Gamma-Ray Bursts
Contents

1. Topics 103

2. Participants 105
   2.1. ICRANet participants ......................... 105
   2.2. Past collaborators .......................... 105
   2.3. Ongoing collaborations ....................... 106
   2.4. Students ..................................... 106

3. Brief description 107
   3.1. GRBs: Historical background .................. 107
   3.2. The three paradigms identifying the “canonical GRB” 107
   3.3. The optically thick “fireshell”? ............... 108
      3.3.1. The fireshell in the Livermore code .... 108
      3.3.2. The fireshell in the Rome code ...... 108
   3.4. The optically thin “fireshell”: the afterglow 108
   3.5. The “canonical GRB” bolometric light curve .. 109
   3.6. The spectra of the afterglow ................. 110
   3.7. On the GRB-SN association ................... 111
   3.8. Theoretical background for GRBs’ empirical correlations 111
   3.9. Application to GRB 031203 ..................... 112
   3.10. Application to GRB 050315 ................... 113
   3.11. Application to GRB 011121 ................... 114
   3.12. Application to GRB 060218 ................... 114
   3.13. Application to GRB 970228 ................... 115

4. Selected publications before 2005 117
   4.1. Refereed journals ............................. 117
   4.2. Conference proceedings ........................ 123

   5.1. Refereed journals ............................. 127
   5.2. Conference proceedings ........................ 131
## Contents

A. GRBs: Historical background ................................................. 137
   A.1. Introduction ............................................................. 137
   A.2. The discovery of GRBs and the early theoretical works .......... 138
   A.3. CGRO, BeppoSAX and the further theoretical developments ... 143

B. The three paradigms identifying the “canonical GRBs” .................. 151
   B.1. The Relative Space-Time Transformation (RSTT) paradigm ..... 151
   B.2. The Interpretation of the Burst Structure (IBS) paradigm .... 154
      B.2.1. The optically thick phase of the fireshell ............... 155
      B.2.2. The afterglow .................................................. 157
   B.3. The GRB-Supernova Time Sequence (GSTS) paradigm ........ 161

C. The optically thick “fireshell” ............................................. 169
   C.1. The fireshell in the Livermore code ............................. 169
      C.1.1. The hydrodynamics and the rate equation ............... 169
      C.1.2. The numerical integration ................................ 170
   C.2. The fireshell in the Rome code .................................. 172
      C.2.1. Era I: expansion of PEM-pulse ............................ 172
      C.2.2. Era II: interaction of the PEM pulse with remnant .... 182
      C.2.3. Era III: expansion of PEMB pulse ......................... 188
      C.2.4. The approach to transparency ............................ 191

D. The optically thin “fireshell”: the afterglow .......................... 197

E. The “canonical GRB” bolometric light curve .............................. 199
   E.1. On the structures in the afterglow peak emission ............. 201
   E.2. The “canonical” GRB scenario: “genuine” and “fake” short GRBs 205

F. The spectra of the afterglow .............................................. 209
   F.1. The luminosity in fixed energy bands ........................... 209
   F.2. The time integrated spectra and the hard-to-soft transition 211
   F.3. Evidence for isotropic emission in GRB991216 ................ 213

G. On the GRB-SN association ................................................ 217
   G.1. GRB 980425 / SN 1998bw / URCA-1 ........................... 217
   G.2. GRB 030329 / SN 2003dh / URCA-2 ............................ 220
   G.3. GRB 031203 / SN 2003lw / URCA-3 ............................ 221
   G.4. The GRB / SN / URCA connection .............................. 221
   G.5. URCA-1, URCA-2 and URCA-3 .................................. 223

H. Theoretical background for GRBs’ empirical correlations ............. 227
   H.1. Spectral-energy correlations .................................... 228
   H.2. The Amati-like correlation in the fireshell model ........... 229
   H.3. Conclusion .......................................................... 233
1. Topics

- The three paradigms identifying the “canonical GRBs”.
- The optically thick “fireshell”.
- The optically thin “fireshell”: the afterglow.
- The “canonical GRB” bolometric light curve.
- The spectra of the afterglow.
- The GRB-SN association.
- Application to different sources.
1. Topics
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3. Brief description

3.1. GRBs: Historical background

The basic steps leading to the birth of relativistic astrophysics are shortly outlined: from the understanding of the thermonuclear evolution of stars, to the discovery of neutron stars in pulsars and the observations of neutron stars and black holes in binary X-ray sources. We then recall the pioneering works of the discovery of Gamma-Ray Bursts (GRBs) and their theoretical explanation, predicting energetics on the order of $10^{54}$ ergs, in terms of the blackholic energy. Finally, we mention the early GRB classification into short and long GRBs, following the BATSE observations of the CGRO satellite, as well as the crucial role of the BeppoSAX satellite, leading to the optical identification and determination of the energetics of GRBs.

3.2. The three paradigms identifying the “canonical GRB”

Soon after the first attempt in the year 2000 of interpreting GRB 991216 in a consistent theoretical framework, our group became aware of the total conceptual new scenario presenting itself in the physics and astrophysics of GRBs. It was not just a problem of parameters’ fitting in some already known theoretical framework. We were in presence of a new conceptual scenario, needing new paradigms to be developed. In three letters published on the same issue of *Astrophysical Journal Letters* in 2001, we introduced these three fundamental new paradigms (*Ruffini et al.*, 2001c,b,a):

1. The Relative Space-Time Transformation (RSTT) paradigm (*Ruffini et al.*, 2001c), linking the comoving time, the laboratory time and the time at the observer, necessary for the description of the GRB phenomenon.

2. The Interpretation of the Burst Structure (IBS) paradigm (*Ruffini et al.*, 2001b), introducing the novel concept of the Proper-GRB (P-GRB) and separating it from the afterglow.

3. The GRB-Supernova Time Sequence (GSTS) paradigm (*Ruffini et al.*, 2001a) introducing the novel concept of induced gravitational collapse.
3. Brief description

3.3. The optically thick “fireshell”

3.3.1. The fireshell in the Livermore code

In appendix “The fireshell in the Livermore code” we recall the basic hydrodynamics and rate equation for the electron-positron plasma. Then we outline the numerical code used to evolve the spherically symmetric general relativistic hydrodynamic equations starting from the dyadosphere. Such a code was not used by us but had already been developed independently for more general astrophysical scenarios by Jim Wilson and Jay Salmonson at the Lawrence Livermore National Laboratory (see Wilson et al., 1998a,b). In our collaboration, the Livermore code has been used in order to validate the correct choice among a variety of different semi-analytic models developed at the University of Rome “La Sapienza”.

3.3.2. The fireshell in the Rome code

In appendix “The fireshell in the Rome code” we first recall the co-variant energy-momentum tensor and the thermodynamic quantities used to describe the electron-positron plasma as well as their expression as functions of Fermi integrals. The thermodynamic equilibrium of the photons and the electron-positron pairs is initially assumed at temperature larger than $e^+ e^-$ pairs creation threshold ($T > 1$ MeV). The numerical code implementing entropy and energy conservations as well as the rate equation for the electron-positron pairs is outlined. We recall, as well, the simulation of different geometries assumed for the fireshell and the essential role of the Livermore code in selecting the correct one among these different possibilities for the dynamics of this plasma composed uniquely of electron, positron and photons (PEM pulse). The correct solution resulted to be the following: the fireshell is expanding in its comoving frame but its thickness is kept constant in the laboratory frame due to the balancing effect of the Lorentz contraction. We then examine the equations for the engulfment of the baryon loading as well as the further expansion of the fireshell composed by electron, positron, photons and baryon (PEMB pulse) up to the transparency point. We again point out the special role of the Livermore code in validating our results. Quite in addition of this validation procedures, the Livermore code has been essential in evidencing an instability occurring at a critical value of the baryon loading parameter $B = 10^{-2}$ (see Fig. C.5 and Ruffini et al., 2000).

3.4. The optically thin “fireshell”: the afterglow

In appendix “The optically thin “fireshell”: the afterglow” we write the energy and momentum conservation equations for the interaction between the
3.5. The “canonical GRB” bolometric light curve

In the appendix “The “canonical GRB” bolometric light curve” we derive the expression for the bolometric luminosity of the GRB afterglow and we address the general issue of the possible explanation of the observed substructures in the GRB prompt emission as due to CBM inhomogeneities. On this topic there exist in the literature two extreme points of view: the one by Fenimore and collaborators (see e.g. [1996, 1999, 1999]) and Piran and collaborators (see e.g. [1997, 1999, 2000, 2001] on one side and the one by Dermer and collaborators [1998, 1999, 1999]) on the other. Fenimore and collaborators have emphasized the relevance of a specific signature to be expected in the collision of a relativistic expanding shell with the CBM, what they call a fast rise and exponential decay (FRED) shape. This feature is confirmed by our analysis (see peaks A, B, C in Fig. E.2). However they also conclude, sharing the opinion by Piran and collaborators, that the variability observed in GRBs is inconsistent with causally connected variations in a single, symmetric, relativistic shell interacting with the ambient material (“external shocks”, [1999]). In their opinion the solution of the short time variability has to be envisioned within the protracted activity of an unspecified “inner engine” ([1997]; see as well [1994, 1998, 1998, 1998]). On the other hand, Dermer and collaborators, by considering an idealized process occurring at a fixed $\gamma = 300$, have reached the opposite conclusions and they purport that GRB light curves are tomographic images of the density distributions of the medium surrounding the sources of GRBs ([1999]). By applying the exact formulas derived in previous appendices, we show that Dermer’s conclusions are correct, and we identify that the “tomography” purported by [1999] leads to CBM clouds consistently on the order of $\sim 10^{14}$ cm. Apparent superluminal effects are introduced. In our treatment we have adopted a simple spherically symmetric approximation for the CBM distribution. We show that the agreement of this approximation with the observations is excellent for Lorentz gamma factors $\gamma > 150$ since the relativistic beaming angle introduced in the previous appendices provides an effective cut-off to the visible CBM structure. For lower Lorentz gamma factors, a three dimensional description of the CBM would be needed and the corresponding treatment is
3. Brief description

We then define the “canonical GRB” light curve with two sharply different components: the Proper-GRB (P-GRB), emitted when the optically thick fireshell of electron-positron plasma originating the phenomenon reaches the transparency, and the afterglow, emitted due to the collision between the remaining optically thin fireshell and the CBM. Our “canonical GRB” scenario puts a special emphasis on the discrimination between “genuine” and “fake” short GRBs:

- The “genuine” short GRBs inherit their features from an intrinsic property of their sources. The very small fireshell baryon loading, in fact, implies that the afterglow time-integrated luminosity is negligible with respect to the P-GRB one.

- The “fake” short GRBs, instead, inherit their features from the environment. The very small CBM density, in fact, implies that the afterglow peak luminosity is lower than the P-GRB one, even if the afterglow total time-integrated luminosity is higher. This deflated afterglow peak can be observed as a “soft bump” following the P-GRB spike, as in GRB 970228 (Bernardini et al., 2007a,b), GRB 060614 (Caito et al., 2007), and the sources analyzed by Norris and Bonnell (2006).

3.6. The spectra of the afterglow

In appendix “The spectra of the afterglow”, having shown in the previous appendices 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 hard to soft drift observed in GRB spectra.

The fundamental assumption is introduced that the X- and gamma ray radiation during the entire afterglow phase has a thermal spectrum in the comoving frame. The ratio \( R = \frac{A_{\text{eff}}}{A_{\text{vis}}} \) between the “effective emitting area” \( A_{\text{eff}} \) of the ABM pulse and its full visible area \( A_{\text{vis}} \) is introduced. Due to the CBM inhomogeneities, composed of clouds with filamentary structure, the ABM emitting region is in fact far from being homogeneous. We have justified the existence of this thermal emission by considering the CBM filamentary structure and its optical thickness (see Ruffini et al., 2005c). The theoretical prediction for the observed spectra starting from these premises has been by far the most complex and, in our opinion, the most elegant aspect of the entire GRB model. In order to compute the luminosity in a fixed energy band
3.7. On the GRB-SN association

At a given value of the arrival time it is necessary to perform a convolution over the given EQuiTemporal Surface (EQTS, see Bianco and Ruffini, 2004, 2005b, and the following report about “Relativistic effects in Physics and Astrophysics”) of an infinite number of elementary contributions, each one characterized by a different value of Lorentz and Doppler factors. Therefore, each observed instantaneous spectrum is theoretically predicted to be the result of a convolution of an infinite number of thermal spectra, each one with a different temperature, over the given EQTS and its shape is theoretically predicted to be non-thermal. Moreover, the observed time-integrated spectra depart even more from a thermal shape, being the convolution over the observation time of an infinite number of non-thermal instantaneous spectra. We confirm in this work the qualitative suggestion advanced by Blinnikov et al. (1999). We then examine the issue of the possible presence or absence of jets in GRBs in the case of GRB 991216. We compare and contrast our theoretically predicted afterglow luminosity in the 2–10 keV band for spherically symmetric versus collimated emission. At these wavelengths the collimated emission can be excluded and data analysis confirms spherical symmetry. In fact, the actual afterglow luminosity in fixed energy bands, in spherical symmetry, does not have a simple power law dependence on arrival time. 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.

3.7. On the GRB-SN association

In appendix “On the GRB-SN association” we apply our theoretical framework to the analysis of all the GRBs associated with Supernovae (SNe). We proceed first to GRB 980425; we go then to GRB 030329; finally, we discuss the late time emission of GRB 031203 observed by XMM and Chandra. We summarize the general results of these GRBs associated with SNe and we make some general conclusions on the relations between GRBs, SNe and the URCA sources. We finally present some novel considerations about our third paradigm and the concept of induced gravitational collapse.

3.8. Theoretical background for GRBs’ empirical correlations

In this appendix we show the existence of a spectral-energy correlation within our “fireshell” model for GRBs. We build a sample of pseudo-GRBs, i.e. a set of theoretically simulated light curves, varying the total energy of the electron-positron plasma $E_{e\pm}^{\text{tot}}$ and keeping the same baryon loading; the parametrization used to describe the distribution of the CBM is the same as well
for all the pseudo-GRBs. The values of these parameters ($B$, $\rho$ and $R$) used in this work are equal to the ones assumed to fit GRB 050315, a Swift burst representing a good example of what in the literature has been addressed as “canonical light curve”. For each GRB of the sample we calculate the $\nu F_\nu$ spectrum integrating the theoretically computed light curve over the total time, namely from our $T_0$, the end of the Proper-GRB (P-GRB), up to the end of our afterglow phase, when the fireshell Lorentz gamma factor is close to unity; we exclude the P-GRB from this spectral computation because, following our “canonical” GRB scenario, this component of the GRB emission is physically different from the other component, that is our afterglow component, so one should take care in no mixing them. We find that the maximum of this spectrum, that is the observed peak energy $E_{p,\text{tot}}$, correlates with the initial electron-positron plasma energy $E_{e^\pm,\text{tot}}$ in a way very similar to the Amati one: $E_{p,\text{tot}} \propto (E_{e^\pm,\text{tot}})^{0.5}$.

3.9. Application to GRB 031203

In appendix “Application to GRB 031203” we show how we are able to predict the whole dynamics of the process which originates the GRB 031203 emission fixing univocally the two free parameters of the model, $E_{e^\pm,\text{tot}}$ and $B$. Moreover, it is possible to obtain the exact temporal structure of the prompt emission taking into account the effective CBM filamentary structure. The important point we like 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. 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. Due to the possibility of reaching a precise identification of the emission process in GRB afterglows by the observations of the instantaneous spectra, it is hoped that further missions with larger collecting area and higher time resolving power be conceived and a systematic attention be given to closer-by GRB sources. 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 et al. (2004a), it appears to us as a under-energetic GRB ($E_{e^\pm,\text{tot}} \approx 10^{50}$ erg), well within the range of applicability of our theory, between $10^{48}$ erg for GRB 980425 (Ruffini et al., 2004a in press) and $10^{54}$ erg for GRB 991216 (Ruffini et al., 2003).
3.10. Application to GRB 050315

Having used GRB 991216 as a prototype, we were constrained by the absence of data in the time range between $\sim 36$ s and $\sim 3500$ s. This same situation was encountered, even more extremely, in all the other sources, like e.g. GRB 970228, GRB 980425, GRB 030329, etc. Fortunately, the launch of the Swift mission changed drastically and positively this situation. We could obtain a continuous set of data from the prompt emission to the latest afterglow phases in multiple energy bands.

In appendix “Application to GRB 050315” we discuss how 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 5 energy bands, with continuous light curves near the beginning of the GRB event, including 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 confirmed 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, fully confirmed from the observations, on the total energy emitted in the P-GRB $E_{P-GRB} = 1.98 \times 10^{51}$ erg and on its temporal separation from the peak of the afterglow $\Delta t_{\text{d}} = 51$ 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 electron-positron plasma $E_{\text{tot}}^{e\pm} = 1.46 \times 10^{53}$ erg and the baryon loading parameter $B = 4.55 \times 10^{-3}$.

4. The “canonical behavior” in almost all the GRB observed by Swift, showing 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” have been related to the fluctuations of the CBM density and of the $\mathcal{R}$ 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.

After the analysis of the above two sources, only the earliest part of the afterglow we theoretically predicted, which corresponds to a bolometric luminosity monotonically increasing with the photon detector arrival time, pre-
ceding 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 byproduct of the above results, we could explain one of the long lasting unanswered puzzles of GRBs: 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 visible area due to relativistic beaming is small compared to the typical size of an CBM cloud. Consequently, any small inhomogeneity in such a cloud produces a marked variation in the GRB light curve. On the other hand, for $\gamma \to 1$, in the latest afterglow phases, the diameter of the EQTS visible area is much bigger than the typical size of an CBM cloud. Therefore, the observed light curve is a superposition of the contribution of many different clouds and inhomogeneities, which produces on average a much smoother light curve (details in Ruffini et al., 2002a, 2003).

3.11. Application to GRB 011121

A flare is a large scale activity in excess on the underlying light curve that manifests as a bump in luminosity rather intense and sharp in the decaying phase of the afterglow. When the first flare was detected by BeppoSAX, on the X-Ray light curve of GRB 011121, it was assumed as an extremely peculiar phenomenon. However, by the advent of the Swift Mission, many flares have been discovered in the light curves of about the 50% of the total amount of X-Ray afterglows observed: it was clear that flares are a very typical feature of GRBs phenomenon.

In our theory the multiwavelenght emission is entirely due to the fully inelastic collisions of the baryonic remnants of the fireshell with the CBM. Flares also, as characteristic parts of the afterglow, can be naturally explained in this context. We realized a first attempt to check this idea analyzing the burst with the first flare observed: GRB 011121.

3.12. Application to GRB 060218

GRB060218 is the best example of a Gamma-Ray Burst (GRB) associated with a Supernova (SN) Ib/c (Campana et al., 2006a). Its extremely long duration is unusual, with the longest $T_{90}$ ever observed ($T_{90} \sim 2100$ s). This source is also interesting since it represents a discriminant between existing GRB theories: it has been pointed out by Soderberg et al. (2006b) and Fan et al.
3.13. Application to GRB 970228

that it is impossible to explain the X- and radio afterglows within the traditional synchrotron model. They attempted to fit only the late radio data after $\sim 10^3$ s and they attributed the nature of the prompt emission to an as yet undetermined “inner engine” (see Soderberg et al., 2006b), possibly a magnetar (Mazzali et al., 2006).

Here we present a detailed fit of the entire X- and $\gamma$-ray light curves including the prompt emission: there is no need here for the prolonged activity of an inner engine. Therefore we explain the unusually high values of the observed $T_{90}$ by our “fireshell” model.

The initial total energy of the electron-positron plasma $E_{\text{tot}}^{e\pm} = 2.32 \times 10^{50}$ erg has a particularly low value, similar to the other GRBs associated with SNe. For the first time, we observe a baryon loading $B = 10^{-2}$ which coincides with the upper limit for the dynamical stability of the fireshell. The effective CBM density shows a radial dependence $n_{\text{cbm}} \propto r^{-\alpha}$ with $1.0 \lesssim \alpha \lesssim 1.7$ and monotonically decreases from 1 to $10^{-6}$ particles/cm$^3$. This behavior is interpreted as being due to a fragmentation in the fireshell. Analogies with the fragmented density and filling factor characterizing Novae are outlined. The fit presented is particularly significant in view of the complete data set available for GRB060218 and of the fact that it fulfills the Amati relation.

3.13. Application to GRB 970228

The discovery by Swift and HETE-2 of an afterglow emission associated possibly with short GRBs opened the new problematic of their nature and classification. The observations of GRB 060614 (Gehrels et al., 2006; Mangano et al., 2007) challenged the standard GRB classification scheme (Klebesadel, 1992; Dezalay et al., 1992) in which the gamma events are branched into two classes: “short” GRBs (events which last less than $\sim 2$s) and “long” GRBs (events which last more than $\sim 2$s). GRB 060614, indeed, “reveals a first short, hard-spectrum episode of emission (lasting 5 s) followed by an extended and somewhat softer episode (lasting $\sim 100$ s)”: a “two-component emission structure” (Gehrels et al., 2006). Moreover, stringent upper limits on the luminosity of the Supernova possibly associated with GRB 060614 have been established (Della Valle et al., 2006; Gal-Yam et al., 2006). Gehrels et al. (2006) concluded that “it is difficult to determine unambiguously which category GRB 060614 falls into” and that, then, GRB 060614, due to its “hybrid” observational properties, “opens the door on a new GRB classification scheme that straddles both long and short bursts” (Gehrels et al., 2006).

These observations motivated Norris and Bonnell (2006) to reanalyze the BATSE catalog identifying a new GRB class with “an occasional softer extended emission lasting tenths of seconds after an initial spikelike emission” (Norris and Bonnell, 2006). In some cases, “the strength of the extended emission converts an otherwise short burst into one with a duration that can be
tens of seconds, making it appear to be a long burst” (Norris and Bonnell, 2006). Hence, Norris and Bonnell (2006) suggested that the standard “long-short” GRB classification scheme “is at best misleading” (Norris and Bonnell, 2006).

In this appendix we will propose GRB 970228 (Costa et al., 1997; Frontera et al., 1998, 2000) as the prototype of these “hybrid” sources, since it shares the same morphology and observational features. We will show that such “hybrid” sources are indeed explainable within our “canonical GRB” scenario in terms of a peculiarly small average value of the CBM density, compatible with a galactic halo environment (see also Bernardini et al., 2007a,b, and sec. E.2 for details).

We analyze BeppoSAX data on GRB 970228 within the “fireshell” model and find that GRB 970228 is a “canonical GRB” as defined in sec. E.2, with the main peculiarity of a particularly low average density of the CBM \( \langle n_{\text{cbm}} \rangle \sim 10^{-3} \) particles/cm\(^3\), consistent with a galactic halo environment. We also simulate the light curve corresponding to a rescaled CBM density profile with \( \langle n_{\text{cbm}} \rangle = 1 \) particle/cm\(^3\). From such a comparison it follows that the total time-integrated luminosity is a faithful indicator of the nature of GRBs, contrary to the peak luminosity which is merely a function of the CBM density.

Moreover, we investigate how GRB 970228 unveils another peculiarity of this class of GRBs: they do not fulfill the “Amati relation”. We provide a theoretical explanation within the fireshell model for the apparent absence of such correlation for the GRBs belonging to this new class.

3.14. Application to GRB 060614

Following our analysis of GRB 970228 and the definition of the “fake” short GRB class (see above), we moved on to the application of our “canonical GRB” scenario to GRB 060614. In this appendix we present a progress report of our analysis.
4. Selected publications before 2005

4.1. Refereed journals


A formula is derived for the mass of a black hole as a function of its “irreducible mass”, its angular momentum, and its charge. It is shown that 50% of the mass of an extreme charged black hole can be converted into energy as contrasted with 29% for an extreme rotating black hole.


Following the classical approach of Sauter, of Heisenberg and Euler and of Schwinger the process of vacuum polarization in the field of a “bare” Kerr-Newman geometry is studied. The value of the critical strength of the electromagnetic fields is given together with an analysis of the feedback of the discharge on the geometry. The relevance of this analysis for current astrophysical observations is mentioned.


The “dyadosphere” has been defined as the region outside the horizon of a black hole endowed with an electromagnetic field (abbreviated to EMBH for “electromagnetic black hole”) where the electromagnetic field exceeds the critical value, predicted by Heisenberg & Euler for $e^\pm$ pair production. In a very short time ($\sim O(\hbar/mc^2)$) a very large number of pairs is created there. We here give limits on the EMBH parameters leading to a Dyadosphere for $10M_\odot$ and $10^5M_\odot$ EMBH’s, and give as well the pair densities as functions of the radial coordinate. We here assume that the pairs reach thermodynamic equilibrium with a photon gas and estimate the average energy per pair as a function of the EMBH mass. These data give the initial conditions for the analysis of an enormous pair-electromagnetic-pulse or “P.E.M. pulse” which naturally leads to relativistic expansion. Basic energy requirements for gamma ray bursts (GRB), including GRB971214 recently observed at $z=3.4$, can be accounted for by processes occurring in the dyadosphere. In this letter we do not address the prob-
lem of forming either the EMBH or the dyadosphere: we establish some inequalities which must be satisfied during their formation process.


We study the relativistically expanding electron-positron pair plasma formed by the process of vacuum polarization around an electromagnetic black hole (EMBH). Such processes can occur for EMBH’s with mass all the way up to \(6 \times 10^5 M_\odot\). Beginning with a idealized model of a Reissner-Nordstrom EMBH with charge to mass ratio \(\xi = 0.1\), numerical hydrodynamic calculations are made to model the expansion of the pair-electromagnetic pulse (PEM pulse) to the point that the system is transparent to photons. Three idealized special relativistic models have been compared and contrasted with the results of the numerically integrated general relativistic hydrodynamic equations. One of the three models has been validated: a PEM pulse of constant thickness in the laboratory frame is shown to be in excellent agreement with results of the general relativistic hydrodynamic code. It is remarkable that this precise model, starting from the fundamental parameters of the EMBH, leads uniquely to the explicit evaluation of the parameters of the PEM pulse, including the energy spectrum and the astrophysically unprecedented large Lorentz factors (up to \(6 \times 10^3\) for a \(10^3 M_\odot\) EMBH). The observed photon energy at the peak of the photon spectrum at the moment of photon decoupling is shown to range from 0.1 MeV to 4 MeV as a function of the EMBH mass. Correspondingly the total energy in photons is in the range of \(10^{52}\) to \(10^{54}\) ergs, consistent with observed gamma-ray bursts. In these computations we neglect the presence of baryonic matter which will be the subject of forthcoming publications.


The interaction of an expanding Pair-Electromagnetic pulse (PEM pulse) with a shell of baryonic matter surrounding a Black Hole with electromagnetic structure (EMBH) is analyzed for selected values of the baryonic mass at selected distances well outside the dyadosphere of an EMBH. The dyadosphere, the region in which a super critical field exists for the creation of e+e- pairs, is here considered in the special case of a Reissner-Nordstrom geometry. The interaction of the PEM pulse with the baryonic matter is described using a simplified model of a slab of constant thickness in the laboratory frame (constant-thickness approximation) as well as performing the integration of the general relativistic hydrodynamical equations. Te validation of the constant-thickness approximation, already presented in a previous paper Ruffini et al. (1999) for a PEM pulse in vacuum, is here generalized to the presence of baryonic matter. It is found that for a baryonic shell of mass-energy less than 1% of the total
4.1. Refereed journals

energy of the dyadosphere, the constant-thickness approximation is in excellent agreement with full general relativistic computations. The approximation breaks down for larger values of the baryonic shell mass, however such cases are of less interest for observed Gamma Ray Bursts (GRBs). On the basis of numerical computations of the slab model for PEM pulses, we describe (i) the properties of relativistic evolution of a PEM pulse colliding with a baryonic shell; (ii) the details of the expected emission energy and observed temperature of the associated GRBs for a given value of the EMBH mass; $10^3 M_\odot$, and for baryonic mass-energies in the range $10^{-8}$ to $10^{-2}$ the total energy of the dyadosphere.


