive an effective blackbody temperature from the peak energy of the Comptonized component. We obtain a temperature $kT_{\text{obs}} = (633 \pm 62)$ keV.

As summarized in Fig. 2.7, the fireshell theory allows for the determination of all essential quantities of the model from the total pair plasma energy $E_{e^+e^-}^{\text{tot}}$ and from the ratio of the energy contained in the P-GRB to $E_{e^+e^-}^{\text{tot}}$. This ratio directly leads to the baryon load $B$, which in conjunction with $E_{e^+e^-}^{\text{tot}}$ and the relation between the predicted and observed temperatures gives the Lorentz factor at transparency, the temperature of the fireshell at transparency, and the radius at transparency.

Given $E_{\text{iso}} = 3.95 \times 10^{52}$ erg and $E_{\text{P-GRB}} = (42.1 \pm 3.8)\% E_{e^+e^-}^{\text{tot}}$, we deduce a baryon load $B = 5.54 \times 10^{-5}$, a Lorentz factor $\gamma = 1.04 \times 10^4$, a temperature at transparency $kT = 1.2$ MeV, and a radius at transparency $r_{\text{tr}} = 7.60 \times 10^{12}$ cm (cf. Table 5.6).

In order to determine the profile of the circumburst medium, a simulation of the prompt emission following the P-GRB has been performed. The simulation starts at the transparency of the fireshell with the parameters that we determined above. A trial-and-error procedure is undertaken, guided by the necessity to fit the lightcurve of GRB 090510. The results of this simulation (reproduction of the lightcurve and spectrum, profile of the circumburst medium) are shown in Fig. 5.16. The average circumburst density is found to be $\langle n_{\text{CBM}} \rangle = 8.7 \times 10^{-6}$ cm$^{-3}$. This low value, typical of galactic halo environments, is consistent with the large offset from the center of the host and further justifies the interpretation of GRB 090510 as a short GRB originating in a binary NS merger.
Figure 5.16: Results of the fireshell simulation of GRB 090510. Upper panel: fit of the prompt emission GBM NaI-n6 lightcurve. Middle panel: fit of the corresponding spectrum including NaI and BGO data. Lower panel: density profile of the CBM inferred from the simulation. Figures reproduced from Enderli et al. (2015).
Precursor emission

There is a weak precursor emission about 0.4 s before the P-GRB (or \(\sim 0.21\) s in the cosmological rest frame). Precursors are commonly seen in long GRBs: Lazzati (2005) found that \(\sim 20\%\) of them show evidence of an emission preceding the main emission by tens of seconds. Short GRBs are less frequently associated with precursors.

No significant emission from the GRB itself is expected prior to the P-GRB – since it marks the transparency of the fireshell – but the precursor may be explainable in the context of a binary neutron star merger by invoking the effects of the interaction between the two NSs just prior to merger. Indeed, it has been suggested that precursor emission in short GRBs may be caused by resonant fragmentation of the crusts (Tsang et al., 2012) or by the interaction of the NS magnetospheres (Hansen & Lyutikov, 2001).

The timescale (\(\sim 0.21\) s between the precursor and the P-GRB) is consistent with a pre-merger origin of the precursor emission. From its formation to its transparency, the fireshell undergoes a swift evolution. The thermalization of the pair plasma is achieved almost instantaneously (\(\sim 10^{-13}\) s, Aksenov et al. 2007); and the \(e^+e^-\) plasma of GRB 090510 reaches the ultra-relativistic regime (i.e. a Lorentz factor \(\gamma > 10\)) in a matter of \(4.2 \times 10^{-2}\) s, according to the numerical simulation. The radius of the fireshell at transparency, \(r_{tr} = 7.60 \times 10^{12}\) cm, corresponds to more than a hundred light-seconds; however relativistic motion in the direction of the observer squeezes the lightcurve by a factor \(\sim 2\gamma^2\), which makes the fireshell capable of traveling that distance under the observed timescale.

The spectral analysis of this precursor is limited by the low number of counts. Muccino et al. (2013b) interpreted the spectrum with a blackbody plus power law model. This leads to a blackbody temperature of \(34.2 \pm 7.5\) keV. The isotropic energy contained in the precursor amounts to \((2.28 \pm 0.39) \times 10^{51}\) erg.

High-energy emission

GRB 090510 is associated with a high-energy emission, consistently with all other observed S-GRBs, i.e. energetic events with \(E_{iso} \gtrsim 10^{52}\) erg. The only case of a S-GRB without GeV emission, namely GRB 090227B, has been explained by the fact that the source was outside the field of view of the LAT at the time of the GRB emission.

