INTERNATIONAL RELATIVISTIC ASTROPHYSICS Ph.D.

Testing a Unified Model for Short and Long Gamma-Ray Bursts and their Connection with Supernovae

Thesis Advisor
Dr. Carlo Luciano Bianco

Ph.D. Student
Dott. Maria Grazia Bernardini

Academic Year 2005–2006
Contents

Introduction 7

1 Gamma-Ray Bursts: Overview 15
  1.1 What are Gamma-Ray Bursts (GRBs)? . . . . . . . . . . . . . 15
    1.1.1 The history of GRBs . . . . . . . . . . . . . . . . . . . . . 15
    1.1.2 Present and future . . . . . . . . . . . . . . . . . . . . . . 16
  1.2 Observational properties . . . . . . . . . . . . . . . . . . . . . 18
  1.3 The “fireball” model . . . . . . . . . . . . . . . . . . . . . . . . 19
    1.3.1 Energy conversion . . . . . . . . . . . . . . . . . . . . . . . 23
    1.3.2 The afterglow . . . . . . . . . . . . . . . . . . . . . . . . . 24
    1.3.3 Jets and collimation . . . . . . . . . . . . . . . . . . . . . . 25
  1.4 Models for GRB progenitors . . . . . . . . . . . . . . . . . . . . 27

2 A Model for GRBs 31
  2.1 The $e^\pm$ creation. . . . . . . . . . . . . . . . . . . . . . . . . 32
  2.2 The plasma expansion . . . . . . . . . . . . . . . . . . . . . . . 33
    2.2.1 The equations of the theory - I . . . . . . . . . . . . . . . 33
    2.2.2 The numerical integration . . . . . . . . . . . . . . . . . . 34
    2.2.3 The equations of the theory - II . . . . . . . . . . . . . . 35
    2.2.4 The expansion of the “fireshell” . . . . . . . . . . . . . 37
    2.2.5 The approach to the transparency . . . . . . . . . . . . . 40
  2.3 The description of the afterglow . . . . . . . . . . . . . . . . . . 42
    2.3.1 The arrival time . . . . . . . . . . . . . . . . . . . . . . . . 48
    2.3.2 The EQuiTemporal Surfaces (EQTSs) . . . . . . . . . . . . 51
## CONTENTS

### 3 GRB Light Curves and Spectra

3.1 Observational properties of GRB light curves .......................... 57  
  3.1.1 The prompt emission .............................................. 57  
  3.1.2 The afterglow ...................................................... 63  
3.2 GRB spectra ....................................................................... 71  
3.3 GRB050315: the “canonical” light curve ................................. 75  
  3.3.1 The fit of the observations ........................................... 77  
  3.3.2 Conclusions on GRB050315 ........................................... 80  
3.4 GRB031203 ........................................................................ 81  
  3.4.1 The fit of the observations ........................................... 81  
  3.4.2 The GRB031203 instantaneous spectrum ......................... 83  
  3.4.3 The GRB031203 time-integrated spectrum and the comparison with the observed data ................................. 86  
  3.4.4 Conclusions on GRB031203 ........................................... 88  

### 4 Short vs Long GRBs

4.1 GRB970228: an hybrid case between long and short GRBs ....... 98  
  4.1.1 The GRB970228 prompt emission .................................. 100  
  4.1.2 Discussion and conclusions ........................................... 101  

### 5 GRB/SN Connection

5.1 Theoretical inferences on the GRBs associated to supernovae. 110  
5.2 GRB980425/SN1998bw/URCA1 ........................................... 114  
  5.2.1 The fit of the observations ........................................... 115  
  5.2.2 The identification of URCA1 ........................................ 118  
5.3 GRB030329/SN2003dh/URCA2 ........................................... 120  
  5.3.1 The prompt emission .................................................. 120  
  5.3.2 The X-ray afterglow emission ....................................... 121  
  5.3.3 The identification of URCA2 ........................................ 124  
5.4 GRB031203/SN2003lw/URCA3 ........................................... 124  
5.5 GRB060218/SN2006aj/URCA4 ........................................... 125  
  5.5.1 The prompt and the afterglow emission ............................ 126
5.5.2 Searching for URCA4 ........................................... 129
5.6 Conclusions on our analysis of GRBs associated to SNe .... 131

Conclusions ................................................................. 135

Attachments ................................................................. 139
Attachment 1 ................................................................. 141
Attachment 2 ................................................................. 147
Attachment 3 ................................................................. 155
Attachment 4 ................................................................. 161
Attachment 5 ................................................................. 171
Attachment 6 ................................................................. 259
Attachment 7 ................................................................. 265
Attachment 8 ................................................................. 271
Attachment 9 ................................................................. 277
Attachment 10 ............................................................... 283
Attachment 11 ............................................................... 339
Attachment 12 ............................................................... 347
Attachment 13 ............................................................... 353
Attachment 14 ............................................................... 363

Bibliography ................................................................. 373
Introduction

Gamma-Ray Bursts (GRBs), short and intense explosions of high energy gamma-rays, are the most intriguing phenomenon in modern astrophysics. It is difficult to trace a “typical” GRB, nevertheless it is possible to establish some observational features to characterize them. The first GRB peculiarity is their enormous observed fluence, between $10^{-7}$ and $10^{-5}$ erg/cm$^2$. The measured redshifts indicate that the total isotropic energy emitted is $\sim 10^{51}$–$10^{54}$ erg, so GRBs are the most energetic events of the whole Universe (Piran, 1999). Their temporal evolution is another peculiar feature. Usually we observe a prompt high-energy emission, characterized by a great variety of temporal profiles. This prompt emission is often followed by a long lasting multiwavelength emission called afterglow, which is characterized by a less complex behavior than the prompt one. It is possible to recognize a “canonical” afterglow behavior (Nousek et al., 2006), where three power-law segments succeed, although in several cases the X-ray afterglow shows a single power-law decay (Chincarini et al., 2005). Sometimes emission in other wavelengths (optical and radio) is detected together with the X-ray one.

Recently the “Fireball” model (Goodman, 1986; Paczyński, 1986) has been addressed as a possible “standard” theory for GRBs. According to this model (section 1.3), GRBs originate from an accretion disk derived from the collapse of a massive star (Collapsar Woosley, 1993; Paczyński, 1998; MacFadyen, Woosley & Heger, 1999) or from the merging of binary systems (NS-NS binaries, Eichler et al., 1989; Narayan, Paczynski & Piran, 1992; NS-BH binaries, Paczyński, 1991; WD-BH binaries, Fryer et al., 1999). The large energy
Introduction

released into a compact region leads to an opaque photon-lepton “fireball” (a plasma whose initial energy is significantly greater than its rest mass), eventually loaded with baryonic matter (Piran, 1999). Such fireball relativistically expands and converts its energy in radiation via collisionless shocks (Piran, 1999). It is commonly believed that the prompt emission is produced via “internal shocks” (Rees & Mészáros, 1994) that arise due to shocks within the flow when fast moving particles catch up with slower ones, while the afterglow emission is produced via “external shocks” (Rees & Mészáros, 1992) which are due to the interaction of the flow with the external medium. The relativistic ejecta are assumed to be collimated within a jet with an half-opening angle $\theta$. In this case the energy involved is smaller than the isotropic energy ($E \sim \theta E_{iso}$) and the rate is higher ($N \sim \theta^{-1} N_{iso}$) (Piran, 2004).

Ruffini and collaborators proposed a different model to explain the GRB phenomenon (chapter 2, Ruffini et al., 2001a,b, 2003, 2005b; Bianco & Ruffini, 2004, 2005a,b). Their idea is that the enormous energy released in a GRB originates from electromagnetic energy extracted from a Reissner-Nordstøm black hole (Christodoulou & Ruffini, 1971): when the black hole electric field exceeds the critical value a vacuum polarization process (Heisenberg & Euler, 1935; Schwinger, 1951) occurs and $e^\pm$ pairs form (Damour & Ruffini, 1975). Such plasma self-accelerate outwards reaching an ultrarelativistic velocity. Then, it engulfs the baryons left over by the gravitational collapse, forming a $e^\pm$–photons–baryons plasma that continue its expansion until it reaches the transparency. At this stage all the pairs annihilate and a flash of photons is emitted, the Proper Gamma-Ray Burst (P-GRB), while the remaining accelerated baryonic matter converts its kinetic energy into radiation via inelastic collisions with the InterStellar Medium (ISM). This emission shows a raising phase, a maximum and a decaying phase, which correspond respectively to the prompt (the peak of the emission) and to the afterglow (the late decaying phase). We often address both these phases with the name “afterglow” in order to emphasize the fact that they are produced by the same mechanism (Ruffini et al., 2001b). The behavior of the light curve (chapter 3) depends
on the ISM structure, ruled in our model by two parameters: the average effective particle number density $\langle n_{ISM} \rangle$ and the fraction of effective emitting area of the shell $\langle R \rangle$ (Ruffini et al., 2004b, 2005a). During the prompt phase, when the Lorenz gamma factor $\gamma$ of the shell is high, even small inhomogeneities in the ISM produce a modulation in the emitted flux (Ruffini et al., 2002). During the afterglow, instead, $\gamma$ decreases and the resulting light curve is smoother.

The emitted radiation in the comoving frame of the expanding shell is assumed to be thermal (chapter 3, Ruffini et al., 2004b), although the observed spectrum is clearly non-thermal. It has been shown (Ruffini et al., 2004b) that each single instantaneous spectrum is the result of an integration of hundreds of thermal spectra over the corresponding “EQuiTemporal Surface” (EQTS, Bianco & Ruffini, 2004, 2005a), namely the locus of source points of the signals arriving at the observer at the same time. This calculation produces a non-thermal instantaneous spectrum in the observer frame.

Surely, the basic novelty of this model is to analyze the GRB phenomenon as a whole, starting from the identification of the progenitor and of the mechanism leading to the creation of the initial $e^\pm$ plasma, and following the evolution of the system until the late phases of the GRB emission. It means that this model does not start from a phenomenological study of the GRBs to infer the details of their source, on the contrary it assumes a well defined origin for GRBs and studies the underlying physics before interpreting the observational data. Moreover, in this model the equations of motion of the system are integrated exactly and in a self-consistent way, in order to obtain its complete evolution once we fix the initial conditions at the moment of the formation of the plasma, namely the total energy $E_{c^\pm}^{\text{tot}}$ stored inside the plasma and its baryon loading $B$ (Ruffini et al., 1999, 2000).

Once we have a complete theory it is necessary to test its predictions in order to check if the physical assumptions that lies at its basis are acceptable, and most of all if the theory really reproduces all the features of the phenomenon under investigation. The aim of this work is to compare the
Introduction

Theoretical results obtained within our model with the main GRBs’ observational properties in order to validate it.

• **GRB light curves and spectra** - We analyzed many GRB light curves (GRB050315 and GRB031203 in chapter 3; GRB970228 in chapter 4; GRB980425, GRB030329 and GRB060218 in chapter 5) showing that it is possible to obtain all the above mentioned GRB’s time variability during the prompt phase. We could reproduce the temporal behavior of the afterglow as well, even for those cases (GRB050315, GRB060218) in which such an emission has been observed in great detail. In our theory the afterglow light curves show a “natural curvature” due to the hard-to-soft spectral evolution. Therefore there is no need to introduce any jet in order to explain the deviation of the late afterglow light curve from the simple power-law behavior. Moreover we analyzed the instantaneous spectra which confirmed their non-thermal shape. We found that the resulting time-integrated spectrum shows a power-law behavior in perfect agreement with the observed one. In particular this has been shown for GRB031203 (see section 3.4).

• **Short vs long GRBs** - The possible existence of two “classes” of GRBs when they are classified on the basis of their duration is naturally explained within our model (chapter 4). The identification of long GRBs with the peak of the afterglow emission leads naturally to the idea that short GRBs are simply P-GRBs without a subsequent afterglow. The different properties (energetic, hardness ratio) of these two classes are explained by the different value of the baryon loading.

The recent discovery of short GRBs with an associated X-ray afterglow represents the evidence for an intermediate situation in which the P-GRB emission is dominant but still there is a weak afterglow emission. The analysis of GRB970228 lead us to the identification of another different situation: we show that in this case the afterglow should be dominant with respect to the P-GRB but due to the low density of the...
surrounding ISM it results less intense but longer. That is why it can be considered as an example of an “hybrid” situation between short and long GRBs.

• **GRB/SN connection (chapter 5)** - It has been found that at least in four cases (GRB980425, GRB030329, GRB031203, GRB060218) long GRBs are temporally and spatially coincident with “Hypernovae” (respectively SN1998bw, SN2003dh, SN2003lw, SN2006aj). Our analysis of all these four GRBs reveals that all their properties can be interpreted within our model, showing some common features in the parameters of these source that can be useful to understand the nature of this association. Moreover we single out in the GRB afterglow an X-ray component whose behavior appears to be similar in all cases. We give reasons to believe that such X-ray emission is possibly related to the supernova event instead of the GRB.

From this work it emerges the possibility to explain most of the GRB observational features in a self-consistent way, drawing a complete picture in which all the different GRB properties correspond only to different values for the fundamental parameters and not to different physical processes.

The detailed analysis of the topics mentioned above, which is discussed in the present thesis, led to the publication of the following accompanying papers:


**Attachment 2** Remo Ruffini, Maria Grazia Bernardini, Carlo Luciano Bianco, Pascal Chardonnet, Federico Fraschetti, Roberto Guida, She-Sheng Xue, “GRB 050315: a step in the proof of the overall GRB structure”, in the
Introduction


Attachment 7  Maria Grazia Bernardini, Carlo Luciano Bianco, Pascal Chardonnet, Federico Fraschetti, Remo Ruffini, She-Sheng Xue, “A New As-


Attachment 12  Remo Ruffini, Maria Grazia Bernardini, Carlo Luciano Bianco, Pascal Chardonnet, Alessandra Corsi, Federico Fraschetti, She-Sheng
Introduction


Chapter 1

Gamma-Ray Bursts: Overview

1.1 What are Gamma-Ray Bursts (GRBs)?

1.1.1 The history of GRBs

*Gamma-Ray Bursts* (GRBs), bright gamma-ray explosions of cosmic origin, were discovered on the ’60s by the *Vela* satellites, an US Army project whose aim was to verify the absence of nuclear tests in the atmosphere or on the Moon. For this purpose they were equipped with X and gamma-ray detectors. The announcement of this discovery was made in 1973 by Klebesadel, Strong and Olsen (Klebesadel, Strong & Olsen, 1973), who reported the detection in 3 years of activity of the two satellites *Vela 5* and *Vela 6*.

Since then, several missions were planned to study GRBs in order to identify their origin and to give order to the grat number of theoretical model born to explain this new, intriguing phenomenon. In fact for a certain period “there were more theoretical models than events observed” (Piran, 1999). Among all, at the beginning of the ’80s the most shared interpretation of GRBs was that they were produced by neutron stars in our galaxy.

The first important step toward the comprehension of this phenomenon was made by the NASA *Burst And Transient Source Experiment* (*BATSE*) on board the *Compton Gamma-Ray Observer* (CGRO, 1991-2000). The main
characteristic of this experiment was to determine with a great accuracy the location of the sources detected. The results were unexpected: BATSE observed, on average, one event per day, and it provided a first hint for the cosmological origin of GRBs. In fact all the events observed by BATSE were distributed isotropically in the sky. This fact was at that time erroneously attributed to the fact that GRBs were a local phenomenon.

The final proof for the cosmological origin of GRBs was given by the italo-dutch satellite BeppoSAX\(^1\) (1997-2002). This satellite was equipped with a gamma-ray detector (Gamma-Ray Burst Monitor; GRBM), together with X-ray Wide Field Cameras (WFCs) and Narrow Field Instruments (NFIs). On February 28, 1997 the WFCs detected with great accuracy the position of a GRB that the NFIs could repoint the same position 8 hours after the burst. What was observed then was a long-lasting X-ray emission from the GRB (Costa et al., 1997). The discovery of an X-ray afterglow associated with the GRB allowed to observe the GRB position with optical telescopes in order to measure the redshift. This confirmed the cosmological origin of GRBs.

1.1.2 Present and future

Currently several missions are devoted to the study of GRBs in order to clarify their nature:

**Swift**\(^1\) (2004) - It is an innovative mission designed specifically for GRB science. Swift’s instruments, the Burst Alert Telescope (BAT), the X-Ray Telescope (XRT) and the Ultra-Violet/Optical Telescope (UVOT), work together to observe GRBs in all the gamma, X and optical bands. When a GRB occurs, the BAT is the first of Swift’s instruments to detect it. Within about 10 seconds of the burst trigger, the BAT produces a burst localization which

---

\(^1\)Beppo in honor of Giuseppe Occhialini, SAX means “Satellite per l’ Astronomia X” (X-ray astronomy satellite)  
\(^1\)http://swift.sonoma.edu/about_swift/
1.1. What are Gamma-Ray Bursts (GRBs)?

is transmitted to ground observers. In addition, the BAT's position is fed to
the spacecraft so a slew can be performed, bringing the GRB into the XRT
and UVOT's field-of-view. In this way Swift provides a rapid localization of
GRBs and a rapid follow-up of the afterglows in different wavelengths.

**INTEGRAL**\(^{\ddagger}\) (2002) - The *International Gamma-Ray Astrophysics Lab-
oratory* (INTEGRAL) can produce a complete map of the sky in the soft
gamma-ray band and it is capable of performing high spectral and spatial
observations in gamma-rays. The INTEGRAL observatory is equipped with
two gamma-ray instruments: a spectrometer (SPI) and an Imager (IBIS).
The observatory is also equipped with X-ray and optical detectors (JEM-X
and OMC respectively) to provide simultaneous observations in these wave-
lengths.

**HETE-2**\(^{§}\) (2000) - HETE-2 is designed to detect and localize GRBs. The
suite of instruments on board (FREGATE - wide-field gamma-ray spectrom-
eters; WXM - wide-field X-ray monitor; SXC - soft X-ray cameras) allows si-
multaneous observations in soft and medium X-ray and gamma-ray energies.
HETE-2 compute the localization of the GRB and transmit the coordinates
as soon as they are calculated. These coordinates are quickly distributed
to ground-based observers to allow detailed studies of the initial phases of
GRBs.

**XMM-Newton**\(^{¶}\) (1999) - The *X-ray Multi-Mirror* mission (XMM-New-
ton) carries high throughput X-ray telescopes with an unprecedent effective
area. The large collecting area and ability to make long uninterrupted expo-
sures provide highly sensitive observations.

\(^{\ast}\)http://heasarc.gsfc.nasa.gov/docs/
\(^{\ddagger}\)http://sci.esa.int/scince-e/www/object/index/
\(^{§}\)http://space.mit.edu/HETE/
\(^{¶}\)http://sci.esa.int/scince-e/www/object/index/
1. Gamma-Ray Bursts: Overview

*Chandra* (1999) - The *Advanced X-ray Astrophysics Facility* (AXAF), renamed “Chandra” in honor of Chandrasekhar, is one of the most sophisticated X-ray observatory. The combination of high resolution, large collecting area and sensitivity to higher energy X-rays make possible for *Chandra* to study extremely faint sources.

*Konus* (1994) - The *Konus* experiment, on board of the *Wind* mission, provides omnidirectional and continuous coverage of cosmic gamma-ray transients. It provides event time profiles in 3 energy ranges, from 10 to 770 keV, with 64 millisecond time resolution. In addition, 2 millisecond resolution is provided during high intensity portions of events.

1.2 Observational properties

GRBs are short and intense explosions of high energy gamma-rays. It is difficult to trace a “typical” GRB, nevertheless it is possible to establish some observational parameters to characterize them.

The first GRB peculiarity is their enormous observed fluence, between $10^{-7}$ and $10^{-5}$ erg/cm$^2$. The possibility to measure the redshift for several GRBs revealed that the total isotropic energy emitted in such events is $\sim 10^{51} - 10^{54}$ erg, so GRBs result to be the most energetic events of the whole Universe (Piran, 1999).

Usually we observe a *prompt* high-energy emission, followed by a long lasting multiwavelength emission called *afterglow*.

Most of the energy during the prompt phase is emitted in gamma-rays although there are some events, named X-Ray Flashes (XRFs, Heise et al., 2001), in which the luminosity in the hard X-rays exceeds the gamma-rays’ one. The gamma-ray observed spectrum appears as non-thermal, well fitted by a phenomenological broken power-law (Band et al., 1993, see section 3.2 for further details) which is not predicted by a specific theoretical model but

∥http://chandra.harvard.edu/about/axaf_mission.html
1.3. The “fireball” model

The GRB non-thermal observed spectrum indicates that the sources must be optically thin but if we estimate the average opacity of the high energy

\[ T_{50} \] is the time between the 25\% and the 75\% of the GRB emission.

is in perfect agreement with observations. The gamma-ray duration ranges from \( 10^{-3} \) to \( 10^{3} \). If we look at the \( T_{50} \) distribution (see Fig. 1.1) for BATSE bursts we can distinguish two main “classes” (Kouveliotou et al., 1993): short bursts and long bursts. The prompt emission light curves are characterized by a great variety of temporal profiles (see e.g. Fig. 1.2): they range from the most simple single-peaked structures to the most complex one, with a time variability up to \( \sim 1 \text{ ms} \) (Piran, 2004).

The afterglow shows a less complex behavior than the prompt one, softening from x-rays to optical to radio. It is possible to recognize a “canonical” behavior (Nousek et al., 2006), where three power-law segments succeed, although in several cases the afterglow shows a single power-law decay (Chincarini et al., 2005).

Figure 1.1: Histogram of the duration of the GRBs observed by BATSE (Paciesas et al., 1999).

![Figure 1.1: Histogram of the duration of the GRBs observed by BATSE (Paciesas et al., 1999).](image_url)
1. Gamma-Ray Bursts: Overview

Figure 1.2: Samples of prompt emission light curves observed by Swift.
gamma-ray to pair production we find a very large optical depth (Piran, 2004). This “compactness problem” (Ruderman, 1975) has been bypassed assuming that the emitting matter moves relativistically toward the observer (Piran, 1999). In this case, in fact, the optical depth is lowered by a factor $\gamma^{(4+2\alpha)}$, where $\gamma$ is the Lorentz factor of the emitting source and $\alpha$ is the high energy spectral index, so when $\gamma \sim 10^2$ this problem is solved.

The simplest way to obtain a relativistic energy flow is in the form of kinetic energy of relativistic particles. A variant that has been suggested is based on the possibility that a fraction of the kinetic energy is carried by Poynting flux (Thompson, 1994; Usov, 1994; Usov & Smolsky, 1996; Mészáros & Rees, 1997c; Katz, 1997), although in all models the power must be converted to kinetic energy somewhere (Piran, 1999).

A model proposed to accelerate particle to relativistic velocities is the “fireball” model (Goodman, 1986; Paczyński, 1986), which currently is the most accepted model for GRBs. The release of a large quantity of gamma-ray photons into a compact region can lead to an opaque photon-lepton “fireball” through the production of $e^\pm$ pairs. The term “fireball” refers here to an opaque plasma whose initial energy is significantly greater than its rest mass (Piran, 1999). Shemi & Piran (1990) and Paczyński (1990) considered the effect of a baryonic load, showing that the ultimate outcome will be the transfer of all the energy of the fireball to the kinetic energy of the baryons.

Consider, first, a pure radiation fireball. The photons with energy $E_1$ could interact with lower energy photons (with energy $E_2$) and produce electron-positron pairs via $\gamma\gamma \rightarrow e^+e^-$ if $\sqrt{E_1E_2} > m_e c^2$. Because of the opacity due to pairs, the radiation cannot escape. The pairs-radiation plasma behaves like a perfect fluid described by the stress-energy tensor $T^{\mu \nu}$ with pressure $p$, energy density $\epsilon$ and equation of state $p = \epsilon/3$. In addition to radiation and $e^\pm$ pairs, astrophysical fireballs may also include some baryonic matter which may be injected with the original radiation or may be present in an atmosphere surrounding the initial explosion (Piran, 1999). These baryons can influence the fireball evolution in two ways. The electrons associated with
1. Gamma-Ray Bursts: Overview

this matter increase the opacity, delaying the escape of radiation. Moreover, the baryons are accelerated with the rest of the fireball and convert part of the radiation energy into bulk kinetic energy.

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

\[(\rho_B U^\mu)_{,\mu} = 0\]  \hspace{1cm} (1.1)
\[(T^{\mu\nu})_{,\nu} = 0,\]  \hspace{1cm} (1.2)

where \(\rho_B\) is the baryon mass density.

The expanding fireball has two basic phases: a radiation dominated phase and a matter dominated phase (Piran, 1999). During the radiation dominated phase \((\gamma \ll (\epsilon_0/\rho_{B0})\gamma_0)\) the conservation equations reduce in the first order in \(\gamma^{-2}\) to these simple scaling laws (Piran, 1999):

\[\gamma \propto r, \hspace{1cm} \rho_B \propto r^{-3}, \hspace{1cm} \epsilon \propto r^{-4}.\]  \hspace{1cm} (1.3)

The matter dominated phase, under the same approximation, is characterized by (Piran, 1999):

\[\gamma \rightarrow \text{const}, \hspace{1cm} \rho_B \propto r^{-2}, \hspace{1cm} \epsilon \propto r^{-8/3}.\]  \hspace{1cm} (1.4)

During this stage, since \(\epsilon \ll \rho_B\), the radiation has no important dynamical effect on the motion and produces no significant radial acceleration. Therefore, \(\gamma\) remains constant on streamlines and the fluid coasts with a constant asymptotic radial velocity. Of course, since each shell moves with a velocity that is slightly less than \(c\) and that is different from one shell to the next, the frozen pulse approximation must ultimately break down at some large radius.

At some point during the expansion, the fireball will become optically thin. From this stage on the radiation and the baryons no longer move with the same velocity and the radiation pressure vanishes. Any remaining radiation will escape freely now and the baryon shells will coast with their own individual velocities.
1.3 The “fireball” model

1.3.1 Energy conversion

Within the standard fireball model the energy transport is in the form of the kinetic energy of a shell of relativistic particles with a width $\Delta$. The kinetic energy is converted to energy of relativistic particles via shocks (Piran, 1999). These particles then release this energy and produce the observed radiation. There are two modes of energy conversion (Piran, 1999): external shocks (Rees & Mészáros, 1992), which are due to interaction with an external medium like the ISM, or internal shocks (Rees & Mészáros, 1994), that arise due to shocks within the flow when fast moving particles catch up with slower ones.

In the standard fireball model, internal shocks are believed to provide the best way to explain the observed temporal structure in GRBs (Piran, 1999). These shocks, that take place at distances of $\sim 10^{15}$ cm from the center, convert two to twenty percent of the kinetic energy of the flow to thermal energy (Piran, 1999), and with this mechanism it is possible to extract at most half of the shell’s energy (Kobayashi, Piran & Sari, 1997; Katz, 1997). Highly relativistic flow with a kinetic energy and a Lorentz factor comparable to the original one remains after the internal shocks.

Sari & Piran (1997) pointed out that if the shell is surrounded by ISM and collisionless shock occurs, the relativistic shell will dissipate by external shocks as well. This predicts an additional smooth burst, with a comparable or possibly greater energy. This is most probably the source of the observed afterglow (Piran, 1999). Therefore, the standard fireball model is characterized by an “internal-external” scenario (Sari & Piran, 1997) in which the GRB itself is produced by internal shocks, while the afterglow is produced by external shocks.

Consider a cold shell (whose internal energy is negligible compared to the rest mass) that overtakes another cold shell or moves into the cold ISM. Generally, two shocks form: an outgoing shock that propagates into the ISM or into the external shell, and a reverse shock that propagates into the inner shell, with a contact discontinuity between the shocked material. Two quan-
1. Gamma-Ray Bursts: Overview

tities determine the shocks’ structure: the Lorentz factor $\Gamma$ of the motion of the inner shell relative to the outer one or the ISM, and the ratio $f$ between the particle number densities in these regions.

There are three interesting cases (Piran, 1999):

- Ultra-relativistic shock ($\Gamma \gg 1$ and $f > \Gamma^2$). This happens during the early phase of an external shock or during the very late internal shock evolution when there is only a single shock. This configuration is called “Newtonian” because the reverse shock is non-relativistic or mildly relativistic (Piran, 1999). In this case the energy conversion takes place in the forward shock (Piran, 1999).

- During the propagation of the shell the density ratio decreases and $f < \Gamma^2$. Both the forward and the reverse shocks are relativistic.

- Internal shocks are characterized by $f \approx 1$, namely both shells have similar densities, and by a Lorentz factor of order of a few describing the relative motion of the shells. Both shocks are mildly relativistic and their strength depends on the relative Lorentz factors of the two shells.

1.3.2 The afterglow

According to the standard fireball model the afterglow is produced when the relativistic ejecta is slowed down by the surrounding matter (Mészáros & Rees, 1997a). At this stage external shocks becomes predominant (Piran, 1999). Initially the process might be radiative, namely a significant fraction of the kinetic energy is dissipated and the radiation process affects the hydrodynamics of the shock (Piran, 2004). Later the radiation processes become less efficient and an adiabatic phase begins during which the radiation losses are minor and do not influence the hydrodynamics (Piran, 2004). Finally, a transition into the Newtonian regime takes place when $\Gamma \approx 1.5$.

The theory of a relativistic shell propagating into the ISM has been worked out in a classical paper by Blandford & McKee (1976). This model is
1.3. The “fireball” model

a self-similar spherical solution describing an adiabatic ultra relativistic blast wave in the limit $\Gamma \gg 1$. For this blast wave, the total energy is proportional to $r^3 \Gamma^2$, leading to the scaling law:

$$\Gamma \propto r^{-3/2}. \quad (1.5)$$

Analogously, it is possible to find for a fully radiative regime another scaling law (Blandford & McKee, 1976):

$$\Gamma \propto r^{-3}. \quad (1.6)$$

The simple adiabatic model assumes that the energy of the GRB is constant. However, the energy could change if additional slower material is ejected behind the initial matter (Piran, 2004). As the initially faster moving matter is slowed down by the circumburst matter, this slower matter eventually catch up and produces “refreshed shocks” (Rees & Mészáros, 1998; Kumar & Piran, 2000a; Sari & Mészáros, 2000). There are two implications for the refreshed shocks: first, the additional energy injection will influence the dynamics of the blast wave (Rees & Mészáros, 1998; Sari & Mészáros, 2000). This would change the decay slope from the canonical one and produce a slower decay in the light curve (Piran, 2004). A second effect is the production of a reverse shock propagating into the slower material when it catches up with the faster one (Kumar & Piran, 2000a). This is of course in addition to the forward shock that propagates into the outer shell. This reverse shock could be episodal or long lasting, depending on the profile of the additional matter (Piran, 2004). The calculation of the shock is slightly different than the calculation of a shell propagating into a cold material (Piran, 2004): here the outer shell has already collided with the ISM, hence it is hot with internal energy exceeding the rest mass energy.

1.3.3 Jets and collimation

The afterglow theory becomes much more complicated if the relativistic ejecta are not spherically distributed. The commonly called “jets” corresponds to relativistic matter ejected into a cone of opening angle $\theta$. The
simplest implication of a jet geometry, that exists regardless of the hydrodynamic evolution, is that once $\Gamma \sim \theta^{-1}$ relativistic beaming of light will become less effective. The radiation was initially beamed locally into a cone with an opening angle $\Gamma^{-1}$ remained inside the cone of the original jet. Now with $\Gamma^{-1} > \theta$ the emission is radiated outside of the initial jet. This has two effects: an “on axis” observer, one that sees the original jet, will detect a jet break due to the faster spreading of the emitted radiation. An “off axis” observer, that could not detect the original emission, will be able to see now an “orphan afterglow”, namely an afterglow without a preceding GRB.

Also the hydrodynamic evolution of the source changes when $\Gamma \sim \theta^{-1}$. Initially, as long as $\Gamma \gg \theta^{-1}$ the motion would be almost conical (Piran, 1994). There isn’t enough time, in the blast wave’s rest frame, for the matter to be affected by the non spherical geometry, and the blast wave will behave as if it was a part of a sphere. When $\Gamma \sim \theta^{-1}$, sideways propagation begins. The sideways expansion causes a change in the hydrodynamic behavior and hence a break in the light curve (Rhoads, 1999; Sari, Piran & Halpern, 1999). The beaming outside of the original jet opening angle also causes a break (Panaitescu & Mészáros, 1999; Rhoads, 1999; Sari, Piran & Halpern, 1999). If the sideways expansion is at the speed of light than both transitions would take place at the same time (Sari, Piran & Halpern, 1999). If the sideways expansion is at the sound speed then the beaming transition would take place first and only later the hydrodynamic transition would occur (Panaitescu & Mészáros, 1999). This would cause a slower and wider transition with two distinct breaks, first a steep break when the edge of the jet becomes visible and later a shallower break when sideways expansion becomes important.

An alternative interpretation for the breaks observed in many afterglow light curves is as viewing angles of a “universal structured jet” (Lipunov, Postnov & Prokhorov, 2001; Rossi et al., 2002; Zhang & Mészáros, 2002) whose energy varies with the angle. These interpretations give different estimates of the overall rate and the energies of GRBs. In either case the energy involved with GRBs is smaller than the isotropic energy and the rate is higher than
1.4 Models for GRB progenitors

The fireball model is independent on the details of the “inner engine” that releases the initial energy (Mészáros, 2002). Nevertheless, simple considerations on the energetic and the time scales leads to the idea that the central engine producing the required energy flow could be an accretion disk. Several scenarios could lead to a black hole - massive accretion disk system. This could include mergers, as Neutron Star-Neutron Star (NS-NS, Eichler et al., 1989; Narayan, Paczyński & Piran, 1992), Neutron Star-Black Hole (NS-BH, Paczyński, 1991) or Neutron Star-White Dwarfs (NS-WD, Fryer et al., 1999) binaries, and models based on “failed supernovae” or “Collapsars” (Woosley, 1993; Paczyński, 1998; MacFadyen, Woosley & Heger, 1999).

Within the standard model it is now believed (Narayan, Piran & Kumar, 2002) that among all the above scenarios Collapsars could produce long bursts and NS-NS (or NS-BH) mergers could produce short bursts. The basic idea is that the duration of the accretion depends on the size of the disk. This means that short bursts must originate from small disks which are naturally produced in mergers. On the other hand long bursts require large disks. An alternative possibility is to have a small disk that is fed continuously. In this case the duration of the process can be longer (Piran, 2004).

The Collapsar model. Woosley (1993) proposed that GRB arise from the collapse of a single Wolf-Rayet star endowed with fast rotation. Paczyński (1998) pointed out that there is evidence that many GRBs are close to star-forming regions and that this suggests that GRBs are linked to cataclysmic deaths of massive stars. Then MacFadyen, Woosley & Heger (1999) begun a series of calculations of a relativistic jet propagation through the stellar envelope of the collapsing star. The collimation of a jet by the stellar mantle was shown to occur analytically by Mészáros & Rees (2001). Zhang, Woosley
1. Gamma-Ray Bursts: Overview

& MacFadyen (2003) numerically confirmed and extended the basic features of this collimation process. All these ingredients led to the Collapsar model.

According to the Collapsar model the massive iron core of a rapidly rotating massive star ($M > 30M_\odot$) collapses to a black hole (either directly or during the accretion phase that follows the core collapse). An accretion disk forms around this black hole and a funnel forms along the rotation axis, where the stellar material has relatively little rotational support. The mass of the accretion disk is around $0.1M_\odot$. Energy can be extracted via neutrino annihilation (MacFadyen, Woosley & Heger, 1999) or via the Bladford-Znajek mechanism. The energy deposited in the surrounding matter will preferably leak out along the rotation axis producing jets with opening angles $< 10^\circ$.

The processes of core collapse, accretion along the polar column (which is essential in order to create the funnel) and the jet propagation through the stellar envelope take together $\sim 10$ sec (MacFadyen, Woosley & Heger, 1999). The duration of the accretion onto the black hole is expected to take several dozen seconds. The jet, as it passes through the star, is modulated by its interaction with the surrounding medium. In this way the Collapsar model attempts to explain the time structure of GRB prompt emission and to produce the variable Lorentz factor necessary for the internal shocks occurrence (Woosley & Bloom, 2006). Moreover it is a prediction of this model that the central engine remains active for a long time after the principal burst is over, potentially contributing to the GRB afterglow (Burrows et al., 2005b). This is because the jet and disk are inefficient at ejecting all the matter in the equatorial plane of the pre-collapse star and some continues to fall back and accrete (MacFadyen & Woosley, 2001). All these arguments imply that Collapsars are expected to produce long GRBs (Piran, 2004).

Neutron stars merging. NS-NS (Eichler et al., 1989; Narayan, Paczynski & Piran, 1992) or NS-BH binary mergers (Paczyński, 1991) also produce a black hole-accretion disk system and are candidates for the inner engines of GRBs, specifically of short GRBs. These mergers take place because of the
1.4. Models for GRB progenitors

decay of the binary orbits due to gravitational radiation emission.

A merger releases $\sim 5 \times 10^{53}$ erg, but most of this energy is in the form of low energy neutrinos and gravitational waves. Still there is enough energy available to power a GRB but it is not clear how the GRB is produced (Piran, 2004). A central question is how does a merger generate the relativistic wind required to power a GRB. Eichler et al. (1989) suggested that about one thousandth of these neutrinos annihilates and produces pairs that in turn produces gamma-rays via $\nu\bar{\nu} \rightarrow e^+e^- \rightarrow \gamma\gamma$. This idea was criticized on several grounds by different authors: the main problem is that it does not produce enough energy. For example Jaroszynski (1996) pointed out that a large fraction of the neutrinos will be swallowed by the black hole that forms.
1. Gamma-Ray Bursts: Overview
Chapter 2

A Model for GRBs

In this chapter we describe in detail the model we use to interpret the GRBs observational properties. As it will be clarified here and in the following chapters, there are many differences between our approach and the one currently addressed as “standard model for GRBs” (see section 1.3). Surely the basic novelty of our approach is that it represents the first and, maybe, the only attempt to analyze the GRB phenomenon as a whole. In fact, starting from the initial condition which characterize the progenitor, we fix uniquely the dynamic of the system since its creation (chapter 2 and Ruffini et al., 2001a,b, 2003, 2005b). Moreover the identification of a single emission mechanism for all the GRB phases (section 3.2 and Ruffini et al., 2004b, 2005a) allows us to obtain light curves and spectra which reproduce correctly the observations (sections 3.3 and 3.4 and Ruffini et al., 2002; Bernardini et al., 2005; Ruffini et al., 2005b, 2006a). In doing this, we calculate the exact solutions for the equations of motion of the system (Bianco & Ruffini, 2004, 2005a), without doing the approximations usually adopted in the “standard model” (Mészáros, Laguna & Rees, 1993; Sari, 1997, 1998; Waxman, 1997c; Rees & Mészáros, 1998; Granot, Piran & Sari, 1999; Panaitescu & Mészáros, 1998; Piran, 1999; Gruzinov & Waxman, 1999; Van Paradijs, Kouveliotou & Wijers, 2000; Mészáros, 2002).
2. A Model for GRBs

2.1 The $e^\pm$ creation.

According to our model, GRBs are produced by a process of energy extraction from a black hole. All the properties of a generic black hole are described by three parameters: its mass $M$, its angular momentum $L$ and its electric charge $Q$. We assume, for simplicity, that in our case $L = 0$. In 1971 Christodoulou & Ruffini (1971) showed that for a Reissner-Nordstrom black hole ($Q \neq 0, L = 0$) a large fraction of energy (up to 50%) can be stored as extractable electromagnetic energy. The mass-energy formula for a charged black hole is (Christodoulou & Ruffini, 1971):

$$E^2 = M^2 c^4 = \left( M_{irr} c^2 + \frac{Q^2}{2r_+} \right)^2$$

$$S = 4\pi r_+^2 = 16\pi \left( \frac{G^2}{c^4} \right) M_{irr}^2,$$

where $M_{irr}$ is the black hole irreducible mass (Christodoulou & Ruffini, 1971), namely the minimum value of the mass left after the energy extraction process, $r_+$ is the horizon radius and $S$ is the horizon surface.

In 1975 Damour & Ruffini (1975) demonstrated that in the neighborhood of a charged black hole the vacuum polarization process (Heisenberg & Euler, 1935; Schwinger, 1951) can occur if the electric field exceeds the critical value

$$\mathcal{E}_c = \frac{m_e^2 c^3}{\hbar e},$$  \hspace{1cm} (2.1)

where $m_e$ and $e$ are the mass and charge of the electron. They found that (see also Preparata, Ruffini & Xue, 1998):

- the polarization process can occur around a black hole of mass between $3.2M_\odot$ and $7.2 \times 10^6 M_\odot$;

- the pair creation process occurs on very short time scales ($t \approx \hbar/(m_e c^2)$) and it is a completely reversible process according to the definition by Christodoulou & Ruffini (1971), leading to an extremely efficient mechanism for the energy extraction;
2.2. The plasma expansion

- the energy extracted is \( \approx 10^{54} \) erg, compatible with the observed GRB isotropic energy.

The pair creation occurs in a region called “dyadosphere” (Preparata, Ruffini & Xue, 1998), between the horizon radius

\[
r_+ = \frac{GM}{c^2} \left( 1 + \sqrt{1 - \frac{Q^2}{GM^2}} \right)
\]

(2.2)

and the “dyadosphere radius” \( r_{ds} \) (Preparata, Ruffini & Xue, 1998), defined as

\[
E(r_{ds}) = \frac{Q}{r_{ds}^2} = E_c.
\]

(2.3)

The total \( e^\pm \) energy stored in this region is (Preparata, Ruffini & Xue, 1998)

\[
E_{e^\pm}^{tot} = \int_{r_+ < r < r_{ds}} \epsilon(r)\alpha d\Sigma,
\]

(2.4)

\[
\epsilon(r) = \frac{(E^2(r) - E_c^2)}{8\pi} = \frac{Q^2}{8\pi r^4} \left[ 1 - \left( \frac{r}{r_{ds}} \right)^4 \right],
\]

(2.5)

where \( \epsilon(r) \) is the electromagnetic energy density measured by a static observer, \( \alpha = \sqrt{1 - \frac{2GM}{c^2r} + \frac{GM^2}{c^4r^2}} \) is the gravitational redshift and \( d\Sigma = \alpha^{-1} r^2 dr d\Omega \) is the 3-dimensional volume element.

2.2 The plasma expansion

2.2.1 The equations of the theory - I

We study now the evolution of a plasma composed by \( e^\pm \), photons and baryons (Ruffini et al., 1999, 2000). Such plasma is described by the stress-energy tensor:

\[
T^{\mu \nu} = pg^{\mu \nu} + (p + \rho)U^\mu U^\nu,
\]

(2.6)

where \( \rho \) is the total energy density of the plasma, \( p \) the pressure and \( U^\mu \) its 4-velocity.
The energy-momentum conservation law is

\[ (T^\mu_\nu)_{\mu} = 0 . \]  

(2.7)

The conservation law for the baryonic number is

\[ (n_B U^\mu)_{\mu} = 0 . \]  

(2.8)

In our analysis we include also the rate equation for \( e^\pm \):

\[ (n_e^\pm U^\mu)_{\mu} = \sigma \bar{v} (n_{e^-}(T)n_{e^+}(T) - n_{e_0^-}n_{e_0^+}) , \]  

(2.9)

where \( \sigma \) is the mean pair annihilation cross section, \( \bar{v} \) is the thermal velocity of \( e^\pm \), \( n_{e^\pm}(T) \) are the proper number densities of \( e^\pm \), given by appropriate Fermi integrals with zero chemical potential, and \( n_{e_0^\pm} \) are the proper number densities at initial time of the expansion. The equilibrium temperature \( T \) is determined by the thermalization processes occurring in the expanding plasma with a total energy density \( \rho = \rho_\gamma + \rho_{e^+} + \rho_{e^-} + \rho_B \), given by the sum of Fermi or Bose integrals, one for each fluid component. We can also, analogously, evaluate the total pressure \( p \). We have, then, the equation of state (\( \Gamma \) is the thermal index)

\[ \Gamma = 1 + \frac{p}{\rho} . \]  

(2.10)

### 2.2.2 The numerical integration

In order to integrate the conservation laws for the plasma it is necessary to simplify the problem. First of all, we have assumed that the system evolves in a Minkowski space-time. This is reasonable if we consider the value of \( g_{00} \) for a Reissner-Nordstrom space-time evaluated at a distance from the black hole \( \bar{r} = 2r_{ds} \) (for \( M = 10M_\odot \) and \( Q/(\sqrt{GM}) = 7.0 \times 10^{-3} \)). We see that

\[ g_{00}(\bar{r}) = 1 - \frac{GM}{c^2 \bar{r}} + \frac{GQ^2}{c^4 \bar{r}^2} \approx 0.98 , \]

so the space-time in which the plasma expands is approximately flat even at short distances from the dyadosphere.
2.2. The plasma expansion

We assume also that the width of the plasma remains constant in the laboratory frame, namely the one in which the progenitor is at rest, throughout the expansion. This proposal, together with other possible descriptions of the expanding plasma, was compared with the exact solutions of the hydrodynamic equations obtained with the Livermore numerical code resulting, among all, the best approximation (see Fig. 2.1 and Ruffini et al., 1999).

2.2.3 The equations of the theory - II

We derive explicitly now, starting from the assumptions presented in section 2.2.2, the equations we use to describe the evolution of the plasma.

From the differential conservation law (2.7), the following integral conservation law can be derived (Synge, 1960):

\[
\int_{\Sigma_t} \xi_\mu T^{\mu\nu} d\Sigma_\nu = E, \tag{2.11}
\]

where \( \xi_\mu \) is the static vector field normalized at unity at spatial infinity, \( \Sigma_t \) is the space-like hypersurface orthogonal to \( \xi_\mu \) and \( d\Sigma_\nu \) is the vector surface element of \( \Sigma_t \). Assuming the constancy of the pulse width and recalling the equation of state (2.10), we get

\[
E = (\Gamma \rho \gamma^2 + p) V, \tag{2.12}
\]

where \( V \) is the volume of the pulse in the laboratory frame and \( V = \gamma V \) is the same volume in the comoving frame. Since the Lorentz factor \( \gamma \) at this stage is high (~50), in what follows we can neglect the pressure term, namely

\[
E = \Gamma \rho \gamma^2 V. \tag{2.13}
\]

This means that

\[
\Gamma \rho_0 \gamma_0^2 V_0 = \Gamma \rho \gamma^2 V, \tag{2.14}
\]

where the subscript “0” refers to quantities evaluated at initial time. This equality is used to define the evolution of the pulse Lorentz factor

\[
\gamma = \gamma_0 \sqrt{\frac{\rho_0 V_0}{\rho V}}. \tag{2.15}
\]
2. A Model for GRBs

Figure 2.1: The exact solution of the 1-dimension hydrodynamic equations obtained by the Livermore numerical code (black squares) is compared with several approximated description of the expanding plasma. Among all, the best assumption has been found the so-called “Slab 1” (solid line) which corresponds to a constant width in the laboratory frame.
2.2. The plasma expansion

Analogously, we can write the integral conservation law for the baryonic number (Eq. (2.8)):

\[
\int_{\Sigma_t} n_B U^\mu d\Sigma_\nu = N_B = n_B \gamma V, \tag{2.16}
\]

and, again,

\[
n_B \gamma_0 V_0 = n_B \gamma V, \tag{2.17}
\]

\[
n_B = n_B \frac{\gamma_0 V_0}{\gamma V}. \tag{2.18}
\]

In order to obtain the evolution of the internal energy density \( \epsilon = \rho - \rho_B (\rho_B = n_B m_p c^2) \) during the expansion of the pulse we must impose the adiabaticity condition:

\[
d(\epsilon V) + p dV = 0. \tag{2.19}
\]

Recalling from Eq. (2.10) that \( p = (\Gamma - 1)\epsilon \), we get

\[
d\ln\epsilon + \Gamma d\ln V = 0. \tag{2.20}
\]

If we integrate this equation we obtain for the internal energy density

\[
\epsilon = \epsilon_0 \left( \frac{V_0}{V} \right)^\Gamma. \tag{2.21}
\]

2.2.4 The expansion of the “fireshell”

After its creation around the progenitor, the \( e^\pm \) plasma starts to expand as a “fireshell” in a region with very low baryonic contamination because of the gravitational collapse of the central black hole (Ruffini et al., 1999). We label the expanding plasma “fireshell” in order to emphasize the difference with the “fireball” presented in section 1.3. In our threatment the plasma behaves as a “shell”, namely it moves as a single shell with a Lorentz factor \( \gamma \) and with constant thickness in the laboratory frame, and all the particles stored inside the plasma move with the same Lorentz factor \( \gamma \).

After this first stage, the pulse reaches the baryonic remnants left over by the collapse, necessary to guarantee the neutrality of the system (Ruffini et
2. A Model for GRBs

Figure 2.2: Lorentz gamma factor versus radial coordinate for two different positions of the baryonic remnants: \( r_B = 50r_{ds} \) and \( r_B = 5r_{ds} \). It is evident the convergence to a common behavior when the system approaches the transparency.

Such baryonic remnants are assumed to be arranged in a spherical shell of width \( \Delta \approx 10r_{ds} \) which is outside the dyadosphere, but near enough than it can be reached by the plasma before it has become transparent. For simplicity, we choose \( r_B = 50r_{ds} \). From our numerical simulations we have found that the following expansion of the pulse is quite insensitive to the position of the baryonic remnants (Ruffini et al., 2003, see Fig. 2.2).

The total mass of the baryonic remnants \( M_B = N_B m_p \), where \( N_B \) is the number of baryons and \( m_p \) is the proton mass, written as a dimensionless parameter in function of \( E^{\pm}_{\text{tot}} \),

\[
B = \frac{M_Bc^2}{E^{\pm}_{\text{tot}}} , \tag{2.22}
\]

is the second free parameter of our theory defining completely, together with \( E^{\pm}_{\text{tot}} \), the dynamics of the system (Ruffini et al., 2000).

In order to study the interaction between the expanding \( e^\pm \) plasma and the shell of baryonic remnants we have to consider some assumptions (Ruffini et al., 2000, 2003):

- the \( e^\pm \) pulse does not change its geometry during the interaction;
- the interaction between them is a totally inelastic collision;
2.2. The plasma expansion

- the baryonic remnants reach the thermal equilibrium with the incoming pulse.

These assumptions are valid if (Ruffini et al., 2000):

- the total energy of the plasma is much larger than the one of the baryonic matter, namely \( B < 10^{-2} \);
- the ratio between the \( e^\pm \) number density \( n_{e^\pm} \) and the baryon number density \( n_B \) is large (e.g. \( n_{e^\pm}/n_B > 10^6 \));
- the Lorentz gamma factor of the incoming pulse is high (\( \gamma \approx 100 \)).

Now we write the energy and momentum conservation for the system. If we consider the collision of the pulse with a sub-shell of baryonic matter between the radii \( r_1 \) and \( r_2 \), with \( r_B < r_1 < r_2 \) and \( r_2 - r_1 < \Delta \), the amount of baryonic matter loaded by the incoming pulse is:

\[
\Delta M = \frac{M_B 4\pi}{3} (r_2^3 - r_1^3) .
\]

(2.23)

The conservation of energy and momentum can be written as (Ruffini et al., 2000, 2003):

\[
(\Gamma \epsilon_0 + \rho_B^0) \gamma_0^2 V_0 + \Delta M = (\Gamma (\epsilon + \Delta \epsilon) + \rho_B + \frac{\Delta M}{V}) \gamma^2 V
\]

\[
(\Gamma \epsilon_0 + \rho_B^0) \gamma_0 U_r^0 V_0 = (\Gamma (\epsilon + \Delta \epsilon) + \rho_B + \frac{\Delta M}{V}) \gamma U_r V,
\]

(2.24)

where \( \Delta \epsilon \) is the increase in the plasma internal energy due to the collision in the comoving frame, \( V \) and \( V = \gamma V \) are, respectively, the volume of the incoming pulse in the laboratory and in the comoving frames and \( U_r \) is the radial component of the 4-velocity of the pulse. The quantities with (without) the subscript “0” are evaluated before (after) the collision. So we get (Ruffini et al., 2000, 2003):

\[
\Delta \epsilon = \frac{1}{\Gamma} \left[ \Gamma \epsilon_0 + \rho_B^0 \frac{\gamma_0 U_r^0 V_0}{U_r V} - \left( \Gamma \epsilon + \rho_B + \frac{\Delta M}{V} \right) \right]
\]

\[
\gamma = \frac{a}{\sqrt{a^2 - 1}}, \quad a = \frac{\gamma_0}{U_r^0} + \frac{\Delta M }{(\Gamma \epsilon_0 + \rho_B^0) \gamma_0 U_r^0 V_0}.
\]

(2.25)
2. A Model for GRBs

The global results of the interaction between the $e^\pm$ pulse and the baryonic remnants are (Ruffini et al., 2000, 2003, see Fig. 2.3):

- an abrupt decrease in the Lorentz factor of the system;
- an increase of its comoving internal energy, with a consequent heating of the plasma in the comoving frame, an increase in the $e^\pm$ number and in the opacity of the system.

2.2.5 The approach to the transparency

After the baryonic matter loading, the pulse composed by $e^\pm-\gamma$-baryons continues its expansion until the plasma cools and becomes optically thin (Ruffini et al., 2000):

$$\int_R dr (n_{e^\pm} + Zn_B)\sigma_T \approx O(1),$$

(2.26)

where $\sigma_T = 0.665 \cdot 10^{-24}$ cm$^2$ is the Thomson cross section, $Z$ is the average number of electrons per baryon and the integration is performed over the width of the pulse in the comoving frame. We have to notice that the presence of the baryons increases the opacity and delays the instant of transparency (Ruffini et al., 1999, 2000, 2003).

Now all the photons stored inside the pulse are emitted in a flash of radiation: the Proper Gamma-Ray Burst (P-GRB; Ruffini et al., 1999, 2000, 2001a, 2003). The remaining accelerated baryons continue their expansion and, interacting with the InterStellar Medium (ISM), produce a prolonged emission: the Afterglow (see chapter 3 and Ruffini et al., 2001a, 2003).

It is important to check if the constant width approximation is still valid until the transparency. As we can see in Fig. 2.3, the assumption of a constant width in the laboratory frame for the shell is in perfect agreement with the Livermore simulation even when we include the baryons in the plasma but only for a small value of baryonic matter ($B = 10^{-4}$ in this simulation). When $B$ goes to its limiting value $10^{-2}$ this approximation is not valid anymore. In
2.2. The plasma expansion

Figure 2.3: The Lorentz gamma factor of the system versus the radial coordinate. After a first stage of free expansion, the plasma impacts with the baryonic remnants with the consequent abrupt decrease on the Lorentz factor. Then, the system accelerates again. We notice that there is still a good agreement between our simulation (dashed line), performed assuming a constant width of the shell in the laboratory frame, and the Livermore one (squared dots), at least for small values of the baryon loading ($B = 10^{-4}$ in this simulation).
2. A Model for GRBs

fact turbulent motions inside the shell can occur and they can even stop the pulse, preventing the GRB occurrence.

We turn now to evaluate the Lorentz factor of the pulse $\gamma_0$ at the transparency. There is a maximum value for $\gamma_0$ (Ruffini et al., 2000):

$$\gamma_{\text{asym}} = \frac{E_{\text{tot}}^\pm}{M_B c^2} = \frac{1}{B} \quad (2.27)$$

that corresponds to a situation in which all the energy of the pulse is converted into baryon kinetic energy. As we can see in Fig. 2.4, when $B$ tends to its maximum value $\gamma_0$ tends to that “asymptotic” value,

$$\gamma_0 \xrightarrow{B \to 10^{-2}} \gamma_{\text{asym}}.$$

It means that the fraction of energy emitted in the P-GRB and the one converted into baryonic kinetic energy depends on the amount of baryons stored inside the pulse (Ruffini et al., 2000, 2003). We will see in chapter 4 that this could provide a possible explanation for the different observational properties of short and long GRBs (Ruffini et al., 2001b, 2003).

2.3 The description of the afterglow

After the emission of the P-GRB, the accelerated baryonic pulse continues its expansion and interacts with the surrounding ISM. In order to study this interaction, we assume that:

- the interaction between the accelerated baryons and the ISM is represented as a sequence of inelastic collisions of the baryons with a series of cold, thin shells of ISM, at rest in the laboratory frame;

- the baryonic shell width remains constant in the laboratory frame;

- the energy released in the collision is emitted instantaneously (“fully radiative” condition, see Ruffini et al., 2003).
2.3. The description of the afterglow

Figure 2.4: Lorentz gamma factors for selected values of the baryon loading $B$ are represented versus the radial coordinate until the transparency is reached. The Lorentz factor at transparency tends to $\gamma_{\text{asym}}$ when $B$ increases.
2. A Model for GRBs

Each ISM shell is assumed to have a mass $\Delta M_{\text{ISM}}$ and a width $\Delta r$ in
the laboratory frame. Its collision with the accelerated baryonic shell releases
an amount of internal energy $\Delta E_{\text{int}}$. Let $\Delta \epsilon$ be the increase in the internal
energy density of the baryonic shell during the collision with a single ISM shell,

$$\rho_B = \frac{(M_B + M_{\text{ism}})c^2}{V}$$  \hspace{1cm} (2.28)

the baryonic matter energy density stored inside the accelerated pulse, both
measured in the comoving frame and

$$M_{\text{ISM}} = \frac{4}{3} \pi (r^3 - r_0^3)m_p n_{\text{ISM}}$$  \hspace{1cm} (2.29)

the amount of ISM mass swept up within the radius $r$.

The conservation of energy and momentum during each collision can be
written as

$$\rho_B \gamma_1^2 V_1 + \Delta M_{\text{ism}} c^2 = \left( \rho_B \frac{V_1}{V_2} + \frac{\Delta M_{\text{ism}} c^2}{V_2} + \Delta \epsilon \right) \gamma_2^2 V_2,$$  \hspace{1cm} (2.30)

$$\rho_B \gamma_1 U_r V_1 = \left( \rho_B \frac{V_1}{V_2} + \frac{\Delta M_{\text{ism}} c^2}{V_2} + \Delta \epsilon \right) \gamma_2 U_r V_2,$$  \hspace{1cm} (2.31)

where the quantities with the index “1” (“2”) are evaluated before (after)
the collision, $V$ is the volume of the accelerated shell in the comoving frame
and $V = \gamma V$ is the same volume in the laboratory frame, $U_r$ is the radial
component of the 4-velocity (Ruffini et al., 1999, 2000, 2003).

From Eqs.(2.30) and (2.31) we get (Ruffini et al., 2003)

$$\Delta \epsilon = \rho_B \frac{\gamma_1 U_r V_1}{\gamma_2 U_r V_2} \left( \rho_B \frac{V_1}{V_2} + \frac{\Delta M_{\text{ism}} c^2}{V_2} \right),$$  \hspace{1cm} (2.32)

$$\gamma_2 = \frac{a}{\sqrt{a^2 - 1}}, \hspace{0.5cm} a = \frac{\gamma_1}{U_r} + \frac{\Delta M_{\text{ism}} c^2}{\rho_B \gamma_1 U_r V_1}.$$  \hspace{1cm} (2.33)

We can write

$$\Delta \epsilon = \frac{E_{\text{int}2}}{V_2} - \frac{E_{\text{int}1}}{V_1} = \frac{E_{\text{int}1} + \Delta E_{\text{int}1}}{V_2} - \frac{E_{\text{int}1}}{V_1} = \frac{\Delta E_{\text{int}1}}{V_2},$$  \hspace{1cm} (2.34)
2.3. The description of the afterglow

since we have assumed a fully radiative regime \( (E_{\text{int}} = 0) \). Substituting this
expression into Eqs.(2.32) and (2.33) we obtain (Ruffini et al., 2003)

\[
\Delta E_{\text{int}} = \rho_{B_1} V_1 \sqrt{1 + 2\gamma_1 \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1}} + \left( \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1} \right)^2 - \rho_{B_1} V_1 \left( 1 + \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1} \right),
\]

(2.35)

\[
\gamma_2 = \frac{\gamma_1 + \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1}}{\sqrt{1 + 2\gamma_1 \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1}} + \left( \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1} \right)^2}.
\]

(2.36)

These are the equations which are numerically integrated in order to
follow the baryonic shell expansion during the afterglow. In Fig. 2.5 is repre-
sented the Lorentz factor of the system versus the radial coordinate from the
initial stages of the expansion to the approach to the non-relativistic regime
(Ruffini et al., 2001a, 2003).

If we consider the limit in which the ISM shells are infinitesimally thin,
so that the relation

\[
\eta = \frac{\Delta M_{\text{ISM}} c^2}{\rho_{B_1} V_1} \ll 1
\]

(2.37)
is satisfied, we can expand Eqs.(2.35) and (2.36) to the first order in \( \eta \) ob-
taining in the differential form

\[
dE_{\text{int}} = (\gamma - 1) dM_{\text{ISM}} c^2,\]

\[
d\gamma = -\gamma^{-1} dM_{\text{ISM}},\]

\[
dM = \frac{1-\varepsilon}{c^2} dE_{\text{int}} + dM_{\text{ISM}},\]

\[
dM_{\text{ISM}} = 4\pi m_\rho n_{\text{ISM}} r^2 dr,
\]

(2.38)

In our model and in the current literature (Piran, 1999; Chiang & Dermer,
1999) a first integral of these equations has been found, leading to expressions
for the Lorentz gamma factor as a function of the radial coordinate. In the
“fully adiabatic condition” (i.e. \( \varepsilon = 0 \)) we have:

\[
\gamma^2 = \frac{\gamma_0^2 + 2\gamma_0 \left( M_{\text{ISM}}/M_B \right) + \left( M_{\text{ISM}}/M_B \right)^2}{1 + 2\gamma_0 \left( M_{\text{ISM}}/M_B \right) + \left( M_{\text{ISM}}/M_B \right)^2},
\]

(2.39)
2. A Model for GRBs

Figure 2.5: Lorentz gamma factor of the system versus radial coordinate for all the stages. I: free expansion of the $e^\pm$ plasma; II: collision with the baryonic remnants; III: expansion of the pulse composed by $e^\pm-\gamma$-baryons; IV: afterglow phase; V: non-relativistic regime. In the point 4 the system reaches the transparency.
while in the “fully radiative condition” (i.e. $\varepsilon = 1$) we have:

$$
\gamma = \frac{1 + (M_{\text{ISM}}/M_B) \left( 1 + \gamma_0^{-1} \right) \left[ 1 + (1/2) (M_{\text{ISM}}/M_B) \right]}{\gamma_0^{-1} + (M_{\text{ISM}}/M_B) \left( 1 + \gamma_0^{-1} \right) \left[ 1 + (1/2) (M_{\text{ISM}}/M_B) \right]},
$$

(2.40)

where $\gamma_0$, $M_B$ and $r_0$ are respectively the values of the Lorentz gamma factor, of the mass of the accelerated baryons and of the radius $r$ at the beginning of the afterglow phase.

A major difference between our treatment and the other ones in the current literature is that we have integrated the above equations analytically, obtaining the explicit form of the equations of motion for the expanding shell in the afterglow for a constant ISM density. For the adiabatic case we have explicitly integrated the differential equation for $r(t)$ in Eq.(2.39), recalling that $\gamma^{-2} = 1 - \left[ dr/ (c dt) \right]^2$, where $t$ is the time in the laboratory reference frame. We have then obtained a new explicit analytic solution of the equations of motion for the relativistic shell in the entire range from the ultra-relativistic to the non-relativistic regimes (Bianco & Ruffini, 2005a):

$$
t = \left( \gamma_0 - \frac{m_i^0}{M_B} \right) \frac{r - r_0}{c \sqrt{\gamma_0^2 - 1}} + \frac{m_i^0}{4 M_B r_0^3 c \sqrt{\gamma_0^2 - 1}} r^4 - r_0^4 + t_0.
$$

(2.41)

Correspondingly, in the fully radiative case we have (Bianco & Ruffini, 2005a):

$$
t = \frac{M_B - m_i^0}{2c \sqrt{C}} (r - r_0) + \frac{r_0 \sqrt{C}}{12 c m_i^0 A^2} \ln \left\{ \frac{[A + (r/r_0)]^3 (A^3 + 1)}{[A^3 + (r/r_0)^3] (A + 1)^3} \right\} - \frac{m_i^0 r_0}{8 c \sqrt{C}}
$$

$$
+ t_0 + \frac{m_i^0 r_0}{8 c \sqrt{C}} \left( \frac{r}{r_0} \right)^4 + \frac{r_0 \sqrt{3C}}{6 c m_i^0 A^2} \left[ \arctan \frac{2 (r/r_0) - A}{A \sqrt{3}} - \arctan \frac{2 - A}{A \sqrt{3}} \right],
$$

(2.42)

where $A = \sqrt{(M_B - m_i^0)/m_i^0}$, $C = M_B^2 \gamma_0 (\gamma_0 - 1)/(\gamma_0 + 1)$ and $m_i^0 = (4/3) \pi m_p n_{\text{ism}} r_0^3$.

In the current literature, following Blandford & McKee (1976), a so-called “ultrarelativistic” approximation $\gamma_0 \gg \gamma \gg 1$ has been widely adopted by many authors to solve Eqs.(2.38) (see e.g. Sari, 1997, 1998; Waxman, 1997c; Rees & Mészáros, 1998; Granot, Piran & Sari, 1999; Panaitescu & Mészáros, 2005).
2. A Model for GRBs

1998; Piran, 1999; Gruzinov & Waxman, 1999; Van Paradijs, Kouveliotou & Wijers, 2000; Mészáros, 2002, and references therein). This leads to simple constant-index power-law relations:

$$\gamma \propto r^{-a}, \quad (2.43)$$

with $a = 3/2$ in the fully adiabatic case and $a = 3$ in the fully radiative case. In the same spirit, instead of Eq.(2.41) and Eq.(2.42), some authors have assumed the following much simpler approximation for the relation between the time and the radial coordinate of the expanding shell, both in the adiabatic radiative and in the fully radiative cases:

$$ct = r, \quad (2.44)$$

while others, like e.g. Panaitescu & Mészáros (1998), have integrated the approximate Eq.(2.43), obtaining:

$$ct = r + \left[ 2 (2a + 1) \frac{\gamma_0^2}{r_0} \right]^{-1} r_0 (r/r_0)^{2a+1}. \quad (2.45)$$

2.3.1 The arrival time

We now have to study the relation between the time at which the photons are emitted from the external surface of the expanding pulse and the time at which they are detected. First of all, we have to take into account the relativistic beaming effect. In fact only a small area centered on the line of sight emits photons that can reach the observer at infinity. The condition for that is (Bianco, Ruffini & Xue, 2001; Ruffini et al., 2002, 2003)

$$\cos\vartheta \geq \frac{v(t)}{c}. \quad (2.46)$$

The maximum allowed $\vartheta$ value corresponds to $\cos \vartheta_{\text{max}} = (v/c)$. In the earliest GRB phases $v \sim c$ and so $\vartheta_{\text{max}} \sim 0$. On the other hand, in the latest phases of the afterglow the baryonic pulse velocity decreases and $\vartheta_{\text{max}}$ tends to $90^\circ$ (see Fig. 2.6 and Ruffini et al., 2002, 2003).
2.3. The description of the afterglow

Figure 2.6: In this figure we show \( \vartheta_{\text{max}} \) (i.e. the angular amplitude of the visible area of the baryonic shell) in degrees as a function of the arrival time at the detector for the photons emitted along the line of sight.
2. A Model for GRBs

We can obtain the relation between the emission time in the laboratory frame \( t \) and the arrival time \( t_a \) of the photons. The general expression for that is (Ruffini et al., 2001a, 2003):

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

(2.47)

We want to include also the effect on the arrival time due to the expansion of the Universe. In fact the frequency of a photon detected on Earth is redshifted with respect to its value when the photon is emitted. So a time interval between two photons \( \Delta t_a \) received on Earth (at a certain redshift \( z \) from the source) and the corresponding time interval \( \Delta t_a \) measured in the neighborhood of the source (at \( z = 0 \)) is (Ruffini et al., 2003):

\[
\Delta t_a = \Delta t_a (1 + z).
\]

(2.48)

Usually in the study of GRBs many authors (see i.e. Fenimore et al., 1999; Waxman, 1997b,c; Rees & Mészáros, 1998; Piran, 1999; Van Paradijs, Kouveliotou & Wijers, 2000; Mészáros, 2002) use an approximated version of Eq.(2.47),

\[
t_a = \frac{t}{2\gamma^2}.
\]

(2.49)

This expression for the arrival time is completely unrealistic because it requires that \( \gamma \) is constant during the motion. This assumption is, of course, not valid for GRBs. In order to prevent this problem, this formula has been modified introducing “by hand” a dependence on time in the Lorentz factor:

\[
t_a = \frac{t}{2\gamma(t)^2}.
\]

(2.50)

This formula is still contradictory because it is obtained firstly assuming \( \gamma \) constant and varying with time.

It has been proposed by Sari (1997) to consider Eq.(2.50) only in a differential way,

\[
dt_a = \frac{dt}{2\gamma(t)^2},
\]

(2.51)
2.3. The description of the afterglow

and to obtain the exact relation integrating it:

\[ t_a = \int_0^t \frac{dt'}{2\gamma(t')^2}. \]  

(2.52)

Assuming the scaling law (2.43) with \( a = 3/2 \) and assuming also \( dt = dr/c \), from Eq.(2.52) we have, then

\[ t_a = \frac{r}{16\gamma^2 c}. \]  

(2.53)

It is worth to notice that this formula corresponds to a first order expansion in \( 1/\gamma^2 \) of the exact expression (2.47) in the particular case in which \( \cos \vartheta = 1 \). This means that such approximate expression is valid only for \( \gamma \gg 1 \), so it cannot be valid during all the GRB’s stages.

2.3.2 The EQuiTemporal Surfaces (EQTSs)

As pointed out long ago by Couderc (1939), in all relativistic expansion the crucial geometrical quantities with respect to a physical observer are the locus of source points of the signals arriving at the observer at the same time.

For a relativistically expanding spherically symmetric source such “EQuiTemporal Surfaces” (EQTSs) are surfaces of revolution about the line of sight. The general expression for their profile, in the form \( \vartheta = \vartheta(r) \), corresponding to an arrival time \( t_a \) of the photons at the detector, can be obtained from (see Ruffini et al., 2003; Bianco & Ruffini, 2004, 2005a, and Figs. 2.6–2.7):

\[ ct_a = ct(r) - r \cos \vartheta + r^*, \]  

(2.54)

where \( r^* \) is the initial size of the expanding source and \( t = t(r) \) is its equation of motion, expressed in the laboratory frame, obtained by Eqs.(2.41) and (2.42). From the definition of the Lorentz gamma factor \( \gamma^{-2} = 1 - (dr/cdt)^2 \), we have in fact:

\[ ct(r) = \int_0^r \left[ 1 - \gamma^{-2}(r') \right]^{-1/2} dr', \]  

(2.55)

where \( \gamma(r) \) comes from the integration of Eqs.(2.38).
2. A Model for GRBs

Figure 2.7: Temporal evolution of the visible area of the baryonic pulse. The green half-circles are the expanding baryonic pulse at radii corresponding to different laboratory times. The red curve marks the boundary of the visible region. In the earliest GRB phases the visible region is squeezed along the line of sight, while in the final part of the afterglow phase almost all the emitted photons reach the observer.
2.3. The description of the afterglow

Figure 2.8: Surfaces of photon emission corresponding to selected values of the photon arrival time at the detector: the EQTSs. The EQTSs represented here (red lines) correspond respectively to values of the arrival time ranging from 5 s (the smallest surface on the left of the plot) to 60 s (the largest one on the right). Each surface differs from the previous one by 5 s. To each EQTS contributes emission processes occurring at different values of the Lorentz gamma factor. The green lines are the boundaries of the visible area of the baryonic pulse.
We have obtained the expressions in the adiabatic and in the fully radiative cases respectively (Bianco & Ruffini, 2005a):

\[
\cos \vartheta = \frac{m_i^0}{4M_B \sqrt{\gamma_0^2 - 1}} \left[ \left( \frac{r}{r_0} \right)^3 - \frac{r_0}{r} \right] + \frac{ct_0}{r} - \frac{ct_a}{r} + \frac{r^*}{r} - \frac{\gamma_0 - (m_i^0/M_B)}{\sqrt{\gamma_0^2 - 1}} \left[ \frac{r_0}{r} - 1 \right] \tag{2.56}
\]

\[
\cos \vartheta = \frac{M_B - m_i^0}{2r \sqrt{C}} (r - r_0) + \frac{m_i^0 r_0}{8r \sqrt{C}} \left[ \left( \frac{r}{r_0} \right)^4 - 1 \right] + \frac{r_0 \sqrt{C}}{12r m_i^0 A^2} \ln \left\{ \frac{[A + (r/r_0)]^3 (A^3 + 1)}{[A^3 + (r/r_0)^3] (A + 1)^3} \right\} + \frac{ct_0}{r} - \frac{ct_a}{r} \tag{2.57}
\]

\[
+ \frac{r^*}{r} + \frac{r_0 \sqrt{3C}}{6r m_i^0 A^2} \left[ \arctan \frac{2 (r/r_0) - A}{A \sqrt{3}} - \arctan \frac{2 - A}{A \sqrt{3}} \right].
\]

This two solutions for the adiabatic and the radiative case are represented for selected values of the arrival time \(t_a\) in Fig. 2.9. The initial conditions at the beginning of the afterglow era are in this case given by \(\gamma_0 = 310.131\), \(r_0 = 1.943 \times 10^{14} \text{ cm}\), \(t_0 = 6.481 \times 10^3 \text{ s}\), \(r^* = 2.354 \times 10^8 \text{ cm}\) (Ruffini et al., 2001a,b, 2002, 2003).
2.3. The description of the afterglow

Figure 2.9: Comparison between EQTSs in the adiabatic regime (red lines) and in the fully radiative regime (green lines). The upper panel shows the EQTSs for $t_a = 5$ s, $t_a = 15$ s, $t_a = 30$ s and $t_a = 45$ s, respectively from the inner to the outer one. The lower panel shows the EQTS at an arrival time of 2 days.
2. A Model for GRBs
Chapter 3

GRB Light Curves and Spectra

3.1 Observational properties of GRB light curves

It is quite difficult to summarize GRBs’ basic features because of their enormous variety. If we look at the long GRBs’ light curves it is possible to distinguish two phases: a “prompt emission” in the gamma-rays lasting tens of seconds, followed by a multiwavelength emission lasting hours from the burst, the “afterglow”.

3.1.1 The prompt emission

The prompt emission is operationally defined as the time period when the gamma-ray instrument detects a signal above the background (Piran, 2004). Usually, a lower-energy emission (X-ray, optical) occurs simultaneously with the gamma-ray one. Sometimes such X-ray signal results to be more intense than the gamma-ray one: bursts in which this situation occurs are called X-Ray Flashes (XRF, Heise et al., 2001).

The main feature of the prompt emission light curve is the great variety of temporal profiles it shows (see section 1.2): we can find very simple light curves with a FRED (Fast Rise Exponential Decay) structure or very complex multipeaked structures on time scales up to $\delta t_a \approx 10$ ms, where $\delta t_a$ is a single pulse observed width (Piran, 2004). It has been found from the analysis of a
3. GRB Light Curves and Spectra

small sample of GRBs observed by BATSE (Fenimore & Ramirez-Ruiz, 2000) an apparent correlation between the temporal variability and the luminosity of the bursts.

If we look at the more complex light curves, they seem to be composed of individual pulses, each of them being the “building block” of the overall light curve (Piran, 2004). Each pulse is characterized by: a) a FRED structure (Norris et al., 1996), b) an hard-to-soft evolution with the peak energy decreasing exponentially with the photon fluence (Norris et al., 1996), c) a low-energy emission delayed compared to the high-energy one (Norris et al., 1996).

Light curves with internal shocks

Such observed behavior of the GRB light curves has been interpreted within the internal shock model (see section 1.3 and Piran, 1999; Mészáros, 2002; Nakar & Piran, 2002b; Piran, 2004). According to this this model both the pulse duration and the separation between the pulses are determined by the same parameter, namely the time interval between the shells emitted by the inner engine.

Consider two shells separated by a distance $L$ (see i.e. Piran, 2004). The Lorentz factor of the slower outer shell is $\Gamma_s = \Gamma$ and that one of the inner faster shell is $\Gamma_F = a\Gamma$ ($a > 2$ for an efficient collision). The shells are ejected at $t_{a_1}$ and $t_{a_2} \approx t_{a_1} + L/c$, where $t_a$ is the time measured in the observer frame. The collision takes place at a radius $R_s \approx 2\Gamma^2 L$. The emitted photons from the collision will reach the observer at time (omitting the photons flight time, and assuming transparent shells):  

$$t_{a_0} \approx t_{a_1} + R_s/(2c\Gamma^2) \approx t_{a_1} + L/c \approx t_{a_2}.$$  

(3.1)

The photons from this pulse are observed almost simultaneously with a photon that was emitted from the inner engine together with the second shell. This argument has been investigated by various numerical simulations (Kobayashi, Piran & Sari, 1997; Daigne & Mochkovitch, 1998; Panaitescu,
3.1. Observational properties of GRB light curves

Spada & Mészáros, 1999), which argue that for internal shocks the observed light curve replicates the temporal activity of the source.

In order to determine the time interval \( \Delta t_a \) between the pulses we should consider multiple collisions. All combinations of multiple collisions can be divided into three types (Piran, 2004). Consider four shells emitted at times \( t_{a_i} \) \((i = 1, 2, 3, 4)\) separated by a distance \( L \). In the collisions of the first type there are two collisions - between the first and the second shells and between the third and the fourth shells. The first collision will be observed at \( t_{a_2} \) while the second one will be observed at \( t_{a_4} \). Therefore the separation between each pulse results to be \( \Delta t_a \approx t_{a_4} - t_{a_2} \approx 2L/c \).

A different collision scenario occurs if the second and the first shells collide, and afterward the third shell takes over and collide with them (the fourth shell does not play any role in this case). The first collision will be observed at \( t_{a_2} \) while the second one will be observed at \( t_{a_3} \). Therefore, \( \Delta t_a \approx t_{a_3} - t_{a_2} \approx L/c \). Numerical simulations (Nakar & Piran, 2002b) show that more than 80% of the efficient collisions follows one of these two scenarios. Therefore one can estimate:

\[
\Delta t_a \approx L/c .
\]

A third type of multiple collisions arises if the third shell collides with the second shell first, and then the merged shell collides with the first one (again the fourth shell does not play any role in this scenario). In this case the two pulses merge and they will arrive almost simultaneously, at the same time with a photon that would have been emitted from the inner engine simultaneously with the third (fastest) shell. Only a 20% fraction exhibits this type of collision (Piran, 2004).