In the framework of the model that uses black holes endowed with electromagnetic structure (EMBH) as the energy source, we study how an elementary spike appears to the detectors. We consider the simplest possible case of a pulse produced by a pure $e^+e^-$ pair-electro-magnetic plasma, the PEM pulse, in the absence of any baryonic matter. The resulting time profiles show a Fast-Rise-Exponential-Decay shape, followed by a power-law tail. This is obtained without any special fitting procedure, but only by fixing the energetics of the process taking place in a given EMBH of selected mass, varying in the range from $10$ to $10^3 M_\odot$ and considering the relativistic effects to be expected in an electron-positron plasma gradually reaching transparency. Special attention is given to the contributions from all regimes with Lorentz $\gamma$ factor varying from $\gamma = 1$ to $\gamma = 10^4$ in a few hundreds of the PEM pulse travel time. Although the main goal of this paper is to obtain the elementary spike intensity as a function of the arrival time, and its observed duration, some qualitative considerations are also presented regarding the expected spectrum and on its departure from the thermal one. The results of this paper will be comparable, when data will become available, with a subfamily of particularly short GRBs not followed by any afterglow. They can also be propedeutical to the study of longer bursts in presence of baryonic matter currently observed in GRBs.


The GRB 991216 and its relevant data acquired from the BATSE experiment and RXTE and Chandra satellites are used as a prototypical case to test the theory linking the origin of gamma ray bursts (GRBs) to the process of vacuum polarization occurring during the formation phase of a black hole endowed with electromagnetic structure (EMBH). The relative space-time transformation paradigm (RSTT paradigm) is presented. It relates the observed signals of GRBs to their past light cones, defining the events on the worldline of the
source essential for the interpretation of the data. Since GRBs present regimes with unprecedentedly large Lorentz $\gamma$ factor, also sharply varying with time, particular attention is given to the constitutive equations relating the four time variables: the comoving time, the laboratory time, the arrival time at the detector, duly corrected by the cosmological effects. This paradigm is at the very foundation of any possible interpretation of the data of GRBs.


Given the very accurate data from the BATSE experiment and RXTE and Chandra satellites, we use the GRB 991216 as a prototypical case to test the EMBH theory linking the origin of the energy of GRBs to the electromagnetic energy of black holes. The fit of the afterglow fixes the only two free parameters of the model and leads to a new paradigm for the interpretation of the burst structure, the IBS paradigm. It leads as well to a reconsideration of the relative roles of the afterglow and burst in GRBs by defining two new phases in this complex phenomenon: a) the injector phase, giving rise to the proper-GRB (P-GRB), and b) the beam-target phase, giving rise to the extended afterglow peak emission (E-APE) and to the afterglow. Such differentiation leads to a natural possible explanation of the bimodal distribution of GRBs observed by BATSE. The agreement with the observational data in regions extending from the horizon of the EMBH all the way out to the distant observer confirms the uniqueness of the model.


The data from the Chandra satellite on the iron emission lines in the afterglow of GRB 991216 are used to give further support for the EMBH theory, which links the origin of the energy of GRBs to the extractable energy of electromagnetic black holes (EMBHs), leading to an interpretation of the GRB-supernova correlation. Following the relative space-time transformation (RSTT) paradigm and the interpretation of the burst structure (IBS) paradigm, we introduce a paradigm for the correlation between GRBs and supernovae. The following sequence of events is shown as kinematically possible and consistent with the available data: a) the GRB-progenitor star $P_1$ first collapses to an EMBH, b) the proper GRB (P-GRB) and the peak of the afterglow (E-APE) propagate in interstellar space until the impact on a supernova-progenitor star $P_2$ at a distance $\leq 2.69 \times 10^{17}$ cm, and they induce the supernova explosion, c) the accelerated baryonic matter (ABM) pulse, originating the afterglow, reaches the supernova remnants 18.5 hours after the supernova explosion and gives rise to the iron emission lines. Some considerations on the dynamical implementation of the paradigm are presented. The concept of induced supernova
explosion introduced here specifically for the GRB-supernova correlation may have more general application in relativistic astrophysics.


The relative-space-time-transformation (RSTT) paradigm and the interpretation of the burst-structure (IBS) paradigm are applied to probe the origin of the time variability of GRBs. Again GRB 991216 is used as a prototypical case, thanks to the precise data from the CGRO, RXTE and Chandra satellites. It is found that with the exception of the relatively inconspicuous but scientifically very important signal originating from the initial “proper gamma ray burst” (P-GRB), all the other spikes and time variabilities can be explained by the interaction of the accelerated-baryonic-matter pulse with inhomogeneities in the interstellar matter. This can be demonstrated by using the RSTT paradigm as well as the IBS paradigm, to trace a typical spike observed in arrival time back to the corresponding one in the laboratory time. Using these paradigms, the identification of the physical nature of the time variability of the GRBs can be made most convincingly. It is made explicit the dependence of a) the intensities of the afterglow, b) the spikes amplitude and c) the actual time structure on the Lorentz gamma factor of the accelerated-baryonic-matter pulse. In principle it is possible to read off from the spike structure the detailed density contrast of the interstellar medium in the host galaxy, even at very high redshift.


Using GRB 991216 as a prototype, it is shown that the intensity substructures observed in what is generally called the “prompt emission” in gamma ray bursts (GRBs) do originate in the collision between the accelerated baryonic matter (ABM) pulse with inhomogeneities in the interstellar medium (ISM). The initial phase of such process occurs at a Lorentz factor $\gamma \sim 310$. The crossing of ISM inhomogeneities of sizes $\Delta R \sim 10^{15}$ cm occurs in a detector arrival time interval of $\sim 0.4$ s implying an apparent superluminal behavior of $\sim 10^5 c$. The long lasting debate between the validity of the external shock model vs. the internal shock model for GRBs is solved in favor of the first.


We have recently proposed three paradigms for the theoretical interpretation of gamma-ray bursts (GRBs). (1) The relative space-time transformation (RSTT) paradigm emphasizes how the knowledge of the entire world-line of the source
4. Selected publications before 2005

from the moment of gravitational collapse is a necessary condition in order to interpret GRB data. (2) The interpretation of the burst structure (IBS) paradigm differentiates in all GRBs between an injector phase and a beam-target phase. (3) The GRB-supernova time sequence (GSTS) paradigm introduces the concept of induced supernova explosion in the supernovae-GRB association. In the introduction the RSTT and IBS paradigms are enunciated and illustrated using our theory based on the vacuum polarization process occurring around an electromagnetic black hole (EMBH theory). The results are summarized using figures, diagrams and a complete table with the space-time grid, the fundamental parameters and the corresponding values of the Lorentz gamma factor for GRB 991216 used as a prototype. In the following sections the detailed treatment of the EMBH theory needed to understand the results of the three above letters is presented. We start from the considerations on the dyadosphere formation. We then review the basic hydrodynamic and rate equations, the equations leading to the relative space-time transformations as well as the adopted numerical integration techniques. We then illustrate the five fundamental eras of the EMBH theory: the self acceleration of the \( e^+ e^- \) pair-electromagnetic plasma (PEM pulse), its interaction with the baryonic remnant of the progenitor star, the further self acceleration of the \( e^+ e^- \) pair-electromagnetic radiation and baryon plasma (PEMB pulse). We then study the approach of the PEMB pulse to transparency, the emission of the proper GRB (P-GRB) and its relation to the “short GRBs”. Particular attention is given to the free parameters of the theory and to the values of the thermodynamical quantities at transparency. Finally the three different regimes of the afterglow are described within the fully radiative and radial approximations: the ultrarelativistic, the relativistic and the nonrelativistic regimes. The best fit of the theory leads to an unequivocal identification of the “long GRBs” as extended emission occurring at the afterglow peak (E-APE). The relative intensities, the time separation and the hardness ratio of the P-GRB and the E-APE are used as distinctive observational test of the EMBH theory and the excellent agreement between our theoretical predictions and the observations are documented. The afterglow power-law indexes in the EMBH theory are compared and contrasted with the ones in the literature, and no beaming process is found for GRB 991216. Finally, some preliminary results relating the observed time variability of the E-APE to the inhomogeneities in the interstellar medium are presented, as well as some general considerations on the EMBH formation. The issue of the GSTS paradigm will be the object of a forthcoming publication and the relevance of the iron-lines observed in GRB 991216 is shortly reviewed. The general conclusions are then presented based on the three fundamental parameters of the EMBH theory: the dyadosphere energy, the baryonic mass of the remnant, the interstellar medium density. An in depth discussion and comparison of the EMBH theory with alternative theories is presented as well as indications of further developments beyond the radial approximation, which will be the subject of paper II in this series. Future needs for specific
GRB observations are outlined.


A theoretical attempt to identify the physical process responsible for the afterglow emission of Gamma-Ray Bursts (GRBs) is presented, leading to the occurrence of thermal emission in the comoving frame of the shock wave giving rise to the bursts. The determination of the luminosities and spectra involves integration over an infinite number of Planckian spectra, weighted by appropriate relativistic transformations, each one corresponding to a different viewing angle in the past light cone of the observer. The relativistic transformations have been computed using the equations of motion of GRBs within our theory, giving special attention to the determination of the equitemporal surfaces. The only free parameter of the present theory is the “effective emitting area” in the shock wave front. A self consistent model for the observed hard-to-soft transition in GRBs is also presented. When applied to GRB 991216 a precise fit ($\chi^2 \simeq 1.078$) of the observed luminosity in the 2–10 keV band is obtained. Similarly, detailed estimates of the observed luminosity in the 50–300 keV and in the 10–50 keV bands are obtained.

4.2. Conference proceedings


The “dyadosphere” (from the Greek word “duas-duados” for pairs) is here defined as the region outside the horizon of a black hole endowed with an electromagnetic field (abbreviated to EMBH for “electromagnetic black hole”) where the electromagnetic field exceeds the critical value, predicted by Heisenberg and Euler for $e^+e^-$ pair production. In a very short time ($\sim O(h/mc^2)$), a very large number of pairs is created there. I give limits on the EMBH parameters leading to a Dyadosphere for $10M_\odot$ and $10^5M_\odot$ EMBH’s, and give as well the pair densities as functions of the radial coordinate. These data give the initial conditions for the analysis of an enormous pair-electromagnetic-pulse or “PEM-pulse” which naturally leads to relativistic expansion. Basic energy requirements for gamma ray bursts (GRB), including GRB971214 recently observed at $z = 3.4$, can be accounted for by processes occurring in the dyadosphere.

4. Selected publications before 2005


If due attention is given in formulating the basic equations for the Gamma-Ray Burst (GRB) phenomenon and in performing the corresponding quantitative analysis, GRBs open a main avenue of inquiring on totally new physical and astrophysical regimes. This program is very likely one of the greatest computational efforts in physics and astrophysics and cannot be actuated using shortcuts. A systematic approach is needed which has been highlighted in three basic new paradigms: the relative space-time transformation (RSTT) paradigm, the interpretation of the burst structure (IBS) paradigm, the GRB-supernova time sequence (GSTS) paradigm. From the point of view of fundamental physics new regimes are explored: (I) the process of energy extraction from black holes; (2) the quantum and general relativistic effects of matter-antimatter creation near the black hole horizon; (3) the physics of ultrarelativistic shock waves with Lorentz gamma factor $\gamma > 100$. From the point of view of astronomy and astrophysics also new regimes are explored: (i) the occurrence of gravitational collapse to a black hole from a critical mass core of mass $M \gtrsim 10M_\odot$, which clearly differs from the values of the critical mass encountered in the study of stars “catalyzed at the endpoint of thermonuclear evolution” (white dwarfs and neutron stars); (ii) the extremely high efficiency of the spherical collapse to a black hole, where almost 99.99% of the core mass collapses leaving negligible remnant; (iii) the necessity of developing a fine tuning in the final phases of thermonuclear evolution of the stars, both for the star collapsing to the black hole and the surrounding ones, in order to explain the possible occurrence of the “induced gravitational collapse”. New regimes are as well encountered from the point of view of nature of GRBs: (I) the basic structure of GRBs is uniquely composed by a proper-GRB (P-GRB) and the afterglow; (II) the long bursts are then simply explained as the peak of the afterglow (the E-APE) and their observed time variability is explained in terms of inhomogeneities in the interstellar medium (ISM); (III) the short bursts are identified with the P-GRBs and the crucial information on general relativistic and vacuum polarization effects are encoded in their spectra and intensity time variability. A new class of space missions to acquire information on such extreme new regimes are urgently needed.

This is a summary of the two talks presented at the Rome GRB meeting by C.L. Bianco and R. Ruffini. It is shown that by respecting the Relative Space-Time Transformation (RSTT) paradigm and the Interpretation of the Burst Structure (IBS) paradigm, important inferences are possible: a) in the new physics occurring in the energy sources of GRBs, b) on the structure of the bursts and c) on the composition of the interstellar matter surrounding the source.


We analyze the data of the Gamma-Ray Burst/Supernova GRB030329/SN2003dh system obtained by HETE-2, R-XTE, XMM and VLT within our theory 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. 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 $\sim 2 \times 10^{53}$ 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, much like in the system GRB980425/SN1998bw, are not part of the GRB afterglow, as interpreted in the literature, 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.


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. 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.

6. A. Corsi, M.G. Bernardini, C.L. Bianco, P. Chardonnet, F. Fraschetti, R.
Ruffini, S.-S. Xue; “GRB 970228 Within the EMBH Model”; in “GAMMA-
RAY BURSTS: 30 YEARS OF DISCOVERY”, Proceedings of the Los
Alamos “Gamma Ray Burst Symposium”, Santa Fe, New Mexico, 8–12
September 2003, E.E. Fenimore, M. Galassi, Editors; AIP Conference

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, $E_{\text{dya}} = 5.1 \times
10^{52}$ ergs, and the baryonic remnant mass $M_B$ in units of $E_{\text{dya}}, B = M_B c^2 / E_{\text{dya}} =
3.0 \times 10^{-3}$. 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 $\mathcal{R}$ 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.

5.1. Refereed journals


It is shown that the concept of a fireball with a definite filamentary structure naturally emerges from the analysis of the spectra of Gamma-Ray Bursts (GRBs). These results, made possible by the recently obtained analytic expressions of the equitemporal surfaces in the GRB afterglow, depend crucially on the single parameter $R$ describing the effective area of the fireball emitting the X-ray and gamma-ray radiation. The X-ray and gamma-ray components of the afterglow radiation are shown to have a thermal spectrum in the comoving frame of the fireball and originate from a stable shock front described self-consistently by the Rankine-Hugoniot equations. Precise predictions are presented on a correlation between spectral changes and intensity variations in the prompt radiation verifiable, e.g., by the Swift and future missions. The highly variable optical and radio emission depends instead on the parameters of the surrounding medium. The GRB 991216 is used as a prototype for this model.


The introduction of the three interpretational paradigms for Gamma-Ray Bursts (GRBs) and recent progress in understanding the X- and gamma-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 “triptich”: 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.

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 in the filamentary structure of the ISM. We predict a clear hard-to-soft behavior in 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.


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.


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 106 s. The theoretically predicted instantaneous spectral distribution over the entire afterglow is presented, confirming a clear hard-to-soft behavior encompassing, continuously, the “prompt emission” all the way to the latest phases of the afterglow.

GRB011121 is analyzed as a prototype to understand the “flares” recently observed by Swift in the afterglow of many GRB sources. Detailed theoretical computation of the GRB011121 light curves in selected energy bands are presented and contrasted with observational BeppoSAX data.


Using the *Swift* data of GRB 050315, we progress on the uniqueness of our theoretically predicted Gamma-Ray Burst (GRB) structure as composed by 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” as due to external shocks. Thanks to the *Swift* observations, we can theoretically fit detailed light curves for selected energy bands on a continuous time scale ranging over 10^6 seconds. The theoretically predicted instantaneous spectral distribution over the entire afterglow confirms a clear hard-to-soft behavior encompassing, continuously, the “prompt emission” all the way to the latest phases of the afterglow. Consequences of the instrumental threshold on the definition of “short” and “long” GRBs are discussed.


GRB970228 is analyzed as a prototype to understand the relative role of short GRBs and their associated afterglows, recently observed by Swift and HETE-II. Detailed theoretical computation of the GRB970228 light curves in selected energy bands are presented and compared with observational BeppoSAX data.


*Context:* The *Swift* satellite has given continuous data in the range 0.3–150 keV from 0 s to 10^6 s for GRB060218 associated with SN2006aj. This Gamma-Ray Burst (GRB) which has an unusually long duration (T\_90 \sim 2100 s) fulfills the Amati relation. These data offer the opportunity to probe theoretical models for GRBs connected with Supernovae (SNe).

*Aims:* We plan to fit the complete \( \gamma \)- and X-ray light curves of this long duration GRB, including the prompt emission, in order to clarify the nature of the progenitors and the astrophysical scenario of the class of GRBs associated with SNe Ib/c.
**Methods:** We apply our “fireshell” model based on the formation of a black hole, giving the relevant references. It is characterized by the precise equations of motion and equitemporal surfaces and by the role of thermal emission.

**Results:** The initial total energy of the electron-positron plasma \( E_{\text{tot}}^{e\pm} = 2.32 \times 10^{50} \, \text{erg} \) has a particularly low value, similar to the other GRBs associated with SNe. For the first time, we observe a baryon loading \( B = 10^{-2} \) which coincides with the upper limit for the dynamical stability of the fireshell. The effective CircumBurst Medium (CBM) density shows a radial dependence \( n_{\text{cbm}} \propto r^{-\alpha} \) with \( 1.0 \lesssim \alpha \lesssim 1.7 \) and monotonically decreases from 1 to \( 10^{-6} \) particles/cm\(^3\). This behavior is interpreted as being due to a fragmentation in the fireshell. Analogies with the fragmented density and filling factor characterizing Novae are outlined. The fit presented is particularly significant in view of the complete data set available for GRB060218 and of the fact that it fulfills the Amati relation.

**Conclusions:** We fit GRB060218, usually considered as an X-Ray Flash (XRF), as a “canonical GRB” within our theoretical model. The smallest possible black hole, formed by the gravitational collapse of a neutron star in a binary system, is consistent with the especially low energetics of the class of GRBs associated with SNe Ib/c. We provide the first evidence for a fragmentation in the fireshell. This fragmentation is crucial in explaining both the unusually large \( T_{90} \) and the consequently inferred abnormally low value of the CBM effective density.


**Context:** The discovery by Swift and HETE-2 of an afterglow emission associated possibly with short GRBs opened the new problematic of their nature and classification. This issue has been further enhanced by the observation of GRB060614 and by a new analysis of the BATSE catalog which led to the identification of a new class of GRBs with “an occasional softer extended emission lasting tenths of seconds after an initial spikelike emission”.

**Aims:** We plan a twofold task: a) to fit this new class of “hybrid” sources within our “canonical GRB” scenario, where all GRBs are generated by a “common engine” (i.e. the gravitational collapse to a black hole); b) to propose GRB970228 as the prototype of the above mentioned class, since it shares the same morphology and observational features.

**Methods:** We analyze BeppoSAX data on GRB970228 within the “fireshell” model and we determine the parameters describing the source and the CircumBurst Medium (CBM) needed to reproduce its light curves in the 40–700 keV and 2–26 keV energy bands.

**Results:** We find that GRB970228 is a “canonical GRB”, like e.g. GRB050315, with the main peculiarity of a particularly low average density of the CBM \( \langle n_{\text{cbm}} \rangle \sim 10^{-3} \) particles/cm\(^3\). We also simulate the light curve corresponding
5.2. Conference proceedings

5.2. Conference proceedings


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 $10^{49}$ ergs, the GRBs are highly variable and can have energetics $10^4 - 10^5$ 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 compo-

A supernova remnant 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 blackhole 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.


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
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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 thritych of a black hole originating the GRB 030329, the supernova SN2003dh and a young neutron star. Analogies to the system GRB 980425–
SN1998bw are outlined.


The $\gamma$-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, $B = M_Bc^2/E_{dya}$. 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 $\gamma$-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.


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 $\gamma$ factor is lower than the critical value 150 which has been found in Ruffini et al. (2002) to be necessary in order to perform the tomography of the ISM surrounding the GRB as suggested by Dermer & Mitman (1999). 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.

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.


Gamma-Ray Bursts (GRBs) represent very likely “the” most extensive computational, theoretical and observational effort ever carried out successfully in physics and astrophysics. The extensive campaign of observation from space based X-ray and $\gamma$-ray observatory, such as the Vela, CGRO, BeppoSAX, HETE-II, INTEGRAL, Swift, R-XTE, Chandra, XMM satellites, have been matched by complementary observations in the radio wavelength (e.g. by the VLA) and in the optical band (e.g. by VLT, Keck, ROSAT). The net result is unprecedented accuracy in the received data allowing the determination of the energetics, the time variability and the spectral properties of these GRB sources. The very fortunate situation occurs that these data can be confronted with a mature theoretical development. Theoretical interpretation of the above data allows progress in three different frontiers of knowledge: a) the ultrarelativistic regimes of a macroscopic source moving at Lorentz gamma factors up to $\sim 400$; b) the occurrence of vacuum polarization process verifying some of the yet untested regimes of ultrarelativistic quantum field theories; and c) the first evidence for extracting, during the process of gravitational collapse leading to the formation of a black hole, amounts of energies up to $10^{55}$ ergs of black-holic energy — a new form of energy in physics and astrophysics. We outline how this progress leads to the confirmation of three interpretation paradigms for GRBs proposed in July 2001. Thanks mainly to the observations by Swift and the optical observations by VLT, the outcome of this analysis points to the existence of a “canonical” GRB, originating from a variety of different initial astrophysical scenarios. The communality of these GRBs appears to be that
they all are emitted in the process of formation of a black hole with a negligible value of its angular momentum. The following sequence of events appears to be canonical: the vacuum polarization process in the dyadosphere with the creation of the optically thick self accelerating electron-positron plasma; the engulfment of baryonic mass during the plasma expansion; adiabatic expansion of the optically thick “fireshell” of electron-positron-baryon plasma up to the transparency; the interaction of the accelerated baryonic matter with the interstellar medium (ISM). This leads to the canonical GRB composed of a proper GRB (P-GRB), emitted at the moment of transparency, followed by an extended afterglow. The sole parameters in this scenario are the total energy of the dyadosphere $E_{dya}$, the fireshell baryon loading $M_B$ defined by the dimensionless parameter $B \equiv M_B c^2 / E_{dya}$, and the ISM filamentary distribution around the source. In the limit $B \to 0$ the total energy is radiated in the P-GRB with a vanishing contribution in the afterglow. In this limit, the canonical GRBs explain as well the short GRBs. In these lecture notes we systematically outline the main results of our model comparing and contrasting them with the ones in the current literature. In both cases, we have limited ourselves to review already published results in refereed publications. We emphasize as well the role of GRBs in testing yet unexplored grounds in the foundations of general relativity and relativistic field theories.
A. GRBs: Historical background

A.1. Introduction

The last century was characterized by three great successes in the field of astrophysics, each one linked to a different energy source:

1. Jean Perrin (1920) and Arthur Eddington (1920) were the first to point out, independently, that the nuclear fusion of four hydrogen nuclei into one helium nucleus could explain the energy production in stars. This idea was put on a solid theoretical base by Atkinson and Houtermans (1929a,b) using George Gamow’s quantum theory of barrier penetration (Gamow and Houtermans 1929) further developed by C.F. von Weizsäcker (1937, 1938). The monumental theoretical work by Hans Bethe (1939), and later by Burbidge et al. (1957), completed the understanding of the basic role of nuclear energy generated by fusion processes in explaining the energy source of main sequence stars (Schwarzschild, 1965).

2. Pulsars, especially NP0532 at the center of the Crab nebula, were discovered by Jocelyn Bell and Tony Hewish (Bell and Hewish, 1967), and many theorists were actively trying to explain them as rotating neutron stars (see Gold, 1968, 1969; Pacini, 1968; Finzi and Wolf, 1968). These had already been predicted by George Gamow using Newtonian physics (Gamow, 1938) and by Robert Julius Oppenheimer and students using General Relativity (Oppenheimer and Serber, 1938; Oppenheimer and Snyder, 1939; Oppenheimer and Volkoff, 1939). The crucial evidence confirming that pulsars were neutron stars came when their energetics was understood (Finzi and Wolf, 1968). The following relation was established from the observed pulsar period \( P \) and its always positive first derivative \( dP/dt \):

\[
\left( \frac{dE}{dt} \right)_{\text{obs}} \simeq 4\pi^2 I_{\text{NS}} \frac{dP}{P^3} dt,
\]

(A.1.1)

where \( \left( \frac{dE}{dt} \right)_{\text{obs}} \) is the observed pulsar bolometric luminosity, \( I_{\text{NS}} \) is its moment of inertia derived from the neutron star theory. This has to be related to the observed pulsar period. This equation not only identifies the role of neutron stars in explaining the nature of pulsars, but
clearly indicates the rotational energy of neutron star as the pulsar energy source.

3. The birth of X-ray astronomy thanks to Riccardo Giacconi and his group (see e.g. Giacconi et al., 1978) 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 and Wheeler, 1971). 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, 1973). 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, 1980). 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. A.1).

These three results clearly exemplify how the identification of the energy source is the crucial factor in reaching the understanding of any astrophysical or physical phenomenon.

The discovery of Gamma-Ray Bursts (GRBs) may well sign a further decisive progress. GRBs can give in principle 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, 1971), which we shall refer in the following as the blackholic energy. The blackholic energy, expected to be emitted during the dynamical process of gravitational collapse leading to the formation of the black hole, generates X- and $\gamma$-ray luminosities $10^{21}$ times larger than the solar luminosity, which manifest themselves in the GRB phenomenon. In the very short time they last, GRBs are comparable with the full electromagnetic luminosity of the entire visible universe.

### A.2. The discovery of GRBs and the early theoretical works

We recall 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, 1975). 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 originated neither on the Earth nor

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1This name is the English translation of the Italian words “energia buconerale”, introduced by Iacopo Ruffini, December 2004, here quoted by his kind permission.
A.2. The discovery of GRBs and the early theoretical works

Figure A.1.: Cygnus X-1, here represented in an artist view, offered the possibility of identifying the first black hole in our galaxy (Leach and Ruffini, 1973). 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-Newman black hole, which has necessarily to be axially symmetric. What identifies the black hole unambiguously is that the mass of Cygnus X-1, observed to be larger than $9M_\odot$, exceeds the absolute upper limit of the neutron star mass, estimated at $3.2M_\odot$ by Rhoades and Ruffini (1974).
A. GRBs: Historical background

Figure A.2. 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, reproduced with permission of the Joseph Henry Laboratories). For details see Landau and Lifshitz (1980) and Rees et al. (1974).

in the Solar System. This discovery luckily occurred when the theoretical understanding of gravitationally collapsed objects, as well as the quantum electrodynamics of the vacuum polarization process, had already reached full maturity.

Three of the most important works in the field of general relativity have certainly been the discovery of the Kerr solution (Kerr, 1963), its generalization to the charged case (Newman et al., 1965) and the formulation by Brandon Carter (1968) 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 1980). 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 1980) and by Ruffini for the Reissner-Nordstrøm geometry (Ruffini, 1973, see Fig. A.2).

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, 1971). In that paper, it was 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. Such a solution is characterized only by three parameters: the mass $M$, the charge $Q$ and the angular
A.2. The discovery of GRBs and the early theoretical works

momentum $L$. This ansatz of the “black hole uniqueness theorem” still today
after thirty years presents challenges to the mathematical aspects of its com-
plete proof (see e.g. Carter, in press; Bini et al., 2002). In addition to the chal-
lenges due to the above mathematical difficulties, in the field of physics this
ansatz contains 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 equa-
tions survive the formation of the horizon has, indeed, extremely profound
physical implications. Any departure from such a minimal configuration ei-
ther collapses on the horizon or is radiated away during the collapse process.
This ansatz is crucial in identifying precisely a standard process of gravita-
tional collapse leading to the formation of the black hole and the emission of
GRBs. Indeed, in this specific case, the Born-like nonlinear (Born, 1934) terms
of the Heisenberg-Euler-Schwinger (Heisenberg and Euler, 1936; Schwinger,
1951) Lagrangian are radiated away prior to the formation of the horizon of
the black hole (see e.g. Ruffini et al., in preparation). 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, 1980),
which allowed the analysis of circular orbits around the black hole, was cru-
cial in reaching the equally interesting discovery of the reversible and irre-
versible transformations of black holes by Christodoulou and Ruffini (1971),
which in turn led to the mass-energy formula of the black hole:

$$ E_{BH}^2 = M^2 c^4 = \left( M_{ir} c^2 + \frac{Q^2}{2\rho_+} \right)^2 + \frac{L^2 c^2}{\rho_+^2}, \quad (A.2.1) $$

with

$$ \frac{1}{\rho_+^4} \left( \frac{G^2}{c^8} \right) \left( Q^4 + 4L^2 c^2 \right) \leq 1, \quad (A.2.2) $$

where

$$ S = 4\pi \rho_+^2 = 4\pi (r_+^2 + \frac{L^2}{c^2 M_{ir}^2}) = 16\pi \left( \frac{G^2}{c^4} \right) M_{ir}^2, \quad (A.2.3) $$

is the horizon surface area, $M_{ir}$ 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. (A.2.2).