The GeV lightcurve of GRB 090510 is plotted in Fig. 5.17. Ruffini et al. (2015c) suggest and argue that the GeV emission is related to the presence of a black hole and its activity. This view is supported by the fact that the GeV emission is delayed with respect to the \(\gamma\) radiation: it starts only after the P-GRB is over.

The GeV emission of GRB 090510 is particularly intense, reaching \(E_{LAT} = (5.78 \pm 0.60) \times 10^{52}\) erg. Such a large value, one of the largest observed among S-GRBs, is consistent with the large angular momentum of the newborn BH.

Theoretical redshift

As explained in Section 5.2.3, the fireshell theory allows for the determination of a theoretical redshift. Since the redshift of GRB 090510 has been spectroscopically obtained, this opens the possibility to check the agreement between the theory and the observations. Following the method outlined in Section 5.2.3, we find a theoretical redshift \(z_{th} = 0.75 \pm 0.17\), which provides a satisfactory agreement with the measured value \(z = 0.903 \pm 0.003\).
5.3.4 Conclusions

GRB 090510 has been analyzed in the light of the recent progress achieved in the fireshell model and the resulting classification of GRBs. We show that GRB 090510 is a S-GRB (or family 2 GRB), and more specifically an event that originates in a binary NS merger leading to a Kerr-Newman BH:

- This analysis leads to a theoretical redshift $z = 0.75 \pm 0.17$ which is close to, and consistent with, the spectroscopically measured value $z = 0.903 \pm 0.003$.

- The GeV emission is conjectured to be related to black hole formation (Ruffini et al., 2015a) and to be a characteristic feature of family 2 GRBs (i.e. S-GRBs and BdHNe). In this interpretation, a delay between the onset of the GeV emission and the P-GRB is expected. GRB 090510 is indeed associated with a delayed GeV emission, which is incidentally one of the most intense ever observed in a S-GRB. This observation is consistent with the NS merger leading to a newborn BH endowed with a large angular momentum.

- The Kerr-Newman nature of the newborn BH is also justified by the P-GRB spectrum. It is indeed best-fitted by a Comptonized component, which we interpret as a convolution of thermal spectra that originates in a dyadotorus.

- The fireshell analysis leads to an average value of the CBM density $\langle n_{\text{CBM}} \rangle = 8.7 \times 10^{-6}$ cm$^{-3}$, which is typical of galactic halos environments where binary NS are expected to migrate due to large natal kicks.

- The late X-ray emission of GRB 090510 does not follow the characteristic patterns expected in binary-driven hypernovae events.

The results presented in this work take place in a larger framework that views both long and short GRBs as products of interactions of binary systems. In this framework the formation of a black hole, or the lack thereof, discriminates respectively between on the one side S-GRB and BdHN (alternatively termed long GRBs) events, and on the other side GRF and XRF events.
Concluding remarks

Taken all together, the works presented in this thesis lead to a self-consistent classification of GRBs in which the observational differences between long and short GRBs are justified by different progenitor systems. The influence of binarity is however equally important in both cases. These two categories, long and short, are further differentiated in two subcategories depending on the presence or the absence of black hole formation. Within the fireshell model, black hole formation is indeed a tremendous energy source and has the potential to significantly alter the phenomenology of a GRB.

In this chapter, we summarize the results presented in the previous chapters as well as the GRB classification that is derived from them, and we elaborate on future prospects for this model.
6.1 Summary

Gamma-ray bursts remain mysterious phenomena. In chapter 1, we gave a comprehensive review of their observational properties, followed by a description of the theoretical frameworks of the fireball and fireshell models in chapter 2.

In chapter 3, we established the foundations of the Induced Gravitational Collapse paradigm. This paradigm aims at explaining the GRB – SN connection in energetic long GRBs. Early hints for the presence of multiple episodes in the $\gamma$-ray emission were found in the analysis of GRB 090618, which was to become a prototypical IGC event, as well as in the analyses of GRB 101023 and GRB 110709B. The $\gamma$-ray emission of these three GRBs is clearly divided in two separate episodes. A time-resolved study of the first episodes highlights the presence of a blackbody component expanding at non-relativistic speeds. These thermal components are not found in the second episodes, which are more energetic than the first ones and are well described by a canonical GRB in the fireshell scenario. This suggests that the two episodes have a different physical origin.