The pulse width is determined by the angular time (neglecting the cooling time): \( \delta t_a = R_s/(2c\Gamma_s^2) \) where \( \Gamma_s \) is the Lorentz factor of the shocked emitting region. If the shells have an equal mass \( (m_1 = m_2) \) then \( \Gamma_s = \sqrt{a}\Gamma \) while if they have equal energy \( (m_1 = am_2) \) then \( \Gamma_s \approx \Gamma \). Therefore the pulse’s width
### 3. GRB Light Curves and Spectra

is

\[ \delta t_a \approx \begin{cases} 
R_s/2a\Gamma^2c \approx L/ac & \text{equal mass,} \\
R_s/2\Gamma^2c \approx L/c & \text{equal energy.}
\end{cases} \]  

(3.3)

The ratio of the Lorentz factors \( a \) determines the collision’s efficiency. For efficient collisions the variations in the shells Lorentz factor (and therefore \( a \)) must be large. It follows from Eqs. 3.2 and 3.3 that for equal energy shells a correlation between the separation and the width of each pulse \((\Delta t_a - \delta t_a)\) arises naturally from the reflection of the shells initial separation in both variables. However, for equal mass shells, \( \delta t_a \) is shorter by a factor \( a \) than \( \Delta t_a \). This shortens the pulses relative to the intervals. Additionally, the large variance of \( a \) would wipe off the \( \Delta t_a - \delta t_a \) correlation. This suggests that equal energy shells are more likely to produce the observed light curves (Piran, 2004).

#### Light curves with external shocks

Dermer & Mitman (1999) claim that it is possible to obtain GRB light curves via external shocks (see section 1.3). They consider the interaction between a single shell and a clumpy ISM, and they point out that if the direction of a specific ISM blob is almost exactly toward the observer, the corresponding angular time will be \( \delta t_a \sim d^2/cr \), where \( d \) is the size of the blob and \( r \) is the radial coordinate of the emitting shell. These special blobs, hence, would produce strong narrow peaks. Dermer & Mitman (1999) present a numerical simulation of light curves produced by such external shocks on a clumpy ISM obtaining \( \delta t_a \sim 1\% \) of the total duration of the prompt emission \( T_a \), and efficiency of up to \( \sim 10\% \).

This analysis of the light curve poses, however, several criticisms toward this model. It has been pointed out by Sari & Piran (1997) and by Fenimore et al. (1999) that external shocks cannot produce highly variable GRBs, namely with substructure on a scale \( \delta t_a \ll T_a \). In fact they suggest that the peaks produced by the interaction with a single ISM cloud that covers most of the shell’s surface does not work because of the curvature of the expanding shell.
3.1. Observational properties of GRB light curves

prevents the shell from engaging the cloud instantaneously. Such situation delays the emission, so it is not possible to reproduce arbitrarily complex structures. If, on the other hand, only a small fraction of the shell emits the radiation it is possible to produce a variable GRB but the process is very inefficient and it requires more ($\sim 10^3$ times) energy that a simple shell (Fenimore et al., 1999).

Our interpretation of the prompt emission light curve

The internal shock model gives a correct way to interpret the GRB prompt emission light curve, although the possibility to have such internal shocks requires the presence of an inner engine with a prolonged activity (Piran, 2004). In our theory the progenitor is the central black hole that, collapsing, produces almost instantaneously the $e^\pm$ plasma. Moreover, as pointed out in section 2.2.4, we approximate the plasma expansion as a single shell which moves with the same Lorentz factor (a "fireshell"), so internal shocks cannot occur.

Our approach to the analysis of the prompt emission is radically different from the external shock scenario as well. In fact, in our model all the GRB emission after the transparency is produced by the interaction of the accelerated baryons with the ISM, but such interaction is modeled as inelastic collisions (see section 2.3 and Ruffini et al., 2002) and not as shocks. The number of such collisions, hence, depends on the ISM density. In this sense if, as it is, the ISM is inhomogeneous the observed light curve is not smooth but presents a temporal behavior which roughly follows the density profile.

In order to understand how this mechanism works it is useful to analyze the time scales characteristic of the bursts. Suppose to have a burst lasting $T_a \approx 20$ s with substructures $\delta t_a \approx 1$ s. If we evaluate these times in the laboratory frame, assuming $\gamma \approx 150$, we have roughly:

$$\delta t \approx \gamma^2 \delta t_a \approx 4.5 \times 10^5 s$$  \hspace{1cm} (3.4)

(for the exact relation between $t$ and $t_a$ see section 2.3.1 and Ruffini et al.,
2005b; Bianco & Ruffini, 2004, 2005a). This determines the characteristic dimension for the inhomogeneity \( \delta L \approx c\delta t = 1.3 \times 10^{16} \) cm, which is consistent with small clouds of interstellar matter.

The simplest way to model the ISM structure is to assume that \( n_{\text{ISM}} \) is a function only of the radial coordinate, \( n_{\text{ISM}} = n_{\text{ISM}}(r) \) (radial approximation). The ISM is arranged in spherical shells of width \( \approx 10^{15} \) cm positioned in such a way that the modulation of the emitted flux coincides with the observed peaks. It is important to notice that, when the accelerated baryons collide with a shell, the increase in the flux is almost immediate due to the photons coming from the line of sight. Then it follows an exponential decrease of the flux due to the contribution of the photons emitted from different angles. In this way we obtain the observed FRED structure for each peak, together with all the other observed peculiarities (hard-to-soft transition, spectral lag).

Of course our “radial approximation” is valid until the visible area of the incoming baryonic pulse is comparable with the characteristic dimensions of the clouds. The transverse dimension of such area is \( R_T = r \sin \vartheta \), where \( \vartheta \sim 1/\gamma \) is the relativistic beaming angle, so we have \( R_T \approx r/\gamma \). We have found in many cases that this approximation cannot be valid during the whole prompt emission. In fact, as it happens for GRB991216 (Ruffini et al., 2002) and GRB050315 (see the following section and Ruffini et al., 2006a), when the accelerated baryons impact with dense clouds of ISM, they are decelerated and their gamma factor drops abruptly. In this situation, after the first peaks the visible area becomes comparable with the size of the clouds and our approximation is not valid anymore. The other situation in which this approximation fails is when the radial coordinate \( r \) at which the prompt emission occurs is big and, again, the size of the visible area of the pulse becomes comparable with the ISM clouds (see for example Guida et al., 2006).

The criticism moved toward the possibility that external shocks can produce variable GRBs (Sari & Piran, 1997; Fenimore et al., 1999) is valid but,
as we have shown here, only when the emitting surface is “big”. During the prompt emission the Lorentz factor is usually very high ($\gamma \approx 150$) and consequently the angular spreading or the curvature of the shell is not relevant. We will show for all the GRBs analyzed in this and in the following chapters (we recall here also GRB991216 (Ruffini et al., 2002, 2003), which represents the first example for the validity of our treatment) that our numerical simulations evidently confirm such possibility.

### 3.1.2 The afterglow

After the prompt emission occurrence, the afterglow multiwavelenght emission starts. Among all, the X-ray afterglow usually is the first and strongest, but shortest signal. The overall energy emitted in this stage is generally a few percent of the GRB total energy. From its early discovery to the most recent missions the observations of the X-ray afterglow usually have started several hours after the prompt emission. In this region the X-ray afterglow fluxes show a phenomenological power-law dependence on $\nu$ and on the observed time $t$ (Piro, 2001): $f_\nu(t) \propto \nu^{-\beta} t^{-\alpha}$, with $\alpha \sim 1.4$ and $\beta \sim 0.9$.

Together with this X-ray emission GRBs show optical and IR afterglow. The observed optical afterglow is typically around 19–20 mag one day after the burst. The signal decays, initially, as a power-law in time, $t^{-\alpha}$ with a typical value of $\alpha \approx 1.2$ and large variations around this value.

Many afterglow light curves show a change in the power-law index to a steeper decline with $\alpha \approx 2$. Such “break” in the afterglow usually is chromatic but in few cases it has been observed in different energy bands. A classical example of such situation was seen in GRB990510 (Harrison et al., 1999; Stanek et al., 1999). It is common to fit the break with a phenomenological formula: $F_\nu(t) = f_* (t/t_*)^{-\alpha_1} \{1 - \exp[-(t/t_*)^{(\alpha_1-\alpha_2)}][t/t_*]^{(\alpha_1-\alpha_2)}\}$ (Piran, 2004). This break is commonly interpreted as a “jet break” (see section 1.3.3) and the time at which such break occurs is used to estimate the opening angle of the jet (Rhoads, 1999; Sari, Piran & Halpern, 1999) or the viewing angle within the standard jet model (Rossi et al., 2002).
3. GRB Light Curves and Spectra

Figure 3.1: Example of GRB afterglow light curves observed by *Swift*, showing the two different trends reported by Chincarini et al. (2005). Picture from Nousek et al. (2006).
3.1. Observational properties of GRB light curves

With the launch of Swift a new era started for the study of the Gamma-Ray Bursts. Swift’s primary goal is not only to detect a statistically significant sample of GRBs, but also to collect data in the X-ray (0.2–10 keV) and optical (1700–6500 Å) bands after the initial few tens of seconds after the trigger. The result is that the afterglow light curve show a more complex behavior than the simple power-law decay observed up to now.

The soft X-ray light curves observed by Swift up to now can be divided in two morphological types (Chincarini et al., 2005): those starting off with a very steep light curve decay and those showing a rather mild initial decay. Most of the observed GRB afterglows belong to the first group, showing what has been called a “canonical” behavior (Nousek et al., 2006, see Fig. 3.1): after the initial steep decay \( F \propto t^{-\alpha_1} \), with \( 3 \leq \alpha_1 \leq 5 \) the light curve shows a shallow decay \( F \propto t^{-\alpha_2} \), with \( 0.5 \leq \alpha_2 \leq 1 \) followed by a somewhat steeper decay \( F \propto t^{-\alpha_3} \), with \( 1 \leq \alpha_3 \leq 1.5 \), consistent with those seen in previous missions (Nousek et al., 2006). The spectrum, except in few cases, remains constant throughout all these stages of the afterglow (Nousek et al., 2006). It is noteworthy that the final “break” has been seen only in less than \(~ 10\%\) of the afterglow followed by Swift (Mészáros, 2006).

The early X-ray light curves obtained with Swift XRT often show flares (Nousek et al., 2006, see Fig. 3.2). Some of these flares have very sharp temporal features where the flux changes significantly on time scales \( \delta t_a \ll T_a \) (Burrows et al., 2005b). Most flares have a very steep rise and decay (with very large temporal rise/decay indices when fitted with a power-law). When the flare is bright enough to follow its spectral evolution, its hardness ratio evolves during the flare, and its spectral index is somewhat different from the one associated with the underlying power-law decay of the X-ray light curve before and after the flare (Burrows et al., 2005b). Furthermore, the fluxes before and after the flare lie approximately on the same power-law decay.
Figure 3.2: Examples of GRB afterglow light curves with X-ray flares (Nousek et al., 2006).
3.1. Observational properties of GRB light curves

Interpretations of the observations within the fireball model

These new observational features have found several possible explanations within the standard fireball model (see section 1.3).

The most accepted explanation for the early rapid flux decay is that such emission is still prompt emission coming from large angles relative to our line of sight that reaches us at late times (Nousek et al., 2006).

An alternative model for the initial fast decay is reverse shock emission from large angles relative to our line of sight (Kobayashi et al., 2005). This emission might be either synchrotron or synchrotron self-Compton. The synchrotron process is expected to produce optical/IR photons, which are up-scattered into the X-ray band by electrons heated by the reverse shock (Kobayashi et al., 2005). This interpretation would require, however, a large Compton Y-parameter, and in turn a very low magnetization of the GRB outflow (Nousek et al., 2006).

Finally, several other models can also be considered to explain this part of the X-ray light curve (Tagliaferri et al., 2005). For example, emission from the hot cocoon\textsuperscript{1} in the context of the Collapsar model (Mészáros & Rees, 2001; Ramirez-Ruiz, Celotti & Rees, 2002) might produce a sufficiently steep flux decay, but would naturally produce a quasi-thermal spectrum which does not agree with the observed power-law spectrum. Photospheric emission as the ejecta becoming optically thin (Rees & Mészáros, 2005; Ramirez-Ruiz, 2005) is also possible, as it may be able to produce significant deviations from a thermal spectrum. Nevertheless it is unclear how this emission would last longer than the prompt gamma-ray emission itself. Tagliaferri et al. (2005) have also suggested that the “patchy shell” model (Kumar & Piran, 2000b), where there are angular inhomogeneities in the outflow, might produce a sufficiently fast decay if our line of sight is within a hot spot in the jet causing a mini-jet break as the flow is decelerated by the external medium. However, this would produce a decay significantly lower than the typical

\textsuperscript{1}A cocoon is the waste heat enclosed by the dense envelope of a collapsing star from a relativistic jet propagating in such stellar envelope (Zhang, Woosley & MacFadyen, 2003).
observed values of $\alpha_1$.

The shallow intermediate flux decay ($\alpha_2$) can be caused by continuous energy injection into the forward shock ("refreshed shocks", see section 1.3) (Nousek et al., 2006). This energy injection can be achieved in two ways: even if the ejecta are emitted promptly but with a range of Lorentz factors, the lower $\Gamma$ shells arrive much later to the foremost fast shells which have already been decelerated (Mészáros, 2006), resulting in a smooth and gradual energy injection in the afterglow shock. In this case the central engine is not active late, but its effects are seen late (Mészáros, 2006). Energy injection could also be caused by a long lasting activity of the central source, which keeps ejecting significant amounts of energy in a highly relativistic outflow up to several hours after the GRB (Nousek et al., 2006). However, this requires the source luminosity to decay very slowly with time, $L \propto t^q$ with $q > -1$, where most of the energy is extracted up to several hours after the GRB. One might be able to distinguish between these two scenarios for energy injection by the help of early broad band observations, since the emission from the reverse shock is expected to be different for these two cases (Nousek et al., 2006).

The third power-law segment of the light curve ($\alpha_3$) is most likely the well known afterglow interpreted as emission from an adiabatic external shock (Sari, Piran & Narayan, 1998; Granot & Sari, 2002).

Many interpretations have been provided also to explain the recently discovered X-ray flares. The most common explanation is a central engine activity which results in internal shocks (or similar energy dissipation events) at later times (Zhang et al., 2006). Another possibility is emission from reverse shock, but the predicted amplitude is too low to interpret all the cases (Burrows et al., 2005b; Zhang et al., 2006). Alternatively such emission could be produced by a multi-component jet (Mészáros & Rees, 2001; Ramirez-Ruiz, Celotti & Rees, 2002; Kumar & Piran, 2000a): the X-ray flare is caused by the deceleration of the wider cocoon component with the ambient medium. In this case, however, the decay after the peak should follow the standard afterglow model, so it cannot interpret the observed rapid fall-off in the flares.
3.1. Observational properties of GRB light curves

(Zhang et al., 2006). The same problem (Zhang et al., 2006) affects also the scenario in which the flare is produced by the energy injection into the decelerating shell by the collision with a high-\(\Gamma\) shell (Kumar & Piran, 2000b).

Our theory of the afterglow emission

Within our theory we don’t need to invoke different physical processes to explain the behavior of the decaying part of the afterglow. The mechanism responsible for such emission is the same that produces the prompt emission: the interaction of the accelerated baryons with the ISM. The main difference in these two stages producing substantially different light curves is that now the Lorentz gamma factor is low (\(\gamma \approx 10\)) so the effect of the ISM inhomogeneities is smoothened. The variability in the afterglow light curve observed by *Swift* arises naturally from the variation in the values of the effective particle number density and in the effective emitting area. In particular the role of the effective emitting area of the shell, \(R\), is relevant during this stage. As it will be clarified in the following section, it is linked to the energy of the emitted radiation. An abrupt increase in \(R\) suppresses the high-energy emission, producing a consequent abrupt decrease in the light curve (initial steep decay). Otherwise, if it remains constant, it can enhance the emission for example during the “plateau” in the light curve (shallow decay). In Fig. 3.3 there are represented the ISM parameters’ behavior compared with one “canonical” afterglow in order to better understand how their trend influences the light curve.

Our interpretation is consistent with the arising difficulty in dividing the prompt emission from the “properly-called” afterglow. The observations of the initial steep decay and of the flares (Nousek et al., 2006), usually attributed to the progenitor late activity (Zhang et al., 2006), have given evidence for an unitary picture of the GRB light curve, enforcing our view of the GRB as a whole, without the necessity to introduce different mechanism to describe each part.

Moreover, it is important to notice that our model assumes spherical
Figure 3.3: ISM effective particle number density and effective emitting area versus radial coordinate for GRB050315 (see section 3.3) compared with its X-ray “canonical” light curve. Even if it is not easy to establish a correspondence between them it is useful to notice the ISM parameters’ trend during the characteristics stages of the afterglow.
symmetry. Again this is consistent with the Swift observations that show the absence of jet breaks at least for small values of the opening angle.

We are working also on the interpretation of the flares observed in the early afterglow as produced by the same process responsible for the afterglow emission. This idea has found some criticism because the variation caused by density inhomogeneities is considered not very significant (Ramirez-Ruiz et al., 2005b; Zhang et al., 2006). Indeed the one-dimensional approximation used in these estimates finds the same problems we described in the previous section. When the Lorentz factor is too small and/or the shell is too distant from the progenitor the visible area of the shell is comparable with the density cloud and this approximation fails. A correct treatment of the 3-dimensional structure of the ISM clouds is needed. We tested our idea on GRB011121 (Bianco, Caito & Ruffini, 2006; Caito et al., 2006a), an old burst observed by BeppoSAX which for the first time showed features similar to the X-ray flares, obtaining good results that demonstrate the validity of such proposal.

### 3.2 GRB spectra

The GRB observed spectrum appears to be non thermal and it usually varies strongly from one burst to another. Nevertheless, an excellent phenomenological fit for the spectrum was introduced by Band et al. (1993) using two power-laws joined smoothly at a break energy \((\alpha - \beta)E_0\):

\[
N(\nu) = N_0 \begin{cases}
(h\nu)^\alpha e^{-\frac{h\nu}{E_0}}, & h\nu < (\alpha - \beta)E_0 \\
((\alpha - \beta)E_0)^{\alpha-\beta}(h\nu)^\beta e^{(\beta-\alpha)}, & h\nu > (\alpha - \beta)E_0.
\end{cases}
\] (3.5)

This function provides an excellent fit to most of the observed spectra but there is no particular theoretical model that predicts this spectral shape.

**The observed Band spectrum has been explained within the standard fireball model** (see section 1.3) as synchrotron emission of the fireball relativistic electrons (Rybicki & Lightman, 1979). The typical energy of
3. GRB Light Curves and Spectra

synchrotron photons depends on the Lorentz factor of the relativistic electron under consideration $\gamma_e$:

$$h\nu_{\text{syn}} = \frac{\hbar e B}{m_e c} \gamma_e \Gamma,$$  \hspace{1cm} (3.6)

where $\Gamma$ is the Lorentz factor of the emitting material and $B$ is the magnetic field.

The instantaneous synchrotron spectrum of a single relativistic electron with an initial energy $\gamma_e m_e c^2$ is approximately a power-law with $F_\nu \propto \nu^{1/3}$ up to $\nu_{\text{syn}}(\gamma_e)$ and an exponential decay above it. This description is suitable when the electron does not loose a significant fraction of its energy into radiation. This requires $\gamma_e$ to be less than a critical value $\gamma_c$ given by $\Gamma \gamma_e m_e c^2 = F(\gamma_c) t$, where $F$ is the spectral power and $t$ refers to the time in the observer frame. When $\gamma_e > \gamma_c$ the spectral power varies as $F_\nu \propto \nu^{-1/2}$.

To calculate the overall spectrum one need to integrate over the electrons’ Lorentz factor distribution. The simplest distribution is $N(\gamma_e) \sim \gamma_e^{-p}$, with $p > 2$. The minimum Lorentz factor of the distribution $\gamma_m$ is

$$\gamma_m = \frac{p-2}{p-1} \langle \gamma_e \rangle,$$  \hspace{1cm} (3.7)

which plays an important role in this treatment as it characterizes the “typical” synchrotron frequency $\nu_m = \nu_{\text{syn}}(\gamma_m)$.

The lowest part of the overall spectrum is always the sum of the contributions of the tails of all the electrons’ emissions: $F_\nu \propto \nu^{1/3}$. The most energetic electrons, instead, will always be cooling rapidly and emit practically all their energy at their synchrotron frequency, thus $F_\nu \propto \nu^{-p/2}$.

In the intermediate frequency region the spectrum varies depending if the electrons are in a “fast cooling” ($\nu_m > \nu_c$) or in a “slow cooling” ($\nu_c > \nu_m$) regimes. The net spectrum in the first case results to be:

$$F_\nu \propto \begin{cases} 
(\nu/\nu_c)^{1/3} F_{\nu,\text{max}}, & \nu < \nu_c \\
(\nu/\nu_c)^{-1/2} F_{\nu,\text{max}}, & \nu_c < \nu < \nu_m \\
(\nu_m/\nu_c)^{-1/2}(\nu/\nu_m)^{-p/2} F_{\nu,\text{max}}, & \nu_m < \nu.
\end{cases}$$  \hspace{1cm} (3.8)
3.2. GRB spectra

In the “slow cooling” regime we have, instead:

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

(3.9)

Fast cooling must take place during the GRB itself: the internal shocks must emit their energy effectively or there will be a serious inefficiency problem (Piran, 2004). Additionally, the pulse won’t be variable if the cooling time is too long. The electrons must cool rapidly and release all their energy. It is most likely that during the early stages of an external shock there will be a transition from fast to slow cooling (Mészáros & Rees, 1997b; Waxman, 1997a; Mészáros, Rees, & Wijers, 1998; Waxman, 1997b).

At low frequencies synchrotron self-absorption may take place. It leads to a steep cutoff of the low-energy spectrum, as \( \nu^{5/2} \) or as \( \nu^2 \) (Piran, 2004).

Inverse Compton (IC) scattering may modify this analysis in several ways. It can influence the spectrum even if the system is optically thin to Compton scattering (Rybicki & Lightman, 1979). In view of the high energies involved, a photon can be inverse Compton scattered just once; multiple scatterings are very unlikely. The effect of IC depends on the Comptonization parameter \( Y = \gamma^2\tau_e \) (\( \tau_e \) is the electrons’ opacity): it becomes important when \( Y > 1 \). Its effect is to add an ultrahigh-energy component to the GRB spectrum and to speed up the cooling of the emitting regions and shorten the cooling time by a factor \( Y \) (Piran, 2004).

Within our treatment we interpret the phenomenological Band spectrum in a completely different way. As it will be clarified in section 3.4, it is not necessary to have a power-law spectrum in the comoving frame to obtain an observed power-law spectrum.

We adopt two basic assumptions (Ruffini et al., 2004b):

- the resulting radiation as viewed in the comoving frame has a thermal spectrum
• the ISM swept up by the front of the baryonic shell is responsible for this thermal emission.

The choice of thermal spectrum is the only possibility if we rule out the existence of the strong magnetic fields that produce the synchrotron emission. In fact such emission requires highly magnetized outflows, but it is not clear how they can be achieved.

In our case the radiation is produced in the inelastic collision between the accelerated baryons and the ISM. The structure of the collision is determined by mass, momentum and energy conservation, i.e. by the constancy of the specific enthalpy, which are standard conditions in the expanding matter rest frames (Zel’dovich & Rayzer, 1966). The only additional free parameter of our model to model this emission process is the size of the “effective emitting area” of the emitting shell: \( A_{\text{eff}} \).

The power emitted in the interaction of the baryonic shell with the ISM inhomogeneities measured in the comoving frame is:

\[
\frac{\Delta E_{\text{int}}}{\Delta t} = 4\pi r^2 \mathcal{R} \sigma T^4, \tag{3.10}
\]

where \( \Delta E_{\text{int}} \) is the internal energy developed in the collision with the ISM in the co-moving frame, \( T \) is the black body temperature in the comoving frame, \( \sigma \) is the Stefan-Boltzmann constant and

\[
\mathcal{R} = \frac{A_{\text{eff}}}{A_{\text{tot}}} \tag{3.11}
\]

is the “surface filling factor” which accounts for the fraction of the shell’s surface becoming active, being the ratio between the “effective emitting area” and the total area \( A_{\text{tot}} \). The ratio \( \mathcal{R} \) is a priori a function that varies as the system evolves so it is evaluated at every given value of the radius \( r \).

We are now ready to evaluate the source luminosity in a given energy band (Ruffini et al., 2004b). The source luminosity at a detector arrival time \( t_a \), per unit solid angle \( d\Omega \) and in the energy band \([\nu_1, \nu_2]\) is given by (see Ruffini et al., 2003):

\[
\frac{dE[\nu_1, \nu_2]}{dt_a d\Omega} = \int_{EQTS} \frac{\Delta \varepsilon}{4\pi} v \cos \vartheta \Lambda^{-4} \frac{dt}{dt_a} W(\nu_1, \nu_2, T_{\text{arr}}) d\Sigma, \tag{3.12}
\]
where $\Delta \varepsilon = \Delta E_{\text{int}}/V$ is the emitted energy density released in the comoving frame assuming, for simplicity, that all the shell is emitting, $\Lambda = \gamma (1 - (v/c) \cos \vartheta)$ is the Doppler factor, $d\Sigma$ is the surface element of the EQTS at detector arrival time $t_d^a$ on which the integration is performed and $T_{\text{arr}}$ is the observed temperature of the radiation emitted from $d\Sigma$:

$$T_{\text{arr}} = \frac{\Lambda^{-1} T}{(1 + z)} .$$  (3.13)

The “effective weight” $W(\nu_1, \nu_2, T_{\text{arr}})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature $T_{\text{arr}}$ to the total integral $aT_{\text{arr}}^4$:

$$W(\nu_1, \nu_2, T_{\text{arr}}) = \frac{1}{aT_{\text{arr}}^4} \int_{\nu_1}^{\nu_2} \rho(T_{\text{arr}}, \nu) \frac{h\nu}{c} d\left(\frac{h\nu}{c}\right)^3 ,$$  (3.14)

where $\rho(T_{\text{arr}}, \nu)$ is the Planckian distribution at temperature $T_{\text{arr}}$:

$$\rho(T_{\text{arr}}, \nu) = \frac{2}{h^3 \exp^{h\nu/(kT_{\text{arr}})} - 1} .$$  (3.15)

Once we have the luminosity in a given energy band in the same way we can evaluate the instantaneous and the time-integrated photon number spectrum. In section 3.4 we will show explicitly in one case the results of such calculation and their agreement with the observed spectrum.

### 3.3 GRB050315: the “canonical” light curve

GRB050315 (Vaughan et al., 2006) has been triggered and located by the BAT instrument (Barthelmy, 2004; Barthelmy et al., 2005a) on board of the Swift satellite (Gehrels et al., 2004) at 20:59:42 UT (Parson et al., 2005). The narrow field instrument XRT (Burrows et al., 2004, 2005a) began observations $\sim 80$ s after the BAT trigger, one of the earliest XRT observations yet made, and continued to detect the source for $\sim 10$ days (Vaughan et al., 2006). The spectroscopic redshift has been found to be $z = 1.949$ (Kelson & Berger, 2005).

Figure 3.4: Our theoretical fit (red line) of the BAT observations (green points) of GRB050315 in the 15–350 keV (a), 15–25 keV (b), 25–50 keV (c), 50–100 keV (d) energy bands (Vaughan et al., 2006). The blue line in panel (a) represents our theoretical prediction for the intensity and temporal position of the P-GRB.
3.3. GRB050315: the “canonical” light curve

We have chosen this burst to illustrate the features of the GRB light curves within our model because it represents a good example of what has been addressed as “canonical light curve”. In fact thanks to the data provided by the Swift satellite we can test our theoretical predictions on the GRB structure presented in sections 3.1.1 and 3.1.2 with a detailed fit of the complete GRB050315 afterglow light curve from the prompt emission all the way to the latest phases without any gap in the observational data.

3.3.1 The fit of the observations

The best fit of the observational data leads to a total energy of the initial $e^\pm$ plasma, $E_{\text{tot}}^{e\pm} = 1.46 \times 10^{53}$ erg (the observational Swift $E_{\text{iso}}$ is $> 2.62 \times 10^{52}$ erg; Vaughan et al., 2006), so that the plasma is created between the radii $r_1 = 5.88 \times 10^6$ cm and $r_2 = 1.74 \times 10^8$ cm with an initial temperature $T = 2.05$ MeV and a total number of pairs $N_{e\pm} = 7.93 \times 10^{57}$. The second parameter of the theory, the baryon loading $B$, is found to be $B = 4.55 \times 10^{-3}$. The transparency point and the P-GRB emission occurs then with an initial Lorentz gamma factor of the accelerated baryons $\gamma_0 = 217.81$ at a distance $r_0 = 1.32 \times 10^{14}$ cm from the progenitor.

The BAT data

In Fig. 3.4 we represent our theoretical fit of the BAT observations in the three energy channels 15–25 keV, 25–50 keV and 50–100 keV and in the whole 15–350 keV energy band.

In our model the GRB emission starts at the transparency point when the P-GRB is emitted; this instant of time is often different from the moment in which the satellite instrument triggers, due to the fact that sometimes the P-GRB is under the instrumental threshold or comparable with it. In order to compare our theoretical predictions with the observations, it is important to estimate and take into account this time shift. In the present case it has been observed (Vaughan et al., 2006) a possible precursor $\approx 50$ s before the trigger. Such a precursor is indeed in agreement with our theoretically
predicted P-GRB emitted isotropic energy (which we theoretically predict to be $E_{P-GRB} = 1.98 \times 10^{51}$ erg) assuming a temporal separation from the peak of the afterglow $\Delta t_a = 51$ s. In Fig. 3.4.a we schematically represent (blue line) our theoretical prediction for the P-GRB.

After the P-GRB emission, all the observed radiation is produced by the interaction of the expanding baryonic shell with the interstellar medium. In order to reproduce the complex time variability of the prompt emission light curve as well as of the afterglow one, we describe the ISM structure as a sequence of overdense spherical regions separated by much less dense regions. In the prompt emission phase, the small angular size of the source visible area due to the relativistic beaming makes such a spherical approximation an excellent one.

The structure of the prompt emission has been reproduced assuming three overdense spherical ISM regions with width $\Delta$ and density contrast $\Delta n/\langle n \rangle$: we chose for the first region, at $r = 4.15 \times 10^{16}$ cm, $\Delta = 1.5 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 5.17$, for the second region, at $r = 4.53 \times 10^{16}$ cm, $\Delta = 7.0 \times 10^{14}$ cm and $\Delta n/\langle n \rangle = 36.0$ and for the third region, at $r = 5.62 \times 10^{16}$ cm, $\Delta = 5.0 \times 10^{14}$ cm and $\Delta n/\langle n \rangle = 85.4$. The ISM mean effective density during this phase is $\langle n_{ISM} \rangle = 0.81$ particles/cm$^3$ and $\langle R \rangle = 1.4 \times 10^{-7}$. With this choice of the density mask we obtain agreement with the observed light curve, as shown in Fig. 3.4. A small discrepancy occurs in coincidence with the last peak: this is due to the fact that at this stage the source visible area due to the relativistic beaming is comparable with the size of the clouds, therefore the spherical shell approximation should be duly modified by a detailed analysis of a full 3-dimensional ISM structure. Fig. 3.4 shows also the theoretical fit of the light curves in the three BAT energy channels in which the GRB has been detected (15–25 keV in Fig. 3.4b, 25–50 keV in Fig. 3.4c, 50–100 keV in Fig. 3.4d).
3.3. GRB050315: the “canonical” light curve

Figure 3.5: Our theoretical fit (blue line) of the XRT observations (green points) of GRB 050315 in the 0.2–10 keV energy band (Vaughan et al., 2006). The theoretical fit of the BAT observations (see Fig. 3.4a) in the 15–350 keV energy band is also represented (red line).
3. GRB Light Curves and Spectra

The XRT data

The same analysis can be applied to explain the features of the XRT light curve in the afterglow phase. In our treatment they are automatically described by the same mechanism responsible for the prompt emission: the baryonic shell expands in an ISM region, between \( r = 9.00 \times 10^{16} \text{ cm} \) and \( r = 5.50 \times 10^{18} \text{ cm} \), which is significantly at lower density \( \langle n_{\text{ISM}} \rangle = 4.76 \times 10^{-4} \text{ particles/cm}^3 \), \( \langle R \rangle = 7.0 \times 10^{-6} \) then the one corresponding to the prompt emission, and this produces a slower decrease of the velocity of the baryons with a consequent longer duration of the afterglow emission. The initial steep decay of the observed flux is due to the smaller number of collisions with the ISM. In Fig. 3.5 is represented our theoretical fit of the XRT data, together with the theoretically computed 15–350 keV light curve of Fig. 3.4a.

3.3.2 Conclusions on GRB050315

In our analysis of GRB050315 we have obtained a good match between the observational data and our predicted luminosity with continuous light curves which range from the “prompt emission” all the way to the latest phases of the afterglow. This certainly supports our model and opens a new phase of using it to identify the astrophysical scenario underlying the GRB phenomena. In particular:

1. We have verified that the “prompt emission” is not necessarily due to the prolonged activity of an inner engine, but we can reproduce its features if we identify it with the peak of the afterglow emission.

2. The “canonical behavior” in almost all the GRBs observed by Swift as well as the time structure of the “prompt emission” naturally arise from the fluctuations of the parameters characterizing the ISM.

3. We have uniquely identified the fundamental parameters characterizing the GRB energetics: the total energy of the \( e^\pm \) plasma \( E_{e^\pm}^{\text{tot}} = 1.46 \times 10^{53} \text{ erg} \) and the baryon loading \( B = 4.55 \times 10^{-3} \).
4. We have a theoretical prediction on the total energy emitted in the P-GRB: \( E_{P-GRB} = 1.98 \times 10^{51} \text{ erg} \), compatible with the observations.

3.4 GRB031203

GRB031203 was observed by IBIS, on board of the INTEGRAL satellite (Mereghetti & Göts, 2003), as well as by XMM (Watson et al., 2004) and *Chandra* (Soderberg et al., 2004) in the 2–10 keV band, and by VLT (Soderberg et al., 2004) in the radio band. It appears as a typical long burst (Sazonov, Lutovinov & Sunyaev, 2004), with a simple profile and a duration of \( \approx 40 \text{ s} \). The burst fluence in the 20–200 keV band is \((2.0 \pm 0.4) \times 10^{-6} \text{ erg/cm}^2\) (Sazonov, Lutovinov & Sunyaev, 2004), and the measured redshift is \( z = 0.106 \) (Prochaska et al., 2004).

3.4.1 The fit of the observations

The best fit of the observational data leads to a total energy of the initial \( e^\pm \) plasma, \( E_{e^\pm}^{\text{tot}} = 1.85 \times 10^{50} \text{ erg} \), so that the plasma is created between the radii \( r_1 = 2.95 \times 10^6 \text{ cm} \) and \( r_2 = 2.81 \times 10^7 \text{ cm} \) with an initial temperature \( T = 1.52 \text{ MeV} \) and a total number of pairs \( N_{e^\pm} = 2.98 \times 10^{55} \). The second parameter of the theory, the baryon loading \( B \), is found to be \( B = 7.4 \times 10^{-3} \). The transparency point and the P-GRB emission occurs then with an initial Lorentz gamma factor of the accelerated baryons \( \gamma_0 = 132.8 \) at a distance \( r_0 = 6.02 \times 10^{12} \text{ cm} \) from the progenitor.

In order to compare our theoretical prediction with the observations, it is important to notice that, as for GRB050315 (see section 3.3), there is a shift between the initial time of the GRB event and the moment in which the satellite instrument has been triggered due to the lack in the detection of the P-GRB which in our theory, we recall, sets the beginning of the GRB

Figure 3.6: Theoretically simulated light curve of the GRB031203 prompt emission in the 20–200 keV energy band (solid red line) compared with the observed data (green points) (Sazonov, Lutovinov & Sunyaev, 2004). The vertical bold red line indicates the time position of P-GRB.
emission. In the present case it results in $\Delta t_a^d = 3.5$ s (see the bold red line in Fig. 3.6).

The structure of the GRB031203 prompt emission, which is a single peak with a slow decay, is reproduced assuming an ISM which has not a constant density but presents several overdense regions with $\langle n_{ISM} \rangle = 0.16$ particle/cm$^3$ and $\langle R \rangle = 1.0 \times 10^{-8}$. Such regions corresponding to the main peak are modeled as three spherical shells with width $\Delta$ and density contrast $\Delta n/\langle n \rangle$: we adopted for the first peak $\Delta = 3.0 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 8$, for the second peak $\Delta = 1.0 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 1.5$ and for the third one $\Delta = 7.0 \times 10^{14}$ cm and $\Delta n/\langle n \rangle = 1$. Due to the finite resolution of the INTEGRAL instrument it is enough to describe the average density distribution compatible with the given accuracy. Only structures at scales of $10^{15}$ cm can be identified, while smaller structures would need a stronger signal and/or a smaller time resolution of the detector.

The result (see Fig. 3.6) shows a good agreement with the light curve reported by Sazonov, Lutovinov & Sunyaev (2004), and it provides a further evidence for the possibility of reproducing light curves with a complex time variability through ISM inhomogeneities.

### 3.4.2 The GRB031203 instantaneous spectrum

In Fig. 3.7 are shown samples of time-resolved spectra for five different values of the arrival time which cover the whole duration of the event. It is manifest from this picture that, although the spectrum in the co-moving frame of the expanding pulse is thermal, the shape of the final spectrum in the laboratory frame is clearly non thermal. In fact, as pointed out in section 3.2, each single instantaneous spectrum is the result of an integration of hundreds of thermal spectra over the corresponding EQTS. This calculation produces a non thermal instantaneous spectrum in the observer frame (see Fig. 3.7).

Another distinguishing feature of the GRBs spectra which is also present in these instantaneous spectra, as shown in Fig. 3.7, is the hard to soft transition during the evolution of the event (Crider et al., 1997; Piran, 1999;
3. GRB Light Curves and Spectra

Figure 3.7: Five different theoretically predicted instantaneous photon number spectrum $N(E)$ for $t_a = 2, 6, 10, 14, 18$ s are here represented (colored curves) together with their own temporal convolution (black bold curve). The shapes of the instantaneous spectra are not blackbodies due to the spatial convolution over the EQTS (see text).
Figure 3.8: The energy of the peak of the instantaneous photon number spectrum $N(E)$ is here represented as a function of the arrival time during the “prompt emission” phase. The clear hard to soft behavior is shown.

Frontera et al., 2000; Ghirlanda, Celotti & Ghisellini, 2002). In fact the peak of the energy distributions $E_p$ drift monotonically to softer frequencies with time (see Fig. 3.8). This feature explains the change in the power-law low energy spectral index $\alpha$ (Band et al., 1993) which at the beginning of the prompt emission of the burst ($t_a^d = 2$ s) is $\alpha = 0.75$, and progressively decreases for later times (see Fig. 3.7). In this way the link between $E_p$ and $\alpha$ identified by Crider et al. (1997) is explicitly shown. This theoretically predicted evolution of the spectral index during the event unfortunately cannot be detected in this particular burst by INTEGRAL because of the not sufficient quality of the data (Sazonov, Lutovinov & Sunyaev, 2004).
3.4.3 The GRB031203 time-integrated spectrum and the comparison with the observed data

The time-integrated observed GRB spectra show a clear power-law behavior. Within a different framework Pozdniakov, Sobol & Sunyaev (1983) argued that it is possible to obtain such power-law spectra from a convolution of many non power-law instantaneous spectra evolving in time. This result was recalled and applied to GRBs by Blinnikov, Kozyreva & Panchenko (1999) assuming for the instantaneous spectra a thermal shape with a temperature changing with time. They showed that the integration of such energy distributions over the observation time gives a typical power-law shape possibly consistent with GRB spectra.

Our specific quantitative model is more sophisticated than the one considered by Blinnikov, Kozyreva & Panchenko (1999): as pointed out in section 3.2, the instantaneous spectrum here is not a black body. Each instantaneous spectrum is obtained by an integration over the corresponding EQTS: it is itself a convolution, weighted by appropriate Lorentz and Doppler factors, of $\sim 10^6$ thermal spectra with variable temperature. Therefore, the resulting spectra are not plain convolutions of thermal spectra: they are convolutions of convolutions of thermal spectra (see Fig. 3.7).

The simple power-law shape of the integrated spectrum is more evident if we sum tens of instantaneous spectra, as in Fig. 3.9. In this case we divided the prompt emission in three different time interval, and for each one we integrated on time the energy distribution. The resulting three time-integrated spectra have a clear non-thermal behavior, and still present the characteristic hard to soft transition.

Finally, we integrated the photon number spectrum $N(E)$ over the whole duration of the prompt event (see again Fig. 3.9): in this way we obtain a typical non-thermal power-law spectrum which results to be in good agreement with the INTEGRAL data (Sazonov, Lutovinov & Sunyaev, 2004) and gives a clear evidence of the possibility that the observed GRBs spectra are originated from a thermal emission.
Figure 3.9: Three theoretically predicted time-integrated photon number spectra $N(E)$ are here represented for $0 \leq t_d^a \leq 5$ s, $5 \leq t_d^a \leq 10$ s and $10 \leq t_d^a \leq 20$ s (colored curves). The hard to soft behavior presented in Fig. 3.8 is confirmed. Moreover, the theoretically predicted time-integrated photon number spectrum $N(E)$ corresponding to the first 20 s of the “prompt emission” (black bold curve) is compared with the data observed by INTEGRAL (Sazonov, Lutovinov & Sunyaev, 2004). This curve is obtained as a convolution of 108 instantaneous spectra, which are enough to get a good agreement with the observed data.
3. GRB Light Curves and Spectra

3.4.4 Conclusions on GRB031203

In this section we confirm how, applying our model to GRB031203, we are able to predict the whole dynamic of the process which originates the GRB emission fixing in a unique way the two free parameters of the model, $E_{\text{tot}}^{\pm}$ and $B$. Moreover, it is possible to obtain the exact temporal structure of the prompt emission taking into account the effective ISM structure.

The important point we want to emphasize is that we can get both the luminosity emitted in a fixed energy band and the photon number spectrum starting from the hypothesis that the radiation emitted in the GRB process is thermal in the co-moving frame of the expanding pulse. It has been clearly shown that, after the correct space-time transformations, both the time-resolved and the time-integrated spectra in the observer frame strongly differ from a Planckian distribution and have a power-law shape, although they originate from strongly time-varying thermal spectra in the co-moving frame. We obtain a good agreement of our prediction with the photon number spectrum observed by INTEGRAL and, in addition, we predict a specific hard-to-soft behavior in the instantaneous spectra.

Despite this GRB is often considered as “unusual” (Watson et al., 2004; Soderberg et al., 2004), in our treatment we are able to explain its low gamma-ray luminosity in a natural way, giving a complete interpretation of all its spectral features. In agreement to what has been concluded by Sazonov, Lutovinov & Sunyaev (2004), it appears to us as an intrinsically subenergetic GRB ($E_{\text{tot}}^{\pm} \approx 10^{50}$ erg), well within the range of applicability of our theory, between $10^{48}$ erg for GRB980425 and $10^{54}$ erg for GRB991216.

In this section we presented only the analysis of GRB031203 prompt emission. A complete discussion on its X-ray afterglow (Watson et al., 2004; Soderberg et al., 2004) and its connection with the supernova SN2003lw (Malesani et al., 2004) is faced in chapter 5 where we threat in detail the GRB/Supernova connection and all the GRB sources that are up to now spectroscopically confirmed associated with a supernova, tracing analogies between them in order to clarify the origin of such connection within our
3.4. GRB031203

model.
3. GRB Light Curves and Spectra
Chapter 4

Short vs Long GRBs

It is well known that Gamma-Ray Bursts are divided in two main classes on the basis of their duration: “short” ($T_{90} < 2$ s) and “long” ($T_{90} > 2$ s) (Kouveliotou et al., 1993). These two classes of bursts appear to have very different observational properties beyond the difference in the duration. It was found that short bursts are typically harder than the long ones (Kouveliotou et al., 1996; Dezalay et al., 1996, see Fig. 4.1), and this enforced the idea that short bursts are a different entity, instead of being, for example, single peaks of long GRBs hidden by noise (see also Nakar & Piran, 2002a). Unfortunately, without the detection of an afterglow and, consequently, the identification of hosts and redshifts nothing could be known about short GRBs.

The existence of these two classes of bursts finds a natural explanation within our model (see chapter 2). As it has been discussed in section 2.2.5, when the transparency condition is reached all the $e^\pm$ annihilate and a flash of photons is emitted: the Proper GRB (P-GRB). The remaining accelerated baryons continue their expansions and, colliding with the InterStellar Medium (ISM), produce the prolonged afterglow emission. The afterglow consists in a raising part, a maximum (the prompt emission) and a decaying phase (the late afterglow emission). It means that a typical GRB light curve in our model is composed by two parts: first we have the P-GRB emission
4. Short vs Long GRBs

Figure 4.1: The hardness-duration correlation for BATSE bursts (Qin et al., 2000). The short bursts (squares) appears to be harder than the long ones (circles). The hardness is defined as the ratio between the flux of the 3rd and the 2nd BATSE channels (100–300 keV and 50–100 keV respectively).
Figure 4.2: The fraction of energy emitted in the P-GRB (red solid curve) and the one emitted in the afterglow (green solid curve) versus the baryon loading $B$ are represented. When the baryon loading increases most of the energy is converted into baryonic kinetic energy and the energy emitted in the P-GRB becomes only a few percent of the total energy (blue solid curve).
4. Short vs Long GRBs

and then the afterglow one.

The total energy of these two emissions is ruled by the baryon loading $B$, whose value fixes the amount of energy emitted in the P-GRB and the one converted into baryonic kinetic energy. In fact the energy carried by the baryons at the transparency is

$$E_B = \gamma_0 M_B c^2 = \gamma_0 B E_{\text{tot}}^\pm,$$

where $\gamma_0$ is the Lorentz factor of the system at the moment of transparency. It means that (see Fig. 4.2):

1. For very small values of the baryon loading ($B \to 0$) almost all the total energy of the initial plasma is emitted in the P-GRB.

2. There is an intermediate situation ($B \approx 10^{-4}$) in which the P-GRB and the afterglow emitted energies are comparable.

3. When $B$ tends to its maximum value ($B \to 10^{-2}$) the P-GRB energy is only a very small fraction of $E_{\text{tot}}^\pm$ and the afterglow is energetically dominant with respect to the P-GRB.

These situations produce completely different light curves (see Fig. 4.3):

1. For $B \to 0$ the light curve is composed only by the P-GRB emission without a following afterglow.

2. When $B \approx 10^{-4}$ (see Fig. 4.3, lower panel) the afterglow peak emission shrinks over the P-GRB and its flux is lower than the P-GRB one.

3. For $B \to 10^{-2}$ the P-GRB appears as a weak signal before the afterglow peak emission which follows after several seconds (see Fig. 4.3, upper panel).

In this scenario we identify short GRBs with the first situation, namely with the P-GRB emission for very small values of the baryon loading, while long bursts coincide with the afterglow emission for intermediate or large
Figure 4.3: Two examples of light curves obtained assuming the same total energy ($E_{\text{tot}}^{\pm} = 10^{53}$) and two different values of the baryon loading $B = 10^{-2}$ and $B = 10^{-4}$. It is manifest from these pictures that when $B$ is large the P-GRB is a small precursor compared with the whole afterglow light curve. Instead when $B$ is lower the P-GRB dominates the prompt emission and the afterglow peak emission is weak. This result has been found assuming a constant duration (5 s) for the P-GRB in both cases.
4. Short vs Long GRBs

$B$ values. In this case, this signal can be above the instrumental threshold depending on the P-GRB flux: in those cases, it appears as the “precursor” often observed in BATSE GRBs (Lazzati, 2005).

One of the main Swift’s results is the “afterglow revolution” for short GRBs. In fact in the year 2005 were detected the X-ray and optical counterparts of two events: GRB050509B (Gehrels et al., 2005) by Swift and, two months later, GRB050709 (Villasenor et al., 2005) by HETE-2. The localization of these afterglows, as for long ones (see section 1.1.1), opens the possibility to observe the parent galaxy and to measure the redshift of these events, obtaining the missing informations to understand their nature. Currently\(^1\) 12 short bursts have been observed and in half cases a redshift has been measured.

The observed afterglows are characterized by a soft long bump following the main event, and by a late time evolution similar to the long GRBs ones, showing a “canonical” behavior and, in several cases, the presence of X-ray flares (Barthelmy et al., 2005c). What has been found from the study of these bursts’ host galaxies and redshifts is that actually they are harder than long GRBs (Amati, 2006). Moreover they appear to be also nearer than what was expected before (the average redshift is $z \sim 0.4$, much smaller than the average $z$ of the long GRBs detected by Swift, $z \sim 2.3$ Guetta, 2006) and, therefore, their luminosity is lower and their local rate is higher (Guetta, 2006; Barthelmy et al., 2005c; Fox et al., 2005). It has been pointed out the apparent absence in those afterglows of a jet break (Campana et al., 2006a; Watson et al., 2006), consequently their emission appears to be at least less collimated than expected. Moreover, it seems that these GRBs are not associated to any type of Supernova (Barthelmy et al., 2005c; Fox et al., 2005).

All these recent observations support the idea that these bursts belong to a different population than the long ones (Fox et al., 2005). In particular their association with non-star-forming host galaxies indicates that they

\(^1\)until June 2006
could not have resulted from any mechanism involving massive star core col-
lapse (Barthelmy et al., 2005c). On the other hand, the similarity of all their
properties strongly suggests a common origin for these events (Fox et al.,
2005), and seems to be consistent with the merging of a compact object bi-
nary (Fox et al., 2005, see also section 1.4), even if the NS-NS binary merger
models predict energy injection times much shorter than, for example, the
200 s observed for GRB050724 (Barthelmy et al., 2005c). BH-NS mergers are
more promising, but even these models cannot extend emission beyond a few
tens of seconds (Barthelmy et al., 2005c).

The recent discovery of an afterglow associated to the short GRBs (Gehrels
et al., 2005) as a soft bump following the main pulse of tens of seconds opens
a new possibility. In fact in order to have such temporal separation between
the P-GRB and the afterglow we need an high value of the baryon loading.
On the other hand the P-GRB flux dominates the prompt emission, suggest-
ing that there is another explanation outside the scheme we presented. In
the following section we will show in greater detail our interpretation of such
scenario.
4. Short vs Long GRBs

4.1 GRB970228: an hybrid case between long and short GRBs

Under this light, we revised our previous work (Corsi et al., 2004) on GRB970228 which, although it appears as “normal” long GRB, shows some analogies with this new situation we have just sketched.

GRB970228 was detected by the Gamma-Ray Burst Monitor (GRBM, 40–700 keV) and Wide Field Cameras (WFC, 2–26 keV) on board BeppoSAX on February 28.123620 UT (Frontera et al., 1998). The burst prompt emission is characterized by an initial 5 s strong pulse followed, after 30 s, by a set of three additional pulses of decreasing intensity (Frontera et al., 1998). Eight hours after the initial detection, the NFIs on board BeppoSAX were pointed at the burst location for a first target of opportunity observation and a new X-ray source was detected (Costa et al., 1997) in the GRB error box: this is the first “afterglow” ever detected (Costa et al., 1997). A fading optical transient has been identified in a position consistent with the X-ray transient (van Paradijs et al., 1997), and its coincidence with a faint galaxy, presumably the GRB host galaxy, allowed to measure its redshift: $z = 0.695$ (Bloom et al., 2001).

In our picture the first main pulse ($T_{90} \sim 5$ s) can be identified with

---

4.1. GRB970228: an hybrid case between long and short GRBs

Figure 4.4: *Beppo*SAX GRBM (40–700 keV) and WFC (2–26 keV) light curves together with our theoretical simulations (solid red lines). The onset of the afterglow peak emission is shifted if we identify the first main peak with the P-GRB (represented qualitatively by the solid blue line).
4. Short vs Long GRBs

the P-GRB, while the three additional pulses coincide with the afterglow peak emission. This idea is enforced by the presence of a discontinuity in the spectral index between the end of the first pulse and the beginning of the others, whose spectrum appears to be more similar to the X-ray afterglow than to the first pulse (Frontera et al., 1998; Costa et al., 1997).

In fact the spectrum during the first 3 s of the second pulse is significantly harder than during the last part of the first pulse (Frontera et al., 1998). Any physical relation between the X-ray component of the GRB and the afterglow emission most likely holds with the last set of pulses, not with the first one (Frontera et al., 1998). This suggests that the emission mechanism producing the X-ray afterglow might be already taking place after the first pulse (Frontera et al., 1998).

4.1.1 The GRB970228 prompt emission

In Fig. 4.4 our theoretical fit of BeppoSAX GRBM (40–700 keV) and WFC (2–26 keV) light curves (Frontera et al., 1998) is represented. Interpreting the first peak as the P-GRB and the three additional pulses as the afterglow peak emission we obtain for the best fit parameters $E_{\text{tot}} = 1.45 \times 10^{54}$ erg and $B = 5.0 \times 10^{-3}$. This implies an initial $e^\pm$ plasma created between the radii $r_1 = 3.52 \times 10^{17}$ cm and $r_2 = 4.87 \times 10^{18}$ cm with $N_{e^\pm} = 1.6 \times 10^{59}$ and with an initial temperature $T = 1.7$ MeV. After the transparency point, the initial Lorentz gamma factor of the accelerated baryons is $\gamma_0 = 199$ at a distance $r_0 = 4.37 \times 10^{14}$ cm from the progenitor.

The structure of the last three pulses has been reproduced (see section 3.1.1) assuming three overdense spherical ISM regions with width $\Delta$ and density contrast $\Delta n/\langle n \rangle$: we chose for the first region, at $r = 3.55 \times 10^{16}$ cm, $\Delta = 2.0 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 30.09$, for the second region, at $r = 5.40 \times 10^{16}$ cm, $\Delta = 3.0 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 3.14$ and for the third region, at $r = 8.20 \times 10^{16}$ cm, $\Delta = 3.0 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 1.59$. The ISM mean effective density during this phase is $\langle n_{\text{ISM}} \rangle = 9.5 \times 10^{-4}$ particles/cm$^3$ and $\langle \mathcal{R} \rangle = 1.5 \times 10^{-7}$. With this choice of the density profile we obtain a
4.1. GRB970228: an hybrid case between long and short GRBs

good agreement with the observed light curve, as shown in Fig. 4.4.

From this analysis of the prompt emission we can predict also the total energy emitted in the P-GRB, \( E_{\text{P-GRB}}^{\text{tot}} = 1.1\% E_{\text{tot}}^{\text{e}} = 1.54 \times 10^{52} \) erg, which is comparable with the isotropic energy emitted in the first pulse (\( E_{\text{obs}}^{\text{tot}} \sim 1.5 \times 10^{52} \) erg in 2 – 700 keV energy band). In this way we obtain a further evidence for the correctness of our interpretation.

4.1.2 Discussion and conclusions

We present here the analysis of GRB970228 prompt emission. Following the observational hints by Frontera et al. (1998) and Costa et al. (1997), in such an analysis we interpret the first observed pulse as the P-GRB emission and the following pulses as the afterglow peak emission. We found out that in this way we obtain the detailed temporal profile of the burst in both the GRBM and WFC energy bands as well as a correct theoretical prediction for the P-GRB emitted energy.

If we recall our classification of short and long GRBs on the basis of the baryon loading we find that GRB970228 shows a very peculiar situation. In fact this case (\( B = 5 \times 10^{-8} \)) lies in the range of “normal” long GRBs, for which the afterglow peak emission dominates with respect to the P-GRB. On the other hand, however, due to the very small value of the effective particle number density (\( \langle n_{\text{ism}} \rangle = 9.5 \times 10^{-4} \) particle/cm\(^3\)) the afterglow peak flux is weak compared with the P-GRB one. In fact even if the total energy emitted in the afterglow is 99% of the total energy and the one emitted in the P-GRB is only the remaining 1%, due to the low ISM effective density the emission results less intense but longer. The combination of these two features reproduces all the observational properties of GRB970228 light curve, namely the temporal separation between the P-GRB and the afterglow on the one hand, and the dominance of the P-GRB emission during the prompt phase of this event on the other. Moreover, Donaghy et al. (2006) have shown that \( T_{90} = 2 \) s as a criterion for distinguishing between short and long GRBs must be revised. In fact they have developed a likelihood method for determining
the probability that a burst is short or long on the basis of its $T_{90}$ duration alone. A striking feature of the resulting probability distribution is that the $T_{90}$ duration at which a burst has an equal probability of being short or long is $T_{90} = 5$ s. If we adopt this criterion the first main pulse of GRB970228 ($T \sim 5$ s) can be still classified as a short GRB, as the identification with the P-GRB naturally implies.

This case suggests the existence of a different “class” of GRBs characterized by an high baryon loading and a very low effective particle number density which shows the same observational features of GRB970228. If we consider the recent observations of short GRBs with afterglow we notice that they potentially belong to this new class. In fact in order to have the temporal separation between the soft bump and the main pulse we need an high value of the baryon loading, but at the same time the main pulse flux dominates the prompt emission as in the case of GRB970228. Even Norris & Bonnell (2006), looking at the BATSE catalog and at the HETE-II and Swift BAT sources, identified a family of sources characterized by having an occasional softer, extended emission lasting tens of seconds after the initial spikelike emission. The authors suggest that the current popular nomenclature for the two classes, SHB (for short hard burst) and LSB (for long soft burst), is at best misleading (Norris & Bonnell, 2006).

Even the recently observed GRB060614 (Gehrels et al., 2006) shows some peculiarities resembling our case. In fact it appears as a long burst, lasting $\approx 100$ s, but it shares some spectral properties with the short ones as the absence of a spectral lag (Gehrels et al., 2006). Its light curve is characterized by a short pulse lasting $\approx 4$ s followed by a long-lasting multipeaked structure (see Fig. 4.5).

We are currently analyzing this source (Caito et al., 2006b), interpreting the first pulse as the P-GRB and the remaining pulses as afterglow. Again, to reproduce its features we need an high baryon loading and a very low effective particle number density of the ISM. If confirmed, this could be a further evidence for the new scenario we have outlined. Also Gehrels et
4.1. GRB970228: an hybrid case between long and short GRBs

Figure 4.5: GRB060614 light curve measured by BAT in 15–350 keV energy band. BAT data analyzed by R. Guida.
4. Short vs Long GRBs

al. (2006) suggested that, because of its “hybrid” observational properties, this source belongs to a subclass of bursts identified by different physical properties.

The low density of the circumburst medium, which appears to be a peculiarity of these sources, suggests that the progenitor for this new family could belong to a binary system of neutron stars, one of those collapsing to the black hole which, according to our model (see section 2.1), results to be the progenitor of GRBs. In fact such systems usually lie in the galactic halo, whose density is around $10^{-3}$ particle/cm$^3$ (Panaitescu, 2006). A possible indication for such scenario is that GRB970228 was, for example, localized on the outskirts of a faint galaxy (van Paradijs et al., 1997), essentially ruling out (Sahu et al., 1997) disruptive events around a central massive black hole (Carter, 1992), even if the high energy emitted in this burst ($\sim 10^{54}$ erg) that we found in our analysis seems more likely to be produced in the collapse of a massive star.
Chapter 5

GRB/SN Connection

Intensive optical, infrared and radio follow-up of GRBs has established that at least a significant fraction of long-duration GRBs are directly connected with supernova (SN) explosions. The main evidence for this association arises from observations of supernova features in the spectra of a few GRB afterglows. Examples of clear cases of the GRB/SN connection are GRB980425/SN1998bw (Galama et al., 1998), GRB030329/SN2003dh (Stanek et al., 1999; Hjorth et al., 2003), GRB031203/SN2003lw (Malesani et al., 2004), GRB021211/SN2002lt (Della Valle et al., 2003), XRF020903 (Soderberg et al., 2005), GRB050525A/SN2005nc (Della Valle et al., 2006a) and more recently GRB060218/SN2006aj (Sollerman et al., 2006). In addition there are about a dozen afterglows which show, days to weeks after the gamma-ray events, rebrightening and/or flattening in their light curves (Zeh, Klose & Hartmann, 2004, e.g.). These bumps are interpreted as SNe emerging out of the GRBs’ afterglows (Bloom et al., 1999; Castro-Tirado & Gorosabel, 1999).

If we focus on the GRBs with a spectroscopically confirmed associated supernova (GRB980425, GRB030329, GRB031203, and GRB060218), we find that all but GRB030329 have gamma-ray energy budgets between 2-4 orders of magnitude fainter than those exhibited by “standard” GRBs. The increasing number of discovery of these subenergetic events (with an associated SN
component) can no longer be considered as a simple collections of peculiar, atypical cases. These bursts were so faint, that they would have been easily missed at cosmological distances, therefore it is likely that they are the most frequent GRBs in the universe (Della Valle et al., 2006a).

The supernovae associated with those events (SN1998bw, SN2003dh, SN2003lw and SN2006aj) appear to belong to the bright tail of the type Ib/c supernovae. In fact the first three supernovae are $\sim 5 - 6$ times more luminous and $\sim 30$ times more energetic than typical type Ib/c supernovae (Mazzali et al., 2006). SN2006aj is intrinsically dimmer than the other 3 above mentioned supernovae, nevertheless it is more luminous than other type Ib/c supernovae (see Fig. 5.1 and Pian et al., 2006). Other distinctive features of the GRB supernovae are the longer risetime (see Fig. 5.1 and Pian et al., 2006) and the greater photospheric expansion velocity (see Fig. 5.2 and Pian et al., 2006). Again, SN2006aj rises and declines as fast as normal supernovae Ib/c, and its photospheric expansion velocity is intermediate between these two groups (Pian et al., 2006). The peculiarities common to all GRB supernovae allow us to consider them as a “subclass” of the type Ib/c supernovae. In fact they have been addressed as hypernovae (Iwamoto et al., 1998), in order to emphasize the extremely high energy involved in these explosions.

The evidence of a connection between GRBs and supernovae leads naturally to several questions:

- **are all supernovae related to GRBs?** According to current SN Ib/c (Della Valle et al., 2006a) and GRB (Schmidt, 2001; Guetta et al., 2004) rates and the average beaming factor $\langle f_b^{-1} \rangle$ estimates (Frail et al., 2001; Guetta, Piran & Waxman, 2005), only less than 4% of type Ib/c supernovae are possibly associated to GRBs (Della Valle et al., 2006a).

---

1 Type I supernovae are defined by the absence of hydrogen. Among them, three subclasses are known: those whose early-time spectra show strong SiII (Ia), prominent HeI (Ib), or neither SiII nor HeI (Ic). Supernovae Ib/c probably result from core collapse in massive stars largely stripped of their hydrogen (Ib) and helium (Ic) envelopes (see e.g. Filippenko, 1997).

2 $f_b^{-1} = 1 - \cos \theta$
Figure 5.1: Absolute magnitude and luminosity of the four spectroscopically identified supernovae associated with GRBs (SN1998bw, SN2003dh, SN2003lw, SN2006aj), of two hypernovae not associated with GRBs (SN1997ef, SN2002ap) and of the normal type Ic SN1994I. Picture from Pian et al. (2006).
Figure 5.2: Photospheric expansion velocities of the same seven supernovae in Fig. 5.1. Picture from Pian et al. (2006).
al., 2006a). This implies that such supernovae must have some other special characteristic than being just massive stars (Della Valle et al., 2006a), as rotation (Woosley & Heger, 2006; Yoon & Langer, 2005; Fryer & Heger, 2005), binarity (Podsiadlowski et al., 2004; Mirabel, 2004), asymmetry (Maeda, Mazzali & Nomoto, 2006) and metallicity (Fruchter et al., 2006).

There is weak evidence that other type of core-collapse supernovae, such as type IIn, can contribute to the supernova population of GRBs (Germany et al., 2000; Turatto et al., 2000; Rigon et al., 2003). The best evidence for the case of an association between a type IIn supernova and a GRB has been provided by Garnavich et al. (2003), who found that the color evolution of the bump associated with GRB011121 is consistent with the color evolution of an underlying supernova (SN2001ke) strongly interacting with a dense circumstellar gas.

Several authors have reported the detection of Fe and other metal lines in GRB X-ray afterglows (Piro et al., 1999). If valid (see Sako, Harrison & Rutledge, 2005, for a critical review), these observations would have broad implications for both GRB emission models and would strongly link GRBs with supernova explosions. However it is worth to note that Swift has not detected X-ray lines in any afterglow so far observed (Della Valle et al., 2006a).

● are all GRBs related to supernovae? The recent discovery of GRB060614 (Della Valle et al., 2006b) seems to rule out the necessity to have a supernova associated to every long GRB. In fact because of its low redshift ($z = 0.125$, Della Valle et al., 2006b), it seemed to be a good candidate to look for an associated supernova. What has been found is that the eventually associated supernova was at least 100 times fainter at optical wavelengths than the other supernovae associated to GRBs (Della Valle et al., 2006b). This fact allows to set an upper limit to the expansion velocity of the supernova ejecta ($v \leq 3500\ km/s$), which is
5. GRB/SN Connection

one order of magnitude smaller than usual (Della Valle et al., 2006b). The observations cannot rule out a possible link of GRB060614 to other type of core collapsing supernovae as type II (Della Valle et al., 2006b), but we simply can consider this as the first evidence that not all long GRBs are related to supernovae (Della Valle et al., 2006b). There is another possible case of a GRB which is not associated to any supernova: GRB060505 (Fynbo et al., 2006). In this case it has been claimed that the eventually associated supernova would have been more than 250 times fainter than SN1998bw at a similar time (Fynbo et al., 2006). Also this case apparently rules out the idea that all long GRBs are associated to supernovae, suggesting that the possible origin of these bursts lies in one of the many supernova-less progenitors (Fynbo et al., 2006).

5.1 Theoretical inferences on the GRBs associated to supernovae.

The most impressive observational peculiarity in the study of GRB/SN association is the apparently constant properties of the supernovae compared with a great variety in the GRB ones. In fact the “optical” properties (i.e. peak luminosity and expansion velocity) of the 4 above mentioned supernovae change by at most 50% while the energies of their associated GRBs cover 4 orders of magnitude (see Tab. 5.1).

This fact may be interpreted in several ways. A possible explanation within the standard fireball model (see section 1.3) is that we may have observed intrinsically similar phenomena under different angles. In this picture GRB030329/SN2003dh may be viewed almost pole-on, GRB980425/SN1998bw relatively off-axis ($15^\circ < \theta < 30^\circ$), while GRB031203/SN2003lw may lie in between (Ramirez-Ruiz et al., 2005a). A consequence of this scenario is that the gamma properties are strongly dependent upon the angle ($\sim \theta^4$), whereas the optical properties are affected much less by changing the view-
5.1. Theoretical inferences on the GRBs associated to supernovae.

Table 5.1: a) see Galama et al. (1998); Greiner et al. (2003); Prochaska et al. (2004); Mirabal et al. (2006); b) see Kaneko et al. (2006); c) Mazzali, P., private communication at MG11 meeting in Berlin, July 2006; d) evaluated fitting the URCA\(s\) with a power law followed by an exponentially decaying part.

<table>
<thead>
<tr>
<th>GRB980425</th>
<th>GRB030329</th>
<th>GRB031203</th>
<th>GRB060218</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{tot}}) (erg)</td>
<td>(1.2 \times 10^{48})</td>
<td>(2.1 \times 10^{52})</td>
<td>(1.8 \times 10^{50})</td>
</tr>
<tr>
<td>(B)</td>
<td>(7.7 \times 10^{-3})</td>
<td>(4.8 \times 10^{-3})</td>
<td>(7.4 \times 10^{-3})</td>
</tr>
<tr>
<td>(\gamma_0)</td>
<td>124</td>
<td>206</td>
<td>133</td>
</tr>
<tr>
<td>(z^a)</td>
<td>0.0085</td>
<td>0.1685</td>
<td>0.105</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{bolom}}) (erg)(^b)</td>
<td>(2.3 \times 10^{49})</td>
<td>(1.8 \times 10^{49})</td>
<td>(3.1 \times 10^{49})</td>
</tr>
<tr>
<td>(E_{\text{kin}}) (erg)(^c)</td>
<td>(1.0 \times 10^{52})</td>
<td>(8.0 \times 10^{51})</td>
<td>(1.5 \times 10^{52})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>URCA1</th>
<th>URCA2</th>
<th>URCA3</th>
<th>URCA4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{URCA}}) (erg)(^d)</td>
<td>(3 \times 10^{48})</td>
<td>(3 \times 10^{49})</td>
<td>(2 \times 10^{49})</td>
</tr>
<tr>
<td>(E_{\text{URCA}}) (E_{\text{SN}})</td>
<td>0.4</td>
<td>6 \times 10^2</td>
<td>8.2</td>
</tr>
<tr>
<td>(E_{\text{URCA}}) (E_{\text{URCA}})</td>
<td>1.7 \times 10^4</td>
<td>1.2 \times 10^3</td>
<td>3.0 \times 10^3</td>
</tr>
</tbody>
</table>

...ing angle up to \(\Delta \theta \sim 30^\circ\) (Della Valle et al., 2006a). The recent event GRB060218/SN2006aj (\(E_{\text{iso}} \sim 6 \times 10^{49}\) erg), may suggest a different interpretation. This GRB may be an example of intrinsically fainter event (Campana et al., 2006b; Pian et al., 2006). Even GRB031203 appears as an intrinsically underluminous event, basing on radio calorimetry and the absence of the signature of an off-axis afterglow (Sazonov, Lutovinov & Sunyaev, 2004; Soderberg et al., 2005). This might indicate that there exists an intrinsic dispersion in the properties of the relativistic ejecta for supernovae having similar optical properties (e.g. peak of luminosity, velocity of the ejecta). This fact is not unconceivable after keeping in mind that the observed relativistic energies at play in the GRB phenomenon, at least in the local universe (\(z < 0.1\)), appear to be just tiny fluctuations (\(10^{-2/-4}\)) of the kinetic energy involved in the “standard” supernovae Ib/c (\(\sim 10^{51}\) erg) or hypernovae explosions (\(\sim 10^{52}\) erg).

It has been proposed (Lamb, Donaghy & Graziani, 2005) a different unified scheme where GRBs, XRRs (X-Ray Rich), XRFs and supernovae Ib/c
5. GRB/SN Connection

are the same phenomenon, but viewed at different angles. Given the rates of GRBs and type Ib/c supernovae (Della Valle et al., 2006a; Schmidt, 2001; Guetta et al., 2004), the unification scenario would work for $\langle f_b^{-1} \rangle \sim 30000$, which would correspond to beaming angles of $\sim 0.5^\circ$. On the other hand the measured $f_b^{-1}$ factors are much smaller, likely in the range $75-500$ (Frail et al., 2001; Guetta, Piran & Waxman, 2005) that corresponds to beaming angles of $\sim 10^\circ - 4^\circ$.

According to our theoretical model (see section 2.1) the energy of the GRB is linked to the extractable energy of black holes. In this framework, the supernova which is often observed in temporal and spatial coincidence with the GRB cannot be interpreted as its progenitor because of the high quantity of ejected matter from the supernova explosion would prevent the GRB occurrence (see section 2.2.4). In fact for such underluminous events the limit on the baryonic remnants left by the collapse $B = 10^{-2}$ corresponds to $M_B \sim 10^{-5} M_\odot$, which is extremely small compared to the $\sim 1 M_\odot$ of ejected mass observed for the hypernovae.

In 2001 Ruffini and collaborators (Ruffini et al., 2001c) proposed a possible explanation for the observed GRB/SN connection: in this work they proposed that both the GRB and the supernova progenitors belong to a binary system. Under special conditions it is possible that the GRB emission triggers the supernova explosion of the companion star. Alternatively, it is possible that the process of gravitational collapse to a black hole producing the GRB is “induced” by the supernova Ib/c on a companion neutron star. The faintness of this GRB class could be in this case naturally explained by the formation of the smallest possible black hole, just over the critical mass of the neutron star (Ruffini, 2006). We are still working on these possible scenarios in order to clarify the reliability of these proposals or, eventually, to trace an intermediate situation in which both the systems (GRB and SN) influence each other.

Having identified the contribution due to the GRB in all the GRB/SN
5.1. Theoretical inferences on the GRBs associated to supernovae.

systems observed so far, in all cases we single out a late time X-ray emission presenting an abrupt exponential decay, after an initial power-law decreasing phase. We named this sources URCAs (Ruffini et al., 2004a) to emphasize their possible relation to the supernova activity as opposed to the black hole formation activity generating the GRB.

In the early days of neutron star physics it was clearly shown by Gamow & Schoenberg (1940, 1941) that the URCA processes are at the very heart of the supernova explosions. The neutrino-antineutrino emission described in the URCA process is the essential cooling mechanism necessary for the occurrence of the process of gravitational collapse of the imploding core. Since then, it has become clear that the newly formed neutron star can be still significantly hot and in its early stages will be associated to 3 major radiating processes (Tsuruta, 1979): a) the thermal radiation from the surface, b) the radiation due to neutrino, kaon, pion cooling, and c) the possible influence in both these processes of the superfluid nature of the supranuclear density neutron gas. We propose that the X-ray emission that we have recognized in all the GRB/SN systems could be the sign of the cooling of the young neutron star born from the supernova explosion (Ruffini et al., 2004a, 2006b).
5. GRB/SN Connection

5.2 GRB980425/SN1998bw/URCA1*

GRB980425 triggered the BeppoSAX GRBM at 21:49:11 UT and was simultaneously detected by the BeppoSAX WFC (Pian et al., 2000). The event has a duration of \( \sim 31 \text{ s} \) in the range 40–700 keV and 40 s in the range 2–26 keV. It exhibited a single, nonstructured peak profile in both bands (Fig. 5.3 Pian et al., 2000). The fluences are \((2.8 \pm 0.5) \times 10^{-6}\) and \((1.8 \pm 0.3) \times 10^{-6}\) ergs/cm\(^2\) in the 40–700 and 2–26 keV energy range, respectively (Pian et al., 2000). This source received particular attention because of its spatial and temporal (\( \sim 1 \) day, Iwamoto et al., 1998) coincidence with the bright type Ic supernova SN1998bw. The low probability of a chance coincidence between them (\( \approx 10^{-4}\), Galama et al., 1998) gave the first evidence for a physical association between GRBs and supernovae.

The follow-up of GRB980425 with BeppoSAX NFI 10 hours, one week and 6 months after the event revealed the presence of two X-ray sources, one (S1) consistent with SN1998bw, and the other (S2) not consistent (Pian et al., 2000). The S1 X-ray light curve shows a decay of a factor of 2 in 6


114
months, much slower than usual X-ray GRB afterglows (Pian et al., 2000). This trend would be similar to the X-ray behavior of other supernovae (Pian et al., 2000). Assuming, as suggested by the positional coincidence and by variability, that S1 is associated with SN1998bw, this is the first detection of medium-energy X-ray emission from a type I supernova and the earliest detection of X-rays after a supernova explosion (Pian et al., 2000). Further observations on March 2002 performed by XMM (Pian et al., 2004) confirmed S2 as a sum of several faint field sources. S1 resulted definitely linked to SN1998bw (Pian et al., 2004), and it showed a faster temporal decay than the one observed by BeppoSAX. The temporal behavior of S1 was confirmed by a further observation performed by Chandra 1281 days after the burst (Kouveliotou et al., 2004).

5.2.1 The fit of the observations

The best fit of GRB980425 observational data (Pian et al., 2000; Frontera et al., 2000) leads to $E_{\text{tot}}^{\pm} = 1.2 \times 10^{48}$ erg and $B = 7.7 \times 10^{-3}$. This implies an initial $e^\pm$ plasma with $N_{e^\pm} = 3.6 \times 10^{53}$ and with an initial temperature $T = 1.2$ MeV. After the transparency point, the initial Lorentz gamma factor of the accelerated baryons is $\gamma_0 = 124$.

The temporal structure of the prompt emission has been reproduced assuming a succession of spherical ISM regions characterized by a width $\Delta$ and a density contrast $\Delta n/\langle n \rangle$: we chose at $r = 2.50 \times 10^{15}$ cm $\Delta = 9.0 \times 10^{14}$ cm and $\Delta n/\langle n \rangle = 2.3 \times 10^{-1}$, at $r = 3.40 \times 10^{15}$ cm $\Delta = 2.6 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 7.5 \times 10^{-1}$, at $r = 6.00 \times 10^{15}$ cm, $\Delta = 1.4 \times 10^{15}$ cm and $\Delta n/\langle n \rangle = 3.8 \times 10^{-1}$. The ISM mean effective density during this phase is $\langle n_{\text{ISM}} \rangle = 2.18 \times 10^{-2}$ particles/cm$^3$ and $\langle \mathcal{R} \rangle = 1.24 \times 10^{-8}$.

In Fig. 5.3 we test our specific theoretical assumptions comparing our theoretically computed light curves in the 40–700 and 2–26 keV energy bands with the observations by the BeppoSAX GRBM and WFC during such time interval (see Pian et al., 2000; Frontera et al., 2000). As described in chapter 2.3, we have used our exact analytic solution for the equations of motion.
Figure 5.3: Theoretical light curves of GRB980425 prompt emission in the 40–700 keV and 2–26 keV energy bands (solid red line), compared with the observed data (green points) respectively from BeppoSAX GRBM and WFC (see Pian et al., 2000; Frontera et al., 2000).
Figure 5.4: Theoretical time integrated spectra of GRB980425 for selected intervals of the detector arrival time during the so-called “prompt emission” (the peak of the afterglow in our model): A) 0 – 5 s, B) 5 – 15 s, C) 15 – 32 s, D) 32 – 54 s (corresponding to panels A, B, C, D in Frontera et al., 2000).
of the baryons (Bianco & Ruffini, 2005b). We have also assumed a thermal emission in the co-moving frame (Ruffini et al., 2004b), duly weighted by appropriate Lorentz and Doppler factors and convolved on the EQuiTemporal Surfaces (EQTS) (Bianco & Ruffini, 2004, 2005a, and section 3.2) to give the instantaneous observed spectrum. We can then compute the theoretical time-integrated spectra in the four selected detector arrival time intervals during the above mentioned first 60 seconds where data are available in the literature (see Frontera et al., 2000, and Fig. 5.4). The results obtained (see Figs. 5.3 and 5.4) show a very satisfactory result.

5.2.2 The identification of URCA1

Thanks to our detailed analysis of GRB980425, we are able to state that the X-ray emission of the source S1 definitely does not belong to the GRB (see Fig. 5.5). In fact, due to the very low energy of the source and of the Lorentz factor at the transparency, we cannot expect such emission at so late times (for details see section 3.1.2). This implies that S1 must be linked to the supernova event instead of the GRB. In order to emphasize the different origin of this source, we named it URCA1, and we possibly interpret it as URCA emission from the neutron star left by the supernova explosion.