From Eq. (A.2.1) follows that the total energy of the black hole $E_{BH}$ can be
split into three different parts: rest mass, Coulomb energy and rotational en-
ergy. In principle both Coulomb energy and rotational energy can be ex-
tracted from the black hole (Christodoulou and Ruffini, 1971). 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. (A.2.2). 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 orbit binding energies has been proven by the observations of Cygnus-X1 (see e.g. [Giacconi et al. 1978]). However, as already mentioned 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.

We also recall that the feasibility of the blackholic energy extraction 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. Heisenberg and Euler ([1936]) clearly evidenced that a static electromagnetic field stronger than the critical value:

\[ E_c = \frac{m_e^2 c^3}{\hbar e} \]  

(A.2.4)

can polarize the vacuum and create electron-positron pairs. 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. in preparation and references therein). From an order-of-magnitude estimate, it would appear that around a nucleus with a charge:

\[ Z_c \simeq \frac{\hbar c}{e} \simeq 137 \]  

(A.2.5)

the electric field can be as strong as 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

\[ Z_c \simeq 173 \]  

(A.2.6)

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

\[ \Delta t \sim \frac{\hbar}{m_e c^2} \simeq 10^{-18} \text{ s} , \]  

(A.2.7)

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

\[ \Delta t \sim \frac{\hbar}{m_p c^2} \simeq 10^{-21} \text{ s} . \]  

(A.2.8)
A.3. CGRO, BeppoSAX and the further theoretical developments

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 meet with analogous difficulties (see e.g. Ruffini et al. in preparation).

Damour and Ruffini (1975) advanced the alternative idea that the critical field condition given in Eq.(A.2.4) could be easily reached, and for a time much larger than the one given by Eq.(A.2.7), in the field of a Kerr-Newman black hole in a range of masses $3.2M_\odot \leq M_{BH} \leq 7.2 \times 10^6 M_\odot$. In that paper there was generalized to the curved Kerr-Newman geometry the fundamental theoretical framework developed in Minkowski space by Heisenberg and Euler (1936) and Schwinger (1951). This result was made possible by the work on the structure of the Kerr-Newman spacetime previously done by Carter (1968) and by the remarkable mathematical craftsmanship of Thibault Damour then working with one of us (RR) as a post-doc in Princeton. We give on this topic some additional details in the next sections.

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

$$E_{\text{max}} = 1.8 \times 10^{54} \left( \frac{M_{BH}}{M_\odot} \right) \text{erg} \ . \quad (A.2.9)$$

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 (see Ruffini, 2001). As we will see, this situation was drastically modified by the observations of BeppoSAX.

A.3. CGRO, BeppoSAX and the further theoretical developments

The mystery of GRBs became deeper as the observations of the BATSE instrument on board of the Compton Gamma-Ray Observatory (CGRO) satellite over 9 years proved the isotropy of these sources in the sky (See Fig. A.3). 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 have been collected in the fourth BATSE catalog (Paciesas et al., 1999, see e.g. Fig. A.4). Analyzing these BATSE sources the existence of two distinct families of sources became clear (see e.g. Kouveliotou et al., 1993; Tavani, 1998): the long bursts, lasting more then one second and softer in

\(^2\)see http://cossc.gsfc.nasa.gov/batse/
2704 BATSE Gamma-Ray Bursts

Figure A.3.: 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.
A.3. CGRO, BeppoSAX and the further theoretical developments

Figure A.4.: Some GRB light curves observed by the BATSE instrument on board of the CGRO satellite.

spectra, and the short bursts (see Fig. A.6), harder in spectra (see Fig. A.5). 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., 1997). Such a discovery 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 made possible in 1997 the identification of the distance of these sources from the Earth and of their tremendous energy of the order up to $10^{54}$ erg/second during the burst, which indeed coincides with the theoretical prediction made by Damour and Ruffini (1975) given in Eq. (A.2.9).
Figure A.5: The energy fluence-averaged hardness ratio for short ($T < 1$ s) and long ($T > 1$ s) GRBs are represented. Reproduced, by his kind permission, from Tavani (1998) where the details are given.
A.3. CGRO, BeppoSAX and the further theoretical developments

Figure A.6.: Status of GRB observations following the BATSE and BeppoSAX observations: On the upper right part of the figure are plotted the number of the observed GRBs as a function of their duration. The bimodal distribution corresponding respectively to the short bursts, upper left figure, and the long bursts, middle figure, is quite evident. The afterglow component is represented in the lowest figures. The theoretical goal is to find a coherent astrophysical explanation for all these different phenomena.
A. GRBs: Historical background

The resonance between the X- and gamma ray astronomy from the satellites and the optical and radio astronomy from the ground, had already marked the great success and development of the astrophysics of binary X-ray sources in the seventies (see e.g. Giacconi et al. [1978]). 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 specific space missions, like HETE-II and Swift, together with the very lucky circumstance of the development of optical technologies for the telescopes, such as Keck in Hawaii and VLT in Chile, offers today opportunities without precedence in the history of mankind.

Turning now to the theoretical progresses, it is interesting that the idea of using an electron-positron plasma as a basis of a GRB model, introduced in Damour and Ruffini [1975], was independently considered years later in a set of papers by Cavallo and Rees [1978], Cavallo and Horstman [1981] and Horstman and Cavallo [1983]. However, 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 creation and consequent evolution 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. (A.2.9), 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 for pairs ($\delta\nu\alpha\varsigma\,\delta\nu\alpha\delta\varsigma$), to be the “dyadosphere” of the black hole, bounded by the black hole horizon and the dyadosphere radius $r_{ds}$ given by (see Ruffini [1998]; Preparata et al. [1998]):

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

where we have introduced the dimensionless mass and charge parameters $\mu = M_{BH}/M_\odot$, $\xi = Q/(M_{BH}\sqrt{G}) \leq 1$. The total energy of the electron-positron pairs, $E_{e\pm}^{tot}$ is equal to the dyadosphere energy $E_{dy\alpha}$.

Our GRB model, like all prevailing models in the existing literature (see e.g. Piran [2005]; Mészáros [2002]; Meszaros [2006] and references therein), is based on the acceleration of an optically thick electron-positron plasma. The mechanism responsible for the origin and the energetics of such a plasma, either in relation to black hole physics or to other physical processes, has often been discussed qualitatively in the GRB scientific literature but never quan-
titatively with explicit equations. The concept of the dyadosphere (Ruffini, 1998; Preparata et al., 1998) is the only attempt, as far as we know, to do this. It relates such an electron-positron plasma to black hole physics and to the features of the GRB progenitor star, using explicit equations that satisfy the existing physical laws (see e.g. Christodoulou and Ruffini (1971); Ruffini et al. (2005a) and references therein, see also Misner et al. (1973)). This step is essential if one wishes to identify the physical origin and energetics of GRBs. All the successive evolution of the electron-positron plasma are independent on this step and are indeed common to all prevailing GRB models in the literature. Of course, great differences still exist between the actual treatments of this evolution in the current literature, as we show in the next sections.

Analogies exist between the concept of dyadosphere and the work of Cavallo and Rees (1978), as well as marked conceptual differences. In the dyadosphere the created electron-positron pairs are assumed to reach thermal equilibrium and have an essential role in the dynamical acceleration process of GRBs. In Cavallo and Rees (1978) it is assumed that the created electron-positron pairs do annihilate in a cascade process in a very short bremsstrahlung time scale: they cannot participate in any way to the dynamical phases of the GRB process. It is interesting that these differences can be checked both theoretically and observationally. It should be possible, in the near future, to evaluate all the cross sections involved by the above annihilation processes and assess by a direct explicit analysis which one of the two above approaches is the correct one. On the other side, such two approaches certainly lead to very different predictions for the GRB structure, especially for the short ones. These predictions will certainly be compared to observations in the near future.

We have already emphasized that 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 special relativity. As one of us (RR) always mention to his 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 (Einstein, 1905) 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.

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 as well as in very high density photon gas. This topic is also very difficult but for a quite different conceptual reason: the process of pair creation, expressed in the classic works of
A. GRBs: Historical background

Heisenberg-Euler-Schwinger ([Heisenberg and Euler, 1936; Schwinger, 1951]) later developed by many others, is based on a very powerful theoretical framework but has not yet been verified by experimental data. Similarly, the creation of electron-positron pairs from high density and high energy photons lacks still today the needed theoretical description. As we will show in the next sections, there is the tantalizing possibility of observing these phenomena, 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 a black hole horizon with all the associated relativistic phenomena of light bending and time dilatation.

For these reasons GRBs offer an authentic new frontier in the field of physics and astrophysics. We recall that in the special relativity field, for the first time, we observe phenomena occurring at Lorentz gamma factors of approximately 400. In the field of relativistic quantum electro-dynamics we see for the first time the interchange between classical fields and high density photon fields with the created quantum matter-antimatter pairs. In the field of general relativity also for the first time we can test the blackholeic 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. In order to build a theoretical GRB model, we have found necessary to establish clear guidelines by introducing three basic paradigms for the interpretation of GRBs.
B. The three paradigms identifying the “canonical GRBs”

B.1. The Relative Space-Time Transformation (RSTT) paradigm

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 ([Einstein] 1905). 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. B.1. If we consider in an inertial frame a source (solid green line) moving with high speed and emitting light signals (dashed red 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 respectively emitted at the origin and after a time interval $\Delta t$ in the laboratory frame, which in our case is the frame where the black hole is at rest. The real velocity of the source is given by:

$$v = \frac{\Delta r}{\Delta t} \quad \text{(B.1.1)}$$

and the apparent velocity is given by:

$$v_{\text{app}} = \frac{\Delta r}{\Delta t_a} \quad \text{(B.1.2)}$$

As pointed out by Einstein the adoption of coordinating light signals simply by their arrival time as in Eq. (B.1.2), 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.
**Figure B.1.** Relation between the arrival time $t_a$ and the laboratory time $t$. Details in Ruffini et al. (2001c, 2003).
B.1. The Relative Space-Time Transformation (RSTT) paradigm

The use of $\Delta t_a$ as a time coordinate should be done with proper care. The relation between $\Delta t_a$ and the correct time parameterization in the laboratory frame has to be taken into account:

$$\Delta t_a = \Delta t - \frac{\Delta r}{c} = \Delta t - \frac{1}{c} \int_{t_o}^{t_o + \Delta t} v(t') \, dt'.$$

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:

$$\Delta t_d^f = (1 + z) \Delta t_a.$$  \hfill (B.1.4)

In the current GRB literature, Eq. (B.1.3) has been systematically neglected by addressing only the afterglow description. Often the integral equation has been approximated by a clearly incorrect instantaneous value:

$$\Delta t_a \simeq \frac{\Delta t}{2\gamma^2}.$$ \hfill (B.1.5)

The attitude has been adopted 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 (1999, 2000), 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 (Rees and Meszaros, 1994; Paczynski and Xu, 1994; Sari and Piran, 1997; Fenimore, 1999; Fenimore et al., 1999).

As we outline in the following sections, this 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 sections 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 D) for which is essential 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.
B. The three paradigms identifying the “canonical GRBs”

We can now turn to the first paradigm, the relative space-time transformation (RSTT) paradigm (Ruffini et al., 2001c) which 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. (B.1.3). 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 $t^a_{\text{d}}$. It is necessary, in order to describe the physics of the source, to derive the laboratory time $t$ as a function of the arrival time $t^a_{\text{d}}$ along the entire past worldline of the source using Eq. (B.1.4).

An additional difference, also linked to special relativity, 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 the following report about “Relativistic effects in Physics and Astrophysics”) 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, 1973).

B.2. The Interpretation of the Burst Structure (IBS) paradigm

We turn now to the second paradigm, which is more complex since it deals with all the different phases of the GRB phenomenon. We first address the dynamical phases following the dyadosphere formation.

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 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 (see Ruffini et al., 1999, 2000, and section C).

The corresponding treatment in the framework of the Cavallo, Rees et al. analysis was performed by Piran et al. (1993) also using a numerical approach, by Bisnovatyi-Kogan and Murzina (1995) using an analytic approach and by Meszaros et al. (1993) using a numerical and semi-analytic approach.
B.2. The Interpretation of the Burst Structure (IBS) paradigm

Although some analogies exist between these treatments, they are significantly different in the theoretical details and in the final results (see Bianco et al., 2006, and section the following report about “Relativistic effects in Physics and Astrophysics”). 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 errors.

B.2.1. The optically thick phase of the fireshell

There are some common conclusions to all these treatments: the electron-positron plasma is initially optically thick and expands reaching very high values of the Lorentz gamma factor until the transparency; the plasma shell expands but the Lorentz contraction is such that its width in the laboratory frame appears to be constant. This self acceleration of the thin shell is the distinguishing factor of GRBs, conceptually very different from the physics of a fireball developed by the inner pressure of an atomic bomb explosion in the Earth’s atmosphere. In the case of GRBs the region interior to the shell is inert and with pressure totally negligible: the entire dynamics occurs on the shell itself. For this reason, we refer in the following to the self accelerating shell as the “fireshell”.

There is a major difference between our approach and the ones of Piran, Mészáros and Rees. In our approach the dyadosphere is assumed to be initially filled uniquely with an electron-positron plasma, without any baryonic contamination. Such an electron-positron plasma expands in substantial agreement with the results presented in the work of Bisnovatyi-Kogan and Murzina (1995). In our model the fireshell of electron-positron pairs and photons (PEM pulse, see Ruffini et al., 1999) evolves and then meets the remnant of the star progenitor of the newly formed black hole. The fireshell is then loaded with baryons. A new fireshell is formed of electron-positron-photons and baryons (PEMB pulse, see Ruffini et al., 2000) which expands all the way until transparency is reached. At transparency the emitted photons give origin to the P-GRB (see Ruffini et al., 2001b, and Fig. B.2).

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

$$B = \frac{M_B c^2}{E_{\text{dy}}}$$  \hspace{1cm} (B.2.1)

which gives direct information about the mass $M_B = N_b m_p$ of the remnant, where $m_p$ is the proton mass. The corresponding treatment done by Piran and collaborators (Shemi and Piran, 1990; Piran et al., 1993) and by Meszaros et al. (1993) differs in one important respect: the baryonic loading is assumed to occur from 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. While our results are comparable with the ones obtained by Piran under
B. The three paradigms identifying the “canonical GRBs”

Figure B.2.: Above: The optically thick phase of the fireshell evolution 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. Details in Ruffini et al. (2003). Below: The P-GRB emitted at the transparency point at a time of arrival $t_d$ which has been computed following the prescriptions of Eq. (B.1.3). Details in Ruffini et al. (2001b, 2003).
the same initial conditions, the set of approximations adopted by Meszaros et al. (1993) appears to be too radical and leads to different results violating energy and momentum conservation (see section the following report about “Relativistic effects in Physics and Astrophysics” and Bianco et al., 2006).

From our analysis (Ruffini et al., 2000) it also becomes clear that such expanding dynamical evolution can only occur for values of $B \leq 10^{-2}$. This prediction, as we will show shortly in the many GRB sources considered, 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 ejected. 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 Fig. B.2 the optically thick phase of the fireshell evolution: we start from a given total electron-positron pairs energy $E_{\text{e\pm}}^{\text{tot}}$; the fireshell self-accelerates outward; an abrupt decrease in the value of the Lorentz gamma factor occurs by the engulfment of the baryonic loading followed by a further self-acceleration until the fireshell becomes transparent.

The photon emission at this transparency point is the 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 $t_{\text{d}} \sim 0.1$ s. These values determine the initial conditions of the afterglow.

**B.2.2. The afterglow**

After reaching transparency and the emission of the P-GRB, the ABM pulse interacts with the CBM and gives rise to the afterglow (see Fig. B.3).

We first look to 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 section E, the transparency condition is determined by a time of arrival $t_{\text{d}}^d$, a value of the Lorentz gamma 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 $E_{\text{e\pm}}^{\text{tot}}$ and $B$ (see Eq. (B.2.1)).

This connection to the optically thick era is missing in the current approach in the literature (see Piran, 1999, and references therein). The initial conditions at the beginning of the afterglow are obtained by a best fit of the later parts of the afterglow. The order of magnitude estimate usually quoted for the characteristic time scale to be expected for a burst emitted by a GRB at the
B. The three paradigms identifying the “canonical GRBs”

Figure B.3: The GRB afterglow phase is here represented together with the optically thick phase (see Fig. B.2). The value of the Lorentz gamma factor is here given from the transparency point all the way to the ultrarelativistic, relativistic and non relativistic regimes. Details in Ruffini et al. (2003).

moment of transparency at the end of the optically thick expansion phase is given by $\tau \sim GM/c^3$. For a $10M_\odot$ black hole this 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., 2005d]). 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, 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.

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 CBM (see Fig. B.4 and Ruffini et al., 2002a).

This approach was first tested on GRB 991216. Both the relative intensity and time separation of the P-GRB and the afterglow were duly explained (see Fig. B.4) choosing a total electron-positron pairs energy $E_{\text{tot}} = 4.83 \times 10^{53}$ erg and a baryon loading $B = 3.0 \times 10^{-3}$ (see Ruffini et al., 2001b, 2002a, 2003, 2005a). Similarly, the temporal substructure in the prompt emission was explicitly shown to be related to the CBM inhomogeneities (see section E.1).

Following this early analysis, and the subsequent ones on additional sources, it became clear that the CBM structure evidenced by our analysis is quite different from the traditional description in the current literature. Far from
B.2. The Interpretation of the Burst Structure (IBS) paradigm

Figure B.4: 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. The prompt emission observed by BATSE 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. The small precursor is identified with the P-GRB. For this source we have $B \simeq 3.0 \times 10^{-3}$ and $\langle n_{cbm} \rangle \sim 1.0$ particles/cm$^3$. Details in Ruffini et al. (2001b, 2002a, 2003, 2005a).
considering analogies with shock wave processes developed within fluidodynamic approach, it appears to us that the correct CBM description is a discrete one, composed of uncorrelated overdense “blobs” of typical size $\Delta R \sim 10^{14}$ cm widely spaced in underdense and inert regions.

We can then formulate the second paradigm, the interpretation of the burst structure (IBS) paradigm (Ruffini et al., 2001b), which covers three fundamental issues leading to the unequivocal identification of the canonical GRB structure:

a) the existence of two different components: the P-GRB and the afterglow related by precise equations determining their relative amplitude and temporal sequence (see Fig. B.5, Ruffini et al., 2003, and section E);

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 the clear confirmation of this result by the Swift data of e.g. GRB 050315 in section J and in Ruffini et al., 2006a,b);

c) the crucial role of the parameter $B$ in determining the relative amplitude.
B.3. The GRB-Supernova Time Sequence (GSTS) paradigm

of the P-GRB to the afterglow and discriminating between the short and the long bursts (see Fig. B.6). Both short and long bursts arise from the same physical phenomena: the gravitational collapse to a black hole endowed with electromagnetic structure and the formation of its dyadosphere.

The fundamental diagram determining the relative intensity of the P-GRB and the afterglow as a function of the dimensionless parameter $B$ is shown in Fig. B.6. The main difference relates to the amount of baryonic matter engulfed by the electron-positron plasma in their optically thick phase prior to transparency. For $B < 10^{-5}$ the intensity of the P-GRB is larger and dominates the afterglow. This corresponds to the “genuine” short bursts (see section E.2 and Bernardini et al., 2007a). For $10^{-5} < B \leq 10^{-2}$ the afterglow dominates the GRB. 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., 2000). This third family should be characterized by smaller values of the Lorentz gamma factors than in the case of the short or long bursts.

Particularly enlightening for the gradual transition to the short bursts as a function of the $B$ parameter is the diagram showing how GRB 991216 bolometric light curve would scale changing the only $B$ value (see Fig. B.7).

Moving from these two paradigms, and the prototypical case of GRB 991216, we have extended our analysis to a larger number of sources, such as GRB 970228 (Bernardini et al., 2007a), GRB 980425 (Ruffini et al., 2004a, in press), GRB 030329 (Bernardini et al., 2004), GRB 031203 (Bernardini et al., 2005a), GRB 050315 (Ruffini et al., 2006b), which have led to a confirmation of the validity of our canonical GRB structure (see Fig. B.8). In addition, progresses have been made in our theoretical comprehension, which will be presented in the section E.2.

B.3. The GRB-Supernova Time Sequence (GSTS) paradigm

Following the result of Galama et al. (1998) who discovered the temporal coincidence of GRB 980425 and SN 1998bw, the association of other nearby GRBs with Type Ib/c SNe has been spectroscopically confirmed (see Tab. B.1). The approaches in the current literature have attempted to explain both the SN and the GRB as two aspects of the same astrophysical phenomenon. Hence, GRBs have been assumed to originate from a specially strong SN process, a hypernova or a collapsar (see e.g. Paczynski, 1998; Kulkarni et al., 1998; Iwamoto et al., 1998; Woosley and Bloom, 2006, and references therein). Both these possibilities imply very dense and strongly wind-like CBM structure.

In our model we assumed that the GRB consistently originates from the gravitational collapse to a black hole. The SN follows instead the very com-
B. The three paradigms identifying the “canonical GRBs”

Figure B.6.: Above: The energy radiated in the P-GRB (the red line) and in the afterglow (the green line), in units of the total electron-positron pairs energy ($E_{\text{tot}}^{e\pm} = E_{\text{dya}}$), are plotted as functions of the $B$ parameter. Below: The arrival time delay between the P-GRB and the peak of the afterglow is plotted as a function of the $B$ parameter for three selected values of $E_{\text{dya}}$. 
Figure B.7.: The bolometric luminosity of a source with the same total energy and CBM distribution of GRB991216 is here represented for selected values of the $B$ parameter, ranging from $B = 10^{-2}$ to $B = 10^{-4}$. The actual value for GRB991216 is $B = 3.0 \times 10^{-3}$. As expected, for smaller values of the $B$ parameter the intensity of the P-GRB increases and the total energy of the afterglow decreases. What is most remarkable is that the luminosity in the early part of the afterglow becomes very spiky and the peak luminosity actually increases.
B. The three paradigms identifying the “canonical GRBs”

Remarkably, they are consistently smaller than, or equal to in the special case of GRB 060218, the absolute upper limit $B \lesssim 10^{-2}$ established in Ruffini et al. (2000). In order to determine the value of the $B$ parameter and the total energy we have performed the complete fit of each source. In particular, we have fitted for each source the observed luminosities in selected energy bands of the entire afterglow including the prompt emission. We have verified that in each source the hard-to-soft spectral evolution is correctly fitted and we have compared the theoretically computed spectral lag with the observations. Where applicable, we have also computed the relative intensity and temporal separation between the P-GRB and the peak of the afterglow and compared these values with the observed ones. The absence of spectral lag in the P-GRB is automatically verified by our model.

Figure B.8.: Same as Fig. B.6 with the values determined for GRB 991216, GRB 030329, GRB 980425, GRB 970228, GRB 050315, GRB 031203, GRB 060218. Remarkably, they are consistently smaller than, or equal to in the special case of GRB 060218, the absolute upper limit $B \lesssim 10^{-2}$ established in Ruffini et al. (2000). In order to determine the value of the $B$ parameter and the total energy we have performed the complete fit of each source. In particular, we have fitted for each source the observed luminosities in selected energy bands of the entire afterglow including the prompt emission. We have verified that in each source the hard-to-soft spectral evolution is correctly fitted and we have compared the theoretically computed spectral lag with the observations. Where applicable, we have also computed the relative intensity and temporal separation between the P-GRB and the peak of the afterglow and compared these values with the observed ones. The absence of spectral lag in the P-GRB is automatically verified by our model.
B.3. The GRB-Supernova Time Sequence (GSTS) paradigm

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<th>$E_{\gamma}^{GRB}$</th>
<th>$E_{\gamma}^{SN}$</th>
<th>$E_{\gamma}^{URCA}$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
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<td>1.8</td>
<td>GRB</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>

Complex pattern of the final evolution of a massive star, possibly leading to a neutron star or to a complete explosion but never to a black hole. The temporal coincidence of the two phenomena, the SN explosion and the GRB, have then to be explained by the novel concept of “induced gravitational collapse”, introduced in Ruffini et al. (2001a). We have to recognize that still today we do not have a precise description of how this process of “induced gravitational collapse” occurs. At this stage, it is more a framework to be implemented by additional theoretical work and observations. Two different possible scenarios have been outlined. In the first version (Ruffini et al. 2001a) we have considered the possibility that the GRBs may have caused the trigger of the SN event. For the occurrence of this scenario, the companion star had to be in a very special phase of its thermonuclear evolution and three different possibilities were considered:

1. A white dwarf, close to its critical mass. In this case, the GRB may implode the star enough to ignite thermonuclear burning.

2. The GRB enhances in an iron-silicon core the capture of the electrons on the iron nuclei and consequently decreases the Fermi energy of the core, leading to the onset of gravitational instability.

3. The pressure waves of the GRB may trigger a massive and instantaneous nuclear burning process leading to the collapse.

More recently (see Ruffini in press a; Ruffini et al. in press), a quite different possibility has been envisaged: the SN, originating from a very evolved core, undergoes explosion in presence of a companion neutron star with a mass...
B. The three paradigms identifying the “canonical GRBs”

Figure B.9: A possible process of gravitational collapse to a black hole “induced” by the Ib/c SN on a companion neutron star in a close binary system. Details in Ruffini (2006).

There are many reasons to propose this concept of “induced gravitational collapse”:

1. The fact that GRBs occur from the gravitational collapse to a black hole.

2. The fact that CBM density for the occurrence of GRBs is inferred from the analysis of the afterglow to be on the order of 1 particle/cm$^3$ (see Tab. B.1) except for few cases (see e.g. sections C and M). This implies that the process of collapse has occurred in a region of space filled with a very little amount of baryonic matter. The only significant contribution to the baryonic matter component in this process is the one represented by the fireshell baryon loading, which is anyway constrained by the inequality $B \leq 10^{-2}$.

3. The fact that the energetics of the GRBs associated with SNe appears to
be particularly weak is consistent with the energy originating from the gravitational collapse to the smallest possible black hole: the one with mass $M$ just over the neutron star critical mass.

There are also at work very clearly selection effects among the association between SNe and GRBs:

1. Many type Ib/c SNe exists without an associated GRB (Guetta and Della Valle, 2007).

2. Some GRBs do not show the presence of a SN associated, although they are close enough for the SN to be observed (see e.g. Della Valle et al., 2006).

3. The presence in all observed GRB-SN systems of an URCA source, a peculiar late time X-ray emission. These URCA sources have been identified and presented for the first time at the Tenth Marcel Grossmann meeting held in Rio de Janeiro (Brazil) in the Village of Urca, and named consequently. They appear to be one of the most novel issues still to be understood on GRBs. We will return on these aspects in the section G.5.

The issue of triggering the gravitational collapse instability 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. The occurrence of new nuclear physics and/or relativistic phenomena is very likely. The general relativistic instability induced on a nearby star by the formation of a black hole needs some very basic new developments.

Only a very preliminary work exists on this subject, by Jim Wilson and his collaborators (see e.g. the paper by Mathews and Wilson, 2005). The reason for the complexity in answering such a question is simply stated: unlike the majority of theoretical work on black holes and binary X-ray sources, which deals mainly with one-body black hole solutions in the Newtonian field of a companion star, we now have to address a many-body problem in general relativity. We are starting in these days to reconsider, in this framework, some classic works by Fermi (1921); Hanni and Ruffini (1973); Majumdar (1947); Papapetrou (1945); Parker et al. (1973); Bini et al. (2007a,b) which may lead to a new understanding of general relativistic effects in these many-body systems. This is a welcome effect of GRBs on the conceptual development of general relativity.
B. The three paradigms identifying the “canonical GRBs”
C. The optically thick “fireshell”

After this excursus on historical background let’s start with the description of equations characterizing the $e^+e^-$ plasma.