Further analysis of the multi-wavelength data of these GRBs showed that their late X-ray emissions follow a regular behavior. After a time $t \approx 2 \times 10^4$ s in their rest-frame, the lightcurves of IGC events obey an overlapping behavior. In addition, the duration of the plateau phase of the late X-ray emission correlates with the total energy of the burst. This causes an additional nesting behavior of the late X-ray emission.

A fourth emission episode may be seen if the GRB occurs close enough to the Earth: all IGC events that benefit from favorable observing conditions have been associated to a supernova, visible in particular as a bump in the optical lightcurve 10 to 15 rest-frame days after trigger. Pisani et al. (2013) built a sample of GRBs that qualify as IGC events. Furthermore, an analysis of the X-ray and optical afterglows of a set of IGC events show that the absorption imprints of their host galaxies are consistent with those of the general long GRB population.

The picture that emerges from these considerations depicts an IGC event in terms of the interactions between a neutron star and an evolved stellar core undergoing a supernova explosion. The onset of the SN explosion and the hypercritical accretion of the ejecta onto the companion NS produce Episode 1. Episode 2 is a canonical GRB caused by the gravitational collapse of the NS to a BH, during which a fireshell is produced. Episode 3 may encompass emission coming from the SN shock breakout, from the SN ejecta, and from the newborn NS. Episode 4 is produced by the peak luminosity of the decay of the $^{56}\text{Ni}$ produced in the SN.

Most GRB – SN events occur in low energetic GRBs. It has been inferred that these systems originate in binary systems similar to those described above. However, in this case the companion NS does not accrete enough matter to collapse to a BH. As a result, no Episode 2 – the energetically most prominent part – is observed. Episodes 3 in low energetic GRBs are seen not to follow the characteristic behaviors of IGC events.

In chapter 4, we reported on the detailed analysis of three GRBs shown to follow the patterns characteristic of IGC events. GRB 130427A, a relatively nearby energetic event, is one of the most luminous GRBs observed to date. This allowed for a wealth of observations in all wavelength ranges to be carried out. In particular, its Episode 3 has been scrutinized in an energy range covering over 10 orders of magnitude. Its late X-ray emission is typical of IGC events. In addition, a thermal component evolving at low Lorentz factor $< 2$ is seen in the early X-ray afterglow spectrum which suggests that the X-ray emission is produced in a mildly relativistic regime. No evidence for substantial beaming is observed. The high-
energy emitter on the other hand has a Lorentz factor $10^{-40}$. Despite this difference, a similar temporal decay in both energy ranges is observed. Within the IGC framework, the X-ray component may be produced by the interaction of the GRB with the SN ejecta, and the high-energy component may be related to the newborn BH, the newborn NS, and the SN ejecta.

GRB 090423 is another remarkable event. It is the farthest GRB to date endowed with a spectroscopic redshift measurement$^1$. Given the distance ($z = 8.2$), we showed that an Episode 1 similar to the one of GRB 090618 could not have been detected with current instrumentation, nor could have been an Episode 4 detected. The analysis of Episode 2 nevertheless highlighted the close similarity with the prototypical GRB 090618; in fact, extrapolating a GRB 090618-like event at the redshift of GRB 090423 demonstrates how similar the two episodes are. The late X-ray emission has also been proven to follow the typical Episode 3 behavior.

GRB 970828 was one of the first GRBs to be associated to an afterglow. It occurred many years before \textit{Swift} and \textit{Fermi} were launched. In spite of the relative lack of high-quality data (which incidentally highlights the importance of instruments of the like of \textit{Swift} and \textit{Fermi} for GRB science), we have shown that GRB 970828 can be reinterpreted in the light of the progress made in the understanding of the IGC paradigm; we found that it is likely to be an IGC event. An Episode 1 including an evolving thermal component was identified, and the Episode 2 was successfully analyzed and fitted as a canonical GRB. Sparse observations of the X-ray afterglow indicate that it followed the typical overlapping behavior of Episodes 3. No counterpart supernova was observed, due to a large extinction at optical wavelengths and to the lack of optical observations when the expected signal would have been the most intense.