Also Pian et al. (2004) noticed that the late X-ray emission of SN1998bw is compatible with cooling radiation from the compact remnant, provided the GRB has swept up all the surrounding material by creating an evacuated cone. Tavani (1997) has shown, in the context of X-ray afterglows of GRBs, that cooling neutron stars with “external” disturbances (e.g., a fallback) may radiate in X-rays with a temporal rate faster than a power-law. A longer diffusion time than considered by Tavani (1997) should be adopted in this case. The predicted decay rates for neutron stars with simple cooling (i.e., no fallback) are much longer than the fading time scale measured by BeppoSAX and XMM for SN1998bw (Page, 1998). However, exotic cooling mechanisms can significantly increase the cooling rate (Slane, Helfand & Murray, 2002).
5.2. GRB980425/SN1998bw/URCA1

Figure 5.5: Theoretical light curves of GRB980425 in the 40–700 keV (red line), 2–26 keV (green line), 2–10 keV (blue line) energy bands, represented together with URCA1 observational data. All observations are by BeppoSAX (Pian et al., 2000), with the exception of the last two URCA1 points, which are observed by XMM and Chandra (Pian et al., 2004; Kouveliotou et al., 2004).
5. GRB/SN Connection

5.3 GRB030329/SN2003dh/URCA2*

GRB030329 has been recorded by several satellites on March 29, 2003 and it has been accurately localized by HETE-2 (Ricker, 2003). A redshift of \( z = 0.1685 \) has been measured (Greiner et al., 2003) for the GRB030329 host galaxy. Although its intrinsic luminosity is in the low end of the distribution for GRBs, its proximity led to a very high fluence (\( 1.2 \times 10^{-4} \text{ erg/cm}^2 \) in the 30–400 keV energy band, Ricker, 2003) for the prompt emission.

The early phases of the GRB030329 X–ray afterglow were observed with two Rossi-XTE pointings obtained 5 hours and 1.24 days after the burst (Marshall & Swank, 2003; Marshall et al., 2003). Unfortunately, no further X–ray data could be collected during the following month. At the beginning of May the GRB position became compatible with the visibility constraints of the XMM-Newton satellite, which performed two observations 37 days and 61 days after the burst. A further XMM observation was performed 258 days after the burst in order to study the late evolution of the X-ray afterglow.

5.3.1 The prompt emission

For GRB030329 we have obtained a total energy \( E_{\text{tot}}^{\pm} = 2.12 \times 10^{52} \text{ erg} \) and a baryon loading \( B = 4.8 \times 10^{-3} \). This implies an initial \( e^{\pm} \) plasma with \( N_{e^{\pm}} = 1.1 \times 10^{57} \) and with an initial temperature \( T = 2.1 \text{ MeV} \). After the transparency point, the initial Lorentz gamma factor of the accelerated baryons is \( \gamma_0 = 206 \). The parameters of the ISM are \( \langle n_{\text{ism}} \rangle = 2.0 \text{ particle/cm}^3 \).

and \(\langle R \rangle = 2.8 \times 10^{-9}\). For the overall energetics and the high value of the Lorentz gamma factor and of \(\langle n_{ism} \rangle\), this source may well represent the limiting case of the low-energy class of GRBs.

The HETE light curve (see Fig. 5.6 upper panel) shows a long, extremely bright GRB, lasting more than 25 s, with a fluence in the band 30 – 400 keV of \(\sim 1.0 \times 10^{-4}\) erg/cm\(^2\). The prompt emission is structured in two peaks: the first one lasts more than 15 s, the second one is shorter and their intensities are comparable. This structure can be reproduced assuming that the ISM is not constantly distributed but is arranged in several density spikes, preserving \(\langle n_{ism} \rangle = 2.0\) particle/cm\(^3\). For GRB030329, the density spikes corresponding to the two main peaks are modeled as two spherical shells with width and density of the same order of magnitude: we adopted for the first peak \(\Delta = 2.0 \times 10^{14}\) cm and \(\Delta n/n = 30\), and for the second peak \(\Delta = 1.0 \times 10^{14}\) cm and \(\Delta n/n = 90\). The result (see Fig. 5.6 lower panel), even though it was not possible to compare directly our simulation with the observed light curve, shows an approximately good agreement with the observations.

### 5.3.2 The X-ray afterglow emission

In the analysis of the X-ray afterglow we considered only the observations by R-XTE (Marshall & Swank, 2003; Marshall et al., 2003): in section 5.3.3 we will provide a different explanation for the nature of the XMM data (Tiengo et al., 2003, 2004). Both the first and the second set of R-XTE data are well fit by the 2–10 keV theoretical light curve (see Fig. 5.7). The apparent break in the light curve is due to the interaction of the pulse with a small cloud of ISM with higher density \((\Delta n/n = 8)\) and size \(\Delta = 2.0 \times 10^{15}\) cm. The presence of this cloud, and probably of other clouds that we cannot see because of the paucity of the X-ray data, can also be the origin of the “rebrightenings” observed in the optical band (Granot, Nakar & Piran, 2003). In this way we don’t need to have a collimated emission in order to explain the behavior of the 2–10 keV light curve, which is consistent with a spherically symmetric
5. GRB/SN Connection

Figure 5.6: Theoretical light curve of GRB030329 in the 30–400 keV energy band (lower panel) compared with HETE-2 observational data (http://space.mit.edu/HETE/Bursts/GRB030329/).
Figure 5.7: Theoretical light curve of GRB030329 in the 30–400 keV (blue line) and 2–10 keV energy bands (red line) compared with R-XTE observational data (pink points, Marshall & Swank, 2003; Marshall et al., 2003) and HETE-2 mean flux (green point, Ricker, 2003).
5. GRB/SN Connection

emitting pulse, as assumed in our model.

5.3.3 The identification of URCA2

Consider now the XMM observations of GRB030329. Tiengo et al. (2004) in their analysis of all these observations noticed the presence of an anomalous flattening in the XMM light curve. They interpreted this behavior in the frame of a structured jet (Tiengo et al., 2004).

Within our theory, whose results for this source are in very good agreement with both the X and gamma observations, we suggest to interpret such observation, in analogy with the case of GRB980425, as an emission related to the supernova instead of the GRB.

If we compare (see Fig. 5.11.B) the light curves of GRB030329 in the 2–400 keV energy band, of SN2003dh in the optical band (Nomoto, 2006; Pian et al., 2006) and of this X-ray emission in 2–10 keV energy band (Tiengo et al., 2003, 2004) with the correspondent GRB980425, SN1998bw and URCA1, we find that the late GRB030329 X-ray emission shows a temporal behavior similar to URCA1. Even the energetic of these two emissions (see Tab. 5.1) are comparable. In analogy with the previous case, we name this X-ray emission URCA2.

5.4 GRB031203/SN2003lw/URCA3*

GRB031203 was observed by XMM-Newton twice, first with an observation beginning 6 hr after the burst and again after 3 days. The afterglow had average 0.2–10 keV fluxes for the first and second observations of \((4.2 \pm 0.1) \times 10^{13}\) and \((1.8 \pm 0.1) \times 10^{13}\) erg/(cm²s) respectively, decaying very slowly according to a power law with an index of \(0.55 \pm 0.05\) (Watson et al.,

The rapid initial decline and subsequent very slow fading of the X-ray afterglow is also similar to that observed in GRB980425 (Watson et al., 2004). The GRB031203 X-ray afterglow has been observed also by Chandra in a single 21.6 ksec exposure beginning at 21:35 UT on 22 January 2004 (Fox et al., 2004). The observed flux revealed a steepening from the last XMM observation (Fox et al., 2004).

In Fig. 5.11 we compare the light curves of the XMM and Chandra observations with the previously identified URCA1 and URCA2. Again it is manifest the common behavior of this late X-ray emission, which shows an initial flattenig followed by a steeper decay. Since we analyzed in detail the GRB031203 prompt emission within (see section 3.4), we start from the ISM parameters’ values obtained and we extrapolate the light curve until the late afterglow phase. Analogously with the previous cases, we find that in this way the late time X-ray emission is out from our prediction (see Fig. 5.11.C), suggesting a different nature than being simply the GRB afterglow. We named this emission URCA3 in analogy with the previous cases.

5.5 GRB060218/SN2006aj/URCA4

GRB060218 has been triggered and located by the BAT instrument (Campana et al., 2006b) on board of the Swift satellite on 18 February 2006 at 03:36:02 UT. It has a very long duration with $T_{90} \sim (2100 \pm 100)$s. The XRT detected a bright, fading point source located at RA (J2000): 03h 21m 39.7s; Dec (J2000): 16d 52’ 01.33” (Kennea et al., 2006). The XRT (Campana et al., 2006b) began observations $\sim 153$ s after the BAT trigger and continued to detect the source for $\sim 12.3$ days (Sakamoto et al., 2006). The source is characterized by a flat gamma ray light curve and a soft spectrum (Barbier et al., 2006). It has an X-ray light curve with a long, slow rise and gradual decline and it is considered an X-ray flash since its peak energy occurs at

5. GRB/SN Connection

$E_p = 4.9^{+0.4}_{-0.3}$ keV (Campana et al., 2006b). The burst fluence in the 15–150 keV band is $(6.8 \pm 0.4) \times 10^{-6}$ erg/cm$^2$ (Sakamoto et al., 2006). The spectroscopic redshift has been found to be $z = 0.033$ (Mirabal et al., 2006). At this redshift the isotropic equivalent energy is $E_{iso} = (1.9 \pm 0.1) \times 10^{49}$ erg (Sakamoto et al., 2006). This faint, low redshift GRB could be a good candidate to be associated with a supernova. In fact it has been found an underlying type Ic supernova: SN2006aj (Pian et al., 2006). This Supernova shows observational features very similar to the other ones associated with GRBs. In particular it has a very large expansion velocity of $v \sim 0.1c$ (Pian et al., 2006), since an emission peak at 4500 Å could be considered as a possible result of the blending of the Fe lines giving rise to a broad absorption (Soderberg et al., 2006).

The source has also been observed with the Advanced CCD Imaging Spectrometer (ACIS) instrument on the Chandra X-ray Observatory (CXO). These observations began on February 26.78 and March 7.55 UT ($t \simeq 8.8$ and 17.4 days) and lasted 20 and 30 ks respectively (Soderberg et al., 2006). Soderberg et al. (2006) have derived the fluence to be $(4.5 \pm 1.4) \times 10^{-14}$ erg/cm$^2$ and $(2.8 \pm 0.9) \times 10^{-14}$ erg/cm$^2$.

5.5.1 The prompt and the afterglow emission

The observational data best fit leads to a total energy of the $e^{\pm}$ plasma $E_{e^{\pm}}^{tot} = 1.85 \times 10^{50}$ erg. The plasma has an initial temperature $T = 1.85$ MeV and a total number of pairs $N_{e^{\pm}} = 1.45 \times 10^{55}$. The second parameter of the theory, the amount of baryonic matter in the plasma, $B = 1.0 \times 10^{-2}$, is the highest value compatible with the stability of the adiabatic optically thick acceleration phase of GRB (see section 2.2.5 and Ruffini et al., 2000). The Lorentz gamma factor of the accelerated baryons at the beginning of the afterglow phase is $\gamma_0 = 99.2$. The ISM average parameters are: $\langle n_{ism} \rangle = 8.90 \times 10^{-7}$ particle/cm$^3$, the smallest among all the GRBs analyzed within our model, and $\langle R \rangle = 3.75 \times 10^{-5}$.

In order to reproduce the time variability of the prompt emission and of
Figure 5.8: GRB060218 prompt emission: a) our theoretical fit (blue line) of the BAT observations in the 15–150 keV energy band (pink points); b) our theoretical fit (red line) of the XRT observations in the 0.1–10 keV energy band (green points) (Data from: Campana et al., 2006b).
5. GRB/SN Connection

Figure 5.9: GRB060218 complete light curves: our theoretical fit (blue line) of the 15–150 keV BAT observations (pink points), our theoretical fit (red line) of the 0.1–10 keV XRT observations (green points) and the 0.1–10 keV Chandra observations (black points) are represented together with our theoretically computed bolometric luminosity (black line) (Data from: Campana et al., 2006b; Soderberg et al., 2006).

the afterglow we assume an inhomogeneous structure for the ISM. During the emission peak in the 15–150 keV, from \(r = 6.90 \times 10^{12} \) cm to \(r = 4.40 \times 10^{17} \) cm, we find a mean effective density \(\langle n_{ISM} \rangle = 3.48 \times 10^{-5} \) particle/cm\(^3\). During the peak of the emission in the 0.1–10 keV, from \(r = 6.90 \times 10^{12} \) cm to \(r = 7.67 \times 10^{17} \) cm, we find a mean effective density \(\langle n_{ISM} \rangle = 7.77 \times 10^{-6} \) particle/cm\(^3\). During the decaying part of the afterglow, from \(r = 7.67 \times 10^{17} \) cm to \(r = 8.00 \times 10^{18} \) cm, we find a mean effective density \(\langle n_{ISM} \rangle = 9.01 \times 10^{-7} \) particle/cm\(^3\). In Fig. 5.8 we see the clear displacement between the gamma (15–150 keV) and X-ray (0.1–10 keV) peak, as well as the longer duration of the X-ray emission compared with the gamma-ray one.

We turn now to the late part of the afterglow. Our theoretical fit of the
5.5. GRB060218/SN2006aj/URCA4

XRT data is represented in Fig. 5.9 as well as the fit of the BAT data. GRB060218 is a further case of Swift “canonical” afterglow, and we demonstrate here once again (see section 3.3) that our theory, based on the assumption that both the prompt and the afterglow emission are just due to the thermal radiation in the comoving frame produced by inelastic collisions with the ISM duly boosted by the relativistic transformations over the EQTSs (see 2.3), is capable to reproduce in detail all the afterglow emission.

GRBs vs XRFs

The GRB060218 peculiarities, the very large value of the baryon loading parameter $B = 1.0 \times 10^{-2}$ and the relatively low total energy of the $e^\pm$ plasma $E_{e^\pm}^{\text{tot}} = 1.85 \times 10^{50}$ erg, together with the very low density of the surrounding medium and the high $\langle R \rangle$, enhance the X-ray emission with respect to the $\gamma$-ray one. That is why this source has been classified as XRF. However we can fit this source with the basic parameters varying within the range of applicability of the model like all other GRBs. There are no basic differences in the fundamental process generating the low redshift sources, like GRB060218, from the high energetic ones at cosmological redshift, as for example GRB050315 (see section 3.3). Similarly, there are no basic differences between “normal” GRBs and XRFs: the underlying mechanism is in both cases the collapse to a black hole and the basic parameters are in the full range of applicability of the theoretical model. For the first time, in GRB060218 we have the possibility to test our model in yet untested and extreme conditions and we conclude that we can naturally explain the long duration and the spectral softness of this GRB.

5.5.2 Searching for URCA4

In analogy with all the previous cases, it is worth to recognize if also in this case there is an X-ray component in the late afterglow belonging to the supernova and not to the GRB. In Fig. 5.10 we represent the Chandra observations in 0.1–10 keV energy band (Soderberg et al., 2006). Such observations can
Figure 5.10: Same as Fig. 5.9, without the bolometric luminosity and with representative curves for the possible URCA4 source in the Chandra observations.
be simply the decaying part of the GRB060218 afterglow. Nevertheless, their intensity and temporal position suggest that they could be the first detection of the “URCA4” emission. This idea becomes more reliable if we superimpose an hypothetical URCA light curve (see Fig. 5.10) to the Chandra observations: we see that they are compatible. Of course further observations are needed in order to verify the temporal behavior typical of the URCA sources and, hence, to prove our hypothesis.

5.6 Conclusions on our analysis of GRBs associated to SNe

In Tab. 5.1 we summarize the representative parameters of the above four GRB/SN systems, including the very large kinetic energy observed in all supernovae (Mazzali, 2006). Some general conclusions on these faint GRBs at low redshift, associated to supernovae Ib/c, can be established on the ground of our analysis:

1. From the detailed fit of their light curves, as well as their accurate spectral analysis, it follows that all the GRB sources presented in this chapter originate consistently from the formation of a black hole. This result extends to this low-energy GRB class at small cosmological redshift the applicability of our model, which now spans over a range of energy of six orders of magnitude from $10^{48}$ to $10^{54}$ ergs. Distinctive of this class is the very high value of the baryon loading which in one case (GRB060218) is very close to the maximum limit compatible with the dynamical stability of the adiabatic optically thick acceleration phase of the GRBs (see section 2.2.5 Ruffini et al., 2000). Correspondingly, the maximum Lorentz gamma factors are systematically smaller than the ones of the more energetic GRBs at large cosmological distances. This in turn implies the smoothness of the observed light curves in the prompt phase. The only exception to this is the case of GRB030329.
Figure 5.11: Theoretically computed light curves of GRB980425 in the 2–700 keV band (A), of GRB030329 in the 2–400 keV band (B) and of GRB031203 in the 2–200 keV band (C) are represented, together with the URCA observational data and qualitative representative curves for their emission, fitted with a power law followed by an exponentially decaying part. The luminosity of the Supernovae in the 3000–24000 Å are also represented (Nomoto, 2006; Pian et al., 2006)
5.6. Conclusions on our analysis of GRBs associated to SNe

2. The accurate fits of the GRBs allow us to infer also some general properties of the ISM. While the size of the clumps of the inhomogeneities is $\Delta \approx 10^{14}$ cm, the average effective density of the ISM is much smaller than in the case of more energetic GRBs: we have in fact $\langle n_{\text{ism}} \rangle$ in the range between $\sim 10^{-6}$ particle/cm$^3$ (GRB060218) and $\sim 10^{-1}$ particle/cm$^3$ (GRB031203), while only in the case of GRB030329 it is $\sim 2$ particle/cm$^3$. We are also currently studying a characteristic trend in the variability of $R$ during some specific bursts (see Dainotti et al., 2006).

3. These four GRB sources present a large variability in their total energy: a factor $10^4$ between GRB980425 and GRB030329. Remarkably, the supernovae emission both in their very high kinetic energy and in their bolometric energy appear to be almost constant respectively $10^{52}$ erg and $10^{49}$ erg. The URCAs present a remarkably steady behavior around a “standard luminosity” and a typical temporal evolution. These facts motivated our suggestion that they are related to the supernovae and not to the GRBs: either to dissipative processes in the Supernova ejecta, or to the formation of a neutron star in the Supernova explosion (Ruffini et al., 2006b).
5. GRB/SN Connection
Conclusions

In this work we compared the theoretical results obtained within the model proposed by Ruffini and collaborators with the main GRB observational properties in order to validate the physical mechanisms that in this theory are assumed to be the origin of the GRB phenomenon.

From this work it emerges the possibility to explain most of the GRB observational features in a self-consistent way, drawing a complete picture in which all the different GRB properties correspond only to different values for the fundamental parameters and not to different physical processes. In particular:

1. Complex GRB light curves can be reproduced via inelastic collisions between an accelerated shell of baryonic matter and the ISM.

2. The “canonical” behavior of the afterglow arises naturally from the same mechanism producing the prompt emission, and the observed light curves show a “natural curvature” that differs from a simple power-law without introducing any departure from spherical symmetry. This is true even for a constant ISM effective particle number density.

3. The assumption of thermal instantaneous spectrum in the baryonic shell comoving frame leads, integrating over the appropriate EQTSs, to power-law time-integrated spectra in the observer frame, in perfect agreement with the observations.

4. A generic GRB is composed by a short emission that corresponds to the P-GRB, followed by a prolonged emission that we call *afterglow* and
that corresponds to both the prompt and the afterglow phases. We find then that two extreme cases arises: a P-GRB without any afterglow, that corresponds to the short GRBs, and an afterglow with a small precursor that corresponds to the long ones. There are also intermediate cases in which the P-GRB is followed by a weak afterglow.

5. All the properties characterizing...... GRBs associated with supernovae arises naturally from our model.

Moreover, the detailed analysis of many GRB sources allowed to trace new features that will help to improve our model and to clarify the astrophysical settings in which GRBs with different observational properties occur. In particular:

1. We found the existence of a new “hybrid” class between short and long GRBs. This class of GRBs is characterized by a prompt emission energetically dominated by the P-GRB followed by an afterglow with a low peak emission. In fact, despite the P-GRB total energy is a relatively small fraction of the total energy, due to the low ISM density the afterglow peak emission results less intense but longer. This peculiar situation (high baryon loading and low ISM particle number density), identified in GRB970228 and, possibly, in other sources as GRB060614, suggests that the progenitor of such sources belongs to a binary system, in which one star collapses to a black hole and produces the GRB.

2. The analysis of all the GRBs associated with supernovae revealed that in all cases there are common features in the parameters of the sources (low energy, high baryon loading) and of the ISM (very low number density) that can be useful to understand the nature of this association.

3. We identified in all the afterglows of the GRBs associated to supernovae an X-ray component, which we called URCA, whose behavior appears to be similar in all cases. The URCA's present a remarkably steady
behavior around a “standard luminosity” and a typical temporal evolution, while the corresponding GRB energies span over four orders of magnitude. These facts motivated our suggestion that they are related to the supernovae and not to the GRBs: either to dissipative processes in the Supernova ejecta, or to the formation of a neutron star in the Supernova explosion (Ruffini et al., 2006b).
Conclusions
Attachments
Attachment 1
Attachments
GRB 050315: A STEP TOWARD UNDERSTANDING THE UNIQUENESS OF THE OVERALL GAMMA-RAY BURST STRUCTURE

Remo Ruffini, Maria Grazia Bernardini, Carlo Luciano Bianco, Federico Fraschetti, Roberto Guida, and She-Sheng Xue

1,2 ICRANet and International Center for Relativistic Astrophysics (ICRA), Piazza della Repubblica 10, I-65100 Pescara, Italy; ruffini@icra.it, xue@icra.it.

2 Dipartimento di Fisica, Università di Roma “La Sapienza,” Piazzale Aldo Moro 5, I-00185 Roma, Italy; maria.bernardini@icra.it, bianco@icra.it.

Received 2006 March 30; accepted 2006 June 1; published 2006 June 29

ABSTRACT

Using the Swift data of GRB 050315, we are making progress toward understanding the uniqueness of our theoretically predicted gamma-ray burst (GRB) structure, which is composed of a proper GRB (P-GRB), emitted at the transparency of an electron-positron plasma with suitable baryon loading, and an afterglow comprising the so-called prompt emission due to external shocks. Thanks to the Swift observations, the P-GRB is identified, and for the first time we can theoretically fit detailed light curves for selected energy bands on a continuous timescale ranging over 10^7 s. The theoretically predicted instantaneous spectral distribution over the entire afterglow is confirmed, confirming a clear hard-to-soft behavior encompassing, continuously, the “prompt emission” all the way to the latest phases of the afterglow.

Subject headings: gamma rays: bursts — gamma rays: observations — radiation mechanisms: thermal

1. INTRODUCTION

GRB 050315 (Vaughan et al. 2006) has been triggered and located by the Burst Alert Telescope (BAT; Barthelmy 2004; Barthelmy et al. 2005) on board the Swift satellite (Gehrels et al. 2004) in 2005 March 15, at 20:59:42 UT (Parsons et al. 2005). The X-Ray Telescope (XRT; Burrows et al. 2004, 2005) observed the P-GRB about 80 s after the BAT trigger, one of the earliest XRT observations yet made, and continued to detect the source for about 10 days (Vaughan et al. 2006). The spectroscopic redshift has been found to be z = 1.949 (Kelson & Berger 2005).

We present here the results of the fit of the Swift data of this source in five energy bands in the framework of our theoretical model (see Ruffini et al. 2001a, 2001b, 2003, 2005a; Bianco & Ruffini 2004, 2005a, 2005b; and references therein), and these results bring us a step closer toward understanding the uniqueness of the overall gamma-ray burst (GRB) structure. In § 2 we recall the essential features of our theoretical model; in § 3 we fit the GRB 050315 observations using both the BAT and the XRT data; in § 4 we present the instantaneous spectra for selected values of the detector arrival time ranging from 60 s (i.e., during the so-called prompt emission) all the way to 3.0 × 10^7 s (i.e., the latest afterglow phases); and in § 5 we present our conclusions.

2. OUR THEORETICAL MODEL

A major difference between our theoretical model and the ones in the current literature (see, e.g., Piran 2005 and references therein) is that what is usually called “prompt emission” in our case coincides with the peak of the afterglow emission and is not due to the prolonged activity of an “inner engine,” which clearly would introduce an additional and independent physical process to explain the GRB phenomenon (Ruffini et al. 2001b). In fact, a basic feature of our model is the sharp distinction between two different components in the GRB structure: (1) the proper GRB (P-GRB), emitted at the moment of transparency of the self-accelerating e^-baryon plasma (see, e.g., Goodman 1986; Paczyński 1986; Shem & Piran 1990; Piran et al. 1993; Mészáros et al. 1993; Grinnell & Wasserman 1998; and Ruffini et al. 1999, 2000, 2001a, 2001b, 2006) and (2) an afterglow described by external shocks and composed of three different regimes (see Ruffini et al. 1999, 2000, 2001b, 2003, and references therein). The first afterglow regime corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time, which corresponds to a substantially constant Lorentz gamma factor of the accelerated baryons. The second regime consists of the bolometric luminosity peak, which corresponds to the “knee” in the decreasing phase of the baryonic Lorentz gamma factor. The third regime corresponds to a bolometric luminosity decreasing with the arrival time, which corresponds to the late deceleration of the Lorentz gamma factor. In some sources, the P-GRB is under the observability threshold. In Ruffini et al. (2001b), we have chosen as a prototype the source GRB 991216, which clearly shows the existence of the P-GRB and the three regimes of the afterglow. Unfortunately, data from the Burst and Transient Source Experiment (BATSE) on board the Compton Gamma Ray Observatory existed only up to 36 s, and data from the Rossi X-Ray Timing Explorer and Chandra only after 3500 s, leaving our theoretical predictions in the whole range between 36 and 3500 s without the support of the comparison with observational data. Nevertheless, both the relative intensity of the P-GRB to the peak of the afterglow in such a source and their corresponding temporal lag were theoretically predicted within a few percent (see Fig. 11 in Ruffini et al. 2003).

The validity of our model has been tested in a variety of other sources besides GRB 991216 (Ruffini et al. 2003), like GRB 980425 (Ruffini et al. 2004b), GRB 030329 (Bernardini et al. 2006), and GRB 031203 (Bernardini et al. 2005). In all these sources as well, the observational data were available only during the prompt emission and during the latest afterglow phases, leaving our theoretical predictions of the in-between evolution untested. Now, thanks to the data provided by the Swift satellite, we are finally able to confirm, by direct comparison with the observational data, our theoretical predictions...
3. THE FIT OF THE OBSERVATIONS

The best fit of the observational data leads to the total energy of the black hole dyadosphere generating the $e^\pm$ plasma, $E_{\text{p}} = 1.46 \times 10^{53}$ ergs (the observational Swift $E_{\text{iso}}$ is $>2.62 \times 10^{52}$ ergs; see Vaughan et al. 2006), so that the plasma is created between the radii $r_1 = 5.88 \times 10^4$ cm and $r_2 = 1.74 \times 10^5$ cm with an initial temperature $T = 2.05$ MeV and a total number of pairs $N_{e^-e^+} = 7.93 \times 10^{52}$. The second parameter of the theory, the amount of baryonic matter $M_b$ in the plasma, is found to be such that $B = M_b c^2/\gamma_{1\delta_{\text{GRB}}} = 4.55 \times 10^{-5}$. The transparency point and the P-GRB emission occur then with an initial Lorentz gamma factor of the accelerated baryons $\gamma_{1\delta_{\text{GRB}}} = 217.81$ at a distance $r = 1.32 \times 10^5$ cm from the black hole.

3.1. The BAT Data

In Figure 1 we illustrate our theoretical fit of the BAT observations in the three energy channels 15–25, 25–50, and 50–100 keV and in the whole 15–350 keV energy band. In our model, the GRB emission starts at the transparency point when the P-GRB is emitted; this instant of time is often different from the moment in time when the satellite instrument is triggered, due to the fact that sometimes the P-GRB is below the instrumental noise threshold or comparable to it. In order to compare our theoretical predictions with the observations, it is important to estimate and take into account this time shift. In the present case of GRB 050315, a possible precursor has been observed before the trigger (see Vaughan et al. 2006). Such a precursor is indeed in agreement with our theoretically predicted P-GRB, both in its emitted isotropic energy (which we theoretically predict to be $E_{\text{p,GRB}} = 1.98 \times 10^{53}$ ergs) and in its temporal separation from the peak of the afterglow (which we theoretically predicted to be $\Delta T_p = 51$ s). In Figure 1a, the blue line shows our theoretical prediction for the P-GRB, in agreement with the observations.

After the P-GRB emission, all the observed radiation is produced by the interaction of the expanding baryonic shell with the interstellar medium (ISM). In order to reproduce the complex time variability of the light curve of the prompt emission as well as of the afterglow, we describe the ISM filamentary structure, for simplicity, as a sequence of overdense spherical regions separated by much less dense regions. Such overdense regions are nonhomogeneously filled, leading to an effective emitting area $A_{\text{eff}}$, determined by the dimensionless parameter $\Sigma = A_{\text{eff}}/A_{\text{vac}}$, where $A_{\text{vac}}$ is the expanding baryonic shell’s...
visible area (see Ruffini et al. 2004a, 2005b for details). Clearly, in order to describe any detailed structure of the time variability, an authentic three-dimensional representation of the ISM structure would be needed. However, this finer description would not change the substantial agreement of the model with the observational data. Anyway, in the prompt emission phase, the small angular size of the source’s visible area due to the relativistic beaming makes for an excellent spherical approximation (see also Ruffini et al. 2002 for details).

The structure of the prompt emission has been reproduced by assuming three overdense spherical ISM regions with width $\Delta$ and density contrast $\Delta n(n)$: we chose for the first region, at $r = 4.15 \times 10^{16}$ cm, $\Delta = 1.5 \times 10^{-3}$ cm and $\Delta n(n) = 5.17$, for the second region, at $r = 4.53 \times 10^{16}$ cm, $\Delta = 7.0 \times 10^{-3}$ cm and $\Delta n(n) = 36.0$, and for the third region, at $r = 5.62 \times 10^{16}$ cm, $\Delta = 5.0 \times 10^{-3}$ cm and $\Delta n(n) = 85.4$. The ISM mean density during this phase is $(\rho)_{\text{ISM}} = 0.81$ particles cm$^{-3}$, and $(R)_{\text{ISM}} = 1.4 \times 10^{-4}$ cm. With this choice of the density mask, we obtain agreement with the observed light curve, as shown in Figure 1. A small discrepancy occurs in coincidence with the last peak; this is due to the fact that at this stage, the source’s visible area due to relativistic beaming is comparable to the size of the clouds, and therefore the spherical shell approximation should be duly modified by a detailed analysis of a full three-dimensional treatment of the ISM filamentary structure. Such a topic is currently under investigation (see also Ruffini et al. 2002 for details). Figure 1 also shows the theoretical fit of the light curves in the three BAT energy channels in which the GRB has been detected (15–25 keV in Fig. 1b, 25–50 keV in Fig. 1c, and 50–100 keV in Fig. 1d).

3.2. The XRT Data

The same analysis can be applied to explain the features of the XRT light curve in the afterglow phase. It has been recently pointed out (Nousek et al. 2006) that almost all the GRBs observed by Swift show a “canonical behavior”: an initial very steep decay followed by a shallow decay and finally a steeper decay. In order to explain these features, many different approaches have been proposed (Mészáros 2006; Nousek et al. 2006; Panaitescu et al. 2006; Zhang et al. 2006). In our treatment, these behaviors are automatically described by the same mechanism responsible for the prompt emission described above: the baryonic shell expands in an ISM region, between $r = 9.00 \times 10^{16}$ cm and $r = 5.50 \times 10^{15}$ cm, which is at a significantly lower density $(\rho)_{\text{ISM}} = 4.76 \times 10^{-4}$ particles cm$^{-3}$, $(R)_{\text{ISM}} = 7.0 \times 10^{-3}$ cm than the one corresponding to the prompt emission, and this produces a slower decrease of the velocity of the baryons with a consequent longer duration of the afterglow emission. The initial steep decay of the observed flux is due to the smaller number of collisions with the ISM.

Figure 2 illustrates our theoretical fit of the XRT data together with the theoretically computed 15–350 keV light curve of Figure 1a (without the BAT observational data, so as to not overwhelm the picture too much).

What is impressive is that no other scenarios need to be advocated in order to explain the features of the light curves: both the prompt emission and the afterglow emission are due to the thermal radiation in the comoving frame produced by inelastic collisions with the ISM, which is duly boosted by the relativistic transformations over the equitemporal surfaces (EQTSs).

4. THE INSTANTANEOUS SPECTRUM

In addition to the luminosity in fixed energy bands, we can also derive the instantaneous photon number spectrum $N(E)$ starting from the same assumptions. In Figure 3, we show samples of time-resolved spectra for eight different values of the arrival time that cover the whole duration of the event. It is evident from this picture that, although the spectrum in the comoving frame of the expanding pulse is thermal, the shape of the final spectrum in the laboratory frame is clearly non-thermal. In fact, as explained in Ruffini et al. (2004a), each single instantaneous spectrum is the result of an integration of thousands of thermal spectra over the corresponding EQTS.

This calculation produces a nonthermal instantaneous spectrum in the observer frame (see Fig. 3).

A distinguishing feature of the GRB spectra that is also present in these instantaneous spectra is the hard-to-soft transition during the evolution of the event (Crider et al. 1997; Frontera et al. 2000; Ghirlanda et al. 2002). In fact, the peak of the energy distribution $E_{\text{peak}}$ drifts monotonically to softer frequencies with time. This feature is linked to the change in the power-law low-energy spectral index $\alpha$ (Band et al. 1993),

**Fig. 2.**—Our theoretical fit (blue line) of the XRT observations (green points) of GRB 050315 in the 0.2–10 keV energy band (Vaughan et al. 2006). The theoretical fit of the BAT observations (see Fig. 1a) of GRB 050315 in the 15–350 keV energy band is also represented (red line).

**Fig. 3.**—Eight theoretically predicted instantaneous photon number spectra $N(E)$ are here represented for different values of the arrival time (colored curves). The hard-to-soft behavior is confirmed.

**Attachment 1**
so the correlation between $\alpha$ and $E_p$ (Crider et al. 1997) is explicitly shown. It is important to stress that there is no difference between the nature of the spectrum during the prompt emission and that during the afterglow phases: the observed energy distribution changes from hard to soft, with continuity, from the prompt emission all the way to the latest phases of the afterglow.

5. CONCLUSIONS

Before the Swift data, our model could not be directly fully tested. With GRB 050315, for the first time, we have obtained a good match between the observational data and our predicted intensities in five energy bands, with continuous light curves from the peak of the GRB event, including the prompt emission, all the way to the latest phases of the afterglow. This certainly suggests that our model and opens a new phase of using it to identify the astrophysical scenario underlying the GRB phenomena. In particular:

1. We have demonstrated that the prompt emission is not necessarily due to the prolonged activity of an inner engine but corresponds to the emission at the peak of the afterglow.

2. We have a clear theoretical prediction for the total energy emitted in the P-GRB, $E_{\text{GRB}} = 1.98 \times 10^{51}$ ergs, and for its temporal separation from the peak of the afterglow $\Delta t_p = 51$ s. To understand the physics of the inner engine, more observational and theoretical attention should be given to the analysis of the P-GRB.

3. We have uniquely identified the basic parameters characterizing the GRB energetics: the total energy of the black hole dyadosphere $E_h = 1.46 \times 10^{52}$ ergs and the baryon-loading parameter $B = 4.55 \times 10^{-3}$.

4. The canonical behavior in almost all the GRBs observed by *Swift* (an initial very steep decay followed by a shallow decay and finally a steeper decay) as well as the time structure of the prompt emission are related to the fluctuations of the ISM density and of the $\gamma$-parameter.

5. The theoretically predicted instantaneous photon number spectrum shows a very clear hard-to-soft behavior continuously and smoothly changing from the prompt emission all the way to the latest afterglow phases.

The first afterglow regime that we theoretically predicted, which corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time and preceding the prompt emission, still remains to be checked by direct observations. We hope in the near future to find an intense enough source, observed by the *Swift* satellite, to verify this still untested theoretical prediction.

As a by-product of the results presented in this Letter, we can now answer one of the long-standing questions concerning GRBs: Why is it that the light curves in the prompt emission show very strong temporal substructures while they are remarkably smooth in the latest afterglow phases? The explanation follows from three factors: (1) the value of the Lorentz $\gamma$ factor, (2) the EQTS structure, and (3) the coincidence of the prompt emission with the peak of the afterglow. For $\gamma \sim 200$, at the peak of the afterglow, the diameter of the EQTS’s visible area due to relativistic beaming is small compared to the typical size of an ISM cloud. Consequently, any small inhomogeneity in such a cloud produces a marked variation in the GRB light curve. On the other hand, for $\gamma \sim 1$, in the latest afterglow phases, the diameter of the EQTS’s visible area is much bigger than the typical size of an ISM cloud. Therefore, the observed light curve is a superposition of the contribution of many different clouds and inhomogeneities, and this superposition produces, on average, a much smoother light curve (details in Ruffini et al. 2002, 2003).

We thank P. Banat, G. Chincarini, A. Moretti, and S. Vaughan for their help in the analysis of the observational data as well as an anonymous referee for his/her useful considerations.

REFERENCES

———. 2006, in Proc. 10th Marcel Grossmann Meeting, ed. M. Novello & S. E. Perez Bergliaffa (Singapore: World Scientific), 2459
Piran, T. 2005, Rev. Mod. Phys., 76, 1143
———. 2005b, Int. J. Mod. Phys. D, 14, 97
Attachment 2
GRB 050315: A step in the proof of the uniqueness of the overall GRB structure

R. Ruffini∗,†, M.G. Bernardini∗,‡, C.L. Bianco∗,†, P. Chardonnet∗,**, F. Fraschetti∗,†, R. Guida∗,† and S.-S. Xue∗,†

∗ICRANet and ICRA, Piazzale della Repubblica 10, I-65100 Pescara, Italy.
†Dipartimento di Fisica, Università “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy.
**Université de Savoie, LAPTH - LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France.
‡Osservatorio Astronomico di Brera, via Bianchi 46, I-23807 Merate (LC), Italy.

Abstract. Using the Swift data of GRB 050315, we progress in proving the uniqueness of our theoretically predicted Gamma-Ray Burst (GRB) structure as composed by a proper-GRB, emitted at the transparency of an electron-positron plasma with suitable baryon loading, and an afterglow comprising the “prompt radiation” as due to external shocks. Detailed light curves for selected energy bands are theoretically fitted in the entire temporal region of the Swift observations ranging over $10^6$ seconds.

Keywords: gamma rays: bursts — radiation mechanisms: thermal — black hole physics

PACS: 98.70.Rz, 44.40.+a, 04.70.-s

INTRODUCTION

GRB 050315 [1] has been triggered and located by the BAT instrument [2, 3] on board the Swift satellite [4] at 2005-March-15 20:59:42 UT [5]. The narrow field instrument XRT [6, 7] began observations $\sim 80$ s after the BAT trigger, one of the earliest XRT observations yet made, and continued to detect the source for $\sim 10$ days [1]. The spectroscopic redshift has been found to be $z = 1.949$ [8]. We present here the first results of the fit of this source in the framework of our theoretical model and point out the new step toward the uniqueness of the explanation of the overall GRB structure made possible by the Swift data of this source.

OUR THEORETICAL MODEL

GRB 050315 observations find a direct explanation in our theoretical model [see 9, 10, 11, 12, 13, 14, and references therein]. We determine the values of the two free parameters which characterize our model: the total energy stored in the Dyadosphere $E_{\text{dyas}}$ and the mass of the baryons left by the collapse $M_{\text{rc}} \equiv BE_{\text{dyas}}$. We follow the expansion of the pulse, composed by the electron-positron plasma initially created by the vacuum polarization process in the Dyadosphere. The plasma self-propels itself outward and engulfs the baryonic remnant left over by the collapse of the progenitor star. As such pulse reaches transparency, the Proper Gamma-Ray Burst (P-GRB) is emitted [15, 16, 10]. The remaining accelerated baryons, interacting with the interstellar medium (ISM), produce the afterglow emission. The ISM is described by the two additional
parameters of the theory: the average particle number density $< n_{\text{ISM}} >$ and the ratio $< R >$ between the effective emitting area and the total area of the pulse [17], which take into account the ISM filamentary structure [18].

The luminosity in fixed energy bands is evaluated integrating over the equitemporal surfaces [EQTSs, see 19, 13], computed using the exact solutions of the afterglow equations of motion [14], the energy density released due to the totally inelastic collisions of the accelerated baryons with the ISM measured in the co-moving frame, duly boosted in the observer frame. In the reference frame co-moving with the accelerated baryonic matter, the radiation produced by this interaction of the ISM with the front of the expanding baryonic shell is assumed to have a thermal spectrum [17].

We reproduce correctly in several GRBs and in this specific case (see e.g. Figs. 2–3) the observed time variability of the prompt emission as well as the remaining part of the afterglow [see e.g. 20, 11, 12, 21, and references therein]. The radiation produced by the interaction of the accelerated baryons with the ISM agrees with observations both for intensity and time structure.

As shown in previous cases (GRB 991216 [11, 22], GRB 980425 [23], GRB 030329 [24], GRB 031203 [21]), also for GRB 050315, using the correct equations of motion, there is no need to introduce a collimated emission to fit the afterglow observations.

The major difference between our theoretical model and the ones in the current literature [see e.g. 25, and references therein] is that what is usually called “prompt emission” in our case coincides with the peak of the afterglow emission and is not due to a different physical process [10]. The verification of this prediction has been up to now tested in a variety of sources like GRB 991216 [11], GRB 980425 [23], GRB 030329 [24], GRB 031203 [21]. However, in all such sources the observational data were available only during the prompt emission and the latest afterglow phases, leaving all the in-between evolution undetermined. Now, thanks to the superb data provided by the Swift satellite, we are finally able to confirm, by direct confrontation with the observational data, our theoretical predictions on the GRB structure [10] with a detailed fit of the complete afterglow light curve of GRB 050315, from the peak (i.e. from the so-called “prompt emission”) all the way to the latest phases without any gap in the observational data.

**GRB 991216**

A basic feature of our model consists in a sharp distinction between two different components in the GRB structure: the proper GRB (P-GRB), emitted at the moment of transparency, followed by an afterglow completely described by external shocks and composed of three different regimes. The first afterglow regime corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time, corresponding to a substantially constant Lorentz gamma factor of the accelerated baryons. The second regime consists of the bolometric luminosity peak, corresponding to the “knee” in the decreasing phase of the baryonic Lorentz gamma factor. The third regime corresponds to a bolometric luminosity decreasing with arrival time, corresponding to the late deceleration of the Lorentz gamma factor.

In some sources the P-GRB is under the observability threshold. In Ruffini et al.
FIGURE 1. This picture shows our prediction on the GRB structure based on the analysis of GRB 991216 [10]. In the main panel there is the bolometric light curve computed using our model and composed by the P-GRB and the afterglow, together with the BATSE noise level. In the lower right panel there is represented the BATSE observation of the prompt emission [see 26, 27], with the clear identification of the observed “main burst” with the peak of the theoretical afterglow light curve and of the observed “pre-cursor” with the theoretically predicted P-GRB (see enlargement). In the lower left panel is represented our theoretical fit of the BATSE observations of the afterglow peak using an inhomogeneous ISM. Details in Ruffini et al. [20, 11, 12].

[10] we have chosen as a prototype the source GRB 991216 which clearly shows the existence of this two components. Both the relative intensity of the P-GRB to the peak of the afterglow, as well as their corresponding temporal lag, have been theoretically predicted within a few percent (see Fig. 11 in Ruffini et al. [11]). The continuous line in the main panel of Fig. 1 corresponds to a constant ISM density averaged over the entire afterglow. The structured curve, shown in the bottom left panel, corresponds
FIGURE 2. Theoretical fit (red line), computed using our model, of the BAT observations (blue points) of GRB 050315 in the 15–350 keV energy band [1].

Theoretical fit in 15-350 keV band
BAT observation in 15-350 keV band

Source Luminosity (erg/(s*strad))
Observed Flux (erg/(s*cm²))
Detector arrival time (s)
Theoretical fit in 15-350 keV band
BAT observation in 15-350 keV band

FIGURE 2. Theoretical fit (red line), computed using our model, of the BAT observations (blue points) of GRB 050315 in the 15–350 keV energy band [1].

to ISM density inhomogeneities which are assumed for simplicity to be spherically symmetric [20]. Clearly, a more precise description of the BATSE light curve (e.g. the two sharp spikes at ∼ 30 s) will need a more refined 3-dimensional description of the ISM filamentary structure [18].

This same approximation of spherically symmetric description of the ISM inhomogeneities is in the following adopted for GRB 050315, and is sufficient to clearly outline the general behavior of the luminosity vs. photon detector arrival time in selected energy bands.

THE FIT OF THE OBSERVATIONS

The best fit of the observational data leads to a total energy of the Dyadosphere $E_{dya} = 1.47 \times 10^{52}$ erg [the observational Swift $E_{iso}$ is $> 2.62 \times 10^{52}$ erg, see Ref. 1], so that the plasma is created between the radii $r_1 = 5.88 \times 10^6$ cm and $r_2 = 1.74 \times 10^9$ cm with an initial temperature $T = 2.05 MeV$ and a total number of pairs $N_{e^+e^-} = 7.93 \times 10^{57}$. The amount of baryonic matter in the remnant is assumed to be such that $B = 4.55 \times 10^{-3}$. The transparency point and the P-GRB emission occurs then with an initial Lorentz gamma factor of the accelerated baryons $\gamma_c = 217.81$ and at a distance $r = 1.32 \times 10^{14}$ cm from the Black Hole. The interstellar medium (ISM) parameters that we assume to best fit the observational data are: $< n_{ism} > = 0.121$ particles/cm³ and $< R > = 2.05 \times 10^{-6}$. The ISM density contrast is found to be $\Delta \rho / \rho \sim 10^2$ on a scale of $5.0 \times 10^{16}$...
FIGURE 3. Theoretical fit (blue line), computed using our model, of the XRT observations (black points) of GRB 050315 in the 0.2–10 keV energy band [1]. The theoretical fit of the BAT observations (see Fig. 2) in the 15–350 keV energy band is also represented (red line).

In Figs. 2 and 3 we represent the theoretically computed GRB 050315 light curves, respectively in the 15–350 keV and in the 0.2-10 keV energy bands, which we obtained using our model, together with the corresponding data observed respectively by the BAT and the XRT instruments on board of the Swift satellite [1]. For completeness, in Fig. 3 is also represented the theoretically computed 15–350 keV light curve of Fig. 2, but not the BAT observational data to not overwhelm the picture too much.

The very good agreement between the theoretical curves and the observations is a most stringent proof of our predictions on the GRB structure [10].

It goes without saying that also in the case of GRB 050315 a more detailed correspondence between the theory and the temporal fine structure of the BAT observational light curve could be achieved with a full 3-dimensional description of the ISM filamentary structure [18].

CONCLUSIONS

In view of the above results, which clearly fits the overall luminosity in fixed energy bands, we will return in a forthcoming publication to the identification of the P-GRB using our theoretically predicted values for both its intensity and its time lag relative to the afterglow peak. We will also address the spectral analysis which is a most powerful
theoretical prediction in order to evidence the continuity between the “prompt radiation” and the late phases of the afterglow and so to prove the uniqueness of the overall GRB structure.

ACKNOWLEDGMENTS

We thank P. Banat, G. Chincarini, A. Moretti and S. Vaughan for their help in the analysis of the observational data.

REFERENCES

Attachment 3
THEORETICAL INTERPRETATION OF THE LUMINOSITY AND SPECTRAL PROPERTIES OF GRB 031203

M aria Grazia Bernardini,1,2 Carlo Luciano Bianco,1,2 Pascal Chardonnnet,1,3 Federico Fraschetti,1,4 Remo Ruffini,1,2 and She-Sheng Xun1,2

Received 2005 July 18; accepted 2005 October 6; published 2005 November 7

ABSTRACT

The X-ray and gamma-ray observations of the source GRB 031203 by INTEGRAL are interpreted within our theoretical model. In addition to a complete spacetime parameterization of the GRB, we specifically assume that the afterglow emission originates from a thermal spectrum in the comoving frame of the expanding baryonic matter shell. By determining the two free parameters of the model and estimating the density and filamentary structure of the ISM, we reproduce the observed luminosity in the 20–200 keV energy band. As in previous sources, the prompt radiation is shown to coincide with the peak of the afterglow, and the luminosity substructure is shown to originate from the ISM filamentary structure of the instantaneous spectra. The time-integrated spectrum over 20 s observed by INTEGRAL is well fitted. Despite the fact that this source has been considered “unusual,” it appears to us to be a normal low-energy GRB.

Subject headings: gamma rays: bursts — gamma rays: observations — radiation mechanisms: thermal

1. INTRODUCTION

GRB 031203 was observed by IBIS on board the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) (Mereghetti & Gómez 2003), as well as by XMM-Newton (Watson et al. 2004) and Chandra (Soderberg et al. 2004) in the radio band. It appears as a typical long burst (Sazonov et al. 2004) with a simple profile and a duration of ≈0.4 s. The burst fluence in the 20–200 keV band is (2.0 ± 0.4) × 10⁻⁶ ergs cm⁻² (Sazonov et al. 2004), and the measured redshift is z = 0.106 (Prochaska et al. 2004). We analyze in the following the gamma-ray signal received by INTEGRAL. The observations in other wavelengths, in analogy with the case of GRB 980425 (Pian et al. 2000; Ruffini et al. 2004b), could be related to the supernova event, as also suggested by Soderberg et al. (2004), and they will be examined elsewhere.

The INTEGRAL observations find a direct explanation in our theoretical model (see Ruffini et al. 2001a, 2001b, 2003, 2005a; Bianco & Ruffini 2005a, 2005b and references therein). We determine the values of the two free parameters that characterize our model: the total energy stored in the dyadosphere $E_{dy}$ and the mass of the baryons left by the collapse of the remnant $M_{dy}$ as $BE_{dy}$ = $M_{dy} c^2$. We follow the expansion of the pulse, composed by the electron-positron plasma initially created by the vacuum polarization process in the dyadosphere. The plasma propels itself outward and engulfs the baryonic remnant left over by the collapse of the progenitor star. As the pulse reaches transparency, the proper gamma-ray burst (P-GRB) is emitted (Ruffini et al. 1999, 2000, 2001b). The remaining accelerated baryons, interacting with the interstellar medium (ISM), produce the afterglow emission. The ISM is described by the two additional parameters of the theory: the average particle number density $n_{\text{ISM}}$ and the ratio $(\gamma)$ between the effective emitting area and the total area of the pulse (Ruffini et al. 2004a), which take into account the ISM filamentary structure (Ruffini et al. 2005c).

We reproduce correctly in several GRBs and in this specific case (see, e.g., Fig. 1) the observed time variability of the prompt emission (see, e.g., Ruffini et al. 2002, 2003, 2005a and references therein). The radiation produced by the interaction of the accelerated baryons with the ISM agrees with observations for both intensity and time structure.

The progress in reproducing the X-ray and gamma-ray emission as originating from a thermal spectrum in the comoving frame of the burst (Ruffini et al. 2004a) leads to the characterization of the instantaneous spectral properties, which are shown to drift from hard to soft during the evolution of the system. The convolution of these instantaneous spectra over the observational timescale is in very good agreement with the observed power-law spectral shape.

As shown in previous cases (see Ruffini et al. 2003, 2005b), so for GRB 031203 as well, when using the correct equations of motion there is no need to introduce a collimated emission to fit the afterglow observations (see also Soderberg et al. 2004, who find this same conclusion starting from different considerations).

2. THE INITIAL CONDITIONS

The best fit of the observational data leads to a total energy of the dyadosphere $E_{dy}$ = 1.85 × 10⁶⁷ ergs. Assuming a black hole mass $M = 10 M_{\odot}$, we then have a black hole charge-to-mass ratio $q = 6.8 \times 10^{-4}$; the plasma is created between the radii $r_1 = 2.95 \times 10^{17}$ cm and $r_2 = 2.81 \times 10^{17}$ cm, with an initial temperature of 1.52 MeV and a total number of pairs $N_{ee} = 2.98 \times 10^{49}$. The amount of baryonic matter in the remnant is $B = 7.4 \times 10^{-3}$. After the transparency point and the P-GRB emission, the initial Lorentz gamma factor of the accelerated baryons $\gamma = 132.8$ at an arrival time at the detector $t' = 8.14 \times 10^{-5}$ s and a distance from the black hole $r = 6.02 \times 10^{19}$ cm. This corresponds to an apparent superluminal velocity along the line of sight of $2.5 \times 10^{4}$ c. The ISM parameters are $n_{\text{ISM}} = 0.3$ particles cm⁻³ and $(\gamma) = 7.81 \times 10^{-4}$.
3. THE GRB LUMINOSITY IN FIXED ENERGY BANDS

The aim of our model is to derive from first principles both the luminosity in selected energy bands and the time-resolved/time-integrated spectra. The luminosity in selected energy bands is evaluated integrating over the equitemporal surfaces (EQTSs; see Bianco & Ruffini 2004, 2005a) the energy density released in the interaction of the accelerated baryons with the ISM measured in the comoving frame, duly boosted in the observer frame. The radiation viewed in the comoving frame of the accelerated baryonic matter is assumed to have a thermal spectrum and to be produced by the interaction of the ISM with the front of the expanding baryonic shell.

In order to evaluate the contributions in the band \([E_1, E_2]\), we have to multiply the bolometric luminosity with an effective weight \(W(E_1, E_2, T_{on})\), where \(T_{on}\) is the observed temperature; \(W(E_1, E_2, T_{on})\) is given by the ratio of the integral over the given energy band of a Planckian distribution at temperature \(T_{on}\) to the total integral \(\Delta T_{on}^{E_{2,1}}\) (Ruffini et al. 2004a). The resulting expression for the emitted luminosity is

\[
\frac{dE_{\text{bol}}}{d\Omega} = \int \frac{\Delta E}{4\pi} \cos \theta \Delta \cos \phi \int dW(E_1, E_2, T_{on}) d\Sigma.
\]

where \(\Delta E = \Delta E_{\text{bol}}/N\) is the energy density released in the interaction of the accelerated baryons with the ISM measured in the comoving frame, \(\Delta = \gamma[1 - (v/c)\cos \theta]\) is the Doppler factor, and \(d\Sigma\) is the surface element at detector arrival time \(t'\) on which the integration is performed (details in Ruffini et al. 2004a).

4. THE GRB 031203 PROMPT EMISSION

In order to compare our theoretical prediction with the observations, it is important to note that there is a shift between the initial time of the GRB event and the moment in which the satellite instrument has been triggered. In fact, in our model the GRB emission starts at the transparency point when the P-GRB is emitted. If the P-GRB is under the threshold of the instrument, the trigger starts a few seconds later with respect to the real beginning of the event. Therefore it is crucial, in the theoretical analysis, to estimate and take into due account this time delay. In the present case it results in \(\Delta t' = 3.5\) s (see Fig. 1, vertical red line). In what follows, the detector arrival time refers to the onset of the instrument.

The structure of the prompt emission of GRB 031203, which is a single peak with a slow decay, is reproduced assuming an ISM that does not have a constant density but presents several density spikes with \(\langle n_{\text{ISM}}\rangle = 0.16\) particles cm\(^{-3}\). Such density spikes corresponding to the main peak are modeled as three spherical shells with width \(\Delta\) and density contrast \(\Delta n/n\): we adopted for the first peak \(\Delta = 3.0 \times 10^{15}\) cm and \(\Delta n/n = 8\), for the second peak \(\Delta = 1.0 \times 10^{14}\) cm and \(\Delta n/n = 1.5\), and for the third one \(\Delta = 7.0 \times 10^{13}\) cm and \(\Delta n/n = 1\). To describe the details of the ISM filamentary structure we would require intensity versus time information with an arbitrarily high resolving power. With the finite resolution of the INTEGRAL instrument, we can only describe the average density distribution compatible with the given accuracy. Only structures at scales of \(10^{19}\) cm can be identified. Smaller structures would need a stronger signal and/or a smaller time resolution of the detector. The three clouds here considered are necessary and sufficient to reproduce the observed light curve; a smaller number would not fit the data, while a larger number is unnecessary and would be indeterminable.

The result (see Fig. 1) shows good agreement with the light curve reported by Sazonov et al. (2004), and it provides further evidence of the possibility of reproducing light curves with a complex time variability through ISM inhomogeneities (Ruffini et al. 2002, 2003, 2005a; see also the analysis of the prompt emission of GRB 991216 in Ruffini et al. 2002).

5. THE GRB 031203 INSTANTANEOUS SPECTRUM

As outlined in § 3, in addition to the luminosity in fixed energy bands we can derive also the instantaneous photon number spectra \(N(E)\). In Figure 2 are shown samples of time-resolved spectra for five different values of the arrival time that cover the whole duration of the event.

It is manifest from this picture that although the spectrum in the comoving frame of the expanding pulse is thermal the shape of the final spectrum in the laboratory frame is clearly nonthermal. In fact, as explained in Ruffini et al. (2004a), each single instantaneous spectrum is the result of an integration of...
hundreds of thermal spectra over the corresponding EQTS. This calculation produces a nonthermal instantaneous spectrum in the observer frame (see Fig. 2).

Another distinguishing feature of the GRB’s spectra that is also present in these instantaneous spectra, as shown in Figure 2, is the hard-to-soft transition during the evolution of the event (Crider et al. 1997; Piran 1999; Frontera et al. 2000; Ghirlanda et al. 2002). In fact, the peaks of the energy distributions $E_p$ drift monotonically to softer frequencies with time (see Fig. 3). This feature explains the change in the power-law low-energy spectral index $\alpha$ (Band et al. 1993), which at the beginning of the prompt emission of the burst ($t'_{\text{prompt}} = 2\, s$) is $\alpha = 0.75$ and progressively decreases for later times (see Fig. 2). In this way the link between $E_p$ and $\alpha$ identified by Crider et al. (1997) is explicitly shown. This theoretically predicted evolution of the spectral index during the event unfortunately cannot be detected in this particular burst by INTEGRAL because of the insufficient quality of the data (poor photon statistics; see Sazonov et al. 2004).

6. THE GRB 031203 TIME-INTEGRATED SPECTRUM AND THE COMPARISON WITH THE OBSERVED DATA

The time-integrated observed GRB spectra show a clear power-law behavior. Within a different framework N. I. Shakura, R. A. Sunyaev, and Ya. B. Zel’’dovich (see, e.g., Pozdnyakov et al. 1983 and references therein) argued that it is possible to obtain such power-law spectra from a convolution of many non–power-law instantaneous spectra evolving in time. This result was recalled and applied to GRBs by Blinnikov et al. (1999) by assuming for the instantaneous spectra a thermal shape with a temperature changing with time. They showed that the integration of such energy distributions over the observation time gives a typical power-law shape possibly consistent with GRB spectra.

Our specific quantitative model is more complicated than the one considered by Blinnikov et al. (1999): as pointed out in § 5, the instantaneous spectrum here is not a blackbody. Each instantaneous spectrum is obtained by an integration over the corresponding EQTS (Bianco & Ruffini 2004, 2005a): it is itself a convolution, weighted by appropriate Lorentz and Doppler factors, of $\sim 10^5$ thermal spectra with variable temp-
Due to the possibility of reaching a precise identification of the emission process in GRB afterglows by observation of the instantaneous spectra, it is hoped that further missions with larger collecting area and higher time-resolving power can be conceived and that systematic attention can be given to nearer GRB sources.

Despite the fact that this GRB is often considered "unusual" (Watson et al. 2004; Soderberg et al. 2004), in our treatment we are able to explain its low gamma-ray luminosity in a natural way, giving a complete interpretation of all its spectral features. In agreement with what has been concluded by Sazonov et al. (2004), it appears to us to be a low-energy GRB ($E_{35} \approx 10^{50}$ ergs) and is well within the range of applicability of our theory, between $10^{50}$ ergs for GRB 980425 (Ruffini et al. 2004b) and $10^{45}$ ergs for GRB 991216 (Ruffini et al. 2003).

The precise knowledge that we have acquired here on GRB 031203 will help in clarifying the overall astrophysical system composed of GRB 031203, SN 2003lw, and the 2–10 keV XMM-Newton and Chandra data (see, e.g., Ruffini et al. 2005a).

We thank an anonymous referee for important remarks. We thank also S. Y. Sazonov, A. A. Lutovinov, and R. A. Sunyaev for their comments on the observational data, as well as L. Titarchuk for discussions on the analysis of the convolutions of instantaneous spectra.

REFERENCES
———. 2005c, Int. J. Mod. Phys. D, 14, 97
Attachment 4
Extracting energy from black holes: “Long” and “short” GRBs and their astrophysical settings(*)

R. RUFFINI(1)(2), M. G. BERNARDINI(1)(2), C. L. BIANCO(1)(2), P. CHARDONNET(1)(3)
F. FRASCHETTI(1)(4), V. GURZADYAN(1)(5), M. LATTANZI(1)(2), L. VITAGLIANO(1)(2)
and S.-S. XUE(1)(2)

(1) ICRA — International Center for Relativistic Astrophysics - Rome, Italy
(2) Dipartimento di Fisica, Università di Roma “La Sapienza” - Piazzale Aldo Moro 5, I-00185
Roma, Italy
(3) Université de Savoie, LAPTH - LAPP, BP 110, F74941 Annecy-le-Vieux Cedex, France
(4) Università di Trento - Via Sommarive 14, I-38050 Povo (Trento), Italy
(5) Yerevan Physics Institute - Alikhanian Brothers Street 2, 375036, Yerevan-36, Armenia

Summary. — The introduction of the three interpretational paradigms for Gamma-Ray Bursts (GRBs) and recent progress in understanding the X- and γ-ray luminosity in the afterglow allow us to make assessments about the astrophysical settings of GRBs. In particular, we evidence the distinct possibility that some GRBs occur in a binary system. This subclass of GRBs manifests itself in a “tryp-tich”: one component formed by the collapse of a massive star to a black hole, which originates the GRB; a second component by a supernova and a third one by a young neutron star born in the supernova event. Similarly, the understanding of the physics of quantum relativistic processes during the gravitational collapse makes possible precise predictions about the structure of short GRBs.

PACS 04.70.-s – Physics of black holes.
PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 97.60.Jd – Neutron stars.
PACS 97.65.Bw – Supernovae.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The basic new approach in our model of GRBs has been summarized in three letters [1-3] and in a variety of articles, including two extensive review papers [4,5]. The difference between our model and all other approaches in the literature consists in:

a) the spacetime parameterization of the GRB structure [1],

b) the identification of two different components in the GRB phenomenon.

The first one is the proper-GRB (P-GRB) which is emitted as the optically thick accelerated phase of GRB reaches transparency. The crucial identification of this phenomenon has usually been neglected in the current literature. The second one is the


© Società Italiana di Fisica 589

163
afterglow, originating from the interaction of the baryonic matter, accelerated in the optically thick phase, with the interstellar medium. At variance with the current literature, the commonly called “prompt radiation” of the long GRBs is considered a part of the afterglow, being an extended afterglow peak emission (E-APE) [2]. The short GRBs are again explained within this unitary model: they correspond to the absence of significant amount of baryonic matter in the optically thick accelerating phase. They coincide with the P-GRBs which in this case are much more prominent, being the afterglow component negligible. See left panel of fig. 1.

c) although the above considerations “a” and “b” applies to all GRBs, there are some GRBs which appear to be associated to supernovae. Our model sharply differentiates between the GRB phenomenon and the supernova process [3]. It evidences the binary nature of the GRB progenitor and opens the problematic of an induced collapse either by the GRB on the supernova progenitor star or by the supernova on the GRB progenitor star.

In addition to these three paradigms, our model advances a specific emission process for the gamma-ray and X-ray afterglows, while optical and radio afterglows (usually observed in the latest phases) are assumed to originate from another emission process [6,7].

On the basis of our GRB model (see [4,5] and references therein), we have recently fitted GRB 991216, GRB 980425, GRB 030329 and GRB 031203. In all four cases the luminosity and the spectral informations are consistent with isotropic emission and no beaming. Some preliminary results on this last source are presented here. In total analogy with the trypits GRB 980425 – SN1998bw – URCA-1 and GRB 030329 – SN2003dh – URCA-2, we are in the presence of a triptych which we call GRB 031203 – SN2003lw – URCA-3. We can clearly see from our theoretical prediction on the X- and γ-ray luminosities (see fig. 2) that there is a late component in the 0.2–10 keV band not connected to the afterglow. This is the emission from URCA-3

2. – On the GRB-supernova connection

We first stress some general considerations originating from comparing and contrasting the considered GRB sources:

1. The value of the $B$ parameter for all sources occurs, as theoretically expected, in the range $[4, 5] 10^{-3} \leq B \leq 10^{-2}$. We have in fact:

<table>
<thead>
<tr>
<th>GRB</th>
<th>$B$</th>
<th>$E_{\text{rem}}$ (erg)</th>
<th>$E_{\text{SN}}$ (erg)</th>
<th>$L_{\text{URCA}}$ (erg/s/str)</th>
</tr>
</thead>
<tbody>
<tr>
<td>991216</td>
<td>$3.0 \times 10^{-3}$</td>
<td>$4.8 \times 10^{53}$</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>980425</td>
<td>$7.0 \times 10^{-3}$</td>
<td>$1.1 \times 10^{48}$</td>
<td>$\sim 10^{49}$</td>
<td>$5.2 \times 10^{49}$</td>
</tr>
<tr>
<td>030329</td>
<td>$4.8 \times 10^{-3}$</td>
<td>$2.1 \times 10^{52}$</td>
<td>$\sim 10^{52}$</td>
<td>$1.9 \times 10^{41}$</td>
</tr>
<tr>
<td>031203</td>
<td>$7.4 \times 10^{-3}$</td>
<td>$1.8 \times 10^{50}$</td>
<td>$\sim 10^{50}$</td>
<td>$1.0 \times 10^{42}$</td>
</tr>
</tbody>
</table>

2. The large difference in the GRB energy of the sources simply relates to the electromagnetic energy of the black hole which turns out to be smaller than the critical value. The fact that the theory is valid over 5 orders of magnitude is indeed very satisfactory.
Fig. 1. – Left: Our theory applied to GRB 991216 (main panel). It is represented the P-GRB (at arrival time between 0.01 s and 0.1 s) and the afterglow starting at 0.1 seconds. Also represented is the BATSE noise threshold. In the upper right panel is represented the corresponding light curve observed by BATSE. The observed precursor (see the enlargement on the left side) precisely coincides in amplitude and arrival time with the theoretically predicted P-GRB. The main part of the “prompt radiation” coincides, both in arrival time and intensity, with the extended emission at the peak of the afterglow (see text). Details in [2, 4, 5]. Right: Predicted observed luminosity and observed spectral hardness of the electromagnetic signal from the gravitational collapse of a collapsing core with $M = 10M_\odot$, $Q = 0.1\sqrt{GM}$ at $z = 1$ as functions of the arrival time $t_d$ at the detector. Details in [8].

3. In both sources GRB 980425 and GRB 030329 the associated supernova energies are similar (details in [9, 10]). The further comparison between the SN luminosity and the GRB intensity is crucial. In the case of GRB 980425 the GRB and the SN energies are comparable, and no dominance of one source over the other can be ascertained. In the case of GRB 030329 the energy of the GRB source is $10^3$ larger than the SN; it is unlikely that the GRB can originate from the SN event.

The above stringent energetic considerations and the fact that GRBs occur also without an observed supernova give further evidence against GRBs originating from supernovae.

3. – URCA-1, URCA-2 and URCA-3

We show in fig. 2 the X- and $\gamma$-ray luminosities of GRB 031203. We turn then to the exciting search for the nature of URCA-1, URCA-2 and URCA-3. The first possibility is that the URCA sources are related to the black hole originating the GRB phenomenon. In order to probe such an hypothesis, it is enough to find even a single case in which an URCA source occurs in association with a GRB and in the absence of an associated
Fig. 2. – Theoretical light curve of GRB 031203 predicted by our model in \( \gamma \)-rays (20–200 keV, solid line) and X-rays (0.2–10 keV, dashed line), together with the observed values (the horizontal bar corresponds to the mean peak flux from INTEGRAL [11]). The dotted lines correspond to the source URCA-3 compared with the experimental data obtained by XMM [12] and Chandra [13].

supernova. Such a result, theoretically unexpected, would open an entire new problematic in relativistic astrophysics and in the physics of black holes.

On the other hand, if indeed, as we expect, the clear association between URCA sources and the supernovae occurring together with the GRBs will be confirmed, then two other possibilities will be favored. First, an emission from processes occurring into the early phases of the supernova remnant expansion or the very exciting possibility that we are observing a newly born neutron star out of the supernova phenomenon. We shall focus in the following only on this last topic.

The need for a rapid cooling process due to neutrino and anti-neutrino emission in the process of gravitational collapse leading to the formation of a neutron star was considered for the first time by George Gamow and Mario Schoenberg in 1941 [14]. It was Gamow who gave to this process the name “Urca process”. Since then, a systematic analysis of the theory of neutron star cooling was advanced by Tsuruta and collaborators [15-18] and by Canuto [19]. X-ray observatories such as Einstein (1978-1981), EXOSAT (1983-1986), ROSAT (1990-1998), and the contemporary missions Chandra and XMM-Newton since 1999 had set very embarrassing and stringent upper limits on the neutron star surface temperature in well known historical supernova remnants (see, e.g., [20]). As an example, the neutron star upper limits on the surface temperature in the case of SN 1006 and the Tycho supernova were significantly lower than the temperatures given by standard cooling times (see, e.g., [20]). Much of the theoretical work has been mainly
directed, therefore, to find theoretical arguments in order to explain such low surface temperature ($T_s \sim 0.5–1.0 \times 10^6$ K) — embarrassingly low, when compared to the initial hot ($\sim 10^{11}$ K) birth of a neutron star in a supernova explosion (see, e.g., [20]). Some relevant steps in this direction have been presented in [21–25]. The youngest neutron star to be searched for using its thermal emission in this context has been the pulsar PSR J0205+6449 in 3C 58 (see, e.g., [25]), which is 820 years old. Recently, evidence for the detection of thermal emission from the crab nebula pulsar was reported in [26] which is, again, 951 years old.

In the case of URCA-1, URCA-2 and URCA-3, we may be exploring a totally different regime: the X-ray emission arising from the first months of existence of a neutron star. The reason of approaching first the issue of the thermal emission from the neutron star surface is important, since in principle it may give information on the equations of state in the core at supranuclear densities, on the detailed mechanism of the formation of the neutron star itself and the related neutrino emission. It is of course possible that the neutron star is initially fast rotating and its early emission is dominated by the magnetospheric emission or by accretion processes from the remnant which would overshadow the thermal emission. In this case a periodic signal related to the neutron star rotational period should in principle be observable if the GRB source is close enough.

Quoting [24]: “The time for a neutron star’s center to cool by the direct URCA process to a temperature $T$ has been estimated to be $t = 20 \left[ T / (10^6 K) \right]^{-4}$ s. The direct URCA process and all the exotic cooling mechanisms only occur at supranuclear densities. Matter at subnuclear densities in neutron star crust cools primarily by diffusion of heat to the interior. Thus the surface temperature remains high, in the vicinity of $10^6$ K or more, until the crust’s heat reservoir is consumed. After this diffusion time, which is on the order of 1–100 years, the surface temperature abruptly plunges to values below $5 \times 10^5$ K”. This result has been confirmed in [27].

The considerations we have quoted above are developed in the case of spherical symmetry and should keep the minds open to additional factors to be taken into account: 1) the presence of rotation and magnetic field which may affect the thermal conductivity and the structure of the surface, as well as the above-mentioned magnetospheric emission; 2) there could be accretion of matter from the expanding nebula; 3) some exciting theoretical possibilities advanced by Dyson on volcanoes on neutron stars [28] and iron helide on neutron star [29]; 4) the possibility of piconuclear reactions on neutron star surface discussed in [30].

All the above are just scientific arguments to attract attention on the abrupt fall in luminosity observed in URCA-1, URCA-2 and URCA-3 which is of the greatest scientific interest and further analysis should be followed to check if a similar behavior will be found in future XMM and Chandra observations.

4. – Astrophysical implications

In addition to these very rich problematics in the field of theoretical physics and theoretical astrophysics, there are also more classical astronomical and astrophysical issues, which will need to be answered if indeed the observations of a young neutron star will be confirmed. An important issue to be addressed will be how the young neutron star can be observed, escaping from being buried under the expelled matter of the collapsing star. A possible explanation can originate from the binary nature of the newly born neutron star: the binary system being formed by the newly formed black hole and the triggered gravitational collapse of a companion evolved star leading, possibly, to a “kick”
on and ejection of the newly born neutron star. Another possibility, also related to the binary nature of the system, is that the supernova progenitor star has been depleted of its outer layer by dynamic tidal effects.

In addition, there are other topics in which our scenario can open new research directions in fundamental physics and astrophysics:

1) The problem of the instability leading to the complete gravitational collapse of a $\sim 10 M_{\odot}$ star needs the introduction of a new critical mass for gravitational collapse, which is quite different from the one for white dwarfs and neutron stars which has been widely discussed in the current literature (see, e.g., [31]).

2) The issue of the trigger of the instability of gravitational collapse induced by the GRB on the progenitor star of the supernova or, vice versa, by the supernova on the progenitor star of the GRB needs accurate timing and the considerations of new relativistic phenomena.

3) The general relativistic instability induced on a nearby star by the formation of a black hole needs some very basic new developments in the field of general relativity. Only a preliminary work exist on this subject (see, e.g., [32]) due to the complexity of the problem: unlike the majority of theoretical work on black holes (which deals mainly with one-body solutions), we have to address here a many-body problem in general relativity. We are starting in these days to reconsider, in this framework, some classic work by Fermi [33], Hanni and Ruffini [34], Majumdar [35], Papapetrou [36], Parker et al. [37], Bini et al. [38] which may lead to a new understanding of general relativistic effects relevant to these astrophysical “triptychs”.

5. – The short GRBs as cosmological candles

After concluding the problematic of the long GRBs and their vast astrophysical implications, we briefly turn to the physics of short GRBs [4, 5]. We first recall some progress in understanding the dynamical phase of collapse, the mass-energy formula and the extraction of black hole energy which have been motivated by the analysis of the short GRBs [8]. In this context progress has also been accomplished on establishing an absolute lower limit to the irreducible mass of the black hole as well as on some critical considerations about the relations of general relativity and the second law of thermodynamics [39]. This last issue has been one of the most debated in theoretical physics in the past thirty years [40-44]. Following these conceptual progresses we analyzed the vacuum polarization process around an overcritical collapsing shell [45, 46]. We evidenced the existence of a separatrix and a dyadosphere trapping surface in the dynamics of the electron-positron plasma generated during the process of gravitational collapse [47]. We then analyzed, using recent progress in the solution of the Vlasov-Boltzmann-Maxwell system, the oscillation regime in the created electron-positron plasma and their rapid convergence to a thermalized spectrum [48]. We concluded by making precise predictions for the spectra, the energy fluxes and characteristic time-scales of the radiation for short-bursts [8] (see right panel in fig. 1).

Ghirlanda et al. [49] have found evidence for an exponential cut-off at high energy in the short burst spectra. From the existence of the separatrix introduced in [48], we may expect such a cut off (see fig. 1), and are currently comparing and contrasting the observations with our model. If they are in good agreement, this would lead for the first time to the identification of a process of gravitational collapse and its general relativistic self-closure as seen from an asymptotic observer.
If our theoretical predictions will be confirmed, we will have a powerful tool for cosmological observations: the independent information about luminosity, time-scale and spectrum can uniquely determine the mass, the electromagnetic structure and the distance from the observer of the collapsing core, see [8]. The short-bursts, in addition to give a detailed information on all general relativistic and relativistic field theory phenomena occurring in the approach to the horizon, may also become the best example of standard candles in cosmology [50].

6. – On the dyadosphere of Kerr-Newman black holes

An interesting proposal was advanced in 2002 [51] that the $e^+e^-$ plasma may have a fundamental role as well in the physical process generating jets in the extragalactic radio sources. The concept of dyadosphere originally introduced in Reissner-Nordström black hole in order to create the $e^+e^-$ plasma relevant for GRBs can also be generalized to the process of vacuum polarization originating in a Kerr-Newman black hole due to magneto-hydrodynamical process of energy extraction (see, e.g., [52] and references therein). The concept therefore introduced here becomes relevant for both the extraction of rotational and electromagnetic energy from the most general black hole [53].

** We are thankful to C. Dermer, H. Kleinert, T. Piran, A. Ringwald, R. Sunyaev, L. Titarchuk, J. Wilson and D. Yakovlev for many interesting theoretical discussions, as well as to L. Amati, L.A. Antonelli, E. Costa, F. Fraschetti, L. Nicastro, E. Pian, L. Piro, M. Tavani and all the BeppoSAX team for assistance in the data analysis, as well as to an anonymous referee for interesting suggestions.

REFERENCES

References


Attachment 5
The Blackholic energy: long and short Gamma-Ray Bursts
(New perspectives in physics and astrophysics from the theoretical understanding of Gamma-Ray Bursts, II)

Remo Ruffini*, Maria Grazia Bernardini†, Carlo Luciano Bianco*, Pascal Chardonnet**, Federico Fraschetti†, Vahe Gurzadyan§, Luca Vitagliano†† and She-Sheng Xue†‡

Abstract. We outline the confluence of three novel theoretical fields in our modeling of Gamma-Ray Bursts (GRBs): 1) the ultrarelativistic regime of a shock front expanding with a Lorentz gamma factor ~ 300; 2) the quantum vacuum polarization process leading to an electron-positron plasma originating the shock front; and 3) the general relativistic process of energy extraction from a black hole originating the vacuum polarization process. There are two different classes of GRBs: the long GRBs and the short GRBs. We here address the issue of the long GRBs. The theoretical understanding of the long GRBs has led to the detailed description of their luminosities in fixed energy bands, of their spectral features and made also possible to probe the astrophysical scenario in which they originate. We are specially interested, in this report, to a subclass of long GRBs which appear to be accompanied by a supernova explosion. We are considering two specific examples: GRB980425/SN1998bw and GRB030329/SN2003dh. While these supernovae appear to have a standard energetics of $10^{49}$ ergs, the GRBs are highly variable and can have energetics $10^9 - 10^{10}$ times larger than the ones of the supernovae. Moreover, many long GRBs occurs without the presence of a supernova. It is concluded that in no way a GRB can originate from a supernova. The precise theoretical understanding of the GRB luminosity we present evidence, in both these systems, the existence of an independent component in the X-ray emission, usually interpreted in the current literature as part of the GRB afterglow. This component has been observed by Chandra and XMM to have a strong decay on scale of months. We have named here these two sources respectively URCA-1 and URCA-2, in honor of the work that George Gamow and Mario Shoenberg did in 1939 in this town of Urca identifying the basic mechanism, the Urca processes, leading to the process of gravitational collapse and the formation of a neutron star and a supernova. The further hypothesis is considered to relate this X-ray source to a neutron star, newly born in the Supernova. This hypothesis should be submitted to further theoretical and observational investigation. Some theoretical developments to clarify the astrophysical origin of this new scenario are outlined. We turn then to the theoretical developments in the short GRBs: we first report some progress in the understanding the dynamical phase of collapse, the mass-energy formula and the extraction of blackholic energy which have been motivated by the analysis of the short GRBs. In this context progress has also been accomplished on establishing an absolute lower limit to the irreducible mass of the black hole as well as on some critical considerations about the relations of general relativity and the second law of thermodynamics. We recall how this last issue has been one of the most debated in theoretical physics in the past thirty years due to the work of Bekenstein and Hawking. Following these conceptual progresses we analyze the vacuum polarization process around an overcritical collapsing shell. We evidence the existence of a separatrix and a dyadosphere trapping surface in the dynamics of the electron-positron plasma generated during the process of gravitational collapse. We then analyze, using recent progress in the solution of the Vlasov-Boltzmann-Maxwell system, the oscillation regime in the created electron-positron plasma and their rapid convergence to a thermalized spectrum. We conclude by making precise predictions for the spectra, the energy fluxes and characteristic time-scales of the radiation for short-bursts. If the precise luminosity variation and spectral hardening of the radiation we have predicted will be confirmed by observations of short-bursts, these systems will play a major role as standard candles in cosmology. These considerations will also be relevant for the analysis of the long-bursts when the baryonic matter contribution will be taken into account.
INTRODUCTION

In the last century the fundamental discoveries of nuclear physics have led to the understanding of the thermonuclear energy source of main sequence stars and explained the basic physical processes underlying the solar luminosity (see e.g. M. Schwarzschild [1]).