C.1. The fireshell in the Livermore code

C.1.1. The hydrodynamics and the rate equation for the plasma of $e^+e^-$-pairs

The evolution of the $e^+e^-$-pair plasma generated in the dyadosphere has been treated in [Ruffini et al. (1999, 2000)]. 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

$$
T_{\mu\nu} = p g_{\mu\nu} + (p + \rho) U^{\mu} U^{\nu},
$$

(C.1.1)

where $\rho$ and $p$ 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

$$
g_{tt}(U^t)^2 + g_{rr}(U^r)^2 = -1,
$$

(C.1.2)

where $U^r$ and $U^t$ are the radial and temporal contravariant components of the 4-velocity and

$$
ds^2 = g_{tt}(r)dt^2 + g_{rr}(r)dr^2 + r^2d\theta^2 + r^2\sin^2\theta d\phi^2,
$$

(C.1.3)

where $g_{tt}(r) \equiv -\alpha^2(r)$, $g_{rr}(r) = \alpha^{-2}(r)$, $\alpha^2 = \alpha^2(r) = 1 - 2M/r + Q^2/r^2$ ($M$ and $Q$ are the total energy and charge of the core as measured at infinity).

The conservation law for baryon number can be expressed in terms of the proper baryon number density $n_B$

$$
(n_B U^\mu)_{,\mu} = g^{-\frac{1}{2}}(g^{-\frac{1}{2}} n_B U^\nu)_{,\nu}
= (n_B U^t)_{,t} + \frac{1}{r^2}(r^2 n_B U^r)_{,r} = 0.
$$

(C.1.4)

The radial component of the energy-momentum conservation law of the plasma
fluid reduces to
\[
\frac{\partial p}{\partial r} + \frac{1}{r^2} \frac{\partial}{\partial t} \left( (p + \rho) U^t U_t \right) + \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 (p + \rho) U^r U_r \right) - \frac{1}{2} (p + \rho) \left[ \frac{\partial g_{tt}}{\partial r} (U^t)^2 + \frac{\partial g_{rr}}{\partial r} (U^r)^2 \right] = 0.
\]
(C.1.5)

The component of the energy-momentum conservation law of the plasma fluid equation along a flow line is
\[
U_{\mu} (T^{\mu\nu})_{,\nu} = -(\rho U^\nu)_{,\nu} - p (U^\nu)_{,\nu},
\]
\[
= -g^{-1} (g^{12} \rho U^\nu)_{,\nu} - pg^{-1} (g^{2} U^\nu)_{,\nu}
\]
\[
= (\rho U^t)_{,t} + \frac{1}{r^2} (r^2 \rho U^r)_{,r}
\]
\[
+ p \left[ (U^t)_{,t} + \frac{1}{r^2} (r^2 U^r)_{,r} \right] = 0.
\]
(C.1.6)

We define also the total proper internal energy density \( \epsilon \) and the baryonic mass density \( \rho_B \) in the comoving frame of the plasma fluid,
\[
\epsilon \equiv \rho - \rho_B, \quad \rho_B \equiv n_B m c^2.
\]
(C.1.7)

**C.1.2. The numerical integration**

A computer code (Wilson et al., 1998a,b) has been used to evolve the spherically symmetric general relativistic hydrodynamic equations starting from the dyadosphere.

We define the generalized gamma factor \( \gamma \) and the radial 3-velocity in the laboratory frame \( V^r \)
\[
\gamma \equiv \sqrt{1 + U^r U_r}, \quad V^r \equiv \frac{U^r}{U^t}.
\]
(C.1.8)

From Eqs. (C.1.3, C.1.2), we then have
\[
(U^t)^2 = \frac{1}{g_{tt}} (1 + g_{rr} (U^r)^2) = \frac{1}{\alpha^2} \gamma^2.
\]
(C.1.9)

Following Eq. (C.1.7), 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 (C.1.4) can then be written as
\[
\frac{\partial D}{\partial t} = -\frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} D V^r \right).
\]
(C.1.11)
C.1. The fireshell in the Livermore code

Eq. (C.1.6) then takes the form,

\[
\frac{\partial E}{\partial t} = - \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} E V^r \right) - p \left[ \frac{\partial \gamma}{\partial t} + \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} \gamma V^r \right) \right].
\]  

(C.1.12)

Defining the radial momentum density in the laboratory frame

\[
S_r \equiv \alpha (p + \rho) U^t U_r = (D + \Gamma E) U_r,
\]  

(C.1.13)

we can express the radial component of the energy-momentum conservation law given in Eq. (C.1.5) by

\[
\frac{\partial S_r}{\partial t} = - \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} S_r V^r \right) - \frac{\partial p}{\partial r} - \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{M}{r^2} - \frac{Q^2}{r^3} \right) \left( \frac{D + \Gamma E}{\gamma} \right) \left[ \left( \frac{\gamma}{\alpha} \right)^2 + \left( \frac{U^t}{\alpha} \right)^2 \right].
\]  

(C.1.14)

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 $N_{e^\pm} \equiv \gamma n_{e^\pm}$ and $N_{e^\pm}(T) \equiv \gamma n_{e^\pm}(T)$, where $n_{e^\pm}(T)$ is the total proper number density of pairs in comoving frame at thermodynamic equilibrium with temperature $T$ in the process $e^+ + e^- \rightarrow \gamma + \gamma + \gamma$ ($n_{e^-}(m, T) = n_{\gamma}(T)$), $n_{e^\pm}$ 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

\[
\frac{\partial N_{e^\pm}}{\partial t} = - \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left( \frac{r^2}{\alpha} N_{e^\pm} V^r \right) + \sigma \bar{v} (N_{e^\pm}^2(T) - N_{e^\pm}^2) / \gamma^2,
\]  

(C.1.15)

These partial differential equations have been integrated in Livermore starting from the dyadosphere distributions given in Fig. 17 (Right) in Ruffini et al. (2003) and assuming as usual ingoing boundary conditions on the horizon of the black hole. A simplified set of ordinary differential equations has been integrated in Rome and the results have been validated by comparison with the ones obtained in Livermore.
C. The optically thick “fireshell”

C.2. The fireshell in the Rome code

C.2.1. 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. Details on the $e^+e^-$ pairs creation are given in the following report about “Critical Field in Physics and Astrophysics of Neutron stars and black holes”.

Recalling that the local number density of electron and positron pairs created as a function of radius is given by (Preparata et al., 1998):

$$n_{e^+e^-}(r) = \frac{Q}{4\pi r^2} \left( \frac{\hbar}{mc} \right) e \left[ 1 - \left( \frac{r}{r_{ds}} \right)^2 \right], \quad (C.2.1)$$

where $r_{ds}$ is the dyadosphere radius (see section A.3 and the following report about “Critical Field in Physics and Astrophysics of Neutron stars and black holes”) the limit on such baryonic contamination, where $\rho_{Bc}$ is the mass-energy density of baryons, is given by

$$\rho_{Bc} \ll m_p n_{e^+e^-}(r) = 3.2 \cdot 10^8 \left( \frac{r_{ds}}{r} \right)^2 \left[ 1 - \left( \frac{r}{r_{ds}} \right)^2 \right] (g/cm^3). \quad (C.2.2)$$

Near the horizon $r \approx r_+$, this gives

$$\rho_{Bc} \ll m_p n_{e^+e^-}(r) = 1.86 \cdot 10^{14} \left( \frac{\xi}{\mu} \right) (g/cm^3), \quad (C.2.3)$$

and near the radius of the dyadosphere $r_{ds}$:

$$\rho_{Bc} \ll m_p n_{e^+e^-}(r) = 3.2 \cdot 10^8 \left[ 1 - \left( \frac{r}{r_{ds}} \right)^2 \right] (g/cm^3). \quad (C.2.4)$$

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. C.1.

The plasma of $e^+e^-$ pairs and photons is described by the covariant energy-momentum tensor $T^{\mu\nu}$ given in Eq. (C.1.1).

It is assumed that the gravitational interaction with central black hole is
Figure C.1: Three different dyadospheres corresponding to the same value of $E_{\text{dy}}$ 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).
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 (Ruffini et al., 1999). 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 \( \epsilon \), given by \( \epsilon = \epsilon_{\text{e}^+} + \epsilon_{\text{e}^-} + \epsilon_{\gamma} \), where \( \epsilon_{\text{e}^+} (\epsilon_{\text{e}^-}) \) is total proper internal energy density of electrons (positrons) and \( \epsilon_{\gamma} \) of photons. The proper number density of pairs \( n_{\text{e}^\pm} \), if the system is in thermodynamic equilibrium initially at temperature \( T \) of order \( T \sim \text{MeV} \), enough for \( e^+ e^- \) pair creation, equals the proper number density of photons \( n_{\gamma} \). This is not valid at lower temperature (Bianco et al., 2001). The pressure is \( p = p_{\text{e}^+} + p_{\text{e}^-} + p_{\gamma} \), where \( p_{\text{e}^\pm} \) are electrons and positrons pressures and \( p_{\gamma} \) is photons pressure. The system is highly relativistic, so the equation of state \( p = \epsilon / 3 \) can be considered valid. This equation of state is represented with thermal index \( \Gamma \):

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

**Fermi integrals**

Thermodynamical quantities introduced above are expressed in terms of integrals over Bose distribution for photons and Fermi distribution for \( e^+ e^- \) pairs with zero chemical potentials \( \mu_{\gamma} \) and \( \mu_{e^\pm} \). 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:

\[
\left( \frac{\partial F}{\partial N} \right)_{T, V} = 0;
\]

by definition chemical potential \( \mu \) is given by

\[
\mu = \left( \frac{\partial F}{\partial N} \right)_{T, V} ;
\]

so that for a system made by a photon gas at equilibrium with matter with respect to creation and adsorption processes, we have \( \mu_{\gamma} = 0 \) (Landau and Lifshitz, 1980). We assume the chemical potential of electrons and positrons to be equal to zero: \( \mu_{\text{e}^-} = \mu_{\text{e}^+} = 0 \). In the following the expressions of thermodynamical quantities as Fermi integrals are listed. The proper number
C.2. The fireshell in the Rome code

The density of electrons \( n_e^- (m, T, \mu_e^-) \) is given by

\[
\frac{2}{\hbar^3} \int \frac{d^3 p}{e^{\frac{(p c)^2}{2kT} + 1}} = \frac{8\pi}{\hbar^3} \int_0^{+\infty} \frac{p^2}{e^{\frac{(p c)^2}{2kT} + 1}} dp = \frac{aT^3 7 1}{8 \pi y} \int_0^{+\infty} \frac{z^2}{e^{z^2 + (mc^2/kT)^2} + 1} dz, \tag{C.2.8}
\]

where \( z = pc/kT \), \( m \) is the electron mass, \( T \) is the temperature of fireshell in comoving frame, \( a = \frac{8\pi^5k^4}{15\hbar^3c^3} = 1.37 \times 10^{26} \) erg/(cm\(^3\) MeV\(^4\)), \( k \) is the Boltzmann constant and \( A = (7/4)(\pi^4/15) \) is a numerical constant introduced for convenience.

Since the thermodynamic equilibrium is assumed and in all cases analyzed 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 one of photons:

\[
n_{e^\pm} \sim n_e^- (T) \sim n_\gamma (T); \tag{C.2.9}
\]

in these conditions the number of particles is conserved:

\[
(n_{e^\pm} U^\mu)_{\mu\ell} = 0. \tag{C.2.10}
\]

Later on, for \( T \ll 1 \text{ MeV} \) (see Fig. C.2), \( e^+ e^- \) pairs go on in annihilation but can not be created anymore, therefore

\[
n_\gamma (T) > n_{e^\pm} > n_{e^\pm} (T) \tag{C.2.11}
\]

as shown in Fig. C.3.

The total proper internal energy density for photons is given by

\[
\epsilon_\gamma = \frac{2}{\hbar^3} \int \frac{h\nu}{e^{h\nu/kT} - 1} d^3 p = aT^4 \tag{C.2.12}
\]

where \( p = h\nu/c \). The total proper internal energy density for electrons is
C. The optically thick “fireshell”

Figure C.2.: Temperature in comoving system as a function of emission time for different values of black hole mass $\mu$. 

$M_{BH}=10^{3}M_{\text{Solar}}$ $\quad$ $M_{BH}=10^{2}M_{\text{Solar}}$ $\quad$ $M_{BH}=10M_{\text{Solar}}$
Figure C.3.: Ratio between number density of pairs $e^+e^- n_{e\pm}$ and number density of photons $n_\gamma (T)$ as a function of emission time for different values of black hole mass $\mu$. 
C. The optically thick “fireshell”

given by:

\[
\epsilon_{e^-} = \frac{2}{\hbar^3} \int \sqrt{(pc)^2 + (mc^2)^2} d^3 p = \frac{8\pi}{\hbar^3} \int_0^{+\infty} p^2 \sqrt{(pc)^2 + (mc^2)^2} e^{\frac{\sqrt{(pc)^2 + (mc^2)^2}}{kt}} \cdot \frac{(pc)^2}{\sqrt{(pc)^2 + (mc^2)^2}} dp = \frac{aT^4}{4A} \int_0^{+\infty} z^2 \frac{\sqrt{z^2 + (mc^2/kT)^2}}{e^{\sqrt{z^2 + (mc^2/kT)^2}} + 1} dz
\]  
(C.2.13)

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

\[
\epsilon_{tot} = aT^4 \left[ 1 + \frac{7}{4} \int_0^{+\infty} \frac{z^2 \sqrt{z^2 + (mc^2/kT)^2}}{e^{\sqrt{z^2 + (mc^2/kT)^2}} + 1} dz \right] 
\]  
(C.2.14)

where the factor 2 in front of the integral takes into account of electrons and positrons.

About the pressure of the photons it holds

\[
p_{\gamma} = \frac{\epsilon_{\gamma}}{3} = \frac{aT^4}{3};
\]  
(C.2.15)

and about the pressure of electrons

\[
p_{e^-} = \frac{2}{3\hbar^3} \int \frac{1}{e^{\frac{\sqrt{(pc)^2 + (mc^2)^2}}{kt}} + 1} \cdot \frac{(pc)^2}{\sqrt{(pc)^2 + (mc^2)^2}} dp = \frac{8\pi}{3\hbar^3} \int_0^{+\infty} p^2 \frac{\sqrt{(pc)^2 + (mc^2)^2}}{e^{\frac{\sqrt{(pc)^2 + (mc^2)^2}}{kt}} + 1} \cdot \frac{(pc)^2}{\sqrt{(pc)^2 + (mc^2)^2}} dp = \frac{aT^4}{4A} \int_0^{+\infty} \frac{z^4}{e^{\sqrt{z^2 + (mc^2/kT)^2}} + 1} \cdot \frac{1}{\sqrt{z^2 + (mc^2/kT)^2}} dz
\]  
(C.2.16)

Therefore the total pressure of PEM-pulse is given by

\[
p_{tot} = \frac{aT^4}{3} \left[ 1 + \frac{7}{4A} \int_0^{+\infty} \frac{z^4}{e^{\sqrt{z^2 + (mc^2/kT)^2}} + 1} \cdot \frac{1}{\sqrt{z^2 + (mc^2/kT)^2}} dz \right].
\]  
(C.2.17)
Numerical code

In the following we recall a zeroth order approximation of the fully relativistic equations of the previous section (Ruffini et al., 1999).

(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 equation 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

$$d(V\epsilon) + pdV = dE + pdV = 0, \quad (C.2.18)$$

where $V$ is the volume of the shell in the comoving frame and $E = V\epsilon$ is the total proper internal energy of plasma (the subscript \(\circ\) refers to the initial values). By using the equation of state Eq.\(\text{(C.2.5)}\) we find

$$d\ln \epsilon + \Gamma d\ln V = 0 \quad (C.2.19)$$

and, by integrating, we find

$$\frac{\epsilon_\circ}{\epsilon} = \left( \frac{V}{V_\circ} \right)^\Gamma \quad (C.2.20)$$

recalling that $V = V\gamma$, where $V$ is the volume in the laboratory frame, we find

$$\frac{\epsilon_\circ}{\epsilon} = \left( \frac{V}{V_\circ} \right)^\Gamma = \left( \frac{V}{V_\circ} \right)^\Gamma \left( \frac{\gamma}{\gamma_\circ} \right)^\Gamma \quad (C.2.21)$$

The total energy conservation of the shell implies (Ruffini et al., 1999):

$$(\Gamma \epsilon)V\gamma^2 = (\Gamma \epsilon_\circ)V_\circ \gamma_\circ^2, \quad (C.2.22)$$

and this gives the evolution for $\gamma$:

$$\gamma = \gamma_\circ \sqrt{\frac{\epsilon_\circ V_\circ}{\epsilon V}} \quad (C.2.23)$$
Substituting this expression for $\gamma$ in (C.2.21) the final equation for proper internal energy density is found

$$\epsilon = \epsilon_0 \left( \frac{\mathcal{V}_0}{\mathcal{V}} \right)^{\frac{r}{r_t}}$$  \hspace{1cm} (C.2.24)

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

$$(n_{e^\pm} U^\mu) \hspace{1cm} (n_{e^\pm} U^\mu)_{,\mu} = \frac{1}{\sqrt{-g}} \left( \sqrt{-g} n_{e^\pm} U^\mu \right)_{,\mu}$$

$$= (n_{e^\pm} U^\mu)_{,\mu} + \frac{1}{r^2} \left( r^2 n_{e^\pm} U^\mu \right)_{,\mu} = 0$$  \hspace{1cm} (C.2.25)

where $g = || g^{\mu\nu} || = -r^4 \sin^2 \theta$ is the determinant of Reissner-Nordstrøm metric. In the system processes of creation and annihilation of particles occur due to collisions between particles. If the number of particles is conserved, it holds $(n_{e^\pm} U^\mu)_{,\mu} = 0$; if not, in the assumptions that only binary collisions between particles occur and in the hypothesis of molecular caos, the Eq.(C.2.25) becomes

$$\sigma \frac{v}{\epsilon_{tot}} [n_{e^-}(T)n_{e^+}(T) - n_{e^-}n_{e^+}]$$  \hspace{1cm} (C.2.26)

where $\sigma$ is the cross section for the process of creation and annihilation of pairs, given by

$$\sigma = \frac{\pi r_e^2}{\alpha_0 + 1} \left[ \frac{\alpha_0^2 + 4\alpha_0 + 1}{\alpha_0^2 - 1} \ln \left( \alpha_0 + \sqrt{\alpha_0^2 - 1} \right) - \frac{\alpha_0 + 3}{\sqrt{\alpha_0^2 - 1}} \right]$$  \hspace{1cm} (C.2.27)

with $\alpha_0 = \frac{E}{m c^2}$ and $E$ total energy of positrons in the laboratory frame, and $r_e = \frac{e^2}{mc^2}$ the classical radius of electron, $v$ is the sound velocity in the fireball:

$$v = c \sqrt{\frac{p_{tot}}{\epsilon_{tot}}}$$  \hspace{1cm} (C.2.28)

and $\overline{\sigma \nu}$ is the mean value of $\sigma \nu$; for $\sigma$ we use as a first approximation the Thomson cross section, $\sigma_T = 0.665 \cdot 10^{-24} \text{cm}^2$; $n_{e^\pm}(T)$ is the total proper number density of electrons and positrons in comoving frame at thermodynamic equilibrium in the process $e^+ + e^- \rightarrow \gamma + \gamma$ ($n_{e^-}(m,T) = n_{\gamma}(T)$), $n_{e^\pm}$ 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 $U^\mu =$
C.2. The fireshell in the Rome code

\( (\gamma, \gamma^v); \) Eq. (C.2.26) in hybrid form becomes

\[
\frac{\partial}{\partial t} (n_{e^\pm} \gamma) - \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 n_{e^\pm} \gamma V^r \right) + \sigma v \left( n_{e^\pm}^2 (T) - n_{e^\pm}^2 \right),
\]

(C.2.29)

valid for electrons and positrons.

Now we have a complete set of equations for numerical integration: (C.2.24), (C.2.23) and (C.2.29).

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 \((\bar{\epsilon}, \bar{n}_{e^\pm})\) for the PEM-pulse, where the average \(\gamma\)-factor is defined by

\[
\gamma = \frac{1}{V} \int V(r) dV,
\]

(C.2.30)

and \(V\) is the total volume of the shell in the laboratory frame (Ruffini et al., 1999).

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 (Ruffini et al., 1999):

- **Sphere.** An expansion with radial component of 4-velocity proportional to the distance from the black hole \(U_r(r) = U \frac{r}{R(t)}\), where \(U\) is the radial component of 4-velocity on the external surface of PEM-pulse (having radius \(R(t)\)), the factor \(\gamma\) from (C.2.30) is

\[
\gamma = \frac{3}{8U^3} \left[ 2U \left( 1 + U^2 \right)^{\frac{3}{2}} - U \left( 1 + U^2 \right)^{\frac{1}{2}} - ln \left( U + \sqrt{1 + U^2} \right) \right];
\]

(C.2.31)

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 \(D = r_{ds} - r_+\) in laboratory frame, with \(U_r(r) = U_r = cost\) 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 (Ruffini et al., 1999) see Fig. C.4. 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 \(D\). In this case \(U_r = \sqrt{\gamma^2 - 1}\), where \(\gamma\) is computed by conservation
C. The optically thick “fireshell”

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 (Piran [1999]). Since $\gamma$ monotonically increases as $\gamma \sim R$ (Ruffini et al. [2001c]), in laboratory frame $T = \gamma T' \sim \text{constant}$ (Ruffini et al., 2000); photons are blue-shifted in laboratory frame in such a way 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 Eq. (C.2.14) numerically computed and Eq. (C.2.24).

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

$$L_\gamma = \frac{1}{\sigma n_{e^+e^-}} \sim 10^{-6}\text{cm}$$  \hspace{1cm} (C.2.32)

while in laboratory frame is given by $\lambda = L_\gamma / \gamma \sim 10^{-8}\text{cm}$. 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 $\mathcal{D} \sim 10^9\text{cm}$) is of the order of $\lambda / \mathcal{D} \simeq 10^{-17}$.

C.2.2. 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 reached yet transparency and not so small that the system will reach enough high value of Lorentz $\gamma$ in order to not be stopped in the collision (see Fig. B.2). For example we choose

$$r_{\text{in}} = 100r_{\text{ds}}, \quad \Delta = 10r_{\text{ds}}.$$  \hspace{1cm} (C.2.33)

The total baryonic mass $M_B = N_B m_p$ is assumed to be a fraction of the dyad-
Figure C.4: Lorentz $\gamma$ 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.
C. The optically thick “fireshell”

dosphere initial total energy \( E_{\text{dya}} \). The total baryon-number \( N_B \) is then expressed as a function of the dimensionless parameter \( B \) given by Eq.\(\text{(B.2.1)}\). We shall see below the role of \( B \) in the determination of the features of the GRBs. We already saw the sense in which \( B \) and \( E_{\text{tot}} = E_{\text{dya}} \) 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” (see section \(\text{B.2.2} \)). For the so called “genuine short bursts” the black hole theory depends on the two other parameters \( \mu, \zeta \), 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 \( n_B \) is assumed to be a constant

\[
    n_B = \frac{N_B}{V_B}, \quad \bar{\rho}_B = m_p n_B c^2.
\]

As the PEM pulse reaches the region \( r_{\text{in}} < r < r_{\text{out}} \), 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 \( M_B, 10^{-8} < B \leq 10^{-2} \) (see Fig. \(\text{C.5} \)); (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., \( 10^6 < n_{e^+e^-}/n_B < 10^{12} \)); (iii) the PEM pulse has a large value of the gamma factor (\( \gamma > 100 \)).

In the collision between the PEM pulse and the baryonic matter at \( r_{\text{out}} > r > r_{\text{in}} \), we impose total conservation of energy and momentum. We consider the collision process between two radii \( r_2, r_1 \) satisfying \( r_{\text{out}} > r_2 > r_1 > r_{\text{in}} \) and \( r_2 - r_1 \ll \Delta \). 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 in the laboratory frame.

As for energy density of dyadosphere, here we also 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.
C.2. The fireshell in the Rome code

Figure C.5.: A sequence of snapshots of coordinate baryon energy density is shown from the one dimensional hydrodynamic calculations of the Livermore code. The radial coordinate is given in units of dyadosphere radii \((r_{ds})\). At \(r \approx 100r_{ds}\) there is located a baryonic matter shell corresponding to a baryon loading \(B = 1.3 \times 10^{-2}\). For this baryon shell mass we see a significant departure from the constant thickness solution for the fireshell dynamics and a clear instability occurs. Details in Ruffini et al. (2000). As we will see, this result, peculiar of our treatment, will play a major role in the theoretical interpretation of GRBs.
C. The optically thick “fireshell”

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.

The conservation of total energy leads to the estimate of the corresponding quantities before (with “\( \circ \)”) and after such a collision

\[ (\Gamma \epsilon_\circ + \bar{\rho}_B^\circ) \gamma_\circ^2 V_\circ + \Delta M = (\Gamma \epsilon + \bar{\rho}_B + \frac{\Delta M}{V} + \Gamma \Delta \epsilon) \gamma^2 V, \]

where \( \Delta \epsilon \) is the corresponding increase of internal energy due to the collision. Similarly the momentum-conservation gives

\[ (\Gamma \epsilon_\circ + \bar{\rho}_B^\circ) \gamma_\circ U_\circ^r V_\circ = (\Gamma \epsilon + \bar{\rho}_B + \frac{\Delta M}{V} + \Gamma \Delta \epsilon) \gamma U_r V, \]

where the radial component of the four-velocity of the PEM pulse is \( U_\circ^r = \sqrt{\gamma_\circ^2 - 1} \) and \( \Gamma \) is the thermal index. We then find

\[ \Delta \epsilon = \frac{1}{\Gamma} \left[ (\Gamma \epsilon_\circ + \bar{\rho}_B^\circ) \frac{\gamma_\circ U_\circ^r V_\circ}{\gamma U_r V} - (\Gamma \epsilon + \bar{\rho}_B + \frac{\Delta M}{V}) \right], \]

\[ \gamma = \frac{a}{\sqrt{a^2 - 1}}, \quad a = \frac{\gamma_\circ}{U_\circ^r} + \frac{\Delta M}{(\Gamma \epsilon_\circ + \bar{\rho}_B^\circ) \gamma_\circ U_\circ^r V_\circ}. \]

These equations determine the gamma factor \( \gamma \) and the internal energy density \( \epsilon = \epsilon_\circ + \Delta \epsilon \) 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 the Lorentz gamma factor and the increase of internal energy as function of \( B \) parameter and also the ultrarelativistic approximation (\( \gamma_\circ \to \infty \)): 
1. an abrupt decrease of the gamma factor given by
\[ \gamma_{\text{coll}} = \gamma_0 \frac{1 + B}{\sqrt{\gamma_0^2 (2B + B^2) + 1}} \rightarrow \infty \rightarrow B + \frac{1}{\gamma_0} \sqrt{B^2 + 2B} , \]

2. an increase of the internal energy in the comoving frame \( E_{\text{coll}} \) developed in the collision given by
\[ \frac{E_{\text{coll}}}{E_{\text{dya}}} = \frac{\sqrt{\gamma_0^2 (2B + B^2) + 1}}{\gamma_0} - \left( \frac{1}{\gamma_0} + B \right) \gamma_0 \rightarrow \infty - B + \frac{1}{\gamma_0} \sqrt{B^2 + 2B} , \]

This approximation applies when the final gamma factor at the end of the PEM pulse era is larger than \( \gamma_{\text{coll}} \), right panel in Fig. B.2.