In chapter 5, we studied short GRBs. The phenomenological distinction between long and short GRBs is indeed well documented. The study of the environment of short GRBs (i.e. host galaxies, location within the host) in particular associates short GRBs with old stellar objects, thus favoring a compact object merger origin. We summarized the case of GRB 090227B, an energetic short GRB taken as a prototypical event of the class of energetic short GRBs. We then analyzed GRB 140619B, motivated in part by progress in neutron star theory. Taking into account in particular the global charge neutrality condition (as opposed to the local charge neutrality condition usually assumed), Belvedere et al. (2012) found a large critical mass $M_{\text{crit}} \approx 2.67 M_\odot$. A stiff equation of state is also favored by recent observations of galactic pulsars that find individual masses as large as $\sim 2 M_\odot$. The application of the fireshell model to GRB 140619B, which did not have a measured redshift, allows for its redshift to be estimated. At $z = 2.67$, this GRB delivered an isotropic-equivalent energy $E_{\text{iso}} \approx 6 \times 10^{52}$ erg. All the fireshell quantities were derived, which led in particular to estimate the average circumburst medium density at $\langle n \rangle \approx 4.7 \times 10^{-5}$ part cm$^{-3}$. We inferred from these characteristics a binary NS merger progenitor and estimated the energy emitted in the form of gravitational wave radiation up to the merger $E_{\text{GW}} = 7.42 \times 10^{52}$ erg. The signal-to-noise ratio in Advanced LIGO would then have been too low to obtain a positive detection. The GeV emission associated with GRB 140619B is also important as few short GRBs are observed to have a GeV emission. We interpreted it as a characteristic feature of energetic short GRBs, and conjectured it originates from the newborn black hole since the onset of the GeV occurs only at the end

$^1$GRB 090423 used to be the farthest object with a spectroscopic redshift measurement. A recent result however found a spectroscopic redshift $z = 8.68$ for the galaxy EGSY8p7 (Zitrin et al., 2015).
of the P-GRB. Finally, an estimation of the rate of short GRBs leading to BH formation was made; we found a rate $\rho_0 \approx 2.6 \times 10^{-4} \, \text{Gpc}^{-3} \text{yr}^{-1}$. This rate leads to an expected number of events at $z \geq 0.9$ of $N = 4^{+6}_{-3}$, consistent with the three events observed by Fermi so far.

We then extended the study of energetic short GRBs by analyzing GRB 090510. This GRB, previously analyzed in Muccino et al. (2013b), was first interpreted as a canonical long GRB exploding in an overdense circumburst medium, making it appear short. This model was later updated, when a better understanding of the IGC paradigm was reached. Instead, we showed that GRB 090510 can be reinterpreted as a binary NS merger leading to the formation of a (rotating) Kerr-Newman black hole. The signature spectrum of the P-GRB was particularly important in order to formulate this conclusion: while a spherically symmetric configuration of the pair-creation region (a dyadosphere) leading to a pure thermal signature is usually assumed, the P-GRB of GRB 090510 was best fitted by a convolution of thermal spectra originating in an axially symmetric configuration of the pair-creation region (a dyadotorus). The analysis of GRB 090510 within the fireshell model led in particular to compute a theoretical redshift in good agreement with its spectroscopic redshift. The presence of a GeV emission, conjectured to originate from the newborn black hole, is another remarkable feature of this GRB.

### 6.2 General conclusions

The works summarized in the previous section helped to build a new taxonomy of GRBs in which all GRBs originate from interactions of binary systems. The formation of a black hole is a core concept in this framework; it discriminates between energetic and less energetic events. The dividing line lies in the vicinity of $E_{\text{iso}} = 10^{52}$ erg. Fig. 6.1 presents this taxonomy, including the observational characteristics associated with each of the four families, which are:

- **Family 1 short GRBs**, or gamma-ray flashes (GRFs): short events with $E_{\text{iso}} \lesssim 10^{52}$ erg, which are associated to a long-lived X-ray emission that does not follow a standard pattern. These events are produced by binary neutron star merging to a single massive neutron star (or alternatively by white dwarf-neutron star mergers).

- **Family 2 short GRBs**, or simply short GRBs (S-GRBs): short events with $E_{\text{iso}} \gtrsim 10^{52}$ erg, which are associated to GeV emission. These events are produced by binary neutron star mergers leading to black hole formation.

- **Family 1 long GRBs**, or X-ray flashes (XRFs): long events with $E_{\text{iso}} \lesssim 10^{52}$ erg, which are associated to a long-lived X-ray emission that does not follow a standard pattern. These events are produced by the interactions of a neutron star in binary orbit with a stellar core undergoing a supernova. The neutron star does not accrete enough matter to collapse to a black hole.