The discovery of pulsars in 1968 (see Hewish et al. [2]) led to the first evidence for the existence of neutron stars, first described in terms of theoretical physics by George Gamow as far back as 1936 [3]. It became clear that the pulsed luminosity of pulsars, at times $10^2 - 10^3$ larger than solar luminosity, was not related to nuclear burning and could be simply explained in term of the loss of rotational energy of a neutron star (Gold [4, 5]). For the first time it became so clear the possible relevance of strong gravitational fields in the energetics of an astrophysical system.

The birth of X-ray astronomy thanks to Riccardo Giacconi and his group (see e.g. Giacconi and Ruffini [6]) led to a still different energy source, originating from the accretion of matter onto a star which has undergone a complete gravitational collapse process: a black hole (see e.g. Ruffini & Wheeler [7]). In this case, the energetics is dominated by the radiation emitted in the accretion process of matter around an already formed black hole. Luminosities up to $10^9$ times the solar luminosity, much larger then the ones of pulsars, could be explained by the release of energy in matter accreting in the deep potential well of a black hole (Leach and Ruffini [8]). This allowed to probe for the first time the structure of circular orbits around a black hole computed by Ruffini and Wheeler (see e.g. Landau and Lifshitz [9]). This result was well illustrated by the theoretical interpretation of the observations of Cygnus-X1, obtained by the Uhuru satellite and by the optical and radio telescopes on the ground (see Fig. 1).

The discovery of gamma-ray bursts (GRBs) sign a further decisive progress. The GRBs give the first opportunity to probe and observe a yet different form of energy: the extractable energy of the black hole introduced in 1971 (Christodoulou and Ruffini [11]), which we shall refer in the following as the blackholic energy\(^2\). The blackholic energy, expected to be emitted during the dynamical process of gravitational collapse leading to the formation of the black hole, generates X-ray luminosities $10^{41}$ times larger than the solar luminosity, although lasting for a very short time.

The extreme regimes of GRBs evidence new and unexplored regimes of theoretical physics. It is the aim of this talk to outline the progress achieved in understanding these astrophysical systems and the theoretically predicted regimes for the first time submitted to direct observational verification.

It is a pleasure to present these results in Brazil. While sitting at the Casino de Urca, George Gamow and Mario Schoenberg in 1939 identified the basic process leading to the formation and cooling of a newly born neutron star (see e.g. M. Schwarzschild [1]). This result was well illustrated by the theoretical interpretation of the observations of Cygnus-X1, obtained by the Uhuru satellite and by the optical and radio telescopes on the ground (see Fig. 1).

We have clear evidence, first advanced in the system GRB980425/SN1998bw (Ruffini et al. [16], Fraschetti et al. [17]) and now confirmed also in the system GRB030329/SN1998bh, that there are in these systems three different components: 1) the GRB source, generated by the collapse to a black hole; 2) the supernova, generated by the collapse driven by the neutrino emission of the Urca process. It is a welcomed coincidence that, during the preparation of my talk at the tenth Marcel Grossmann Meeting [12], examining the data of the recently observed GRB 030329, we have received a confirmation of a scenario we have recently outlined in three papers giving the theoretical paradigms for the understanding of GRBs (Ruffini et al. [13, 14, 15]).

We then turn to the analysis of the short GRBs. We first review some progress in the study of the general relativistic collapse of a shell of matter endowed with electromagnetic fields, which has been motivated by the study of the short GRBs. We then deduce from these theoretical developments some consequences for the interpretation of the mass-energy formula of the black hole, as well as some conceptual consequences for the relation between general relativity and thermodynamics. We also apply some recent progress on the solution of the Einstein-Maxwell-Blasov equations to the thermalization process occurring in the electron-positron plasma generated by the vacuum polarization process.
The identification of the first black hole in our galaxy: Cygnus X-1

- \( \Phi = 10^{37} \text{ erg/s} = 10^4 L_\odot \)
- \( = 0.01 (dm/dt)_{\text{acc}} c^2 \)
- Absence of pulsation due to uniqueness of Kerr-Newmann black holes
- \( M > 3.2 M_\odot \)

Leach & Ruffini, 1973

Figure 1. Cygnus X-1 offered the possibility of identifying the first black hole in our galaxy (Leach and Ruffini [8]). The luminosity \( \Phi \) of \( 10^4 \) solar luminosities points to the accretion process into a neutron star or a black hole as the energy source. The absence of pulsation is naturally explained either by a non-magnetized neutron star or a Kerr-Newmann black hole, which has necessarily to be axially symmetric. What identifies the black hole unambiguously is that the mass of Cygnus X-1, larger than \( 9 M_\odot \), exceeds the absolute upper limit of the neutron star mass, estimated at \( 3.2 M_\odot \) by Rhoades and Ruffini [10].

We finally give a very specific theoretical prediction on the burst structure to be expected in short GRBs. We then proceed to the conclusions and some general considerations about this novel astrophysical scenario.

THE ENERGETICS OF GAMMA-RAY BURSTS

It is well known how GRBs were detected and studied for the first time using the Vela satellites, developed for military research to monitor the non-violation of the Limited Test Ban Treaty signed in 1963 (see e.g. Strong [18]). It was clear from the early data of these satellites, which were put at 150,000 miles from the surface of Earth, that the GRBs did not originate either on the Earth nor in the Solar System.

The mystery of these sources became more profound as the observations of the BATSE instrument on board of the Compton Gamma-Ray Observatory (CGRO) satellite\(^3\) over 9 years proved the isotropy of these sources in the sky (See Fig. 2). In addition to these data, the CGRO satellite gave an unprecedented number of details on the GRB structure, on their spectral properties and time variabilities which became encoded in the fourth BATSE catalog [19] (see e.g.

---

\(^3\) see http://cossc.gsfc.nasa.gov/batse/
Fig. 2. Position in the sky, in galactic coordinates, of 2000 GRB events seen by the CGRO satellite. Their isotropy is evident. Reproduced from BATSE web site by their courtesy.

Out of the analysis of these BATSE sources it soon became clear (see e.g. Kouveliotou et al. [20], Tavani [21]) the existence of two distinct families of sources: the long bursts, lasting more then one second and softer in spectra, and the short bursts (see Fig. 5), harder in spectra (see Fig. 4). We shall return shortly on this topic.

The situation drastically changed with the discovery of the afterglow by the Italian-Dutch satellite BeppoSAX (Costa et al. [22]) and the possibility which led to the optical identification of the GRBs by the largest telescopes in the world, including the Hubble Space Telescope, the Keck Telescope in Hawaii and the VLT in Chile, and allowed as well the identification in the radio band of these sources. The outcome of this collaboration between complementary observational technique has led to the possibility of identifying in 1997 the distance of these sources from the Earth and their tremendous energy of the order up to $10^{54}$ erg/second during the burst. It is interesting, as we will show in the following, that an energetics of this magnitude for the GRBs had previously been predicted out of first principles already in 1974 by Damour and Ruffini [23].

The resonance between the X- and gamma ray astronomy from the satellites and the optical and radio astronomy from the ground, had already marked in the seventies the great success and development of the astrophysics of binary X-ray sources (see e.g. Giacconi & Ruffini [6]). This resonance is re-proposed here for GRBs on a much larger scale. The use of much larger satellites, like Chandra and XMM-Newton, and dedicated space missions, like HETE-2 and, in the near future, Swift, and the very fortunate circumstance of the coming of age of the development of unprecedented optical technologies for the telescopes offers opportunities without precedence in the history of mankind. In parallel, the enormous scientific interest on the nature of GRB sources and the exploration, not only of new regimes, but also of totally novel conceptual physical process of the blackholic energy, make the knowledge of GRBs an authentic new
THE COMPLEXITY AN SELF-CONSISTENCY OF GRB MODELING

The study of GRBs is very likely “the” most extensive computational and theoretical investigation ever done in physics and astrophysics. There are at least three different fields of research which underlie the foundation of the theoretical understanding of GRBs. All three, for different reasons, are very difficult.

The first field of research is the field of special relativity. As I always mention to my students in the course of theoretical physics, this field is paradoxically very difficult since it is extremely simple. In approaching special relativistic phenomena the extremely simple and clear procedures expressed by Einstein in his 1905 classic paper [24] are often ignored. Einstein makes use in his work of very few physical assumptions, an almost elementary
The second field of research essential for understanding the energetics of GRBs deals with quantum electrodynamics and the relativistic process of pair creation in overcritical electromagnetic fields. This topic is also very difficult but for a quite different conceptual reason: the process of pair creation, expressed in the classic works of Heisenberg-Euler-Schwinger [25, 26] later developed by many others, is based on a very powerful theoretical framework but has never been verified by experimental data. The quest for creating electron-positron pairs by vacuum polarization processes in heavy ion collisions or in lasers has not yet been successfully achieved in Earth-bound experiments (see e.g. Ruffini, Vitagliano, Xue [27]). As we will show here, there is the tantalizing possibility of observing this phenomenon, for the...
first time, in the astrophysical setting of GRBs on a more grandiose scale.

There is a third field which is essential for the understanding of the GRB phenomenon: general relativity. In this case, contrary to the case of special relativity, the field is indeed very difficult, since it is very difficult both from a conceptual, technical and mathematical point of view. The physical assumptions are indeed complex. The entire concept of geometrization of physics needs a new conceptual approach to the field. The mathematical complexity of the pseudo-Riemannian geometry contrasts now with the simple structure of the pseudo-Euclidean Minkowski space. The operational definition of the observable quantities has to take into account the intrinsic geometrical properties and also the cosmological settings of the source. With GRBs we have the possibility to follow, from a safe position in an asymptotically flat space at large distance, the formation of the horizon of a black hole with all the associated relativistic phenomena of light bending and time dilatation. Most important, as we will show in details in this presentation, general relativity in connection with quantum phenomena offers, with the blackholic energy, the explanation of the tremendous GRB energy sources.

For these reasons GRBs offer an authentic new frontier in the field of physics and astrophysics. It is appropriate to mention some of the goals of such a new frontier in the above three fields. We recall in the special relativity field, for the first time, we observe phenomena occurring at Lorentz gamma factors of approximately 300. In the field of relativistic quantum electro-dynamics we see for the first time the interchange between classical fields and the created quantum matter-antimatter pairs. In the field of general relativity also for the first time we can test the blackholic energy which is the basic energetic physical variable underlying the entire GRB phenomenon.

The most appealing aspect of this work is that, if indeed these three different fields are treated and approached
with the necessary technical and scientific maturity, the model which results has a very large redundancy built-in. The approach requires an unprecedented level of self-consistency. Any departures from the correct theoretical treatment in this very complex system lead to exponential departures from the correct solution and from the correct fit of the observations.

It is so that, as the model is being properly developed and verified, its solution will have existence and uniqueness.

**GRBs and special relativity**

The ongoing dialogue between our work and the one of the workers on GRBs, rests still on some elementary considerations presented by Einstein in his classic article of 1905 [24]. These considerations are quite general and even precede Einstein’s derivation, out of first principles, of the Lorentz transformations. We recall here Einstein’s words: “We might, of course, content ourselves with time values determined by an observer stationed together with the watch at the origin of the co-ordinates, and co-ordinating the corresponding positions of the hands with light signals, given out by every event to be timed, and reaching him through empty space. But this co-ordination has the disadvantage that it is not independent of the standpoint of the observer with the watch or clock, as we know from experience”.

The message by Einstein is simply illustrated in Fig. 6. If we consider in an inertial frame a source (solid line) moving with high speed and emitting light signals (dashed lines) along the direction of its motion, a far away observer will measure a delay $\Delta t_a$ between the arrival time of two signals emitted at the origin and after a time interval $\Delta t$ in the laboratory frame. The real velocity of the source is given by:

$$v = \frac{\Delta r}{\Delta t}$$  \hspace{1cm} (1)

and the apparent velocity is given by:

$$v_{\text{app}} = \frac{\Delta r}{\Delta t_a}$$  \hspace{1cm} (2)

As pointed out by Einstein the adoption of coordinating light signals simply by their arrival time as in Eq.(2), without an adequate definition of synchronization, is incorrect and leads to unsurmountable difficulties as well as to apparently “superluminal” velocities as soon as motions close to the speed of light are considered.

The use of $\Delta t_a$ as a time coordinate, often tacitly adopted by astronomers, should be done, if at all, with proper care. The relation between $\Delta t_a$ and the correct time parameterization in the laboratory frame has to be taken into account:

$$\Delta t_a = \Delta t - \frac{\Delta r}{c} = \Delta t - \frac{1}{c} \int_{t_1}^{t_2} v(t') \, dt'.$$  \hspace{1cm} (3)

In other words, the relation between the arrival time and the laboratory time cannot be done without a knowledge of the speed along the entire world-line of the source. In the case of GRBs, such a worldline starts at the moment of gravitational collapse. It is of course clear that the parameterization in the laboratory frame has to take into account the cosmological redshift $z$ of the source. We then have, at the detector:

$$\Delta t_a^d = (1 + z) \Delta t_a.$$  \hspace{1cm} (4)

In the current GRB literature, Eq.(3) has been systematically neglected by addressing only the afterglow description neglecting the previous history of the source. Often the integral equation has been approximated by a clearly incorrect instantaneous value:

$$\Delta t_a \simeq \frac{\Delta t}{2 \gamma^2}.$$  \hspace{1cm} (5)

The attitude has been adopted that it should be possible to consider separately the afterglow part of the GRB phenomenon, without the knowledge of the entire equation of motion of the source. This point of view has reached its most extreme expression in the works reviewed by Piran [29, 30], where the so-called “prompt radiation”, lasting on the order of $10^5$ s, is considered as a burst emitted by the prolonged activity of an “inner engine”. In these models, generally referred to as the “internal shock model”, the emission of the afterglow is assumed to follow the “prompt radiation” phase [31, 32, 33, 34, 35].
As we outline in the following, such an extreme point of view originates from the inability of obtaining the time scale of the “prompt radiation” from a burst structure. These authors consequently appeal to the existence of an “ad hoc” inner engine in the GRB source to solve this problem.

We show in the following how this difficulty has been overcome in our approach by interpreting the “prompt radiation” as an integral part of the afterglow and not as a burst. This explanation can be reached only through a relativistically correct theoretical description of the entire afterglow (see section 13). Within the framework of special relativity we show that it is not possible to describe a GRB phenomenon by disregarding the knowledge of the entire past worldline of the source. We show that at $10^2$ seconds the emission occurs from a region of dimensions $t_0 + \Delta t$.
of approximately $10^{16}$ cm, well within the region of activity of the afterglow. This point was not appreciated in the current literature due to the neglect of the apparent superluminal effects implied by the use of the “pathological” parametrization of the GRB phenomenon by the arrival time of light signals.

An additional difference between our treatment and the ones in the current literature relates to the assumption of the existence of scaling laws in the afterglow phase: the power law dependence of the Lorentz gamma factor on the radial coordinate is usually systematically assumed. From the proper use of the relativistic transformations and by the direct numerical and analytic integration of the special relativistic equations of motion we demonstrate (see section ) that no simple power-law relation can be derived for the equations of motion of the system. This situation is not new for workers in relativistic theories: scaling laws exist in the extreme ultrarelativistic regimes and in the Newtonian ones but not in the intermediate fully relativistic regimes (see e.g. Ruffini [36]).

**GRBs and general relativity**

Three of the most important works in the field of general relativity have certainly been the discovery of the Kerr solution [37], its generalization to the charged case (Newman et al. [38]) and the formulation by Brandon Carter [39] of the Hamilton-Jacobi equations for a charged test particle in the metric and electromagnetic field of a Kerr-Newman solution (see e.g. Landau and Lifshitz [9]). The equations of motion, which are generally second order differential equations, were reduced by Carter to a set of first order differential equations which were then integrated by using an effective potential technique by Ruffini and Wheeler for the Kerr metric (see e.g. Landau and Lifshitz [9]) and by Ruffini for the Reissner-Nordström geometry (Ruffini [36], see Fig. 7).

All the above mathematical results were essential for understanding the new physics of gravitationally collapsed objects and allowed the publication of a very popular article: “Introducing the black hole” (Ruffini and Wheeler [7]). In that paper, we advanced the ansatz that the most general black hole is a solution of the Einstein-Maxwell equations, asymptotically flat and with a regular horizon: the Kerr-Newman solution, characterized only by three parameters: the mass $M$, the charge $Q$ and the angular momentum $L$. This ansatz of the “black hole uniqueness theorem” still today after thirty years presents challenges to the mathematical aspects of its complete proof (see e.g. Carter [41] and Bini et al. [42]). In addition to these mathematical difficulties, in the field of physics this ansatz contains the most profound consequences. The fact that, among all the possible highly nonlinear terms characterizing the gravitationally collapsed objects, only the ones corresponding solely to the Einstein Maxwell equations survive the formation of the horizon has, indeed, extremely profound physical implications. Any departure from such a minimal configuration either collapses on the horizon or is radiated away during the collapse process. This ansatz is crucial in identifying precisely the process of gravitational collapse leading to the formation of the black hole and the emission of GRBs. Indeed, in this specific case, the Born-like nonlinear [43] term of the Heisenberg-Euler-Schwinger [25, 26] Lagrangian are radiated away prior to the formation of the horizon of the black hole (see e.g. Ruffini et al. [27]). Only the nonlinearity corresponding solely to the classical Einstein-Maxwell theory is left as the outcome of the gravitational collapse process.

The same effective potential technique (see Landau and Lifshitz [9]), which allowed the analysis of circular orbits around the black hole, was crucial in reaching the equally interesting discovery of the reversible and irreversible transformations of black holes by Christodoulou and Ruffini [11], which in turn led to the mass-energy formula of the black hole:

$$E_{BH}^2 = M^2 c^4 = \left( M c^2 + \frac{Q^2}{2 \rho_+} \right)^2 + \frac{L^2 c^2}{\rho_+^2},$$  

(6)

with

$$\frac{1}{\rho_+^2} \left( \frac{G}{c^3} \right) \left( \frac{Q^2}{c^4} + 4L^2 c^2 \right) \leq 1,$$  

(7)

where

$$S = 4\pi \rho_+^2 = 4\pi (r_+^2 + \frac{L^2}{c^2 M^2}) = 16\pi \left( \frac{G}{c^4} \right) M^2,$$  

(8)

is the horizon surface area, $M_\text{ir}$ is the irreducible mass, $r_+$ is the horizon radius and $\rho_+$ is the quasi-spheroidal cylindrical coordinate of the horizon evaluated at the equatorial plane. Extreme black holes satisfy the equality in Eq.(7).

From Eq.(6) follows that the total energy of the black hole $E_{BH}$ can be split into three different parts: rest mass, Coulomb energy and rotational energy. In principle both Coulomb energy and rotational energy can be extracted from...
the black hole (Christodoulou and Ruffini [11]). The maximum extractable rotational energy is 29% and the maximum extractable Coulomb energy is 50% of the total energy, as clearly follows from the upper limit for the existence of a black hole, given by Eq.(7). We refer in the following to both these extractable energies as the blackholic energy.

The existence of the black hole and the basic correctness of the circular orbits has been proven by the observations of Cygnus-X1 (see e.g. Giacconi and Ruffini [6]). However, in binary X-ray sources, the black hole uniquely acts passively by generating the deep potential well in which the accretion process occurs. It has become tantalizing to look for astrophysical objects in order to verify the other fundamental prediction of general relativity that the blackholic energy is the largest energy extractable from any physical object.

As we shall see in the next section, the feasibility of the extraction of the blackholic energy has been made possible by the quantum processes of creating, out of classical fields, a plasma of electron-positron pairs in the field of black holes. The manifestation of such process of energy extraction from the black hole is astrophysically manifested by the occurrence of GRBs.
GRBs and quantum electro-dynamics

That a static electromagnetic field stronger than a critical value:

$$E_c = \frac{m_e^2 c^3}{\hbar e}$$ (9)

can polarize the vacuum and create electron-positron pairs was clearly evidenced by Heisenberg and Euler [25]. The major effort in verifying the correctness of this theoretical prediction has been directed in the analysis of heavy ion collisions (see Ruffini et al. [27] and references therein). From an order-of-magnitude estimate, it appears that around a nucleus with a charge:

$$Z_c \simeq \frac{\hbar e}{c^2} \simeq 137$$ (10)

the electric field can be stronger than the electric field polarizing the vacuum. A more accurate detailed analysis taking into account the bound states levels around a nucleus brings to a value of

$$Z_c \simeq 173$$ (11)

for the nuclear charge leading to the existence of a critical field. From the Heisenberg uncertainty principle it follows that, in order to create a pair, the existence of the critical field should last a time

$$\Delta t \sim \frac{\hbar}{m_e c^2} \simeq 10^{-18} \text{s},$$ (12)

which is much longer then the typical confinement time in heavy ion collisions which is

$$\Delta t \sim \frac{\hbar}{m_p c^2} \simeq 10^{-21} \text{s}. $$ (13)

This is certainly a reason why no evidence for pair creation in heavy ion collisions has been obtained although remarkable effort has been spent in various accelerators worldwide. Similar experiments involving laser beams encounter analogous difficulties (see e.g. Ruffini et al. [27] and references therein).

The alternative idea was advanced in 1975 [23] that the critical field condition given in Eq.(9) could be reached easily, and for a time much larger than the one given by Eq.(12), in the field of a Kerr-Newman black hole in a range of masses $3.2 M_\odot \leq M_{BH} \leq 7.2 \times 10^6 M_\odot$. In that paper we have generalized to the curved Kerr-Newman geometry the fundamental theoretical framework developed in Minkowski space by Heisenberg-Euler [25] and Schwinger [26]. This result was made possible by the work on the structure of the Kerr-Newman spacetime previously done by Carter [39] and by the remarkable mathematical craftsmanship of Thibault Damour then working with me as a post-doc in Princeton.

The maximum energy extractable in such a process of creating a vast amount of electron-positron pairs around a black hole is given by:

$$E_{\text{max}} = 1.8 \times 10^{54} (M_{BH}/M_\odot) \text{ erg}. $$ (14)

We concluded in that paper that such a process “naturally leads to a most simple model for the explanation of the recently discovered $\gamma$-rays bursts”.

At that time, GRBs had not yet been optically identified and nothing was known about their distance and consequently about their energetics. Literally thousands of theories existed in order to explain them and it was impossible to establish a rational dialogue with such an enormous number of alternative theories. We did not pursue further our model until the results of the BeppoSAX mission, which clearly pointed to the cosmological origin of GRBs, implying for the typical magnitude of their energy precisely the one predicted by our model.

It is interesting that the idea of using an electron-positron plasma as a basis of a GRB model was independently introduced years later in a set of papers by Cavallo and Rees [44], Cavallo and Horstman [45] and Horstman and Cavallo [46]. These authors did not address the issue of the physical origin of their energy source. They reach their conclusions considering the pair creation and annihilation process occurring in the confinement of a large amount of energy in a region of dimension $\sim 10$ km typical of a neutron star. No relation to the physics of black holes nor to the energy extraction process from a black hole was envisaged in their interesting considerations, mainly directed to the study of the opacity and the consequent dynamics of such an electron-positron plasma.
After the discovery of the afterglows and the optical identification of GRBs at cosmological distances, implying exactly the energetics predicted in Eq.(14), we returned to the analysis of the vacuum polarization process around a black hole and precisely identified the region around the black hole in which the vacuum polarization process and the consequent creation of electron-positron pairs occur. We defined this region, using the Greek name dyad for pairs (δυας, δυαδος), to be the “dyadosphere” of the black hole, bounded by the black hole horizon and the dyadosphere radius $r_{ds}$ given by (see Ruffini [47], Preparata et al. [48] and Fig.8):

$$r_{ds} = \left(\frac{\hbar}{mc}\right)^{\frac{1}{2}} \left(\frac{GM}{c^2}\right)^{\frac{1}{2}} \left(\frac{m_p}{m}\right)^{\frac{1}{2}} \left(\frac{\xi}{q_p}\right)^{\frac{1}{2}} \left(\frac{Q}{\sqrt{GM}}\right)^{\frac{1}{2}} = 1.12 \cdot 10^8 \sqrt{\mu \xi} \text{ cm},$$

where we have introduced the dimensionless mass and charge parameters $\mu = M_{BH}/M_\odot$, $\xi = Q/(M_{BH} \sqrt{G}) \leq 1$.

The analysis of the dyadosphere was developed, at that time, around an already formed black hole. In recent months we have been developing the dynamical formation of the black hole and correspondingly of the dyadosphere during the process of gravitational collapse, reaching some specific signatures which may be detectable in the structure of the short and long GRBs (Cherubini et al. [50], Ruffini and Vitagliano [51, 52], Ruffini et al. [49, 53, 54]).

**THE DYNAMICAL PHASES FOLLOWING THE DYADOSPHERE FORMATION**

Many details of this topic have been presented in great details in Ruffini et al. [28].

After the vacuum polarization process around a black hole, one of the topics of the greatest scientific interest is the analysis of the dynamics of the electron-positron plasma formed in the dyadosphere. This issue was addressed by
The optically thick phase of our model are qualitatively represented in this diagram. There are clearly recognizable 1) the PEM pulse phase, 2) the impact on the baryonic remnant, 3) the PEMB pulse phase and the final approach to transparency with the emission of the P-GRB (see Fig. 10). Details in Ruffini et al. [28].

us in a very effective collaboration with Jim Wilson at Livermore. The numerical simulations of this problem were developed at Livermore, while the semi-analytic approach was developed in Rome (Ruffini et al. [55]).

The corresponding treatment in the framework of the Cavallo et al. analysis was performed by Piran et al. [56] also using a numerical approach, by Bisnovaty-Kogan and Murzina [57] using an analytic approach and by Mészáros, Laguna and Rees [58] using a numerical and semi-analytic approach.

Although some analogies exists between these treatments, they are significantly different in the theoretical details and in the final results. Since the final result of the GRB model is extremely sensitive to any departure from the correct treatment, it is indeed very important to detect at every step the appearance of possible fatal errors.

A conclusion common to all these treatments is that the electron-positron plasma is initially optically thick and expands till transparency reaching very high values of the Lorentz gamma factor. A second point, which is common, is the discovery of a new clear feature: the plasma shell expands but the Lorentz contraction is such that its width in the laboratory frame appears to be constant.

There is however a major difference between our approach and the ones of Piran, Mészáros and Rees, in that the dyadosphere is assumed by us to be filled uniquely with an electron-positron plasma. Such a plasma expands in substantial agreement with the results presented in the work of Bisnovati-Kogan and Murzina [57]. In our model the pulse of electron-positron pairs and photons (PEM Pulse, see Ruffini et al. [55]) evolves and at a radius on the order of $10^{19}$ cm it encounters the remnant of the star progenitor of the newly formed black hole. The PEM pulse is then loaded with baryons. A new pulse is formed of electron-positron-photons and baryons (PEMB Pulse, see Ruffini et al. [59]) which expands all the way until transparency is reached. At transparency the emitted photons give origin to what we define as the Proper-GRB (see Ruffini et al. [14] and Fig. 9).

In our approach, the baryon loading is measured by a dimensionless quantity

$$B = \frac{M_B c^2}{E_{dyad}}$$

(16)

which gives direct information about the mass $M_B$ of the remnant. The corresponding treatment done by Piran and collaborators (Shemi & Piran [60], Piran et al. [56]) and by Mészáros, Laguna and Rees [58] differs in one important respect: the baryonic loading is assumed to occur since the beginning of the electron-positron pair formation and no relation to the mass of the remnant of the collapsed progenitor star is attributed to it.

A marked difference also exists between our description of the rate equation for the electron-positron pairs and the ones by those authors. While our results are comparable with the ones obtained by Piran under the same initial conditions, the set of approximations adopted by Mészáros, Laguna and Rees [58] appears to be too radical and leads to very different results violating energy and momentum conservation (see Bianco et al. [61]).
From our analysis (Ruffini et al. [59]) it also becomes clear that such expanding dynamical evolution can only occur for values of $B < 10^{-2}$. This prediction, as we will show shortly in the three GRB sources considered here, is very satisfactorily confirmed by observations.

From the value of the $B$ parameter, related to the mass of the remnant, it therefore follows that the collapse to a black hole leading to a GRB is drastically different from the collapse to a neutron star. While in the case of a neutron star collapse a very large amount of matter is expelled, in many instances well above the mass of the neutron star itself, in the case of black holes leading to a GRB only a very small fraction of the initial mass ($\sim 10^{-2}$ or less) is expelled. The collapse to a black hole giving rise to a GRB appears to be much smoother than any collapse process considered until today: almost 99.9% of the star has to be collapsing simultaneously!

We summarize in Figs. 9–10 the optically thick phase of GRBs in our model: we start from a given dyadosphere of energy $E_{\text{dyad}}$, the pair-electromagnetic pulse (PEM pulse) self-accelerates outward typically reaching Lorentz gamma factors $\gamma \sim 200$ at $r \sim 10^{10}$ cm; at this point the collision of the PEM pulse with the remnant of the progenitor star occurs with an abrupt decrease in the value of the Lorentz gamma factor; a new pair-electromagnetic-baryon pulse (PEMB pulse) is formed which self-accelerates outward until the system becomes transparent.

The photon emission at this transparency point is the Proper-GRB (P-GRB). An accelerated beam of baryons with an initial Lorentz gamma factor $\gamma_0$ starts to interact with the interstellar medium at typical distances from the black hole of $r_0 \sim 10^{14}$ cm and at a photon arrival time at the detector on the Earth surface of $t^a_{\text{det}} \sim 0.1$ s. These values determine the initial conditions of the afterglow.

**Figure 10.** The P-GRB emitted at the transparency point at a time of arrival $t^a_{\text{det}}$ which has been computed following the prescriptions of Eq.(3). Details in Ruffini et al. [14, 28].
THE DESCRIPTION OF THE AFTERGLOW

After reaching transparency and the emission of the P-GRB, the accelerated baryonic matter (the ABM pulse) interacts with the interstellar medium (ISM) and gives rise to the afterglow (see Fig. 11). Also in the descriptions of this last phase many differences exist between our treatment and the other ones in the current literature.

The initial value problem

The initial conditions of the afterglow era are determined at the end of the optically thick era when the P-GRB is emitted. As recalled in the last section, the transparency condition is determined by a time of arrival \( t_{\text{d}} \), a value of the gamma Lorentz factor \( \gamma \), a value of the radial coordinate \( r_{\gamma} \), an amount of baryonic matter \( M_B \) which are only functions of the two parameters \( E_{\text{dy}} \) and \( B \) (see Eq.(16)). It is appropriate here to emphasize again that, in order to have the expansion leading to an observed GRB, one must have \( B < 10^{-2} \).

This connection to the optically thick era is missing in the current approach in the literature which attributes the origin of the “prompt radiation” to an unspecified inner engine activity (see Piran [29] and references therein). The initial conditions at the beginning of the afterglow era are obtained by a best fit of the later parts of the afterglow. This approach is quite unsatisfactory since, as we will explicitly show, the theoretical treatments currently adopted in the description of the afterglow are not correct. The fit using an incorrect theoretical treatment leads necessarily to the wrong conclusions as well as, in turn, to the determination of incorrect initial conditions.

The equations of the afterglow dynamics

Let us first summarize the commonalities between our approach and the ones in the current literature. In both cases (see Piran [29], Chiang & Dermer [62] and Ruffini et al. [28]) a thin shell approximation is used to describe the
collision between the ABM pulse and the ISM:

\[ dE_{\text{int}} = (\gamma - 1) dM_{\text{int}} c^2, \quad (17a) \]
\[ d\gamma = -\frac{\gamma - 1}{\gamma} dM_{\text{int}}, \quad (17b) \]
\[ dM = \frac{1}{\gamma} dE_{\text{int}} + dM_{\text{int}}, \quad (17c) \]
\[ dM_{\text{int}} = 4\pi m_p n_{\text{ISM}} r^2 dr, \quad (17d) \]

where \( E_{\text{int}}, \gamma \) and \( M \) are respectively the internal energy, the Lorentz factor and the mass-energy of the expanding pulse, \( n_{\text{ISM}} \) is the ISM number density which is assumed to be constant, \( m_p \) is the proton mass, \( \epsilon \) is the emitted fraction of the energy developed in the collision with the ISM and \( M_{\text{int}} \) is the amount of ISM mass swept up within the radius \( r: M_{\text{int}} = (4/3)\pi (r^3 - r_0^3) m_p n_{\text{ISM}}, \) where \( r_0 \) is the starting radius of the shock front. In general, an additional condition is needed in order to determine \( \epsilon \) as a function of the radial coordinate. In the following, \( \epsilon \) is assumed to be constant and such an approximation appears to be correct in the GRB context.

In both our work and in the current literature (see Piran [29], Chiang & Dermer [62] and Ruffini et al. [28]) a first integral of these equations has been found, leading to expressions for the Lorentz gamma factor as a function of the radial coordinate. In the following, \( \epsilon \) is assumed to be constant and such an approximation appears to be correct in the GRB context.

A major difference between our treatment and the other ones in the current literature is that we have integrated the integral of these equations has been found, leading to expressions for the Lorentz gamma factor as a function of the radial coordinate. In the following, \( \epsilon \) is assumed to be constant and such an approximation appears to be correct in the GRB context.

\[ \gamma^2 = \frac{\gamma^2 + 2\gamma (M_{\text{int}}/M_B) + (M_{\text{int}}/M_B)^2}{1 + 2\gamma (M_{\text{int}}/M_B) + (M_{\text{int}}/M_B)^2}, \quad (18) \]
\[ \gamma = \frac{1 + (M_{\text{int}}/M_B) \left[ 1 + (\gamma - 1) \right] \left[ 1 + (1/2) (M_{\text{int}}/M_B) \right]}{\gamma^2 + (M_{\text{int}}/M_B) \left[ 1 + (\gamma - 1) \right] \left[ 1 + (1/2) (M_{\text{int}}/M_B) \right]}, \quad (19) \]

where \( \gamma \) and \( M_B \) are respectively the values of the Lorentz gamma factor and of the mass of the accelerated baryons at the beginning of the afterglow phase and \( r_0 \) is the value of the radius \( r \) at the beginning of the afterglow phase.

A major difference between the treatment and the other ones in the current literature is that we have integrated the above equations analytically, obtaining the explicit analytic form of the equations of motion for the expanding shell in the afterglow for a constant ISM density. For the fully radiative case we have explicitly integrated the differential equation for \( r(t) \) in Eq.(19), recalling that \( \gamma^2 = 1 - \left[ dr/(cdt) \right]^2 \), where \( t \) is the time in the laboratory reference frame. We have then obtained a new explicit analytic solution of the equations of motion for the relativistic shell in the entire range from the ultra-relativistic to the non-relativistic regime:

\[ t = \frac{M_B - m_i^0}{2\gamma \sqrt{c}} (r - r_0) + \frac{\sqrt{\gamma^2 + 2\gamma (M_{\text{int}}/M_B) + (M_{\text{int}}/M_B)^2}}{\gamma^2 (1 + (\gamma - 1) \left[ 1 + (1/2) (M_{\text{int}}/M_B) \right])} \left( \frac{m_i^0}{\sqrt{c}} \right) \left\{ \arctan \left( \frac{2(t - t_0)}{A \sqrt{\gamma^2}} \right) - \frac{2}{\sqrt{\gamma^2}} \right\}, \quad (20) \]

where \( A = \sqrt{(MB - m_i^0)/m_i^0}, \quad C = MB\gamma (\gamma - 1)/(\gamma + 1) \) and \( m_i^0 = (4/3)\pi m_p n_{\text{ISM}} r_0^3. \)

Correspondingly, in the adiabatic case we have:

\[ t = \left( \frac{\sqrt{\gamma^2 + 2\gamma (M_{\text{int}}/M_B) + (M_{\text{int}}/M_B)^2}}{\gamma^2 \sqrt{c}} \right) \left( \frac{m_i^0}{\sqrt{c}} \right) \left\{ \arctan \left( \frac{2(t - t_0)}{A \sqrt{\gamma^2}} \right) - \frac{2}{\sqrt{\gamma^2}} \right\} + t_0, \quad (21) \]

In the current literature, following Blandford and McKee [63], a so-called “ultrarelativistic” approximation \( \gamma \gg 1 \) has been widely adopted by many authors to solve Eqs.(17) (see e.g. Sari [64, 65], Waxman [66], Rees & Mészáros [67], Granot et al. [68], Panaitescu & Mészáros [69], Piran [29], Gruzinov & Waxman [70], van Paradijs et al. [71], Mészáros [72] and references therein). This leads to simple constant-index power-law relations:

\[ \gamma = r^{-a}, \quad (22a) \]

with \( a = 3 \) in the fully radiative case and \( a = 3/2 \) in the fully adiabatic case. This simple relation is in stark contrast to the complexity of Eq.(19) and Eq.(18) respectively. In the same spirit, instead of Eq.(20) and Eq.(21), some authors
have assumed the following much simpler approximation for the relation between the time and the radial coordinate of the expanding shell, both in the fully radiative and in the fully adiabatic cases:

\[ ct = r, \] (22b)

while others, like e.g. Panaitescu & Mészáros [69], have integrated the approximate Eq.(22a), obtaining:

\[ ct = r \left[ 1 + (4a + 2)^{-1} \gamma^{-2}(r) \right]. \] (22c)

Again, it is appropriate here to emphasize the stark contrast between Eqs.(22b),(22c) and the exact analytic solutions of Eqs.(17), expressed in Eqs.(20),(21).

The equitemporal surfaces (EQTSs)

As pointed out long ago by Couderc [73], in all relativistic expansion the crucial geometrical quantities with respect to a physical observer are the "equitemporal surfaces" (EQTSs), namely the locus of source points of the signals arriving at the observer at the same time.

For a relativistically expanding spherically symmetric source the EQTSs are surfaces of revolution about the line of sight. The general expression for their profile, in the form \( \vartheta = \vartheta(r) \), corresponding to an arrival time \( t_a \) of the photons at the detector, can be obtained from (see e.g. Ruffini et al. [28], Bianco and Ruffini [74, 75] and Figs. 12–14):

\[ ct_a = ct(r) - r \cos \vartheta + r^*, \] (23)

where \( r^* \) is the initial size of the expanding source, \( \vartheta \) is the angle between the radial expansion velocity of a point on its surface and the line of sight, and \( t = t(r) \) is its equation of motion, expressed in the laboratory frame, obtained by the integration of Eqs.(17). From the definition of the Lorentz gamma factor \( \gamma^2 = 1 - (dr/cdt)^2 \), we have in fact:

\[ ct(r) = \int_0^r \left[ 1 - \gamma^{-2}(r') \right]^{-1/2} dr', \] (24)

where \( \gamma(r) \) comes from the integration of Eqs.(17).

We have obtained the expressions in the adiabatic case and in the fully radiative cases respectively (see Bianco and Ruffini [75]):

\[
\cos \vartheta = \frac{m_i^2}{4M_B \sqrt{\frac{c^2}{r^2} - 1}} \left[ \left( \frac{r}{r_a} \right)^3 - \frac{r_a}{r} \right] + \frac{ct_a}{r} \] \tag{25}

\[
- \frac{c t_a}{r} + r^* = \frac{\gamma - (m_i/M_B)}{\sqrt{\frac{c^2}{r^2} - 1}} \left[ \frac{r_a}{r} - 1 \right].
\]

\[
\cos \vartheta = \frac{M_B - m_i^2}{2r \sqrt{C}} (r - r_a) + \frac{m_i r_0}{8r \sqrt{C}} \left[ \left( \frac{r}{r_a} \right)^4 - 1 \right]
\] \tag{26}

\[
+ \frac{r_c \sqrt{C}}{12m_i A^2} \ln \left\{ \frac{A + (r/r_0)^{1/3} (A^3 + 1)}{A^3 + (r/r_0)^{1/3} (A + 1)^3} \right\} + \frac{ct_a}{r} - \frac{c t_a}{r}
\]

\[
+ \frac{r^*}{r} + \frac{r_c \sqrt{C}}{6m_i A^2} \left[ \arctan \frac{2(r/r_0) - A}{A^2} - \arctan \frac{2(-A)}{A^2} \right].
\]

The two EQTSs are represented at selected values of the arrival time \( t_a \) in Fig. 16, where the illustrative case of GRB 991216 has been used as a prototype. The initial conditions at the beginning of the afterglow era are in this case given by \( \gamma_1 = 310.131, r_0 = 1.943 \times 10^{14} \text{ cm}, t_0 = 6.481 \times 10^3 \text{ s, } r^* = 2.354 \times 10^8 \text{ cm} \) (see Ruffini et al. [13, 14, 76, 28]).
Figure 12. Not all values of $\vartheta$ are allowed. Only photons emitted at an angle such that $\cos \vartheta \geq (v/c)$ can be viewed by the observer. Thus the maximum allowed $\vartheta$ value $\vartheta_{\text{max}}$ corresponds to $\cos \vartheta_{\text{max}} = (v/c)$. In this figure we show $\vartheta_{\text{max}}$ (i.e. the angular amplitude of the visible area of the ABM pulse) in degrees as a function of the arrival time at the detector for the photons emitted along the line of sight (see text). In the earliest GRB phases $v \sim c$ and so $\vartheta_{\text{max}} \sim 0$. On the other hand, in the latest phases of the afterglow the ABM pulse velocity decreases and $\vartheta_{\text{max}}$ tends to the maximum possible value, i.e. $90^\circ$. Details in Ruffini et al. [76, 28]

The bolometric luminosity of the source

We assume that the internal energy due to kinetic collision is instantly radiated away and that the corresponding emission is isotropic. As in section , let $\Delta \varepsilon$ be the internal energy density developed in the collision. In the comoving frame the energy per unit of volume and per solid angle is simply

$$\left( \frac{dE}{dV d\Omega} \right) = \frac{\Delta \varepsilon}{4\pi}$$

(27)

due to the fact that the emission is isotropic in this frame. The total number of photons emitted is an invariant quantity independent of the frame used. Thus we can compute this quantity as seen by an observer in the comoving frame (which we denote with the subscript “$\circ$”) and by an observer in the laboratory frame (which we denote with no subscripts). Doing this we find:

$$\frac{dN_\gamma}{dt d\Omega d\Sigma} = \left( \frac{dN_\gamma}{dt d\Omega d\Sigma} \right)_\circ \Lambda^{-3} \cos \vartheta,$$

(28)

where $\cos \vartheta$ comes from the projection of the elementary surface of the shell on the direction of propagation and $\Lambda = \gamma (1 - \beta \cos \vartheta)$ is the Doppler factor introduced in the two following differential transformation

$$d\Omega_\circ = d\Omega \times \Lambda^{-2}$$

(29)
Figure 13. The diameter of the visible area is represented as a function of the ABM pulse radius. In the earliest expansion phases ($\gamma \sim 310$) $\vartheta_{\text{max}}$ is very small (see left pane and Fig. 14), so the visible area is just a small fraction of the total ABM pulse surface. On the other hand, in the final expansion phases $\vartheta_{\text{max}} \rightarrow 90^\circ$ and almost all the ABM pulse surface becomes visible. Details in Ruffini et al. [76, 28]

for the solid angle transformation and

$$d\vartheta = dt \times \Lambda^{-1}$$

(30)

for the time transformation. The integration in $d\Sigma$ is performed over the visible area of the ABM pulse at laboratory time $t$, namely with $0 \leq \vartheta \leq \vartheta_{\text{max}}$ and $\vartheta_{\text{max}}$ defined in section (see Figs. 12–14). An extra $\Lambda$ factor comes from the energy transformation:

$$E_\vartheta = E \times \Lambda.$$  

(31)

See also Chiang and Dermer [62]. Thus finally we obtain:

$$\frac{dE}{d\vartheta d\Omega} = \left(\frac{dE}{d\vartheta d\Sigma}\right) \Lambda^{-4} \cos \vartheta.$$  

(32)

Doing this we clearly identify $\left(\frac{dE}{d\vartheta d\Sigma}\right)$ as the energy density in the comoving frame up to a factor $\frac{1}{4\pi}$ (see Eq.(27)). Then we have:

$$\frac{dE}{d\vartheta d\Omega} = \int \frac{\Delta E}{4\pi} \cos \vartheta \Lambda^{-4} d\Sigma,$$  

(33)

where the integration in $d\Sigma$ is performed over the ABM pulse visible area at laboratory time $t$, namely with $0 \leq \vartheta \leq \vartheta_{\text{max}}$ and $\vartheta_{\text{max}}$ defined in section. Eq.(33) gives us the energy emitted toward the observer per unit solid angle and per unit laboratory time $t$ in the laboratory frame.
What we really need is the energy emitted per unit solid angle and per unit detector arrival time \( dE/d\Omega \), so we must use the complete relation between \( d\Sigma/dt \) and \( t \) given in Eq.(23). First we have to multiply the integrand in Eq.(33) by the factor \( (dt/d\Sigma) \) to transform the energy density generated per unit of laboratory time \( t \) into the energy density generated per unit arrival time \( d\Sigma \). Then we have to integrate with respect to \( d\Sigma \) over the equitemporal surface (EQTS, see section ) of constant arrival time \( t \) instead of the ABM pulse visible area at laboratory time \( t \). The analog of Eq.(33) for the source luminosity in detector arrival time is then:

\[
\frac{dE}{d\Omega} = \int_{EQTS} \frac{\Delta r}{4\pi} v \cos \theta \Lambda^{-4} \frac{dt}{d\Sigma}. \tag{34}
\]

It is important to note that, in the present case of GRB 991216, the Doppler factor \( \Lambda^{-4} \) in Eq.(34) enhances the apparent luminosity of the burst, as compared to the intrinsic luminosity, by a factor which at the peak of the afterglow is in the range between \( 10^{10} \) and \( 10^{12} \).

We are now able to reproduce in Fig. 17 the general behavior of the luminosity starting from the P-GRB to the latest phases of the afterglow as a function of the arrival time. It is generally agreed that the GRB afterglow originates from an ultrarelativistic shell of baryons with an initial Lorentz factor \( \gamma \sim 200–300 \) with respect to the interstellar medium (see e.g. Ruffini et al. [28], Bianco & Ruffini [74] and references therein). Using GRB 991216 as a prototype, in Ruffini et al. [13, 14] we have shown how from the time varying bolometric intensity of the afterglow it is possible to infer the average density \( \langle n_{\text{ISM}} \rangle = 1 \text{ particle/cm}^3 \) of the Interstellar Medium (ISM) in a region of approximately \( 10^{17} \) cm surrounding the black hole giving rise to the GRB phenomenon.
Figure 15. Due to the extremely high and extremely varying Lorentz gamma factor, photons reaching the detector on the Earth at the same arrival time are actually emitted at very different times and positions. We represent here the surfaces of photon emission corresponding to selected values of the photon arrival time at the detector: the equitemporal surfaces (EQTS). Such surfaces differ from the ellipsoids described by Rees in the context of the expanding radio sources with typical Lorentz factor $\gamma \sim 4$ and constant. In fact, in GRB 991216 the Lorentz gamma factor ranges from 310 to 1. The EQTSs represented here (solid lines) correspond respectively to values of the arrival time ranging from $5\, s$ (the smallest surface on the left of the plot) to $60\, s$ (the largest one on the right). Each surface differs from the previous one by $5\, s$. To each EQTS contributes emission processes occurring at different values of the Lorentz gamma factor. The dashed lines are the boundaries of the visible area of the ABM pulse and the black hole is located at position $(0,0)$ in this plot. Note the different scales on the two axes, indicating the very high EQTS “effective eccentricity”. The time interval from $5\, s$ to $60\, s$ has been chosen to encompass the E-APE emission, ranging from $\gamma = 308.8$ to $\gamma = 56.84$. Details in Ruffini et al. [76, 28].

It was shown in Ruffini et al. [76] that the theoretical interpretation of the intensity variations in the prompt phase in the afterglow implies the presence in the ISM of inhomogeneities of typical scale $10^{15}\, \text{cm}$. Such inhomogeneities were there represented for simplicity as spherically symmetric over-dense regions with $\langle n^{\text{od}}_{\text{ism}} \rangle \simeq 10^2 \langle n_{\text{ism}} \rangle$ separated by under-dense regions with $\langle n^{\text{ud}}_{\text{ism}} \rangle \simeq 10^{-2} \langle n_{\text{ism}} \rangle$ also of typical scale $\sim 10^{15}\, \text{cm}$ in order to keep $\langle n_{\text{ism}} \rangle$ constant.

The summary of these general results are shown in Fig. 18, where the P-GRB, the emission at the peak of the afterglow in relation to the “prompt emission” and the latest part of the afterglow are clearly identified for the source GRB 991216. Details in Ruffini et al. [28].
Figure 16. Comparison between EQTSs in the adiabatic regime (solid lines) and in the fully radiative regime (dashed lines). The left plot shows the EQTSs for $t_a = 5$ s, $t_a = 15$ s, $t_a = 30$ s and $t_a = 45$ s, respectively from the inner to the outer one. The right plot shows the EQTS at an arrival time of 2 days. Details in Bianco and Ruffini [75].

Figure 17. Bolometric luminosity of P-GRB and afterglow as a function of the arrival time. Details in Ruffini et al. [28]. Reproduced and adapted from Ruffini et al. [77] with the kind permission of the publisher.
THE THEORY OF THE LUMINOSITY IN FIXED ENERGY BANDS AND SPECTRA OF THE AFTERGLOW

Having obtained a general agreement between the observed luminosity variability and our treatment of the bolometric luminosity, we have further developed the model in order to explain

a) the details of the observed luminosity in fixed energy bands, which are the ones actually measured by the detectors on the satellites

b) the instantaneous as well as the average spectral distribution in the entire afterglow and

c) the observed hard to soft drift observed in GRB spectra.

In order to do so we have developed (Ruffini et al. [78]) a more detailed theory of the structure of the shock front giving rise to the afterglow. We have modeled the interaction between the ultrarelativistic shell of baryons and the ISM by a shock front with three well-defined layers (see e.g. secs. 85–89, 135 of Landau & Lifshitz [79], ch. 2 and sec. 13–15 of Zel’dovich & Rayzer [80] and sec. IV, 11–13 of Sedov [81]). From the back end to the leading edge of this shock front there is:

a) A compressed high-temperature layer, of thickness Δ', in front of the relativistic baryonic shell, created by the accumulated material swept up in the ISM.

b) A thin shock front, with a jump ΔT in the temperature which has been traditionally estimated in the comoving

Figure 18. The detailed features of GRB 991216 evidenced by our theoretical models are here reproduced. The P-GRB, the “prompt radiation” and what is generally called the afterglow. It is clear that the prompt radiation coincides with the extended afterglow peak emission (E-APE) and has been considered as a burst only as a consequence of the high noise threshold in the observations. Details in Ruffini et al. [76, 28].
frame by the Rankine-Hugoniot adiabatic equations:
\[
\Delta T \simeq \left(\frac{3}{16}\right) m_p \delta v^2 / k \simeq 1.5 \times 10^{11} \left[ \delta v / (10^5 \text{km} \text{s}^{-1}) \right]^2 \text{K}, \tag{35}
\]
where \( \delta v \) is the velocity jump, \( m_p \) is the proton mass and \( k \) is Boltzmann's constant. Of course such a treatment, valid for \( \gamma \sim 1 \), has to be modified (see below) in our novel treatment for the \( \gamma \sim 200 \) case relevant to GRBs.

e) A pre-shock layer of ISM swept-up matter at much lower density and temperature, both of which change abruptly at the thin shock front behind it.

At larger distances ahead of the expanding fireball the ISM is at still smaller densities. The upper limit to the temperature jump at the thin shock front, given in Eq.(35), is due to the transformation of kinetic energy to thermal energy, since the particle mean free path is assumed to be less than the thickness of the layer (a). The thermal emission of the observed X- and gamma ray radiation, which as seen from the observations reveals a high level of stability, is emitted in the above region (a) due to the sharp temperature gradient at the thin shock front described in the above region (b).

The optical and radio emission comes in our model from the extended region (c). The description of such a region, unlike the sharp and well-defined temperature gradient occurring in region (b), requires magnetohydrodynamic simulations of the evolution of the electron energy distribution of the synchrotron emission. Such analysis has been performed using 3-D Eulerian MHD codes for the particle acceleration models to produce the energy spectrum of cosmic rays at supernova envelope fronts (see e.g. McKee and Cowie [82], Tenorio-Tagle et al. [83], Stone and Norman [84], Jun & Jones [85]). Other challenges are the magnetic field and the instabilities. We mention two key phenomena: first, the importance of the development of Kelvin-Helmholtz and Rayleigh-Taylor instabilities ahead of the thin shock front. The second is the dual effect that the shock front has on the ISM initial magnetic field, first through the compression of the swept-up matter containing the field and secondly the amplification of the radial magnetic field component due to the Rayleigh-Taylor instability. Simulations of both effects (see e.g. Jun and Jones [85] and references therein), modeling the synchrotron radio emission for an expanding supernova shell at various initial magnetic field and ISM parameter values, shows for example that the presence of an initial tangential magnetic field component may essentially affect the resulting magnetic field configuration and hence the outgoing radio flux and spectrum. Among the additional effects to be taken into account are the initial inhomogeneity of the ISM and the contribution of magnetohydrodynamic turbulence.

In our approach we focus uniquely on the X- and gamma ray radiation, which appears to be conceptually much simpler than the optical and radio emission. It is perfectly predictable by a set of constitutive equations (see next section), which leads to directly verifiable and very stable features in the spectral distribution of the observed GRB afterglows. In line with the observations of GRB 991216 and other GRB sources, we assume in the following that the X- and gamma ray luminosity represents approximately 90% of the energy flux of the afterglow, while the optical and radio emission represents only the remaining 10%.

This approach differs significantly from the other ones in the current literature, where attempts are made to explain at once all the multi-wavelength emission in the radio, optical, X and gamma ray as coming from a common origin which is linked to boosted synchrotron emission. Such an approach has been shown to have a variety of difficulties (Ghirlanda et al. [86], Preece et al. [87]) and cannot anyway have the instantaneous variability needed to explain the structure in the "prompt radiation" in an external shock scenario, which is indeed confirmed by our model.

The equations determining the luminosity in fixed energy bands

Here the fundamental new assumption is adopted (see also Ruffini et al. [88]) that the X- and gamma ray radiation during the entire afterglow phase has a thermal spectrum in the co-moving frame. The temperature is then given by:
\[
T_e = \frac{\Delta E_{\text{int}}}{4\pi^2 \Delta \tau \sigma R} \left(4\pi^2 \Delta \tau \sigma R \right)^{1/4}, \tag{36}
\]
where \( \Delta E_{\text{int}} \) is the internal energy developed in the collision with the ISM in a time interval \( \Delta \tau \) in the co-moving frame, \( \sigma \) is the Stefan-Boltzmann constant and
\[
R = A_{\text{eff}} / A, \tag{37}
\]
is the ratio between the "effective emitting area" of the afterglow and the surface area of radius \( r \). In GRB 991216 such a factor is observed to be decreasing during the afterglow between: \( 3.01 \times 10^{-8} \geq R \geq 5.01 \times 10^{-12} \) (Ruffini et al. [88]).
The temperature in the comoving frame of the shock front corresponding to the density distribution with the six spikes A,B,C,D,E,F presented in Ruffini et al.\textsuperscript{5}. The dashed line corresponds to an homogeneous distribution with \(n_{\text{ism}} = 1\). Details in Ruffini et al. [78].

The temperature in the comoving frame corresponding to the density distribution described in Ruffini et al. [76] is shown in Fig. 19.

We are now ready to evaluate the source luminosity in a given energy band. The source luminosity at a detector arrival time \(t_{da}\), per unit solid angle \(d\Omega\) and in the energy band \([\nu_1, \nu_2]\) is given by (see Ruffini et al. [28, 88]):

\[
\frac{dE_{[\nu_1,\nu_2]}}{dt_{da}d\Omega} = \int_{t_{EQTS}} \frac{\Delta \epsilon}{4\pi} \nu \cos \theta \Lambda^{-4} \frac{dt}{dt_{da}} W(\nu_1, \nu_2, T_{arr}) \ d\Sigma, \tag{38}
\]

where \(\Delta \epsilon = \Delta E_{\text{int}}/V\) is the energy density released in the interaction of the ABM pulse with the ISM inhomogeneities measured in the comoving frame, \(\Lambda = \gamma(1 - (v/c) \cos \theta)\) is the Doppler factor, \(W(\nu_1, \nu_2, T_{arr})\) is an “effective weight” required to evaluate only the contributions in the energy band \([\nu_1, \nu_2]\), \(d\Sigma\) is the surface element of the EQTS at detector arrival time \(t_{da}\) on which the integration is performed (see also Ruffini et al. [76]) and \(T_{arr}\) is the observed temperature of the radiation emitted from \(d\Sigma\):

\[
T_{arr} = T_{\gamma}/[\gamma(1 - (v/c) \cos \theta)(1 + z)]. \tag{39}
\]

The “effective weight” \(W(\nu_1, \nu_2, T_{arr})\) is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature \(T_{arr}\) to the total integral \(aT_{arr}^4\):

\[
W(\nu_1, \nu_2, T_{arr}) = \frac{1}{aT_{arr}^4} \int_{\nu_1}^{\nu_2} \rho(T_{arr}, \nu) \left(\frac{\hbar \nu}{c}\right)^3 d\nu, \tag{40}
\]
where $\rho(T_{\text{arr}}, \nu)$ is the Planckian distribution at temperature $T_{\text{arr}}$:

$$\rho(T_{\text{arr}}, \nu) = \left(\frac{2}{\hbar^3}\right) \frac{\hbar \nu}{e^{\hbar \nu/(kT_{\text{arr}})} - 1}$$  \hspace{1cm} (41)

ON THE TIME INTEGRATED SPECTRA AND THE HARD-TO-SOFT SPECTRAL TRANSITION

We turn now to the much debated issue of the origin of the observed hard-to-soft spectral transition during the GRB observations (see e.g. Frontera et al. [89], Ghirlanda et al. [86], Piran [29], Piro et al. [90]). We consider the instantaneous spectral distribution of the observed radiation for three different EQTSs:

- $t_{\text{d}} = 10\text{ s}$, in the early radiation phase near the peak of the luminosity,
- $t_{\text{d}} = 1.45 \times 10^5\text{ s}$, in the last observation of the afterglow by the Chandra satellite, and
- $t_{\text{d}} = 10^4\text{ s}$, chosen in between the other two (see Fig. 20).

The observed hard-to-soft spectral transition is then explained and traced back to:

1. a time decreasing temperature of the thermal spectrum measured in the comoving frame,
2. the GRB equations of motion,
3. the corresponding infinite set of relativistic transformations.

A clear signature of our model is the existence of a common low-energy behavior of the instantaneous spectrum represented by a power-law with index $\alpha = +0.9$. This prediction will be possibly verified in future observations.

Starting from these instantaneous values, we integrate the spectra in arrival time obtaining what is usually fit in the literature by the “Band relation” (Band et al. [91]). Indeed we find for our integrated spectra a low energy spectral index $\alpha = -1.05$ and an high energy spectral index $\beta < -16$ when interpreted within the framework of a Band relation (see Fig. 21). This theoretical result can be submitted to a direct confrontation with the observations of GRB 991216.

Figure 20. The instantaneous spectra of the radiation observed in GRB 991216 at three different EQTS respectively, from top to bottom, for $t_{\text{d}} = 10\text{ s}$, $t_{\text{d}} = 10^7\text{ s}$ and $t_{\text{d}} = 1.45 \times 10^5\text{ s}$. These diagrams have been computed assuming a constant $\langle n_{\text{com}} \rangle \simeq 1$ particle/cm$^3$ and clearly explains the often quoted hard-to-soft spectral evolution in GRBs. Details in Ruffini et al. [88].
Figure 21. The time-integrated spectrum of the radiation observed in GRB 991216. The low energy part of the curve below 10 keV is fit by a power-law with index $\alpha = -1.05$ and the high energy part above 500 keV is fit by a power-law with an index $\beta < -16$. Details in Ruffini et al. [88].

and, most importantly, the entire theoretical framework which we have developed can now be applied to any GRB source. The theoretical predictions on the luminosity in fixed energy bands so obtained can be then straightforwardly confronted with the observational data.

THE THREE PARADIGMS FOR THE INTERPRETATION OF GRBS

Having outlined the main features of our model and shown its application to GRB 991216 used as a prototype, before addressing the two new sources which are going to be the focus of this presentation, we recall the three paradigms for the interpretation of GRBs we had previously introduced.

The first paradigm, the relative space-time transformation (RSTT) paradigm (Ruffini et al. [13]) emphasizes the importance of a global analysis of the GRB phenomenon encompassing both the optically thick and the afterglow phases. Since all the data are received in the detector arrival time it is essential to know the equations of motion of all relativistic phases with $\gamma > 1$ of the GRB sources in order to reconstruct the time coordinate in the laboratory frame, see Eq.(3). Contrary to other phenomena in nonrelativistic physics or astrophysics, where every phase can be examined separately from the others, in the case of GRBs all the phases are inter-related by their signals received in arrival time $t_{da}$. There is the need, in order to describe the physics of the source, to derive the laboratory time $t$ as a function of the arrival time $t_{da}$ along the entire past worldline of the source using Eq.(4).

The second paradigm, the interpretation of the burst structure (IBS) paradigm (Ruffini et al. [14]) covers three fundamental issues:
a) the existence, in the general GRB, of two different components: the P-GRB and the afterglow related by precise equations determining their relative amplitude and temporal sequence (see Ruffini et al. [28]);
b) what in the literature has been addressed as the “prompt emission” and considered as a burst, in our model is not a burst at all — instead it is just the emission from the peak of the afterglow (see Fig. 18);
c) the crucial role of the parameter $B$ in determining the relative amplitude of the P-GRB to the afterglow and discriminating between the short and the long bursts (see Fig. 22). Both short and long bursts arise from the same physical phenomena: the dyadosphere. The absence of baryonic matter in the remnant leads to the short bursts and no
afterglow. The presence of baryonic matter with $B < 10^{-2}$ leads to the afterglow and consequently to its peak emission which gives origin to the so-called long bursts.

The third paradigm, the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [15]), deals with the relation of the GRB and the associated supernova process, and acquires a special meaning in relation to the sources GRB 980425 and GRB 030329 as we will show in the following.

We now shortly illustrate some consequences of these three paradigms.

**Long bursts are E-APEs**

The order of magnitude estimate usually quoted for the the characteristic time scale to be expected for a burst emitted by a GRB at the moment of transparency at the end of the expansion of the optically thick phase is given by $\tau \sim GM/c^3$, which for a $10M_\odot$ black hole will give $\sim 10^{-3}$ s. There are reasons today not to take seriously such an order of magnitude estimate (see e.g. Ruffini et al. [54]). In any case this time is much shorter than the ones typically observed in “prompt radiation” of the long bursts, from a few seconds all the way to $10^2$ s. In the current literature (see e.g. Piran [29] and references therein), in order to explain the “prompt radiation” and overcome the above difficulty it has been generally assumed that its origin should be related to a prolonged “inner engine” activity preceding the afterglow which is not well identified.

To us this explanation has always appeared logically inconsistent since there remain to be explained not one but two very different mechanisms, independent of each other, of similar and extremely large energetics. This approach has generated an additional very negative result: it has distracted everybody working in the field from the earlier very
interesting work on the optically thick phase of GRBs.

The way out of this dichotomy in our model is drastically different: 1) indeed the optically thick phase exists, is crucial to the GRB phenomenon and terminates with a burst: the P-GRB; 2) the “prompt radiation” follows the P-GRB; 3) the “prompt radiation” is not a burst: it is actually the temporally extended peak emission of the afterglow (E-APE). The observed structures of the prompt radiation can all be traced back to inhomogeneities in the interstellar medium (see Fig. 18 and Ruffini et al. [76]).

Short bursts are P-GRBs

The fundamental diagram determining the relative intensity of the P-GRB and the afterglow as a function of the dimensionless parameter $\mathcal{B}$ has been shown in Fig. 22. The underlying machine generating the short and the long GRBs is identical: in both cases is the dyadosphere. The main difference relates to the amount of baryonic matter engulfed by the electron-positron plasma in their optically thick phase prior to transparency. In the limit of small $\mathcal{B} < 10^{-5}$ the intensity of the P-GRB is larger and dominates the afterglow. This corresponds to the short bursts. For $10^{-5} < \mathcal{B} < 10^{-2}$ the afterglow dominates the GRBs and we have the so-called “long bursts”. For $\mathcal{B} > 10^{-2}$ we may observe a third class of “bursts”, eventually related to a turbulent process occurring prior to transparency (Ruffini et al. [59]). This third family should be characterized by smaller values of the Lorentz gamma factors than in the case of the short or long bursts.

The trigger of multiple gravitational collapses

The relation between the GRBs and the supernovae is one of the most complex aspects to be addressed by our model, which needs the understanding of new fields of general relativistic physics in relation to yet unexplored many-body solutions in a substantially new astrophysical scenario.

As we will show in the two systems GRB980425/SN1998bw and GRB030329/SN2003dh which we are going to discuss next, there is in each one the possibility of an astrophysical “triptych” formed by:
1) the formation of the black hole and the emission of the GRB,
2) the gravitational collapse of an evolved companion star, leading to a supernova,
3) a clearly identified URCA source whose nature appears to be of the greatest interest.

This new astrophysical scenario presents new challenges:
a) The identification of the physical reasons of the instability leading to the gravitational collapse of a $\sim 10M_\odot$ star, giving origin to the black hole. Such an implosion must occur radially with negligible mass of the remnant ($\mathcal{B} < 10^{-2}$).
b) The identification of the physical reasons for the instability leading to the gravitational collapse of an evolved companion star, giving origin to the supernova.
c) The theoretical issues related to the URCA sources, which range today in many possible directions: from the physics of black holes, to the physical processes occurring in the expanding supernova remnants, and finally to the very exciting possibility that we are observing for the first time a newly born neutron star. The main effort in the next sections is to show that the detailed understanding we have reached for the GRB phenomenon and its afterglow allows us to state, convincingly, that the URCA source, contrary to what established in the current literature, is not part of the GRB nor of its afterglow.

We will draw in the conclusions some considerations on the possible nature of the URCA sources.

APPLICATIONS

We illustrate the application of our GRB model to two different systems, which are quite different in the energetics but are both related to supernovae: GRB 980425 and GRB 030329. We will let the gradual theoretical understanding of the system to unveil the underlying astrophysical scenario.

---

4 A picture or carving in three panels side by side; e.g., an altarpiece with a central panel and two flanking panels half its size that fold over it [Webster’s New collegiate dictionary, G. & C. Merriam Co. (Springfield, Massachussets, U.S.A., 1977)]
The “divide et impera” concept applied to the system GRB 980425 / SN 1998bw. Four different components are identified: the GRB 980425, the SN 1998bw, and the two sources S1 and S2.

In addition to the source GRB 980425 and the supernova SN1998bw, two X-ray sources have been found by BeppoSAX in the error box for the location of GRB 980425: a source S1 and a source S2 (Pian et al. [95]), which have been traditionally interpreted either as a background source or as a part of the GRB afterglow. See Fig. 23. Our approach has been: to first comprehend the entire afterglow of GRB 980425 within our theory. This allows the computation of the luminosity in given energy bands, the spectra, the Lorentz gamma factors, and more generally of all the dynamical aspects of the source. Having characterized the features of GRB 980425, we can gradually approach the remaining part of the scenario, disentangling the GRB observations from those of the supernova and then disentangling both the GRB and the supernova observations from those of the sources S1 and S2. This leads to a natural identification of distinct events and to their autonomous astrophysical characterization.

Our best fit for GRB 980425 corresponds to $E_{\text{dy}} = 1.1 \times 10^{48}$ ergs, $B = 7 \times 10^{-3}$ and the ISM average density...
The bolometric luminosity as a function of the arrival time. The peak of the P-GRB is just below the observational noise level. The average number density is found to be $\langle n_{\text{ISM}} \rangle = 0.02$ particle/cm$^3$. The plasma temperature and the total number of pairs in the dyadosphere are respectively $T = 1.028$ MeV and $N_{e^\pm} = 5.3274 \times 10^{53}$. The light curve of the GRB is shown in Figs. 24–25. The P-GRB is under the threshold and in the case of this source is not observable (see Ruffini et al. [16], Fraschetti et al. [17]).

The characteristic parameter $R$, defining the filamentary structure of the ISM, monotonically decreases from $4.81 \times 10^{-10}$ to $2.65 \times 10^{-12}$). The results are given in Fig. 26 where the bolometric luminosity is represented together with the optical data of SN1998bw, the source $S1$ and the source $S2$. It is then clear that GRB 980425 is separated both from the supernova data and from the sources $S1$ and $S2$.

While the occurrence of the supernova in relation to the GRB has already been discussed within the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [15]), we like to address here a different fundamental issue: the nature of the source $S1$ which we have named, in celebration of the work of Gamow and Shoenberg, URCA-1. It is clear, from the theoretical predictions of the afterglow luminosity, that the URCA-1 cannot be part of the afterglow (see Figs. 24, 26). There are three different possibilities for the explanation of such source:

1) Its possible relation to the black hole formed during the process of gravitational collapse leading to the GRB emission.

2) Its possible relation to emission originating in the early phases of the expansion of the supernova remnant.

3) The very exciting possibility that for the first time we are observing a newly born neutron star out of the supernova phenomenon.

While some general considerations will be discussed in the conclusions, we would like to stress here the paramount importance of following the further time history of URCA-1 and of the source $S2$. If, as we propose, $S2$ is a background...
The observation by BeppoSAX of the peak of the afterglow in the 40–700 keV energy band is fitted by our model.

source, its flux should be practically constant in time and this source has nothing to do with the GRB 980425 / SN1998bw system. The drastic behavior of the URCA-1 luminosity reported in the talk by Elena Pian in this meeting, showing the latest URCA-1 observations by the XMM and Chandra satellites, is crucial for the understanding of the nature of this source. Some very qualitative luminosity curves are sketched in Fig. 26, illustrating the possible time evolution of URCA-1. They are still very undetermined today due to a lack of attention to these observational data and, consequently, to the lack of a detailed theoretical model of the phenomenon. We therefore propose to have a dedicated attention to the astrophysical “triptych” GRB 980425 / SN 1998bw / URCA-1.

GRB 030329 / SN 2003dh

We have adopted for our modeling of GRB030329 a spherically symmetric distribution for the source and, as initial conditions at $t = 10^{-21}$ s, an $e^+e^-$-photon neutral plasma lying between the radii $r_1 = 2.9 \times 10^6$ cm and $r_2 = 9.0 \times 10^7$ cm. The temperature of such a plasma is 2.1 MeV, the total energy $E_{\text{tot}} = 2.1 \times 10^{52}$ erg and the total number of pairs $N_{e^+e^-} = 1.1 \times 10^{57}$. The baryonic matter component $M_B$ is the second free parameter of our theory: $B = 4.8 \times 10^{-3}$. At the emission of the P-GRB, the Lorentz gamma factor is $\gamma = 183.6$ and the radial coordinate is $r_0 = 5.3 \times 10^{13}$ cm. The ISM average density is best fit by $<n_{\text{ISM}} > = 1$ particle/cm$^3$. The third free parameter of our theory is given by $1.1 \times 10^{-7} < \dot{M} < 5.0 \times 10^{-11}$.

We then obtain (see also Bernardini et al. [97]) for the GRB 030329 the luminosities in given energy bands, computed in the range 2–400 keV with very high accuracy. Figs. 27–30 shows the results for the luminosities in

Figure 25. The observation by BeppoSAX of the peak of the afterglow in the 40–700 keV energy band is fitted by our model.
the 30–400 keV and 2–10 keV bands, including the “prompt radiation”. Subsequently, the theoretically predicted GRB spectra have been evaluated at selected values of the arrival time (Ruffini et al. [98]).

The splendid news received the evening before the presentation of this talk is graphically represented by the XMM observations shown in Fig. 30. Again, the XMM observations, like the corresponding ones of GRB 980425, occur after the decaying part of the afterglow and, in analogy to the one occurring in the system GRB 980425 / SN 1998bw / URCA-1, we call this source URCA-2. Further observations by XMM are highly recommended to follow the URCA-2 temporal evolution. Also in this system we are dealing with an astrophysical “triptych”: GRB 030329 / SN 2003dh / URCA-2.

ON THE SHORT GRBS

By the analysis of the first and second BATSE catalogs Tavani in 1998 [21] (see Fig. 4) confirmed the previous results by Kouveliotou et al. [20] on the existence of two families of GRBs: the so-called “long-bursts” with a soft spectrum and duration $\Delta t > 2.5$ sec and the “short-bursts” with harder spectrum and duration $\Delta t < 2.5$ sec. In 2001 we have

---

5 see http://cossc.gsfc.nasa.gov/batse/
Figure 27. The luminosity in the 2–10 keV and in the 30–400 keV energy bands predicted by our model are fitted to the data of R-XTE (GCN Circ. 1996 [99]) and HETE-2 (GCN Circ. 1997 [100]) respectively. The SN 2003dh optical luminosity is given by the crosses (Hjorth et al. [101]). Details in Bernardini et al. [97].

proposed the theory [14] that both short-bursts and long-bursts originate from the same underlying physical process: the vacuum polarization of electromagnetic overcritical gravitational collapse leading to the creation of $e^+ - e^-$ pairs at the expenses of the “blackholic” energy [11]. The difference between the short-bursts and long-bursts in this theory is mainly due to the amount of baryonic matter, described by the dimensionless parameter $B$ previously mentioned, encountered by the $e^+ e^-$ pairs in their relativistic expansion (see Fig. 31). Short-bursts occur in a range of $B$: 

$$0 < B < 10^{-5}, \quad (42)$$

and the long-bursts occur for:

$$10^{-5} < B < 10^{-2}. \quad (43)$$

Compare and contrast Fig. 11 with Fig. 31.

An indirect support of our theory was given by Schmidt [103] who has shown that short-bursts and long-bursts have the same isotropic-equivalent characteristic peak luminosity.

In recent work we have systematically developed the theoretical background of the process of gravitational collapse of matter involving an electromagnetic field with field strength higher than the critical value for $e^+ e^-$ pair creation [50, 51, 52, 53, 104, 49]. The goal has been to clarify the physical nature of the process of extracting the “blackholic” energy by the creation of $e^+ e^-$ matter pairs [11] and to analyze the electromagnetic radiation emission process during the transient dynamical phases of the gravitational collapse, leading to the final formation of the black hole.

All the considerations presented in the description of the long GRBs were based on a dyadosphere of an already formed black hole, presented in section . This approximate treatment is very satisfactory in estimating the general...
dependence of the energy of the P-GRB, the kinetic energy of the baryonic matter pulse generating the afterglow and consequently the intensity of the afterglow itself. In particular it is possible to obtain the overall time structure of the GRB and especially the time of the release of the P-GRB in respect to the moment of gravitational collapse and its relative intensity with respect to the afterglow. If, however, we address the issue of the detailed temporal structure of the P-GRB and its detailed spectral distribution, the dynamical considerations on the dyadosphere formation, which we are going to present in the following sections, are needed (see also [53]). In turn, this detailed analysis is needed in order to describe the general relativistic effects close to the horizon formation. As expressed already in section , all general relativistic quantum field theory effects are encoded in the fine structure of the P-GRB. As emphasized in section , the only way to differentiate between solutions with same \( E_{\text{dyads}} \) but different black hole mass and charge is to observe the P-GRBs in the limit \( B \to 0 \), namely, to observe the short GRBs (see Fig. 31).

**SOME PROPAEDEUTIC ANALYSIS FOR THE DYNAMICAL FORMATION OF THE BLACK HOLE**

While the formation in time of the dyadosphere is the fundamental phenomena we are interested in, we can get an insight on the issue of gravitational collapse of an electrically charged star core studying in details a simplified model, namely a thin shell of charged dust.

**On the collapsing charged shell in general relativity**

In [105, 106] it is shown that the problem of a collapsing charged shell in general relativity can be reduced to a set of ordinary differential equations. We reconsider here the following relativistic system: a spherical shell of electrically charged dust...
charged dust which is moving radially in the Reissner-Nordström background of an already formed nonrotating black hole of mass \( M_1 \) and charge \( Q_1 \), with \( Q_1 \leq M_1 \).

The world surface spanned by the shell divides the space-time into two regions: an internal one \( \mathcal{M}_- \) and an external one \( \mathcal{M}_+ \). The line element in Schwarzschild like coordinate is [50]

\[
\begin{align*}
\mathcal{L}^2 &= \begin{cases} 
-f_+ dt^2 + f_+^{-1} dr^2 + r^2 d\Omega^2 & \text{in } \mathcal{M}_+ \\
-f_- dt^2 + f_-^{-1} dr^2 + r^2 d\Omega^2 & \text{in } \mathcal{M}_- 
\end{cases},
\end{align*}
\]

(44)

where \( f_+ = 1 - \frac{2M}{R} + \frac{Q_1^2}{R^2} \), \( f_- = 1 - \frac{2M_0}{R} + \frac{Q_0^2}{R^2} \), and \( t_+ \) and \( t_- \) are the Schwarzschild-like time coordinates in \( \mathcal{M}_+ \) and \( \mathcal{M}_- \) respectively. \( M \) is the total mass-energy of the system formed by the shell and the black hole, measured by an observer at rest at infinity and \( Q = Q_0 + Q_1 \) is the total charge: sum of the charge \( Q_0 \) of the shell and the charge \( Q_1 \) of the internal black hole.