In this phase of expansion, another thermodynamic quantity has not been considered: the chemical potential \( \mu \) of the electrons from ionization of baryonic remnant. We remind that the total proper number density of electrons of ionization is given by
\[ n_e^{-}(m, T, \mu) = \frac{aT^3 71}{8 \pi} \int_0^{+\infty} \frac{z^2}{e^{z^2+(mc^2/kT)^2+\mu/kT}+1} dz \quad (\text{C.2.41}) \]

four equations are imposed to find a formula useful for numerical computation: the first one is the thermodynamical equilibrium of fireball, or
\[ n_{e^\pm}(T_o) = n_{\gamma}(T_o) ; \quad (\text{C.2.42}) \]
the second one is
\[ n_e^{\pm} = \bar{Z} n_B \quad (\text{C.2.43}) \]
where \( 1/2 < \bar{Z} < 1 \), with \( \bar{Z} = 1 \) for hydrogen atoms and \( \bar{Z} = 1/2 \) for baryonic matter in general; the third one derives from the definition of \( B \) \[ \text{B.2.1}, \]
and states a relation between the two densities \( n_B \) and \( n_{e^\pm} \): from definition of \( B \), we have
\[ \frac{N_B}{N_{e^\pm}(T_o)} = \frac{B E_{\text{dya}}}{m_p c^2 N_{e^\pm}(T_o)} = 10^b \quad (\text{C.2.44}) \]
where \( T_o \) is the initial temperature of fireshell and \( b \) is a parameter \( (b < 0) \) defined by \[ \text{C.2.44} \]; so if \( V_o \) is the initial volume of dyadosphere and \( w \) the initial volume of the baryonic shell
\[ n_B^o = 10^b n_{e^\pm}(T_o) \frac{V_o}{w} ; \quad (\text{C.2.45}) \]

finally the fourth one is the conservation law of baryonic matter
\[ (n_e^{-} U^\mu)_{\mu} = 0 . \quad (\text{C.2.46}) \]
Therefore the chemical potential $\mu$ is numerically determined at a certain time of expansion if the initial temperature $T_\circ$ of fireshell and the initial volume of baryonic shell $w$ are known and, at that time, the volume $V$, the temperature $T$ and the Lorentz factor $\gamma$ of the fireball, the volume of the baryonic shell swept up $vb$ and the ratio $n_{e^-}^{b}/n_{e^+}^{b}(T)$:

$$2\zeta(3)\bar{T}10^b n_{e^+}^{b}(T) T_\circ^3 w \left(\frac{vb}{w}\right) = \int_0^{+\infty} e^{\frac{z^2}{2} + \frac{(mc^2/kT)^2 - \mu/kT}{2}} \frac{dz}{\sqrt{z^2 + (mc^2/kT)^2 + \mu/kT}} + 1 \quad (C.2.47)$$

where the factor in brackets $\left(\frac{vb}{w}\right)$ must be considered only for $r > r_{out}$, while the proportionality factor is the function zeta of Riemann $\zeta(x)$ for computation of $n_x$, with $\zeta(3) = 1.202$.

Therefore the equations for this phase are (C.2.29), (C.2.36), (C.2.39), (C.2.40), and (C.2.47).

### C.2.3. 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:

$$\int_R dr (n_{e^\pm} + \bar{Z} n_B) \sigma_T \simeq O(1), \quad (C.2.48)$$

where $\sigma_T = 0.665 \cdot 10^{-24}$ 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 expansion 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 $\Delta = 10r_{ds}$ at rest at a radius of $100r_{ds}$ and $B \simeq 1.3 \cdot 10^{-4}$.

In analogy with the special relativistic treatment for the PEM pulse, presented above (see also Ruffini et al., 1999), for the adiabatic expansion of the PEMB pulse in the constant-slab approximation described by the Rome codes.
C.2. The fireshell in the Rome code

Figure C.6: 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 $E_{dya} = 3.1 \times 10^{54}$ erg and $B = 1.3 \times 10^{-4}$, $r_{in} = 100r_{ds}$ and $\Delta = 10r_{ds}$. The result is in accordance with the scheme of a fireshell with constant thickness in laboratory frame which is valid up to $B = 10^{-2}$.
Figure C.7.: 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 $\gamma_{\text{asy}} = E_{\text{dya}} / (M_Bc^2) = 10^4, 10^5, 10^6$ are also plotted. The collision of the PEM pulse with the baryonic remnant occurs at $r/r_{ds} = 100$ where the jump occurs. Right: The $\gamma$ factor (red line) at the transparency point is plotted as a function of the $B$ parameter. The asymptotic value (green line) $E_{\text{dya}} / (M_Bc^2)$ is also plotted.

In these equations ($r > r_{\text{out}}$) the comoving baryonic mass and number densities are $\tilde{\rho}_B = M_B / V$ and $n_B = N_B / V$, where $V$ is the comoving volume of the PEMB pulse.

The result is shown in Fig. C.6 (Ruffini et al., 2000) 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 (Ruffini et al., 2000). 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 $B \simeq 1.3 \cdot 10^{-2}$ 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. (C.2.48) is reached as a function of $B$ (see Fig. C.7). 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 $E_{\text{dya}}$ is transferred into the kinetic energy of the baryons (see also Ruffini et al., 2000).

In Fig. C.7-Left 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. (C.2.48) is reached. The “asymptotic” gamma factor

$$\gamma_{\text{asym}} \equiv \frac{E_{\text{dya}}}{M_B c^2}$$  \hspace{1cm} (C.2.53)

is also shown for each curve. The closer the gamma value approaches the “asymptotic” value 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. C.7-Right).

### C.2.4. The approach to transparency: the thermodynamical quantities

As the condition of transparency expressed by Eq. (C.2.48) is reached the injector phase terminates. The electromagnetic energy of the PEMB pulse is released in the form of free-streaming photons — the P-GRB. The remaining energy of the PEMB pulse is released as an ABM pulse.

We now proceed to the analysis of the approach to the transparency condition. It is then necessary to turn from the pure dynamical description of the PEMB pulse described in the previous sections to the relevant thermodynamic parameters. Also such a description at the time of transparency needs the knowledge of the thermodynamical parameters in all previous eras of the GRB.

As above we shall consider as a typical case a black hole of $E_{\text{dya}} = 3.1 \times 10^{54}$ erg and $B = 10^{-2}$. One of the key thermodynamical parameters is represented by the temperature of the PEM and PEMB pulses. It is given as a function of the radius both in the comoving and in the laboratory frames in Fig. C.8. Before the collision the PEM pulse expands keeping its temperature in the laboratory frame constant while its temperature in the comoving frame
C. The optically thick “fireshell”

falls (see Ruffini et al., 1999). In fact we have:

\[
\frac{d(\epsilon \gamma^2 V)}{dt} = 0,
\]

where the baryon mass-density is \( \rho_B = 0 \) and the thermal energy-density of photons and \( e^+e^- \)-pairs is \( \epsilon = \sigma_B T^4(1 + f_{e^+e^-}), \) \( \sigma_B \) is the Boltzmann constant and \( f_{e^+e^-} \) is the Fermi-integral for \( e^+ \) and \( e^- \). This leads to

\[
\epsilon \gamma^2 V = E_{\text{dy}} \quad T^4 \gamma^2 V = \text{const.}
\]

Since \( e^+ \) and \( e^- \) in the PEM pulse are extremely relativistic, we have the equation of state \( p \simeq \epsilon/3 \) and the thermal index defined in Eq. (C.2.5) \( \Gamma \simeq 4/3 \) in the evolution of PEM pulse. Eq. (C.2.55) is thus equivalent to

\[
T^3 \gamma V \simeq \text{const.}
\]

These two equations (C.2.54) and (C.2.56) result in the constancy of the laboratory temperature \( T \gamma \) in the evolution of the PEM pulse.

It is interesting to note that Eqs. (C.2.55) and (C.2.56) hold as well in the cross-over region where \( T \sim m_e c^2 \) and \( e^+e^- \) annihilation takes place. In fact from the conservation of entropy it follows that asymptotically we have

\[
\frac{(VT^3)_{T < m_e c^2}}{(VT^3)_{T > m_e c^2}} = \frac{11}{4},
\]

exactly for the same reasons and physics scenario discussed in the cosmological framework by Weinberg (see e.g. Eq. (15.6.37) of Weinberg, 1972). The same considerations when repeated for the conservation of the total energy \( \epsilon \gamma V = \epsilon \gamma^2 V \) following from Eq. (C.2.54) then lead to

\[
\frac{(VT^4 \gamma)_{T < m_e c^2}}{(VT^4 \gamma)_{T > m_e c^2}} = \frac{11}{4}.
\]

The ratio of these last two quantities gives asymptotically

\[
T_0 = (T \gamma)_{T > m_e c^2} = (T \gamma)_{T < m_e c^2},
\]

where \( T_0 \) is the initial average temperature of the dyadosphere at rest.

During the collision of the PEM pulse with the remnant we have an increase in the number density of \( e^+e^- \) pairs (see Fig. C.8). This transition corresponds to an increase of the temperature in the comoving frame and a decrease of the temperature in the laboratory frame as a direct effect of the dropping of the gamma factor (see Fig. C.7).

After the collision we have the further acceleration of the PEMB pulse (see
C.2. The fireshell in the Rome code

Figure C.8.: Left: The temperature of the plasma in the comoving frame $T'(\text{MeV})$ (the red line) and in the laboratory frame $\gamma T'$ (the green line) are plotted as functions of the radius in the unit of the dyadosphere radius $r_{ds}$. Right: The number densities $n_{e^+ e^-}(T)$ (the red line) computed by the Fermi integral and $n_{e^+ e^-}$ (the green line) computed by the rate equation (see section C.1.1) are plotted as functions of the radius. $T' \ll m_e c^2$, two curves strongly divergent due to $e^+ e^-$-pairs frozen out of the thermal equilibrium. The peak at $r \simeq 100 r_{ds}$ is due to the internal energy developed in the collision.
Figure C.9.: The energy of the non baryonic components of the PEMB pulse (the red line) and the kinetic energy of the baryonic matter (the green line) in unit of the total energy are plotted as functions of the radius in the unit of the dyadosphere radius $r_{ds}$. 
C.2. The fireshell in the Rome code

Fig. C.7. The temperature now decreases both in the laboratory and the co-moving frame (see Fig. C.8). Before the collision the total energy of the $e^+e^-$ pairs and the photons is constant and equal to $E_{\text{dya}}$. After the collision

$$E_{\text{dya}} = E_{\text{Baryons}} + E_{e^+e^-} + E_{\text{photons}}, \quad (C.2.60)$$

which includes both the total energy $E_{e^+e^-} + E_{\text{photons}}$ of the nonbaryonic components and the kinetic energy $E_{\text{Baryons}}$ of the baryonic matter

$$E_{\text{Baryons}} = \bar{\rho}_B V (\gamma - 1). \quad (C.2.61)$$

In Fig. C.9 we plot both the total energy $E_{e^+e^-} + E_{\text{photons}}$ of the nonbaryonic components and the kinetic energy $E_{\text{Baryons}}$ of the baryonic matter as functions of the radius for the typical case $E_{\text{dya}} = 3.1 \times 10^{54}$ erg and $B = 10^{-2}$. Further details are given in [Ruffini et al. (2000)].
C. The optically thick “fireshell”
D. The optically thin “fireshell”: the afterglow

The consensus has been reached that the afterglow emission originates from a relativistic thin shell of baryonic matter propagating in the CBM and that its description can be obtained from the relativistic conservation laws of energy and momentum. In both our approach and in the other ones in the current literature (see e.g. Piran [1999]; Chiang and Dermer [1999]; Ruffini et al. [2003]; Bianco and Ruffini [2005a]) such conservations laws are used. The main difference is that in the current literature an ultra-relativistic approximation, following the Blandford and McKee (1976) self-similar solution, is widely adopted while we use the exact solution of the equations of motion. We express such equations in a finite difference formulation. For the differential formulation, which will be most useful in comparing and contrasting our exact solutions with the ones in the current literature, see the following report about “Relativistic effects in Physics and Astrophysics”.

In analogy and by extension of the results obtained for the PEM and PEMB pulse cases, we also assume that the expansion of the ABM pulse through the CBM occurs keeping its width constant in the laboratory frame, although the results are quite insensitive to this assumption. Then we assume that this interaction can be represented by a sequence of inelastic collisions of the expanding ABM pulse with a large number of thin and cold CBM spherical shells at rest in the laboratory frame. Each of these swept up shells of thickness $\Delta r$ has a mass $\Delta M_{\text{cbm}}$ and is assumed to be located between two radial distances $r_1$ and $r_2$ (where $r_2 - r_1 = \Delta r \ll r_1$) in the laboratory frame. These collisions create an internal energy $\Delta E_{\text{int}}$.

We indicate by $\Delta \epsilon$ the increase in the proper internal energy density due to the collision with a single shell and by $\rho_{B}$ the proper energy density of the swept up baryonic matter. This includes the baryonic matter composing the remnant, already swept up in the PEMB pulse formation, and the baryonic matter from the CBM swept up by the ABM pulse:

$$\rho_{B} = \frac{(M_{B} + M_{\text{cbm}}) c^2}{V}. \quad (D.0.1)$$

Here $V$ is the ABM pulse volume in the comoving frame, $M_{B}$ is the mass of the baryonic remnant and $M_{\text{cbm}}$ is the CBM mass swept up from the trans-
D. The optically thin “fireshell”: the afterglow

parenity point through the $r$ in the laboratory frame:

$$M_{cbm} = m_p n_{cbm} \frac{4\pi}{3} (r^3 - r_0^3), \quad (D.0.2)$$

where $m_p$ the proton mass and $n_{cbm}$ the number density of the CBM in the laboratory frame.

The energy conservation law in the laboratory frame at a generic step of the collision process is given by

$$\rho_{B_1} \gamma_1^2 V_1 + \Delta M_{cbm} c^2 = \left( \rho_{B_1} \frac{V_1}{V_2} + \frac{\Delta M_{cbm} c^2}{V_2} + \Delta \epsilon \right) \gamma_2^2 V_2, \quad (D.0.3)$$

where the quantities with the index “1” are calculated before the collision of the ABM pulse with an elementary shell of thickness $\Delta r$ and the quantities with “2” after the collision, $\gamma$ is the gamma factor and $V$ the volume of the ABM pulse in the laboratory frame so that $V = \gamma V$. The momentum conservation law in the laboratory frame is given by

$$\rho_{B_1} \gamma_1 U_{r_1} V_1 = \left( \rho_{B_1} \frac{V_1}{V_2} + \frac{\Delta M_{cbm} c^2}{V_2} + \Delta \epsilon \right) \gamma_2 U_{r_2} V_2, \quad (D.0.4)$$

where $U_r = \sqrt{\gamma^2 - 1}$ is the radial covariant component of the four-velocity vector (see Ruffini et al., 1999, 2000). We thus obtain

$$\Delta \epsilon = \rho_{B_1} \gamma_1 U_{r_1} V_1 - \left( \rho_{B_1} \frac{V_1}{V_2} + \frac{\Delta M_{cbm} c^2}{V_2} \right), \quad (D.0.5)$$

$$\gamma_2 = \frac{a}{\sqrt{a^2 - 1}}, \quad a \equiv \frac{\gamma_1}{U_{r_1}} + \frac{\Delta M_{cbm} c^2}{\rho_{B_1} \gamma_1 U_{r_1} V_1}, \quad (D.0.6)$$

We can use for $\Delta \epsilon$ the following expression

$$\Delta \epsilon = \frac{E_{int_2}}{V_2} - \frac{E_{int_1}}{V_1} = \frac{E_{int_1} + \Delta E_{int}}{V_2} - \frac{E_{int_1} + \Delta E_{int}}{V_1} = \frac{\Delta E_{int}}{V_2} \quad (D.0.7)$$

because we have assumed a “fully radiative regime” and so $E_{int_1} = 0$. Substituting Eq. (D.0.6) in Eq. (D.0.5) and applying Eq. (D.0.7), we obtain:

$$\Delta E_{int} = \rho_{B_1} V_1 \left[ 1 + 2 \gamma_1 \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1} + \left( \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1} \right)^2 \right] - \rho_{B_1} V_1 \left( 1 + \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1} \right), \quad (D.0.8)$$

$$\gamma_2 = \frac{\gamma_1 + \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1}}{\sqrt{1 + 2 \gamma_1 \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1} + \left( \frac{\Delta M_{cbm} c^2}{\rho_{B_1} V_1} \right)^2}}, \quad (D.0.9)$$
E. The “canonical GRB” bolometric light curve

We assume that the internal energy due to kinetic collision is instantly radiated away and that the corresponding emission is isotropic. 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

$$\left( \frac{dE}{dVd\Omega} \right)_o = \frac{\Delta \varepsilon}{4\pi} \quad (E.0.1)$$

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 “$o$”) and by an observer in the laboratory frame (which we denote with no subscripts). Doing this we find:

$$\frac{dN_\gamma}{dt d\Omega d\Sigma} = \left( \frac{dN_\gamma}{dt d\Omega d\Sigma} \right)_o \Lambda^{-3} \cos \vartheta, \quad (E.0.2)$$

where $\vartheta$ is the angle between the radial expansion velocity of a point on the fireshell surface and the line of sight, $\cos \vartheta$ 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

$$d\Omega_o = d\Omega \times \Lambda^{-2} \quad (E.0.3)$$

for the solid angle transformation and

$$dt_o = dt \times \Lambda^{-1} \quad (E.0.4)$$

for the time transformation. An extra $\Lambda$ factor comes from the energy transformation:

$$E_o = E \times \Lambda \quad (E.0.5)$$

(see also Chiang and Dermer, 1999). Thus finally we obtain:

$$\frac{dE}{dt d\Omega d\Sigma} = \left( \frac{dE}{dt d\Omega d\Sigma} \right)_o \Lambda^{-4} \cos \vartheta. \quad (E.0.6)$$
E. The “canonical GRB” bolometric light curve

Doing this we clearly identify \( \left( \frac{dE}{dtd\Omega} \right) \) as the energy density in the comoving frame up to a factor \( \frac{v}{4\pi} \) (see Eq. (E.0.1)). Then we have:

\[
\frac{dE}{dtd\Omega} = \int_{\text{shell}} \frac{\Delta\varepsilon}{4\pi} v \cos \theta \Lambda^{-4} d\Sigma,
\]

(E.0.7)

where 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 \( \theta_{\text{max}} \) is the boundary of the visible region defined by (see also the following report about “Relativistic effects in Physics and Astrophysics”):

\[
\cos \theta_{\text{max}} = \frac{v}{c}.
\]

(E.0.8)

Eq. (E.0.7) 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 \( t_d \), so we must use the complete relation between \( t_d \) and \( t \) given by (see also the following report about “Relativistic effects in Physics and Astrophysics”):

\[
t_d = (1+z) \left[ t - \frac{r}{c} (t) \cos \theta + \frac{r^*}{c} \right],
\]

(E.0.9)

where \( r^* \) is the initial size of the fireshell. First we have to multiply the integrand in Eq. (E.0.7) by the factor \( \left( dt/dt_d \right) \) to transform the energy density generated per unit of laboratory time \( t \) into the energy density generated per unit arrival time \( t_d \). Then we have to integrate with respect to \( d\Sigma \) over the EQTS corresponding to arrival time \( t_d \) instead of the ABM pulse visible area at laboratory time \( t \). The analog of Eq. (E.0.7) for the source luminosity in detector arrival time is then:

\[
\frac{dE_\gamma}{dt_d d\Omega} = \int_{\text{EQTS}} \frac{\Delta\varepsilon}{4\pi} v \cos \theta \Lambda^{-4} \frac{dt}{dt_d} d\Sigma.
\]

(E.0.10)

It is important to note that, in the present case of GRB 991216, the Doppler factor \( \Lambda^{-4} \) in Eq. (E.0.10) 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. B.5 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 \( \gamma_o \sim 200–300 \) with respect to the CBM (see e.g. Ruffini et al., 2003; Bianco and Ruffini, 2004 and references therein). Using GRB 991216 as a prototype, in
Table E.1.: For each CBM density peak represented in Fig. E.1 we give the initial radius $r$, the corresponding comoving time $\tau$, laboratory time $t$, arrival time at the detector $t_{da}$, diameter of the ABM pulse visible area $d_v$, Lorentz factor $\gamma$ and observed duration $\Delta t_{da}$ of the afterglow luminosity peaks generated by each density peak. In the last column, the apparent motion in the radial coordinate, evaluated in the arrival time at the detector, leads to an enormous “superluminal” behavior, up to $9.5 \times 10^4 c$.

<table>
<thead>
<tr>
<th>Peak</th>
<th>$r$ (cm)</th>
<th>$\tau$ (s)</th>
<th>$t$ (s)</th>
<th>$d_v$ (cm)</th>
<th>$\Delta t_{da}$ (s)</th>
<th>$\gamma$</th>
<th>$\Delta t_{da}$ (s) = $\frac{\gamma}{2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$4.50 \times 10^{16}$</td>
<td>$4.88 \times 10^{16}$</td>
<td>$1.50 \times 10^{16}$</td>
<td>$15.8$</td>
<td>$2.95 \times 10^{14}$</td>
<td>$0.400$</td>
<td>$303.8$</td>
</tr>
<tr>
<td>B</td>
<td>$5.20 \times 10^{16}$</td>
<td>$5.74 \times 10^{16}$</td>
<td>$1.73 \times 10^{16}$</td>
<td>$19.0$</td>
<td>$3.89 \times 10^{14}$</td>
<td>$0.622$</td>
<td>$265.4$</td>
</tr>
<tr>
<td>C</td>
<td>$5.70 \times 10^{16}$</td>
<td>$6.54 \times 10^{16}$</td>
<td>$1.93 \times 10^{16}$</td>
<td>$22.9$</td>
<td>$5.03 \times 10^{14}$</td>
<td>$1.13$</td>
<td>$200.5$</td>
</tr>
<tr>
<td>D</td>
<td>$6.20 \times 10^{16}$</td>
<td>$7.64 \times 10^{16}$</td>
<td>$2.07 \times 10^{16}$</td>
<td>$30.1$</td>
<td>$9.03 \times 10^{14}$</td>
<td>$5.16$</td>
<td>$139.9$</td>
</tr>
<tr>
<td>E</td>
<td>$6.50 \times 10^{16}$</td>
<td>$9.22 \times 10^{16}$</td>
<td>$2.17 \times 10^{16}$</td>
<td>$55.9$</td>
<td>$2.27 \times 10^{15}$</td>
<td>$10.2$</td>
<td>$57.23$</td>
</tr>
<tr>
<td>F</td>
<td>$6.80 \times 10^{16}$</td>
<td>$1.10 \times 10^{16}$</td>
<td>$2.27 \times 10^{16}$</td>
<td>$87.4$</td>
<td>$2.42 \times 10^{15}$</td>
<td>$10.6$</td>
<td>$56.24$</td>
</tr>
</tbody>
</table>

Ruffini et al. (2001c,b) we have shown how from the time varying bolometric intensity of the afterglow it is possible to infer the average density $\langle n_{cbm} \rangle = 1$ particle/cm$^3$ of the CBM in a region of approximately $10^{17}$ cm surrounding the black hole giving rise to the GRB phenomenon.

The summary of these general results are shown in Fig. B.4, 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. (2003).

E.1. On the structures in the afterglow peak emission

We are now ready to reconsider the problem of the CBM inhomogeneity generating the temporal substructures in the E-APE by integrating on the EQTS surfaces and improving on the considerations based on the purely radial approximation. It was shown in Ruffini et al. (2002a) that the theoretical interpretation of the intensity variations in the prompt phase in the afterglow implies the presence in the CBM of inhomogeneities of typical scale $10^{15}$ cm. Such inhomogeneities were there represented for simplicity as spherically symmetric over-dense regions with $\langle n_{od}^{cbm} \rangle \simeq 10^2 \langle n_{cbm} \rangle$ separated by under-dense regions with $\langle n_{ud}^{cbm} \rangle \simeq 10^{-2} \langle n_{cbm} \rangle$ also of typical scale $\sim 10^{15}$ cm in order to keep $\langle n_{cbm} \rangle$ constant (see Fig. E.1 and Tab. E.1).

The results are given in Fig. E.2. We obtain, in perfect agreement with the observations:

1. the theoretically computed intensity of the A, B, C peaks as a function of the CBM inhomogeneities;

2. the fast rise and exponential decay shape for each peak;
Figure E.1.: The density profile (“mask”) of an CBM cloud used to reproduce the GRB 991216 temporal structure. As before, the radial coordinate is measured from the black hole. In this cloud we have six “spikes” with over-density separated by low density regions. Each spike has the same spatial extension of $10^{15}$ cm. The cloud average density is $\langle n_{\text{cbm}} \rangle = 1$ particle/cm$^3$. 
E.1. On the structures in the afterglow peak emission

Figure E.2.: Left: The BATSE data on the E-APE of GRB 991216 (source: Curves (1999)) together with an enlargement of the P-GRB data (source: Response (1999)). For convenience each E-APE peak has been labeled by a different uppercase Latin letter. Right: The source luminosity connected to the mask in Fig. E.1 is given as a function of the detector arrival time (red “spiky” line) with the corresponding curve for the case of constant $n_{cbm} = 1 \text{ particle/cm}^3$ (green smooth line) and the BATSE noise level (blue horizontal line). The “noise” observed in the theoretical curves is due to the discretization process adopted, described in Ruffini et al. (2002a), for the description of the angular spreading of the scattered radiation. For each fixed value of the laboratory time we have summed 500 different contributions from different angles. The integration of the equation of motion of this system is performed in 22,314,500 contributions to be considered. An increase in the number of steps and in the precision of the numerical computation would lead to a smoother curve.

3. A continuous and smooth emission between the peaks.

Interestingly, the signals from shells E and F, which have a density inhomogeneity comparable to A, are undetectable. The reason is due to a variety of relativistic effects and partly to the spreading in the arrival time, which for A, corresponding to $\gamma = 303.8$ is 0.4s while for E (F) corresponding to $\gamma = 57.23$ (56.24) is of 10.2 s (10.6 s) (see Tab. E.1 and Ruffini et al. 2002a).

In the case of D, the agreement with the arrival time is reached, but we do not obtain the double peaked structure. The ABM pulse visible area diameter at the moment of interaction with the D shell is $\sim 1.0 \times 10^{15} \text{ cm}$, equal to the extension of the CBM shell (see Tab. E.1 and Ruffini et al. 2002a). Under these conditions, the concentric shell approximation does not hold anymore: the disagreement with the observations simply makes manifest the need for a more detailed description of the three dimensional nature of the CBM cloud.
The physical reasons for these results can be simply summarized: we can distinguish two different regimes corresponding in the afterglow of GRB 991216 respectively to $\gamma > 150$ and to $\gamma < 150$. For different sources this value may be slightly different. In the E-APE region ($\gamma > 150$) the GRB substructure intensities indeed correlate with the CBM inhomogeneities. In this limited region (see peaks A, B, C) the Lorentz gamma factor of the ABM pulse ranges from $\gamma \sim 304$ to $\gamma \sim 200$. The boundary of the visible region is smaller than the thickness $\Delta R$ of the inhomogeneities (see Tab. E.1). Under this condition the adopted spherical approximation is not only mathematically simpler but also fully justified. The angular spreading is not strong enough to wipe out the signal from the inhomogeneity spike.

As we descend in the afterglow ($\gamma < 150$), the Lorentz gamma factor decreases markedly and in the border line case of peak D $\gamma \sim 140$. For the peaks E and F we have $\gamma \sim 50$ and, under these circumstances, the boundary of the visible region becomes much larger than the thickness $\Delta R$ of the inhomogeneities (see Tab. E.1). A three dimensional description would be necessary, breaking the spherical symmetry and making the computation more difficult. However we do not need to perform this more complex analysis for peaks E and F: any three dimensional description would a fortiori augment the smoothing of the observed flux. The spherically symmetric description of the inhomogeneities is already enough to prove the overwhelming effect of the angular spreading (Ruffini et al., 2002a).

From our analysis we show that the Dermer and Mitman (1999) conclusions are correct for $\gamma \sim 300$ and do indeed hold for $\gamma > 150$. However, as the gamma factor drops from $\gamma \sim 150$ to $\gamma \sim 1$ (see Fig B.3), the intensity due to the inhomogeneities markedly decreases also due to the angular spreading (events E and F). The initial Lorentz factor of the ABM pulse $\gamma \sim 310$ decreases very rapidly to $\gamma \sim 150$ as soon as a fraction of a typical CBM cloud is engulfed (see Tab. E.1). We conclude that the “tomography” is indeed effective, but uniquely in the first CBM region close to the source and for GRBs with $\gamma > 150$.