- **Family 2 long GRBs**, or binary-driven hypernovae (BdHNe), or simply long GRBs (L-GRBs): long events with $E_{\text{iso}} \gtrsim 10^{52}$ erg, which are associated to GeV emission and whose late X-ray emission follows a standard behavior. These events are produced by the interactions of a neutron star in binary orbit with a stellar core undergoing a supernova. The neutron star rapidly accretes enough matter to collapse to a black hole.
6.2 General conclusions

All GRBs are composite and originate from binary systems

<table>
<thead>
<tr>
<th>Binary progenitor</th>
<th>Short GRBs</th>
<th>Long GRBs</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN</td>
<td>NS–NS or WD–NS</td>
<td>CO core–NS</td>
</tr>
<tr>
<td>BH</td>
<td>never</td>
<td>always</td>
</tr>
<tr>
<td>Hard spectrum</td>
<td>E\textsubscript{\gamma} &lt; 10\textsuperscript{52} erg</td>
<td>E\textsubscript{\gamma} &gt; 10\textsuperscript{52} erg</td>
</tr>
<tr>
<td>X-ray Afterglow</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>GeV emission</td>
<td>(without scaling)</td>
<td>(without scaling)</td>
</tr>
<tr>
<td>Outcome</td>
<td>massive NS</td>
<td>black hole</td>
</tr>
<tr>
<td>Rates (Gpc\textsuperscript{-3}y\textsuperscript{-1})</td>
<td>1–10</td>
<td>(1.2–6.5)x10\textsuperscript{-4}</td>
</tr>
</tbody>
</table>

Figure 6.1: Summary of the GRB taxonomy derived from the works presented in this thesis.

Space-time diagrams that summarize the sequence of events happening in binary-driven hypernovae, X-ray flashes, S-GRBs, and gamma-ray flashes, are depicted respectively in Figs. 6.2, 6.3, 6.4, 6.5.

Future refinements of the model presented in this thesis will rely crucially on the state of GRB instrumentation. Currently, Swift and Fermi are both working flawlessly and keep recording high-quality data. Looking ahead, the SVOM mission (Space-based Variable Objects Monitor) is due to be launched in 2021. This multi-instrument satellite-born mission was designed to put emphasis on high-redshift (z > 6) GRBs (likely to be BdHNe events, more luminous and thus more easily detectable than other GRB families) and on faint, soft nearby events. In addition, the detection or non-detection of gravitational wave emission by Advanced LIGO and Advanced Virgo will also constrain models and rates of binary compact object mergers.
Figure 6.2: Space-time diagram illustrating the sequence of events during an IGC GRB. The stellar core (green line) undergoes a SN explosion at point A, forming a new neutron star ($\nu$NS, red line). The SN ejecta starts to interact with the companion NS (blue line) at point B, initiating Episode 1. Emission from Episode 1 reaches the $\nu$NS at point C. Accretion of matter leads the companion NS to collapse to a BH (black line) at point D: a canonical fireshell GRB is emitted and produces an Episode 2. Point E marks the transition from Episode 2 to Episode 3. Point F highlights the optical peak luminosity of the SN, referred to as Episode 4.
6.2 General conclusions

Figure 6.3: Space-time diagram illustrating the sequence of events in a set-up similar to the IGC one, but without the collapse of the companion neutron star. The stellar core (green line) undergoes a SN explosion at point A, forming a new neutron star (νNS, red line). The SN ejecta starts to interact with the companion NS (blue line) at point B, initiating Episode 1. Emission from Episode 1 reaches the νNS at point C. Point D highlights the optical peak luminosity of the SN, referred to as Episode 4.
Figure 6.4: Space-time diagram of a binary neutron star merger leading to black hole formation (“family 2 short GRB” or S-GRB). The binary orbit gradually shrinks due to energy loss through gravitational waves emission (yellow-brown). At point A, the merger occurs: the fireshell (in red) is created and starts its expansion. It reaches transparency at point B, emitting the P-GRB (light purple). The prompt emission (deep purple) then follows. The dashed lines represent the GeV emission (delayed relative to the start of the GRB) originating in the black hole surroundings.
Figure 6.5: Space-time diagram of a binary neutron star merger leading to a massive neutron star ("family 1 short GRB" or gamma-ray flash). The binary orbit gradually shrinks due to energy loss through gravitational wave emission (yellow-brown). At point point A, the merger occurs; however, the resulting object is not massive enough to go beyond the NS critical mass. No collapse to a black hole occurs. A short X-ray emission lasting less than 2 s is produced (deep blue), before a late soft X-ray emission takes over (light blue). No GeV emission is observed.
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