Indicating by \( R \) the radius of the shell and by \( T_\infty \) its time coordinate, the equations of motion of the shell become [51]

\[
\begin{align*}
\frac{dR}{d\tau} &= \frac{1}{\mathcal{M}(\tau)} \left( M - M_1 + \frac{M_0^2}{2R} - \frac{Q_0 Q_1}{R} \right)^2 - f_+ (R) \\
\frac{dT_\infty}{d\tau} &= \frac{1}{\mathcal{M}(\tau)} \left( M - M_1 + \frac{M_0^2}{2R} - \frac{Q_0 Q_1}{R} \right)^2 - f_- (R),
\end{align*}
\]

(45)

\[
\begin{align*}
\frac{dT_\infty}{d\tau} &= \frac{1}{\mathcal{M}(\tau)} \left( M - M_1 + \frac{M_0^2}{2R} - \frac{Q_0 Q_1}{R} \right),
\end{align*}
\]

(46)
Figure 30. The dotted line represents our theoretically predicted GRB030329 light curve in γ-rays (30-400 keV) with the horizontal bar corresponding to the mean peak flux from HETE-2 (GCN Circ. 1997 [100]). The solid line represents the corresponding one in X-rays (2-10 keV) with the experimental data obtained by R-XTE (GCN Circ. 1996 [99]). The remaining points refer respectively to the optical VLT data (Hjorth et al. [101]) of SN2003bw and to the X-ray XMM data (Tiengo et al. [102]) of URCA-2. The dash-dotted lines corresponds to qualitative luminosity curves expected for URCA-2. It is interesting to compare and contrast these results with the ones for GRB980425/SN1998bw (see Fig. 3 in Ruffini et al. [16]). Details in Ruffini et al. [98].

where $M_0$ is the rest mass of the shell and $\tau$ is its proper time. Eqs.(45,46) (together with Eq.(44)) completely describe a 5-parameter ($M$, $Q$, $M_1$, $Q_1$, $M_0$) family of solutions of the Einstein-Maxwell equations. Note that Eqs.(45,46) imply that

$$M - M_1 - \frac{Q_1^2}{2M^2} - \frac{Q_1}{M} > 0$$

holds for $R > M + \sqrt{M^2 - Q^2}$ if $Q < M$ and for $R > M_1 + \sqrt{M_1^2 - Q_1^2}$ if $Q > M$.

For astrophysical applications [53] the trajectory of the shell $R = R(T_\gamma)$ is obtained as a function of the time coordinate $T_\gamma$ relative to the space-time region $\mathcal{M}_\gamma$. In the following we drop the $+$ index from $T_\gamma$. From Eqs.(45,46) we have

$$\frac{dR}{dT} = \frac{dR}{d\tau} \frac{d\tau}{dT} = \pm F \sqrt{\Omega^2 - F},$$

(48)
In our theory the short GRBs originate by the same basic process leading also to the long GRBs (see Fig. 11) in the limiting case of no baryonic matter present ($\beta \rightarrow 0$). The optically thick electron-positron pairs expand to ultrarelativistic Lorentz gamma factors reaching, then, transparency. The emission at the transparency point originates the short GRBs.

where

\[ F \equiv f_\star(R) = 1 - \frac{2M}{R} + \frac{Q^2}{R^2}, \]  
\[ \Omega \equiv \Gamma - \frac{M^2 - Q^2}{2\hat{M}R^2}, \]  
\[ \Gamma = \frac{M - M_1}{M_0}. \]  

Since we are interested in an imploding shell, only the minus sign case in (48) will be studied. We can give the following physical interpretation of $\Gamma$. If $M - M_1 \geq M_0$, $\Gamma$ coincides with the Lorentz $\gamma$ factor of the imploding shell at infinity; from Eq.(48) it satisfies

\[ \Gamma = \frac{1}{\sqrt{1 - (\frac{dR}{dT})_{R=\infty}}} \geq 1. \]  

When $M - M_1 < M_0$ then there is a turning point $R^*$, defined by $\frac{dR}{dT}_{R=R^*} = 0$. In this case $\Gamma$ coincides with the "effective potential" at $R^*$:

\[ \Gamma = \sqrt{f_\star(R^*)} + M_0 \left( \frac{M_1^2}{2R^*} + \frac{Q_1^2}{2R^*} + \frac{Q_0 Q_1}{R^*} \right) \leq 1. \]  

The solution of the differential equation (48) is given by:

\[ \int dT = -\int \frac{\Omega}{F\sqrt{\Omega - F}} dR. \]  

Figure 31. In our theory the short GRBs originate by the same basic process leading also to the long GRBs (see Fig. 11) in the limiting case of no baryonic matter present ($\beta \rightarrow 0$). The optically thick electron-positron pairs expand to ultrarelativistic Lorentz gamma factors reaching, then, transparency. The emission at the transparency point originates the short GRBs.
The functional form of the integral (54) crucially depends on the degree of the polynomial \( P(R) = R^2 (\Omega^2 - F) \), which is generically two, but in special cases has lower values. We therefore distinguish the following cases:

1. \( M = M_0 + M_1; Q_1 = M_1; Q = M; P(R) \) is equal to 0, we simply have

\[
R(T) = \text{const.}
\]  

(55)

2. \( M = M_0 + M_1; M^2 - Q^2 = M_1^2 - Q_1^2; Q \neq M; P(R) \) is a constant, we have

\[
T = \text{const} + \frac{1}{2\sqrt{M^2 - Q^2}} \left[ (R + 2M)R 
+ r^2 \log \left( \frac{R^2 - M^2}{M^2} \right) + r^2 \log \left( \frac{R^2 - M^2}{Q^2} \right) \right].
\]  

(56)

3. \( M = M_0 + M_1; M^2 - Q^2 \neq M_1^2 - Q_1^2; P(R) \) is a first order polynomial and

\[
T = \text{const} + 2R\sqrt{\Omega^2 - F} \left[ \frac{M_0 R}{3(M^2 - Q^2 - M_1^2 + Q_1^2)} 
+ \frac{(M_0^2 - Q^2 - Q_1^2)}{3(M^2 - Q^2 - M_1^2 + Q_1^2)} \right] 
- \frac{1}{\sqrt{M^2 - Q^2}} r^2 \arctanh \left( \frac{\sqrt{Q^2 - F}}{\sqrt{M^2 - Q^2}} \right) 
- \frac{1}{r^2} \arctanh \left( \frac{\sqrt{Q^2 - F}}{\sqrt{M^2 - Q^2}} \right),
\]  

(57)

where \( \Omega_x \equiv \Omega (r_x) \).

4. \( M \neq M_0 + M_1; P(R) \) is a second order polynomial and

\[
T = \text{const} - \frac{1}{2\sqrt{M^2 - Q^2}} \left[ \frac{2\sqrt{M^2 - Q^2}}{1^{2} - 1} R \sqrt{\Omega^2 - F} 
+ \frac{r^2}{\sqrt{M^2 - Q^2}} \right] 
+ \frac{r^2}{\sqrt{M^2 - Q^2}} \log \left( \frac{R\sqrt{\Omega^2 - F}}{M} \right) 
- \frac{2M_0 (1^{2} - 1) \log \left( \frac{R\sqrt{\Omega^2 - F}}{M} \right)}{M_0 (1^{2} - 1)} 
\]

(58)

Of particular interest is the time varying electric field \( \partial_r \xi = \frac{\partial \xi}{\partial r} \) on the external surface of the shell. In order to study the variability of \( \partial_r \xi \) with time it is useful to consider in the tidimensional space of parameters \( (R, T, \delta \xi) \) the parametric curve \( \mathcal{C} \) : \( (R = \lambda, \ T = T(\lambda), \ \delta \xi = \frac{\delta \xi}{\lambda}) \). In astrophysical applications [53] we are specially interested in the family of solutions such that \( \frac{dT}{dR} = 0 \) when \( R = \infty \) which implies that \( \Gamma = 1 \). In Fig. 32 we plot the collapse curves in the plane \( (T, R) \) for different values of the parameter \( \xi = \frac{\delta \xi}{\lambda} \), \( 0 < \xi < 1 \). The initial data \( (T_0, R_0) \) are chosen so that the integration constant in equation (57) is equal to 0. In all the cases we can follow the details of the approach to the horizon which is reached in an infinite Schwarzschild time coordinate. In Fig. 32 we plot the parametric curves \( \mathcal{C} \) in the space \( (R, T, \delta \xi) \) for different values of \( \xi \). Again we can follow the exact asymptotic behavior of the curves \( \mathcal{C}, \delta \xi \) reaching the asymptotic value \( \frac{\delta \xi}{\lambda} \). The detailed knowledge of this asymptotic behavior is of great relevance for the observational properties of the black hole formation (see e.g. [51]).

In the case of a shell falling in a flat background \( M_1 = Q_1 = 0 \) Eq.(45) reduces to

\[
\left( \frac{dT}{dR} \right)^2 = \frac{1}{\Omega^2} \left( M + \frac{M_0}{\sqrt{Q^2}} - \frac{M_1^2}{\sqrt{Q^2}} \right)^2 - 1.
\]  

(59)
Introducing the total radial momentum $P \equiv M_0 u^r = M_0 \frac{\partial R}{\partial \tau}$ of the shell, we can express the kinetic energy of the shell as measured by static observers in $\mathcal{M}$ as $T \equiv -M_0 \gamma^\mu \xi_\mu - M_0 = \sqrt{P^2 + M_0^2} - M_0$. Then from equation (59) we have

$$M = \frac{M_0^2}{2R} + \frac{Q^2}{2R} - \frac{Q^2}{2T+} + \sqrt{P^2 + M_0^2} = M_0 + T - \frac{M_0^2}{2R} + \frac{Q^2}{2T+}, \quad (60)$$

where we choose the positive root solution due to the constraint (47). Eq.(60) is the mass formula of the shell, which depends on the time-dependent radial coordinate $R$ and kinetic energy $T$. If $M \geq Q$, a black hole is formed and we have

$$M = M_0 + T_+ - \frac{M_0^2}{2T+} + \frac{Q^2}{2T+}, \quad (61)$$

where $T_+ \equiv T (r_+)$ and $r_+ = M + \sqrt{M^2 - Q^2}$ is the radius of external horizon of the black hole.
On the physical origin of the terms in mass formula of the black hole

We know from the Christodoulou-Ruffini black hole mass formula that

\[ M = M_0 + \frac{Q^2}{2\mu}, \]  
(62)

so it follows that

\[ M_{\text{tot}} = M_0 - \frac{M^2}{2\mu} + T_+, \]  
(63)

namely that \( M_{\text{tot}} \) is the sum of only three contributions: the rest mass \( M_0 \), the gravitational potential energy and the kinetic energy of the rest mass evaluated at the horizon. \( M_{\text{tot}} \) is independent of the electromagnetic energy, a fact noticed by Bekenstein [107]. We have taken one further step here by identifying the independent physical contributions to \( M_{\text{tot}} \).

Next we consider the physical interpretation of the electromagnetic term \( \frac{Q^2}{2\mu} \), which can be obtained by evaluating the conserved Killing integral

\[ \int_{\Sigma} n^\mu T_{\mu\nu}^{\text{em}} \, d\Sigma^\nu = \int_0^\infty r^2 dr \int_0^\frac{\pi}{2} d\cos \theta \int_0^{2\pi} d\phi \, T^{\text{em}}_{00} \bigg|_0 \]

\[ = \frac{Q^2}{2\mu}, \]  
(64)

where \( \Sigma \) is the space-like hypersurface in \( M \) described by the equation \( t = \text{const} \), with \( d\Sigma^\nu \) as its surface element vector and where \( T_{\mu\nu}^{\text{em}} \) is the energy-momentum tensor of the electromagnetic field. The quantity in Eq.(64) differs from the purely electromagnetic energy between two conceptually physically different processes, depending on whether the electric field strength \( E \) is smaller or greater than the critical value \( E_c \), which can be obtained by evaluating the maximum value \( E_c = \frac{\mu}{\lambda_c} \) of the electric field around a black hole is reached at the horizon. We then have the following:

1. For \( E < E_c \), the leading energy extraction mechanism consists of a sequence of discrete elementary decay processes of a particle into two oppositely charged particles. The condition \( E < E_c \) implies

\[ \xi = \frac{Q^2}{\lambda_c^2 \mu} \approx \frac{10^{-6} M^2}{M_\odot} \quad \text{if} \quad \frac{M}{M_\odot} \leq 10^6 \]

\[ \xi = \frac{1}{\lambda_c} \quad \text{if} \quad \frac{M}{M_\odot} > 10^6, \]  
(65)

where \( \lambda_c \) is the Compton wavelength of the electron. [109] and [110] have defined as the effective ergosphere the region around a black hole where the energy extraction processes occur. This region extends from the horizon \( r_+ \).
up to a radius

\[ r_{\text{Erg}} = \frac{GM}{c^2} \left[ 1 + \sqrt{1 - \xi^2 \left( 1 - \frac{e^2}{Gm^2 e} \right)} \right] \]

\[ \simeq \frac{\xi}{1 - \sqrt{1 - \xi^2}} \frac{Q}{e} m e c^2. \]  
(66)

The energy extraction occurs in a finite number \( N_{\text{PD}} \) of such discrete elementary processes, each one corresponding to a decrease of the black hole charge. We have

\[ N_{\text{PD}} \simeq \frac{Q}{e}. \]  
(67)

Since the total extracted energy is (see Eq. (62)) \( E_{\text{tot}} = \frac{Q^2}{2} + \frac{r}{r_{\text{Erg}}} \), we obtain for the mean energy per accelerated particle

\[ \langle E \rangle_{\text{PD}} = \frac{\xi}{1 - \sqrt{1 - \xi^2}} \frac{e}{m e c^2} \sim \frac{\xi}{1 - \sqrt{1 - \xi^2}} m e c^2, \]

which gives

\[ \langle E \rangle_{\text{PD}} \lesssim \left\{ \begin{array}{ll} \frac{M}{M_\odot} \times 10^{21} \text{eV} & \text{if } \frac{M}{M_\odot} \leq 10^6 \smallskip \\
10^3 \text{eV} & \text{if } \frac{M}{M_\odot} > 10^6 \end{array} \right. \]  
(68)

One of the crucial aspects of the energy extraction process from a black hole is its back reaction on the irreducible mass expressed in [11]. Although the energy extraction processes can occur in the entire effective ergosphere defined by Eq. (66), only the limiting processes occurring on the horizon with zero kinetic energy can reach the maximum efficiency while approaching the condition of total reversibility (see Fig. 2 in [11] for details). The farther from the horizon that a decay occurs, the more it increases the irreducible mass and loses efficiency. Only in the complete reversibility limit [11] can the energy extraction process from an extreme black hole reach the upper value of 50% of the total black hole energy.

2. For \( \xi \geq \xi_0 \) the leading extraction process is a collective process based on an electron-positron plasma generated by the vacuum polarization, (see Fig. 8) as discussed in section III in [28]. The condition \( \xi \geq \xi_0 \) implies

\[ \frac{GM/c^2}{\xi} \left( \frac{\xi}{1 - \xi^2} \right)^{-1} \simeq 2 \times 10^{-6} \frac{M}{M_\odot} \leq \frac{\xi}{1 - \sqrt{1 - \xi^2}} \leq 1. \]  
(70)

This vacuum polarization process can occur only for a black hole with mass smaller than \( 2 \times 10^6 M_\odot \). The electron-positron pairs are now produced in the dyadosphere of the black hole, (note that the dyadosphere is a subregion of the effective ergosphere) whose radius \( r_{\text{ds}} \) is given in Eq. (15). We have \( r_{\text{ds}} \ll r_{\text{Erg}} \). The number of particles created and the total energy stored in dyadosphere are given in Eqs. (17,18) of Ref. [51] respectively and we have approximately

\[ N_{e^+ e^-} \simeq \left( \frac{\xi}{\xi_0} \right) \frac{Q}{e}, \]  
(71)

\[ E_{\text{ds}} \simeq \frac{Q}{e} \]  
(72)

The mean energy per particle produced in the dyadosphere \( \langle E \rangle_{\text{ds}} = \frac{E_{\text{ds}}}{N_{e^+ e^-}} \) is then

\[ \langle E \rangle_{\text{ds}} \simeq \frac{Q}{e} \left( \frac{\xi}{\xi_0} \right) \frac{e}{m e c^2}, \]

which can be also rewritten as

\[ \langle E \rangle_{\text{ds}} \simeq \frac{1}{2} \left( \frac{r}{r_{\text{Erg}}} \right) m e c^2 \sim \sqrt{\frac{10^3}{M_\odot}} \text{keV}. \]  
(74)

Such a process of vacuum polarization, occurring not at the horizon but in the extended dyadosphere region \( (r_{\text{ds}} \leq r \leq r_{\text{Erg}}) \) around a black hole, has been observed to reach the maximum efficiency limit of 50% of the total mass-energy of an extreme black hole (see e.g. [48]). The conceptual justification of this result follows from the present work: the \( e^+ e^- \) creation process occurs at the expense of the Coulomb energy given by Eq. (64) and
Figure 33. Space-time diagram of the collapse process leading to the formation of the dyadosphere. As the collapsing core crosses the dyadosphere radius the pair creation process starts, and the pairs thermalize in a neutral plasma configuration. Then also the horizon is crossed and the singularity is formed.

does not affect the irreducible mass given by Eq. (63), which indeed, as we have proved, does not depend of the electromagnetic energy. In this sense, \( \delta M_{\text{irr}} = 0 \) and the transformation is fully reversible. This result will be further validated by the study of the dynamical formation of the dyadosphere, which we have obtained using the present work and [50] (see [49, 53]).

Let us now compare and contrast these two processes. We have

\[
e_{\text{Erel}} \approx \left( \frac{\xi}{\lambda} \right) r
\]

(75)

\[
N_{\text{dy}} \approx \left( \frac{\xi}{\lambda} \right) N_{\text{PD}}
\]

(76)

\[
\langle E \rangle_{\text{dy}} \approx \left( \frac{\xi}{\lambda} \right) \langle E \rangle_{\text{PD}}
\]

(77)

Moreover we see (Eqs. (69), (74)) that \( \langle E \rangle_{\text{PD}} \) is in the range of energies of UHECR, while for \( \xi \sim 0.1 \) and \( M \sim 10M_{\odot} \), \( \langle E \rangle_{\text{dy}} \) is in the gamma ray range. In other words, the discrete particle decay process involves a small number of particles with ultra high energies (\( \sim 10^{21} \text{eV} \)), while vacuum polarization involves a much larger number of particles with lower mean energies (\( \sim 10 \text{MeV} \)).

Having so established and clarified the basic conceptual processes of the energetic of the black hole, we are now ready to approach, using the new analytic solution obtained, the dynamical process of vacuum polarization occurring during the formation of a black hole as qualitatively represented in Fig. 33. The study of the dyadosphere dynamical formation as well as of the electron-positron plasma dynamical evolution will lead to the first possibility of directly observing the general relativistic effects approaching the black hole horizon.

CONTRIBUTION OF THE SHORT GRBS TO THE BLACK HOLE THEORY

On the gravitational binding energy of white dwarf and neutron stars

The aim of this section is to point out how the knowledge obtained from the black hole model is of relevance also for the basic theory of black holes and further how very high precision verification of general relativistic effects in the very strong field near the formation of the horizon should be expected in the near future.

We shall first see how Eq.(63) for \( M_{\text{fr}} \),

\[
M_{\text{fr}} = M_0 - \frac{\delta M_{\text{irr}}}{\chi^2} + T_+,
\]

(78)
leads to a deeper physical understanding of the role of the gravitational interaction in the maximum energy extraction process of a black hole. This formula can also be of assistance in clarifying some long lasting epistemological issue on the role of general relativity, quantum theory and thermodynamics.

It is well known that if a spherically symmetric mass distribution without any electromagnetic structure undergoes free gravitational collapse, its total mass-energy $M$ is conserved according to the Birkhoff theorem: the increase in the kinetic energy of implosion is balanced by the increase in the gravitational energy of the system. If one considers the possibility that part of the kinetic energy of implosion is extracted then the situation is very different: configurations of smaller mass-energy and greater density can be attained without violating Birkhoff theorem.

We illustrate our considerations with two examples: one has found confirmation from astrophysical observations, the other promises to be of relevance for gamma ray bursts (GRBs) (see [51]). Concerning the first example, it is well known from the work of [111] that at the endpoint of thermonuclear evolution, the gravitational collapse of a spherically symmetric star can be stopped by the Fermi pressure of the degenerate electron gas (white dwarf). A configuration of equilibrium can be found all the way up to the critical number of particles

$$N_{\text{cri}} = 0.775 \frac{m_n}{\mu_0}$$

(79)

where the factor 0.775 comes from the coefficient $\frac{3.098}{\mu}$ of the solution of the Lane-Emden equation with polytropic index $n = 3$, and $m_P = \sqrt{\frac{\mu}{\kappa}}$ is the Planck mass, $m_0$ is the nucleon mass and $\mu$ the average number of electrons per nucleon. As the kinetic energy of implosion is carried away by radiation the star settles down to a configuration of mass

$$M = N_{\text{cri}} m_0 - U,$$

(80)

where the gravitational binding energy $U$ can be as high as $5.72 \times 10^{-4} N_{\text{cri}} m_0$.

Similarly Gamov (see [112]) has shown that a gravitational collapse process to still higher densities can be stopped by the Fermi pressure of the neutrons (neutron star) and Oppenheimer [113] has shown that, if the effects of strong interactions are neglected, a configuration of equilibrium exists also in this case all the way up to a critical number of particles

$$N_{\text{cri}} = 0.398 \frac{m_n}{\mu_0}$$

(81)

where the factor 0.398 comes now from the integration of the Tolman-Oppenheimer-Volkoff equation (see e.g. [114]). If the kinetic energy of implosion is again carried away by radiation of photons or neutrinos and antineutrinos the final configuration is characterized by the formula (80) with $U \lesssim 2.48 \times 10^{-4} N_{\text{cri}} m_0$.

These considerations and the existence of such large values of the gravitational binding energy have been at the heart of the explanation of astrophysical phenomena such as red-giant stars and supernovae: the corresponding measurements of the masses of neutron stars and white dwarfs have been carried out with unprecedented accuracy in binary systems [115].

On the minimum value of the reducible mass of a black hole formed in a spherically symmetric gravitational collapse

From a theoretical physics point of view it is still an open question how far such a sequence can go: using causality nonviolating interactions, can one find a sequence of braking and energy extraction processes by which the density and the gravitational binding energy can increase indefinitely and the mass-energy of the collapsed object be reduced at will? This question can also be formulated in the mass-formula language of a black hole given in [11] (see also [51]): given a collapsing core of nucleons with a given rest mass-energy $M_0$, what is the minimum irreducible mass of the black hole which is formed?

Following [50] and [51], consider a spherical shell of rest mass $M_0$ collapsing in a flat space-time. In the neutral case the irreducible mass of the final black hole satisfies the equation (see [51])

$$M_{\text{irr}} = M = M_0 - \frac{M_0^2}{2G} + T_+,$$

(82)

where $M$ is the total energy of the collapsing shell and $T_+$ the kinetic energy at the horizon $r_+$. Recall that the area $S$ of the horizon is [11]

$$S = 4\pi r_+^2 = 16\pi M_{\text{irr}}^2$$

(83)
Figure 34. Collapse curves for neutral shells with rest mass $M_0$ starting at rest at selected radii $R^*$ computed by using the exact solutions given in [50]. A different value of $M_{irr}$ (and therefore of $r_+$) corresponds to each curve. The time parameter is the Schwarzschild time coordinate $t$ and the asymptotic behavior at the respective horizons is evident. The limiting configuration $M_{irr} = M_0^2$ (solid line) corresponds to the case in which the shell is trapped, at the very beginning of its motion, by the formation of the horizon.

where $r_+ = 2M_{irr}$ is the horizon radius. The minimum irreducible mass $M_{irr}^{(\text{min})}$ is obtained when the kinetic energy at the horizon $T_+$ is 0, that is when the entire kinetic energy $T_+$ has been extracted. We then obtain the simple result

$$M_{irr}^{(\text{min})} = M_0^2.$$  \hspace{1cm} (84)

We conclude that in the gravitational collapse of a spherical shell of rest mass $M_0$ at rest at infinity (initial energy $M_i = M_0$), an energy up to 50% of $M_0c^2$ can in principle be extracted, by braking processes of the kinetic energy. In this limiting case the shell crosses the horizon with $T_+ = 0$. The limit $M_0^2$ in the extractable kinetic energy can further increase if the collapsing shell is endowed with kinetic energy at infinity, since all that kinetic energy is in principle extractable.

In order to illustrate the physical reasons for this result, using the formulas of [50], we have represented in Fig. 34 the world lines of spherical shells of the same rest mass $M_0$, starting their gravitational collapse at rest at selected radii $R^*$. These initial conditions can be implemented by performing suitable braking of the collapsing shell and concurrent kinetic energy extraction processes at progressively smaller radii (see also Fig. 35). The reason for the existence of the minimum (84) in the black hole mass is the “self closure” occurring by the formation of a horizon in the initial configuration (thick line in Fig. 34).

Is the limit $M_{irr} \rightarrow M_0^2$ actually attainable without violating causality? Let us consider a collapsing shell with charge $Q$. If $M \geq Q$ a black hole is formed. As pointed out in [51] the irreducible mass of the final black hole does not depend on the charge $Q$. Therefore Eqs.(82) and (84) still hold in the charged case with $r_+ = M + \sqrt{M^2 - Q^2}$. In Fig. 35 we consider the special case in which the shell is initially at rest at infinity, i.e. has initial energy $M_i = M_0$, for three different values of the charge $Q$. We plot the initial energy $M_i$, the energy of the system when all the kinetic energy of implosion has been extracted as well as the sum of the rest mass energy and the gravitational binding energy $-M_0^2/R$ of the system (here $R$ is the radius of the shell). In the extreme case $Q = M_0$, the shell is in equilibrium at all radii (see [50]) and the kinetic energy is identically zero. In all three cases, the sum of the extractable kinetic energy $T_+$ and the electromagnetic energy $Q^2/R$ reaches 50% of the rest mass energy at the horizon, according to Eq.(84).

What is the role of the electromagnetic field here? If we consider the case of a charged shell with $Q \approx M_0$, the electromagnetic repulsion implements the braking process and the extractable energy is entirely stored in the electromagnetic field surrounding the black hole (see [51]). In [51] we have outlined two different processes of electromagnetic energy extraction. We emphasize here that the extraction of 50% of the mass-energy of a black hole is not specifically linked to the electromagnetic field but depends on three factors: a) the increase of the gravitational energy during the collapse, b) the formation of a horizon, c) the reduction of the kinetic energy of implosion. Such
Figure 35. Energetics of a shell such that $M_i = M_0$, for selected values of the charge. In the first diagram $Q = 0$; the dashed line represents the total energy for a gravitational collapse without any braking process as a function of the radius $R$ of the shell; the solid, stepwise line represents a collapse with suitable braking of the kinetic energy of implosion at selected radii; the dotted line represents the rest mass energy plus the gravitational binding energy. In the second and third diagram $Q/M_0 = 0.7$, $Q/M_0 = 1$ respectively; the dashed and the dotted lines have the same meaning as above; the solid lines represent the total energy minus the kinetic energy. The region between the solid line and the dotted line corresponds to the stored electromagnetic energy. The region between the dashed line and the solid line corresponds to the kinetic energy of collapse. In all the cases the sum of the kinetic energy and the electromagnetic energy at the horizon is 50% of $M_0$. Both the electromagnetic and the kinetic energy are extractable. It is most remarkable that the same underlying process occurs in the three cases: the role of the electromagnetic interaction is twofold: a) to reduce the kinetic energy of implosion by the Coulomb repulsion of the shell; b) to store such an energy in the region around the black hole. The stored electromagnetic energy is extractable as shown in [51].

conditions are naturally met during the formation of an extreme black hole but are more general and can indeed occur in a variety of different situations, e.g. during the formation of a Schwarzschild black hole by a suitable extraction of the kinetic energy of implosion (see Fig. 34 and Fig. 35).

On the Bekenstein-Hawking consideration of incompatibility between general relativity and thermodynamics

Now consider a test particle of mass $m$ in the gravitational field of an already formed Schwarzschild black hole of mass $M$ and go through such a sequence of braking and energy extraction processes. Kaplan [116] found for the energy $E$ of the particle as a function of the radius $r$

$$E = m \sqrt{1 - \frac{2M}{r}}$$

(85)

It would appear from this formula that the entire energy of a particle could be extracted in the limit $r \to 2M$. Such 100% efficiency of energy extraction has often been quoted as evidence for incompatibility between General Relativity and the second principle of Thermodynamics (see [117] and references therein). J. Bekenstein and S. Hawking have gone as far as to consider General Relativity not to be a complete theory and to conclude that in order to avoid
inconsistencies with thermodynamics, the theory should be implemented through a quantum description [117, 118]. Einstein himself often expressed the opposite point of view (see e.g. [119]).

The analytic treatment presented in [50] can clarify this fundamental issue. It allows to express the energy increase $E$ of a black hole of mass $M_1$ through the accretion of a shell of mass $M_0$ starting its motion at rest at a radius $R$ in the following formula which generalizes Eq.(85):

$$E \equiv M - M_1 = -\frac{M_0^2}{2M} + M_0\sqrt{1 - \frac{2M_0}{R}}.$$  

(86)

where $M = M_1 + E$ is clearly the mass-energy of the final black hole. This formula differs from the Kaplan formula (85) in three respects: a) it takes into account the increase of the horizon area due to the accretion of the shell; b) it shows the role of the gravitational self energy of the imploding shell; c) it expresses the combined effects of a) and b) in an exact closed formula.

The minimum value $E_{\text{min}}$ of $E$ is attained for the minimum value of the radius $R = 2M$: the horizon of the final black hole. This corresponds to the maximum efficiency of the energy extraction. We have

$$E_{\text{min}} = -\frac{M_0^2}{2M} + M_0\sqrt{1 - \frac{2M_0}{R_{\text{min}}}} = -\frac{M_0^2}{2M_{\text{max}}} + M_0\sqrt{1 - \frac{M_0}{M_{\text{max}}}},$$

or solving the quadratic equation and choosing the positive solution for physical reasons

$$E_{\text{min}} = \frac{1}{4} \left( \sqrt{M_1^2 + M_0^2 - M_0^2} \right).$$

(88)

The corresponding efficiency of energy extraction is

$$\eta_{\text{max}} = \frac{E_{\text{max}}}{M_0} = 1 - \frac{1}{\frac{1}{2} \frac{M_0}{M_{\text{max}}}} \left( \sqrt{1 + \frac{M_1^2}{M_0^2}} - 1 \right),$$

(89)

which is strictly smaller than 100% for any given $M_0 \neq 0$. It is interesting that this analytic formula, in the limit $M_1 \ll M_0$, properly reproduces the result of equation (84), corresponding to an efficiency of 50%. In the opposite limit $M_1 \gg M_0$ we have

$$\eta_{\text{max}} \simeq 1 - \frac{1}{4} \frac{M_0}{M_{\text{max}}}.$$

(90)

Only for $M_0 \rightarrow 0$, Eq.(89) corresponds to an efficiency of 100% and correctly represents the limiting reversible transformations introduced in [11]. It seems that the difficulties of reconciling General Relativity and Thermodynamics are ascribable not to an incompleteness of General Relativity but to the use of the Kaplan formula in a regime in which it is not valid. The generalization of the above results to stationary black holes is being considered.

**ON A SEPARATRIX IN THE GRAVITATIONAL COLLAPSE TO AN OVERCRITICAL ELECTROMAGNETIC BLACK HOLE**

We are now ready to analyze the dynamical properties of an electron–positron–photon plasma created by the vacuum polarization process occurring around a charged gravitationally collapsing core of an initially neutral star are examined within the framework of General Relativity and Quantum Field Theory. The Reissner–Nordström geometry is assumed to apply between the collapsing core and the oppositely charged remnant of the star. The appearance of a separatrix at radius $R$, well outside the asymptotic approach to the horizon, is evidenced. The neutral electron–positron–photon plasma created at radii $r > R$ self-propels outwards to infinity, following the classical PEM–pulse analysis [55, 59]. The plasma created at $r < R$ remains trapped and follows the gravitational collapse of the core only contributing to the reduction of the electromagnetic energy of the black hole and to the increase of its irreducible mass. This phenomenon has consequences for the observational properties of gamma–ray bursts and is especially relevant for the theoretical prediction of the temporal and spectral structure of the short bursts.

The formulation of the physics of the *dyadosphere* of an electromagnetic black hole (black hole) has been until now approached by assuming the vacuum polarization process à la Sauter–Heisenberg–Euler–Schwinger [120, 25, 26] in the field of an already formed Kerr–Newmann [23] or Reissner–Nordström black hole [48, 51]. This acausal approach is certainly valid in order to describe the overall energetics and the time development of the gamma–ray bursts (GRBs)
reaching a remarkable agreement between the observations and the theoretical prediction, in particular with respect to:
a) the existence of a proper gamma–ray burst (P–GRB) [13], b) the afterglow detailed luminosity function and spectral properties [121, 28, 76] and c) the relative intensity of the P–GRB to the afterglow [14, 121, 28].

This acausal approach has to be improved by taking into account the causal dynamical process of the formation of the dyadosphere as soon as the detailed description on timescales of $10^{-4} - 10^{-3}$s of the P–GRB are considered. Such a description leads to theoretical predictions on the time variability of the P–GRB spectra which may become soon testable by a new class of specially conceived space missions.

We report progress in this theoretically challenging process which is marked by distinctive and precise quantum and general relativistic effects. These new results have been made possible by the recent progress in Refs. [50], [51] and especially [104]. There it was demonstrated the intrinsic stability of the gravitational amplification of the electromagnetic field at the surface of a charged star core collapsing to a black hole. The $e^+ e^-$ plasma generated by the vacuum polarization process around the core is entangled in the electromagnetic field [49]. The $e^+ e^-$ pairs do thermalize in an electron–positron–photon plasma on a time scale $10^4 - 10^5$ times larger than $h/m_e c$ [104], where $c$ is the speed of light and $m_e$ the electron mass. As soon as the thermalization has occurred, a dynamical phase of this electrically neutral plasma starts following the considerations already discussed in [53, 59]. While the temporal evolution of the $e^+ e^- \gamma$ plasma takes place, the gravitationally collapsing core moves inwards, giving rise to a further amplified supercritical field, which in turn generates a larger amount of $e^+ e^-$ pairs leading to a yet higher temperature in the newly formed $e^+ e^- \gamma$ plasma. We report, in the following, progress in the understanding of this crucial dynamical process: the main difference from the previous treatments is the fact that we do not consider an already formed black hole but we follow the dynamical phase of the formation of the dyadosphere and of the asymptotic approach to the horizon by examining the time varying process at the surface of the gravitationally collapsing core.

The space–time external to the surface of the spherically symmetric collapsing core is described by the Reissner-Nordström geometry [122] with line element

$$ds^2 = -\alpha^2 dt^2 + \alpha^2 dr^2 + r^2 d\Omega^2,$$  \hspace{1cm} (91)

with $d\Omega^2 = d\theta^2 + \sin^2 \theta d\phi^2$, $\alpha^2 = \alpha^2 (r) = 1 - 2M/r + Q^2/r^2$, where $M$ and $Q$ are the total energy and charge of the core as measured at infinity. On the core surface, which at the time $t_0$ has radial coordinate $r_0$, the electromagnetic field strength is $\mathbf{E} = E(r_0) = Q/\bar{r}_0^2$. The equation of core’s collapse is (see [50]):

$$\frac{dr_0}{dt} = \frac{a^2(r_0)}{r_0} \sqrt{H^2(r_0) - \alpha^2(r_0)}$$  \hspace{1cm} (92)

where $H(r_0) = M/r_0 - \frac{M_0^2 + Q^2}{r_{0m}^2}$ and $M_0$ is the core rest mass. Analytic expressions for the solution of Eq.(92) were given in [50]. We here recall that the dyadosphere radius is defined by $\tilde{c} = n_m c/h \approx 1$ and $r_0 = \sqrt{H/\alpha^2}$, where $c$ is the electron charge. In each slab the process of vacuum polarization leading to $e^+ e^-$ pair creation is considered. As shown in [104, 49], the pairs created oscillate [123, 124, 125, 126] with ultrarelativistic velocities and partially annihilate into photons; the electric field oscillates around zero and the amplitude of such oscillations decreases with a characteristic time of the order of $10^4 - 10^5 h/m_e c$. The electric field is effectively screened to the critical value $E_c$ to the critical value $E_c^0$.

The energy density in the pairs and photons, as a function of $r_0$, is given by [51]

$$\varepsilon_0 (r_0) = \frac{1}{8\pi} \left( 2c^2 - \varepsilon_r^2 \right) = \frac{c^2}{8\pi} \left( \frac{m_e^4}{m_e^2} \right)^2 - 1. \hspace{1cm} (93)$$

The number densities of $e^+ e^-$ pairs and photons at thermal equilibrium we have $n_{e^+, e^-} \approx n_{\gamma}$, corresponding the equilibrium temperature $T_0$, which is clearly a function of $r_0$ and is different for each slab, is such that

$$\varepsilon (T_0) = \varepsilon_0 (T_0) + \varepsilon_e (T_0) + \varepsilon_{e^-} (T_0) = \varepsilon_0,$$  \hspace{1cm} (94)
with $\varepsilon$ and $n$ given by Fermi (Bose) integrals (with zero chemical potential):

$$\varepsilon_{\gamma{\gamma}}(T_0) = \frac{2}{\pi\hbar^2} \int_{T_0}^{\gamma^+} \left( \frac{E^2 - \varepsilon_0^2}{2\varepsilon_0^2} \right)^{1/2} E^2 dE, \quad \varepsilon_{\gamma}(T_0) = \frac{2}{\pi\hbar^2} (kT_0)^3,$$

(95)

$$n_{\gamma{\gamma}}(T_0) = \frac{1}{\pi\hbar^2} \int_{T_0}^{\gamma^+} \left( \frac{E^2 - \varepsilon_0^2}{2\varepsilon_0^2} \right)^{1/2} E dE, \quad n_{\gamma}(T_0) = \frac{2}{h} (kT_0)^3,$$

(96)

where $k$ is the Boltzmann constant. From the conditions set by Eqs.(94), (95), (96), we can now turn to the dynamical evolution of the $e^+e^-\gamma$ plasma in each slab. We use the covariant conservation of energy momentum and the rate equation for the number of pairs in the Reissner–Nordström geometry external to the star core:

$$\nabla_v T^{\alpha\beta} = 0, \quad \nabla_v (n_{\gamma{\gamma}} \varepsilon^{\alpha\beta}) = \mathcal{E} \left[ n_{\gamma{\gamma}}(T) - n_{\gamma{\gamma}}(T_0) \right],$$

(97)

where $T^{\alpha\beta} = (\varepsilon + p) u^\alpha u^\beta + pg^{\alpha\beta}$ is the energy–momentum tensor of the plasma with proper energy density $\varepsilon$ and proper pressure $p$. $u^\alpha$ is the fluid 4–velocity, $n_{\gamma{\gamma}}$ is the number of pairs, $n_{\gamma{\gamma}}(T)$ is the equilibrium number of pairs and $\mathcal{E}$ is the mean of the product of the $e^+e^-$ annihilation cross-section and the thermal velocity of pairs. We follow closely the treatment which we developed for the consideration of a plasma generated in the dyadosphere of an already formed black hole [55, 59]. It was shown in [55, 59] that the plasma expands as a pair–electromagnetic pulse (PEM pulse) of constant thickness in the laboratory frame. Since the expansion, hydrodynamical timescale is much larger than the pair creation ($\hbar/m_e c^3$) and the thermalization ($10^2 - 10^3\hbar/m_e c^3$) time-scales, in each slab the plasma remains at thermal equilibrium in the initial phase of the expansion and the right hand side of the rate Eq.(97) is effectively 0, see Fig. 24 (second panel) of [28] for details.

If we denote by $\hat{\xi}^\mu$ the static Killing vector field normalized at unity at spacial infinity and by $\{\Sigma_i\}$, the family of space–like hypersurfaces orthogonal to $\hat{\xi}^\mu$ ($t$ being the Killing time) in the Reissner–Nordström geometry, from Eqs.(97), the following integral conservation laws can be derived (see for instance [127, 128])

$$\int_{\Sigma_i} \hat{\xi}_v T^{\alpha\beta} d\Sigma_0 = E, \quad \int_{\Sigma_i} n_{\gamma{\gamma}} \varepsilon^{\alpha\beta} d\Sigma_0 = N_{\gamma{\gamma}},$$

(98)

where $d\Sigma_0 = \alpha^{-2} \hat{\xi}_v r^2 \sin\theta dr d\theta d\phi$ is the vector surface element, $E$ the total energy and $N_{\gamma{\gamma}}$ the total number of pairs which remain constant in each slab. We then have

$$ [(\varepsilon + p)^2 - p]^2 = \mathcal{E}, \quad n_{\gamma{\gamma}} \gamma \alpha^{-1} \mathcal{E} = \mathfrak{N}_{\gamma{\gamma}},$$

(99)

where $\mathcal{E}$ and $\mathfrak{N}_{\gamma{\gamma}}$ are constants and

$$\gamma = \alpha^{-1} \sqrt{\alpha^{-4} \left( \frac{d\alpha}{dt} \right)^2 - 1},$$

(100)

is the Lorentz $\gamma$ factor of the slab as measured by static observers. We can rewrite Eqs.(98) for each slab as

$$\left( \frac{dr}{dt} \right)^2 = \alpha^4 f_0, \quad \left( \frac{d\theta}{dt} \right)^2 = \left( \frac{\alpha^2}{\alpha^{-1} \mathfrak{N}_{\gamma{\gamma}}} \right)^2 \left( \frac{\alpha^2}{\mathcal{E}} \right)^2 - \frac{\alpha^4}{\mathcal{E}^2}, \quad f_0 = 1 - \left( \frac{\alpha^2}{\alpha^{-1} \mathfrak{N}_{\gamma{\gamma}}} \right)^2 \left( \frac{\alpha^2}{\mathcal{E}} \right)^2,$$

(101)

(102)

(103)

where $f_{\alpha} \theta$ refers to quantities evaluated at selected initial times $t_0 > 0$, having assumed $r(t_0) = r_0, \, dr/dt_{t_0} = 0, \, T(t_0) = T_0$.

Eq.(101) is only meaningful when $f_0 > 0$. From the structural analysis of such equation it is clearly identifiable a critical radius $\bar{R}$ such that:

- for any slab initially located at $r_0 > \bar{R}$ we have $f_0(r) > 0$ for any value of $r \geq r_0$ and $f_0(r) < 0$ for $r \leq r_0$; therefore a slab initially located at a radial coordinate $r_0 > \bar{R}$ moves outwards,
- for any slab initially located at $r_0 < \bar{R}$ we have $f_0(r) \geq 0$ for any value of $r_0 < r \leq r_0$ and $f_0(r) < 0$ for $r \geq r_0$; therefore a slab initially located at a radial coordinate $r_0 < \bar{R}$ moves inwards and is trapped by the gravitational field of the collapsing core.
We define the surface \( r = \bar{R} \), the dyadosphere trapping surface (DTS). The radius \( \bar{R} \) of DTS is generally evaluated by the condition \( \left. \frac{\partial R}{\partial r} \right|_{r=\bar{R}} = 0 \). \( \bar{R} \) is so close to the horizon value \( r_+ \) that the initial temperature \( T_0 \) satisfies \( kT_0 \gg m_e c^2 \) and we can obtain for \( \bar{R} \) an analytical expression. Namely the ultrarelativistic approximation of all Fermi integrals, Eqs.(95) and (96), is justified and we have \( n_{r=\bar{R}} \propto T^3 \) and therefore \( f_{\alpha \beta} = 1 - (T/T_0)^6 (\alpha_0/\alpha)^3 (r/r_0)^4 (r \leq \bar{R}) \).

The defining equation of \( \bar{R} \), together with (103), then gives

\[
\bar{R} = 2M \left[ 1 + \left( 1 - 3Q^2/4M^2 \right)^{1/2} \right] > r_+.
\]

(104)

In the case of a black hole with \( M = 20M_\odot \), \( Q = 0.1M \), we compute:

- the fraction of energy trapped in DTS:

\[
E = \int_{r_+}^{r_0} \alpha \omega_0 d\Sigma \simeq 0.53 \int_{r_+}^{r_0} \alpha \omega_0 d\Sigma;
\]

(105)

- the world–lines of slabs of plasma for selected \( r_0 \) in the interval \((\bar{R}, r_0)\) (see Fig. 36);

- the world–lines of slabs of plasma for selected \( r_0 \) in the interval \((r_+, \bar{R})\) (see Fig. 37).

At time \( t \equiv t_0(\bar{R}) \) when the DTS is formed, the plasma extends over a region of space which is almost one order of magnitude larger than the dyadosphere and which we define as the effective dyadosphere. The values of the Lorentz \( \gamma \) factor, the temperature and \( e^+ e^- \) number density in the effective dyadosphere are given in Fig. 38.

In conclusion we see how the causal description of the dyadosphere formation can carry important messages on the time variability and spectral distribution of the P–GRB due to quantum effects as well as precise signature of General Relativity.

**DESCRIPTION OF THE ELECTRON-POSITRON PLASMA OSCILLATIONS BY GENERALIZED VLASOV-BOLTZMANN-MAXWELL EQUATION IN THE PEM PULSE PHASE**

We describe the creation and evolution of electron-positron pairs in a strong electric field as well as the pairs annihilation into photons. The formalism is based on generalized Vlasov equations, which are numerically integrated. We recover previous results about the oscillations of the charges, discuss the electric field screening and the relaxation of the system to a thermal equilibrium configuration. The timescale of the thermalization is estimated to be \( \sim 10^7 - 10^8 \ h/m_e c^2 \).

On the observability of electron-positron pairs created in vacuum polarization in Earth bound experiment and in astrophysics

Three different earth-bound experiments and one astrophysical observation have been proposed for identifying the polarization of the electronic vacuum due to a supercritical electric field \( (\delta \gg \delta_c \equiv m_e^2 c^2/\epsilon \hbar) \), where \( m_e \) and \( \epsilon \) are the electron mass and charge) postulated by Sauter-Heisenberg-Euler-Schwinger [120]:

1. In central collisions of heavy ions near the Coulomb barrier, as first proposed in [129, 130] (see also [131, 132, 133]). Despite some apparently encouraging results [134], such efforts have failed so far due to the small contact time of the colliding ions [135, 136, 137, 138, 139]. Typically the electromagnetic energy involved in the collisions of heavy ions with impact parameter \( h \simeq 10^{-12} \) cm is \( E_1 \sim 10^{-6} \) erg and the lifetime of the diatomic system is \( t_1 \sim 10^{-22} \) s.

2. In collisions of an electron beam with optical laser pulses: a signal of positrons above background has been observed in collisions of a 46.6 GeV electron beam with terawatt pulses of optical laser in an experiment at the Final Focus Test Beam at SLAC [140]; it is not clear if this experimental result is an evidence for the vacuum polarization phenomenon. The energy of the laser pulses was \( E_2 \sim 10^7 \) erg, concentrated in a space-time region of spacial linear extension (focal length) \( l_2 \sim 10^{-3} \) cm and temporal extension (pulse duration) \( t_2 \sim 10^{-12} \) s [140].
Figure 36. World line of the collapsing charged core (dashed line) as derived from Eq.(92) for a black hole with $M = 20M_\odot$, $Q = 0.1M$; world lines of slabs of plasma for selected radii $r_0$ in the interval $(\bar{R}, r_{ds})$. At time $t$ the expanding plasma extends over a region which is almost one order of magnitude larger than the dyadosphere. The small rectangle in the right bottom is enlarged in Fig. 37.

3. At the focus of an X-ray free electron laser (XFEL) (see [141, 142, 143] and references therein). Proposals for this experiment exist at the TESLA collider at DESY and at the LCLS facility at SLAC [141]. Typically the electromagnetic energy at the focus of an XFEL can be $E_3 \sim 10^6$erg, concentrated in a space-time region of spacial linear extension (spot radius) $l_3 \sim 10^{-8}$cm and temporal extension (coherent spike length) $t_3 \sim 10^{-13}$s [141].
and from astrophysics

1. around an electromagnetic black hole (black hole) [23, 48, 144], giving rise to the observed phenomenon of gamma-ray bursts (GRB) [13, 14, 15, 76]. The electromagnetic energy of an black hole of mass $M \sim 10M_\odot$ and charge $Q \sim 0.1M_\odot/\sqrt{G}$ is $E_4 \sim 10^{54}$erg and it is deposited in a space-time region of spatial linear extension $l_4 \sim 10^8$cm [48, 51] and temporal extension (collapse time) $t_4 \sim 10^{-2}$s [104].

**On the role of transparency condition in the electron-positron plasma**

In addition to their marked quantitative difference in testing the same basic physical phenomenon, there is a very important conceptual difference among these processes: the first three occur in a transparency condition in which the created electron-positron pairs and, possibly, photons freely propagate to infinity, while the one in the black hole occurs in an opacity condition [59]. Under the opacity condition a thermalization effect occurs and a final equipartition between the $e^+e^-$ and $\gamma$ is reached. Far from being just an academic issue, this process and its characteristic timescale is of the greatest importance in physics and astrophysics. It has been shown by a numerical simulation done in Livermore and an analytic work done in Rome [59], that, as soon as the thermalization of $e^+e^-$ and $\gamma$ created around a black hole has been reached, the plasma self propels outwards and this process is at the very heart of the gamma-ray burst (GRB) phenomenon. A critical step was missing up to now: how to bridge the gap between the creation of pairs in the supercritical field of the black hole and the thermalization of the system to a plasma configuration. We report some progress on this topic with special attention to the timescale needed for the thermalization of the newly created $e^+e^-$ pairs in the background field. The comparison of the thermalization timescale to the one of gravitational collapse, which occurs on general relativistic timescale, is at the very ground of the comprehension of GRBs [104].

The evolution of a system of particle-antiparticle pairs created by the Schwinger process has been often described by a transport Vlasov equation (see, for example, [145, 146]). More recently it has been showed that such an equation can be derived from quantum field theory [147, 148, 149]. In the homogeneous case, the equations have been numerically integrated taking into account the back reaction on the external electric field [123, 124, 125, 126]. In many papers (see [150] and references therein) a phenomenological term describing equilibrating collisions is introduced in the transport equation which is parameterized by an effective relaxation time $\tau$. In [150] one further step is taken by allowing time variability of $\tau$; the ignorance on the collision term is then parameterized by a free dimensionless constant. The introduction of a relaxation time corresponds to the assumption that the system rapidly evolves towards thermal equilibrium. In this paper we focus on the evolution of a system of $e^+e^-$ pairs, explicitly taking into account the scattering processes $e^+e^- \leftrightarrow \gamma\gamma$. Since we are mainly interested in a system in which the electric field varies on...
Figure 38. Physical parameters in the effective dyadosphere: Lorentz $\gamma$ factor, proper temperature and proper $e^+e^-$ number density as functions at time $\bar{t}$ for a black hole with $M = 20M_\odot$ and $Q = 0.1M_\odot$.

The macroscopic length scale ($l \sim 10^8\text{cm}$, above), we can limit ourselves to a homogeneous electric field. Also, we will use transport equations for electrons, positrons and photons, with collision terms, coupled to Maxwell equations. There is no free parameter here: the collision terms can be exactly computed, since the QED cross sections are known. Starting from a regime which is far from thermal equilibrium, we find that collisions do not prevent plasma oscillations in the initial phase of the evolution and analyse the issue of the timescale of the approach to a $e^+e^-\gamma$ plasma equilibrium configuration, which is the most relevant quantity in the process of gravitational collapse [104].

The Vlasov-Boltzmann-Maxwell equations and their solutions

The motion of positrons (electrons) is the resultant of three contributions: the pair creation, the electric acceleration and the annihilation damping. The homogeneous system consisting of electric field, electrons, positrons and photons
can be described by the equations
\[
\frac{\partial}{\partial t} f_e + eE \frac{\partial}{\partial p} f_e = \mathcal{S}(E, p) - \frac{1}{(2\pi)^3} \varepsilon^{-1} p C_e(t, p), \tag{106}
\]
\[
\frac{\partial}{\partial t} f_\gamma = \frac{2}{(2\pi)^5} \varepsilon^{-1} k C_\gamma(t, k), \tag{107}
\]
\[
\frac{\partial}{\partial t} E = -j_\beta(E) - j_\epsilon(t), \tag{108}
\]
where \( f_e = f_e(t, p) \) is the distribution function in the phase-space of positrons (electrons), \( f_\gamma = f_\gamma(t, k) \) is the distribution function in the phase-space of photons, \( E \) is the electric field, \( e_p = (p \cdot p + m_e^2)^{1/2} \) is the energy of an electron of 3-momentum \( p \) (\( m_e \) is the mass of the electron) and \( \varepsilon_k = (k \cdot k)^{1/2} \) is the energy of a photon of 3-momentum \( k \). \( f_e \) and \( f_\gamma \) are normalized so that \[ \int \frac{dp}{(2\pi)^3} f_e(t, p) = n_e(t), \int \frac{dk}{(2\pi)^3} f_\gamma(t, k) = n_\gamma(t), \] where \( n_e \) and \( n_\gamma \) are number densities of positrons (electrons) and photons, respectively. The term
\[
\mathcal{S}(E, p) = (2\pi)^3 \frac{dN}{dE dp} = -|E| \log \left[ 1 - \exp \left( -\frac{\pi}{|E|} \right) \right] \delta(p_1)
\]
is the Schwinger source for pair creation (see \[123, 124\]): \( p_1 \) and \( p_\perp \) are the components of the 3-momentum \( p \) parallel and orthogonal to \( E \). We assume that the pairs are produced at rest in the direction parallel to the electric field \[123, 124\]. We also have, in Eqs. (106), (107) and (108),
\[
\mathcal{G}_e(t, p) \simeq \left\{ \frac{d^3 p}{(2\pi)^3} \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \delta^4(p + p_1 - k_1 - k_2) \times \mathcal{M}^\dagger \left[ f_e(p_1) f_e(p_2) - f_\gamma(k_1) f_\gamma(k_2) \right] \right\}, \tag{110}
\]
\[
\mathcal{G}_\gamma(t, k) \simeq \left\{ \frac{d^3 p}{(2\pi)^3} \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} \delta^4(p_1 + p_2 - k - k_1) \times \mathcal{M}^\dagger \left[ f_e(p_1) f_e(p_2) - f_\gamma(k_1) f_\gamma(k_2) \right] \right\}, \tag{111}
\]
which describe probability rates for pair creation by photons and pair annihilation into photons, \( \mathcal{M} = \mathcal{M}_{e^+(p_1)e^-(p_2)\gamma(k_1)}\gamma(k_2) \) being the matrix element for the process \( e^+(p_1)e^-(p_2) \to \gamma(k_1)\gamma(k_2) \). Note that the collisional terms (110) and (111) are either inapplicable or negligible in the case of the above three earth-bound experiments where the created pairs do not originate a dense plasma. They have been correctly neglected in previous works (see e. g. \[143\]). Collisional terms have also been considered in the different physical context of vacuum polarization by strong chromoelectric fields. Unlike the present QED case, where expressions for the cross sections are known exactly, in the QCD case the cross sections are yet unknown and such collisional terms are of a phenomenological type and useful uniquely near the equilibrium regime \[150\]. Finally \( j_\beta(E) = 2 \frac{p E}{(2\pi)^3} e_p \mathcal{S}(E, p) \) and \( j_\epsilon(t) = 2en_e \int \frac{dp}{(2\pi)^3} p \cdot E \mathcal{S}(E, p) \) are polarization and conduction current respectively (see \[146\]). In Eqs. (110) and (111) we neglect, as a first approximation, Pauli blocking and Bose enhancement (see e.g. \[124\]). By suitably integrating (106) and (107) over the phase spaces of positrons (electrons) and photons, we find the following exact equations for mean values:
\[
\frac{d}{dt} n_e = S(E) - n_e^2 \langle \sigma_\text{el} \rangle + n_e n_\gamma \langle \sigma_\text{am} \rangle, \tag{112a}
\]
\[
\frac{d}{dt} n_\gamma = 2n_e^2 \langle \sigma_\text{el} \rangle - 2n_\gamma^2 \langle \sigma_\text{am} \rangle, \tag{112b}
\]
\[
\frac{d}{dt} \langle E \rangle = en_e E \langle \sigma_\text{el} \rangle + \frac{2}{3} E \cdot j_\beta - n_e^2 \langle \sigma_\text{el} \rangle + n_\gamma^2 \langle \sigma_\text{am} \rangle, \tag{112c}
\]
\[
\frac{d}{dt} \langle \mathcal{S} \rangle = 2n_e^2 \langle \sigma_\text{el} \rangle - 2n_\gamma^2 \langle \sigma_\text{am} \rangle, \tag{112d}
\]
\[
\frac{d}{dt} \langle p \rangle = en_e E - n_e^2 \langle \sigma_\text{el} \rangle + n_\gamma^2 \langle \sigma_\text{am} \rangle, \tag{112e}
\]
\[
\frac{d}{dt} \langle p_\perp \rangle = -2en_e \langle \sigma_\text{el} \rangle - j_\epsilon(t), \tag{112f}
\]
where, for any function of the momenta
\[
\langle F(p_1, \ldots, p_n) \rangle \equiv n_e^{-n} \int \frac{dp_1}{(2\pi)^3} \cdots \frac{dp_n}{(2\pi)^3} F(p_1, \ldots, p_n) f_e(p_1) \cdots f_e(p_n), \tag{113}
\]
\[
\langle G(k_1, \ldots, k_n) \rangle \equiv n_\gamma^{-n} \int \frac{dk_1}{(2\pi)^3} \cdots \frac{dk_n}{(2\pi)^3} G(k_1, \ldots, k_n) f_\gamma(k_1) \cdots f_\gamma(k_n). \tag{114}
\]
Furthermore $v'$ is the relative velocity between electrons and positrons, $v''$ is the relative velocity between photons. $\sigma_1 = \sigma_1 (s_{\text{CoM}})$ is the total cross section for the process $e^+ - e^- \to \gamma\gamma$ and $\sigma_2 = \sigma_2 (k_{\text{CoM}})$ is the total cross section for the process $\gamma\gamma \to e^+ e^-$ (here $s_{\text{CoM}}$ is the energy of a particle in the reference frame of the center of mass).

In order to evaluate the mean values in system (112) we need some further hypotheses on the distribution functions. Let us define $p_1, \bar{\delta}_1$ and $\bar{p}_1^2$ such that $\langle p_1 \rangle = \bar{p}_1, \langle \bar{\delta}_1 \rangle = \bar{p}_1^2 = \bar{p}_1^2 + m_0^2/2$. We assume

$$f_s (r, p) \propto n_s (t) \delta (p - \bar{p}_s) \delta (\bar{p}_1^2 - \bar{p}_1^2).$$

(115)

Since in the scattering $e^+ e^- \to \gamma\gamma$ the coincidence of the scattering direction with the incidence direction is statistically favored, we also assume

$$f_s (r, k) \propto n_s (t) \delta (k_1^2 - k_1^2) \delta (k_1 - k_1) + \delta (k_1 + k_1),$$

(116)

where $k_1$ and $k_2$ have analogous meaning as $p_1$ and $p_2$ and the terms $\delta (k_1 - k_1)$ and $\delta (k_1 + k_1)$ account for the probability of producing, respectively, forwardly scattered and backwardly scattered photons. Since the Schwinger source term (109) implies that the positrons (electrons) have initially fixed $p_1, p_1 = 0$, assumption (115) ($(116)$) means that the distribution of $p_1 (k_1)$ does not spread too much with time and, analogously, that the distribution of energies is sufficiently peaked to be describable by a $\delta$–function. The dependence on the momentum of the distribution functions has been discussed in [124, 148]. Approximations (115), (116) reduce Eqs. (112) to a system of ordinary differential equations. In average, since the inertial reference frame we fix coincides with the center of mass frame for the processes $e^+ e^- \to \gamma\gamma$, $s_{\text{CoM}} \approx \bar{e}$ for each species. Substituting (115) and (116) into (112) we find

$$\frac{d}{dt} \rho_1 = S (\bar{e}) - 2n_0 e_{\text{C}} (\rho_1)^2 \left| \pi_1 \right| + 2n_0 e_{\text{C}} (\rho_2),$$

$$\frac{d}{dt} \rho_2 = 4n_0 e_{\text{C}} (\rho_1)^2 \left| \pi_1 \right| - 4n_0 e_{\text{C}} (\rho_2),$$

$$\frac{d}{dt} \rho_3 = en_0^2 (\rho_1)^2 \left| \pi_1 \right| + \frac{1}{2} n_0^2 (\rho_2)^2 - 2n_0 \rho_1 \rho_2 \left| \pi_1 \right| + 2n_0 \rho_2 \rho_3,$$

$$\frac{d}{dt} \rho_4 = 4n_0^2 \rho_2 \rho_3 \left| \pi_1 \right| - 4n_0^2 \rho_4 \rho_3,$$

$$\frac{d}{dt} \rho_5 = en_0^2 - 2n_0 \rho_1 \rho_5 \left| \pi_1 \right| + J_\rho (\bar{e}),$$

$$\frac{d}{dt} \rho_6 = -2en_0 \rho_3 \left| \pi_1 \right| - J_\rho (\bar{e}),$$

(117)

where $\rho_2 = n_0 \bar{\delta}_2, \rho_7 = n_0 \bar{\delta}_7, \rho_8 = n_0 \bar{\delta}_8, \rho_9 = n_0 \bar{\delta}_9$ are the energy density of positrons (electrons), the energy density of photons and the density of “parallel momentum” of positrons (electrons), $\bar{e}$ is the electric field strength and $J_\rho$ the unique component of $J_\rho$ parallel to $E$. $\sigma_1$ and $\sigma_2$ are evaluated at $s_{\text{CoM}} = \bar{e}$ for each species. Note that Eqs.(117) are “classical” in the sense that the only quantum information is encoded in the terms describing pair creation and scattering probabilities. Eqs.(117) are consistent with energy density conservation: $\frac{d}{dt} \left( \rho_1 + \rho_2 + \frac{1}{2} \rho_3 \right) = 0$.

The initial conditions for Eqs.(117) are $n_0 = n_0 = \rho_2 = \rho_7 = \rho_8 = \rho_9 = 0$, $\bar{e} = \bar{e}_0$. In Fig. 39 the results of the numerical integration for $\bar{e}_0 = 9/\bar{e}_C$ is shown. The integration stops at $t = 150 \bar{\tau}_c$ (where $\bar{\tau}_c = \bar{e}/m_e c^2$). Each variable is represented in units of $m_e$ and $c = \bar{e}/m_e c^2$. The numerical integration confirms [123, 124] that the system undergoes plasma oscillations: a) the electric field oscillates with decreasing amplitude rather than abruptly reaching the equilibrium value; b) electrons and positrons oscillate in the electric field direction, reaching ultrarelativistic velocities; c) the role of the $e^+ e^- \to \gamma\gamma$ scattering is marginal in the early time of the evolution, the electrons are too extremely relativistic and consequently the density of photons builds up very slowly (see. details in Fig. 39).

At late times the system is expected to relax to a plasma configuration of thermal equilibrium and assumptions (115) and (116) have to be generalized to take into account quantum spreading of the distribution functions. It is nevertheless interesting to look at the solutions of Eqs.(117) in this regime. In Fig. 40 we plot the numerical solution of Eqs.(117) but the integration extends here all the way up to $t = 7000 \bar{\tau}_c$ (the time scale of oscillations is not resolved in these plots). It is interesting that the leading term recovers the expected asymptotic behavior: a) the electric field is screened to about the critical value: $\bar{e} \simeq \bar{e}_c$ for $t \sim 10^3 - 10^4 \bar{\tau}_c > \bar{\tau}_c$; b) the initial electromagnetic energy density is distributed over electron-positron pairs and photons, indicating energy equipartition; c) photons and electron-positron pairs number densities are asymptotically comparable, indicating number equipartition. At such late times a regime of thermalized electrons-positrons-photons plasma begins and the system is describable by hydrodynamic equations [104, 59].

We provided a very simple formalism apt to describe simultaneously the creation of electron-positron pairs by a strong electric field $\bar{e} \gtrsim \bar{e}_c$ and the pairs annihilation into photons. As discussed in literature, we find plasma oscillations. In particular the collisions do not prevent such a feature. This is because the momentum of electrons
(positrons) is very high, therefore the cross section for the process $e^+e^- \rightarrow \gamma\gamma$ is small and the annihilation into photons is negligible in the very first phase of the evolution. As a result, the system takes some time ($t \sim 10^3 - 10^4 \tau_e$) to thermalize to a $e^+e^-\gamma$ plasma equilibrium configuration. We finally remark that, at least in the case of electromagnetic Schwinger mechanism, the picture could be quite different from the one previously depicted in literature, where the system is assumed to thermalize in a very short time (see [150] and references therein).

It is conceivable that in the race to first identify the vacuum polarization process à la Sauter-Euler-Heisenberg-Schwinger, the astrophysical observations will reach a positive result before earth-bound experiments, much like in the case of the discovery of lines in the Sun chromosphere by J. N. Lockyer in 1869, later identified with the Helium spectral lines by W. Ramsay in 1895 [151].

**OBSERVATIONAL SIGNATURES OF AN ELECTROMAGNETIC OVERCRITICAL GRAVITATIONAL COLLAPSE AND PREDICTION OF SPECTRAL EVOLUTION OF SHORT GRBS**

We finally present theoretical predictions for the spectral, temporal and intensity signatures of the electromagnetic radiation emitted during the process of the gravitational collapse of a stellar core to a black hole, during which electromagnetic field strengths rise over the critical value for $e^+e^-$ pair creation. The last phases of this gravitational collapse are studied, using the result presented in the previous sections, leading to the formation of a black hole with a subcritical electromagnetic field, likely with zero charge, and an outgoing pulse of initially optically thick $e^+e^-$-photon plasma. Such a pulse reaches transparency at Lorentz gamma factors of $10^7 - 10^8$. We find a clear signature in the outgoing electromagnetic signal, drifting from a soft to a hard spectrum, on very precise time-scales and with a very specific intensity modulation.

We outline finally the relevance of these theoretical results for the understanding of short gamma-ray bursts.

**The model**

The dynamics of the collapse of an electrically-charged stellar core, separating itself from an oppositely charged remnant in an initially neutral star, was first modeled by an exact solution of the Einstein-Maxwell equations corresponding to a shell of charged matter in Ref. [50]. The fundamental dynamical equations and their analytic solutions were obtained, revealing the amplification of the electromagnetic field strength during the process of collapse and the asymptotic approach to the final static configuration. The results, which properly account for general relativistic effects, are summarized in Fig. 1 and Fig. 2 of Ref. [50].

A first step toward the understanding of the process of extracting energy from a black hole was obtained in Ref. [51], where it was shown how the extractable electromagnetic energy is not stored behind the horizon but is actually distributed all around the black hole. Such a stored energy is in principle extractable, very efficiently, on time-scales $\sim h/m_e c^2$, by a vacuum polarization process à la Sauter-Heisenberg-Euler-Schwinger [120, 25, 26]. Such a process occurs if the electromagnetic field becomes larger than the critical field strength $E_c$ for $e^+e^-$ pair creation. In Ref. [51] we followed the approach of Damour and Ruffini [23] in order to evaluate the energy density and the temperature of the created $e^+e^-$-photon plasma. As a byproduct, a formula for the irreducible mass of a black hole was also derived solely in terms of the gravitational, kinetic and rest mass energies of the collapsing core. This surprising result allowed us in Ref. [52] to obtain a deeper understanding of the maximum limit for the extractable energy during the process of gravitational collapse, namely 50% of the initial energy of the star: the well known result of a 50% maximum efficiency for energy extraction in the case of a Reissner-Nordström black hole [11] then becomes a particular case of a process of much more general validity.

The crucial issue of the survival of the electric charge of the collapsing core in the presence of a copious process of $e^+e^-$ pair creation was addressed in Refs. [49, 53]. By using theoretical techniques borrowed from plasma physics and statistical mechanics [146, 123, 124, 125, 148, 149, 126] based on a generalized Vlasov equation, it was possible to show that while the core keeps collapsing, the created $e^+e^-$ pairs are entangled in the overcritical electric field. The electric field itself, due to the back reaction of the created $e^+e^-$ pairs, undergoes damped oscillations in sign finally settling down to the critical value $E_c$. The pairs fully thermalize to an $e^+e^-$-photon plasma on time-scales typically $\sim 10^3 - 10^4 \tau_e$. The last phases of this gravitational collapse are studied, using the result presented in the previous sections, leading to the formation of a black hole with a subcritical electromagnetic field, likely with zero charge, and an outgoing pulse of initially optically thick $e^+e^-$-photon plasma. Such a pulse reaches transparency at Lorentz gamma factors of $10^7 - 10^8$. We find a clear signature in the outgoing electromagnetic signal, drifting from a soft to a hard spectrum, on very precise time-scales and with a very specific intensity modulation.

We outline finally the relevance of these theoretical results for the understanding of short gamma-ray bursts.
Figure 39. Plasma oscillations. We set $E_0 = 9E_c$, $t < 150\tau_C$ and plot: a) electromagnetic field strength; b) electrons energy density; c) electrons number density; d) photons energy density; e) photons number density as functions of time.

of the order of $10^2$–$10^4h/m_e c^2$. During this characteristic damping time, which we recall is much larger than the pair creation time-scale $h/m_e c^2$, the core moves inwards, collapsing with a speed $0.2$–$0.8c$, further amplifying the electric field strength at its surface and enhancing the pair creation process.

Turning now to the dynamical evolution of such an $e^+e^-$ plasma we recall that, after some original attempt to consider a steady state emission [152, 153], the crucial progress was represented by the understanding that during the optically thick phase such a plasma expands as a thin shell. There exists a fundamental relation between the width
Figure 40. Plasma oscillations. We set $E_0 = 9E_c$, $t < 7000\tau_C$ and plot: a) electromagnetic field strength; b) electrons energy density; c) electrons number density; d) photons energy density; e) photons number density as functions of time - the oscillation period is not resolved in these plots. The model used should have a breakdown at a time much earlier than $7000\tau_C$ and therefore this plot contains no more than qualitative informations.

of the expanding shell and the Lorentz gamma factor. The shell expands, but the Lorentz contraction is such that its width in laboratory frame appears to be constant. Such a result was found in [56] on the basis of a numerical approach, further analyzed in Bisnovatyi-Kogan and Murzina [57] on the basis of an analytic approach. Attention to the role of the rate equations governing the $e^-e^-$ annihilation were given in [154], where approximations to the full equation were introduced. These results were improved in two important respects in 1999 and 2000 [55, 59]: the initial conditions were made more accurate by the considerations of the dyadosphere as well as the dynamics of the shell was improved.
by the self-consistent solution of the hydrodynamical equation and the rate equation for the $e^+ e^-$ plasma following both an analytic and numerical approach.

We are now ready to report the result of using the approach in [55, 59] in this general framework describing the dynamical formation of the dyadosphere.

The first attempt to analyze the expansion of the newly generated and thermalized $e^+ e^-$-photon plasma was made in Ref. [49]. The initial dynamical phases of the expansion were analyzed, using the general relativistic equations of Ref. [50] for the gravitational collapse of the core. A separatrix was found in the motion of the plasma at a critical radius $R$: the plasma created at radii larger than $R$ expands to infinity, while the one created at radii smaller than $R$ is trapped by the gravitational field of the collapsing core and implodes towards the black hole. The value of $R$ was found in Ref. [49] to be $R = 2GM/c^2(1 + (1 - 3Q^2/4GM^2)^{1/2})$, where $M$ and $Q$ are the mass and the charge of the core, respectively.

We now pursue further the evolution of such a system, describing the dynamical phase of the expansion of the pulse of the optically thick plasma all the way to the point where the transparency condition is reached. Some pioneering work in this respect were presented in Goodman in 1986 [155]. In this process the pulse reaches ultrarelativistic regimes with Lorentz factor $\gamma \sim 10^2$–$10^4$. The spectra, the luminosities and the time-sequences of the electromagnetic signals captured by a far-away observer are analyzed here in detail for the first time. The relevance of these theoretical results for short-bursts is then discussed.

**The expansion of the $e^+ e^- \gamma$ plasma as a discrete set of elementary slabs**

We discretize the gravitational collapse of a spherically symmetric core of mass $M$ and charge $Q$ by considering a set of events along the world line of a point of fixed angular position on the collapsing core surface. Between each of these events we consider a spherical shell slab of plasma of constant coordinate thickness $\Delta r$ so that:

1. $\Delta r$ is assumed to be a constant which is small with respect to the core radius;
2. $\Delta r$ is assumed to be large with respect to the mean free path of the particles so that the statistical description of the $e^+ e^- \gamma$ plasma can be used;
3. There is no overlap among the slabs and their union describes the entirety of the process.

We check that the final results are independent of the special value of the chosen $\Delta r$.

In order to describe the dynamics of the expanding plasma pulse the energy-momentum conservation law and the rate equation for the number of pairs in the Reissner-Nordström geometry external to the collapsing core have to be integrated:

$$T^{\mu\nu} = 0,$$

$$\left(n_{e^+ e^-} u^\mu\right)_{\mu} = \rho \left[ n_{e^+ e^-} (T) - n_{e^+ e^-} \right], \quad (118)$$

where $T^{\mu\nu} = (e + p) u^\mu u^\nu + pg^{\mu\nu}$ is the energy-momentum tensor of the plasma with proper energy density $e$ and proper pressure $p$, $u^\mu$ is the fluid 4-velocity, $n_{e^+ e^-}$ is the pair number density, $n_{e^+ e^-} (T)$ is the equilibrium pair number density at the temperature $T$ of the plasma and $\rho \tau$ is the mean of the product of the $e^+ e^-$ annihilation cross-section and the thermal velocity of the pairs. We use Eqs. (118) and (119) to study the expansion of each slab, following closely the treatment developed in Refs [55, 59] where it was shown how a homogeneous slab of plasma expands as a pair-electromagnetic pulse (PEM pulse) of constant thickness in the laboratory frame. Two regimes can be identified in the expansion of the slabs:

1. In the initial phase of expansion the plasma experiences the strong gravitational field of the core and a fully general relativistic description of its motion is needed. The plasma is sufficiently hot in this first phase that the $e^+ e^-$ pairs and the photons remain at thermal equilibrium in it. As shown in Ref. [49], under these circumstances, the right hand side of Eqs. (119) is effectively 0 and Eqs. (118) and (119) are equivalent to:

$$\left(\frac{d n}{d r_\tau}\right)^2 = \alpha^2 \left[ 1 - \left(\frac{\epsilon_{e^+ e^-}}{\epsilon_{\gamma}}\right)^2 \left(\frac{n_{e^+ e^-}}{n_{\gamma}}\right)^2 \left(\frac{\rho}{\epsilon_{\gamma}}\right)^2 \left(\frac{\tau}{\tau_{\gamma}}\right)^4 \right],$$

$$\left(\frac{\epsilon_{e^+ e^-}}{\epsilon_{\gamma}}\right)^2 = \left(\frac{\epsilon_{\gamma}}{\epsilon_{e^+ e^-}}\right) \left(\frac{n_{e^+ e^-}}{n_{\gamma}}\right)^2 \left(\frac{\rho}{\epsilon_{\gamma}}\right)^2 - \frac{\rho}{\epsilon_{\gamma}} \left(\frac{\tau}{\tau_{\gamma}}\right)^4, \quad (120)$$
Figure 41. Expansion of the plasma created around an overcritical collapsing stellar core with $M = 10 M_\odot$ and $Q = 0.1 \sqrt{GM}$.

Upper diagram: world lines of the plasma. Lower diagram: Lorentz $\gamma$ factor as a function of the radial coordinate $r$.

where $r$ is the radial coordinate of a slab of plasma, $\alpha = \left[1 - 2MG/c^2r + GQ^2/c^4r^2\right]^{1/2}$ is the gravitational redshift factor and the subscript "0" refers to quantities evaluated at the initial time.

2. At asymptotically late times the temperature of the plasma drops below an equivalent energy of $0.5 \text{ MeV}$ and the $e^+e^-$ pairs and the photons can no longer be considered to be in equilibrium: the full rate equation for pair annihilation needs to be used. However, the plasma is so far from the central core that gravitational effects can be neglected. In this new regime, as shown in Ref. [55], Eqs.(118) and (119) reduce to:

$$\frac{\epsilon_0}{\epsilon} = \left(\frac{\gamma V}{\gamma_0 V_0}\right) \Gamma,$$

$$\gamma \gamma_0 = \sqrt{\frac{\epsilon_0 V_0}{\epsilon V}},$$

(121)

where $\Gamma = 1 + p/\epsilon$, $\gamma$ is the volume of a single slab as measured in the laboratory frame by an observer at rest with the black hole, $N_{e^+e^-} = \gamma n_{e^+e^-}$ is the pair number density as measured in the laboratory frame by an observer at rest with the black hole, and $N_{e^+e^-}(T)$ is the equilibrium laboratory pair number density.

The reaching of transparency and the signature of the outgoing gamma ray signal

Eqs.(120) and (121) must be separately integrated and the solutions matched at the transition between the two regimes. The integration stops when each slab of plasma reaches the optical transparency condition given by

$$\int_0^\Delta \sigma_T n_{e^+e^-} dr \sim 1,$$

(122)

where $\sigma_T$ is the Thomson cross-section and the integral extends over the radial thickness $\Delta r$ of the slab. The evolution of each slab occurs without any collision or interaction with the other slabs; see the upper diagram in Fig. 41. The outer layers are colder than the inner ones and therefore reach transparency earlier; see the lower diagram in Fig. 41.

In Fig. 41, Eqs.(120) and (121) have been integrated for a core with

$M = 10 M_\odot; \quad Q = 0.1 \sqrt{GM};$

(123)

the upper diagram represents the world lines of the plasma as functions of the radius, while the lower diagram shows the corresponding Lorentz $\gamma$ factors. The overall independence of the result of the dynamics on the number $N$ of the
slabs adopted in the discretization process or analogously on the value of $\Delta r$ has also been checked. We have repeated the integration for $N = 10$, $N = 100$ reaching the same result to extremely good accuracy. The results in Fig. 41 correspond to the case $N = 10$.

We now turn to the results in Fig. 42, where we plot both the theoretically predicted luminosity $L$ and the spectral hardness of the signal reaching a far-away observer as functions of the arrival time $t_a$. Since all three of these quantities depend in an essential way on the cosmological redshift factor $z$, see Refs. [156, 121], we have adopted a cosmological redshift $z = 1$ for this figure.

As the plasma becomes transparent, gamma ray photons are emitted. The energy $\hbar \omega$ of the observed photon is $\hbar \omega = kT/\gamma (1 + z)$, where $k$ is the Boltzmann constant, $T$ is the temperature in the comoving frame of the pulse and $\gamma$ is the Lorentz factor of the plasma at the transparency time. We also recall that if the initial zero of time is chosen as the time when the first photon is observed, then the arrival time $t_a$ of a photon at the detector in spherical coordinates centered on the black hole is given by [156, 121]:

$$t_a = (1 + z) \left[ t + \frac{\Phi}{c} - \frac{r(\tau)}{c} \cos \theta \right]$$

(124)

where $(t, r(\tau), \theta, \phi)$ labels the laboratory emission event along the world line of the emitting slab and $r_0$ is the initial

Figure 42. Predicted observed luminosity and observed spectral hardness of the electromagnetic signal from the gravitational collapse of a collapsing core with $M = 10M_\odot$, $Q = 0.1\sqrt{GM}$ at $z = 1$ as functions of the arrival time $t_a$. 