One of the most striking feature in our analysis is clearly represented by the fact that the inhomogeneities of a mask of radial dimension of the order of $10^{17}$ cm give rise to arrival time signals of the order of 20 s. This outstanding result implies an apparent “superluminal velocity” of $\sim 10^5 c$ (see Tab. E.1). The “superluminal velocity” here considered, first introduced in Ruffini et al. (2001c), refers to the motion along the line of sight. This effect is proportional to $\gamma^2$. It is much larger than the one usually considered in the literature, within the context of radio sources and microquasars (see e.g. Mirabel and Rodriguez 1994), referring to the component of the velocity at right angles to the line of sight (see details in Ruffini et al. 2002a). This second effect is in fact proportional to $\gamma$ (see Rees, 1966). We recall that this “superluminal velocity” was the starting point for the enunciation of the RSTT paradigm (Ruffini et al. 2001c), emphasizing the need of the knowledge of the entire
past worldlines of the source. This need has been further clarified here in
the determination of the EQTS surfaces which indeed depend on an integral
of the Lorentz gamma factor extended over the entire past worldlines of the
source. In turn, therefore, the agreement between the observed structures and
the theoretical predicted ones (see Figs. B.4, E.2) is also an extremely stringent
additional test on the values of the Lorentz gamma factor determined as a
function of the radial coordinate within the fireshell model (see Fig. B.3).

E.2. The “canonical” GRB scenario: “genuine” and “fake” short GRBs

Summarizing, unlike treatments in the current literature (see e.g. [Piran, 2005;
Meszaros, 2006] and references therein), we define a “canonical GRB” light
curve with two sharply different components (see Fig. B.4 and [Ruffini et al.,
2001b, 2007; Bernardini et al., 2007a):

1. **The P-GRB:** it has the imprint of the black hole formation, an harder
   spectrum and no spectral lag ([Bianco et al., 2001; Ruffini et al., 2005d]).

2. **The afterglow:** it presents a clear hard-to-soft behavior ([Bernardini et al.,
   2005a; Ruffini et al., 2004b, 2006b]; the peak of the afterglow contributes
to what is usually called the “prompt emission” (see e.g. [Ruffini et al.,
   2001b, 2006b; Dainotti et al., 2007]).

The ratio between the total time-integrated luminosity of the P-GRB (namely,
its total energy) and the corresponding one of the afterglow is the crucial
quantity for the identification of GRBs’ nature. Such a ratio, as well as the
temporal separation between the corresponding peaks, is a function of the $B$
parameter ([Ruffini et al., 2001b]).

When the P-GRB is the leading contribution to the emission and the after-
glow is negligible we have a “genuine” short GRB ([Ruffini et al., 2001b). This
is the case where $B \lesssim 10^{-5}$ (see Fig. B.8): in the limit $B \to 0$ the afterglow
vanishes (see Fig. B.8). In the other GRBs, with $10^{-4} \lesssim B \lesssim 10^{-2}$, the after-
glow contribution is generally predominant (see Fig. B.8; for the existence of
the upper limit $B \lesssim 10^{-2}$ see [Ruffini et al., 2000; Dainotti et al., 2007]). Still,
this case presents two distinct possibilities:

- The afterglow peak luminosity is larger than the P-GRB one. A clear
  example of this situation is GRB 991216, represented in Fig. B.4

- The afterglow peak luminosity is smaller than the P-GRB one. A clear
  example of this situation is GRB 970228, represented in Fig. M.1

The simultaneous occurrence of an afterglow with total time-integrated lu-
minosity larger than the P-GRB one, but with a smaller peak luminosity, is
E. The “canonical GRB” bolometric light curve

indeed explainable in terms of a peculiarly small average value of the CBM density, compatible with a galactic halo environment, and not due to the intrinsic nature of the source (see Fig. M.1 and Bernardini et al., 2007a). Such a small average CBM density deflates the afterglow peak luminosity. Of course, such a deflated afterglow lasts much longer, since the total time-integrated luminosity in the afterglow is fixed by the value of the $B$ parameter (see above and Fig. M.3). In this sense, GRBs belonging to this class are only “fake” short GRBs. This is GRB class identified by Norris and Bonnell (2006), which also GRB 060614 belongs to, and which has GRB 970228 as a prototype (Bernardini et al., 2007a).

Our “canonical GRB” scenario, therefore, especially points out the need to distinguish between “genuine” and “fake” short GRBs:

- The “genuine” short GRBs inherit their features from an intrinsic property of their sources. The very small fireshell baryon loading, in fact, implies that the afterglow time-integrated luminosity is negligible with respect to the P-GRB one.

- The “fake” short GRBs, instead, inherit their features from the environment. The very small CBM density, in fact, implies that the afterglow peak luminosity is lower than the P-GRB one, even if the afterglow total time-integrated luminosity is higher. This deflated afterglow peak can be observed as a “soft bump” following the P-GRB spike, as in GRB 970228 (Bernardini et al., 2007a), GRB 060614 (Caito et al., in preparation), and the sources analyzed by Norris and Bonnell (2006).

A sketch of the different possibilities depending on the fireshell baryon loading $B$ and the average CBM density $\langle n_{cbm}\rangle$ is given in Fig. E.3.
Figure E.3.: A sketch summarizing the different possibilities predicted by the "canonical GRB" scenario depending on the fireshell baryon loading $B$ and the average CBM density $\langle n_{cbm} \rangle$. 
E. The “canonical GRB” bolometric light curve
F. The spectra of the afterglow

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 section F.1), 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., 2002; Preece et al., 1998) 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.

F.1. The luminosity in fixed energy bands

Here the fundamental new assumption is adopted (see also Ruffini et al., 2004b) that the X and gamma ray radiation during the entire afterglow phase has a thermal spectrum in the comoving frame. The temperature is then given by:

\[ T_s = \left( \frac{\Delta E_{\text{int}}}{4\pi r^2 \Delta \tau \sigma R} \right)^{1/4}, \]  

(F.1.1)

where \( \Delta E_{\text{int}} \) is the internal energy developed in the collision with the CBM in a time interval \( \Delta \tau \) in the co-moving frame, \( \sigma \) is the Stefan-Boltzmann constant and

\[ R = \frac{A_{\text{eff}}}{A_{\text{vis}}}, \]  

(F.1.2)

is the ratio between the “effective emitting area” of the ABM pulse of radius \( r \) and its total visible area, which accounts for the CBM filamentary structure (Ruffini et al., 2005c). Due to the CBM inhomogeneities the ABM emitting region is in fact far from being homogeneous. In GRB 991216 such a factor is observed to be decreasing during the afterglow between: \( 3.01 \times 10^{-8} \geq R \geq \)
F. The spectra of the afterglow

Figure F.1.: 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 Fig. E.1. The green line corresponds to an homogeneous distribution with $n_{cbm} = 1$. Details in Ruffini et al. (2005c).

5.01 $\times 10^{-12}$ (Ruffini et al., 2004b).

The temperature in the comoving frame corresponding to the density distribution described in Ruffini et al. (2002a) is shown in Fig. F.1.

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., 2003, 2004b):

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

where $\Delta \epsilon = \Delta E_{int}/V$ is the energy density released in the interaction of the ABM pulse with the CBM 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., 2005c) and $T_{arr}$ is
The observed temperature of the radiation emitted from \( d\Sigma \):

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

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 \( aT_{\text{arr}}^4 \):

\[
W(\nu_1, \nu_2, T_{\text{arr}}) = \frac{1}{aT_{\text{arr}}^4} \int_{\nu_1}^{\nu_2} \rho(T_{\text{arr}}, \nu) \frac{(h\nu)^3}{c},
\]

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

\[
\rho(T_{\text{arr}}, \nu) = \left( \frac{2}{h^3} \right) \frac{h\nu}{e^{h\nu/(kT_{\text{arr}})} - 1}
\]

**F.2. The time integrated spectra and the hard-to-soft 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., 2000; Ghirlanda et al., 2002; Piran, 1999; Piro et al., 1999]). We consider the instantaneous spectral distribution of the observed radiation for three different EQTSs:

- \( t_{\text{d}}^{\text{a}} = 10 \) s, in the early radiation phase near the peak of the luminosity,
- \( t_{\text{d}}^{\text{a}} = 1.45 \times 10^5 \) s, in the last observation of the afterglow by the Chandra satellite, and
- \( t_{\text{d}}^{\text{a}} = 10^4 \) s, chosen in between the other two (see Fig. [F.2]).

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”
Figure F.2.: The instantaneous spectra of the radiation observed in GRB 991216 at three different EQTS respectively, from top to bottom, for $t_d^a = 10$ s, $t_d^a = 10^4$ s and $t_d^a = 1.45 \times 10^5$ s. These diagrams have been computed assuming a constant $\langle n_{cbm} \rangle \simeq 1$ particle/cm$^3$ and clearly explain the often quoted hard-to-soft spectral evolution in GRBs. Details in [Ruffini et al. (2004b)].
F.3. Evidence for isotropic emission in GRB991216

We give in Fig. F.4 the results of the fit of the GRB 991216 light curves in the two energy bands 50–300 keV (observed by BATSE) and 2–10 keV (observed by R-XTE and Chandra). We already pointed out in the previous section the agreement with the data of the “prompt” radiation obtained by BATSE in the energy range 50–300 keV (see blue line in Fig. F.4). We here show 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 red line in Fig. F.4). These data refer to the decaying part of the afterglow and cover a time span of \( \sim 10^6 \) s.
Figure F.4.: Above: Best fit of the afterglow data of GRB 991216. The blue line is the luminosity in the 50–300 keV energy band. The red line is the luminosity in the 2–10 keV band computed assuming spherical symmetry. The observational data from R-XTE and Chandra (see Halpern et al., 2000) are perfectly consistent with such an assumption. The presence of a $\theta_0 = 3^\circ$ half-opening beaming angle (green line) is ruled out. Below: Enlargement of the plot in the region of the afterglow observational data from R-XTE and Chandra.
We have also computed, within our global self-consistent approach which fits both the “prompt” radiation and the decaying part of the afterglow, the flux in the 2–10 keV range which would be expected for a beamed emission with half opening angle $\theta_o = 3^\circ$, which is the value claimed in the current literature for GRB 991216 (see Halpern et al., 2000 and Fig. F.4). The presence of beaming is manifest, as expected, in the decaying part of the afterglow and is incompatible with the data. In fact, the actual afterglow luminosity in fixed energy bands, in spherical symmetry, does not have a simple power law dependence on arrival time (see Fig. F.4). 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 approximate equations (see the following report about “Relativistic effects in Physics and Astrophysics” and Bianco and Ruffini, 2004, 2005b, a, 2006). 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 Fig. F.4 and Ruffini et al., 2006c).
F. The spectra of the afterglow
G. On the GRB-SN association

Models of GRBs based on a single source (the “collapsar”) generating both the SN and the GRB abounds in the literature (see e.g. Woosley and Bloom, 2006). Since the two phenomena are qualitatively very different, in our approach we have emphasized the concept of induced gravitational collapse, which occurs strictly in a binary system. The SN originates from a star evolved out of the main sequence and the GRB from the collapse to a black hole. The concept of induced collapse implies at least two alternative scenarios. In the first, the GRB triggers a SN explosion in the very last phase of the thermonuclear evolution of a companion star (Ruffini et al., 2001a). In the second, the early phases of the SN induce gravitational collapse of a companion neutron star to a black hole (Ruffini, 2006). Of course, in absence of SN, there is also the possibility that the collapse to a black hole, generating the GRB, occurs in a single star system or in the final collapse of a binary neutron star system. Still, in such a case there is also the possibility that the black hole progenitor is represented by a binary system composed by a white dwarf and/or a neutron star and/or a black hole in various combinations. What is most remarkable is that, following the “uniqueness of the black hole” (see Ruffini, in pressb), all these collapses lead to a common GRB independently of the nature of their progenitors.

Having obtained success in the fit of GRB 991216, as well as of GRB 031203 and GRB 050315 (see sections I and J), we turn to the application of our theoretical analysis to the GRBs associated with SNe. We start with GRB 980425 / SN 1998bw. We have however to caution about the validity of this fit. From the available data of BeppoSAX, BATSE, XMM and Chandra, only the data of the prompt emission ($t_d < 10^2$ s) and of the latest afterglow phases ($t_d > 10^5$ s all the way to more than $10^8$ s!) were available. Our fit refers only to the prompt emission, as usually interpreted as the peak of the afterglow. The fit, therefore, represents an underestimate of the GRB 980425 total energy and in this sense it is not surprising that it does not fit the Amati et al. (2002) relation. The latest afterglow emission, the URCA-1 emission, presents a different problematic which we will shortly address (see below).

G.1. GRB 980425 / SN 1998bw / URCA-1

The best fit of the observational data of GRB 980425 (Pian et al., 2000; Frontera et al., 2000) leads to $E_{\text{tot}} = 1.2 \times 10^{48}$ erg and $B = 7.7 \times 10^{-3}$. This implies
Figure G.1.: Theoretical light curves of GRB 980425 prompt emission in the 40–700 keV and 2–26 keV energy bands (red line), compared with the observed data respectively from Beppo-SAX GRBM and WFC (see [Pian et al. 2000; Frontera et al. 2000]).
Figure G.2.: Theoretical light curves of GRB 980425 in the 40–700 keV (red line), 2–26 keV (green line), 2–10 keV (blue line) energy bands, represented together with URCA-1 observational data. All observations are by BeppoSAX (Pian et al., 2000), with the exception of the last two URCA-1 points, which is observed by XMM and Chandra (Pian et al., 2004; Kouveliotou et al., 2004).
G. On the GRB-SN association

an initial $e^\pm$ plasma with $N_{e^+e^-} = 3.6 \times 10^{53}$ 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 variability of the luminosity, due to the inhomogeneities of the CBM, is characterized by a density contrast $\delta n/n \sim 10^{-1}$ on a length scale of $\Delta \sim 10^{14}$ cm. We determine the effective CBM parameters to be: $\langle n_{cbm} \rangle = 2.5 \times 10^{-2}$ particle/cm$^3$ and $\langle R \rangle = 1.2 \times 10^{-8}$.

In Fig. G.1 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 the first 60 s of data (see Pian et al., 2000; Frontera et al., 2000). The agreement between observations and theoretical predictions in Fig. G.1 is very satisfactory.

In Fig. G.2 we summarize some of the problematic implicit in the old pre-Swift era: data are missing in the crucial time interval between 60 s and $10^5$ s, when the BeppoSAX NFI starts to point the GRB 980425 location. In this region we have assumed, for the effective CBM parameters, constant values inferred by the last observational data. Currently we are relaxing this condition, also in view of the interesting paper by Ghisellini et al. (2006).

The follow-up of GRB980425 with BeppoSAX NFI 10 hours, one week and 6 months after the event revealed the presence of an X-ray source consistent with SN1998bw (Pian et al., 2000), confirmed also by observations by XMM (Pian et al., 2004) and Chandra (Kouveliotou et al., 2004). The S1 X-ray light curve shows a decay much slower than usual X-ray GRB afterglows (Pian et al., 2000). We then address to this peculiar X-ray emission as “URCA-1” (see section B.3 and the following sections). In Fig. G.3A we represent the URCA-1 observations (Pian et al., 2000, 2004; Kouveliotou et al., 2004). The separation between the light curves of GRB 980425 in the 2–700 keV energy band, of SN 1998bw in the optical band (Nomoto et al., 2007; Pian et al., 2006), and of the above mentioned URCA-1 observations is evident.

G.2. GRB 030329 / SN 2003dh / URCA-2

For GRB 030329 we have obtained (see Bernardini et al., 2004, 2005b, Ruffini et al., in press) a total energy $E_{tot}^e = 2.12 \times 10^{52}$ erg and a baryon loading $B = 4.8 \times 10^{-3}$. This implies an initial $e^\pm$ plasma with $N_{e^+e^-} = 1.1 \times 10^{57}$ and with an initial temperature $T = 2.1$ MeV. After the transparency point, the initial Lorentz gamma factor of the accelerated baryons is $\gamma_0 = 206$. The effective CBM parameters are $\langle n_{cbm} \rangle = 2.0$ particle/cm$^3$ and $\langle R \rangle = 2.8 \times 10^{-9}$, with a density contrast $\delta n/n \sim 10$ on a length scale of $\Delta \sim 10^{14}$ cm. The resulting fit of the observations, both of the prompt phase and of the afterglow have been presented in Bernardini et al. (2004, 2005b). We compare in Fig. G.3B the light curves of GRB 030329 in the 2–400 keV energy band, of SN 2003dh in the optical band (Nomoto et al., 2007; Pian et al., 2006) and of the possible
Table G.1.: a) see Kaneko et al. (2007); b) Mazzali, P., private communication at MG11 meeting in Berlin, July 2006; c) evaluated fitting the URCA-s with a power law followed by an exponentially decaying part; d) evaluated assuming a mass of the neutron star $M = 1.5 M_\odot$ and $T \sim 5–7$ keV in the source rest frame; e) see Galama et al. (1998); Greiner et al. (2003); Prochaska et al. (2004); Mirabal et al. (2006).

![Table G.1:](image)

**G.3. GRB 031203 / SN 2003lw / URCA-3**

We will show in section I the detailed analysis of GRB 031203 which leads to a total energy $E_{\text{tot}}^e = 1.85 \times 10^{50}$ erg and to a baryon loading $B = 7.4 \times 10^{-3}$. This implies an initial $e^\pm$ plasma with $N_{e^+e^-} = 3.0 \times 10^{55}$ and with an initial temperature $T = 1.5$ MeV. After the transparency point, the initial Lorentz gamma factor of the accelerated baryons is $\gamma_\circ = 132$. The effective CBM parameters are $\langle n_{\text{cbm}} \rangle = 1.6 \times 10^{-1}$ particle/cm$^3$ and $\langle R \rangle = 3.7 \times 10^{-9}$, with a density contrast $\delta n/n \sim 10$ on a length scale of $\Delta \sim 10^{15}$ cm. In Fig. G.3C we compare the light curves of GRB 031203 in the 2–200 keV energy band, of SN 2003lw in the optical band (Nomoto et al., 2007; Pian et al., 2006) and of the possible URCA-3 emission observed by XMM-EPIC in the 0.2–10 keV energy band (Watson et al., 2004) and by Chandra in the 2–10 keV energy band (Soderberg et al., 2004).

**G.4. The GRB / SN / URCA connection**

In Tab. G.1 we summarize the representative parameters of the above three GRB-SN systems together with GRB 060218-SN 2006aj which will be presented in section I, including the very large kinetic energy observed in all SNe (Mazzali, 2006). Some general conclusions on these weak GRBs at low redshift, associated to SN 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 above GRB sources 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...
**Figure G.3.** Theoretically computed light curves of GRB 980425 in the 2–700 keV band (A), of GRB 030329 in the 2–400 keV band (B) and of GRB 031203 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 SNe in the 3000 – 24000 Å are also represented (Nomoto et al., 2007; Pian et al., 2006).
G.5. URCA-1, URCA-2 and URCA-3

now spans over a range of energy of six orders of magnitude from $10^{48}$ to $10^{54}$ ergs [Ruffini et al., 2003, 2004a, in press; Bernardini et al., 2004, 2005b, a; Ruffini et al., 2006b]. Distinctive of this class is the very high value of the baryon loading which in one case (GRB 060218, see section L and Dainotti et al., 2007) is very close to the maximum limit compatible with the dynamical stability of the adiabatic optically thick acceleration phase of the GRBs (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 so-called “prompt phase”. The only exception to this is the case of GRB 030329.

2) The accurate fits of the GRBs allow us to infer also some general properties of the CBM. While the size of the clumps of the inhomogeneities is $\Delta \approx 10^{14}$ cm, the effective CBM average density is consistently smaller than in the case of more energetic GRBs: we have in fact $\langle n_{cbm} \rangle$ in the range between $\sim 10^{-6}$ particle/cm$^3$ (GRB 060218) and $\sim 10^{-1}$ particle/cm$^3$ (GRB 031203), while only in the case of GRB 030329 it is $\sim 2$ particle/cm$^3$. We are also currently studying a characteristic trend in the variability of $R$ during some specific bursts as well as the physical origin of the consistently smaller effective CBM density $\langle n_{cbm} \rangle$ values observed in these sources (see Dainotti et al., 2007).

3) Still within their weakness these four GRB sources present a large variability in their total energy: a factor $10^4$ between GRB 980425 and GRB 030329. Remarkably, the SNe 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 URCA sources present also a remarkably steady behavior around a “standard luminosity” and a typical temporal evolution. The weakness in the energetics of GRB 980425 and GRB 031203, and the sizes of their dyadospheres, suggest that they originate from the formation of the smallest possible black hole, just over the critical mass of the neutron star (see Fig. B.9 and Ruffini, 2006).

G.5. URCA-1, URCA-2 and URCA-3

We turn to the search for the nature of URCA-1, URCA-2 and URCA-3. These systems are not yet understood and may have an important role in the comprehension of the astrophysical scenario of GRB sources. It is important to perform additional observations in order to verify if the URCA sources are related to the black hole originating the GRB phenomenon or to the SN. Even a single observation of an URCA source with a GRB in absence of a SN would prove their relation with the black hole formation. Such a result is today theoretically unexpected and would open new problematics in relativistic astrophysics and in the physics of black holes. Alternatively, even a single observation of an URCA source during the early expansion phase of a Type Ib/c
SN in absence of a GRB would prove the early expansion phases of the SN remnants. In the case that none of such two conditions are fulfilled, then the URCA sources must be related to the GRBs occurring in presence of a SN. In such a case, one of the possibilities would be that for the first time we are observing a newly born neutron star out of the supernova phenomenon unveiled by the GRB. This last possibility would offer new fundamental information about the outcome of the gravitational collapse, and especially about the equations of state at supranuclear densities and about a variety of fundamental issues of relativistic astrophysics of neutron stars.

The names of “URCA-1” and “URCA-2” for the peculiar late X-ray emission of GRB 980425 and GRB 030329 were given in the occasion of the Tenth Marcel Grossmann meeting held in Rio de Janeiro (Brazil) in the Village of Urca (see Ruffini et al., 2005b). Their identification was made at that time and presented at that meeting. However, there are additional reasons for the choice of these names. Another important physical phenomenon was indeed introduced in 1941 in the same Village of Urca by George Gamow and Mario Schoenberg (see Gamow and Schoenberg, 1941). 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 there considered for the first time. It was Gamow who named this cooling as “Urca process” (see Gamow, 1970). Since then, a systematic analysis of the theory of neutron star cooling was advanced by Tsuruta (1964, 1979); Tsuruta and Cameron (1966); Tsuruta et al. (2002); Canuto (1978). 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, 1987). 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, 1987). 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, 1987). Some important contributions in this researches have been presented by van Riper (1988, 1991); Burrows and Lattimer (1986); Lattimer et al. (1994); Yakovlev and Pethick (2004). The youngest neutron star to be searched for thermal emission has been the pulsar PSR J0205+6449 in 3C 58 (see e.g. Yakovlev and Pethick, 2004), which is 820 years old! Trümper (2005) reported evidence for the detection of thermal emission from the crab nebula pulsar which is, again, 951 years old.

URCA-1, URCA-2 and URCA-3 may explore a totally different regime: the X-ray emission possibly from a recently born neutron star in the first days —
months of its existence. The thermal emission from the young neutron star surface would in principle 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 with the related neutrino emission. It is also possible that the neutron star is initially fast rotating and its early emission could be dominated by the magnetospheric emission or by accretion processes from the remnant which would overshadow the thermal emission. A periodic signal related to the neutron star rotational period should in principle be observable in a close enough GRB-SN system. In order to attract attention to this problematic, we have given in Tab. G.1 an estimate of the corresponding neutron star radius for URCA-1, URCA-2 and URCA-3. It has been pointed out (see e.g., Pian et al., 2000) the different spectral properties between the GRBs and the URCA. It would be also interesting to compare and contrast the spectra of all URCA in order to evidence any analogy among them. Observations of a powerful URCA source on time scales of 0.1–10 seconds would be highly desirable.
G. On the GRB-SN association
Theoretical background for GRBs’ empirical correlations

The possibility to detect GRBs up to very high redshifts (up to $z = 6.29$, Kawai et al., 2005; Antonelli et al., 2005) makes it tempting to try to use them as standard candles to constrain the cosmological parameters, similarly to SNe Ia. The problem is that GRBs appear to be anything but standard candles because they have a very wide range of isotropic equivalent luminosities and energy outputs. While there is good motivation for such cosmological applications of GRBs, there are many practical difficulties. Several correlations between various properties of the prompt emission (Amati, 2006; Ghirlanda et al., 2004; Firmani et al., 2006; Yonetoku et al., 2004), and in some cases also of the afterglow emission (Liang and Zhang, 2005), have been found up to date, that can be useful to calibrate GRBs as better standard candles. There is no good sample of nearby ($z \ll 1$) GRBs that can be used in order to calibrate these correlations. Furthermore the few known nearby events appear to be intrinsically very different from events at higher redshifts (Liang et al., 2007). It could exist a significant evolution of the intrinsic properties of GRBs with redshift (also between intermediate and high redshifts) which could be hard to disentangle from cosmological effects (Liang et al., 2007).

Beyond their cosmological use, all these correlations, if firmly established, could give very important hints on the physics of GRBs.

Starting from these phenomenological spectral-energy relations existing in literature, we tried to find similar results within the fireshell model, which is very important, both for cosmology and for the physics of GRBs.

Due to the lack of low redshift GRBs, all the observational results existing up to now have been obtained from high redshift GRBs, with the consequence that they depend on the cosmological parameters they pretend to constrain. This is well known as the circularity problem (Firmani et al., 2005): hopefully it will be solved if the low redshift GRB sample is increased enough. Currently, the only way to avoid this circular logic is to find a theoretical model that could account for some of these correlations naturally.

In this chapter we will show the existence of a spectral-energy correlation within our fireshell model. The two physical quantities peculiar of the model that will result correlated are the total energy of the initial electron-positron plasma $E_{e^+e^-}^{tot}$, and the $\nu F_\nu$ total time integrated spectrum observed peak energy $E_{p,\nu}^{tot}$. In the following we will motivate the choice of these quantities, and we will point out in which way they are calculated.
H. Theoretical background for GRBs’ empirical correlations

Beyond the importance for cosmology, the existence of a correlation between peculiar physical quantities is a strong indication of the self-consistence of the theoretical model.

H.1. Spectral-energy correlations

Many empirical spectral-energy correlations exist, some are purely phenomenological and assumption free while others are based on assumptions and are dependent on model, basically the standard fireball model (Piran, 1999). Some correlations assume spherical symmetry while others assume collimated (jet) emission. This last case was triggered by the observation by Frail et al. (2001) that the collimation corrected energetics of those GRBs of known jet aperture angles clustered into a narrow distribution, $E_\gamma = (1 - \cos \theta_j) E_{iso} \sim 10^{51}$ erg.

The opening angle of the jet is estimated within the standard model as

$$\theta_j = 0.161 \left( \frac{t_{jet,d}}{1+z} \right)^{3/8} \left( \frac{n \eta_{\gamma}}{E_{iso,52}} \right)^{1/8}; \ H$$

$$\theta_j = 0.2016 \left( \frac{t_{jet,d}}{1+z} \right)^{1/4} \left( \frac{\eta_{\gamma} A_*}{E_{iso,52}} \right)^{1/4}; \ W \quad (H.1.1)$$

where $t_{jet,d}$ is the break time measured in days and $z$ is the redshift. The efficiency $\eta_{\gamma}$ relates the isotropic kinetic energy of the fireball $E_{k,iso}$ to the prompt emitted energy $E_{iso}$: $E_{k,iso} = E_{iso}/\eta_{\gamma}$. Usually, it is assumed a constant value for all bursts, i.e. $\eta_{\gamma} = 0.2$ (after its first use by Frail et al. (2001), following the estimate of this parameter in GRB970508 Frail et al. (2000)). In the homogeneous (H) case, $n$ is the CircumBurst density, independent from the radial coordinate; for the wind (W) case, the density is a function of the radial coordinate, $n(r) = A r^{-2}$ and $A_*$ is the value of $A (A = \dot{M}_w/(4\pi v_w) = 5 \times 10^{11} A_* \ g \ cm^{-1})$ when setting the wind mass loss rate to $\dot{M}_w = 10^{-5} M_\odot yr^{-1}$ and the wind velocity to $v_w = 10^3 \ km \ s^{-1}$. Usually, a constant value (i.e. $A_* = 1$) is adopted for all bursts.

The most important spectral-energy correlations are:

- **The Amati relation**: It was historically the first correlation discovered, considering *BeppoSAX* bursts (Amati et al., 2002). It was found that the isotropic-equivalent radiated energy of the prompt emission $E_{iso}$ is correlated with the cosmological rest-frame $\nu F_\nu$ spectrum peak energy $E_{p,i}$: $E_{p,i} \propto E_{iso}^{0.5}$. This correlation, recently updated (Amati, 2006) to a larger sample, holds for all but two long bursts, while no short burst satisfies it. The long burst outliers are GRB980425 and the debated GRB031203 (Watson et al., 2006b). As far as short bursts are concerned, there are two cases: the burst with an initial spike-like emission followed by a
H.2. The Amati-like correlation in the fireshell model

A correlation similar to the Amati one exists between peculiar physical quantities of the fireshell model; the model assumes spherical symmetry so nor
jet angle $\theta_j$ nor any quantities related to it are defined. Furthermore, there is clearly no way to distinguish the prompt from the rest of the GRB emission because the afterglow phase encompass the prompt emission as well. In particular, within our “canonical” GRB scenario the P-GRB plus the afterglow peak emission contribute to the prompt emission. In the Amati relation instead the two quantities correlated concerns only the prompt phase.

In order to be consistent with our model, we considered only our afterglow phase, because the P-GRB is a sharply physically different component and it has no sense to try to find a correlation between the spectrum and the total energy of something that is a mixing of them as the prompt emission. Furthermore, the observations that the initial spikelike emission, which we identify with the P-GRBs, as well as all the “genuine” short GRBs (always identified with P-GRBs within our model) do not fulfill the Amati relation (Amati, 2006, 2007) is a confirmation of the validity of this idea.

The two physical quantities correlated are the total energy of the initial plasma $E_{\text{tot}}^{\pm}$, and the $\nu F_{\nu}$ total time integrated observed spectrum peak energy $E_{p,\text{tot}}$. It is important to stress the fact that the spectrum is calculated integrating over the total duration of the afterglow phase, that is, from the end of the P-GRB up to when the fireshell stops.

The sample we constructed for the correlation is a sample of pseudo-GRBs with the total $E_{\text{tot}}^{\pm}$ energy ranging from $10^{51}$ to $10^{54}$ erg. We theoretically simulated the spectra and the light curves of these sources keeping the same $B$ parameter that we use to fit GRB050315 (detailed discussion on the analysis of GRB 050315 is presented in section J), $B = 4.55 \times 10^{-3}$. In fact, this is a typical value for a “normal” long GRB. The parametrization that we use to describe the distribution of the CBM for the pseudo-GRBs of the sample also is the same that we use to fit GRB050315 (see sec. J.1). This is evidently an approximation, that resemble the approximation used in the Ghirlanda correlation: in the calculation of the aperture angle of the jet $\theta_j$, the same efficiency $n_\gamma$ and the same value of CircumBurst density and profile are assumed for all burst, taking the value estimated in GRB970508 (Frail et al., 2001).

Clearly the light curves we simulated don’t fit any GRB, and for this reason we call this a sample of pseudo-GRBs.

Fig. H.1 shows the result of the correlation. As already said before, in the x axis is the total energy of the $e^{\pm}$ pairs plasma $E_{\text{tot}}^{\pm}$ while on the y axis is the $\nu F_{\nu}$ total time integrated observed spectrum observed peak energy $E_{p,\text{tot}}$. As already pointed out above, it is important to stress the fact that the spectrum is calculated integrating the light curves from the beginning of the afterglow (this instant of time coincide with the end of the P-GRB emission) up to the end of the simulated light curve, that is when the fireshell stops at gamma Lorentz factor close to 1.

The correlation is quite good, with the same slope of the Amati relation, within the error on the peak energy $E_{p,\text{tot}}$. The total energy of the $e^{\pm}$ pairs plasma is imposed, so clearly there is no error in this variable, instead the
H.2. The Amati-like correlation in the fireshell model

Figure H.1.: The $\nu F_{\nu}$ total time integrated spectrum observed peak energy (red points) for the sample of pseudo-GRBs with different total energy of the $e^\pm$ pairs plasma. The total energy $E_{\text{tot}}^{e\pm}$ range from $10^{51}$ to $10^{53}$. The black line represent a power law with the same slope of the Amati relation, and fit perfectly the points.
peak energy $E_{p,tot}$ is calculated every time by the simulation; because of the numerical analysis, the spectrum is not a continuous function but a discrete one, so it is difficult to define an error on the maximum value $E_{p,tot}$. Choosing, conservatively, the 10% as the error, we checked, looking at each spectrum, that this value is reasonable. Fig. [H.2] shows one of these spectra, the one of the pseudo-GRB with total energy $E_{tot} = 3.40 \times 10^{51}$ erg; In the plot, it is clearly indicated the error on the maximum energy as the zone in which we can assume that every points of the curve has horizontal tangent.

The correlation extends from $10^{51}$ to $10^{53}$, and the best fit function has the same slope of the Amati relation, $E_{p,i} \propto E_{iso}^{0.5}$. The normalization is clearly different from the Amati one, but this is also due to the fact that we did not rescale the peak energy for the cosmological redshift, because our sample is made by objects at the same redshift; in order to calculate the intrinsic (rest frame) peak energy, the factor $(1+z)$ has to be taken into account.
H.3. Conclusion

We have used the effective CircumBurst medium structure derived for GRB 050315 in simulating a “gedanken” family of GRBs, ranging in total energy of the $e^\pm$ plasma from $10^{51}$ to $10^{54}$ erg. This family is indeed endowed with the same effective CBM density profile, with the same value of the baryon loading $B$ but with significantly different energetics.

We found for this “gedanken” family of processes a correlation between the $\nu F_\nu$ total time integrated observed spectrum peak energy $E_{p,tot}$ and the initial total energy of the $e^\pm$ plasma $E_{e^\pm,tot}$: $E_{p,tot} \propto (E_{e^\pm,tot})^{0.5}$.

This resembles the well known Amati relation, between the isotropic-equivalent radiated energy of the prompt emission $E_{iso}$ and the cosmological rest-frame prompt $\nu F_\nu$ spectrum peak energy $E_{p,i}$: $E_{p,i} \propto E_{iso}^{0.5}$.

This result was obtained without considering the P-GRB in the spectral computation, according to our “canonical” GRB scenario.
H. Theoretical background for GRBs’ empirical correlations
I. Application to GRB 031203

GRB 031203 was observed by IBIS, on board of the INTEGRAL satellite (see Mereghetti and Gotz, 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 et al., 2004a), with a simple profile and a duration of \( \approx 40 \) s. The burst fluence in the 20 – 200 keV band is \((2.0 \pm 0.4) \times 10^{-6}\) erg/cm\(^2\) (Sazonov et al., 2004a), 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., 2004a, in press), 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. We reproduce correctly the observed time variability of the prompt emission (see Fig. I.1 and Bernardini et al., 2005a). The radiation produced by the interaction of the optically thin fireshell with the CBM agrees with observations both for intensity and time structure.

The progress in reproducing the X and \( \gamma \)-ray emission as originating from a thermal spectrum in the comoving frame of the burst (Ruffini et al., 2004b) leads to the characterization of the instantaneous spectral properties which are shown to drift from hard to soft during the evolution of the system (see section F.2). The convolution of these instantaneous spectra over the observational time scale is in very good agreement with the observed power-law spectral shape.

I.1. The initial conditions

The best fit of the observational data leads to a total energy of the electron-positron plasma \( E_{\text{tot}}^\gamma = 1.85 \times 10^{50} \) erg. Assuming a black hole mass \( M = 10M_\odot \), we then have a black hole charge to mass ratio \( \xi = 6.8 \times 10^{-3} \); the plasma is created between the radii \( r_1 = 2.95 \times 10^6 \) cm and \( r_2 = 2.81 \times 10^7 \) cm with an initial temperature \( T = 1.52 \) MeV and a total number of pairs \( N_{e\pm} = 2.98 \times 10^{55} \). 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 is \( \gamma_0 = 132.8 \) at an arrival time at
the detector $t_d = 8.14 \times 10^{-3}$ s and a distance from the Black Hole $r = 6.02 \times 10^{12}$ cm. The CBM parameters are: $< n_{cbm} > = 0.3$ particle/cm$^3$ and $< R > = 7.81 \times 10^{-9}$.

I.2. 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/integrated spectra. We recall that the luminosity in selected energy bands is evaluated integrating over the EQTSs (see Ruffini et al., 2004b, and section F.1) the energy density released in the interaction of the accelerated baryons with the CBM measured in the co-moving 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 CBM with the front of the expanding baryonic shell.

In order to evaluate the contributions in the band $[\nu_1, \nu_2]$ we have to multiply the bolometric luminosity with an “effective weight” $W(\nu_1, \nu_2, T_{arr})$, where $T_{arr}$ is the observed temperature. $W(\nu_1, \nu_2, T_{arr})$ is given by the ratio of the integral over the given energy band of a Planckian distribution at temperature $T_{arr}$ to the total integral $aT_{arr}^4$ (Ruffini et al., 2004b). The resulting expression for the emitted luminosity is Eq.(F.1.3).

I.3. The “prompt emission”

In order to compare our theoretical prediction with the observations, it is important to notice 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 $\Delta t_d = 3.5$ s (see the bold red line in Fig. I.1). In what follows, the detector arrival time is referred 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 CBM which has not a constant density but presents several density spikes with $< n_{cbm} > = 0.16$ particle/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 $\Delta = 1.0 \times 10^{15}$ cm and $\Delta n/n = 1.5$ and for the third one $\Delta = 7.0 \times 10^{14}$ cm and $\Delta n/n = 1$. To describe the details of the CBM filamentary structure
Figure I.1.: Theoretically simulated light curve of the GRB 031203 prompt emission in the 20 – 200 keV energy band (solid red line) is compared with the observed data (green points) from Sazonov et al. (2004a). The vertical bold red line indicates the time position of P-GRB.
Figure I.2.: Five different theoretically predicted instantaneous photon number spectrum $N(E)$ for $t_d = 2, 6, 10, 14, 18$ 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).

we would require an intensity vs. 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 $10^{15}$ 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. I.1) shows a good agreement with the light curve reported by Sazonov et al. (2004a), and it provides a further evidence for the possibility of reproducing light curves with a complex time variability through CBM inhomogeneities (Ruffini et al., 2002a, 2003, 2005a).
I.4. The instantaneous spectrum

As outlined in section F.2, in addition to the the luminosity in fixed energy bands we can derive also the instantaneous photon number spectrum $N(E)$. In Fig. I.2 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 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. (2004b) and in section F.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. I.2).

Another distinguishing feature of the GRBs spectra which is also present in these instantaneous spectra, as shown in Fig. I.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 peak of the energy distributions $E_p$ drift monotonically to softer frequencies with time (see Fig. I.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 ($t_d = 2$ s) is $\alpha = 0.75$, and progressively decreases for later times (see Fig. I.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 not sufficient quality of the data (poor photon statistics, see Sazonov et al., 2004a).

I.5. The time-integrated spectrum: comparison with the observed data

The time-integrated observed GRB spectra show a clear power-law behavior. Within a different framework Shakura, Sunyaev and Zel’dovich (see e.g. Pozdniakov 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) 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 section F.2, the instantaneous spectrum here is not a black body. Each instantaneous spectrum is
Figure I.3.: 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.
I.5. The time-integrated spectrum vs. the observed data

Figure I.4.: Three theoretically predicted time-integrated photon number spectra $N(E)$ are here represented for $0 \leq t_{da}^d \leq 5$ s, $5 \leq t_{da}^d \leq 10$ s and $10 \leq t_{da}^d \leq 20$ s (colored curves). The hard to soft behavior presented in Fig. I.3 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 (green points, see Sazonov et al., 2004a,b). This curve is obtained as a convolution of 108 instantaneous spectra, which are enough to get a good agreement with the observed data.

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 time-integrated spectra are not plain convolutions of thermal spectra: they are convolutions of convolutions of thermal spectra (see Fig. I.2).

The simple power-law shape of the integrated spectrum is more evident if we sum tens of instantaneous spectra, as in Fig. I.4. 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
I. Application to GRB 031203

duration of the prompt event (see again Fig. 1.4); in this way we obtain a typical non-thermal power-law spectrum which results to be in good agreement with the INTEGRAL data (see Sazonov et al., 2004a,b) and gives a clear evidence of the possibility that the observed GRBs spectra are originated from a thermal emission.

The precise knowledge we have here acquired on GRB 031203 helps in clarifying the overall astrophysical system GRB 031203 - SN 2003lw - the 2 – 10 keV XMM and Chandra data (see sections G.3 and G.5 where the late 2 – 10 keV XMM and Chandra data are also discussed).
J. Application to GRB 050315

GRB 050315 (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 2005-March-15 20:59:42 UT (Parsons et al., 2005). The narrow field instrument XRT (Burrows et al., 2004, 2005) began observations ∼80 s after the BAT trigger, one of the earliest XRT observations yet made, and continued to detect the source for ∼10 days (Vaughan et al., 2006). The spectroscopic redshift has been found to be $z = 1.949$ (Kelson and Berger, 2005).

We present here the results of the fit of the Swift data of this source in 5 energy bands in the framework of our theoretical model, pointing out a new step toward the uniqueness of the explanation of the overall GRB structure. We first recall the essential features of our theoretical model; then we fit the GRB 050315 observations by both the BAT and XRT instruments; we also 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 $3.0 \times 10^4$ s (i.e. the latest afterglow phases).

J.1. The fit of the observations

The best fit of the observational data leads to a total energy of the black hole dyadosphere, generating the $e^\pm$ plasma, $E_{\text{tot}}^{e\pm} = 1.46 \times 10^{53}$ erg (the observational Swift $E_{\text{iso}}^{e\pm}$ is $>2.62 \times 10^{52}$ erg, see Vaughan et al., 2006), so that the plasma is created between the radii $r_1 = 5.88 \times 10^9$ cm and $r_2 = 1.74 \times 10^8$ cm with an initial temperature $T = 2.05 MeV$ and a total number of pairs $N_{e^+e^-} = 7.93 \times 10^{57}$. The second parameter of the theory, the amount $M_B$ of baryonic matter in the plasma, is found to be such that $B \equiv M_Bc^2/E_{\text{dy}} = 4.55 \times 10^{-3}$. 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 $r = 1.32 \times 10^{14}$ cm from the black hole.

J.1.1. The BAT data

In Fig. J.1. 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.
Figure J.1.: Our theoretical fit (red line) of the BAT observations (green points) of GRB 050315 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.
J.1. The fit of the observations

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 noise 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 of GRB 050315 it has been observed (see Vaughan et al., 2006) a possible precursor before the trigger. Such a precursor is indeed in agreement with our theoretically predicted P-GRB, both in its isotropic energy emitted (which we theoretically predict to be $E_{P-GRB} = 1.98 \times 10^{51}$ erg) and its temporal separation from the peak of the afterglow (which we theoretically predicted to be $\Delta t_a^d = 51$ s). In Fig. J.1, 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. 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 CBM 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 $A_{eff}$ determined by the dimensionless parameter $R$ (see previous sections and Ruffini et al., 2004b, 2005c, for details). Clearly, in order to describe any detailed structure of the time variability an authentic three dimensional representation of the CBM 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 visible area due to the relativistic beaming makes such a spherical approximation an excellent one (see also for details Ruffini et al., 2002a).

The structure of the “prompt emission” has been reproduced assuming three overdense spherical CBM 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 CBM mean density during this phase is $\langle n_{cbm} \rangle = 0.81$ 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. J.1. 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 three-dimensional treatment of the CBM filamentary structure. Such a topic is currently under investigation (see also for details Ruffini et al., 2002a). Fig. J.1 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.
Figure J.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. J.1a) in the 15–350 keV energy band is also represented (red line).

J.1.2. 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 (Meszaros, 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 CBM region, between \( r = 9.00 \times 10^{16} \) cm and \( r = 5.50 \times 10^{18} \) cm, which is significantly at lower density \( \langle n_{cbm} \rangle = 4.76 \times 10^{-4} \) 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 CBM. In Fig. J.2 is represented our theoretical fit of the XRT data, together with the theoretically computed 15–350 keV light curve of Fig. J.1a (without the BAT observational data to not overwhelm the picture too much).

What is impressive is that no different scenarios need to be advocated in order to explain the features of the light curves: both the prompt and the afterglow emission are just due to the thermal radiation in the comoving frame produced by inelastic collisions with the CBM duly boosted by the relativistic transformations over the EQTSs.

**J.2. The instantaneous spectrum**

In addition to the luminosity in fixed energy bands we can derive also the instantaneous photon number spectrum $N(E)$ starting from the same assumptions. In Fig. J.3 are shown samples of time-resolved spectra for eight 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 comoving frame of the expanding pulse is thermal, the shape of the final spec-
trum in the laboratory frame is clearly non thermal. In fact, as explained in Ruffini et al. (2004b), each single instantaneous spectrum is the result of an integration of thousands of thermal spectra over the corresponding EQTS. This calculation produces a non thermal instantaneous spectrum in the observer frame (see Fig. 1.3).

A distinguishing feature of the GRBs spectra which is also present in these instantaneous spectra 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 peak of the energy distribution $E_p$ 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), 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 in the nature of the spectrum during the prompt and 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.

### J.3. Problems with the definition of “long” GRBs

The confirmation by *Swift* of our prediction of the overall afterglow structure, and especially the coincidence of the “prompt emission” with the peak of the afterglow, opens a new problematic in the definition of the long GRBs. It is clear, in fact, that the identification of the “prompt emission” in the current GRB literature is not at all intrinsic to the phenomenon but is merely due to the threshold of the instruments used in the observations (e.g. BATSE in the 50–300 keV energy range, or BeppoSAX GRBM in 40–700 keV, or *Swift* BAT in 15–350 keV). As it is clear from Fig. 1.4, there is no natural way to identify in the source a special extension of the peak of the afterglow that is not the one purely defined by the experimental threshold. It is clear, therefore, that long GRBs, as defined till today, are just the peak of the afterglow and there is no way, as explained above, to define their “prompt emission” duration as a characteristic signature of the source. As the *Swift* observations show, the duration of the long GRBs has to coincide with the duration of the entire afterglow. A Kouveliotou - Tavani plot of the long GRBs, done following our interpretation which is clearly supported by the recent *Swift* data (see Fig. 1.4), will present enormous dispersion on the temporal axis.

We recall that in our theory both “short” and “long” GRBs originate from the same process of black hole formation. The major difference between the two is the value of the baryon loading parameter $B$ (see Fig. B.6). In the limit of small baryon loading, all the plasma energy is emitted at the transparency in the P-GRB, with negligible afterglow observed flux. For higher values of the baryon loading, the relative energy content of the P-GRB with respect to the afterglow diminishes (see Ruffini et al. 2005a, and references therein).
Figure J.4.: Same as Fig. J.2. The horizontal green lines corresponds to different possible instrumental thresholds. It is clear that long GRB durations are just functions of the observational threshold.
K. Application to GRB 011121

K.1. A widely debated issue: the interpretation of flares

A flare is a large scale activity in excess on the underlying light curve that manifests as a bump in luminosity rather intense and sharp in the decaying phase of the X-Ray afterglow.

When the first flare was detected by BeppoSAX, on the X-Ray light curve of GRB 011121, it was assumed as an extremely peculiar phenomenon. However, by the advent of the Swift Mission, many flares have been discovered in the light curves of about the 50% of the total amount of X-Ray afterglows observed: it was clear that flares are a very typical feature of GRBs phenomenon. The many observations collected until today show that flares are random events that manifest in different shapes and in all sizes, in each kind of burst (both long and short) and at each measure of redshift. X-Ray flares have been observed in all phases of the X-Ray light curve, the peak time ranges between 95 s and 75 ks. There are light curves with more than one flare, although the more frequent case exhibits one single pulse on the Gamma-Ray peak followed by one or two flares. They are often characterized by large flux variations, can be strongly energetics and in some cases flares have surpassed the original GRB (ex. GRB 060526). This extreme variability and, in particular, the smallness of the time interval in which these big variation of flux happens, makes hard to give reason of such a phenomenon.

As discussed in the previous sections, in our theory the multiwavelength emission is entirely due to the fully inelastic collisions of the baryonic remnants of the fireshell with the CBM. Flares also, as characteristic parts of the afterglow, can be naturally explained in this context. The most relevant results of recent data analysis made on big samples (Chincarini et al., 2007; Falcone et al., 2007) are consistent with our hypothesis of inelastic collisions as the origin of flares. In fact, first of all, flares manifest until very late times and follow the typical hard to soft evolution; then, bumps become broader as the time increases, consistently with a general trend of GRB light curves. Moreover, the distribution of intensity ratios between successive Gamma-Ray pulses and that between successive X-Ray flares is the same, while there is no correlation between the number of pulses of the Gamma-Ray emission and the number of X-Ray flares. These last features seem to establish a common origin of Gamma-Ray bumps and X-Ray flares, and this is consistent with
our hypothesis concerning to which the entire emission (from the Gamma ‘Prompt emission’ to the late Afterglow phase) is generated by the same inelastic collisions process.

On the other hand, it is difficult to conciliate all these aspects within the standard model or any other model founded on an internal shock process (eventually followed by an external shock phase). In particular, is hardly explained the presence of flares at very late times and their strong, rapid variation of flux. As already said, this is one of the most debated peculiarity of the appearing flares. It has been found that \( \langle dt/t \rangle = 0.13 \pm 0.10 \), corresponding to variations of flux of one or also two orders of magnitude. It’s a shared opinion that an external shock scenario can’t reproduce a similar range of variability, but we are able to show that this is consistent with our fully inelastic collision hypothesis. This assumption implies just the consideration of the three-dimensional structure of the CBM, until now neglected for the radial approximation modeling for the CBM profile. We realized a first attempt to check this idea by its application on the burst with the first flare observed, GRB 011121.

K.2. The first step on the first flare: analysis of GRB 011121

GRB 011121 is a near, long burst with \( T_{90} = 28 \) s and redshift \( z = 0.36 \) (Infante et al., 2001). Its fluence (Price et al., 2002) is \( 2.4 \times 10^{-5} \) erg/cm\(^2\) that corresponds, in the hypothesis of isotropic emission at the observed redshift, to an energy in the band \( 2 - 700 \) keV of \( 2.8 \times 10^{52} \) erg. This is the second brightest source detected by BeppoSAX in \( \gamma \)-rays and X-rays. At the time \( t = 240 \) s, in the X-ray \( 2 - 26 \) keV energy band, there is a big flare (Piro et al., 2005; Greiner et al., 2003). It lasts about seventy seconds (\( dt/t \sim 0.29 \)) and corresponds to a bump of an order of magnitude in luminosity. It is however very soft, since its energy is about 3% of the total amount of the prompt emission (Piro et al., 2005).

In figure K.1 we present the observed GRB 011121 light curves in the three different energy bands we analyzed, together with their theoretical fit in the framework of our model: \( 40 - 700 \) keV, \( 2 - 26 \) keV, \( 2 - 10 \) keV. Looking at the observational data we can see that the \( 40 - 700 \) keV energy band light curve presents a temporal profile particularly regular, smooth and homogeneous, while the \( 2 - 26 \) keV light curve has a remarkably irregular profile. This is quite anomalous, in fact generally the light curves in these energy bands presents just the opposite trend.

In figure K.1 there is also an enlargement of the flare of this source that shows in detail the comparison between the theoretical light curve and the observational data.
K.2. The first step on the first flare: analysis of GRB 011121

In the computation of the theoretical light curve for the flare we reproduce it as due to a spherical cloud of CBM along the line of sight introducing, in this way, a three-dimensional structure for the Circum Burst Medium. In fact, in the first approximation, we assume a modeling of thin spherical shells for the distribution of the CBM. This allows us to consider a purely radial profile in the expansion (Ruffini et al., 2002a, 2003). This radial approximation is valid until the visible area of emission of photons is sufficiently small with respect to the characteristic size of the CBM shell. The visible area of emission is defined by the maximum value of the viewing angle; it varies with time and is inversely proportional to the Lorentz Gamma Factor (see the previous). So it happens that, at the beginning of the expansion, when the Gamma Factor is big (about $10^2$), the effective distribution of the CBM doesn’t matter for the narrowness of the viewing angle but, at the end of the expansion, the remarkable lessening of the Gamma Factor produces a strong increase of the viewing angle and a correct estimation of the CBM by the introduction of the angular coordinate distribution becomes necessary.

We can see that our results are in very good agreement with the observational data, also in the late tail of the flare. In particular, the short time variability has been successfully reproduced.

Here we performed just a first attempt of application of our interpretation of flares and we found an encouraging result. Now we plan to verify our hypothesis by its application to other sources and to produce a detailed cinematic and dynamic theory concerning this fundamental features of Gamma-Ray Burst.

**Figure K.1:** Left: Theoretical fit of the GRB 011121 light curves in the 40 – 700 keV (BeppoSAX GRBM), 2 – 26 keV (BeppoSAX WFC), 2/10 keV (BeppoSAX NFI). Right: Enlargement of the Flare.
K. Application to GRB 011121
L. Application to GRB 060218

GRB 060218 triggered the BAT instrument of *Swift* on 18 February 2006 at 03:36:02 UT and has a $T_{90} = (2100 \pm 100)$ s (Cusumano et al., 2006). The XRT instrument (Kennea et al., 2006; Cusumano et al., 2006) began observations $\sim 153$ s after the BAT trigger and continued 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 (XRF) since its peak energy occurs at $E_p = 4.9^{+0.4}_{-0.3}$ keV (Campana et al., 2006a). It has been observed by the *Chandra* satellite on February 26.78 and March 7.55 UT ($t \simeq 8.8$ and 17.4 days) for 20 and 30 ks respectively (Soderberg et al., 2006b). The spectroscopic redshift has been found to be $z = 0.033$ (Sollerman et al., 2006; Mirabal et al., 2006). The corresponding isotropic equivalent energy is $E_{iso} = (1.9 \pm 0.1) \times 10^{50}$ erg (Sakamoto et al., 2006) which sets this GRB as a low luminous one, consistent with most of the GRBs associated with SNe (Liang et al., 2007; Cobb et al., 2006; Guetta and Della Valle, 2007).

GRB 060218 is associated with SN2006aj whose expansion velocity is $v \sim 0.1c$ (Fatkhullin et al., 2006; Soderberg et al., 2006a; Cobb et al., 2006). The host galaxy of SN2006aj is a low luminosity, metal poor star forming dwarf galaxy (Wiersema et al., 2007), similar to the ones of other GRBs associated with SNe (Moffet al., 2006; Sollerman et al., 2006).

L.1. The fit of the observed data

In this section we present the fit of our fireshell model to the observed data (see Figs. [L.1] [L.4]). The fit leads to a total energy of the $e^\pm$ plasma $E_{e^\pm}^{tot} = 2.32 \times 10^{50}$ erg, with an initial temperature $T = 1.86$ MeV and a total number of pairs $N_{e^\pm} = 1.79 \times 10^{55}$. The second parameter of the theory, $B = 1.0 \times 10^{-2}$, is the highest value ever observed and is close to the limit for the stability of the adiabatic optically thick acceleration phase of the fireshell (for further details see Ruffini et al., 2000). The Lorentz gamma factor obtained solving the fireshell equations of motion (Bianco and Ruffini, 2005b,a) is $\gamma_0 = 99.2$ at the beginning of the afterglow phase at a distance from the progenitor $r_0 = 7.82 \times 10^{12}$ cm. It is much larger than $\gamma \sim 5$ estimated by Kaneko et al. (2007) and Toma et al. (2007).
Figure L.1.: GRB 060218 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 0.3–10 keV energy band (green points) (Data from: Campana et al. 2006a).
The procedure of the fit

In Fig. L.1 we show the afterglow light curves fitting the prompt emission both in the BAT (15–150 keV) and in the XRT (0.3–10 keV) energy ranges, as expected in our “canonical GRB” scenario (Dainotti et al., 2007). Initially the two luminosities are comparable to each other, but for a detector arrival time $t_a > 1000$ s the XRT curves becomes dominant. The displacement between the peaks of these two light curves leads to a theoretically estimated spectral lag greater than 500 s in perfect agreement with the observations (see Liang et al., 2006). We obtain that the bolometric luminosity in this early part coincides with the sum of the BAT and XRT light curves (see Fig. L.4) and the luminosity in the other energy ranges is negligible.