---

Attachments

234
position of the slab. The projection of the plot in Fig. 42 onto the $t_a-L$ plane gives the total luminosity as the sum of the partial luminosities of the single slabs. The sudden decrease of the intensity at the time $t = 0.040466$ s corresponds to the creation of the separatrix introduced in Ref. [53]. We find that the duration of the electromagnetic signal emitted by the relativistically expanding pulse is given in arrival time by

$$
\Delta t_a \sim 5 \times 10^{-2} s .
$$

The projection of the plot in Fig. 42 onto the $kT_{obs}-t_a$ plane describes the temporal evolution of the spectral hardness. We observe a precise soft-to-hard evolution of the spectrum of the gamma ray signal from $\sim 10^2$ KeV monotonically increasing to $\sim 1$ MeV. We recall that $kT_{obs} = kT / (1 + z)$.

The above quantities are clearly functions of the cosmological redshift $z$, of the charge $Q$ and the mass $M$ of the collapsing core. We present in Fig. 3 the arrival time interval for $M$ ranging from $\sim 10 M_\odot$ to $10^3 M_\odot$, keeping $Q = 0.1 \sqrt{GM}$. The arrival time interval is very sensitive to the mass of the black hole:

$$
\Delta t_a \sim 10^{-2} - 10^{-1} s .
$$

Similarly the spectral hardness of the signal is sensitive to the ratio $Q/\sqrt{GM}$ [54]. Moreover the duration, the spectral hardness and luminosity are all sensitive to the cosmological redshift $z$ (see Ref. [54]). All the above quantities can also be sensitive to a possible baryonic contamination of the plasma due to the remnant of the progenitor star which has undergone the process of gravitational collapse.

**CONCLUSIONS**

**On the GRB-Supernova connection**

We first stress some general considerations originating from comparing and contrasting the three GRB sources we have discussed:

1. The value of the $B$ parameter for all three sources occurs, as theoretically expected, in the allowed range (see Fig. 22)

$$
10^{-5} \leq B \leq 10^{-2} .
$$
We have in fact:

\[
\text{GRB 991216 } B = 3.0 \times 10^{-3} \quad E_{\text{dya}} = 4.8 \times 10^{53} \text{ erg} \\
\text{GRB 980425 } B = 7.0 \times 10^{-3} \quad E_{\text{dya}} = 1.1 \times 10^{48} \text{ erg} \\
\text{GRB 030329 } B = 4.8 \times 10^{-3} \quad E_{\text{dya}} = 2.1 \times 10^{52} \text{ erg}
\]

2. The enormous difference in the GRB energy of the sources simply relates to the electromagnetic energy of the black hole given in Eq.(6) which turns out to be smaller than the critical value given by Eq.(7). The fact that the theory is valid over 5 orders of magnitude is indeed very satisfactory.

3. Also revealing is the fact that in both sources GRB 980425 and GRB 030329 the associated supernova energies are similar. We have, in fact, for both SN 1998bw and SN 2003dh an energy \( \sim 10^{49} \text{ erg} \). Details in Fraschetti et al. [17] and Bernardini et al. [97]. The further comparison between the SN luminosity and the GRB intensity is crucial. In the case of GRB 980425 the GRB and the SN energies are comparable, and no dominance of one source over the other can be ascertained. In the case of GRB 030329 the energy of the GRB source is \( 10^3 \) larger than the SN: in no way the GRB can originate from the SN event.

The above stringent energetics considerations and the fact that GRBs occur also without an observed supernova give a strong evidence that GRBs cannot originate from supernovae.

**URCA-1 and URCA-2**

We turn now to the most exciting search for the nature of URCA-1 and URCA-2. We have already mentioned above that a variety of possibilities naturally appear. The first possibility is that the URCA sources are related to the black hole originating the GRB phenomenon. In order to probe such an hypothesis, it would be very important to find even a single case in which an URCA source occurs in association with a GRB and in absence of an associated supernova. Such a result, theoretically unexpected, would open an entire new problematic in relativistic astrophysics and in the physics of black holes.

If indeed, as we expect, the clear association between URCA sources and the supernovae occurring together with the GRBs, then it is clear that the analysis of the other two possibilities will be favored. Namely, an emission from processes occurring in the early phases of the expansion of the supernova remnant or the very exciting possibility that for the first time we are observing a newly born neutron star out of the supernova phenomenon. Of course, this last hypothesis is the most important one, since it would offer new fundamental information about the outcome of the gravitational collapse, about the equations of state at supranuclear densities and about a variety of fundamental issues of relativistic astrophysics of neutron stars. We shall focus in the following only on this last topic.

We have already recalled how the need for a rapid cooling process due to neutrino anti-neutrino emission in the process of gravitational collapse leading to the formation of a neutron star was considered for the first time by George Gamow and Mario Schoenberg in 1941 [157]. It was Gamow who gave this process the name “Urca process”, see and . Since then, a systematic analysis of the theory of neutron star cooling was advanced by Tsuruta [158, 159], Tsuruta and Cameron [160], Tsuruta et al. [161] and Canuto [162]. The coming of age of X-ray observatories such as Einstein (1978-1981), EXOSAT (1983-1986), ROSAT (1990-1998), and the contemporary missions of Chandra and XMM-Newton since 1999 dramatically presented an observational situation establishing very embarrassing and stringent upper limits to the surface temperature of neutron stars in well known historical supernova remnants (see e.g. Romani [163]). It was so that, for some remnants, notably SN 1006 and the Tycho supernova, the upper limits to the surface temperatures were significantly lower than the temperatures given by standard cooling times (see e.g. Romani [163]). Much of the theoretical works has been mainly directed, therefore, to find theoretical arguments in order to explain such low surface temperature \( T \sim 0.5–1.0 \times 10^8 \text{ K} \) — embarrassingly low, when compared to the initial hot \( (\sim 10^{11} \text{ K}) \) birth of a neutron star in a supernova explosion (see e.g. Romani [163]). Some very important steps in this direction of research have been represented by the works of Van Riper [164, 165], Lattimer and his group [166, 167] and by the most extensive work of Yakovlev and his group [168]. The youngest neutron star to be searched for using its thermal emission in this context has been the pulsar PSR J0205+6449 in 3C 58 (see e.g. Yakovlev and Pethick [168]), which is 820 years old! Recently, evidence for the detection of thermal emission from the crab nebula pulsar was reported by Trumper [169] which is, again, 951 years old.

In the case of URCA-1 and URCA-2, we are exploring a totally different regime: the X-ray emission possibly from a recently born neutron star in the first days – months of its existence, where no observations have yet been performed.
and no embarrassing constraints upper limits on the surface temperature exist. The reason of approaching first the issue
of the thermal emission from the neutron star surface is extremely important, since in principle it can give information
on the equations of state in the core at supranuclear densities and on the detailed mechanism of the formation of the
neutron star itself and the related neutrino emission. It is of course possible that the neutron star is initially fast rotating
and its early emission is dominated by the magnetospheric emission or by accretion processes from the remnant which
would overshadow the thermal emission. In that case a periodic signal related to the neutron star rotational period
should in principle be observable in a close enough GRB source provided the suitable instrumentation from the Earth.

The literature on young born neutron star is relatively scarce today. There are some very interesting contributions
which state: “The time for a neutron star’s center to cool by the direct URCA process to a temperature $T$ has been
estimated to be $t = 20 \left[ T / \left(10^8 K\right) \right]^{-4}$ s. The direct URCA process and all the exotic cooling mechanisms only occur
at supranuclear densities. Matter at subnuclear densities in neutron star crust cools primarily by diffusion of heat to the
interior. Thus the surface temperature remains high, in the vicinity of $10^8$ K or more, until the crust’s heat reservoir is
consumed. After this diffusion time, which is on the order of 1–100 years, the surface temperature abruptly plunges to
values below $5 \times 10^5$ K” (Lattimer et al. [167]). “Soon after a supernova explosion, the young neutron star has large
temperature gradients in the inner part of the crust. While the powerful neutrino emission quickly cools the core, the
crust stays hot. The heat gradually flows inward on a conduction time scale and the whole process can be thought of
as a cooling wave propagation from the center toward the surface” (Gnedin et al. [170]).

The two considerations we have quoted above are developed in the case of spherical symmetry and we would like to
keep the mind open, in this new astrophysical field, to additional factors, some more traditional than others, to be taken
into account. Among the traditional ones we recall: 1) the presence of rotation and magnetic field which may affect
the thermal conductivity and the structure of the surface, as well as the above mentioned magnetospheric emission;
2) there could be accretion of matter from the expanding nebula; and, among the nontraditional ones, we recall 3)
some exciting theoretical possibilities advanced by Dyson on volcanoes on neutron stars [171] as well as iron helide
on neutron star [172], as well as the possibility of piconuclear reactions on neutron star surface discussed in Lai &
Salpeter [173].

All the above are just scientific arguments to attract attention on the abrupt fall in luminosity reported in this meeting
on URCA-1 by Elena Pian which is therefore, in this light, of the greatest scientific interest and further analysis should
be followed to check if a similar behavior will be found in future XMM and Chandra observations also in URCA-2.

**Astrophysical implications**

In addition to these very rich problematics in the field of theoretical physics and theoretical astrophysics, there are
also more classical astronomical and astrophysical issues, which will need to be answered if indeed the observations
of a young neutron star will be confirmed. An important issue to be addressed will be how the young neutron star can
be observed, escaping from being buried under the expelled matter of the collapsing star. A possible explanation can
originate from the binary nature of the newly born neutron star: the binary system being formed by the newly formed
black hole and the triggered gravitational collapse of a companion evolved star leading, possibly, to a “kick” on and
ejection of the newly born neutron star. Another possibility, also related to the binary nature of the system, is that the
supernova progenitor star has been depleted of its outer layer by dynamic tidal effects.

In addition, there are other topics in which our scenario can open new research directions in fundamental physics
and astrophysics:
1) The problem of the instability leading to the complete gravitational collapse of a $\sim 10M_\odot$ star needs the introduction
of a new critical mass for gravitational collapse, which is quite different from the one for white dwarfs and neutron
stars which has been widely discussed in the current literature (see e.g. Giacconi & Ruffini [6]).
2) The issue of the trigger of the instability of gravitational collapse induced by the GRB on the progenitor star
of the supernova or, vice versa, by the supernova on the progenitor star of the GRB needs accurate timing and the
considerations of new relativistic phenomena.
3) The general relativistic instability induced on a nearby star by the formation of a black hole needs some very basic
new developments in the field of general relativity.

Only a very preliminary work exists on this subject, by Jim Wilson and his collaborators, see e.g. the paper by
Mathews and Wilson [174]. The reason for the complexity in answering such a question is simply stated: unlike the
majority of theoretical work on black holes, which deals mainly with one-body solutions, we have to address here a
many-body problem in general relativity. We are starting in these days to reconsider, in this framework, some classic
work by Fermi [175], Hanni and Ruffini [176], Majumdar [177], Papapetrou [178], Parker et al. [179], Bini et al. [180]

which may lead to a new understanding of general relativistic effects relevant to these astrophysical “triptychs”.

The short GRBs

After concluding the problematic of the long GRBs and their vast astrophysical implications, we have turned to

the physics of short GRBs. We first report some progress in the understanding the dynamical phase of collapse, the

mass-energy formula and the extraction of blackholic energy which have been motivated by the analysis of the short

GRBs. In this context progress has also been accomplished on establishing an absolute lower limit to the irreducible

mass of the black hole as well as on some critical considerations about the relations of general relativity and the

second law of thermodynamics. We recall how this last issue has been one of the most debated in theoretical physics

in the past thirty years due to the work of Bekenstein and Hawking. Following these conceptual progresses we analyze

the vacuum polarization process around an overcritical collapsing shell. We evidence the existence of a separatrix

and a dyadosphere trapping surface in the dynamics of the electron-positron plasma generated during the process

of gravitational collapse. We then analyze, using recent progress in the solution of the Vlasov-Boltzmann-Maxwell

system, the oscillation regime in the created electron-positron plasma and their rapid convergence to a thermalized

spectrum. We conclude by making precise predictions for the spectra, the energy fluxes and characteristic time-scales

of the radiation for short-bursts.

Short GRBs as cosmological candles

The characteristic spectra, time variabilities and luminosities of the electromagnetic signals from collapsing overcrit-

cical stellar cores have been derived from first principles, and they agree with preliminary observations of short-bursts

[19]. Hopefully new space missions will be planned, with temporal resolution down to fractions of μs and higher

collecting area and spectral resolution than at present, in order to verify the detailed agreement between our model and

the observations. It is now clear that if our theoretical predictions will be confirmed, we will have a very powerful tool

for cosmological observations: the independent information about luminosity, time-scale and spectrum can uniquely

determine the mass, the electromagnetic structure and the distance from the observer of the collapsing core, see e.g.

Fig. 43 and Ref. [54]. In that case short-bursts, in addition to give a detailed information on all general relativistic and

relativistic field theory phenomena occurring in the approach to the horizon, may also become the best example of

standard candles in cosmology [181]. We are currently analyzing the introduction of baryonic matter in the optically

thick phase of the expansion of the electron-positron plasma, within this detailed time-varying description of the gravitational

collapse, which may affect the structure of the Proper-GRB (P-GRB) [13] as well as the structure of the long-bursts

[28].

On the dyadosphere of Kerr-Newman black holes

An interesting proposal was advanced in 2002 [182] that the $e^+e^-$ plasma may have a fundamental role as well in the

physical process generating jets in the extragalactic radio sources. The concept of dyadosphere originally introduced

in Reissner-Nordström black hole in order to create the $e^+e^-$ plasma relevant for GRBs can also be generalized to the

process of vacuum polarization originating in a Kerr-Newman black hole due to magneto-hydrodynamical process of

energy extraction (see e.g. [183] and references therein). The concept therefore introduced here becomes relevant for

both the extraction of rotational and electromagnetic energy from the most general black hole [11].

* * *

After the completion of these lectures, we have become aware that Ghirlanda et al. [184] have given evidence for

the existence of an exponential cut off at high energies in the spectra of short bursts. We are currently comparing and

contrasting these observational results with the predicted cut off in Fig. 42 which results from the existence of the

separatrix introduced in [49]. The observational confirmation of the results presented in Fig. 42 would lead for the first
time to the identification of a process of gravitational collapse and its general relativistic self-closure as seen from an asymptotic observer.

ACKNOWLEDGMENTS

We are thankful to Charles Dermer, Hagen Kleinert, Tsvi Piran, Andreas Ringwald, Rashid Sunyaev, Lev Titarchuk, Jim Wilson and Dima Yakovlev for many interesting theoretical discussions, as well as to Lorenzo Amati, Lucio Angela Antonelli, Enrico Costa, Filippo Frontera, Luciano Nicastro, Elena Pian, Luigi Piro, Marco Tavani and all the BeppoSAX team for assistance in the data analysis.

THE NUMERICAL INTEGRATION OF THE HYDRODYNAMICS AND THE RATE EQUATIONS IN THE LIVERMORE CODE

The hydrodynamics and the rate equations for the plasma of $e^+ e^-$-pairs

The evolution of the $e^+ e^-$-pair plasma generated in the dyadosphere has been treated in two papers [55, 59]. We recall here the basic governing equations in the most general case in which the plasma fluid is composed of $e^+ e^-$-pairs, photons and baryonic matter. The plasma is described by the stress-energy tensor

\[ T^{\mu\nu} = p g^{\mu\nu} + (p + \rho) U^{\mu} U^{\nu}, \]

where $p$ and $\rho$ are respectively the total proper energy density and pressure in the comoving frame of the plasma fluid and $U^\mu$ is its four-velocity, satisfying

\[ g_{\mu\nu} (U^\mu)^2 + g_{\nu\alpha} (U^\nu)^2 = -1, \]

where $U^\mu$ and $U^\nu$ are the radial and temporal contravariant components of the 4-velocity and

\[ d^2 s = g_{\nu\alpha}(r)d^2 r + g_{\nu\alpha}(r)d^2 \theta + r^2 \sin^2 \theta d^2 \phi, \]

where $g_{\nu\alpha}(r) \equiv -\alpha^2(r)$ and $g_{\nu\alpha}(r) = \alpha^2(r)$.

The conservation law for baryon number can be expressed in terms of the proper baryon number density $n_B$

\[ (n_B U^\mu)_\mu = g^{-1/2} (g^{1/2} n_B U^\nu)_\nu = (n_B U^\nu)_\nu + \frac{1}{r^2} (r^2 n_B U^\nu)_r = 0. \]

The radial component of the energy-momentum conservation law of the plasma fluid reduces to

\[ \frac{\partial p}{\partial r} + \frac{1}{r} \frac{\partial}{\partial r} \left( (p + \rho) U^r U_r \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 (p + \rho) U^\nu U_r \right) - \frac{1}{2} (p + \rho) \left[ \frac{\partial g_{\nu\alpha}}{\partial r} (U^\nu)^2 + \frac{\partial g_{\nu\alpha}}{\partial r} (U^\alpha)^2 \right] = 0. \]

The component of the energy-momentum conservation law of the plasma fluid equation along a flow line is

\[ U_\mu (T^{\mu \nu})_\nu = -(\rho U^\nu)_\nu - p (U^\nu)_\nu, \]

\[ = -g^{-1/2} (g^{1/2} \rho U^\nu)_\nu - g^{-1/2} (g^{1/2} U^\nu)_\nu, \]

\[ = (\rho U^\nu)_\nu + \frac{1}{r^2} (r^2 \rho U^\nu)_\nu, \]

\[ + p (U^\nu)_\nu + \frac{1}{r^2} (r^2 U^\nu)_r = 0. \]

We define also the total proper internal energy density $\varepsilon$ and the baryonic mass density $\rho_B$ in the comoving frame of the plasma fluid,

\[ \varepsilon \equiv \rho - \rho_B, \quad \rho_B \equiv n_B mc^2. \]
The numerical integration

A computer code [185, 186] has been used to evolve the spherically symmetric general relativistic hydrodynamic equations starting from the dyadosphere [55].

We define the generalized gamma factor $\gamma$ and the radial 3-velocity in the laboratory frame $V_r$

$$\gamma \equiv \sqrt{1 + U_r U_r}, \quad V_r' \equiv \frac{U_r'}{U_r}.$$  \hspace{1cm} (135)

From Eqs.(130, 129), we then have

$$(U_r')^2 = - \frac{1}{g_{tt}} (1 + g_{rr}(U_r)^2) = 1 \alpha^2 \gamma^2.$$  \hspace{1cm} (136)

Following Eq.(134), we also define

$$E \equiv \epsilon \gamma, \quad D \equiv \rho B \gamma, \quad \tilde{\rho} \equiv \rho \gamma$$

so that the conservation law of baryon number (131) can then be written as

$$\frac{\partial D}{\partial t} = - \alpha \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha^2} D V_r \right).$$  \hspace{1cm} (138)

Eq.(133) then takes the form,

$$\frac{\partial E}{\partial t} = - \alpha \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} E V_r \right) - \alpha \frac{\partial p}{\partial r} - \alpha \frac{(M_r^2 - Q^2 r^3)}{\gamma} \left( D + \Gamma E \right) \left( \frac{\gamma}{\alpha} \right)^2 + \left( U_r' \right)^2.$$  \hspace{1cm} (139)

Defining the radial momentum density in the laboratory frame

$$S_r \equiv \alpha (p + \rho) U_r U_r = (D + \Gamma E) U_r,$$  \hspace{1cm} (140)

we can express the radial component of the energy-momentum conservation law given in Eq.(132) by

$$\frac{\partial S_r}{\partial t} = - \alpha \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} S_r V_r \right) - \alpha \frac{\partial p}{\partial r}$$

$$- \frac{\alpha}{2} (p + \rho) \left( \frac{\partial g_{tt}}{\partial r} (U_r')^2 + \frac{\partial g_{rr}}{\partial r} (U_r)^2 \right)$$

$$= - \alpha \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} S_r V_r \right) - \alpha \frac{\partial p}{\partial r}$$

$$- \alpha \left( \frac{M_r^2 - Q^2}{\gamma} \right) \left( D + \Gamma E \right) \left( \frac{\gamma}{\alpha} \right)^2 + \left( U_r' \right)^2.$$  \hspace{1cm} (141)

In order to determine the number-density of $e^+ e^-$ pairs, we use the pair rate equation. We define the $e^+ e^-$ pair density in the laboratory frame $N_{\pm} \equiv \gamma n_{\pm}$ and $N_{\pm}(T) \equiv \gamma n_{\pm}(T)$, where $n_{\pm}(T)$ is the total proper number density of pairs in comoving frame at thermodynamic equilibrium with temperature $T$ in the process $e^+ e^- \rightarrow \gamma + \gamma$ ($n_{\pm}(m,T) = n_{\pm}(T)$). $n_{\pm}$ is the total proper number density of pairs in comoving frame at a generic time before reaching the equilibrium. We write the rate equation in the form

$$\frac{\partial N_{\pm}}{\partial t} = - \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} N_{\pm} V_r \right) + \frac{\sigma v}{\alpha} (N_{\pm}^2(T) - N_{\pm}^2)/\gamma^2.$$  \hspace{1cm} (142)

These equations are integrated starting from the dyadosphere distributions given in Fig. 17 (Right) in [28] and assuming as usual ingoing boundary conditions on the horizon of the black hole.
THE NUMERICAL INTEGRATION OF THE HYDRODYNAMICS AND THE RATE EQUATIONS IN THE ROME CODE

Era I: expansion of PEM-pulse

After the explosion from the dyadosphere a thermal plasma of $e^+ e^-$ pairs and photons optically thick with respect to scattering processes begins to expand at ultrarelativistic velocity. In this era the expansion takes place in a region of very low baryonic contamination.

Recalling that the local number density of electron and positron pairs created as a function of radius is given by

$$n_{e^+ e^-}(r) = \frac{Q}{4\pi \rho_0^2} \left[1 - \left(\frac{r}{r_0}\right)^2\right],$$

(143)

the limit on such baryonic contamination, where $\rho_0$ is the mass-energy density of baryons, is given by

$$\rho_{B_e} \ll m_e \cdot 2 \cdot 10^8 \left(\frac{r_0}{\rho_0}\right)^2 \left(\frac{r}{r_0}\right)^2 (g/cm^3).$$

(144)

Near the horizon $r \sim r_+, \text{this gives}$

$$\rho_{B_e} \ll m_e n_{e^+ e^-}(r) = 1.86 \cdot 10^{14} \left(\frac{r}{\rho_0}\right)^2 (g/cm^3),$$

(145)

and near the radius of the dyadosphere $r_{dI}$:

$$\rho_{B_e} \ll m_e n_{e^+ e^-}(r) = 3.2 \cdot 10^8 \left(\frac{r}{r_{dI}}\right)^2 (g/cm^3).$$

(146)

Such conditions can be easily satisfied in the collapse to a black hole, but not necessarily in a collapse to a neutron star.

Consequently we have solved the equations governing a plasma composed solely of $e^+ e^-$ pairs and electromagnetic radiation, starting at time zero from the dyadosphere configurations corresponding to constant density in Fig. 44.

The plasma of $e^+ e^-$ pairs and photons is described by the covariant energy-momentum tensor:

$$T^{\mu \nu} = pg^{\mu \nu} + (p + p) U^{\mu} U^{\nu} + \Delta T^{\mu \nu}$$

(147)

where $p$ and $\rho$ are respectively total proper energy density and pressure in the comoving system; $U^{\mu}$ are contravariant components of 4-velocity and $\Delta T^{\mu \nu}$ takes into account of dissipative effects due to heat conduction and viscosity, but in this treatment it has been neglected. In general we have $g_{\mu \nu} U^{\mu} U^{\nu} = -1$. For a spherically symmetric motion this reduces to $g_{tt}(U^t)^2 + g_{rr}(U^r)^2 = -1$, where $U^t$ and $U^r$ are respectively temporal and radial contravariant components of 4-velocity $U^\mu$.

It is assumed that the gravitational interaction with central black hole is negligible with respect to the total energy of PEM-pulse such that a fluid expansion with special relativistic equations can be considered. Moreover it is assumed that photons remain trapped inside fireball until complete transparency, i.e. the emission of electromagnetic radiation is negligible during the first phases of expansion, being therefore adiabatic [55]. This assumption is valid until the photon mean free path is negligible with respect to the thickness of pulse.

The thermodynamic quantities used to describe the process are the total proper internal energy density of pulse $\varepsilon$, given by $\varepsilon = \varepsilon_e + \varepsilon_e + \varepsilon_T$, where $\varepsilon_e$ is total proper internal energy density of electrons (positrons) and $\varepsilon_T$ of photons. The proper number density of pairs $n_{e^+ e^-}$, if the system is in thermodynamic equilibrium initially at temperature $T$ of order $T \sim MeV$, enough for $e^+ e^-$ pair creation, equals the proper number density of photons $n_T$. This is not valid at lower temperature [156]. The pressure $p = p_e + p_e + p_T$, where $p_e$ and $p_T$ is electrons and positrons pressures and $p_T$ is photons pressure. The system is highly relativistic, so the equation of state $p = \varepsilon/3$ can be considered valid. This equation of state is represented with thermal index $\Gamma$:

$$\Gamma = 1 + \frac{p}{\varepsilon},$$

(148)

241
Figure 44. Three different dyadospheres corresponding to the same value and to different values of the two parameters $\mu$ and $\xi$ are given. The three different configurations are markedly different in their spatial extent as well as in their energy-density distribution (see text).
Fermi integrals

Thermodynamical quantities before introduced are expressed in terms of integrals over Bose distribution for photons and Fermi distribution for $e^+e^-$ pairs with zero chemical potentials $\mu_e$ and $\mu_{e^\mp}$. We begin from the reaction $e^+ + e^- \rightarrow \gamma + \gamma$. From statistical mechanics it is known that given a thermodynamic system at temperature $T$ kept inside a volume $V$ and made of a number of particle variable $N$, the thermodynamic equilibrium is expressed by the condition that the potential free energy of Helmholtz $F (T, V, N)$ is stationary with respect to $N$ variations:

$$
\left( \frac{\partial F}{\partial N} \right)_T = 0; \tag{149}
$$

by definition chemical potential $\mu$ is given by

$$
\mu = \left( \frac{\partial F}{\partial N} \right)_T; \tag{150}
$$

so that for a system made by a photon gas at equilibrium with matter with respect to creation and adsorption processes, we have $\mu_\gamma = 0$ [187]. Therefore the chemical potential of electrons and positrons associated to reaction $e^+ + e^- \rightarrow \gamma + \gamma$ is equal and opposite: $\mu_{e^-} = -\mu_{e^+} = \mu$; moreover also $\mu$ must be zero since the total electric charge of fireball is zero: if $Q$ is total electric charge of fireball, we have

$$
Q = e \left[ n_{e^-} (m, T, \mu) - n_{e^+} (m, T, -\mu) \right] = 0 \tag{151}
$$

where $n_{e^\pm} (m, T, \mu)$ is given by

$$
n_{e^\pm} (m, T, \mu) = \frac{aT^3 7 \frac{1}{k}}{8 \frac{\sqrt{\pi}}{A}} \int_0^{\ln m/kT} \frac{e^{-z}}{e^{1/2} \pm \frac{\sqrt{2 \pi m^2 kT^2}}{e^{1/2}}} dz; \tag{152}
$$

so $\mu = 0$.

In the following the expressions of thermodynamical quantities as Fermi integrals are listed. The proper number density of electrons [188] is given by

$$
n_{e^-} (m, T, \mu_{e^-}) = \frac{2}{h^3} \int \frac{d^3 p}{\sqrt{\left[ p^2 + (mc^2)^2 \right]^2}} = \frac{8\pi}{h^3} \int_0^{\ln m/kT} \frac{p^2}{e^{1/2} \pm \frac{\sqrt{2 \pi m^2 kT^2}}{e^{1/2}}} dp = \frac{aT^3 7 \frac{1}{k}}{8 \frac{\sqrt{\pi}}{A}} \int_0^{\ln m/kT} \frac{e^{-z}}{e^{1/2} \pm \frac{\sqrt{2 \pi m^2 kT^2}}{e^{1/2}}} dz, \tag{153}
$$

where $z = pc/kT$, $m$ is the electron mass, $T[\text{MeV}]$ is the temperature of fireball in comoving frame, $a$ is a constant given by $a = 8\pi^3 k^4/15h^3 \epsilon_3 = 1.37 \cdot 10^{26} \text{erg} \cdot \text{cm}^3 \text{MeV}^{-2}$, $k$ is the Boltzmann constant and $A = (7/4)(\pi^2/15)$ is a numerical constant introduced for convenience.

Since the thermodynamic equilibrium is assumed and in all cases considered the initial temperature is larger than $e^+e^-$ pairs creation threshold ($T = 1 \text{ MeV}$), the proper number density of electrons is roughly equal to that of photons:

$$
n_{e^-} \sim n_{e^-} (T) \sim n_T (T); \tag{154}
$$

in these conditions the number of particles is conserved:

$$
(n_{e^-} U^p)_{\mu} = 0. \tag{155}
$$

Later on, for $T \ll 1 \text{ MeV}$ (see Fig. 45), $e^+e^-$ pairs go on in annihilation but can not be created anymore, therefore

$$
n_T (T) > n_{\gamma} > n_{e^\pm} (T) \tag{156}
$$
Figure 45. Temperature in comoving system as a function of emission time for different values of black hole mass $\mu$.

as shown in Fig. 46.

The total proper internal energy density for photons is given by

$$
\varepsilon_\gamma = \frac{2}{\hbar^3} \int \frac{h \nu}{e^{\hbar \nu/kT} - 1} d^3 p = aT^4
$$

where $p = h\nu/c$. The total proper internal energy density for electrons is given by:

$$
\varepsilon_e^e = \frac{2}{\hbar^3} \int \frac{\sqrt{\left(p/c\right)^2 + \left(mc^2/kT\right)^2}}{e^{\sqrt{\left(p/c\right)^2 + \left(mc^2/kT\right)^2}} - 1} d^3 p = aT^4 \frac{71}{4A} \int_0^\infty \frac{z^2}{e^{z^2 + (mc^2/kT)^2}} dz
$$

(157)
where \( z = pc/kT \) and the integral is computed numerically. Therefore the total proper internal energy density of the PEM-pulse, summing up all the contributions of photons and \( e^+e^- \) pairs, is given by

\[
\epsilon_{\text{tot}} = aT^4 \left[ 1 + \frac{7}{4A} \int_0^{\infty} \frac{z^2 \sqrt{z^2 + (mc^2/kT)^2}}{e^{\sqrt{z^2 + (mc^2/kT)^2}} + 1} \, dz \right]
\]

(159)

where the factor 2 in front of the integral takes into account of electrons and positrons.

About the pressure of the photons it holds

\[
p_\gamma = \frac{\epsilon_{\gamma}}{3} = \frac{aT^4}{3};
\]

(160)
and about the pressure of electrons

\[
p_{e^-} = \frac{2}{3h^3} \int e^{\sqrt{\frac{(pc)^2}{mc^2} + \frac{(mc^2)^2}{kT}}} + 1 \sqrt{(pc)^2 + (mc^2)^2} d^3 p =
\]

\[
= 8\pi \int_0^{\infty} \int_0^{\infty} \sum_0^{\infty} \frac{p^2}{e^{\sqrt{\frac{(pc)^2}{mc^2} + \frac{(mc^2)^2}{kT}}} + 1} \frac{(pc)^2}{(pc)^2 + (mc^2)^2} dp =
\]

\[
= \frac{a}{4} \int_0^{\infty} \int_0^{\infty} \sum_0^{\infty} \frac{z^4}{e^{\sqrt{z^2 + (me^2/kT)^2}} + 1} \frac{1}{\sqrt{z^2 + (me^2/kT)^2}} dz.
\]

(161)

Therefore the total pressure of PEM-pulse is given by

\[
p_{tot} = \frac{a}{4} \int_0^{\infty} \int_0^{\infty} \sum_0^{\infty} \frac{z^4}{e^{\sqrt{z^2 + (me^2/kT)^2}} + 1} \frac{1}{\sqrt{z^2 + (me^2/kT)^2}} dz.
\]

(162)

**Numerical code**

In the following we recall a zeroth order approximation of the fully relativistic equations of the previous section [55]:

(i) Since we are mainly interested in the expansion of the \( e^+ e^- \) plasma away from the black hole, we neglect the gravitational interaction.

(ii) We describe the expanding plasma by a special relativistic set of equations.

In the PEM-pulse phase the expansion in vacuum is described by a set of equations expressing:

- entropy conservation, because of the assumption that emission of electromagnetic radiation is negligible up to transparency;
- energy conservation, because the increase of kinetic energy is compensated by a decrease of total internal energy.

For the expansion of a single shell, the adiabaticity is given by

\[
d(V_\epsilon) + p dV = dE + p dV = 0,
\]

(163)

where \( V \) is the volume of the shell in the comoving frame and \( E = V_\epsilon \) is the total proper internal energy of plasma. By using the equation of state 148 we find

\[
dlnV + \Gamma dlnV = 0
\]

(164)

and, by integrating, we find

\[
\frac{\bar{\Gamma}_0}{\bar{\Gamma}} = \left( \frac{V}{V_0} \right)^\Gamma,
\]

(165)

recalling that the volume of the fireball in the comoving frame is given by \( V = V' \bar{\Gamma} \), where \( V' \) is the volume in the laboratory frame, we find

\[
\frac{\bar{\Gamma}_0}{\bar{\Gamma}} = \left( \frac{V'}{V_0} \right)^\Gamma = \left( \frac{V'}{V_0} \right)^\Gamma \left( \frac{\bar{\Gamma}}{\bar{\Gamma}_0} \right)^\Gamma.
\]

(166)

The total energy conservation of the shell implies [55]:

\[
(\bar{\Gamma} \bar{\epsilon}) V' \bar{\gamma}_0^2 = (\bar{\Gamma} \bar{\epsilon}_0) V \bar{\gamma}_0^2;
\]

(167)

and this gives the evolution for \( \bar{\gamma} \):

\[
\bar{\gamma} = \bar{\gamma}_0 \left( \frac{\epsilon_0}{\epsilon} \right)^\frac{V}{V_0}.
\]

(168)
Substituting this expression for $\bar{\gamma}$ in (166) the final equation for proper internal energy density is found

$$\bar{\varepsilon} = \bar{\varepsilon}_e \left( \frac{\bar{\gamma}_e}{\bar{\tau}} \right)^{\frac{1}{2}}$$  \hspace{1cm} (169)$$

The evolution of a plasma of $e^+e^-$ pairs and photons should be treated by relativistic hydrodynamics equations describing the variation of the number of particles in the process. The 4-vector number density of pairs is defined $(n_{\pm, U^\mu})$, which in the comoving frame reduces to the 4-vector $(n_{\pm, 0,0,0})$. The law of number conservation for pairs is

$$(n_{\pm, U^\mu})_{\mu} = \frac{1}{\sqrt{-g}} \left( \sqrt{-g} n_{\pm, U^\mu} \right)_{\mu} = \left( n_{\pm, U^\mu} \right)_{\mu} + \frac{1}{\sqrt{-g}} \left( r^2 n_{\pm, U^\nu} \right)_{\nu} = 0$$  \hspace{1cm} (170)$$

where $g = g^{\mu \nu}$ is the determinant of the metric. The system processes of creation and annihilation of particles occur due to collisions between particles. If the number of particles is conserved, it holds $(n_{\pm, U^\mu})_{\mu} = 0$; if instead it is not conserved, in the assumptions that only binary collisions between particles occur and in the hypothesis of molecular chaos, the Eq.(170) becomes

$$(n_{\pm, U^\mu})_{\mu} = \sigma_r [n_{\pm, T}(T) n_{\pm, (T) - n_{\pm, 0})]$$  \hspace{1cm} (171)$$

where $\sigma$ is the cross section for the process of creation and annihilation of pairs, given by

$$\sigma = \pi n_e^2 \left[ \frac{\alpha^2 + 4\alpha + 1}{\alpha^2 - 1} \ln \left( \alpha + \sqrt{\alpha^2 - 1} \right) - \frac{\alpha + 3}{\sqrt{\alpha^2 - 1}} \right],$$  \hspace{1cm} (172)$$

with $\alpha = \frac{E}{m_e c}$, $E$ total energy of positrons in the laboratory frame, and $r_e = \frac{e}{mc}$ the classical radius of electron, $v$ is the sound velocity in the fireball

$$v = c \sqrt{\frac{n_e \sigma_r}{\epsilon_{tot}}},$$  \hspace{1cm} (173)$$

and $\sigma_r$ is the mean value of $\sigma_v$; for $\sigma$ we use as a first approximation the Thomson cross section, $\sigma_T = 0.665 \cdot 10^{-24} \text{cm}^2$; $n_{\pm, T}$ is the total proper number density of electrons and positrons in comoving frame at thermodynamic equilibrium in the process $e^+ + e^- \to \gamma + \gamma$ ($n_{\pm, (T)} = n_{\pm, 0}$), $n_{\pm, 0}$ is the total proper number density of electrons and positrons in comoving frame at a generic time before reaching the equilibrium. Using the approximation of special relativity, the 4-velocity is written $U^\mu = (\bar{\gamma}, \bar{\gamma}_e^T)$; substituting to $n_{\pm, T}(T)$ the $\bar{\gamma}$-factor and to $n_{\pm, 0}$ the $\bar{\gamma}_e$-factor, Eq.(171) in hybrid form becomes

$$\frac{\partial (\bar{\gamma} \bar{n}_{\pm, T})}{\partial t} = - \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \bar{\gamma} \bar{n}_{\pm, T} \bar{\gamma}_e^T \right) + \sigma_r (\bar{n}_{\pm, T}^2 - \bar{n}_{\pm, 0}^2),$$  \hspace{1cm} (174)$$

valid for electrons and positrons.

Now we have a complete set of equations for numerical integration: (169), (168) $\varepsilon$ la (174).

If we now turn from a single shell to a finite distribution of shells, we can introduce the average values of the proper internal energy and pair number densities $(\bar{\varepsilon}, \bar{n}_{\pm, \bar{R}})$ for the PEM-pulse, where the average $\bar{\gamma}$-factor is defined by

$$\bar{\gamma} = \frac{1}{\bar{\tau}} \int \bar{\tau}(r) d\bar{\gamma},$$  \hspace{1cm} (175)$$

and $\bar{\gamma}$ is the total volume of the shell in the laboratory frame [55].

In principle we could have an infinite number of possible schemes to define geometry of the expanding shell. Three different possible schemes have been proposed [55]:

- Sphere. An expansion with radial component of 4-velocity proportional to the distance to the black hole $U_r(r) = U_r (\bar{R}(r))$, where $U$ is the radial component of 4-velocity on the external surface of PEM-pulse (having radius $\bar{R}(r)$), the factor $\bar{\gamma}$ from (175) is

$$\bar{\gamma} = \frac{3}{8 U^2} \left[ 2U (1+U^2)^{\frac{1}{2}} - U (1+U^2)^{\frac{1}{2}} - \ln \left( U + \sqrt{1+U^2} \right) \right];$$  \hspace{1cm} (176)$$

this distribution corresponds to a uniform and time decreasing density, like in Friedmann model for the universe;
• Slab 1. An expansion with thickness of fireball constant $\mathcal{D} = r_{ds} - r_{+}$ in laboratory frame in which the black hole is at rest, with $U_{r}(r) = U_{r} \approx \text{const}$ and $\gamma = \sqrt{1 + U_{r}^{2}}$; this distribution does not require an average;

• Slab 2. An expansion with thickness of fireball constant in comoving frame of PEM-pulse.

The result has been compared with the one of hydrodynamic equation in general relativity [55] (see Fig. 47). Excellent agreement has been found with the scheme in which the thickness of fireball is constant in laboratory frame: what happens is that the thickness in comoving frame increases, but due to the Lorentz contraction, it is kept constant in laboratory frame and equal to $\mathcal{D} = (r_{ds} - r_{+})$. In this case $U_{r} = \sqrt{\mathcal{P} - T}$, where $\mathcal{P}$ is computed by conservation equations.

A similar situation occurs for the temperature of PEM-pulse. In the comoving frame the temperature decreases as $T' \sim R^{-1}$, in accordance with results in literature [29]. Since $\gamma$ monotonically increases as $\gamma \sim R$ [13], in laboratory frame $T = \gamma T' \sim \text{constant}$ [59]; photons are blue-shifted in laboratory frame in such away that, at least in the first phase, the temperature measured by an observer at infinity is constant. The numerical value of the temperature of equilibrium at each instant is found by imposing the equivalence, within a certain precision, of (159) numerically computed and (169).

Even if the PEM-pulse is optically thick in the expansion before transparency, photons located at a distance from the external surface less their mean free path can escape and reach the observer at infinity. The mean free path in the comoving frame is given by

$$L_{\mathcal{P}} = \frac{1}{\sigma_{\text{p}} c \gamma} \sim 10^{-6}\text{cm}$$

while in laboratory frame is given by $\lambda = L_{\mathcal{P}}/\gamma \sim 10^{-8}\text{cm}$. However the luminosity emitted at this stage is negligible, since the ratio between $\lambda$ and the thickness of the fireball $\mathcal{D}$ in the laboratory frame (with $\mathcal{D} = (r_{ds} - r_{+}) \sim 10^{6}\text{cm}$) is of the order of $\lambda/\mathcal{D} \simeq 10^{-17}$.

Era II: interaction of the PEM pulse with remnant

The PEM pulse expands initially in a region of very low baryonic contamination created by the process of gravitational collapse. As it moves outside the baryonic remnant of the progenitor star is swept up. The existence of such a remnant is necessary in order to guarantee the overall charge neutrality of the system: the collapsing core has the opposite charge of the remnant and the system as a whole is clearly neutral. The number of extra charges in the baryonic remnant negligibly affects the overall charge neutrality of the PEM pulse.

The baryonic matter remnant is assumed to be distributed well outside the dyadosphere in a shell of thickness $\Delta$ between an inner radius $r_{\text{in}}$ and an outer radius $r_{\text{out}} = r_{\text{in}} + \Delta$ at a distance from the black hole not so big that the PEM pulse expanding in vacuum has not yet reached transparency and not so small that the system will reach enoughly high value of Lorentz $\gamma$ in order not to be stopped in the collision (see Fig. 9). For the sake of an example we choose

$$r_{\text{in}} = 100r_{ds}, \quad \Delta = 10r_{ds}.$$

The total baryonic mass $M_{B} = N_{\text{b}}m_{p}$ is assumed to be a fraction of the dyadosphere initial total energy $E_{\text{dya}}$. The total baryon-number $N_{\text{b}}$ is then expressed as a function of the dimensionless parameter $B$ given by

$$B = \frac{N_{\text{b}} m_{p} c^{2}}{E_{\text{dya}}}.$$  

where $B$ is a parameter in the range $10^{-8} - 10^{-7}$ and $m_{p}$ is the proton mass. We shall see below the role of $B$ in the determination of the features of the GRBs. We saw in section the sense in which $B$ and $E_{\text{dya}}$ can be considered to be the only two free parameters of the black hole theory for the entire GRB family, the so called "long bursts". For the so called "short bursts" the black hole theory depends on the two other parameters $\mu$, $\xi$, since in that case $B = 0$ since most of the energy, unless the whole energy, in the pulse is emitted at transparency. The baryon number density $n_{\text{b}}$ is assumed to be a constant

$$n_{\text{b}} = \frac{N_{\text{b}}}{V_{B}} = \frac{m_{p} n_{\text{e}} c^{2}}{\bar{\rho}_{\text{e}}^{2}}.$$
Figure 47. Lorentz $\bar{\gamma}$ factor as a function of radial coordinate. Three schemes of expansion of PEM-pulse (see text) are compared with solution of hydrodynamics relativistic equations numerically integrated for a black hole with $\mu = 10^3$ and $\xi = 0.1$. The result is in accordance with the scheme of a fireball with constant thickness in laboratory frame.

As the PEM pulse reaches the region $r_{in} < r < r_{out}$, it interacts with the baryonic matter which is assumed to be at rest. In our model we make the following assumptions to describe this interaction:

- the PEM pulse does not change its geometry during the interaction;
- the collision between the PEM pulse and the baryonic matter is assumed to be inelastic,
- the baryonic matter reaches thermal equilibrium with the photons and pairs of the PEM pulse.

These assumptions are valid if: (i) the total energy of the PEM pulse is much larger than the total mass-energy of baryonic matter $M_B$, $10^{-3} < B < 10^{-2}$, (ii) the ratio of the comoving number density of pairs and baryons at the moment of collision $n_{e^+e^-}/n_B$ is very high (e.g., $10^6 < n_{e^+e^-}/n_B < 10^{12}$) and (iii) the PEM pulse has a large value of the gamma factor ($100 < \bar{\gamma}$).

In the collision between the PEM pulse and the baryonic matter at $r_{out} > r > r_{in}$, we impose total conservation of energy and momentum. We consider the collision process between two radii $r_2, r_1$ satisfying $r_{out} > r_2 > r_1 > r_{in}$ and
The amount of baryonic mass acquired by the PEM pulse is

\[ \Delta M = \frac{M_B}{V_B} \frac{4\pi}{3} (r_2^3 - r_1^3), \]  

where \( M_B/V_B \) is the mean-density of baryonic matter at rest.

As for energy density of dyadosphere, here also we choose a simplification for the energy density; in fact during the passage of the shell a deposition of material on the external surface of the fireball creates; however we neglected this effect and assumed that this material after collision diffuses instantaneously in the pulse with a constant density:

\[ n_B' = \frac{N_B'}{V}, \]

where \( N_B' \) is the number of particle of the remnant shell swept up by the pulse and \( V \) is the comoving volume of the fireball.

The conservation of total energy leads to the estimate of the corresponding quantities before (with “\( \circ \)” and after such a collision

\[ (\Gamma e_\circ + \rho_B^\circ) U_\circ^Y + \Delta M = (\Gamma e + \rho_B + \frac{\Delta M}{V}) U^Y, \]

where \( \Delta e \) is the corresponding increase of internal energy due to the collision. Similarly the momentum-conservation gives

\[ (\Gamma e_\circ + \rho_B^\circ) \gamma U_\circ^Y = (\Gamma e + \rho_B + \frac{\Delta M}{V}) \gamma U^Y, \]

where the radial component of the four-velocity of the PEM pulse is \( U^r = \sqrt{\gamma - 1} \) and \( \Gamma \) is the thermal index. We then find

\[ \Delta e = \frac{1}{\Gamma} \left[ (\Gamma e_\circ + \rho_B^\circ) \frac{\gamma U_\circ^Y}{\gamma U^Y} - (\Gamma e + \rho_B + \frac{\Delta M}{V}) \right], \]

\[ \gamma = \frac{a}{\sqrt{a^2 + 1}}, \quad a = \frac{\gamma}{U^r} + \frac{\Delta M}{(\Gamma e_\circ + \rho_B^\circ) \gamma U_\circ^Y}. \]

These equations determine the gamma factor \( \gamma \) and the internal energy density \( \varepsilon = \varepsilon_\circ + \Delta e \) in the capture process of baryonic matter by the PEM pulse.

The effect of the collision of the PEM pulse with the remnant leads to the following consequences:

- a reheating of the plasma in the comoving frame but not in the laboratory frame; an increase of the number of \( e^+e^- \) pairs and of free electrons originated from the ionization of those atoms remained in the baryonic remnant; correspondingly this gives an overall increase of the opacity of the pulse;
- the more the amount of baryonic matter swept up, the more internal energy of the PEMB pulse is converted in kinetic energy of baryons.

By describing the interaction of PEM pulse with remnant as completely inelastic collision of two particles, one can compute by the energy-momentum conservation equation the decrease of Lorentz \( \gamma \) and the increase of internal energy as function of \( B \) parameter and also the ultrarelativistic approximation (\( \gamma \to \infty \)):

1. an abrupt decrease of the gamma factor given by

\[ \gamma_{\text{coll}} = \gamma - \frac{1 + B}{\sqrt{\gamma^2 (2B + B^2) + 1}} \to \gamma_{\infty} = \frac{B + 1}{\sqrt{B^2 + 2B}}, \]

where \( \gamma_{\infty} \) is the gamma factor of the PEM pulse before the collision,

2. an increase of the internal energy in the comoving frame \( \varepsilon_{\text{coll}} \) developed in the collision given by

\[ \frac{E_{\text{coll}}}{E_{\text{dy}}} = \frac{\sqrt{\gamma^2 (2B + B^2) + 1}}{\gamma} - \left( \frac{1}{\gamma} + B \right) \to \gamma_{\infty} - B + \sqrt{B^2 + 2B}. \]
This approximation applies when the final gamma factor at the end of the PEM pulse era is larger than γ_{coll}, right panel in Fig. 9. In this phase of expansion, another thermodynamic quantity has not been considered: the chemical potential μ of the electrons from ionization of baryonic remnant. We remind that the total proper number density of electrons of ionization is given by

\[ n_e^\gamma(m, T, \mu) = \frac{aT^3}{k} \frac{7}{8} \frac{1}{A} \int_0^{\infty} \frac{z^2}{e^{\sqrt{z^2 + m^2/c^2} T^2} + 1} dz \]  

(187)

four equations are imposed to find a formula useful for numerical computation: the first one is the thermodynamical equilibrium of fireball, or

\[ \dot{n}_e^+ (T_c) = \dot{n}_B(T) ; \] 

(188)

where \( 1/2 < Z < 1 \), with \( Z = 1 \) for hydrogen atoms and \( Z = 1/2 \) for baryonic matter in general; the third one derives from the definition of \( B \), and states a relation between the two densities \( \dot{n}_B \) and \( \dot{n}_e^+ \): from definition of \( B \), we have

\[ \frac{N_B}{N_{e^\gamma}(T_c)} = \frac{B E_{dia}}{m_e c^2} \frac{1}{N_{e^\gamma}(T_c)} = 10^b \]  

(190)

where \( T_c \) is the initial temperature of fireball and \( b \) is a parameter (\( 0 < b \)) defined by (190); so if \( V_i \) is the initial volume of dyadosphere and \( w \) the initial volume of the baryonic shell

\[ \dot{n}_B = 10^b \dot{n}_e^+ (T_c) V_i \]  

(191)

finally the fourth one is the conservation law of baryonic matter

\[ (\dot{n}_e^+, U^\mu)_{e^\gamma} = 0. \] 

(192)

Therefore the chemical potential \( \mu \) is numerically determined at a certain time of expansion if the initial temperature \( T_c \) of fireball and the initial volume of baryonic shell \( w \) are known and, at that time, the volume \( V_i \), the temperature \( T \) and the Lorentz factor \( \gamma \) of the fireball, the volume of the baryonic shell swept up \( vb \) and the ratio \( \dot{n}_e^+ (T) \) of \( \dot{n}_e^+ (T_c) ; \)

\[ 2 \zeta(3) Z^1 10^b \frac{\dot{n}_e^+ (T)}{\dot{n}_e^+ (T_c)} \frac{T_0^3 w}{T^3 V \gamma} \left( \frac{vb}{w} \right) = \int_0^1 \frac{z^2}{e^{\sqrt{z^2 + (mc^2/c)^2} T^2} + 1} \frac{dz}{z} \] 

(193)

where the factor in brackets \( (\frac{vb}{w}) \) must be considered only for \( r > r_{out} \), while the proportionality factor is the function zeta of Riemann \( \zeta(3) \) for computation of \( n_p \), with \( \zeta(3) = 1.202 \).

Therefore the equations for this phase are (185), (186), (182), (174) and (193).

**Era III: expansion of PEMB pulse**

After the engulfment of the baryonic matter of the remnant the plasma formed of \( e^+ e^- \) -pairs, electromagnetic radiation and baryonic matter expands again as a sharp pulse, namely the PEMB pulse. The calculation is continued as the plasma fluid expands, cools and the \( e^+ e^- \) pairs recombine until it becomes optically thin:

\[ \int dr (\dot{n}_e^+ + \dot{Z}_e^+ \sigma_T) \simeq O(1), \] 

(194)

where \( \sigma_T = 0.665 \cdot 10^{-25} \text{cm}^2 \) is the Thomson cross-section and the integration is over the radial interval of the PEMB pulse in the comoving frame. In order to study the PEMB pulse evolution the validity of the slab approximation adopted for the PEM pulse phase has to be verified; otherwise the full hydrodynamics relativistic equations should be integrated. The PEMB pulse evolution firstly has been simulated by integrating the general relativistic hydrodynamical
equations with the Livermore codes, for a total energy in the dyadosphere of $3.1 \times 10^{54}$ erg and a baryonic shell of thickness $\Delta = 10 r_{\odot}$ at rest at a radius of $100 r_{\odot}$ and $B \approx 1.3 \cdot 10^{-5}$.

In analogy with the special relativistic treatment for the PEM pulse, presented in section (see also [55]), for the adiabatic expansion of the PEMB pulse in the constant-slab approximation described by the Rome codes the following hydrodynamical equations with $\bar{\rho}_B \neq 0$ has been found

\[ \frac{\dot{\bar{\rho}}_B}{\bar{\rho}_B} = \frac{V}{\bar{V}} \frac{\dot{\gamma}}{\gamma}, \]
\[ \frac{\dot{\bar{\epsilon}}}{\bar{\epsilon}} = \left( \frac{V}{\bar{V}} \right)^\gamma \left( \frac{\dot{\gamma}}{\bar{\gamma}} \right)^\Gamma, \]
\[ \dot{\gamma} = \frac{\bar{\gamma}}{\gamma} \left( \frac{(\bar{\gamma} + \bar{\rho}_B)\bar{\gamma}}{(\bar{\gamma} + \rho_B)\gamma} \right), \]
\[ \frac{\partial}{\partial t} (N_d) = -N_d \frac{1}{\gamma} \frac{\partial \gamma}{\partial t} + \frac{1}{\gamma} \frac{\partial (N_d^2 (T) - N_d^2)}{\partial t}. \]

In these equations ($r > r_{\text{rad}}$) the comoving baryonic mass and number densities are $\dot{\bar{\rho}}_B = M_B/V$ and $\dot{\bar{\rho}}_B = N_B/V$, where $V$ is the comoving volume of the PEMB pulse.

The result is shown in Fig. 48 [59] where the bulk gamma factor as computed from the Rome and Livermore codes are compared and very good agreement has been found. This validates the constant-thickness approximation in the case of the PEMB pulse as well. On this basis we easily estimate a variety of physical quantities for an entire range of values of $B$.

For the same black hole different cases have been considered [59]. The results of the integration show that for the first parameter range the PEMB pulse propagates as a sharp pulse of constant thickness in the laboratory frame, but already for $B \approx 1.3 \cdot 10^{-5}$ the expansion of the PEMB pulse becomes much more complex, turbulence phenomena can not be neglected any more and the constant-thickness approximation ceases to be valid.

It is also interesting to evaluate the final value of the gamma factor of the PEMB pulse when the transparency condition given by Eq.(194) is reached as a function of $B$, see Fig. 49. For a given black hole, there is a maximum value of the gamma factor at transparency. By further increasing the value of $B$ the entire $E_{\text{shfl}}$ is transferred into the kinetic energy of the baryons (see also [59]).

In Fig. 49Left we plot the gamma factor of the PEMB pulse as a function of radial distance for different amounts of baryonic matter. The diagram extends to values of the radial coordinate at which the transparency condition given by Eq.(194) is reached. The “asymptotic” gamma factor

\[ \bar{\gamma}_{\text{asym}} = \frac{E_{\text{shfl}}}{B \gamma c^2} \]

is also shown for each curve. The closer the gamma value approaches the “asymptotic” value (199) at transparency, the smaller the intensity of the radiation emitted in the burst and the larger the amount of kinetic energy left in the baryonic matter (see Fig. 49Right).

**ON URCA PROCESS**

From G. Gamow [189]:

“The summer of 1939 I spent with my family vacation on the Copacabana beach in Rio de Janeiro. One evening, visiting the famous Casino da Urca to watch the gamblers, I was introduced to a young theoretical physicist born on an Amazon River plantation, named Mario Schoenberg. We became friends, and I arranged for him a Guggenheim visiting the famous Casino da Urca to watch the gamblers, I was introduced to a young theoretical physicist born on

![](attachment:formula.png)

The summer of 1939 I spent with my family vacation on the Copacabana beach in Rio de Janeiro. One evening, visiting the famous Casino da Urca to watch the gamblers, I was introduced to a young theoretical physicist born on an Amazon River plantation, named Mario Schoenberg. We became friends, and I arranged for him a Guggenheim fellowship to spend a year in Washington to work with me in nuclear astrophysics. His visit was very successful, and we hit upon a process which could be responsible for the vast stellar explosions known as supernovae. The trick is done by alternative absorption and reemission of one of the thermal electrons in the very hot (billions of degrees!) stellar interior by various atomic nucleai. Both processes are accompanied by the emission of neutrinos and antineutrinos which, possessing tremendous penetrating power, pass through the body of a star like a swarm of mosquitoes through chicken wire and carry with them large amount of energy. Thus, the stellar interior cools rapidly, the pressure drops, and the stellar body collapse with a great explosion of light and heat.
Figure 48. Lorentz $\gamma$ factor as a function of radial coordinate from the PEMB-pulse simulation is compared with the $\gamma$ factor as solution of hydrodynamics relativistic equations numerically integrated (open squares) for $E_{\text{dya}} = 3.1 \times 10^{54}$ erg and $B = 1.3 \times 10^{-4}$, $r_0 = 100 r_{\text{ds}}$ and $\Delta = 10 r_{\text{ds}}$. The result is in accordance with the scheme of a fireball with constant thickness in laboratory frame which is valid up to $B = 10^{-2}$.

All this is too complicate to explain in non technical words, and I am mentioning it only as background for how we came to give that process is name. We called it the Urca process, partially to commemorate the casino in which we first met, and partially because the Urca process results in a rapid disappearance of thermal energy from the interior of the star, similar to the rapid disappearance of money from the pockets of the gamblers of the Casino d’Urca. Sending our article “On the Urca process” for publication on the physical review I was worried that the Editor would ask why we called the process “Urca”. After much thought I decided to say that this is short for “UnRecordable Cooling Agent”, but they never asked. Today, there are other known cooling processes involving neutrinos which work even faster than the Urca process. For example, a neutrino pair can be formes instead of two gamma quanta in the annihilation of a positive and negative electrons"
Figure 49. Left) The gamma factors are given as functions of the radius in units of the dyadosphere radius for selected values of $B$ for the typical case $E_{\text{dya}} = 3.1 \times 10^{54}$ erg. The asymptotic values $\gamma_{\text{asy}} = E_{\text{dya}}/(MBc^2) = 10^4, 10^3, 10^2$ are also plotted. The collision of the PEM pulse with the baryonic remnant occurs at $r/r_{\text{ds}} = 100$ where the jump occurs. Right) The $\gamma$ factor (the solid line) at the transparency point is plotted as a function of the $B$ parameter. The asymptotic value (the dashed line) $E_{\text{dya}}/(MBc^2)$ is also plotted.
REFERENCES

105. Israel, W., 1966, Nuovo Cimento B, 44, 1
Attachment 6
Evidence for isotropic emission in GRB991216

R. Ruffini a,b,*, M.G. Bernardini a,b, C.L. Bianco a,b, P. Chardonnet a,c, F. Fraschetti a,d, S.-S. Xue a,b

a ICRA, International Center for Relativistic Astrophysics, Dip. Fisica, Univ. Roma "La Sapienza", P.le A. Moro 5, 00185 Roma, Italy
b Dip. Fisica, Univ. Roma "La Sapienza", P.le A. Moro 5, 00185 Roma, Italy
c Univ. Savoie, LAPTH – LAPP, BP 110, 74941 Annecy-le-Vieux Cedex, France
d Univ. Trento, Via Sommarive 14, 38050 Povo (Trento), Italy

Received 11 March 2005; received in revised form 19 May 2005; accepted 19 May 2005

Abstract

The issue of the possible presence or absence of jets in GRBs is here re-examined for GRB991216. We compare and contrast our theoretically predicted afterglow luminosity in the 2–10 keV band for spherically symmetric versus jetted emission. At these wavelengths the jetted emission can be excluded and data analysis confirms spherical symmetry. These theoretical fits are expected to be improved by the forthcoming data of the Swift mission.

© 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: Gamma-ray bursts; Radiation mechanisms: thermal; Black hole physics

1. Introduction

We recall that the determination of the presence or absence of jets in Gamma-Ray Burst (GRB) afterglows is examined for GRB 991216 in which a narrow half-opening beaming angle \( \theta_n = 3^\circ \) has been claimed (Halpern et al., 2000). We show that the afterglow is consistent with a spherically symmetric distribution. The choice of GRB 991216 is motivated by the superb set of data existing in the “prompt” emission (in the band 50–300 keV observed by BATSE GRB Rapid Burst Response 1999) and in the afterglow (in the band 2–10 keV observed by R-XTE and Chandra, see Corbet and Smith, 2002; Halpern et al., 2000; Piro et al., 2000). In recent publications (see Ruffini et al., 2003b, and references therein) we have developed basic formulas for the GRB model. This development differs somewhat from the usual presentation in the literature. The differences includes: (a) the entire spacetime parametrization of the GRB phenomenon starting from the moment of gravitational collapse, to the optically thick accelerated phase, all the way to the afterglow (Ruffini et al., 2001a); (b) the identification of the “prompt” radiation as the early emission in the afterglow era (Ruffini et al., 2001b, 2002); and (c) a marked distinction between the sharp \( X \) and \( \gamma \) radiation, which is energetically predominant in the afterglow (\( \sim 90\% \)), and the highly variable radiation in the optical and radio bands which is generally much weaker, observed in the late afterglow phases and, in some cases, absent (Ruffini et al., 2004b). The usual presentations in the literature consider the afterglow radiation in all wavelength from the \( \gamma \) rays all the way to the radio as originating from a unique physical process mainly related to synchrotron radiation (see e.g., Piran, 2004, and references therein). In our approach, we assume instead that the \( X \) and \( \gamma \) radiation originates from the emission in the shock front with a thermal spectrum in the co-moving frame (Ruffini et al., 2004b). The optical and radio emission is assumed to be emitted by the matter compressed in the pre-shock
region, possibly with contributions from magnetic fields and synchrotron emission (Ruffini et al., 2004b, 2005). This progress has allowed to obtain very specific theoretical predictions for the luminosity of the entire afterglow in fixed $X$ and $\gamma$ energy bands (Ruffini et al., 2004b, 2005).

We have fitted by a unified theoretical approach the “prompt” radiation and the decaying part of the afterglow. The “prompt” radiation has been shown to coincide with the emission of the peak of the afterglow (Ruffini et al., 2001a,b, 2002).

2. The free parameters and the equations of our model and the fit of GRB 991216

Our model depends: (a) on the initial conditions at the beginning of the afterglow era, which are functions of the only two free parameters describing the source: the total energy $E_{\text{tot}}$, which coincides with the dyadosphere energy $E_{\text{dyad}}$ (see Ruffini et al., 2003b, and references therein), and the amount $M_B$ of baryonic matter left over from the gravitational collapse of the progenitor star, which is determined by the dimensionless parameter $B = M_B c^2 / E_{\text{dyad}}$ (see Ruffini et al., 2000); (b) on the equations of motion of the accelerated baryonic matter pulse which, interacting with the ISM, gives origin to the afterglow (Ruffini et al., 2003b, and references therein); and (c) on the afterglow EQUITemporal Surfaces (EQTS, see Ruffini et al., 2002; Bianco and Ruffini, 2004, 2005) as well as on the two independent variables describing the interstellar medium (ISM): the ISM density $n_{\text{ISM}}$ and the parameter $\mathcal{A} = A_{\text{eff}} / A_{\text{brm}}$, which gives the ratio between the “effective emitting area” $A_{\text{eff}}$ and the accelerated baryonic matter (ABM) pulse surface area $A_{\text{brm}}$. This factor $\mathcal{A}$, with the density $n_{\text{ISM}}$ is sufficient to identify the ISM filamentary structure and the basic physical process originating the X and $\gamma$ flux in GRB afterglows (Ruffini et al., 2004b, 2005). For GRB 991216, we have (see Ruffini et al., 2003b): $E_{\text{dyad}} = 4.83 \times 10^{53}$ erg, $B = 2.7 \times 10^{-3}$. This leads to the following conditions at the beginning of the afterglow era for the photon detector arrival time, the ABM pulse radius, its Lorentz gamma factor and its synchrotron emission (Ruffini et al., 2004b, 2005).

$W(v_1, v_2, T_{\text{arr}})$ is the flux in GRB afterglows (Ruffini et al., 2004, 2005) as well as on the the effective weight” required to evaluate only the contributions in the energy band $[v_1, v_2]$, $d\Sigma$ is the surface element of the EQTS at detector arrival time $t_d$ on which the integration is performed (see Ruffini et al., 2002; Bianco and Ruffini, 2004, 2005) and $T_{\text{arr}}$ is the observed temperature of the radiation emitted from $d\Sigma$.

The thermalization process due to the optically thick condition generated by the ISM filamentary structure has been discussed in Ruffini et al. (2005). The “effective weight” $W(v_1, v_2, T_{\text{arr}})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature $T_{\text{arr}}$ to the total integral $a^{dV}_{\text{arr}}$:

$$W(v_1, v_2, T_{\text{arr}}) = \frac{1}{a^{dV}_{\text{arr}}} \int_{v_1}^{v_2} \rho(T_{\text{arr}}, v) v (h v / c)^3, \tag{4}$$

where $\rho(T_{\text{arr}}, v)$ is the Planckian distribution at temperature $T_{\text{arr}}$:

$$\rho(T_{\text{arr}}, v) = \frac{2}{h^3 c^3 (\hbar c T_{\text{arr}})^{3/2}}. \tag{5}$$

The estimate of the theoretically predicted luminosity in a fixed energy band as a function of the initial data is then perfectly well defined both for the “prompt” radiation and the decaying part of the afterglow. Almost $10^5$ paths with different temperatures and different Lorentz boosts have to be considered in the integration over the EQTSs. We give in Fig. 1, the results in the two energy bands 50–300 keV (observed by BATSE) and 2–10 keV (observed by R-XTE and Chandra). It is most remarkable that the best fit of the descending part of the afterglow (for a photon arrival time at the detector $t_d > 10^3$ s) is obtained by a constant factor $\mathcal{A} = 1.0 \times$
We point out the agreement with the data of the "prompt" radiation obtained by BATSE in the energy range 50–300 keV (see the dotted line in Fig. 1). We have succeeded as well in the fit of the data obtained by the R-XTE and Chandra satellites (Halpern et al., 2000) in the energy range 2–10 keV (see dashed line in Fig. 1). These data refer to the decaying part of the afterglow. These fits cover a time span of $\sim 10^5$ s and it is remarkable that they are a sole function of the two variables $\theta$ and $n_{\text{ism}}$ which have a constant value in this region. We have also computed, within this global self-consistent approach which fits both the "prompt" radiation and the decaying part of the afterglow, the flux in the

$$10^{-10} \text{ and a constant } n_{\text{ism}} = 3.0 \text{ particles/cm}^3.$$
2–10 keV range which would be expected for a beamed emission with half opening angle $\theta = 3^\circ$, see Fig. 1. The presence of beaming manifest itself, as expected, in the decaying part of the afterglow and is incompatible with the data.

### 3. Conclusions

Our theory sharply differs from the so-called “state of the art” in this field. Instead of the traditional multi-wavelength approach, we differentiate the mechanisms for the sharp $X$ and $\gamma$ radiation, originating in the shock front with a thermal spectrum in the co-moving frame, from the ones originating the radio and optical radiation, which we expect to be emitted ahead of the shock front by more traditional processes. We expect improvements in the accuracy of the fits by the advent of the Swift satellite. We also like to point out that additional and independent evidence for GRB spherical symmetry comes from the fit of the spectral data (Ruffini et al., 2004a). We can then draw the following general conclusions: (1) It is clear that a spherically symmetric expansion of the GRB afterglow is perfectly consistent with the data, rather than a narrow jet as previous authors have concluded. (2) The actual afterglow luminosity in fixed energy bands, in spherical symmetry, does not have a simple power law dependence on arrival time (see Fig. 1). This circumstance has been erroneously interpreted, in the usual presentation in the literature, as a broken power-law supporting the existence of jet-like structures in GRBs. Moreover, the slope of the beamed emission and the arrival time at which the break occurs have been there computed using the incorrect equations of motion for the afterglow and the incorrect EQTSs (Bianco and Ruffini, 2004, 2005). (3) If one assumes the presence of jets in a consistent afterglow theory, one finds that the break corresponding to the purported beaming appears at an arrival time incompatible with the observations (see (b) in Fig. 1). In addition to the source GRB991216, our model has been applied successfully, assuming spherical symmetry, to GRB980425 (see Ruffini et al., 2004a), GRB030329 (see Ruffini et al., 2003a) and to GRB970228 (see Corsi et al., 2004). The GRB spherical symmetry unambiguously points to the electromagnetic energy component of the black hole extractable energy as the GRB energy source (Christodoulou and Ruffini, 1971; Damour and Ruffini, 1975).

### References


Attachment 7
A New Astrophysical “Triptych”:
GRB030329/SN2003dh/URCA-2

M.G. Bernardini*, C.L. Bianco*, P. Chardonnet†, F. Fraschetti***, R. Ruffini* and S.-S. Xue*

*ICRA - International Center for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy.
†Université de Savoie, LAPTH - LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France.
***Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy.

Abstract. We analyze the data of the Gamma-Ray Burst/Supernova GRB030329/SN2003dh system obtained by HETE-2 (gcn [1]), R-XTE (gcn [2]), XMM (Tiengo et al. [3]) and VLT (Hjorth et al. [4]) within our theory (Ruffini et al. [5] and references therein) for GRB030329. By fitting the only three free parameters of the EMBH theory, we obtain the luminosity in fixed energy bands for the prompt emission and the afterglow (see Fig. 1). Since the Gamma-Ray Burst (GRB) analysis is consistent with a spherically symmetric expansion, the energy of GRB030329 is $E = 2.1 \times 10^{52}$ erg, namely $\sim 2 \times 10^{3}$ times larger than the Supernova energy. We conclude that either the GRB is triggering an induced-supernova event or both the GRB and the Supernova are triggered by the same relativistic process. In no way the GRB can be originated from the supernova. We also evidence that the XMM observations (Tiengo et al. [3]), much like in the system GRB980425/SN1998bw (Ruffini et al. [6], Pian and et al. [7]), are not part of the GRB afterglow, as interpreted in the literature (Tiengo et al. [3]), but are associated to the Supernova phenomenon. A dedicated campaign of observations is needed to confirm the nature of this XMM source as a newly born neutron star cooling by generalized URCA processes.

A distinctive feature of our model, developed in the framework of the three interpretational paradigms (Ruffini et al. [8, 9, 10]), has been the relation between the photon arrival time at the detector $t_d$ and the photon emission time $t$ (see Ruffini et al. [5, 9, 11]):

$$t_d = (1 + z) \left( t - \int_0^t \frac{v(t')}{c} dt' + r^* \cos \theta \right) + \frac{r^*}{c},$$

(1)

where $r(t)$, $v(t)$ and $\gamma(t)$ are the radial coordinate, the velocity and the Lorentz gamma factor of the expanding shell, $r^* = r(t = 0)$, $\theta$ is the angle between the velocity of the emission point of the photon and the line of sight and $z$ is the cosmological redshift of the source.

In contrast with the relation between $t_d$ and $t$ used in the literature, which depends on an instantaneous value of the Lorentz $\gamma$ factor (see e.g. Rees and Mészáros [12], Eq.(30) in Piran [13], Eq.(2) in van Paradijs et al. [14], Eq.(2) in Mészáros [15]), Eq.(1) contains an integral which is a function of all previous values of the Lorentz gamma factor along the source world-line since the time $t = 0$. Therefore the knowledge of the Equations Of Motion (EOM) of the source is crucial to the evaluation of Eq.(1). In turns all the quantities which are computed using the EQuiTemporal Surfaces (EQTS, Ruffini et al. [5, 11], Bianco and Ruffini [16]) determined from Eq.(1) become themselves very
FIGURE 1. The dotted line represents our theoretically predicted GRB030329 light curve in $\gamma$-rays (30-400 keV) with the horizontal bar corresponding to the mean peak flux from HETE-2 (gcn [1]). The solid line represents the corresponding one in X-rays (2-10 keV) with the experimental data obtained by R-XTE (gcn [2]). The remaining points refer respectively to the optical VLT data (Hjorth et al. [4]) of SN2003bw and to the X-ray XMM data (Tiengo et al. [3]) of URCA-2. The dash-dotted line corresponds to cooling theoretical curves of young neutron stars by generalized URCA processes. It is interesting to compare and contrast these results with the ones for GRB980425/SN1998bw (see Fig. 3 in Ruffini et al. [6]).

The determination of the EOM leads to a quite complex treatment, which starts from a very special set of initial conditions, proven to be unique. This treatment fits the observed luminosities with a large number of redundancy checks on the EOM (see Fig. 1). It fits as well the time variability in the prompt radiation self-consistently with the determination of the EOM [19].

We have adopted a spherically symmetric distribution for the GRB source and, as initial conditions at $t = 10^{-21}$ s, an $e^+ - e^-$-photon neutral plasma lying between the radii $r_1 = 2.9 \times 10^6$ cm and $r_2 = 9.0 \times 10^7$ cm. The temperature of such a plasma is 2.1 MeV, the total energy $E_{tot} = 2.1 \times 10^{52}$ erg and the total number of pairs $N_{e^+e^-} = 1.1 \times 10^{57}$. These conditions have been derived evaluating the vacuum polarization processes (Damour and Ruffini [20]) occurring in the dyadosphere of an EMBH (Ruffini [5, 17]).
The total energy \( E_{\text{tot}} \) coincides with the dyadosphere energy \( E_{\text{dya}} \) which is the first independent parameter of the EMBH theory. The optically thick electron-positron plasma created in the dyadosphere self-propels itself outward reaching ultrarelativistic velocities (Ruffini et al. [27]) and then interacts with the baryonic matter of the remnant of the progenitor star. The baryonic matter component \( M_B \) is the second free parameter of the EMBH theory:

\[
B = \frac{M_B c^2}{E_{\text{dya}}} = 4.8 \times 10^{-3}.
\]

The \( e^+e^- \)-photon-baryon plasma by further expansion becomes optically thin (Ruffini et al. [28]). As the transparency condition is reached, the Proper-GRB (P-GRB) is emitted with an extremely relativistic shell of Accelerated Baryonic Matter (the ABM pulse) with initial Lorentz gamma factor of \( \gamma = 183.6 \). It is this ABM pulse which produces the afterglow through its interaction with the ISM, whose average density is best fitted by \( <n_{\text{ISM}}> = 1 \text{ particle/cm}^3 \). In such a collision the “fully radiative condition” is implemented (for details see Ruffini et al. [5]): the internal energy \( \Delta E_{\text{int}} \) which results is instantaneously radiated away.

We have recently assumed that the radiation emitted in the collision between the ABM pulse and the ISM has a thermal spectrum measured in the ABM pulse comoving frame (Ruffini et al. [18]). In our approach the source luminosity is derived from an infinite set of foliations of events on the EQTS, each one characterized by a different thermal spectrum in the comoving frame boosted by a different relativistic transformation obtained from the EOM. The third free parameter of the EMBH theory describes this process of generating the thermal spectrum in the comoving frame. It is given by

\[
1.1 \times 10^{-7} < R = \frac{A_{\text{eff}}}{A_{\text{abm}}} < 5.0 \times 10^{-11},
\]

where \( A_{\text{abm}} \) is the ABM pulse external surface area and \( A_{\text{eff}} \) is the ABM pulse effective emitting area.

We can then obtain for the GRB030329 the luminosities in given energy bands, computed in the range 2-400 keV with very high accuracy. Fig. 1 shows the results for the luminosities in the 30-400 keV and 2-10 keV bands. Subsequently, the theoretically predicted GRB spectra have been evaluated at selected values of the arrival time [19]. We can now compare these results with those for GRB980425/SN1998bw (Ruffini et al. [6]). We conclude that:

a) The intensity of the GRB versus the Supernova, comparable in the case of GRB980425, becomes \( 2 \times 10^3 \) times larger in the case of GRB030329. This crucial fact clearly indicates beyond any doubt the independence of the GRB phenomenon from the Supernova (Ruffini et al. [10]). Moreover, the GRB is generally energetically dominant on the supernova; either the GRB is triggering an induced-supernova event or both the GRB and the Supernova are triggered by the same relativistic process. In no way the GRB can originate from the supernova.

b) In both systems the XMM observations point to the existence of an additional X-ray source, which we consider related to the Supernova phenomenon and not to the GRB. There is the distinct possibility that this source originates from the emission of a newly formed hot neutron star, cooling via generalized URCA processes (Ruffini et al. [6]). It has been recently proposed (Ruffini et al. [29]) to indicate this new physical and astrophysical systems as URCA-1 for GRB980425/SN1998bw and URCA-2 for GRB030329/SN2003dh. A dedicated campaign of observations with XMM is urgently needed in order to explore this unprecedented “triptych” astrophysical systems, formed by a GRB, an induced-supernova and possibly a newly born pulsating hot neutron star.

Details of this results are going to be published in [19].
REFERENCES


270
Attachment 8
GRB 970228 Within the EMBH Model

A. Corsi*, M.G. Bernardini*, C.L. Bianco*, P. Chardonnet†, F. Fraschetti**, R. Ruffini* and S.-S. Xue*

*ICRA - International Center for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy.
†Université de Savoie, LAPTH - LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France.
**Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy.

Abstract. We consider the gamma-ray burst of 1997 February 28 (GRB 970228) within the ElectroMagnetic Black Hole (EMBH) model. We first determine the value of the two free parameters that characterize energetically the GRB phenomenon in the EMBH model, that is to say the dyadosphere energy, \(E_{\text{dyas}} = 5.1 \times 10^{52}\) ergs, and the baryonic remnant mass \(M_B\) in units of \(E_{\text{dyas}}\), \(B = M_B c^2 / E_{\text{dyas}} = 3.0 \times 10^{-3}\). Having in this way estimated the energy emitted during the beam-target phase, we evaluate the role of the InterStellar Medium (ISM) number density (\(n_{\text{ISM}}\)) and of the ratio \(R\) between the effective emitting area and the total surface area of the GRB source, in reproducing the observed profiles of the GRB 970228 prompt emission and X-ray (2-10 keV energy band) afterglow. The importance of the ISM distribution three-dimensional treatment around the central black hole is also stressed in this analysis.

The GRB 970228 [1] had an important role in solving the origin of GRBs through the first detection of counterparts at other wavelengths: the afterglow phenomenon, long-lived multi-wavelength emission, was discovered following GRB 970228 at X-ray ([2], Costa et al. [3]) and optical ([4], van Paradijs et al. [5]) wavelengths.

We consider of great interest to compare the predictions of the ElectroMagnetic Black Hole (EMBH) theory (see Ruffini et al. [6] and references therein) with the first afterglow observed by the Beppo-SAX satellite.

We are also interested in testing the efficiency of the model in reproducing the GRB 970228 prompt emission: in the 40-700 keV energy band the burst was characterized by an initial 5 s strong pulse followed, after about 30 s, by three additional pulses of decreasing intensity (Frontera et al. [7]). The InterStellar Medium (ISM) number density (\(n_{\text{ISM}}\)) inhomogeneities have an important role in interpreting this profile within the EMBH model.

Our analysis starts establishing the value of the two free parameters that determine energetically the GRB phenomenon in the EMBH model: the total energy deposited in the dyadosphere \(E_{\text{dyas}}\) (Ruffini et al. [8]) and the amount of the baryonic matter left over in the collapse process of the EMBH progenitor star (Ruffini et al. [8]), that can be parametrized by the dimensionless parameter \(B = M_B c^2 / E_{\text{dyas}}\).

With the choice of \(E_{\text{dyas}} = 5.1 \times 10^{52}\) ergs and \(B = 3.0 \times 10^{-3}\), the EMBH model predicts that a 98% of the total energy \(E_{\text{dyas}}\) is emitted during the so-called beam-target phase (Ruffini et al. [9]), that is to say during the collision of the Accelerated Baryonic Matter-pulse (ABM-pulse) with the ISM (Ruffini et al. [6]). During this phase,
the internal energy developed in the collision is instantaneously radiated away (fully radiative condition) and, as a consequence, the resulting shape of the light curve is strictly linked to the ISM distribution and number density (Ruffini et al. [10]). We use a one-dimensional treatment of the ISM, where the \( n_{\text{ISM}} \) is a function of the radial distance from the central black hole (Ruffini et al. [10]).

In order to reproduce the observed profile of the GRB 970228, \( n_{\text{ISM}} \) has to range between the values of \( 10^{-2} \) particles/cm\(^3\) and 200 particles/cm\(^3\) in the region of space within \( 2.00 \times 10^{15} \) cm and \( 4.95 \times 10^{16} \) cm from the central black hole. Since \( 2.00 \times 10^{15} \) cm and beyond \( 4.95 \times 10^{16} \) cm, the ISM number density has a constant value of 1 particle/cm\(^3\) (details are given in Ruffini et al. [11], Ruffini et al. [12]).

The correct spectral distribution of the energy emitted during the beam-target phase depends on the \( R \) parameter (Ruffini et al. [13]). As a consequence, the theoretical curves in selected energy bands are strictly related to this parameter. \( R \) is a function of the radial distance from the EMBH and it represents the ratio between the effective emitting area of the ABM-pulse and its total surface area:

\[
\mathcal{R} = \frac{A_{\text{eff}}}{A_{\text{ABM}}} \tag{1}
\]

According to Ruffini et al. [13], by assuming a black-body spectrum in the co-moving frame for the radiation emitted during the collision with the ISM, the spectral distribution of the energy emitted results to be dependent on the temperature of the emitting black body (Ruffini et al. [13], Ruffini et al. [14]):

\[
T = \left( \frac{\Delta E_{\text{int}}}{4\pi r^2 \Delta \tau \sigma \mathcal{R}} \right)^{1/4} \tag{2}
\]

where \( \Delta E_{\text{int}} \) is the proper internal energy developed in the collision of the ABM-pulse with the ISM in the proper time interval \( \Delta \tau \), \( r \) is the radial coordinate of the ABM-pulse, \( \sigma \) is the Stefan-Boltzmann constant.

In the case of GRB 970228 we find \( \mathcal{R} \) monotonically varying from \( 3.7 \times 10^{-12} \) to \( 8.8 \times 10^{-11} \) when the radial coordinate \( r \) goes from \( 7.0 \times 10^{14} \) cm to \( 5.0 \times 10^{17} \) cm. With this result, the first peak in the 40-700 keV observed light curve is correctly reproduced by the model (details are given in Ruffini et al. [11], Ruffini et al. [12]). The three additional pulses, that follow the first one after a gap in the emission, are reproduced by the model in terms of the mean luminosity. The Fast Rise Exponential Decay (FRED) shape that emerges in the theoretical light curve is a consequence of the one-dimensional treatment of the ISM. To solve this problem, a three-dimensional treatment of the ISM distribution is required (details are given in Ruffini et al. [11], Ruffini et al. [12]).

About the X-ray afterglow, in Fig.1 we present the theoretical curve in the 2-10 keV energy band compared with the observed data by Beppo-SAX (Costa et al. [3]) and ASCA [15]. The afterglow phase corresponds to the ABM-pulse expansion in the region beyond \( 4.95 \times 10^{16} \) cm, where the number density of the ISM has a constant value, \( n_{\text{ISM}} = 1 \) particle/cm\(^3\). We can see that there is a good agreement (\( \chi^2 = 0.5 \)) between the theoretical light curve in the 2-10 keV energy band and the observed data by Beppo-SAX and ASCA.
FIGURE 1. Afterglow 2-10 keV: the solid line represents the theoretical light curve for the 2-10 keV emission in the EMBH model. The points are the GRB 970228 2-10 keV afterglow data observed by Beppo-SAX (Costa et al. [3]) and ASCA ([15]).

From this analysis we conclude that:

- a mask of density inhomogeneities of the ISM is needed in the region of space between $2.00 \times 10^{15}$ cm and $4.95 \times 10^{16}$ cm from the black hole, in order to reproduce the structure of the GRB 970228 prompt emission;
- a three-dimensional treatment of the ISM is required in order to improve the theoretical predictions of the model (details are given in Ruffini et al. [11], Ruffini et al. [12]);
- finally, a good result is obtained with a constant value of the $n_{ISM} = 1$ particle/cm$^3$ for the 2-10 keV afterglow emission.

REFERENCES

1. IAU Circ. 6572 (1997).
2. IAU Circ. 6576 (1997).
Attachments

15. IAU Circ. 6593 (1997).
Attachment 9
Attachments
The GRB 980425-SN1998bw Association in the EMBH Model

F. Fraschetti∗, M.G. Bernardini†, C.L. Bianco†, P. Chardonnet∗∗, R. Ruffini† and S.-S. Xue†

∗Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy
†ICRA - International Centre for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy
∗∗Université de Savoie, LAPTH - LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France

Abstract. Our GRB theory, previously developed using GRB 991216 as a prototype, is here applied to GRB 980425. We fit the luminosity observed in the 40–700 keV, 2–26 keV and 2–10 keV bands by the BeppoSAX satellite. In addition the supernova SN1998bw is the outcome of an “induced gravitational collapse” triggered by GRB 980425, in agreement with the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [1]). A further outcome of this astrophysically exceptional sequence of events is the formation of a young neutron star generated by the SN1998bw event (Ruffini et al. [2]). A coordinated observational activity is recommended to further enlighten the underlying scenario of this most unique astrophysical system.

Our GRB theory (Ruffini et al. [3, 4, 1, 5, 6] and references therein), previously successfully applied to GRB 991216 used as a prototype, is applied to GRB 980425 (Pian et al. [7]) and SN1998bw (Galama and et al. [8]). This event allows to test the validity of the theory over a range of energies of 6 orders of magnitude: both sources appear to be spherically symmetric and the respective total energies are \( E_{\text{tot}} \approx 5 \times 10^{53} \) ergs and \( E_{\text{tot}} \approx 10^{48} \) ergs.

The theory, therefore, explains all the observed features of the bolometric intensity variations of the afterglow as well as the spectral properties of the source and, in the specific case of GRB 980425 (Ruffini et al. [2]), it also allows to clarify the general astrophysical scenario in which the GRB actually occurs. In this system, in fact, we propose that GRB 980425 has been the trigger of a phenomenon of “induced gravitational collapse” (Ruffini et al. [1]) originating the supernova explosion and we also witness the birth of a young neutron star out of the supernova event. This extraordinary coincidence of these three astrophysical events represents an unprecedented scenario of fundamental importance in the field of relativistic astrophysics.

The observational situation of this system is quite complex. In addition to the source GRB 980425 and the supernova SN1998bw, two X-ray sources have been found by BeppoSAX in the error box for the location of GRB 980425: a source \( S1 \) and a source \( S2 \) (Pian et al. [7]). Our approach is the following. We first interpret the GRB 980425 within the EMBH theory. This allows the computation of the luminosity, spectra, Lorentz gamma factors, and more generally all the dynamical aspects of the source. Having characterized the features of GRB 980425, we can gradually approach the remaining part of the scenario, disentangling the GRB observations from the supernova ones and
from the sources S1 and S2. This leads to a natural time sequence of events and to their autonomous astrophysical characterization.

Our approach has focused on identifying the energy extraction process from the black hole (Christodoulou and Ruffini [9]) as the basic energy source for the GRB phenomenon. The distinguishing feature is a theoretically predicted source energetics all the way up to $1.8 \times 10^{54} (M_{BH}/M_\odot)$ ergs for $3.2 M_\odot \leq M_{BH} \leq 7.2 \times 10^9 M_\odot$ (Damour and Ruffini [10]). In particular, the formation of a “dyadosphere”, during the gravitational collapse leading to a black hole endowed with electromagnetic structure (EMBH) has been indicated as the initial boundary conditions of the GRB process (Ruffini [11], Preparata et al. [12]).

The equations of motion in our theory depend only on two free parameters: the total energy $E_{tot}$, which coincides with the dyadosphere energy $E_{dya}$, and the amount $M_B$ of baryonic matter left over from the gravitational collapse of the progenitor star, which is determined by the dimensionless parameter $B = M_B c^2/E_{dya}$. Our best fit corresponds to $E_{dya} = 1.1 \times 10^{48}$ ergs, $B = 7 \times 10^{-3}$ and the ISM average density is found to be $\langle n_{ism} \rangle = 0.02$ particle/cm$^3$. The plasma temperature and the total number of pairs in the dyadosphere are respectively $T = 1.028$ MeV and $N_{e\pm} = 5.3274 \times 10^{53}$.

Recently, within the EMBH theory, we have developed an attempt to theoretically derive the GRB spectra out of first principles as well as the GRB luminosity in fixed energy bands (Ruffini et al. [13]). We have adopted three basic assumptions: a) the resulting radiation as viewed in the comoving frame during the afterglow phase has a thermal spectrum and b) the ISM swept up by the front of the shock wave, with a Lorentz gamma factor between 300 and 2, is responsible for this thermal emission. e) We also assume, like in our previous papers (Ruffini et al. [3, 4, 5, 6]), that the expansion occurs with spherical symmetry.

The temperature $T$ of the black body in the comoving frame is then

$$ T = \left( \frac{\Delta E_{int}}{4 \pi r^2 \Delta \tau \sigma R} \right)^{1/4}, \quad (1) $$

where $R = A_{eff}/A_{abm}$ is the ratio between the “effective emitting area” and the ABM pulse surface $A_{abm}$ (in this case the best fit value of $R$ is monotonically decreasing from $4.81 \times 10^{-10}$ to $2.65 \times 10^{-12}$), $\sigma$ is the Stefan-Boltzmann constant and $\Delta E_{int}$ is the proper internal energy developed in the collision between the ABM pulse and the ISM in the proper time interval $\Delta \tau$ (see Ruffini et al. [6, 13]). The ratio $R$, which is a priori a function that varies as the system evolves, is evaluated at every given value of the laboratory time $t$.

All the subsequent steps are now uniquely determined by the equations of motion of the system. The basic tool in this calculation involves the definition of the EQuiTemporal Surfaces (EQTS) for the relativistic expanding ABM pulse as seen by an asymptotic observer. The key to determining such EQTS (see Fig. 1 in Ruffini et al. [5]) is the relation between the time $t$ in the laboratory frame at which a photon is emitted from the ABM pulse external surface and the arrival time $t_\text{d}^*$ at which it reaches the detector.

The results are given in Fig. 1 where the luminosity is computed as a function of the arrival time for three selected energy bands.
In Fig. 1 the luminosities in the three bands are represented together with the optical data of SN1998bw (black dots), the source S1 (black squares) and the source S2 (open circles). It is then clear that GRB 980425 is separated both from the supernova data and from the sources S1 and S2.

While the occurrence of the supernova in relation to the GRB has already been discussed with the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [1]), we like to address here a different fundamental issue: the possibility of observing the birth of a newly formed neutron star, possibly pulsating, out of the supernova event, which in turn has been triggered by the GRB 980425.

In the early days of neutron star physics it was clearly shown by (Gamow and Schoenberg [16]) that the URCA processes are at the very heart of the supernova explosions. The neutrino-antineutrino emission described in the URCA process is the essential cooling mechanism necessary for the occurrence of the process of gravitational collapse of the imploding core. Since then, it has become clear that the newly formed neutron star can be still significantly hot and in its early stages will be associated to three major radiating processes (Tsuruta [17, 18], Tsuruta et al. [19], Canuto [15]):

a) the thermal radiation from the surface, b) the radiation due to neutrino, kaon, pion cooling.
cooling, and c) the possible influence in both these processes of the superfluid nature of
the supra-nuclear density neutron gas. Qualitative representative curves for these cooling
processes, which are still today very undetermined due to the lack of observational data,
are shown in Fig. 1.

It is of paramount importance to follow the further time history of the two sources
S1 and S2. If, as we propose, S2 is a background source, its flux should be practically
constant in time and this source has nothing to do with the GRB 980425 / SN1998bw
system. If S1 is indeed the cooling radiation emitted by the newly born neutron star,
it should be possible to notice a very drastic behavior in its luminosity as qualitatively
expresses in Fig. 1.

The complete details on the source with all numerical values and explicit relations is
going to appear in (Ruffini et al. [20]).

REFERENCES
2. Ruffini, R., Bernardini, M. G., Bianco, C. L., Chardonnet, P., Fraschetti, F., and Xue, S.-S.,
“GRB 980425, SN1998bw and the EMBH Model,” in Proceedings of the 34th COSPAR Scientific
Perspectives in Physics and Astrophysics from the Theoretical Understanding of Gamma-Ray Bursts,”
in COSMOLOGY AND GRAVITATION: Xth Brazilian School of Cosmology and Gravitation: 25th
Fiore, F., Frontera, F., Giommi, P., Masetti, N., Muller, J., Nicastro, L., Oosterbroek, T., Orlandini,
M., Owens, A., Palazzi, E., Parmar, A., Piro, L., incl Zand, J., Castro-Tirado, A., Coletta, A., Fiume,
8. Canuto, V., “Neutron Stars, Physics and astrophysics of neutron stars and black holes,” in
Proceedings of the International School of Physics “Enrico Fermi”, edited by R. Giacconi and R. Ruffini,
Attachment 10
BLACK HOLE PHYSICS AND ASTROPHYSICS: THE GRB-SUPERNOVA CONNECTION AND URCA-1–URCA-2

R. RUFFINI, M. G. BERNARDINI, C. L. BIANCO, L. VITAGLIANO and S.-S. XUE
ICRA – International Center for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy

P. CHARDONNET
ICRA – International Center for Relativistic Astrophysics and Université de Savoie, LAPTH - LAPP, BP 110, F-74911 Annecy-le-Vieux Cedex, France

F. FRASCHETTI
ICRA – International Center for Relativistic Astrophysics and Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy

V. GURZADYAN
ICRA – International Center for Relativistic Astrophysics and Yerevan Physics Institute, Alhakanian Brothers Street 2, 375036, Yerevan-36, Armenia

We outline the confluence of three novel theoretical fields in our modeling of Gamma-Ray Bursts (GRBs): 1) the ultrarelativistic regime of a shock front expanding with a Lorentz gamma factor \( \sim 300 \); 2) the quantum vacuum polarization process leading to an electron-positron plasma originating the shock front; and 3) the general relativistic process of energy extraction from a black hole originating the vacuum polarization process. There are two different classes of GRBs: the long GRBs and the short GRBs. We here address the issue of the long GRBs. The theoretical understanding of the long GRBs has led to the detailed description of their luminosities in fixed energy bands, of their spectral features and made also possible to probe the astrophysical scenario in which they originate. We are specially interested in this report, to a subclass of long GRBs which appear to be accompanied by a supernova explosion. We are considering two specific examples: GRB980425/SN1998bw and GRB030329/SN2003dh. While these supernovae appear to have a standard energetics of \( 10^{51} \) ergs, the GRBs are highly variable and can have energetics \( 10^{51} - 10^{52} \) times larger than the ones of the supernovae. Moreover, many long GRBs occurs without the presence of a supernova. It is concluded that in no way a GRB can originate from a supernova. The precise theoretical understanding of the GRB luminosity we present evidence, in both these systems, the existence of an independent component in the X-ray emission, usually interpreted in the current literature as part of the GRB afterglow. This component has been observed by Chandra and XMM to have a strong decay on scale of months. We have named here these two sources respectively URCA-1 and URCA-2, in honor of the work that George Gamow and Mario Shoenberg did in 1939 in this town of Urca identifying the basic mechanism, the Urca processes, leading to the process of gravitational collapse and the formation of a neutron star and a supernova. The further hypothesis is considered to relate this X-ray source to a neutron star, newly born in the Supernova. This hypothesis should be submitted to further theoretical and observational investigation. Some theoretical developments to clarify the astrophysical origin of this new scenario are outlined.
1. Introduction

In the last century the fundamental discoveries of nuclear physics have led to the understanding of the thermonuclear energy source of main sequence stars and explained the basic physical processes underlying the solar luminosity (see e.g. M. Schwarzschild [1]).

The discovery of pulsars in 1968 (see Hewish et al. [2]) led to the first evidence for the existence of neutron stars, first described in terms of theoretical physics by George Gamow as far back as 1936 [3]. It became clear that the pulsed luminosity of pulsars, at times $10^{32} - 10^{33}$ larger than solar luminosity, was not related to nuclear burning and could be simply explained in term of the loss of rotational energy of a neutron star (Gold [4, 5]). For the first time it became so clear the possible relevance of strong gravitational fields in the energetics of an astrophysical system.

The birth of X-ray astronomy thanks to Riccardo Giacconi and his group (see e.g. Giacconi and Ruffini [6]) led to a still different energy source, originating from the accretion of matter onto a star which has undergone a complete gravitational collapse process: a black hole (see e.g. Ruffini & Wheeler [7]). In this case, the energetics is dominated by the radiation emitted in the accretion process of matter around an already formed black hole. Luminosities up to $10^4$ times the solar luminosity, much larger than the ones of pulsars, could be explained by the release of energy in matter accreting in the deep potential well of a black hole (Leach and Ruffini [8]). This allowed to probe for the first time the structure of circular orbits around a black hole computed by Ruffini and Wheeler (see e.g. Landau and Lifshitz [9]). This result was well illustrated by the theoretical interpretation of the observations of Cygnus-X1, obtained by the Uhuru satellite and by the optical and radio telescopes on the ground (see Fig. 1).

The discovery of gamma-ray bursts (GRBs) sign a further decisive progress. The GRBs give the first opportunity to probe and observe a yet different form of energy: the extractable energy of the black hole introduced in 1971 (Christodoulou and Ruffini [11]), which we shall refer in the following as the blackhole energy.¹ The blackhole energy, expected to be emitted during the dynamical process of gravitational collapse leading to the formation of the black hole, generates X-ray luminosities $10^{21}$ times larger than the solar luminosity, although lasting for a very short time.

The extreme regimes of GRBs evidence new and unexplored regimes of theoretical physics. It is the aim of this talk to outline the progress achieved in understanding these astrophysical systems and the theoretically predicted regimes for the first time submitted to direct observational verification.

It is a pleasure to present these results in this village of Urca, in the beautiful city of Rio. While sitting at the Casino de Urca, George Gamow and Mario Schoenberg in 1939 identified the basic process leading to the formation and cooling of a newly

¹This name is the English translation of the Italian words “energia buonenerale”, introduced by Jacopo Ruffini, December 2004, here quoted by his kind permission.
The identification of the first black hole in our galaxy: Cygnus X-1

- $\Phi = 10^{37}\ erg/s = 10^{4}L_{\odot}$
  
  - $= 0.01(dm/dt)_{\text{sec}}c^{2}$

- Absence of pulsation due to uniqueness of Kerr-Newmann black holes

- $M > 3.2\ M_{\odot}$

Leach & Ruffini, 1973

Figure 1. Cygnus X-1 offered the possibility of identifying the first black hole in our galaxy (Leach and Ruffini [8]). The luminosity $\Phi$ of $10^{4}$ solar luminosities points to the accretion process into a neutron star or a black hole as the energy source. The absence of pulsation is naturally explained either by a non-magnetized neutron star or a Kerr-Newmann black hole, which has necessarily to be axially symmetric. What identifies the black hole unambiguously is that the mass of Cygnus X-1, larger than $9M_{\odot}$, exceeds the absolute upper limit of the neutron star mass, estimated at $3.2M_{\odot}$ by Rhode and Ruffini [10].

... born neutron star (see Appendix A). They called this process essentially related to the emission of neutrinos and antineutrinos the Urca process. It is a welcomed coincidence that, in the last hours, while preparing this talk, examining the data of the recently observed GRB 030329, we have received a confirmation of a scenario we have recently outlined in three papers giving the theoretical paradigms for the understanding of GRBs (Ruffini et al. [12, 13, 14]).

We have clear evidence, first advanced in the system GRB980425/SN1998bw (Ruffini et al. [15], Fraschetti et al. [16]) and now confirmed also in the system GRB030329/SN1003dh, that there are in these systems three different components: 1) the GRB source, generated by the collapse to a black hole; 2) the supernova, generated by the collapse of an evolved star; 3) an additional X-ray source which is not related, unlike what is at times stated in the literature, to the GRB afterglow. In honour of the work done in the town of Urca by George Gamow and Mario Schoenberg, identifying in the neutrino emission of the Urca process the basic mechanism leading to the process of gravitational collapse and the formation of a relativistic compact star, we named these two X-ray sources URCA-1, the one formed in
the system GRB980425/SN1998bw, and URCA-2, the one formed in the system
GRB030329/SN2003dh. We shall now recall some of the main steps in reaching
this understanding out of the GRB phenomenon and explore possible explanation
of the origin of these two sources.

2. The Energetics of Gamma-Ray Bursts

It is well known how GRBs were detected and studied for the first time using the
Vela satellites, developed for military research to monitor the non-violation of the
Limited Test Ban Treaty signed in 1963 (see e.g. Strong [17]). It was clear from the
early data of these satellites, which were put at 150,000 miles from the surface of
Earth, that the GRBs did not originate either on the Earth nor in the Solar System.

The mystery of these sources became more profound as the observations of the
BATSE instrument on board of the Compton Gamma-Ray Observatory (CGRO)
satelliteb over 9 years proved the isotropy of these sources in the sky (See Fig. 2).
In addition to these data, the CGRO satellite gave an unprecedented number of
details on the GRB structure, on their spectral properties and time variabilities
which become encoded in the fourth BATSE catalog [18] (see e.g. Fig. 3). Out
of the analysis of these BATSE sources it soon became clear (see e.g. Kouveliotou

bsee http://cosc.gsfc.nasa.gov/batse/
Figure 3. Some GRB light curves observed by the BATSE instrument on board of the CGRO satellite.

et al. [19], Tavani [20]) the existence of two distinct families of sources: the long bursts, lasting more than one second and softer in spectra, and the short bursts (see Fig. 5), harder in spectra (see Fig. 4). We shall return shortly on this topic.

The situation drastically changed with the discovery of the afterglow by the Italian-Dutch satellite BeppoSAX (Costa et al. [21]) and the possibility which led to the optical identification of the GRBs by the largest telescopes in the world, including the Hubble Space Telescope, the Keck Telescope in Hawaii and the VLT in Chile, and allowed as well the identification in the radio band of these sources. The outcome of this collaboration between complementary observational technique has led to the possibility of identifying in 1997 the distance of these sources from the Earth and their tremendous energy of the order up to $10^{51}$ erg/second during the burst. It is interesting, as we will show in the following, that an energetics of
this magnitude for the GRBs had previously been predicted out of first principles already in 1974 by Damour and Ruffini [22].

The resonance between the X- and gamma ray astronomy from the satellites and the optical and radio astronomy from the ground, had already marked in the seventies the great success and development of the astrophysics of binary X-ray sources (see e.g. Giacconi & Ruffini [6]). This resonance is re-proposed here for GRBs on a much larger scale. The use of much larger satellites, like Chandra and XMM-Newton, and dedicated space missions, like HETE-2 and, in the near future, Swift, and the very fortunate circumstance of the coming of age of the development of unprecedented optical technologies for the telescopes offers opportunities without precedence in the history of mankind. In parallel, the enormous scientific interest on the nature of GRB sources and the exploration, not only of new regimes, but also of totally novel conceptual physical process of the blackholic energy, make the knowledge of GRBs an authentic new frontier in the scientific knowledge.
3. The Complexity a Self-Consistency of GRB Modeling

The study of GRBs is very likely “the” most extensive computational and theoretical investigation ever done in physics and astrophysics. There are at least three different fields of research which underlie the foundation of the theoretical understanding of GRBs. All three, for different reasons, are very difficult.

The first field of research is the field of special relativity. As I always mention to my students in the course of theoretical physics, this field is paradoxically very difficult since it is extremely simple. In approaching special relativistic phenomena the extremely simple and clear procedures expressed by Einstein in his 1905 classic paper [23] are often ignored. Einstein makes use in his work of very few physical assumptions, an almost elementary mathematical framework and gives constant attention to a proper operational definition of all observable quantities. Those who work on GRBs use at times very intricate, complex and often wrong theoretical approaches lacking the necessary self-consistency. This is well demonstrated in the current literature on GRBs.
The second field of research essential for understanding the energetics of GRBs deals with quantum electrodynamics and the relativistic process of pair creation in overcritical electromagnetic fields. This topic is also very difficult but for a quite different conceptual reason: the process of pair creation, expressed in the classic works of Heisenberg-Euler-Schwinger [24, 25] later developed by many others, is based on a very powerful theoretical framework but has never been verified by experimental data. The quest for creating electron-positron pairs by vacuum polarization processes in heavy ion collisions or in lasers has not yet been successfully achieved in Earth-bound experiments (see e.g. Ruffini, Vitagliano, Xue [26]). As we will show here, there is the tantalizing possibility of observing this phenomenon, for the first time, in the astrophysical setting of GRBs on a more grandiose scale.

There is a third field which is essential for the understanding of the GRB phenomenon: general relativity. In this case, contrary to the case of special relativity, the field is indeed very difficult, since it is very difficult both from a conceptual, technical and mathematical point of view. The physical assumptions are indeed complex. The entire concept of geometrization of physics needs a new conceptual approach to the field. The mathematical complexity of the pseudo-Riemannian geometry contrasts now with the simple structure of the pseudo-Euclidean Minkowski space. The operational definition of the observable quantities has to take into account the intrinsic geometrical properties and also the cosmological settings of the source. With GRBs we have the possibility to follow, from a safe position in an asymptotically flat space at large distance, the formation of the horizon of a black hole with all the associated relativistic phenomena of light bending and time dilatation. Most important, as we will show in details in this presentation, general relativity in connection with quantum phenomena offers, with the blackhole energy, the explanation of the tremendous GRB energy sources.

For these reasons GRBs offer an authentic new frontier in the field of physics and astrophysics. It is appropriate to mention some of the goals of such a new frontier in the above three fields. We recall in the special relativity field, for the first time, we observe phenomena occurring at Lorentz gamma factors of approximately 300. In the field of relativistic quantum electro-dynamics we see for the first time the interchange between classical fields and the created quantum matter-antimatter pairs. In the field of general relativity also for the first time we can test the blackhole energy which is the basic energetic physical variable underlying the entire GRB phenomenon.

The most appealing aspect of this work is that, if indeed these three different fields are treated and approached with the necessary technical and scientific maturity, the model which results has a very large redundancy built-in. The approach requires an unprecedented level of self-consistency. Any departures from the correct theoretical treatment in this very complex system lead to exponential departures from the correct solution and from the correct fit of the observations.
It is so that, as the model is being properly developed and verified, its solution will have existence and uniqueness.

3.1. **GRBs and special relativity**

The ongoing dialogue between our work and the one of the workers on GRBs, rests still on some elementary considerations presented by Einstein in his classic article of 1905 [23]. These considerations are quite general and even precede Einstein’s derivation, out of first principles, of the Lorentz transformations. We recall here Einstein’s words: “We might, of course, content ourselves with time values determined by an observer stationed together with the watch at the origin of the co-ordinates, and co-ordinating the corresponding positions of the hands with light signals, given out by every event to be timed, and reaching him through empty space. But this co-ordination has the disadvantage that it is not independent of the standpoint of the observer with the watch or clock, as we know from experience”.

The message by Einstein is simply illustrated in Fig. 6. If we consider in an inertial frame a source (solid line) moving with high speed and emitting light signals (dashed lines) along the direction of its motion, a far away observer will measure a delay $\Delta t_o$ between the arrival time of two signals emitted at the origin and after a time interval $\Delta t$ in the laboratory frame. The real velocity of the source is given by:

$$u = \frac{\Delta r}{\Delta t} \quad (1)$$
and the apparent velocity is given by:

$$v_{\text{app}} = \frac{\Delta r}{\Delta t_a},$$  \hspace{1cm} (2)

As pointed out by Einstein the adoption of coordinating light signals simply by their arrival time as in Eq. (2), without an adequate definition of synchronization, is incorrect and leads to unsurmountable difficulties as well as to apparently “super-luminal” velocities as soon as motions close to the speed of light are considered.

The use of $\Delta t_a$ as a time coordinate, often tacitly adopted by astronomers, should be done, if at all, with proper care. The relation between $\Delta t_a$ and the correct time parameterization in the laboratory frame has to be taken into account:

$$\Delta t_a = \Delta t - \frac{\Delta r}{c} = \Delta t - \frac{1}{c} \int_{t_0}^{t_0 + \Delta t} v(t') dt'.$$ \hspace{1cm} (3)

In other words, the relation between the arrival time and the laboratory time cannot be done without a knowledge of the speed along the entire world-line of the source. In the case of GRBs, such a worldline starts at the moment of gravitational collapse. It is of course clear that the parameterization in the laboratory frame has to take into account the cosmological redshift $z$ of the source. We then have, at the detector:

$$\Delta t_a^d = (1 + z) \Delta t_a.$$ \hspace{1cm} (4)

In the current GRB literature, Eq. (3) has been systematically neglected by addressing only the afterglow description neglecting the previous history of the source. Often the integral equation has been approximated by a clearly incorrect instantaneous value:

$$\Delta t_a = \frac{\Delta t}{2 \gamma^2}.$$ \hspace{1cm} (5)

The attitude has been adopted that it should be possible to consider separately the afterglow part of the GRB phenomenon, without the knowledge of the entire equation of motion of the source.

This point of view has reached its most extreme expression in the works reviewed by Piran [28, 29], where the so-called “prompt radiation”, lasting on the order of $10^2$ s, is considered as a burst emitted by the prolonged activity of an “inner engine”. In these models, generally referred to as the “internal shock model”, the emission of the afterglow is assumed to follow the “prompt radiation” phase [30]–[34].

As we outline in the following, such an extreme point of view originates from the inability of obtaining the time scale of the “prompt radiation” from a burst structure. These authors consequently appeal to the existence of an “ad hoc” inner engine in the GRB source to solve this problem.

We show in the following how this difficulty has been overcome in our approach by interpreting the “prompt radiation” as an integral part of the afterglow and not as a burst. This explanation can be reached only through a relativistically correct theoretical description of the entire afterglow (see Section 5). Within the framework
of special relativity we show that it is not possible to describe a GRB phenomenon by disregarding the knowledge of the entire past worldline of the source. We show that at $10^2$ seconds the emission occurs from a region of dimensions of approximately $10^{16}$ cm, well within the region of activity of the afterglow. This point was not appreciated in the current literature due to the neglect of the apparent superluminal effects implied by the use of the “pathological” parametrization of the GRB phenomenon by the arrival time of light signals.

An additional difference between our treatment and the ones in the current literature relates to the assumption of the existence of scaling laws in the afterglow phase: the power law dependence of the Lorentz gamma factor on the radial coordinate is usually systematically assumed. From the proper use of the relativistic transformations and by the direct numerical and analytic integration of the special relativistic equations of motion we demonstrate (see Section 5.2) that no simple power-law relation can be derived for the equations of motion of the system. This situation is not new for workers in relativistic theories: scaling laws exist in the extreme ultrarelativistic regimes and in the Newtonian ones but not in the intermediate fully relativistic regimes (see e.g. Ruffini [35]).

3.2. GRBs and general relativity

Three of the most important works in the field of general relativity have certainly been the discovery of the Kerr solution [36], its generalization to the charged case (Newman et al. [37]) and the formulation by Brandon Carter [38] of the Hamilton-Jacobi equations for a charged test particle in the metric and electromagnetic field of a Kerr-Newman solution (see e.g. Landau and Lifshitz [9]). The equations of motion, which are generally second order differential equations, were reduced by Carter to a set of first order differential equations which were then integrated by using an effective potential technique by Ruffini and Wheeler for the Kerr metric (see e.g. Landau and Lifshitz [9]) and by Ruffini for the Reissner-Nordström geometry (Ruffini [35], see Fig. 7).

All the above mathematical results were essential for understanding the new physics of gravitationally collapsed objects and allowed the publication of a very popular article: “Introducing the black hole” (Ruffini and Wheeler [7]). In that paper, we advanced the ansatz that the most general black hole is a solution of the Einstein-Maxwell equations, asymptotically flat and with a regular horizon: the Kerr-Newman solution, characterized only by three parameters: the mass $M$, the charge $Q$ and the angular momentum $L$. This ansatz of the “black hole uniqueness theorem” still today after thirty years presents challenges to the mathematical aspects of its complete proof (see e.g. Carter [40] and Bini et al. [41]). In addition to these mathematical difficulties, in the field of physics this ansatz contains the most profound consequences. The fact that, among all the possible highly nonlinear terms characterizing the gravitationally collapsed objects, only the ones corresponding solely to the Einstein Maxwell equations survive the formation of the horizon
The effective potential of a Kerr-Newmann geometry

Figure 7. The effective potential corresponding to the circular orbits in the equatorial plane of a black hole is given as a function of the angular momentum of the test particle. This diagram was originally derived by Ruffini and Wheeler (right picture). For details see Landau and Lifshitz [9] and Rees, Ruffini and Wheeler [30].

has, indeed, extremely profound physical implications. Any departure from such a minimal configuration either collapses on the horizon or is radiated away during the collapse process. This ansatz is crucial in identifying precisely the process of gravitational collapse leading to the formation of the black hole and the emission of GRBs. Indeed, in this specific case, the Born-like nonlinear [42] term of the Heisenberg-Euler-Schwinger [24, 25] Lagrangian are radiated away prior to the formation of the horizon of the black hole (see e.g. Ruffini et al. [26]). Only the nonlinearity corresponding solely to the classical Einstein-Maxwell theory is left as the outcome of the gravitational collapse process.

The same effective potential technique (see Landau and Lifshitz [9]), which allowed the analysis of circular orbits around the black hole, was crucial in reaching the equally interesting discovery of the reversible and irreversible transformations of black holes by Christodoulou and Ruffini [11], which in turn led to the mass-energy formula of the black hole:

$$E^2_{BH} = M^2 c^4 = \left( M^2 c^2 + \frac{Q^2}{2 \rho_*} \right)^2 + \frac{L^2 c^2}{\rho_*^2},$$

(6)
with
\[ \frac{1}{\rho_+^2} \left( \frac{G^2}{c^4} \right) (Q^4 + 4L^2c^2) \leq 1, \] (7)

where
\[ S = 4\pi\rho_+^2 = 4\pi\left( r_+^2 + \frac{L^2}{c^2M_\bullet} \right) = 16\pi \left( \frac{G^2}{c^4} \right) M_\bullet^2, \] (8)
is the horizon surface area, \( M_\bullet \) is the irreducible mass, \( r_+ \) is the horizon radius and \( \rho_+ \) is the quasi-spheroidal cylindrical coordinate of the horizon evaluated at the equatorial plane. Extreme black holes satisfy the equality in Eq. (7).

From Eq. (6) follows that the total energy of the black hole \( E_{BH} \) can be split into three different parts: rest mass, Coulomb energy and rotational energy. In principle both Coulomb energy and rotational energy can be extracted from the black hole (Christodoulou and Ruffini [11]). The maximum extractable rotational energy is 29% and the maximum extractable Coulomb energy is 50% of the total energy, as clearly follows from the upper limit for the existence of a black hole, given by Eq. (7). We refer in the following to both these extractable energies as the blackholic energy.

The existence of the black hole and the basic correctness of the circular orbits has been proven by the observations of Cygnus-X1 (see e.g. Giacconi and Ruffini [6]). However, in binary X-ray sources, the black hole uniquely acts passively by generating the deep potential well in which the accretion process occurs. It has become tantalizing to look for astrophysical objects in order to verify the other fundamental prediction of general relativity that the blackholic energy is the largest energy extractable from any physical object.

As we shall see in the next section, the feasibility of the extraction of the blackholic energy has been made possible by the quantum processes of creating, out of classical fields, a plasma of electron-positron pairs in the field of black holes. The manifestation of such process of energy extraction from the black hole is astrophysically manifested by the occurrence of GRBs.

3.3. GRBs and quantum electro-dynamics

That a static electromagnetic field stronger than a critical value:
\[ E_c = \frac{m_e^2 c^3}{\hbar e} \] (9)
can polarize the vacuum and create electron-positron pairs was clearly evidenced by Heisenberg and Euler [24]. The major effort in verifying the correctness of this theoretical prediction has been directed in the analysis of heavy ion collisions (see Ruffini et al. [26] and references therein). From an order-of-magnitude estimate, it appears that around a nucleus with a charge:
\[ Z_e \approx \frac{\hbar c}{e^2} \approx 137 \] (10)
the electric field can be stronger than the electric field polarizing the vacuum. A more accurate detailed analysis taking into account the bound states levels around a nucleus brings to a value of

$$Z_c \approx 173$$

for the nuclear charge leading to the existence of a critical field. From the Heisenberg uncertainty principle it follows that, in order to create a pair, the existence of the critical field should last a time

$$\Delta t \sim \frac{\hbar}{m_e c^2} \approx 10^{-18} \text{s},$$

which is much longer than the typical confinement time in heavy ion collisions which is

$$\Delta t \sim \frac{\hbar}{m_{pe} c^2} \approx 10^{-21} \text{s}.$$  

This is certainly a reason why no evidence for pair creation in heavy ion collisions has been obtained although remarkable effort has been spent in various accelerators worldwide. Similar experiments involving laser beams encounter analogous difficulties (see e.g. Ruffini et al. [26] and references therein).

The alternative idea was advanced in 1975 [22] that the critical field condition given in Eq. (9) could be reached easily, and for a time much larger than the one given by Eq. (12), in the field of a Kerr-Newman black hole in a range of masses $3.2M_\odot \leq M_{BH} \leq 7.2 \times 10^8 M_\odot$. In that paper we have generalized to the curved Kerr-Newman geometry the fundamental theoretical framework developed in Minkowski space by Heisenberg-Euler [24] and Schwinger [25]. This result was made possible by the work on the structure of the Kerr-Newman spacetime previously done by Carter [38] and by the remarkable mathematical craftsmanship of Thibault Damour then working with me as a post-doc in Princeton.

The maximum energy extractable in such a process of creating a vast amount of electron-positron pairs around a black hole is given by:

$$E_{\text{max}} = 1.8 \times 10^{54} (M_{BH}/M_\odot) \text{ erg}.$$  

We concluded in that paper that such a process “naturally leads to a most simple model for the explanation of the recently discovered $\gamma$-rays bursts”.

At that time, GRBs had not yet been optically identified and nothing was known about their distance and consequently about their energetics. Literally thousands of theories existed in order to explain them and it was impossible to establish a rational dialogue with such an enormous number of alternative theories. We did not pursue further our model until the results of the BeppoSAX mission, which clearly pointed to the cosmological origin of GRBs, implying for the typical magnitude of their energy precisely the one predicted by our model.

It is interesting that the idea of using an electron-positron plasma as a basis of a GRB model was independently introduced years later in a set of papers by
Cavallo and Rees [43], Cavallo and Horstman [44] and Horstman and Cavallo [45]. These authors did not address the issue of the physical origin of their energy source. They reach their conclusions considering the pair creation and annihilation process occurring in the confinement of a large amount of energy in a region of dimension \( \sim 10 \text{ km} \) typical of a neutron star. No relation to the physics of black holes nor to the energy extraction process from a black hole was envisaged in their interesting considerations, mainly directed to the study of the opacity and the consequent dynamics of such an electron-positron plasma.

After the discovery of the afterglows and the optical identification of GRBs at cosmological distances, implying exactly the energetics predicted in Eq. (14), we returned to the analysis of the vacuum polarization process around a black hole and precisely identified the region around the black hole in which the vacuum polarization process and the consequent creation of electron-positron pairs occur. We defined this region, using the Greek name dyad for pairs (δυάν-δυάνος), to be the “dyadosphere” of the black hole, bounded by the black hole horizon and the dyadosphere radius \( r_{ds} \) given by [see Ruffini [46], Preparata et al. [47] and Fig. 8]:

\[
r_{ds} = \left( \frac{h}{mc} \right)^{\frac{1}{2}} \left( \frac{GM}{c^2} \right)^{\frac{1}{2}} \left( \frac{m_p}{m} \right)^{\frac{1}{2}} \left( \frac{e}{q_p} \right)^{\frac{1}{2}} \left( \frac{Q}{\sqrt{GM}} \right)^{\frac{1}{2}} = 1.12 \cdot 10^8 \sqrt{\mu} \xi \text{ cm}, \quad (15)
\]

where we have introduced the dimensionless mass and charge parameters \( \mu = M_{BH}/M_\odot, \xi = Q/(M_{BH}\sqrt{G}) \leq 1 \).

The analysis of the dyadosphere was developed, at that time, around an already formed black hole. In recent months we have been developing the dynamical formation of the black hole and correspondingly of the dyadosphere during the process
of gravitational collapse, reaching some specific signatures which may be detectable in the structure of the short and long GRBs (Cherubini et al. [49], Ruffini and Vitagliano [50, 51], Ruffini et al. [48, 52, 53]).

4. The Dynamical Phases Following the Dyadosphere Formation

Many details of this topic have been presented in great details in Ruffini et al. [27].

After the vacuum polarization process around a black hole, one of the topics of the greatest scientific interest is the analysis of the dynamics of the electron-positron plasma formed in the dyadosphere. This issue was addressed by us in a very effective collaboration with Jim Wilson at Livermore. The numerical simulations of this problem were developed at Livermore, while the semi-analytic approach was developed in Rome (Ruffini et al. [54]).

The corresponding treatment in the framework of the Cavallo et al. analysis was performed by Piran et al. [55] also using a numerical approach, by Bisnovatyi-Kogan and Murzina [56] using an analytic approach and by Mészáros, Laguna and Rees [57] using a numerical and semi-analytic approach.

Although some analogies exists between these treatments, they are significantly different in the theoretical details and in the final results. Since the final result of the GRB model is extremely sensitive to any departure from the correct treatment, it is indeed very important to detect at every step the appearance of possible fatal errors.

A conclusion common to all these treatments is that the electron-positron plasma is initially optically thick and expands till transparency reaching very high values of the Lorentz gamma factor. A second point, which is common, is the discovery of a new clear feature: the plasma shell expands but the Lorentz contraction is such that its width in the laboratory frame appears to be constant.

There is however a major difference between our approach and the ones of Piran, Mészáros and Rees, in that the dyadosphere is assumed by us to be filled uniquely with an electron-positron plasma. Such a plasma expands in substantial agreement with the results presented in the work of Bisnovatyi-Kogan and Murzina [56]. In our model the pulse of electron-positron pairs and photons (PEM Pulse, see Ruffini et al. [54]) evolves and at a radius on the order of 10^{10} cm it encounters the remnant of the star progenitor of the newly formed black hole. The PEM pulse is then loaded by baryons. A new pulse is formed of electron-positron-photons and baryons (PEMB Pulse, see Ruffini et al. [58]) which expands all the way until transparency is reached. At transparency the emitted photons give origin to what we define as the Proper-GRB (see Ruffini et al. [13] and Fig. 9).

In our approach, the baryon loading is measured by a dimensionless quantity

\[ B = \frac{M_B c^2}{E_{\text{syn}}} \]

which gives direct information about the mass \( M_B \) of the remnant. The correspond-
Figure 9. The optically thick phase of our model are qualitatively represented in this diagram. There are clearly recognizable 1) the PEM pulse phase, 2) the impact on the baryonic remnant, 3) the PEMB pulse phase and the final approach to transparency with the emission of the P-GRB (see Fig. 10). Details in Ruffini et al. [27].

ing treatment done by Piran and collaborators (Shemi & Piran [59], Piran et al. [55]) and by Mészáros, Laguna and Rees [57] differs in one important respect: the baryonic loading is assumed to occur since the beginning of the electron-positron pair formation and no relation to the mass of the remnant of the collapsed progenitor star is attributed to it.

A marked difference also exists between our description of the rate equation for the electron-positron pairs and the ones by those authors. While our results are comparable with the ones obtained by Piran under the same initial conditions, the set of approximations adopted by Mészáros, Laguna and Rees [57] appears to be too radical and leads to very different results violating energy and momentum conservation (see Bianco et al. [60]).

From our analysis (Ruffini et al. [58]) it also becomes clear that such expanding dynamical evolution can only occur for values of $B < 10^{-2}$. This prediction, as we will show shortly in the three GRB sources considered here, is very satisfactorily confirmed by observations.

From the value of the $B$ parameter, related to the mass of the remnant, it therefore follows that the collapse to a black hole leading to a GRB is drastically different from the collapse to a neutron star. While in the case of a neutron star collapse a very large amount of matter is expelled, in many instances well above the mass of the neutron star itself, in the case of black holes leading to a GRB only a very small fraction of the initial mass ($\sim 10^{-2}$ or less) is expelled. The collapse to a black hole giving rise to a GRB appears to be much smoother than any collapse process considered until today: almost 99.9% of the star has to be collapsing simultaneously!
386

Figure 10. The P-GRB emitted at the transparency point at a time of arrival $t_0^p$ which has been computed following the prescriptions of Eq. (3). Details in Ruffini et al. [13, 27].

We summarize in Figs. 9–10 the optically thick phase of GRBs in our model: we start from a given dyadosphere of energy $E_{\text{dyad}}$; the pair-electromagnetic pulse (PEM pulse) self-accelerates outward typically reaching Lorentz gamma factors $\gamma \sim 200$ at $r \sim 10^{10}$ cm; at this point the collision of the PEM pulse with the remnant of the progenitor star occurs with an abrupt decrease in the value of the Lorentz gamma factor; a new pair-electromagnetic-baryon pulse (PEMB pulse) is formed which self-accelerates outward until the system becomes transparent.

The photon emission at this transparency point is the Proper-GRB (P-GRB). An accelerated beam of baryons with an initial Lorentz gamma factor $\gamma_0$ starts to interact with the interstellar medium at typical distances from the black hole of $r_0 \sim 10^{14}$ cm and at a photon arrival time at the detector on the Earth surface of $t_0^p \sim 0.1$ s. These values determine the initial conditions of the afterglow.

5. The Description of the Afterglow

After reaching transparency and the emission of the P-GRB, the accelerated baryonic matter (the ABM pulse) interacts with the interstellar medium (ISM) and gives
rise to the afterglow (see Fig. 11). Also in the descriptions of this last phase many differences exist between our treatment and the other ones in the current literature.

5.1. The initial value problem

The initial conditions of the afterglow era are determined at the end of the optically thick era when the P-GRB is emitted. As recalled in the last section, the transparency condition is determined by a time of arrival $t_0$, a value of the gamma Lorentz factor $\gamma_0$, a value of the radial coordinate $r_0$, an amount of baryonic matter $M_B$ which are only functions of the two parameters $E_{\text{diss}}$ and $B$ (see Eq. (16)). It is appropriate here to emphasize again that, in order to have the expansion leading to an observed GRB, one must have $B < 10^{-2}$.

This connection to the optically thick era is missing in the current approach in the literature which attributes the origin of the "prompt radiation" to an unspecified inner engine activity (see Piran [28] and references therein). The initial conditions at the beginning of the afterglow era are obtained by a best fit of the later parts of the afterglow. This approach is quite unsatisfactory since, as we will explicitly show, the theoretical treatments currently adopted in the description of the afterglow are not correct. The fit using an incorrect theoretical treatment leads necessarily to the wrong conclusions as well as, in turn, to the determination of incorrect initial conditions.

5.2. The equations of the afterglow dynamics

Let us first summarize the commonalities between our approach and the ones in the current literature. In both cases (see Piran [28], Chiang & Dermer [61] and Ruffini
et al. [27]) a thin shell approximation is used to describe the collision between the ABM pulse and the ISM:

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

(17a) \hspace{1cm} (17b) \hspace{1cm} (17c) \hspace{1cm} (17d)

where \( E_{\text{int}} \), \( \gamma \) and \( M \) are respectively the internal energy, the Lorentz factor and the mass-energy of the expanding pulse, \( n_{\text{ism}} \) is the ISM number density which is assumed to be constant, \( m_p \) is the proton mass, \( \varepsilon \) is the emitted fraction of the energy developed in the collision with the ISM and \( M_{\text{ism}} \) is the amount of ISM mass swept up within the radius \( r \): \( M_{\text{ism}} = (4/3)\pi(r^3 - r_o^3)m_p n_{\text{ism}} \), where \( r_o \) is the starting radius of the shock front. In general, an additional condition is needed in order to determine \( \varepsilon \) as a function of the radial coordinate. In the following, \( \varepsilon \) is assumed to be constant and such an approximation appears to be correct in the GRB context.

In both our work and in the current literature (see Piran [28], Chiang & Dermer [61] and Ruffini et al. [27]) a first integral of these equations has been found, leading to expressions for the Lorentz gamma factor as a function of the radial coordinate. In the “fully adiabatic condition” (i.e. \( \varepsilon = 0 \)) we have:

\[ \gamma^2 = \frac{\gamma_o^2 + 2\gamma_o (M_{\text{ism}}/M_B) - (M_{\text{ism}}/M_B)^2}{1 + 2\gamma_o (M_{\text{ism}}/M_B) + (M_{\text{ism}}/M_B)^2}, \]  

(18)

while in the “fully radiative condition” (i.e. \( \varepsilon = 1 \)) we have:

\[ \gamma = \frac{1 + (M_{\text{ism}}/M_B) \left(1 + \gamma_o^{-1}\right) \left[1 + (1/2) (M_{\text{ism}}/M_B)\right]}{\gamma_o^{-1} + (M_{\text{ism}}/M_B) \left(1 + \gamma_o^{-1}\right) \left[1 + (1/2) (M_{\text{ism}}/M_B)\right]}, \]  

(19)

where \( \gamma_o \) and \( M_B \) are respectively the values of the Lorentz gamma factor and of the mass of the accelerated baryons at the beginning of the afterglow phase and \( r_o \) is the value of the radius \( r \) at the beginning of the afterglow phase.

A major difference between our treatment and the other ones in the current literature is that we have integrated the above equations analytically, obtaining the explicit analytic form of the equations of motion for the expanding shell in the afterglow for a constant ISM density. For the fully radiative case we have explicitly integrated the differential equation for \( \tau(t) \) in Eq. (19), recalling that \( \gamma^{-2} = 1 - |dv/(c dt)|^2 \), where \( t \) is the time in the laboratory reference frame. We have then obtained a new explicit analytic solution of the equations of motion for the relativistic shell in the entire range from the ultra-relativistic to the non-relativistic...
regimes:

\[
t = \frac{M_B - m_0^2}{2c\sqrt{c}} (r - r_a) + \frac{r_0 \sqrt{c}}{12c m_0^2 A^2} \ln \left\{ \frac{[A + (r/r_0)]^3 (A^3 + 1)}{A^3 + (r/r_0)^3 (A + 1)} \right\} - \frac{m_0^2 r_0}{8c\sqrt{c}} \\
+ t_0 + \frac{m_0^2 r_0}{8c\sqrt{c}} \left( \frac{r}{r_0} \right)^4 + \frac{r_0 \sqrt{3c}}{6c m_0^2 A^3} \left[ \arctan \frac{2(r/r_0) - A}{A\sqrt{3}} - \arctan \frac{2 - A}{A\sqrt{3}} \right] \tag{20}
\]

where \( A = \sqrt{(M_B - m_0^2)/m_0^2}, \ C = M_B^2(\gamma_0 - 1)/(\gamma_0 + 1) \) and \( m_0^2 = (4/3) \pi m_p n_{\text{sm}}^{\text{B}} g_0^3 \).

Correspondingly, in the adiabatic case we have:

\[
t = \left( \gamma_0 - \frac{m_0^2}{M_B} \right) \frac{r - r_a}{c\sqrt{\gamma_0^2 - 1}} + \frac{m_0^2}{4M_B r_0^2} \frac{r^4 - r_a^4}{c\sqrt{\gamma_0^2 - 1}} + t_0. \tag{21}
\]

In the current literature, following Blandford and McKee [62], a so-called "ultra-relativistic" approximation \( \gamma_0 \gg \gamma \gg 1 \) has been widely adopted by many authors to solve Eqs. (17d) (see e.g. Sari [63, 64], Waxman [65], Rees & Mészáros [66], Granot et al. [67], Panaitescu & Mészáros [68], Piran [28], Gruzinov & Waxman [69], van Paradijs et al. [70], Mészáros [71] and references therein). This leads to simple constant-index power-law relations:

\[
\gamma \propto r^{-a}, \tag{22a}
\]

with \( a = 3 \) in the fully radiative case and \( a = 3/2 \) in the fully adiabatic case. This simple relation is in stark contrast to the complexity of Eq. (19) and Eq. (18) respectively. In the same spirit, instead of Eq. (20) and Eq. (21), some authors have assumed the following much simpler approximation for the relation between the time and the radial coordinate of the expanding shell, both in the fully radiative and in the fully adiabatic cases:

\[
ct = r, \tag{22b}
\]

while others, like e.g. Panaitescu & Mészáros [68], have integrated the approximate Eq. (22a), obtaining:

\[
ct = r \left[ 1 + (4a + 2)^{-1} \gamma^{-2} (r) \right]. \tag{22c}
\]

Again, it is appropriate here to emphasize the stark contrast between Eqs. (22b), (22c) and the exact analytic solutions of Eqs. (17), expressed in Eqs. (20) and (21).

5.3. The equitemporal surfaces (EQTSs)

As pointed out long ago by Couderc [72], in all relativistic expansion the crucial geometrical quantities with respect to a physical observer are the "equitemporal surfaces" (EQTSs), namely the locus of source points of the signals arriving at the observer at the same time.
For a relativistically expanding spherically symmetric source the EQTSs are surfaces of revolution about the line of sight. The general expression for their profile, in the form $\theta = \hat{\theta}(r)$, corresponding to an arrival time $t_o$ of the photons at the detector, can be obtained from (see e.g. Ruffini et al. [27], Bianco and Ruffini [73, 74] and Figs. 12–14):

$$c t_o = c t (r) - r \cos \theta + r^*,$$  \hfill (23)

where $r^*$ is the initial size of the expanding source, $\theta$ is the angle between the radial expansion velocity of a point on its surface and the line of sight, and $t = t(r)$ is its equation of motion, expressed in the laboratory frame, obtained by the integration of Eqs. (17). From the definition of the Lorentz gamma factor $\gamma^{-2} = 1 - (dr/cd\theta)^2$, we have in fact:

$$c t (r) = \int_0^r [1 - \gamma^{-2} (r')]^{-1/2} dr',$$  \hfill (24)

where $\gamma(r)$ comes from the integration of Eqs. (17).
Figure 13. The diameter of the visible area is represented as a function of the ABM pulse radius. In the earliest expansion phases ($\gamma \sim 300$) $\vartheta_{\text{max}}$ is very small (see left pass and Fig. 14), so the visible area is just a small fraction of the total ABM pulse surface. On the other hand, in the final expansion phases $\vartheta_{\text{max}} \rightarrow 90^\circ$ and almost all the ABM pulse surface becomes visible. Details in Ruffini et al. [75, 27]

We have obtained the expressions in the adiabatic case and in the fully radiative cases respectively (see Bianco and Ruffini [74]):

$$\cos \vartheta = \frac{m^2}{4M_B \sqrt{\gamma^2 - 1}} \left[ \left( \frac{r}{r_0} \right)^3 - \frac{r_0}{r} \right] + \frac{c t_o}{r}$$

$$- \frac{c t_o}{r} + \frac{r^*}{r} - \frac{r_0 - (m^2/M_B)}{\sqrt{\gamma^2 - 1}} \left[ \frac{r_0}{r} - 1 \right].$$

(25)

$$\cos \vartheta = \frac{M_B - m^2}{2r \sqrt{C}} (r - r_0) + \frac{m^2 r_0}{8r \sqrt{C}} \left( \frac{r}{r_0} \right)^4 - 1$$

$$+ \frac{r_0 \sqrt{C}}{12rm^2 A^2} \ln \left[ \frac{[A + (r/r_0)^2] A^3 + 1}{[A^3 + (r/r_0)^3] (A + 1)^3} \right] + \frac{c t_o}{r} - \frac{c t_o}{r}$$

$$+ \frac{r^*}{r} + \frac{r_0 \sqrt{C}}{6rm^2 A^2} \left[ \arctan \frac{2(r/r_0) - A}{A \sqrt{3}} - \arctan \frac{2 - A}{A \sqrt{3}} \right].$$

(26)
Figure 14. This figure shows the temporal evolution of the visible area of the ABM pulse. The dashed half-circles are the expanding ABM pulse at radii corresponding to different laboratory times. The black curve marks the boundary of the visible region. The black hole is located at position (0,0) in this plot. Again, in the earliest GRB phases the visible region is squeezed along the line of sight, while in the final part of the afterglow phase almost all the emitted photons reach the observer. This time evolution of the visible area is crucial to the explanation of the GRB temporal structure. Details in Ruffini et al. [75, 27].

The two EQTs are represented at selected values of the arrival time $t_0$ in Fig. 16, where the illustrative case of GRB 991216 has been used as a prototype. The initial conditions at the beginning of the afterglow era are in this case given by $\gamma_0 = 310.131$, $r_0 = 1.943 \times 10^{14}$ cm, $t_0 = 6.481 \times 10^3$ s, $r^* = 2.354 \times 10^9$ cm (see Ruffini et al. [12, 13, 75, 27]).

5.4. The bolometric luminosity of the source

We assume that the internal energy due to kinetic collision is instantly radiated away and that the corresponding emission is isotropic. As in Section 5.2, let $\Delta x$ be the internal energy density developed in the collision. In the comoving frame the
Figure 15. Due to the extremely high and extremely varying Lorentz gamma factor, photons reaching the detector on the Earth at the same arrival time are actually emitted at very different times and positions. We represent here the surfaces of photon emission corresponding to selected values of the photon arrival time at the detector: the \textit{equi-temporal surfaces} (EQTS). Such surfaces differ from the ellipsoids described by Rees in the context of the expanding radio sources with typical Lorentz factor $\gamma \sim 4$ and constant. In fact, in GRB 991216 the Lorentz gamma factor ranges from 310 to 1. The EQTSs represented here (solid lines) correspond respectively to values of the arrival time ranging from 5 s (the smallest surface on the left of the plot) to 60 s (the largest one on the right). Each surface differs from the previous one by 5 s. To each EQTS contributes emission processes occurring at different values of the Lorentz gamma factor. The dashed lines are the boundaries of the visible area of the ABM pulse and the black hole is located at position $(0, 0)$ in this plot. Note the different scales on the two axes, indicating the very high EQTS “effective eccentricity”. The time interval from 5 s to 60 s has been chosen to encompass the E-APR emission, ranging from $\gamma = 308.8$ to $\gamma = 56.84$. Details in Ruffini et al. [75, 27]

energy per unit of volume and per solid angle is simply

$$\left( \frac{dE}{dV d\Omega} \right) = \frac{\Delta \varepsilon}{4\pi}$$

(27)

due to the fact that the emission is isotropic in this frame. The total number of photons emitted is an invariant quantity independent of the frame used. Thus we can compute this quantity as seen by an observer in the comoving frame (which we denote with the subscript “$c$”) and by an observer in the laboratory frame (which
Figure 16. Comparison between EQTSs in the adiabatic regime (solid lines) and in the fully radiative regime (dashed lines). The upper plot shows the EQTSs for $t_a = 5$ s, $t_a = 15$ s, $t_a = 30$ s and $t_a = 45$ s, respectively from the inner to the outer one. The lower plot shows the EQTS at an arrival time of 2 days. Details in Bianco and Ruffini [74].
we denote with no subscripts). Doing this we find:

$$\frac{dN_\gamma}{dt d\Omega d\Sigma} = \left( \frac{dN_\gamma}{dt d\Omega d\Sigma} \right)_\circ \Lambda^{-3} \cos \theta,$$

(28)

where \( \cos \theta \) comes from the projection of the elementary surface of the shell on the direction of propagation and \( \Lambda = \gamma(1 - \beta \cos \theta) \) is the Doppler factor introduced in the two following differential transformations

$$d\Omega_\circ = d\Omega \times \Lambda^{-2}$$

(29)

for the solid angle transformation and

$$dt_\circ = dt \times \Lambda^{-1}$$

(30)

for the time transformation. The integration in \( d\Sigma \) is performed over the visible area of the ABM pulse at laboratory time \( t \), namely with \( 0 \leq \theta \leq \theta_{\text{max}} \) and \( \theta_{\text{max}} \) defined in Section 5.3 (see Figs. 12–14). An extra \( \Lambda \) factor comes from the energy transformation:

$$E_\circ = E \times \Lambda.$$  

(31)

See also Chiang and Dermer [61]. Thus finally we obtain:

$$\frac{dE}{dt d\Omega d\Sigma} = \left( \frac{dE}{dt d\Omega d\Sigma} \right)_\circ \Lambda^{-4} \cos \theta.$$ 

(32)

Doing this we clearly identify \( \left( \frac{dE}{dt d\Omega d\Sigma} \right)_\circ \) as the energy density in the comoving frame up to a factor \( \frac{\Delta \varepsilon}{4\pi} \) (see Eq. (27)). Then we have:

$$\frac{dE}{dt d\Omega} = \int_{\Omega_{\text{shell}}} \frac{\Delta \varepsilon}{4\pi} v \cos \theta \Lambda^{-4} \, d\Sigma,$$

(33)

where the integration in \( d\Sigma \) is performed over the ABM pulse visible area at laboratory time \( t \), namely with \( 0 \leq \theta \leq \theta_{\text{max}} \) and \( \theta_{\text{max}} \) defined in Section 5.3. Eq. (33) gives us the energy emitted toward the observer per unit solid angle and per unit laboratory time \( t \) in the laboratory frame.

What we really need is the energy emitted per unit solid angle and per unit detector arrival time \( t_\circ \), so we must use the complete relation between \( t_\circ \) and \( t \) given in Eq. (23). First we have to multiply the integrand in Eq. (33) by the factor \( (dt/dt_\circ) \) to transform the energy density generated per unit of laboratory time \( t \) into the energy density generated per unit arrival time \( t_\circ \). Then we have to integrate with respect to \( d\Sigma \) over the equitemporal surface (EQTS, see Section 5.3) of constant arrival time \( t_\circ \) instead of the ABM pulse visible area at laboratory time \( t \). The analog of Eq. (33) for the source luminosity in detector arrival time is then:

$$\frac{dE_\gamma}{dt_\circ d\Omega} = \int_{\text{EQTS}} \frac{\Delta \varepsilon}{4\pi} v \cos \theta \Lambda^{-4} \frac{dt}{dt_\circ} d\Sigma.$$ 

(34)
It is important to note that, in the present case of GRB 991216, the Doppler factor $\Delta^{-4}$ in Eq. (34) enhances the apparent luminosity of the burst, as compared to the intrinsic luminosity, by a factor which at the peak of the afterglow is in the range between $10^{10}$ and $10^{12}$!

We are now able to reproduce in Fig. 17 the general behavior of the luminosity starting from the P-GRB to the latest phases of the afterglow as a function of the arrival time. It is generally agreed that the GRB afterglow originates from an ultrarelativistic shell of baryons with an initial Lorentz factor $\gamma_0 \sim 200–300$ with respect to the interstellar medium (see e.g. Ruffini et al. [27], Bianco & Ruffini [73] and references therein). Using GRB 991216 as a prototype, in Ruffini et al. [12, 13] we have shown how from the time varying bolometric intensity of the afterglow it is possible to infer the average density $\langle n_{\text{ism}} \rangle = 1 \text{ particle/cm}^3$ of the Interstellar Medium (ISM) in a region of approximately $10^{17}$ cm surrounding the black hole giving rise to the GRB phenomenon.

It was shown in Ruffini et al. [75] that the theoretical interpretation of the intensity variations in the prompt phase in the afterglow implies the presence in the ISM of inhomogeneities of typical scale $10^{15}$ cm. Such inhomogeneities were there represented for simplicity as spherically symmetric over-dense regions with
Figure 18. The detailed features of GRB 991216 evidenced by our theoretical models are here reproduced. The P-GRB, the "prompt radiation" and what is generally called the afterglow. It is clear that the prompt radiation coincides with the extended afterglow peak emission (E-APE) and has been considered as a burst only as a consequence of the high noise threshold in the observations. Details in Ruffini et al. [75, 27].

\[ \langle n_{\text{ion}} \rangle \approx 10^2 \langle n_{\text{ion}} \rangle \text{ separated by under-dense regions with } \langle n_{\text{ion}} \rangle \approx 10^{-2} \langle n_{\text{ion}} \rangle \text{ also of typical scale } \sim 10^{15} \text{ cm in order to keep } \langle n_{\text{ion}} \rangle \text{ constant.} \]

The summary of these general results are shown in Fig. 18, where the P-GRB, the emission at the peak of the afterglow in relation to the "prompt emission" and the latest part of the afterglow are clearly identified for the source GRB 991216. Details in Ruffini et al. [27].

6. The Theory of the Luminosity in Fixed Energy Bands and Spectra of the Afterglow

Having obtained a general agreement between the observed luminosity variability and our treatment of the bolometric luminosity, we have further developed the model in order to explain

(a) the details of the observed luminosity in fixed energy bands, which are the ones actually measured by the detectors on the satellites,
(b) the instantaneous as well as the average spectral distribution in the entire afterglow and
(c) the observed hard to soft drift observed in GRB spectra.

In order to do so we have developed (Ruffini et al. [77]) a more detailed theory of the structure of the shock front giving rise to the afterglow. We have modeled the interaction between the ultrarelativistic shell of baryons and the ISM by a shock front with three well-defined layers (see e.g. Secs. 85–89, 135 of Landau & Lifshitz [78], ch. 2 and Secs. 13–15 of Zel’’dovich & Raizer [79] and Sec. IV, 11–13 of Sedov [80]). From the back end to the leading edge of this shock front there is:

(a) A compressed high-temperature layer, of thickness \( \Delta' \), in front of the relativistic baryonic shell, created by the accumulated material swept up in the ISM.

(b) A thin shock front, with a jump \( \Delta T \) in the temperature which has been traditionally estimated in the comoving frame by the Rankine–Hugoniot adiabatic equations:

\[
\Delta T \simeq (3/16) m_p \delta v^2/k \approx 1.5 \times 10^{11} \left[ \delta v/(10^5 \text{km s}^{-1}) \right]^2 K, \tag{35}
\]

where \( \delta v \) is the velocity jump, \( m_p \) is the proton mass and \( k \) is Boltzmann’s constant. Of course such a treatment, valid for \( \gamma \sim 1 \), has to be modified (see below) in our novel treatment for the \( \gamma \sim 200 \) case relevant to GRBs.

(c) A pre-shock layer of ISM swept-up matter at much lower density and temperature, both of which change abruptly at the thin shock front behind it.

At larger distances ahead of the expanding fireball the ISM is at still smaller densities. The upper limit to the temperature jump at the thin shock front, given in Eq. (35), is due to the transformation of kinetic energy to thermal energy, since the particle mean free path is assumed to be less than the thickness of the layer (a). The thermal emission of the observed X- and gamma ray radiation, which as seen from the observations reveals a high level of stability, is emitted in the above region (a) due to the sharp temperature gradient at the thin shock front described in the above region (b).

The optical and radio emission comes in our model from the extended region (c). The description of such a region, unlike the sharp and well-defined temperature gradient occurring in region (b), requires magnetohydrodynamic simulations of the evolution of the electron energy distribution of the synchrotron emission. Such analysis has been performed using 3-D Eulerian MHD codes for the particle acceleration models to produce the energy spectrum of cosmic rays at supernova envelope fronts (see e.g. McKee and Cowie [81], Tenorio-Tagle et al. [82], Stone and Norman [83], Jun & Jones [84]). Other challenges are the magnetic field and the instabilities. We mention two key phenomena: first, the importance of the development of Kelvin-Helmholtz and Rayleigh-Taylor instabilities ahead of the thin shock front. The second is the dual effect that the shock front has on the ISM initial magnetic field, first through the compression of the swept-up matter containing the field
and secondly the amplification of the radial magnetic field component due to the Rayleigh-Taylor instability. Simulations of both effects (see e.g. Jun and Jones [84] and references therein), modeling the synchrotron radio emission for an expanding supernova shell at various initial magnetic field and ISM parameter values, shows for example that the presence of an initial tangential magnetic field component may essentially affect the resulting magnetic field configuration and hence the outgoing radio flux and spectrum. Among the additional effects to be taken into account are the initial inhomogeneity of the ISM and the contribution of magnetohydrodynamic turbulence.

In our approach we focus uniquely on the X- and gamma ray radiation, which appears to be conceptually much simpler than the optical and radio emission. It is perfectly predictable by a set of constitutive equations (see next section), which leads to directly verifiable and very stable features in the spectral distribution of the observed GRB afterglows. In line with the observations of GRB 991216 and other GRB sources, we assume in the following that the X- and gamma ray luminosity represents approximately 90% of the energy flux of the afterglow, while the optical and radio emission represents only the remaining 10%.

This approach differs significantly from the other ones in the current literature, where attempts are made to explain at once all the multi-wavelength emission in the radio, optical, X and gamma ray as coming from a common origin which is linked to boosted synchrotron emission. Such an approach has been shown to have a variety of difficulties [Ghirlanda et al. [85], Preece et al. [96]) and cannot anyway have the instantaneous variability needed to explain the structure in the “prompt radiation” in an external shock scenario, which is indeed confirmed by our model.

6.1. The equations determining the luminosity in fixed energy bands

Here the fundamental new assumption is adopted (see also Ruffini et al. [87]) that the X- and gamma ray radiation during the entire afterglow phase has a thermal spectrum in the co-moving frame. The temperature is then given by:

\[ T_i = \left( \Delta E_{\text{int}} / \left( 4\pi r^2 \Delta \tau \sigma R \right) \right)^{1/4} \]

where \( \Delta E_{\text{int}} \) is the internal energy developed in the collision with the ISM in a time interval \( \Delta \tau \) in the co-moving frame, \( \sigma \) is the Stefan-Boltzmann constant and

\[ R = A_{\text{eff}} / A. \]

is the ratio between the “effective emitting area” of the afterglow and the surface area of radius \( r \). In GRB 991216 such a factor is observed to be decreasing during the afterglow between: \( 3.01 \times 10^{-8} \geq R \geq 5.01 \times 10^{-12} \) (Ruffini et al. [87]).

The temperature in the comoving frame corresponding to the density distribution described in Ruffini et al. [75] is shown in Fig. 19.
We are now ready to evaluate the source luminosity in a given energy band. The source luminosity at a detector arrival time $t_d$, per unit solid angle $d\Omega$ and in the energy band $[\nu_1, \nu_2]$ is given by (see Ruffini et al. [27, 87]):

$$\frac{dE^{[\nu_1, \nu_2]}_{\text{in}}}{dE_d d\Omega} = \frac{\Delta \varepsilon}{4\pi} v \cos \vartheta \Lambda^{-4} \frac{dt}{d\varpi} W(\nu_1, \nu_2, T_\text{arr}) d\Sigma, \quad (38)$$

where $\Delta \varepsilon = \Delta E_{\text{int}} / V$ is the energy density released in the interaction of the ABM pulse with the ISM inhomogeneities measured in the comoving frame, $\Lambda = \gamma (1 - (v/c) \cos \vartheta)$ is the Doppler factor, $W(\nu_1, \nu_2, T_\text{arr})$ is an “effective weight” required to evaluate only the contributions in the energy band $[\nu_1, \nu_2]$, $d\Sigma$ is the surface element of the EQTS at detector arrival time $t_d$, on which the integration is performed (see also Ruffini et al. [75]) and $T_\text{arr}$ is the observed temperature of the radiation emitted from $d\Sigma$:

$$T_\text{arr} = T_S / [\gamma (1 - (v/c) \cos \vartheta)(1 + z)]. \quad (39)$$

The “effective weight” $W(\nu_1, \nu_2, T_\text{arr})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature $T_\text{arr}$. to the total
integral $aT_{\text{arr}}^4$:

\[ W(\nu_1, \nu_2, T_{\text{arr}}) = \frac{1}{aT_{\text{arr}}^4} \int_{\nu_1}^{\nu_2} \rho(T_{\text{arr}}, \nu) d \left( \frac{\hbar \nu}{c} \right)^3, \]

where $\rho(T_{\text{arr}}, \nu)$ is the Planckian distribution at temperature $T_{\text{arr}}$:

\[ \rho(T_{\text{arr}}, \nu) = \frac{(2/\hbar^2) \hbar \nu}{e^{\hbar \nu/(kT_{\text{arr}})} - 1} \]


We turn now to the much debated issue of the origin of the observed hard-to-soft spectral transition during the GRB observations (see e.g. Frontera et al. [88], Ghirlanda et al. [85], Piran [28], Piro et al. [89]). We consider the instantaneous spectral distribution of the observed radiation for three different EQTSs:

- $\tau_a^d = 10$ s, in the early radiation phase near the peak of the luminosity,
- $\tau_a^d = 1.45 \times 10^5$ s, in the last observation of the afterglow by the Chandra satellite, and
- $\tau_a^d = 10^4$ s, chosen in between the other two (see Fig. 20).

![Figure 20](https://via.placeholder.com/150)

Figure 20. The instantaneous spectra of the radiation observed in GRB 991216 at three different EQTS respectively, from top to bottom, for $\tau_a^d = 10$ s, $\tau_a^d = 10^4$ s and $\tau_a^d = 1.45 \times 10^5$ s. These diagrams have been computed assuming a constant ($n_{\text{ion}}(z) \approx 1$ particle/cm$^3$) and clearly explains the often quoted hard-to-soft spectral evolution in GRBs. Details in Ruffini et al. [87].
The observed hard-to-soft spectral transition is then explained and traced back to:

1. A time decreasing temperature of the thermal spectrum measured in the comoving frame,
2. The GRB equations of motion,
3. The corresponding infinite set of relativistic transformations.

A clear signature of our model is the existence of a common low-energy behavior of the instantaneous spectrum represented by a power-law with index $\alpha = -0.9$. This prediction will be possibly verified in future observations.

Starting from these instantaneous values, we integrate the spectra in arrival time obtaining what is usually fit in the literature by the “Band relation” (Band et al. [90]). Indeed we find for our integrated spectra a low energy spectral index $\alpha = -1.05$ and an high energy spectral index $\beta < -16$ when interpreted within the framework of a Band relation (see Fig. 21). This theoretical result can be submitted to a direct confrontation with the observations of GRB 991216 and, most importantly, the entire theoretical framework which we have developed can now be applied to any GRB source. The theoretical predictions on the luminosity in fixed energy bands so obtained can be then straightforwardly confronted with the observational data.
8. The Three Paradigms for the Interpretation of GRBs

Having outlined the main features of our model and shown its application to GRB 991216 used as a prototype, before addressing the two new sources which are going to be the focus of this presentation, we recall the three paradigms for the interpretation of GRBs we had previously introduced.

The first paradigm, the relative space-time transformation (RSTT) paradigm (Ruffini et al. [12]) emphasizes the importance of a global analysis of the GRB phenomenon encompassing both the optically thick and the afterglow phases. Since all the data are received in the detector arrival time it is essential to know the equations of motion of all relativistic phases with $\gamma > 1$ of the GRB sources in order to reconstruct the time coordinate in the laboratory frame, see Eq. (3). Contrary to other phenomena in nonrelativistic physics or astrophysics, where every phase can be examined separately from the others, in the case of GRBs all the phases are inter-related by their signals received in arrival time $t^a_\gamma$. There is the need, in order to describe the physics of the source, to derive the laboratory time $t$ as a function of the arrival time $t^a_\gamma$ along the entire past worldline of the source using Eq. (4).

The second paradigm, the interpretation of the burst structure (IBS) paradigm (Ruffini et al. [13]) covers three fundamental issues:

(a) the existence, in the general GRB, of two different components: the P-GRB and the afterglow related by precise equations determining their relative amplitude and temporal sequence (see Ruffini et al. [27]);

(b) what in the literature has been addressed as the “prompt emission” and considered as a burst, in our model is not a burst at all — instead it is just the emission from the peak of the afterglow (see Fig. 18);

(c) the crucial role of the parameter $B$ in determining the relative amplitude of the P-GRB to the afterglow and discriminating between the short and the long bursts (see Fig. 22). Both short and long bursts arise from the same physical phenomena: the dyadosphere. The absence of baryonic matter in the remnant leads to the short bursts and no afterglow. The presence of baryonic matter with $B < 10^{-2}$ leads to the afterglow and consequently to its peak emission which gives origin to the so-called long bursts.

The third paradigm, the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [14]), deals with the relation of the GRB and the associated supernova process, and acquires a special meaning in relation to the sources GRB 980425 and GRB 030329 as we will show in the following.

We now shortly illustrate some consequences of these three paradigms.

8.1. Long bursts are E-APEs

The order of magnitude estimate usually quoted for the the characteristic time scale to be expected for a burst emitted by a GRB at the moment of transparency at the
end of the expansion of the optically thick phase is given by \( \tau \sim GM/c^3 \), which for a 10\( M_\odot \) black hole will give \( \sim 10^{-3} \) s. There are reasons today not to take seriously such an order of magnitude estimate (see e.g. Ruffini et al. [53]). In any case this time is much shorter than the ones typically observed in “prompt radiation” of the long bursts, from a few seconds all the way to 10\(^2\) s. In the current literature (see e.g. Piran [28] and references therein), in order to explain the “prompt radiation” and overcome the above difficulty it has been generally assumed that its origin should be related to a prolonged “inner engine” activity preceding the afterglow which is not well identified.

To us this explanation has always appeared logically inconsistent since there remain to be explained not one but two very different mechanisms, independent of each other, of similar and extremely large energetics. This approach has generated an additional very negative result: it has distracted everybody working in the field from the earlier very interesting work on the optically thick phase of GRBs.

The way out of this dichotomy in our model is drastically different: 1) indeed the optically thick phase exists, is crucial to the GRB phenomenon and terminates with a burst: the P-GRB; 2) the “prompt radiation” follows the P-GRB; 3) the “prompt radiation” is not a burst: it is actually the temporally extended peak emission of the afterglow (E-APE). The observed structures of the prompt radiation can all be traced back to inhomogeneities in the interstellar medium (see Fig. 18 and Ruffini et al. [75]).
8.2. Short bursts are P-GRBs

The fundamental diagram determining the relative intensity of the P-GRB and the afterglow as a function of the dimensionless parameter $B$ has been shown in Fig. 22. The underlying machine generating the short and the long GRBs is identical: in both cases is the dyadosphere. The main difference relates to the amount of baryonic matter engulfed by the electron-positron plasma in their optically thick phase prior to transparency. In the limit of small $B < 10^{-5}$ the intensity of the P-GRB is larger and dominates the afterglow. This corresponds to the short bursts. For $10^{-5} < B < 10^{-2}$ the afterglow dominates the GRBs and we have the so-called “long bursts”. For $B > 10^{-2}$ we may observe a third class of “bursts”, eventually related to a turbulent process occurring prior to transparency (Ruffini et al. [58]). This third family should be characterized by smaller values of the Lorentz gamma factors than in the case of the short or long bursts.

8.3. The trigger of multiple gravitational collapses

The relation between the GRBs and the supernovae is one of the most complex aspects to be addressed by our model, which needs the understanding of new fields of general relativistic physics in relation to yet unexplored many-body solutions in a substantially new astrophysical scenario.

As we will show in the two systems GRB980425/ SN1998bw and GRB030329/ SN2003dh which we are going to discuss next, there is in each one the possibility of an astrophysical “triptych”\(^{e}\) formed by:

1. the formation of the black hole and the emission of the GRB,
2. the gravitational collapse of an evolved companion star, leading to a supernova,
3. a clearly identified URCA source whose nature appears to be of the greatest interest.

This new astrophysical scenario presents new challenges:

(a) The identification of the physical reasons of the instability leading to the gravitational collapse of a $\sim 10M_\odot$ star, giving origin to the black hole. Such an implosion must occur radially with negligible mass of the remnant ($B < 10^{-2}$).
(b) The identification of the physical reasons for the instability leading to the gravitational collapse of an evolved companion star, giving origin to the supernova.
(c) The theoretical issues related to the URCA sources, which range today in many possible directions: from the physics of black holes, to the physical processes occurring in the expanding supernova remnants, and finally to the very exciting possibility that we are observing for the first time a newly born neutron star.

---

4 A picture or carving in three panels side by side; esp: an altarpiece with a central panel and two flanking panels half its size that fold over it [Webster’s New collegiate dictionary, G. & C. Merriam Co. (Springfield, Massachusetts, U.S.A., 1977)]
we have reached for the GRB phenomenon and its afterglow allows us to state, convincingly, that the URCA source, contrary to what established in the current literature, is not part of the GRB nor of its afterglow.

We will draw in the conclusions some considerations on the possible nature of the URCA sources.

9. Applications

We illustrate the application of our GRB model to two different systems, which are quite different in the energetics but are both related to supernovae: GRB 980425 and GRB 030329. We will let the gradual theoretical understanding of the system to unveil the underlying astrophysical scenario.

9.1. GRB 980425/SN 1998bw

Approaches in the current literature have always attempted to explain both the supernova and the GRB as two aspects of a single phenomenon assuming that the GRB takes its origin from a specially strong and yet unobserved supernova process: a hypernova (see Paczynski [91], Kulkarni [92], Iwamoto [93]).

We have taken a very different approach, following Cicero’s classic aphorism “divide et impera”, which was adopted as the motto of the Roman empire: “divide and conquer”. In this specific case of GRBs, which are indeed a very complex system, we plan to divide and identify the truly independent physical constituents and conquer the understanding of the underlying astrophysical process. As we will see, this approach will lead to an unexpected and much richer scenario.

In addition to the source GRB 980425 and the supernova SN1998bw, two X-ray sources have been found by BeppoSAX in the error box for the location of GRB 980425: a source S1 and a source S2 (Pian et al. [94]), which have been traditionally interpreted either as a background source or as a part of the GRB afterglow. See Fig. 23. Our approach has been: to first comprehend the entire afterglow of GRB 980425 within our theory. This allows the computation of the luminosity in given energy bands, the spectra, the Lorentz gamma factors, and more generally of all the dynamical aspects of the source. Having characterized the features of GRB 980425, we can gradually approach the remaining part of the scenario, disentangling the GRB observations from those of the supernova and then disentangling both the GRB and the supernova observations from those of the sources S1 and S2. This leads to a natural identification of distinct events and to their autonomous astrophysical characterization.

Our best fit for GRB 980425 corresponds to $E_{\text{syn}} = 1.1 \times 10^{48}$ ergs, $B = 7 \times 10^{-3}$ and the ISM average density is found to be $\langle n_{\text{ISM}} \rangle = 0.02$ particle/cm$^3$. The plasma temperature and the total number of pairs in the dyadosphere are respectively $T = 1.028$ MeV and $N_{e,8} = 5.3274 \times 10^{53}$. The light curve of the GRB is shown in
Figs. 24–25. The P-GRB is under the threshold and in the case of this source is not observable (see Ruffini et al. [15], Fraschetti et al. [16]).

The characteristic parameter $R$, defining the filamentary structure of the ISM, monotonically decreases from $4.81 \times 10^{-10}$ to $2.65 \times 10^{-12}$). The results are given in Fig. 26 where the bolometric luminosity is represented together with the optical data of SN1998bw, the source $S1$ and the source $S2$. It is then clear that GRB 980425 is separated both from the supernova data and from the sources $S1$ and $S2$.

While the occurrence of the supernova in relation to the GRB has already been discussed within the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al. [14]), we like to address here a different fundamental issue: the nature of the source $S1$ which we have named, in celebration of the work of Gamow and Shoenberg, URCA-1. It is clear, from the theoretical predictions of the afterglow luminosity, that the URCA-1 cannot be part of the afterglow (see Figs. 24, 26). There are three different possibilities for the explanation of such source:

1. Its possible relation to the black hole formed during the process of gravitational collapse leading to the GRB emission.
(2) Its possible relation to emission originating in the early phases of the expansion of the supernova remnant.

(3) The very exciting possibility that for the first time we are observing a newly born neutron star out of the supernova phenomenon.

While some general considerations will be discussed in the conclusions, we would like to stress here the paramount importance of following the further time history of URCA-1 and of the source S2. If, as we propose, S2 is a background source, its flux should be practically constant in time and this source has nothing to do with the GRB 980425/SN1998bw system. The drastic behavior of the URCA-1 luminosity reported in the talk by Elena Pian in this meeting, showing the latest URCA-1 observations by the XMM and Chandra satellites, is crucial for the understanding of the nature of this source. Some very qualitative luminosity curves are sketched in Fig. 20, illustrating the possible time evolution of URCA-1. They are still very undetermined today due to a lack of attention to these observational data and, consequently, to the lack of a detailed theoretical model of the phenomenon. We therefore propose to have a dedicated attention to the astrophysical “triptych” GRB 980425/SN 1998bw/URCA-1.
The prompt emission of GRB 980425 and the fit in the EMBH model

Figure 25. The observation by BeppoSAX of the peak of the afterglow in the 40–700 keV energy band is fitted by our model.

9.2. GRB 030329/SN 2003dh

We have adopted for our modeling of GRB030329 a spherically symmetric distribution for the source and, as initial conditions at $t = 10^{-21}$ s, an $e^+e^-$-photon neutral plasma lying between the radii $r_1 = 2.9 \times 10^6$ cm and $r_2 = 9.0 \times 10^7$ cm. The temperature of such a plasma is 2.1 MeV, the total energy $E_{\text{tot}} = 2.1 \times 10^{52}$ erg and the total number of pairs $N_{e^+e^-} = 1.1 \times 10^{57}$. The baryonic matter component $M_B$ is the second free parameter of our theory: $B = 4.8 \times 10^{-3}$. At the emission of the P-GRB, the Lorentz gamma factor is $\gamma_v = 183.6$ and the radial coordinate is $r_e = 5.3 \times 10^{13}$ cm. The ISM average density is best fit by $\langle n_{\text{ISM}} \rangle = 1$ particle/cm$^3$.

The third free parameter of our theory is given by $1.1 \times 10^{-7} < \mathcal{R} < 5.0 \times 10^{-11}$.

We then obtain (see also Bernardini et al. [96] in these proceedings) for the GRB 030329 the luminosities in given energy bands, computed in the range 2–400 keV with very high accuracy. Figures 27–30 shows the results for the luminosities in the 30–400 keV and 2–10 keV bands, including the “prompt radiation”. Subsequently, the theoretically predicted GRB spectra have been evaluated at selected values of the arrival time (Ruffini et al. [97]).
The splendid news received the evening before the presentation of this talk is graphically represented by the XMM observations shown in Fig. 30. Again, the XMM observations, like the corresponding ones of GRB 980425, occur after the decaying part of the afterglow and, in analogy to the one occurring in the system GRB 980425/SN 1998bw/URCA-1, we call this source URCA-2. Further observations by XMM are highly recommended to follow the URCA-2 temporal evolution. Also in this system we are dealing with an astrophysical “triptych”: GRB 030329/SN 2003dh/URCA-2.

10. Conclusions

10.1. On the GRB–Supernova connection

We first stress some general considerations originating from comparing and contrasting the three GRB sources we have discussed:

(1) The value of the $B$ parameter for all three sources occurs, as theoretically expected, in the allowed range (see Fig. 22)
Figure 27. The luminosity in the 2–10 keV and in the 30–400 keV energy bands predicted by our model are fitted to the data of RXTE (GCN Circ. 1996 [98]) and HETE-2 (GCN Circ. 1997 [99]) respectively. The SN 2005dh optical luminosity is given by the crosses (Hjorth et al. [100]). Details in Bernardini et al. [96].

Figure 28. The details of the theoretical fit of the prompt radiation of GRB 030329 have been reproduced by the filamentary structure in the ISM in our model. Details in Bernardini et al. [96].
Figure 29. The perfect fit of the late part of the afterglow of our theoretical model for the 2–10 keV energy bands. The data refers to the RXTE observations (GCN Circ. 1996 [98]). Details in Bernardini et al. [96].

\[ 10^{-5} \leq B \leq 10^{-2} \]  

(42)

We have in fact:

GRB 991216 \( B = 3.0 \times 10^{-3} \) \( E_{\text{syn}} = 4.8 \times 10^{53} \) erg

GRB 980425 \( B = 7.0 \times 10^{-3} \) \( E_{\text{syn}} = 1.1 \times 10^{58} \) erg

GRB 030329 \( B = 4.8 \times 10^{-3} \) \( E_{\text{syn}} = 2.1 \times 10^{52} \) erg

(2) The enormous difference in the GRB energy of the sources simply relates to the electromagnetic energy of the black hole given in Eq. (6) which turns out to be smaller than the critical value given by Eq. (7). The fact that the theory is valid over 5 orders of magnitude is indeed very satisfactory.

(3) Also revealing is the fact that in both sources GRB 980425 and GRB 030329 the associated supernova energies are similar. We have, in fact, for both SN 1998bw and SN 2003dh an energy \( \sim 10^{49} \) erg. Details in Fraschetti et al. [16] and Bernardini et al. [96]. The further comparison between the SN luminosity and the GRB intensity is crucial. In the case of GRB 980425 the GRB and the SN energies are comparable, and no dominance of one source over the other can be ascertained. In the case of GRB 030329 the energy of the GRB source is \( 10^{5} \) larger than the SN; in no way the GRB can originate from the SN event.
The above stringent energetics considerations and the fact that GRBs occur also without an observed supernova give a strong evidence that GRBs cannot originate from supernovae.

10.2. URCA-1 and URCA-2

We turn now to the most exciting search for the nature of URCA-1 and URCA-2. We have already mentioned above that a variety of possibilities naturally appear. The first possibility is that the URCA sources are related to the black hole originating the GRB phenomenon. In order to probe such an hypothesis, it would be very important to find even a single case in which an URCA source occurs in association with a GRB and in absence of an associated supernova. Such a result, theoretically unexpected, would open an entirely new problematic in relativistic astrophysics and in the physics of black holes.
If indeed, as we expect, the clear association between URCA sources and the supernovae occurring together with the GRBs, then it is clear that the analysis of the other two possibilities will be favored. Namely, an emission from processes occurring in the early phases of the expansion of the supernova remnant or the very exciting possibility that for the first time we are observing a newly born neutron star out of the supernova phenomenon. Of course, this last hypothesis is the most important one, since it would offer new fundamental information about the outcome of the gravitational collapse, about the equations of state at supranuclear densities and about a variety of fundamental issues of relativistic astrophysics of neutron stars. We shall focus in the following only on this last topic.

We have already recalled how the need for a rapid cooling process due to neutrino anti-neutrino emission in the process of gravitational collapse leading to the formation of a neutron star was considered for the first time by George Gamow and Mario Schoenberg in 1941 [102]. It was Gamow who gave this process the name “Urca process”, see Appendix A and Appendix B. Since then, a systematic analysis of the theory of neutron star cooling was advanced by Tsuruta [103, 104], Tsuruta and Cameron [105], Tsuruta et al. [106] and by Camuto [107]. The coming of age of X-ray observatories such as Einstein (1978-1981), EXOSAT (1983-1986), ROSAT (1990-1998), and the contemporary missions of Chandra and XMM-Newton since 1999 dramatically presented an observational situation establishing very embarrassing and stringent upper limits to the surface temperature of neutron stars in well known historical supernova remnants (see e.g. Romani [108]). It was so that, for some remnants, notably SN 1006 and the Tycho supernova, the upper limits to the surface temperatures were significantly lower than the temperatures given by standard cooling times (see e.g. Romani [108]). Much of the theoretical works has been mainly directed, therefore, to find theoretical arguments in order to explain such low surface temperature $T_s \sim 0.5-1.0 \times 10^6$ K — embarrassingly low, when compared to the initial hot ($\sim 10^{11}$ K) birth of a neutron star in a supernova explosion (see e.g. Romani [108]). Some very important steps in this direction of research have been represented by the works of Van Riper [109, 110], Lattimer and his group [111, 112] and by the most extensive work of Yakovlev and his group [113]. The youngest neutron star to be searched for using its thermal emission in this context has been the pulsar PSR J0205+6449 in 3C 58 (see e.g. Yakovlev and Pethick [113]), which is 820 years old! Recently, evidence for the detection of thermal emission from the crab nebula pulsar was reported by Trumper [114] which is, again, 951 years old.

In the case of URCA-1 and URCA-2, we are exploring a totally different regime: the X-ray emission possibly from a recently born neutron star in the first days — months of its existence, where no observations have yet been performed and no embarrassing constraints upper limits on the surface temperature exist. The reason of approaching first the issue of the thermal emission from the neutron star surface is extremely important, since in principle it can give information on the equations of state in the core at supranuclear densities and on the detailed mechanism of
the formation of the neutron star itself and the related neutrino emission. It is of course possible that the neutron star is initially fast rotating and its early emission is dominated by the magnetospheric emission or by accretion processes from the remnant which would overshadow the thermal emission. In that case a periodic signal related to the neutron star rotational period should in principle be observable in a close enough GRB source provided the suitable instrumentation from the Earth.

The literature on young born neutron star is relatively scarce today. There are some very interesting contributions which state: “The time for a neutron star’s center to cool by the direct URCA process to a temperature $T$ has been estimated to be $t \approx 20 \left[ T/(10^9 K) \right]^{-4}$ s. The direct URCA process and all the exotic cooling mechanisms only occur at subnuclear densities. Matter at subnuclear densities in neutron star crust cools primarily by diffusion of heat to the interior. Thus the surface temperature remains high, in the vicinity of $10^8$ K or more, until the crust’s heat reservoir is consumed. After this diffusion time, which is on the order of 1–100 years, the surface temperature abruptly plunges to values below $5 \times 10^5$ K” (Lattimer et al. [112]). “Soon after a supernova explosion, the young neutron star has large temperature gradients in the inner part of the crust. While the powerful neutrino emission quickly cools the core, the crust stays hot. The heat gradually flows inward on a conduction time scale and the whole process can be thought of as a cooling wave propagation from the center toward the surface” (Gnedin et al. [115]).

The two considerations we have quoted above are developed in the case of spherical symmetry and we would like to keep the mind open, in this new astrophysical field, to additional factors, some more traditional than others, to be taken into account. Among the traditional ones we recall: 1) the presence of rotation and magnetic field which may affect the thermal conductivity and the structure of the surface, as well as the above mentioned magnetospheric emission; 2) there could be accretion of matter from the expanding nebula; and, among the nontraditional ones, we recall 3) some exciting theoretical possibilities advanced by Dyson on volcanoes on neutron stars [116] as well as iron helide on neutron star [117], as well as the possibility of piconuclear reactions on neutron star surface discussed in Lai & Salpeter [118].

All the above are just scientific arguments to attract attention on the abrupt fall in luminosity reported in this meeting on URCA-1 by Elena Pian which is therefore, in this light, of the greatest scientific interest and further analysis should be followed to check if a similar behavior will be found in future XMM and Chandra observations also in URCA-2.

10.3. Astrophysical implications

In addition to these very rich problematics in the field of theoretical physics and theoretical astrophysics, there are also more classical astronomical and astrophysical issues, which will need to be answered if indeed the observations of a young neutron
star will be confirmed. An important issue to be addressed will be how the young neutron star can be observed, escaping from being buried under the expelled matter of the collapsing star. A possible explanation can originate from the binary nature of the newly born neutron star: the binary system being formed by the newly formed black hole and the triggered gravitational collapse of a companion evolved star leading, possibly, to a “kick” on and ejection of the newly born neutron star. Another possibility, also related to the binary nature of the system, is that the supernova progenitor star has been depleted of its outer layer by dynamic tidal effects.

In addition, there are other topics in which our scenario can open new research directions in fundamental physics and astrophysics:

1. The problem of the instability leading to the complete gravitational collapse of a $\sim 10M_\odot$ star needs the introduction of a new critical mass for gravitational collapse, which is quite different from the one for white dwarfs and neutron stars which has been widely discussed in the current literature (see e.g. Giacconi & Ruffini [6]).

2. The issue of the trigger of the instability of gravitational collapse induced by the GRB on the progenitor star of the supernova or, vice versa, by the supernova on the progenitor star of the GRB needs accurate timing and the considerations of new relativistic phenomena.

3. The general relativistic instability induced on a nearby star by the formation of a black hole needs some very basic new developments in the field of general relativity.

Only a very preliminary work exists on this subject, by Jim Wilson and his collaborators, see e.g. the paper by Mathews and Wilson in these proceedings [119]. The reason for the complexity in answering such a question is simply stated: unlike the majority of theoretical work on black holes, which deals mainly with one-body solutions, we have to address here a many-body problem in general relativity. We are starting in these days to reconsider, in this framework, some classic work by Fermi [120], Hanni and Ruffini [121], Majumdar [122], Papapetrou [123], Parker et al. [124], Bini et al. [125] which may lead to a new understanding of general relativistic effects relevant to these astrophysical “triptychs”.

Acknowledgments

We are thankful to Rashid Sunyaev, Lev Titarchuk, Jim Wilson and Dima Yakovlev for many interesting theoretical discussions, as well as to Lorenzo Amati, Lucio Angelo Antonelli, Enrico Costa, Filippo Frontera, Luciano Nicastro, Elena Pian, Luigi Piro, Marco Tavani and all the BeppoSAX team for assistance in the data analysis.
Appendix A. On the Urca Process

From G. Gamow [126]:

“The summer of 1939 I spent with my family vacation on the Copacabana beach in Rio de Janeiro. One evening, visiting the famous Casino da Urca to watch the gamblers, I was introduced to a young theoretical physicist born on an Amazon River plantation, named Mario Schoenberg. We became friends, and I arranged for him a Guggenheim fellowship to spend a year in Washington to work with me in nuclear astrophysics. His visit was very successful, and we hit upon a process which could be responsible for the vast stellar explosions known as supernovae. The trick is done by alternative absorption and reemission of one of the thermal electrons in the very hot (billions of degrees!) stellar interior by various atomic nuclei. Both processes are accompanied by the emission of neutrinos and antineutrinos which, possessing tremendous penetrating power, pass through the body of a star like a swarm of mosquitoes through chicken wire and carry with them large amount of energy. Thus, the stellar interior cools rapidly, the pressure drops, and the stellar body collapse with a great explosion of light and heat.

All this is too complicated to explain in nontechnical words, and I am mentioning it only as background for how we came to give that process its name. We called it the Urca process, partially to commemorate the casino in which we first met, and partially because the Urca process results in a rapid disappearance of thermal energy from the interior of the star, similar to the rapid disappearance of money from the pockets of the gamblers of the Casino da Urca. Sending our article “On the Urca process” for publication in The Physical Review I was worried that the Editor would ask why we called the process “Urca”. After much thought I decided to say that this is short for “UnRecordable Cooling Agent”, but they never asked. Today, there are other known cooling processes involving neutrinos which work even faster than the Urca process. For example, a neutrino pair can be formed instead of two gamma quanta in the annihilation of a positive and negative electrons”.

Attachment 10
Appendix B. Casino da Urca Today

References

420

96. M.G. Bernardini, C.L. Bianco, P. Chardonnnet, F. Fraschetti, R. Ruffini, S.-S. Xue, in these proceedings.
119. R. Mathews, J. Wilson, in these proceedings.
Attachment 11
GENERAL FEATURES OF GRB 030329 IN THE EMBH MODEL

MARIA GRAZIA BERNARDINI, CARLO LUCIANO BIANCO, REMO RUFTINI,
SHE-SHENG XUE

ICRA – International Center for Relativistic Astrophysics,
c/o Dipartimento di Fisica, Università di Roma “La Sapienza”,
Piazzale Aldo Moro 5, I-00185 Roma, Italy

PASCAL CHARDONNET

Université de Savoie – LAPTH LAPP – BP110
74941 Annecy-le-Vieux, Cedex, France

FEDERICO FRASCETTI

Università di Trento,
Via Sommarive 14, I-38050 Povo (Trento), Italy

GRB 030329 is considered within the EMBH model. We determine the three free parameters and deduce its luminosity in given energy bands comparing it with the observations. The observed substructures are compared with the predictions of the model: by applying the result that substructures observed in the extended afterglow peak emission (E-APE) do indeed originate in the collision of the accelerated baryonic matter (ABM) pulse with the inhomogeneities in the interstellar medium around the black-hole, masks of density inhomogeneities are considered in order to reproduce the observed temporal substructures. The induced supernova concept is applied to this system and the general consequences that we are witnessing are the formation of a cosmological triplet of a black hole originating the GRB 030329, the supernova SN2003dh and a young neutron star. Analogies to the system GRB 990425-SN1998bw are outlined.

GRB 030329 has been detected on March 29, 2003. Its very high fluence for the prompt emission (1.2 × 10^{-4} in the 30–400 keV band, as measured by HETE 1) and the bright afterglow allowed to observe it in detail at all wavelengths. In particular its X-rays afterglow was observed by Rossi-XTE 2,3, and by XMM-Newton 4. Its unusual brightness is due to the fact that this burst is quite near; the redshift of its host galaxy is z = 0.1685 5,6. Analysing the optical afterglow 7 days after the burst, it has been found the spectroscopic evidence of an underlying Type Ic supernova with a large expansion velocity 7,8.

In order to describe the GRB 030329 source we have adopted a spherically symmetric distribution and, as initial conditions at t = 10^{-21} s, an e^+–e^−–photon neutral plasma lying between the radii r_1 = 2.9 × 10^6 cm and r_2 = 9.0 × 10^7 cm. The temperature of such a plasma is 2.1 MeV, the total energy E_{tot} = 2.1 × 10^{52} erg and
the total number of pairs $N_{e^+e^-} = 1.1 \times 10^{57}$. These conditions have been derived evaluating the vacuum polarization processes occurring in the dyadosphere of an EMBH. The total energy $E_{\text{tot}}$ coincides with the dyadosphere energy $E_{\text{dy}}$, which is the first independent parameter of the EMBH theory. The optically thick electron–positron plasma created in the dyadosphere self-propels itself outward reaching ultrarelativistic velocities and then interacts with the baryonic matter of the remnant of the progenitor star. This baryonic matter component $M_B$ is the second free parameter of the EMBH theory: $B = M_B c^2 / E_{\text{dy}} = 4.8 \times 10^{-5}$. The $e^+e^-$–photon–baryon plasma by further expansion becomes optically thin. As the transparency condition is reached, the Proper–GRB (P–GRB) is emitted with an extremely relativistic shell of Accelerated Baryonic Matter (the ABM pulse) with initial Lorentz gamma factor of $\gamma = 183.6$. It is this ABM pulse which produces the afterglow, through its interaction with the InterStellar Medium (ISM), whose average density is best fitted by $<n_{\text{ISM}} > = 1 \text{ particle/cm}^3$.

In order to obtain the instantaneous luminosity in selected energy bands, which is necessary for the comparison with the observed data, we assume that the radiation emitted in the collision between the ABM pulse and the ISM has a thermal
spectrum measured in the ABM pulse comoving frame \(^{18}\). In our approach the source luminosity is derived from an infinite set of foliations of events on the EQui-Temporal Surfaces (EQTS, which are the surfaces emitting photons with the same arrival time \(^{19,20}\), each one characterized by a different thermal spectrum in the comoving frame boosted by a different relativistic transformation obtained from the equations of motion. The third free parameter of the EMBH theory describes this process of generating the thermal spectrum in the comoving frame. It is given by
\[
R = \frac{A_{\text{eff}}}{A_{\text{com}}},
\]
where \(A_{\text{com}}\) is the ABM pulse external surface area and \(A_{\text{eff}}\) is the ABM pulse effective emitting area. In our case \(R\) is slowly variable, ranging from \(8.0 \times 10^{-9}\) to \(5.0 \times 10^{-8}\). We can then obtain for the GRB 030329 the luminosities in given energy bands, computed in the range \(2 - 400\, keV\) with very high accuracy. Figure 1 shows the results for the luminosities in the \(30 - 400\, keV\) and \(2 - 10\, keV\) bands: both the light curves show a good agreement with the observations from HETE \(^{1}\) (\(30 - 400\, keV\)) and R-XTE \(^{2,3}\) (\(2 - 10\, keV\)).

Let’s analyse now in more detail how the light curve obtained from our model can explain the experimental features of this source. If we focus our attention on the prompt emission, we can see from the HETE light curve\(^{a}\) (see Fig.2.a) that GRB 030329 is a long, extremely bright GRB, lasting more than 25 s, with a fluence in the band \(30 - 400\, keV\) of \(\approx 1.0 \times 10^{-4}\, erg/cm^2\). The emission is structured in two peaks: the first one lasts more than 15 s, the second one is shorter and their intensities are comparable.

This structure can be reproduced assuming that the ABM pulse, which expands in an ISM with \(n_{\text{ISM}} = 1\, \text{particle/cm}^3\), interacts with a region in which the ISM is not constantly distributed but is arranged in several density spikes, preserving \(< n_{\text{ISM}} > = 1\, \text{particle/cm}^3\). For GRB 030329, the density spikes corresponding to the two main peaks are modeled as two spherical shells with width and density of the same order of magnitude: we adopted for the first peak \(\Delta = 2.0 \times 10^{14}\, cm\) and \(\Delta n/n = 30\), and for the second peak \(\Delta = 1.0 \times 10^{14}\, cm\) and \(\Delta n/n = 90\). The two spikes are separated by a distance of \(5.7 \times 10^{15}\, cm\). The result (see Fig.2.b) shows a good agreement with the observed light curve and it provides a further evidence for the possibility of reproducing light curves with a complex time variability throught external shocks (see also the analysis of the prompt emission of GRB 991216 in \(^{20}\)). This is possible because of a “superluminal” effect: due to the very high Lorentz gamma factor in this region (\(\gamma \approx 180\)), the ABM pulse can interact with density spikes of width \(\approx 1.0 \times 10^{14}\, cm\) producing signals that last \(\approx 10\, s\). The apparent speed of the photons emitted is \(3 \times 10^4\, c\).

A remarkable feature of this source is its connection with the SN2003dh \(^{7,8}\). It has been proposed \(^{20,21}\) that the supernova explosion is the result of an induced gravitational collapse. This hypothesis, applied for GRB 980425–SN1998bw \(^{22}\), is confirmed in this case by the fact that GRB 030329 is energetically dominant on

\(^{a}\)http://space.mit.edu/HETE/Bursts/GRB030329
the supernova, with an intensity $2 \times 10^3$ larger.

In our analysis of this source we are not considering the measures from XMM 4. In fact, in analogy with GRB 980425–SN1998bw 22 (see Fig. 3), if we consider this X–rays emission not linked to the GRB afterglow but to the supernova event, also in this case we are observing a distinct source URCA-2 generated in the supernova explosion (see Ruffini et al.20 and references therein).

References
Figure 3. The remarkable analogy of the GRB 03032 and the GRB 980425 is clearly shown in this figure, compared with Fig. 1: the solid line corresponds to our theoretically predicted GRB 980425 light curve in $\gamma$-rays (30 – 700 keV), with the horizontal bar corresponding to the mean peak flux from GRBM. The dashed and the dotted line represent the light curve in X-rays (2 – 26 keV and 2 – 10 keV respectively) with the experimental data obtained by WFC. The remaining points refer to the optical data of SN1998bw and to the X-ray sources S1 and S2 detected by MECS. The other lines correspond to the expected luminosity of URCA-1, identified with the source S1.

Attachments

2464

Attachment 12
GRB 970228 AND ITS ASSOCIATED SUPERNova WITHIN THE EMBH MODEL

R. RUFFINI, M.G. BERNARDINI, C.L. BIANCO, A. CORSI AND S.-S. XUE
ICRA - International Center for Relativistic Astrophysics and Dipartimento di Fisica,
Università di Roma "La Sapienza", Piazzale Aldo Moro 5, I-00185 Roma, Italy.

P. CHARDONNET
Université de Savoie, LAPTH - LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France.

F. FRASCETTI
Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy.

The γ-ray burst of 1997 February 28 is analyzed within the Electromagnetic Black Hole model. We first estimate the value of the total energy deposited in the dyadosphere, $E_{dya}$, and the amount of baryonic matter left over by the EMBH progenitor star, $B = M_B c^2/E_{dya}$. We then consider the role of the interstellar medium number density $n_{ISM}$ and of the ratio $R$ between the effective emitting area and the total surface area of the γ-ray burst source, in reproducing the prompt emission and the X-ray afterglow of this burst. Some considerations are also done concerning the possibility of explaining, within the theory, the observed evidence for a supernova in the optical afterglow.

The γ-ray burst of 1997 February 28 (GRB 970228) was the first for which the afterglow phenomenon was observed: the subarcminute localization of the γ-ray burst (GRB) by the BeppoSAX satellite allowed the identification of a counterpart at X-ray$^{2,3}$ and optical$^{4,5}$ wavelengths. The unusual temporal properties of the optical afterglow possibly relate this burst to a supernova event$^8$.

Here we compare the observed properties of GRB 970228 with the predictions of the ElectroMagnetic Black Hole (EMBH) theory (see Ruffini et al.$^{11}$ and references therein).

The two free parameters that determine energetically the GRB phenomenon in this model are the total energy deposited in the dyadosphere$^{11}$, $E_{dya}$, and the amount of the baryonic matter left over by the EMBH progenitor star$^{11}$, $B = M_B c^2/E_{dya}$. With $E_{dya} = 5.1 \times 10^{52}$ ergs and $B = 3.0 \times 10^{-3}$, a 98% of the total energy $E_{dya}$ is emitted in the beam-target phase$^{11}$, that is to say in the collision of the Accelerated Baryonic Matter-pulse (ABM-pulse) with the InterStellar Medium (ISM). During this phase, the internal energy developed in the collision is instantaneously radiated away (fully radiative condition) and the shape of the resulting light curve is strictly linked to the ISM distribution and number density$^{10}$. 

2465
We use a one-dimensional treatment of the ISM, where \( n_{ISM} \) is a function of the radial distance \( r \) from the central black hole\(^{10} \).

GRB 970228 prompt emission in the 40-700 keV energy band was characterized by an initial 5 s strong pulse followed, after about 30 s, by three additional pulses of decreasing intensity\(^7 \).

In order to reproduce the observed light curves within the EMBH model, \( n_{ISM} \) has to range between the values of \( 10^{-2} \) particles/cm\(^3\) and 200 particles/cm\(^3\) in the region of space where \( 2.00 \times 10^{15} \text{ cm} < r < 4.95 \times 10^{16} \text{ cm} \) (details given in Ruffini \textit{et al.}\(^{14} \)). Before \( r = 2.00 \times 10^{15} \text{ cm} \) and beyond \( r = 4.95 \times 10^{16} \text{ cm} \), \( n_{ISM} \) has a constant value of 1 particle/cm\(^3\).

The spectral distribution of the energy emitted during the beam-target phase depends on the \( R \) parameter\(^{12,13} \), so that the theoretical curves in selected energy bands are strictly related to it. \( R \) is the ratio between the effective emitting area of the ABM-pulse and its total surface area. Choosing \( 1.0 \times 10^{-17} < R < 2.0 \times 10^{-11} \) in the region where \( 7.0 \times 10^{14} \text{ cm} < r < 5.0 \times 10^{17} \text{ cm} \), the first pulse observed in the 40-700 keV light curve is correctly reproduced by the model\(^{14} \). The three additional pulses are reproduced in terms of their mean luminosity. The Fast Rise Exponential Decay (FRED) shape that emerges in the theoretical curve is a consequence of the one-dimensional structure of the ISM distribution and requires an improvement toward a three-dimensional treatment\(^{14} \).

![GRB 970228 Afterglow 2-10 keV](image)

**Figure 1.** GRB 970228 X-ray afterglow: the solid line is the theoretical light curve for the 2-10 keV emission in the EMBH model; the points are GRB 970228 2-10 keV afterglow data observed by Beppo-SAX and ASCA. A good agreement between the theoretical curve and the observed data is evident.
For what concerns the X-ray afterglow, in Fig. 1 we present the 2-10 keV theoretical light curve compared with the observed data by Beppo-SAX and ASCA in the same energy band. In the case of GRB 970228, the afterglow phase corresponds to the ABM-pulse expansion in the region beyond $4.95 \times 10^{19}$ cm, where the number density of the ISM has a constant value, $n_{\text{ISM}} = 1$ particle/cm$^3$. A good agreement ($\chi^2 = 0.5$) between the theoretical light curve and the observed data is evident.

In the optical band, GRB 970228 afterglow showed unusual temporal properties. At late times from the trigger ($t > 25$ days) the optical light curve decreased more slowly than at early times ($t < 5$ days): this behaviour could be explained by a type-Ic supernova that might have overtaken the light curve nearly two weeks after the burst.

In the framework of the EMBH model, the GRB-Supernova Time Sequence (GSTS) paradigm relates the GRB phenomenon with a supernova event. According to this paradigm, the Proper-GRB (P-GRB) and the Extended Afterglow Peak Emission (E-APE) propagate and impact, with their photon and neutrino components, on a supernova progenitor star, inducing a supernova explosion. In this scenario we can set a lower limit for the distance $D$ between the central black-hole and the supernova progenitor star: $D$ should be greater than the radial distance at which the transparency condition is reached and the P-GRB is emitted. In the case of GRB 970228, we have $D \geq 6.2 \times 10^{13}$ cm.

We thus conclude that, in order to explain GRB 970228 high-energy prompt emission within the EMBH model, a variable profile of the ISM number density is needed and a three-dimensional treatment of the ISM distribution is also required to improve the theoretical predictions; simply using a constant ISM number density, the observed X-ray afterglow is correctly reproduced by the model; finally, a type-Ic supernova dominating the late optical afterglow can possibly be explained within the theory by invoking the GSTS paradigm.

References

1. E. Costa et al., IAU Circ. 6572 (1997).
2. E. Costa et al., IAU Circ. 6576 (1997).
Attachments
INFERENCES ON THE ISM STRUCTURE AROUND GRB980425 AND GRB 980425 - SN1998BW ASSOCIATION IN THE EMBH MODEL

F. FRASCHETTI
ICRA, International Center for Relativistic Astrophysics, Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy, E-mail: fraschetti@icra.it.

M. G. BERNARDINI, C. L. BIANCO, R. RUFFINI AND S.-S. XUE
ICRA, International Center for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Roma, Italy.

P. CHARDONNET
ICRA, International Center for Relativistic Astrophysics and Université de Savoie, LAPTH - LAPP, BP 116, F-74941 Annecy-le-Vieux Cedex, France.

We determine the four free parameters within the EMBH model for GRB 980425 and deduce its luminosity in given energy bands, its spectra and its time variability in the prompt radiation. We compute the basic kinematical parameters of GRB 980425. In the extended afterglow peak emission the Lorentz γ factor is lower than the critical value 150 which has been found in (24) to be necessary in order to perform the tomography of the ISM surrounding the GRB as suggested by (7). The detailed structure of the density inhomogeneities as well as the effects of radial apparent superluminal effects are evaluated within the EMBH model. Under the assumption that the energy distribution of emitted radiation is thermal in the comoving frame, time integrated spectra of EMBH model for prompt emission are computed. The induced supernova concept is applied to this system and general consequences on the astrophysical and cosmological scenario are derived.

Our GRB theory (21,22,23,24,25 and references therein), previously successfully applied to GRB 991216 used as a prototype, is applied to GRB 980425 (14) and SN1998bw (10). This event allows to test the validity of the theory over a range of energies of 6 orders of magnitude: both sources appear to be spherically symmetric and the respective total energies are $E_{\text{tot}} \simeq 5 \times 10^{53}$ ergs and $E_{\text{tot}} \simeq 10^{48}$ ergs.

The theory, therefore, explains all the observed features of the bolometric intensity variations of the afterglow as well as the spectral properties of the source and, in the specific case of GRB 980425 (20,27), it also allows to clarify the general astrophysical scenario in which the GRB actually occurs. In this system, in fact, we propose that GRB 980425 has been the trigger of a phenomenon of “induced

2451
gravitational collapse\(^{23}\) originating the supernova explosion and we also witness
the birth of a young neutron star out of the supernova event. This coincidence of
these three astrophysical events represents an unprecedented scenario in the field of
relativistic astrophysics.

The observational situation of this system is quite complex (see fig.1). In addi-
tion to the source GRB 980425 and the supernova SN1998bw, two X-ray sources
have been found by BeppoSAX in the error box for the location of GRB 980425: a
source S1 and a source S2 \(^{14}\); the optical data are reported too \(^{13}\). Our approach
is the following. We first interpret the GRB 980425 within the EMBH theory. This
allows the computation of the luminosity, spectra, Lorentz gamma factors, and more
generally all the dynamical aspects of the source. Having characterized the features
of GRB 980425, we can gradually approach the remaining part of the scenario, dis-
entangling the GRB observations from the supernova ones and from the sources S1
and S2. This leads to a natural time sequence of events and to their autonomous
astrophysical characterization.

Figure 1. The wealth and complex set of observational data in \(X\) and optical bands associated
to GRB 980425. The continuous line represent the theoretical prediction of EMBH model. The
optical data of SN 1998bw and the X ray data from BeppoSAX of source S1 are in boxes.

Our approach has focused on identifying the energy extraction process from
the black hole \(^{5}\) as the basic energy source for the GRB phenomenon. The distin-
guishing feature is a theoretically predicted source energetics all the way up to
1.8 \(\times\) 10\(^{54}\) \((M_{BH}/M_{\odot})\) ergs for 3.2\(M_{\odot}\) \(\leq M_{BH} \leq 7.2 \times 10^{8}\)\(M_{\odot}\) \(^{6}\). In particular,
the formation of a “dyadosphere”, during the gravitational collapse leading to a black hole endowed with electromagnetic structure (EMBH) has been indicated as the initial boundary conditions of the GRB process (20–18).

Traditionally, following the observations of the 
Vela
 (18) and 
CGRO
 satellites, GRBs have been characterized by few parameters such as the fluence, the characteristic duration (\(T_{90}\) or \(T_{50}\)) and the global time averaged spectral distribution (2). With the observations of 
BeppoSAX
 and the discovery of the afterglow, and the consequent optical identification, the distance of the GRB source has been determined and consequently the total energetics of the source has been added as a crucial parameter.

The observed energetics of GRBs, computed for spherically symmetric explosions, do coincide with the ones theoretically predicted in (2). This has been the major reason which has motivated us to reconsider and develop in full details the EMBH model. For simplicity, we have considered the vacuum polarization process occurring in an already formed Reissner-Nordström black hole (20–18), whose dyadosphere has an energy \(E_{\text{dps}}\). It is clear, however, that this is only an approximation to the real dynamical description of the process of gravitational collapse to an EMBH. In order to prepare the background for attacking this extremely complex dynamical process, we have clarified some basic theoretical issues, necessary to implement the description of the fully dynamical process of gravitational collapse to an EMBH (see 30–31–4).

The equations of motion in our theory depend only on two free parameters: the total energy \(E_{\text{tot}}\), which coincides with the dyadosphere energy \(E_{\text{dps}}\), and the amount \(M_p\) of baryonic matter left over from the gravitational collapse of the progenitor star, which is determined by the dimensionless parameter \(B = M_Bc^2/E_{\text{dps}}\). Our best fit corresponds to \(E_{\text{dps}} = 1.1 \times 10^{48}\) ergs, \(B = 7 \times 10^{-3}\) and the other parameter given by ISM average density is found to be \((n_{\text{ISM}}) = 0.02\) particle/cm\(^3\). The plasma temperature and the total number of pairs in the dyadosphere are respectively \(T = 1.03\) MeV and \(N_{e^\pm} = 5.33 \times 10^{53}\).

Any astrophysical model attempting a complete explanation of GRBs must reproduce not only the temporal substructure of light curves but also the spectral evolution. Among the models trying to explain the energy distribution of the observed radiation, the most referred one is the Band model (2), based on an empirical formula for time integrated spectrum not directly related to the underlying physical processes, but introduced in order to take into account of the high variability of the spectral features of GRBs. The Band function is essentially made of two smoothly

---

\(^{a}\) see http://cossc.gsfc.nasa.gov/batse/

\(^{b}\) see http://www.asdc.asi.it/bepposax/
connected power laws:

\[
N(E) = \begin{cases} 
A \left( \frac{E}{100 \text{ keV}} \right)^{\alpha} \exp \left( -\frac{E}{E_0} \right) & \text{for } E \leq (\alpha - \beta) E_0 \\
A E^\beta \left[ \frac{(\alpha - \beta) E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \exp(\beta - \alpha) & \text{for } E \geq (\alpha - \beta) E_0
\end{cases}
\]  

(1)

where \(N(E)\) is the photon count number in photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\). The free parameters, which are the result of the fits, are \(A\), the normalization constant at 100 keV; \(\alpha\), the low energy power law spectral index; \(\beta\), the high energy power law spectral index; \(E_0\), related to the peak energy in the \(E - F_E\) diagram (\(F_E\) is the flux in keV/cm\(^2\)sec keV) by \(E_{peak} = (\alpha + 2)E_0\); \(E_{peak}\) represents the energy at which most of the luminosity is emitted. Moreover Band parameters do not have universal values but vary from burst to burst: from an analysis of the spectra of twelve bursts with known redshifts (\(^1\)), it has been found a large dispersion in Band parameters.

A physical model proposed to explain the observed spectra is based on the assumption that the electrons behind the shock front of the expanding system accelerated in a magnetic field emit synchrotron radiation, if energy distribution of the relativistic electrons has a single power law form. However in (\(^{17-12}\)) the authors have shown that the standard model of synchrotron emission does not give a good explanation of the whole observed spectra since the theoretical prediction of the low energy spectral index is violated for a non negligible part of the BATSE sample.

Recently, within the EMBH theory, we have developed an attempt to theoretically derive the GRB spectra out of first principles as well as the GRB luminosity in fixed energy bands (\(^{20}\)). We have adopted three basic assumptions: a) the resulting radiation as viewed in the comoving frame during the afterglow phase has a thermal spectrum and b) the ISM swept up by the front of the shock wave, with a Lorentz gamma factor between 300 and 2, is responsible for this thermal emission. c) We also assume, like in our previous papers (\(^{21-22-24-25}\)), that the expansion occurs with spherical symmetry.

The temperature \(T\) of the black body in the comoving frame is then

\[
T = \left( \frac{\Delta E_{int}}{4\pi r^2 \Delta \tau \sigma R} \right)^{1/4},
\]

(2)

where the parameter \(R = A_{eff}/A_{abm}\) is the ratio between the “effective emitting area” and the ABM pulse surface \(A_{abm}\) (in this case the best fit value of \(R\) is monotonically decreasing from \(4.8 \times 10^{-12}\) to \(2.6 \times 10^{-12}\)), \(\sigma\) is the Stefan-Boltzmann constant and \(\Delta E_{int}\) is the proper internal energy developed in the collision between the ABM pulse and the ISM in the proper time interval \(\Delta \tau\) (\(^{26-28}\)). The ratio \(R\),
which is a priori a function that varies as the system evolves, is evaluated at every given value of the laboratory time $t$.

The basic tool in this calculation involves the definition of the EQuiTemporal Surfaces (EQTS) for the relativistic expanding ABM pulse as seen by an asymptotic observer. The key to determining such EQTS (see Fig. 1 in 24) is the relation between the time $t$ in the laboratory frame at which a photon is emitted from the ABM pulse external surface and the arrival time $t_a'$ at which it reaches the detector. For such a relation, different approximations exist in the literature (see e.g. 5–22, 33–40 and see also the review by Piran15).

The source luminosity at a detector arrival time $t_a'$ per unit solid angle $d\Omega$ and in the energy band $[\nu_1, \nu_2]$ is given by (22):

$$\frac{dE^{[\nu_1, \nu_2]}_{a'}}{dt_a' d\Omega} = \int_{\text{EQTS}} \frac{\Delta\varepsilon}{4\pi} \nu \cos \theta \Lambda^4 \frac{dt}{dt_a'} W(\nu_1, \nu_2, T_{\text{arr}}) d\Omega,$$

where $\Delta\varepsilon = \Delta E_{\text{int}}/V$ is the energy density released in the interaction of the ABM pulse with the ISM inhomogeneities measured in the comoving frame, $\Lambda = \gamma(1 - (v/c) \cos \theta)$ is the Doppler factor, $W(\nu_1, \nu_2, T_{\text{arr}})$ is an “effective weight” required to evaluate only the contributions in the energy band $[\nu_1, \nu_2]$, $d\Omega$ is the surface element of the EQTS at detector arrival time $t_a'$ on which the integration is performed (24).
and $T_{\text{arr}}$ is the observed temperature of the radiation emitted from $d\Sigma$:

$$T_{\text{arr}} = \frac{T}{\gamma \left(1 - \frac{z}{c} \cos \theta \right) (1 + z)}.$$  \hspace{1cm} (4)

The “effective weight” $W(\nu_1, \nu_2, T_{\text{arr}})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at a temperature $T_{\text{arr}}$ to the total integral $aT_{\text{arr}}^4$:

$$W(\nu_1, \nu_2, T_{\text{arr}}) = \frac{1}{aT_{\text{arr}}^4} \int_{\nu_1}^{\nu_2} \rho(T_{\text{arr}}, \nu) d \left(\frac{h\nu}{c}\right)^3,$$  \hspace{1cm} (5)

where $\rho(T_{\text{arr}}, \nu)$ is the Planckian distribution at temperature $T_{\text{arr}}$:

$$\rho(T_{\text{arr}}, \nu) = \frac{2}{h^3} \exp\left(\frac{h\nu}{kT_{\text{arr}}}\right) - 1.$$  \hspace{1cm} (6)

The results are given in Fig. 1 (see also fig. 2 in \textsuperscript{26}) where the luminosity is computed as a function of the arrival time for three selected energy bands. Time integrated spectra predictions of EMBH model for prompt emission in $X$ and $\gamma$ ranges as received at the detector (see fig. 2) are in very good agreement with data from \textsuperscript{\textsuperscript{26}}. The temperature in the comoving frame given in eq. 2 varies in time, therefore, due to time delay of photons emitted at large angles from the line of sight, at fixed arrival time the spectrum must be a superposition of black bodies corresponding to different temperatures: the larger is the visible area of the surface of the pulse, the wider is the temperature interval of the corresponding pure black bodies.

The extremely low value of total energy emitted in GRB 980425 ($E_{\text{tot}} \simeq 10^{49}\text{erg}$) with respect to the energy estimate of SN 1998bw ($E_{\text{tot}}/E_{SN} \simeq 10^{-1}$) made possible observation of light curve of the underlying Supernova which if induced by a more energetic GRB could remain hidden by its predominant emission. This indicates that the rate of SN events associated to GRB could be at present underestimated.

While the occurrence of the supernova in relation to the GRB has already been discussed with the GRB-Supernova Time Sequence (GSTS) paradigm \textsuperscript{(23)}, we like to address here the different fundamental issue of the source URCA-1 which is clearly very different from the GRB and Supernova.

In the early days of neutron star physics it was clearly shown by \textsuperscript{(11)} that the URCA processes are at the very heart of the supernova explosions. The neutrino-antineutrino emission described in the URCA process is the essential cooling mechanism necessary for the occurrence of the process of gravitational collapse of the imploding core. In honour of this we have named URCA-1 this X-ray source. One of the possibilities is that we are observing a newly formed neutron star still significantly hot and in its early stages. Three major radiating processes have to be considered \textsuperscript{(3,5,36–37)}: a) the thermal radiation from the surface, b) the radiation due to neutrino, kaon, pion cooling, and c) the possible influence in both these processes of the superfluid nature of the supra-nuclear density neutron gas.
Table 1. Gamma factor for selected events and their space-time coordinates: \( r \) is the radial coordinate in the laboratory frame, \( t \) is the laboratory time and \( t_\odot \) is the photon arrival time at the detector. The points 1, 2, 3, 4 mark the beginning of first four “eras” until the transparency point (point 4). The points A, B, C correspond to three events respectively before, during and after the peak of the E-APE. The points D, E, F, G, H, I, J are taken in the decaying part of the afterglow. The last column shows how the apparent motion in the radial coordinate, evaluated in the arrival time at the detector, leads to an enormous apparent “superluminal” behaviour. This illustrates the impossibility of using such a classical estimate in regimes of high gamma Lorentz factor.

<table>
<thead>
<tr>
<th>Point</th>
<th>( r(\text{cm}) )</th>
<th>( t(\text{s}) )</th>
<th>( t_\odot(\text{s}) )</th>
<th>( \gamma )</th>
<th>“Superluminal” ( \nu \equiv \frac{r}{t_\odot} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( 8.79 \times 10^8 )</td>
<td>( 2.60 \times 10^{-5} )</td>
<td>( 2.03 \times 10^{-5} )</td>
<td>1.027</td>
<td>14c</td>
</tr>
<tr>
<td>2</td>
<td>( 2.89 \times 10^8 )</td>
<td>( 9.56 \times 10^{-3} )</td>
<td>( 2.13 \times 10^{-4} )</td>
<td>28.423</td>
<td>47c</td>
</tr>
<tr>
<td>3</td>
<td>( 3.45 \times 10^8 )</td>
<td>( 1.14 \times 10^{-2} )</td>
<td>( 2.19 \times 10^{-4} )</td>
<td>8.647</td>
<td>53c</td>
</tr>
<tr>
<td>4</td>
<td>( 4.31 \times 10^1 )</td>
<td>( 14.4 )</td>
<td>( 7.65 \times 10^{-1} )</td>
<td>138.803</td>
<td>1.9 \times 10^4c</td>
</tr>
<tr>
<td>A</td>
<td>( 4.31 \times 10^4 )</td>
<td>( 1.34 \times 10^4 )</td>
<td>( 3.65 )</td>
<td>129.819</td>
<td>3.7 \times 10^4c</td>
</tr>
<tr>
<td>B</td>
<td>( 6.00 \times 10^1 )</td>
<td>( 2.00 \times 10^5 )</td>
<td>( 5.87 )</td>
<td>115.309</td>
<td>3.4 \times 10^4c</td>
</tr>
<tr>
<td>C</td>
<td>( 6.50 \times 10^1 )</td>
<td>( 2.17 \times 10^5 )</td>
<td>( 6.98 )</td>
<td>84.704</td>
<td>3.1 \times 10^4c</td>
</tr>
<tr>
<td>D</td>
<td>( 1.02 \times 10^4 )</td>
<td>( 3.40 \times 10^5 )</td>
<td>( 19.2 )</td>
<td>53.982</td>
<td>1.6 \times 10^4c</td>
</tr>
<tr>
<td>E</td>
<td>( 1.07 \times 10^4 )</td>
<td>( 3.57 \times 10^5 )</td>
<td>( 98.5 )</td>
<td>6.510</td>
<td>3.6 \times 10^4c</td>
</tr>
<tr>
<td>F</td>
<td>( 1.12 \times 10^4 )</td>
<td>( 3.74 \times 10^5 )</td>
<td>( 3.00 \times 10^2 )</td>
<td>6.469</td>
<td>1.2 \times 10^4c</td>
</tr>
<tr>
<td>G</td>
<td>( 1.17 \times 10^4 )</td>
<td>( 3.90 \times 10^5 )</td>
<td>( 5.00 \times 10^2 )</td>
<td>6.426</td>
<td>7.8 \times 10^4c</td>
</tr>
<tr>
<td>H</td>
<td>( 1.29 \times 10^4 )</td>
<td>( 4.30 \times 10^5 )</td>
<td>( 1.00 \times 10^4 )</td>
<td>6.309</td>
<td>4.3 \times 10^4c</td>
</tr>
<tr>
<td>I</td>
<td>( 2.67 \times 10^4 )</td>
<td>( 8.99 \times 10^5 )</td>
<td>( 1.00 \times 10^4 )</td>
<td>4.101</td>
<td>89c</td>
</tr>
<tr>
<td>J</td>
<td>( 4.31 \times 10^4 )</td>
<td>( 1.49 \times 10^6 )</td>
<td>( 5.00 \times 10^4 )</td>
<td>2.097</td>
<td>29c</td>
</tr>
</tbody>
</table>

It is of paramount importance to follow the further time history of the two sources S1 and S2. If, as we propose, S2 is a background source, its flux should be practically constant in time and this source has nothing to do with the GRB 980425 / SN1998bw system. If S1 is indeed the cooling radiation emitted by the newly born neutron star, it should be possible to notice a very drastic behavior in its luminosity as qualitatively expressed in Fig. 3 in (26). In this respect the results presented in this meeting on XMM by E. Pian (14) offer a most important confirmation.

The complete details on the source with all numerical values and explicit relations is going to appear in (29).

References
2458

Attachment 14
GRB 980425, SN1998BW and the EMBH model

R. Ruffini a,*, M.G. Bernardini a, C.L. Bianco a, P. Chardonnet b, F. Fraschetti c, S.-S. Xue a

a ICRA – International Centre for Relativistic Astrophysics and Dipartimento di Fisica, Università di Roma “La Sapienza”, Piazzale Aldo Moro 5, I-00185 Rome, Italy
b Université de Savoie, LAPTH – LAPP, BP 110, F-74941 Annecy-le-Vieux Cedex, France
c Università di Trento, Via Sommarive 14, I-38050 Povo (Trento), Italy

Received 5 June 2003; accepted 10 June 2003

Abstract

The EMBH model, previously developed using GRB 991216 as a prototype, is here applied to GRB 980425. We fit the luminosity observed in the 40–700 keV, 2–26 keV and 2–10 keV bands by the BeppoSAX satellite. In addition we present a novel scenario in which the supernova SN1998bw is the outcome of an “induced gravitational collapse” triggered by GRB 980425, in agreement with the GRB-Supernova Time Sequence (GSTS) paradigm [Ruffini, R., Bianco, C.L., Chardonnet, P., Fraschetti, F., Xue, S.-S. On a possible GRB-supernova time sequence. Astrophys. J. 555, L117–L120, 2001c]. A further outcome of this astrophysically exceptional sequence of events is the formation of a young neutron star generated by the SN1998bw event. A coordinated observational activity is recommended to further enlighten the underlying scenario of this most unique astrophysical system.

© 2004 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: γ-ray bursts; EMBH model; GRB 980425; SN1998BW

1. Introduction

The aim of this talk is to present the application of the EMBH theory, previously successfully applied to GRB 991216 used as a prototype, to the case of GRB 980425 (Pian et al., 2000) and SN1998bw (Galama et al., 1998). This is a particularly important test for the validity of the EMBH theory over a range of energies of six orders of magnitude: as we will see, both sources appear to be spherically symmetric and the respective total energies are $E_{\text{tot}} \approx 5 \times 10^{53} \text{ergs}$ and $E_{\text{tot}} \approx 10^{48} \text{ergs}$. We recall that the EMBH theory (see Ruffini et al., 2003b) depends only on three parameters, the energy of the dyadosphere $E_{\text{dyas}}$, the $B$ parameter and the factor $\beta$ describing the interstellar medium (ISM) porosity. The theory, therefore, explains all the observed features of the bolometric intensity variations of the afterglow as well as the spectral properties of the source and, in the specific case of GRB 980425, it also allows to clarify the general astrophysical scenario in which the GRB actually occurs. In this system, in fact, we propose that GRB 980425 has been the trigger of a phenomenon of “induced gravitational collapse” (Ruffini et al., 2001c) originating the supernova explosion and we also witness the birth of a young neutron star out of the supernova event. This extraordinary coincidence of these three astrophysical events represents an unprecedented scenario of fundamental importance in the field.
of relativistic astrophysics. Using the EMBH theory we shall explore: (a) The process of black hole formation in the event GRB 980425 (Pian et al., 2000), (b) The concept of “induced gravitational collapse”, introduced in the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al., 2001c), and its link to a very special supernova type in SN1998bw (Galama et al., 1998), and finally (c) The observation for the first time of the cooling of a hot newly formed neutron star.

The observational situation of this system is quite complex. In addition to the source GRB 980425 and the supernova SN1998bw, two X-ray sources have been found by BeppoSAX in the error box for the location of GRB 980425: a source S1 and a source S2 (Pian et al., 2000). Since the nature of the two sources S1 and S2 was not clear, a variety of slopes in the decaying part of the afterglow have been proposed (see Fig. 1). Kulkarni et al. (1998) have proposed to explain both the supernova SN1998bw and the GRB 980425 observations by a new class of GRBs, distinctly different from the cosmological ones, both originated by a single unusual supernova event. Similarly, Iwamoto et al. (1998) have tried to explain both the supernova event and the GRB with a new kind of supernova with an extremely large explosion energy, larger than \(10^{52}\) ergs, which they identify with the “hypernovae” predicted by Paczyński (1998). In this approach a totally novel concept is introduced: the supernova itself is assumed to originate in the process of gravitational collapse to a black hole of a massive progenitor star (\(\sim 40 M_\odot\)) with a particularly large angular momentum and strong magnetic field. A large rotational energy of the black hole extracted with a strong magnetic field is called in, by these authors, to explain the successful explosion of this “hypernova” leading both to the GRB and the supernova.

Our approach is drastically different. We first interpret the GRB 980425 within the EMBH theory. This allows the computation of the luminosity, spectra, Lorentz factors, and more generally all the dynamical aspects of the source. Having characterized the features of GRB 980425, we can gradually approach the remaining part of the scenario, disentangling the GRB observations from the supernova ones and from the sources S1 and S2. This leads to a natural time sequence of events and to their autonomous astrophysical characterization.

2. The energetics, dynamical parameters and space–time parametrization of GRB 980425

Our approach has focused on identifying the energy extraction process from the black hole (Christodoulou...
the basic energy source for the GRB phenomenon. The distinguishing feature is a theoretically predicted source energetics all the way up to \(1.8 \times 10^{54} \times \mathcal{M}_{\odot}/\mathcal{M}_c\) ergs for \(3.2 \times 10^8 \mathcal{M}_c \leq \mathcal{M}_{\text{BH}} \lesssim 7.2 \times 10^8 \mathcal{M}_c\) (Damour and Ruffini, 1975). In particular, the formation of a “dyadosphere”, during the gravitational collapse leading to a black hole endowed with electromagnetic structure (EMBH) has been indicated as the initial boundary conditions of the GRB process (Ruffini, 1998; Preparata et al., 1998). Our model has been referred as “the EMBH model”, although the EMBH physics only determines the initial boundary conditions of the GRB process by specifying the physical parameters and spatial extension of the neutral electron positron plasma originating the phenomenon created in the dyadosphere. The creation of this plasma is due to the vacuum polarization process occurring in a supercritical field by the Heisenberg–Euler–Schwinger process (see Heisenberg and Euler, 1935; Schwinger, 1951; Damour and Ruffini, 1975; Preparata et al., 1998).

Traditionally, following the observations of the Vela (Strong, 1975) and CGRO, satellites, GRBs have been characterized by few parameters such as the fluence, the characteristic duration \(T_{90}\) or \(T_{90}\) and the global time averaged spectral distribution (Band et al., 1993).

With the observations of BeppoSAX and the discovery of the afterglow, and the consequent optical identification, the distance of the GRB source has been determined and consequently the total energetics of the source has been added as a crucial parameter.

The observed energetics of GRBs, computed for spherically symmetric explosions, do coincide with the ones theoretically predicted in Damour and Ruffini (1975). This has been the major reason which has motivated us to reconsider and develop in full details the EMBH model. For simplicity, we have considered the vacuum polarization process occurring in an already formed Reissner–Nördstrom black hole (Ruffini, 1998; Preparata et al., 1998), whose dyadosphere has an energy \(E_{\text{dy}}\). It is clear, however, that this is only an approximation to the real dynamical description of the process of gravitational collapse to an EMBH. In order to prepare the background for attacking this extremely complex dynamical process, we have clarified some basic theoretical issues, necessary to implement the description of the fully dynamical process of gravitational collapse to an EMBH (see Ruffini and Vitagliano, 2002, 2003; Cherubini et al., 2002).

We have then given the constitutive equations for the five eras in the EMBH model (see for details Ruffini et al., 2003a, and references therein). The Era I: the \(e^+e^-\) pairs plasma, initially at \(\gamma = 1\), self propels itself away from the dyadosphere as a sharp pulse (the PEM pulse), reaching Lorentz \(\gamma\) factor of the order of 100 (Ruffini et al., 1999). The Era II: the PEM pulse, still optically thick, engulfs the remnant left over in the process of gravitational collapse of the progenitor star with a drastic reduction of the \(\gamma\) factor; the mass \(\mathcal{M}_c\) of this engulfed baryonic material is expressed by the dimensionless parameter \(B = M_{\text{dy}} \gamma^2 E_{\text{dy}}\) (Ruffini et al., 2000). The Era III: the newly formed pair-electromagnetic-baryonic (PEMB) pulse, composed of \(e^+e^-\) pair and of the electrons and baryons of the engulfed material, self-propels itself outward reaching in some sources Lorentz \(\gamma\) factors of \(10^3\)–\(10^4\); this era stops when the transparency condition is reached and the emission of the proper-GRB (P-GRB) occurs (Bianco et al., 2001). The Era IV: the resulting accelerated baryonic matter (ABM) pulse, ballistically expanding after the transparency condition has been reached, collides at ultrarelativistic velocities with the baryons and electrons of the ISM which is assumed to have an average constant number density, giving origin to the afterglow. The Era V: this era represents the transition from the ultrarelativistic regime to the relativistic and then to the non relativistic ones (see Ruffini et al., 2003a,b and references therein).

The EMBH model differs in many respects from the models in the current literature. The major difference consists in the following points:

(a) The appropriate theoretical description of all the above mentioned five eras is implemented, as well as the evaluation of the process of vacuum polarization originating the dyadosphere. The description of the inner engine originating the GRBs has never been addressed in the necessary details in the literature;

(b) The dynamical equations as well as the description of the phenomenon in the laboratory time and the time sequence carried by light signals recorded at the detector have been explicitly integrated (see e.g. Ruffini et al., 2003a,b). In doing so we have also corrected a basic conceptual inadequacy, common to all the current works on GRBs, which led to an improper space-time parametrization of the GRB phenomenon, preempting all these works from their predictive power: the relation between the photon arrival time at the detector and their emission time in the laboratory frame, expressed in our approach by an integral of a function of the Lorentz \(\gamma\) factor extended over all the past source worldlines, has been in the current literature expressed as a function of an instantaneous value of the Lorentz \(\gamma\) factor. These two approaches are conceptually very different and lead to significant qualitative differences (Ruffini et al., 2003a,b and references therein);
The equations of motion in our model depend only on two free parameters: the total energy $E_{\text{tot}}$, which coincides with the dyadosphere energy $E_{\text{dya}}$, and the amount $M_B$ of baryonic matter left over from the gravitational collapse of the progenitor star, which is determined by the dimensionless parameter $B = M_B c^2 / E_{\text{dya}}$. The best fit of GRB 980425 is reproduced in Table 1. It correspond to $E_{\text{dya}} = 1.1 \times 10^{53}$ ergs, $B = 7 \times 10^{-6}$ and the ISM average density is found to be $n_{\text{ISM}} = 0.02$ particle/cm$^3$. The plasma temperature and the total number of pairs in the dyadosphere are, respectively, $T = 1.028$ MeV and $N_{\text{pair}} = 5.3274 \times 10^{53}$.

3. The GRB 980425 luminosity in selected energy bands predicted by the EMBH model

Recently, within the EMBH model, we have developed an attempt to theoretically derive the GRB spectra out of first principles as well as the GRB luminosity in fixed energy bands (Ruffini et al., 2003c). We have adopted three basic assumptions: (a) The resulting radiation as viewed in the comoving frame during the afterglow phase has a thermal spectrum, (b) the ISM swept up by the front of the shock wave, with a Lorentz $\gamma$ factor between 300 and 2, is responsible for this thermal emission. (c) We also adopt, like in our previous papers (Ruffini et al., 2001a,b, 2002, 2003b), that the expansion occurs with spherical symmetry. This three assumptions are different from the ones adopted in the GRB literature, in which the afterglow emission is believed to originate from synchrotron emission in the production of a shock or reverse shock generated when the assumed jet-like ejecta encounter the external medium (see e.g. Giblin et al., 2002 and references therein).

In the EMBH model the structure of the shock is determined by mass, momentum and energy conservation: the constancy of the specific enthalpy, which is a standard condition in shock rest frames (Zel’dovich and Rayzer, 1966) and have been used in our derivation (Ruffini et al., 2003b). The only free parameter of our model is the size of the “effective emitting area” in the shock wave front: $A_{\text{eff}}$. Since the determination of this free parameter is performed here by empirically fitting the observational data, we avoid ambiguities due to the absence of relevant theoretical and laboratory results on relativistic shocks for Lorentz factor $\gamma \sim 300$.

The temperature $T$ of the black body in the comoving frame is then

$$T = \left( \frac{\Delta E_{\text{tot}}}{4 \pi r^2 \Delta r \sigma T^4} \right)^{1/4},$$

where $\sigma = A_{\text{eff}} / A_{\text{abm}}$ is the ratio between the “effective emitting area” and the ABM pulse surface $A_{\text{abm}}$, $\sigma$ is the Stefan–Boltzmann constant and $\Delta E_{\text{tot}}$ is the proper internal energy develop-

Table 1

<table>
<thead>
<tr>
<th>Points</th>
<th>$r$ (cm)</th>
<th>$t$ (s)</th>
<th>$\gamma$</th>
<th>“Superluminal” $v = \frac{c}{c}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$8.79 \times 10^4$</td>
<td>$2.60 \times 10^{-5}$</td>
<td>$2.03 \times 10^{-5}$</td>
<td>$1.027$</td>
</tr>
<tr>
<td>2</td>
<td>$8.49 \times 10^2$</td>
<td>$5.6 \times 10^{-5}$</td>
<td>$1.33 \times 10^{-4}$</td>
<td>$28.423$</td>
</tr>
<tr>
<td>3</td>
<td>$3.45 \times 10^6$</td>
<td>$1.14 \times 10^{-2}$</td>
<td>$2.19 \times 10^{-3}$</td>
<td>$8.647$</td>
</tr>
<tr>
<td>4</td>
<td>$4.31 \times 10^{11}$</td>
<td>$14.4$</td>
<td>$7.65 \times 10^{-4}$</td>
<td>$138.863$</td>
</tr>
<tr>
<td>$A$</td>
<td>$4.01 \times 10^{13}$</td>
<td>$1.34 \times 10^4$</td>
<td>$3.65$</td>
<td>$129.819$</td>
</tr>
<tr>
<td>$B$</td>
<td>$6.00 \times 10^{11}$</td>
<td>$2.00 \times 10^3$</td>
<td>$5.87$</td>
<td>$115.309$</td>
</tr>
<tr>
<td>$C$</td>
<td>$6.50 \times 10^{13}$</td>
<td>$2.17 \times 10^2$</td>
<td>$6.98$</td>
<td>$84.704$</td>
</tr>
<tr>
<td>$D$</td>
<td>$1.02 \times 10^{15}$</td>
<td>$3.40 \times 10^1$</td>
<td>$19.2$</td>
<td>$53.982$</td>
</tr>
<tr>
<td>$E$</td>
<td>$1.07 \times 10^{15}$</td>
<td>$3.57 \times 10^1$</td>
<td>$98.5$</td>
<td>$6.510$</td>
</tr>
<tr>
<td>$F$</td>
<td>$1.12 \times 10^{15}$</td>
<td>$3.74 \times 10^1$</td>
<td>$3.00 \times 10^2$</td>
<td>$6.469$</td>
</tr>
<tr>
<td>$G$</td>
<td>$1.17 \times 10^{15}$</td>
<td>$3.90 \times 10^1$</td>
<td>$5.00 \times 10^2$</td>
<td>$6.426$</td>
</tr>
<tr>
<td>$H$</td>
<td>$1.29 \times 10^{15}$</td>
<td>$4.30 \times 10^1$</td>
<td>$1.00 \times 10^3$</td>
<td>$6.389$</td>
</tr>
<tr>
<td>$I$</td>
<td>$2.67 \times 10^{15}$</td>
<td>$8.99 \times 10^{-1}$</td>
<td>$1.00 \times 10^4$</td>
<td>$4.101$</td>
</tr>
<tr>
<td>$J$</td>
<td>$4.31 \times 10^{15}$</td>
<td>$1.49 \times 10^1$</td>
<td>$5.00 \times 10^4$</td>
<td>$2.097$</td>
</tr>
</tbody>
</table>

The points 1,2,3,4 mark the beginning of first four “cras” (see Ruffini et al., 2003a,b) until the transparency point (point 4). The points A, B, C correspond to three events, respectively, before, during and after the peak of the E-APE. The points D, E, F, G, H, I, J are taken in the decaying part of the afterglow. The last column shows how the apparent motion in the radial coordinate, evaluated in the arrival time at the detector, leads to an enormous apparent “superluminal” behaviour. This illustrates the impossibility of using such a classical estimate in regimes of high $\gamma$ Lorentz factor.
oped in the collision between the ABM pulse and the ISM proper time interval $\Delta t$ (see Ruffini et al., 2003b,c). The ratio $\delta$, which is a priori a function that varies as the system evolves, is evaluated at every given value of the laboratory time $t$.

All the subsequent steps are now uniquely determined by the equations of motion of the system. The basic tool in this calculation involves the definition of the EQui-Temporal Surfaces (EQTS) for the relativistic expanding ABM pulse as seen by an asymptotic observer. The key to determining such EQTS (see Ruffini et al., 2002) is the relation between the time $t$ in the laboratory frame at which a photon is emitted from the ABM pulse external surface and the arrival time $t_a$ at which it reaches the detector. We have instead adopted the equations (see Ruffini et al., 2002, 2003b):

$$t_a = \left(1 + \frac{z}{c}\right) \left(1 - \frac{\rho_0}{c^2} \cos \vartheta + \frac{\rho_0}{c} \right)$$

$$= \left(1 + \frac{z}{c}\right) \left(1 - \frac{\rho_0}{c^2} \cos \vartheta + \frac{\rho_0}{c} \right)$$

$$= \left(1 + \frac{z}{c}\right) \left(1 - \frac{1}{\gamma^2(t')} \frac{dr}{c} + \frac{\rho_0}{c} \left(1 - \cos \vartheta\right) \right)$$

where $z$ is the cosmological redshift of the source, $\rho_0 = \rho(t = 0)$ and $\vartheta$ is the angle subtended by the emission point of the photon on the ABM pulse external surface, having defined $\vartheta = 0$ along the line of sight. For such a relation, different approximations exist in the literature (see e.g. Fenimore et al., 1996; Sari, 1997, 1998; Rees and Mészáros, 1998; Fenimore et al., 1999; Granot et al., 1999 and see also the reviews by Piran, 1999). There are both quantitative and qualitative important differences in the use of Eq. (3) instead of the ones usually adopted in the literature (Ruffini et al., 2003b). It is a matter of fact that only the use of the EQTS defined by Eq. (3) allows to fit the observational data and that even a very minor departure from it leads to unacceptable results. It is also important to recall that this inadequacy in the current literature in the relation between the arrival time and the laboratory time has affected also all the estimates of the power-law slopes in the afterglow, preempting all current theoretical considerations in the literature of their predictive power. All the considerations about beaming in GRBs existing in the current literature have to be reformulated on the ground of the proper theoretical treatment and of Eq. (3) (see Ruffini et al., 2003b). Having so determined the EQTS we have been able to evaluate the source luminosity in a given energy band, in agreement with the above mentioned new assumptions (Ruffini et al., 2003c).

We can now proceed to the best fit of the GRB 980425 observed data. The best fit of the observed luminosity in selected energy bands has been obtained for the above mentioned values of the parameters $E_{\text{peak}}, B$ and for $\delta$ monotonically decreasing from $4.81 \times 10^{-10}$ to $2.65 \times 10^{-12}$. The results are given in Fig. 2 where the luminosity is computed as a function of the arrival time for three selected energy bands.

We can then conclude:

1. The best fit is obtainable under almost perfect spherical symmetry. This has been proven as a result of an analysis of unprecedented redundancy: the luminosity

---

**Fig. 2.** (a) The light curve computed within the EMBH model in $\gamma$-rays (40–700 keV) is represented; the horizontal bar represents the peak flux in the 40–700 keV band measured by the GRBM (Frontera et al., 2000). The horizontal dotted line represents the noise level of the GRBM detector. (b) The light curve computed within the EMBH model in hard X-rays in the 2–26 keV band with the peak flux and time duration from WFC (Frontera et al., 2000). (c) The light curve computed within the EMBH model in hard X-rays in the 2–10 keV band with the experimental data in the same band from WFC (Pian et al., 2000).
curves are obtained from an integration over almost $10^7$ different paths, relating the observer to the EQTS. This procedure tests, to a very high level of accuracy, any departure from spherical symmetry as well as any departure from the computed equations of motion of the source (Ruffini et al., 2003b). This same circumstance was encountered in GRB 991216 (Ruffini et al., 2003b).

2. Each luminosity curve as a function of the arrival time presents complex behavior, which could be erroneously interpreted as evidence for breaks in the power-law indexes leading to erroneous inferences on the possible existence of jets (Ruffini et al., 2003c).

3. Although each luminosity curve presents some special features, the bolometric luminosity has a very clear and simple power-law behavior with the “golden value” index $n = 1.6$ (Ruffini et al., 2003b).

4. The new astrophysical scenario and the newly born neutron star

In Fig. 3 the luminosities in the three bands are represented together with the optical data of SN1998bw (black dots), the source S1 (black squares) and the source S2 (open circles). It is then clear that GRB 980425 is separated both from the supernova data and from the sources S1 and S2.

While the occurrence of the supernova in relation to the GRB has already been discussed with the GRB-Supernova Time Sequence (GSTS) paradigm (Ruffini et al., 2001c), we like to address here a different fundamental issue: the possibility of observing the birth of a newly formed neutron star out of the supernova event, which in turn has been triggered by the GRB 980425.

In the early days of neutron star physics it was clearly shown by Gamow and Schoenberg (1940, 1941) that the URCA processes are at the very heart of the supernova explosions. The neutrino–antineutrino emission described in the URCA process is the essential cooling mechanism necessary for the occurrence of the process of gravitational collapse of the imploding core. Since then, it has become clear that the newly formed neutron star can be still significantly hot and in its early stages will be associated to three major radiating processes (Tsuruta, 1964, 1979; Tsuruta et al., 2002; Canuto, 1978): (a) the thermal radiation from the surface; (b) the radiation due to neutrino, kaon, pion cooling; (c) the possible influence in both these processes of the superfluid nature of the supra-nuclear density neutron gas. Qualitative representative curves for these cooling processes, which are still today very undetermined due to the lack of observational data, are shown in Fig. 3.

It is of paramount importance to follow the further time history of the two sources S1 and S2. If, as we propose, S2 is a background source, its flux should be practically constant in time and this source has...
nothing to do with the GRB 980425/SN1998bw system. If S1 is indeed the cooling radiation emitted by the newly born neutron star, it should be possible to notice a very drastic behavior in its luminosity as qualitatively expresses in Fig. 3.

5. Conclusions

It is particularly attractive, in conclusion, to emphasize some of the analogies and the differences between the case of GRB 991216 and the one of GRB 980425:

1. In both these sources a GRB and, independently, a supernova event are present. In the case of GRB 991216 the inferences of the supernova can be obtained only on the ground of the emission of iron lines (Piro et al., 2000; Ruffini et al., 2001c). In the present case of GRB 980425 we have a very fortunate circumstance: the GRB source is much weaker and is much closer to us (z = 1.0 for GRB 991216 and z = 0.00835 for GRB 980425). This situation is particularly important for obtaining detailed data on the supernova and on the possible occurrence of a newly born neutron star. This occurrence could not be observed in GRB 991216 due to the very large distance and to the overwhelming X-ray luminosity of the afterglow (see Ruffini et al., 2003b).

2. The energetics of GRB 991216 is $E_{\gamma} = 4.83 \times 10^{53}$ ergs, while the one of GRB 980425 is $E_{\gamma} = 1.1 \times 10^{48}$ ergs. It is very impressive that the EMBH model applies over a range of more than six orders of magnitude, giving important inferences on the source as well as on the structure of the ISM surrounding the source. It is significant that in both sources the condition of spherical symmetry appears to be strongly implemented and this fact is a very clear discriminant among all possible sources of energy for GRBs.

3. The main difference between GRB 991216 and GRB 980425 is then traced back, within the EMBH model, to the different parameters occurring in the dyadosphere and to the nature of the “effective” Reissner–Nordström geometry which we have used as a reliable estimate for the dynamical processes of gravitational collapse leading to the formation of the EMBH. For GRB 991216 we have a ratio between the electromagnetic energy and the total mass of the imploing core, described by the parameter $Q/M$, given by $Q/M = 0.23$ while for GRB 980425 we have $Q/M = 6.5 \times 10^{-4}$. In both cases a reasonable mass of the black hole is $M_{BH} \approx 10 M_{\odot}$ (Ruffini et al., 2003b).

A dedicated observational campaign, both with XMM and Chandra, to follow the cooling of the newly formed neutron star is needed in order to gain for the first time information on this extremely important astrophysical process.

References


Bibliography


BIBLIOGRAPHY


Mereghetti, S., & Göts, D. 2003, GCN Circ. 2460.


Ricker, G.R. 2003, IAU Circ. 8101.


BIBLIOGRAPHY


BIBLIOGRAPHY

BIBLIOGRAPHY