We recall that at $t_a \sim 10^4$ s there is a sudden enhancement in the radio luminosity and there is an optical luminosity dominated by the SN2006aj emission (see Campana et al., 2006a; Soderberg et al., 2006b; Fan et al., 2006). Although our analysis addresses only the BAT and XRT observations, for $r > 10^{18}$ cm corresponding to $t_a > 10^4$ s the fit of the XRT data implies two new features: 1) a sudden increase of the $R$ factor from $R = 1.0 \times 10^{-11}$ to $R = 1.6 \times 10^{-6}$, corresponding to a significantly more homogeneous effective CBM distribution (see Fig. L.5b); 2) an XRT luminosity much smaller than the bolometric one (see Fig. L.4). These theoretical predictions may account for the energetics of the enhancement of the radio and possibly optical and UV luminosities. Therefore, we identify two different regimes in the afterglow, one for $t_a < 10^4$ s and the other for $t_a > 10^4$ s. Nevertheless, there is a unifying feature: the determined effective CBM density decreases with the distance $r$ monotonically and continuously through both these two regimes from $n_{cbm} = 1$ particle/cm$^3$ at $r = r_o$ to $n_{cbm} = 10^{-6}$ particle/cm$^3$ at $r = 6.0 \times 10^{18}$ cm: $n_{cbm} \propto r^{-\alpha}$, with $1.0 \lesssim \alpha \lesssim 1.7$ (see Fig. L.5a).

Our assumption of spherical symmetry is supported by the observations which set for GRB 060218 an opening beaming angle larger than $\sim 37^\circ$ (Liang et al., 2007; Campana et al., 2006a; Soderberg et al., 2006b; Guetta and Della Valle, 2007).

L.2. The procedure of the fit

The arrival time of each photon at the detector depends on the entire previous history of the fireshell (Ruffini et al., 2001c). Moreover, all the observables depends on the EQTS (Bianco and Ruffini, 2004, 2005b) which, in turn, depend crucially on the equations of motion of the fireshell. The CBM engulfment has to be computed self-consistently through the entire dynamical evolution of the fireshell and not separately at each point. Any change in the CBM distribution strongly influences the entire dynamical evolution of the fireshell and, due to the EQTS structure, produces observable effects up to a much later time. For example if we change the density mask at a certain distance from the black hole we modify the shape of the lightcurve and con-
sequently the evolution changes at larger radii corresponding to later times. Anyway the change of the density is not the only problem to face in the fitting of the source, in fact first of all we have to choose the energy in order to have Lorentz gamma factor sufficiently high to fit the entire GRB. In order to show the sensitivity of the fitting procedure I also present two examples of fits with the same value of $B$ and different value of $E_{tot}^e$.

The first example has an $E_{tot}^e = 1.36 \times 10^{50}$ erg. This fit resulted unsuccessfully as we see from the Fig. L.2, because the bolometric lightcurve is under the XRT peak of the afterglow. This means that the value of the energy chosen is too small to fit any data points after the peak of the afterglow. So we have to increase the value of the Energy to have a better fit. In fact the parameters values have been found with various attempt in order to obtain the best fit.

The second example is characterized by $E_{tot}^e = 1.61 \times 10^{50}$ erg and the all the data are fitted except for the last point from $2.0 \times 10^2$ s to the end (see Fig. L.3). I attempt to fit these last points trying to diminishes the $R$ values in order to enhance the energy emission, but again the low value of the Lorentz gamma factor, that in this case is 3 prevent the fireshell to expand. So again in this case the value of the Energy chosen is too small, but it is better than the previous attempt. In this case we increased the energy value of the 24%, but it is not enough so we decide to increase 16%.

So the final fit is characterized by the $B = 1.0 \times 10^{-2}$ and by the $E_{tot}^e = 2.32 \times 10^{50}$ erg. With this value of the energy we are able to fit all the experimental points.

### L.3. The fireshell fragmentation

GRB 060218 presents different peculiarities: the extremely long $T_{90}$, the very low effective CBM density decreasing with the distance and the largest possible value of $B = 10^{-2}$. These peculiarities appear to be correlated. Following Ruffini et al. (in press), we propose that in the present case the fireshell is fragmented. This implies that the surface of the fireshell does not increase any longer as $r^2$ but as $r^\beta$ with $\beta < 2$. Consequently, the effective CBM density $n_{cbm}$ is linked to the actual one $n_{cbm}^{act}$ by:

$$n_{cbm} = R_{shell} n_{cbm}^{act}, \quad \text{with} \quad R_{shell} \equiv (r^*/r)^\alpha,$$  \hspace{1cm} (L.3.1)

where $r^*$ is the starting radius at which the fragmentation occurs and $\alpha = 2 - \beta$ (see Fig. L.5a). For $r^* = r_o$ we have $n_{cbm}^{act} = 1 \text{ particles/cm}^3$, as expected for a "canonical GRB" (Ruffini et al., 2007) and in agreement with the apparent absence of a massive stellar wind in the CBM (Soderberg et al., 2006b; Fan et al., 2006; Li, 2007).

The $R$ parameter defined in Eq. (L.3.2) has to take into account both the effect of the fireshell fragmentation ($R_{shell}$) and of the effective CBM porosity.
Figure L.2: GRB 060218 light curves with $E_{\text{tot}} = 1.36 \times 10^{50}$ erg: our theoretical fit (blue line) of the 15–150 keV BAT observations (pink points), our theoretical fit (red line) of the 0.3–10 keV XRT observations (green points) and the 0.3–10 keV Chandra observations (black points) are represented together with our theoretically computed bolometric luminosity (black line) (Data from Campana et al. (2006a), Soderberg et al. (2006b)).
Figure L.3.: GRB 060218 light curves with $E_{\text{tot}}^{15-150\text{ keV}} = 1.61 \times 10^{50}$ erg: our theoretical fit (blue line) of the 15–150 keV BAT observations (pink points), our theoretical fit (red line) of the 0.3–10 keV XRT observations (green points) and the 0.3–10 keV Chandra observations (black points) are represented together with our theoretically computed bolometric luminosity (black line). Data from: Campana et al. (2006a); Soderberg et al. (2006b).
**Figure L.4.** GRB 060218 complete light curves: our theoretical fit (blue line) of the 15–150 keV BAT observations (pink points), our theoretical fit (red line) of the 0.3–10 keV XRT observations (green points) and the 0.3–10 keV *Chandra* observations (black points) are represented together with our theoretically computed bolometric luminosity (black line) (Data from: Campana et al., 2006a; Soderberg et al., 2006b).
Figure L.5: The CBM distribution parameters: a) the effective CBM number density (red line) monotonically decreases with the distance $r$ following Eq. (L.3.1) (green line); b) the $R$ parameter vs. distance.
L.4. Binaries as progenitors of GRB-SN systems

The phenomenon of the clumpiness of the ejecta, whose measure is the filling factor, is an aspect well known in astrophysics. For example, in the case of Novae the filling factor has been measured to be in the range $10^{-2} - 10^{-5}$ (Ederoclite et al., 2006). Such a filling factor coincides, in our case, with $R_{\text{shell}}$.

(L.3.2)

\[ R \equiv R_{\text{shell}} \times R_{\text{cbm}}. \]

The majority of the existing models in the literature appeal to a single astrophysical phenomenon to explain both the GRB and the SN (“collapsar”, see e.g. Woosley and Bloom, 2006). On the contrary, a distinguishing feature of our theoretical approach is to differentiate between the SN and the GRB process. The GRB is assumed to occur during the formation process of a black hole. The SN is assumed to lead to the formation of a neutron star (NS) or to a complete disruptive explosion without remnants and, in no way, to the formation of a black hole. In the case of SN2006aj the formation of such a NS has been actually inferred by Maeda et al. (2007) because of the large amount of $^{58}\text{Ni}$ ($0.05 M_\odot$). Moreover the significantly small initial mass of the SN progenitor star $M \approx 20 M_\odot$ is expected to form a NS rather than a black hole when its core collapses (Maeda et al., 2007; Ferrero et al., 2007; Mazzali et al., 2006; Nomoto et al., 2007). In order to fulfill both the above requirement, we assume that the progenitor of the GRB and the SN consists of a binary system formed by a NS close to its critical mass collapsing to a black hole, and a companion star evolved out of the main sequence originating the SN. The temporal coincidence between the GRB and the SN phenomenon is explained in term of the concept of “induced” gravitational collapse (Ruffini et al., 2001a, in press). There is also the distinct possibility of observing the young born NS out of the SN (see e.g. Ruffini et al. [in press] and references therein).

It has been often proposed that GRBs associated with SNe Ib/c, at smaller redshift $0.0085 < z < 0.168$ (see e.g. Della Valle, 2006, and references therein), form a different class, less luminous and possibly much more numerous than the high luminosity GRBs at higher redshift (Pian et al., 2006; Soderberg et al., 2004; Maeda et al., 2007; Della Valle, 2006). Therefore they have been proposed to originate from a separate class of progenitors (Liang et al., 2007; Cobb et al., 2006). In our model this is explained by the nature of the progenitor system leading to the formation of the black hole with the smallest possible mass: the one formed by the collapse of a just overcritical NS (Ruffini, in pressa; Ruffini et al., in press).

The recent observation of GRB 060614 at $z = 0.125$ without an associated
SN (Della Valle et al., 2006; Mangano et al., 2007) gives strong support to our scenario, alternative to the collapsar model. Also in this case the progenitor of the GRB appears to be a binary system composed of two NSs or a NS and a white dwarf.

L.5. Conclusions

GRB 060218 presents a variety of peculiarities, including its extremely large $T_{90}$ and its classification as an XRF. Nevertheless, a crucial point of our analysis is that we have successfully applied to this source our “canonical GRB” scenario.

Within our model there is no need for inserting GRB 060218 in a new class of GRBs, such as the XRFs, alternative to the “canonical” ones. This same point recently received strong observational support in the case of GRB 060218 (Liang et al., 2006) and a consensus by other models in the literature (Kaneko et al., 2007).

The anomalously long $T_{90}$ led us to infer a monotonic decrease in the CBM effective density giving the first clear evidence for a fragmentation in the fireshell. This phenomenon appears to be essential in understanding the features of also other GRBs (see e.g. GRB 050315 in Ruffini et al. in press; Bernardini et al., 2007a).

Our “canonical GRB” scenario originates from the gravitational collapse to a black hole and is now confirmed over a $10^6$ range in energy (see e.g. Ruffini et al., 2007, and references therein). It is clear that, although the process of gravitational collapse is unique, there is a large variety of progenitors which may lead to the formation of black holes, each one with precise signatures in the energetics. The low energetics of the class of GRBs associated with SNe, and the necessity of the occurrence of the SN, naturally leads in our model to identify their progenitors with the formation of the smallest possible black hole originating from a NS overcoming his critical mass in a binary system. For GRB 060218 there is no need within our model for a new or unidentified source such as a magnetar or a collapsar.

GRB 060218 is the first GRB associated with SN with complete coverage of data from the onset all the way up to $\sim 10^6$ s. This fact offers an unprecedented opportunity to verify theoretical models on such a GRB class. For example, GRB 060218 fulfills the Amati et al. (2002) relation unlike other sources in its same class. This is particularly significant, since GRB 060218 is the only source in such a class to have an excellent data coverage without gaps. We are currently examining if the missing data in the other sources of such a class may have a prominent role in their non-fulfillment of the Amati et al. (2002) relation (Dainotti et al., in preparation; see also Ghisellini et al., 2006).
M. Application to GRB 970228

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

The BeppoSAX observations of GRB 970228 prompt emission revealed a discontinuity in the spectral index between the end of the first pulse and the beginning of the three additional ones (Costa et al., 1997; Frontera et al., 1998, 2000). The spectrum during the first 3 s of the second pulse is significantly harder than during the last part of the first pulse (Frontera et al., 1998, 2000), while the spectrum of the last three pulses appear to be consistent with the late X-ray afterglow (Frontera et al., 1998, 2000). This was soon recognized by Frontera et al. (1998, 2000) as pointing to an emission mechanism producing the X-ray afterglow already taking place after the first pulse.

As shown in sec. E.2, the simultaneous occurrence of an afterglow with total time-integrated luminosity larger than the P-GRB one, but with a smaller peak luminosity, is indeed explainable in terms of a peculiarly small average value of the CBM density and not due to the intrinsic nature of the source. In this sense, GRBs belonging to this class are only “fake” short GRBs. We show that GRB 970228 is a very clear example of this situation. We identify the initial spikelike emission with the P-GRB, and the late soft bump with the peak of the afterglow. GRB 970228 shares the same morphology and observational features with the sources analyzed by Norris and Bonnell (2006) as well as with e.g. GRB 050709 (Villasisnor et al., 2005), GRB 050724 (Campana et al., 2006b) and GRB 060614 (see appendix N and Gehrels et al., 2006). Therefore, we propose GRB 970228 as a prototype for this new GRB class.
M.1. The analysis of GRB 970228 prompt emission

In Fig. M.1 we present the theoretical fit of BeppoSAX GRBM (40–700 keV) and WFC (2–26 keV) light curves of GRB 970228 prompt emission (Frontera et al. 1998). Within our “canonical GRB” scenario we identify the first main pulse with the P-GRB and the three additional pulses with the afterglow peak emission, consistently with the above mentioned observations by Costa et al. (1997) and Frontera et al. (1998). Such last three pulses have been reproduced assuming three overdense spherical CBM regions (see Fig. M.2) with a very good agreement (see Fig. M.1).

We therefore obtain for the two parameters characterizing the source in our model

\[ E^{\text{tot}}_{e^\pm} = 1.45 \times 10^{54} \text{ erg} \] and \[ B = 5.0 \times 10^{-3} \]. This implies an initial \( e^\pm \) plasma created between the radii \( r_1 = 3.52 \times 10^7 \text{ cm} \) and \( r_2 = 4.87 \times 10^8 \text{ cm} \) with a total number of \( e^\pm \) pairs \( N_{e^\pm} = 1.6 \times 10^{59} \) and an initial temperature \( T = 1.7 \text{ MeV} \). The theoretically estimated total isotropic energy emitted in the P-GRB is \( E_{P-GRB} = 1.1\% E^{\text{tot}}_{e^\pm} = 1.54 \times 10^{52} \text{ erg} \), in excellent agreement with the one observed in the first main pulse (\( E_{P-GRB}^{\text{obs}} \sim 1.5 \times 10^{52} \text{ erg} \) in 2–700 keV energy band, see Fig. M.1), as expected due to their identification. After the transparency point at \( r_0 = 4.37 \times 10^{14} \text{ cm} \) from the progenitor, the initial Lorentz gamma factor of the fireshell is \( \gamma_0 = 199 \). On average, during the afterglow peak emission phase we have for the CBM \( \langle R \rangle = 1.5 \times 10^{-7} \) and \( \langle n_{cbm} \rangle = 9.5 \times 10^{-4} \text{ particles/cm}^3 \). This very low average value for the CBM density is compatible with the observed occurrence of GRB 970228 in its host galaxy’s halo (Sahu et al. 1997; van Paradijs et al. 1997; Panaitescu, 2006) and it is crucial in explaining the light curve behavior.

The values of \( E^{\text{tot}}_{e^\pm} \) and \( B \) we determined are univocally fixed by two tight constraints. The first one is the total energy emitted by the source all the way up to the latest afterglow phases (i.e. up to \( \sim 10^6 \) s). The second one is the ratio between the total time-integrated luminosity of the P-GRB and the corresponding one of the whole afterglow (i.e. up to \( \sim 10^6 \) s). In particular, in GRB 970228 such a ratio results to be \( \sim 1.1\% \) (see Fig. B.8). However, the P-GRB peak luminosity actually results to be much more intense than the afterglow one (see Fig. M.1). This is due to the very low average value of the CBM density \( \langle n_{cbm} \rangle = 9.5 \times 10^{-4} \text{ particles/cm}^3 \), which produces a less intense afterglow emission. Since the afterglow total time-integrated luminosity is fixed, such a less intense emission lasts longer than what we would expect for an average density \( \langle n_{cbm} \rangle \sim 1 \text{ particles/cm}^3 \).

M.2. Rescaling the CBM density

We present now an explicit example in order to probe the crucial role of the average CBM density in explaining the relative intensities of the P-GRB and of the afterglow peak in GRB 970228. We keep fixed the basic parameters of
Figure M.1.: The “canonical GRB” light curve theoretically computed for the prompt emission of GRB 970228. BeppoSAX GRBM (40–700 keV, above) and WFC (2–26 keV, below) light curves (data points) are compared with the afterglow peak theoretical ones (solid lines). The onset of the afterglow coincides with the end of the P-GRB (represented qualitatively by the dotted lines). For this source we have $B \simeq 5.0 \times 10^{-3}$ and $\langle n_{cbm} \rangle \sim 10^{-3}$ particles/cm$^3$. 
Figure M.2.: The CBM density profile we assumed to reproduce the last three pulses of the GRB 970228 prompt emission (red line), together with its average value $\langle n_{\text{cbm}} \rangle = 9.5 \times 10^{-4}$ particles/cm$^3$ (green line).

... the source, namely the total energy $E_{\text{tot}}$ and the baryon loading $B$, therefore keeping fixed the P-GRB and the afterglow total time-integrated luminosities. Then we rescale the CBM density profile given in Fig. M.2 by a constant numerical factor in order to raise its average value to the standard one $\langle n_{\text{ism}} \rangle = 1$ particle/cm$^3$. We then compute the corresponding light curve, shown in Fig. M.3.

We notice a clear enhancement of the afterglow peak luminosity with respect to the P-GRB one in comparison with the fit of the observational data presented in Fig. M.1. The two light curves actually crosses at $t_d = 1.8 \times 10^4$ s since their total time-integrated luminosities must be the same. The GRB “rescaled” to $\langle n_{\text{ism}} \rangle = 1$ particle/cm$^3$ appears to be totally similar to, e.g., GRB 050315 (Ruffini et al., 2006b) and GRB 991216 (Ruffini et al., 2003, 2004b, 2005a).

It is appropriate to emphasize that, although the two underlying CBM density profiles differ by a constant numerical factor, the two afterglow light curves in Fig. M.3 do not. This is because the absolute value of the CBM density at each point affects in a non-linear way all the following evolution of the fireshell due to the feedback on its dynamics (Bianco and Ruffini, 2005a). Moreover, the shape of the surfaces of equal arrival time of the photons at the detector (EQTS) is strongly elongated along the line of sight (Bianco and Ruffini, 2005b). Therefore photons coming from the same CBM density region are observed over a very long arrival time interval.
M.2. Rescaling the CBM density

Figure M.3.: The theoretical fit of the BeppoSAX GRBM observations (red line, see Fig. [M.1]) is compared with the afterglow light curve in the 40–700 keV energy band obtained rescaling the CBM density to $\langle n_{cbm} \rangle = 1$ particle/cm$^3$ keeping constant its shape and the values of the fundamental parameters of the theory $E_{e^\pm}^{tot}$ and $B$ (black line). The P-GRB duration and luminosity (blue line), depending only on $E_{e^\pm}^{tot}$ and $B$, are not affected by this process of rescaling the CBM density.
M. Application to GRB 970228

M.3. GRB 970228 and the Amati relation

We turn now to the “Amati relation” (Amati et al., 2002; Amati, 2006) between the isotropic equivalent energy emitted in the prompt emission $E_{\text{iso}}$ and the peak energy of the corresponding time-integrated spectrum $E_{\text{p,i}}$ in the source rest frame. It has been shown by Amati et al. (2002); Amati (2006) that this correlation holds for almost all the “long” GRBs which have a redshift and an $E_{\text{p,i}}$ measured, but not for the ones classified as “short” (Amati, 2006). If we focus on the “fake” short GRBs, namely the GRBs belonging to this new class, at least in one case (GRB 050724 Campana et al., 2006b) it has been shown that the correlation is recovered if also the extended emission is considered (Amati, 2007).

It clearly follows from our treatment that for the “canonical GRBs” with large values of the baryon loading and high $\langle n_{\text{cbm}} \rangle$, which presumably are most of the GRBs for which the correlation holds, the leading contribution to the prompt emission is the afterglow peak emission. The case of the “fake” short GRBs is completely different: it is crucial to consider separately the two components since the P-GRB contribution to the prompt emission in this case is significant.

To test this scenario, we evaluated from our fit of GRB 970228 $E_{\text{iso}}$ and $E_{\text{p,i}}$ only for the afterglow peak emission component, i.e. from $t_a^d = 37$ s to $t_a = 81.6$ s. We found an isotropic energy emitted in the 2–400 keV energy band $E_{\text{iso}} = 1.5 \times 10^{52}$ erg, and $E_{\text{p,i}} = 90.3$ keV. As it is clearly shown in Fig. M.4, the sole afterglow component of GRB 970228 prompt emission is in perfect agreement with the Amati relation. If this behavior is confirmed for other GRBs belonging to this new class, this will enforce our identification of the “fake” short GRBs. This result will also provide a theoretical explanation for the apparent absence of such correlation for the initial spikelike component in the different nature of the P-GRB.

M.4. Conclusions

We conclude that GRB 970228 is a “canonical GRB” with a large value of the baryon loading quite near to the maximum $B \sim 10^{-2}$ (see Fig. B.8). The difference with e.g. GRB 050315 (Ruffini et al., 2006b) or GRB 991216 (Ruffini et al., 2003, 2004b, 2005a) is the low average value of the CBM density $\langle n_{\text{cbm}} \rangle \sim 10^{-3}$ particles/cm$^3$ which deflates the afterglow peak luminosity. Hence, the predominance of the P-GRB, coincident with the initial spikelike emission, over the afterglow is just apparent: 98.9% of the total time-integrated luminosity is indeed in the afterglow component. Such a low average CBM density is consistent with the occurrence of GRB 970228 in the galactic halo of its host galaxy (Sahu et al., 1997; van Paradijs et al., 1997), where lower CBM densities have to be expected (Panaitescu, 2006).
Figure M.4.: The estimated values for $E_{p,i}$ and $E_{iso}$ obtained by our analysis (black dot) compared with the “Amati relation” (Amati et al. 2002): the solid line is the best fitting power law (Amati 2006) and the dashed lines delimit the region corresponding to a vertical logarithmic deviation of 0.4 (Amati 2006). The uncertainty in the theoretical estimated value for $E_{p,i}$ has been assumed conservatively as 20%.
We propose GRB 970228 as the prototype for the new class of GRBs comprising GRB 060614 and the GRBs analyzed by Norris and Bonnell (2006). We naturally explain the hardness and the absence of spectral lag in the initial spikelike emission with the physics of the P-GRB originating from the gravitational collapse leading to the black hole formation. The hard-to-soft behavior in the afterglow is also naturally explained by the physics of the relativistic fireshell interacting with the CBM, clearly evidenced in GRB 031203 (Bernardini et al., 2005a) and in GRB 050315 (Ruffini et al., 2006b). Also justified is the applicability of the Amati relation to the sole afterglow component (see Amati, 2006, 2007).

This class of GRBs with $z \sim 0.4$ appears to be nearer than the other GRBs detected by Swift ($z \sim 2.3$, see Guetta, 2006). This may be explained by the afterglow peak luminosity deflation. The absence of a jet break in those afterglows has been pointed out (Campana et al., 2006b; Watson et al., 2006a), consistently with our spherically symmetric approach. Their association with non-star-forming host galaxies appears to be consistent with the merging of a compact object binary (Barthelmy et al., 2005b; Fox et al., 2005). It is here appropriate, however, to caution on this conclusion, since the association of GRB 060614 and GRB 970228 with the explosion of massive stars is not excluded (Della Valle et al., 2006; Galama et al., 2000).

Most of the sources of this class appear indeed not to be related to bright “Hypernovae”, to be in the outskirts of their host galaxies (Fox et al., 2005, see above) and a consistent fraction of them are in galaxy clusters with CBM densities $\langle n_{cbm} \rangle \sim 10^{-3}$ particles/cm$^3$ (see e.g. Lewis et al., 2003; Berger et al., 2007). This suggests a spiraling out binary nature of their progenitor systems (Kramer, in press) made of neutron stars and/or white dwarfs leading to a black hole formation.

Moreover, we verified the applicability of the Amati relation to the sole afterglow component in GRB 970228 prompt emission, in analogy with what happens for some of the GRBs belonging to this new class. In fact it has been shown by Amati (2006, 2007) that the “fake” short GRBs do not fulfill the $E_{p,i}-E_{iso}$ correlation when the sole spiklike emission is considered, while they do if the long soft bump is included. Since the spikelike emission and the soft bump contributions are comparable, it is natural to expect that the soft bump alone will fulfill the correlation as well.

Within our “canonical GRB” scenario the sharp distinction between the P-GRB and the afterglow provide a natural explanation for the observational features of the two contributions. We naturally explain the hardness and the absence of spectral lag in the initial spikelike emission with the physics of the P-GRB originating from the gravitational collapse leading to the black hole formation. The hard-to-soft behavior in the afterglow is also naturally explained by the physics of the relativistic fireshell interacting with the CBM, clearly evidenced in GRB 031203 (Bernardini et al., 2005a) and in GRB 050315 (Ruffini et al., 2006b). Therefore, we expect naturally that the $E_{p,i}-E_{iso}$ correla-
tion holds only for the afterglow component and not for the P-GRB. Actually we find that the correlation is recovered for the afterglow peak emission of GRB 970228.

In the original work by Amati et al. (2002); Amati (2006) only the prompt emission is considered and not the late afterglow one. In our theoretical approach the afterglow peak emission contributes to the prompt emission and continues up to the latest GRB emission. Hence, the meaningful procedure within our model to recover the Amati relation is to look at a correlation between the total isotropic energy and the peak of the time-integrated spectrum of the whole afterglow. A first attempt to obtain such a correlation has already been performed using GRB 050315 as a template, giving very satisfactory results (see section H).
N. Application to GRB 060614

The explosion of GRB 060614, detected by the Swift satellite, produced a deep break in the GRB scenario opening new horizons of investigation, because it can’t be traced back to any traditional scheme of classification. In fact, it manifests peculiarities of both long bursts and short bursts and, moreover, it is the first case of long duration near GRBs without any bright Ib/c associated Supernova.

GRB 060614 is a near long burst, it lasts about one hundred seconds ($T_{90} = (102 \pm 5)$s [Gehrels et al., 2006]) and its redshift is $z = 0.125$ (Price et al., 2006). However, its morphology appears sharply different from the typical one of long bursts [N.1]: its light curve presents a short, hard and multi-peaked episode (about 5s) followed by a softer, prolonged emission (e.g. Della Valle et al., 2006). This burst manifests a strong hard to soft evolution in the first 400s of data (Mangano et al., 2007); a standard XRT, Optical and UV afterglow have been detected until 4ks after the trigger with some achromatic breaks at $29.7 \pm 4.4$ ks (Optical and UV energy band), at $36.6 \pm 2.4$ks (X-Ray energy band) and at 104ks (from Optical to X-Ray frequencies) (Mangano et al., 2007).

The estimated isotropic energy of GRB 060614 at the measured redshift is $E_{iso} = 2.5 \times 10^{51}$ erg, that is more than the energy of a short but less than the one of a typical long burst. Moreover, has been found that the isotropic energy corresponding to the first hard episode is about one seventh of the total energy released: $E_{iso,1p} = 3.5 \times 10^{50}$ erg. The total fluence in the Gamma-Ray $15 – 150$ kev energy band is $F = (2.17 \pm 0.04) \times 10^{-5}$ erg cm$^{-2}$, the 20% emitted during the initial group of peaks, where the peak energy reaches the value of 300 keV before decreasing until 8 keV during the BAT-XRT overlap time (about 80 s). The result is an upper limit to the average energy just over the BAT threshold ($E \leq 24$ keV [Mangano et al., 2007]).

N.1. Long vs short GRB’s properties

The most accepted classification in the actual GRB scenario is the separation between Short Hard Bursts and Long Soft Bursts, each one with specific characteristics concerning the environment and the origin inferred (Klebesadel, 1992; Dezalay et al., 1992). GRB 060614 seems to contradict this sharp division, not belonging evidently neither to the first nor to the second class. In fact, it should be a long burst for its duration, because it’s very close to its host galaxy and because it fulfills all the empirical relations satisfied by
Figure N.1.: GRB 060614 profile: on the X-axes we have the time from the trigger, on the Y-axes there are, in the above graph, the count rate, and, in the below one, the hardness ratio of the source. We can note the hardly-structured morphology both in the first spikelike emission and in the softer tail. Reproduced from Mangano et al. (2007), with the kind permission of the Editor.
long bursts ($E_{\text{rest}}^p - E_{\text{iso}}$ correlation, $E_{\text{gam}} - E_{\text{iso}}$ correlation, $L_{p,iso} - E_{\text{rest}}^p$ correlation); also the intermediate value of the total energy is compatible with this class (although just on the border line). On the other hand, its host galaxy has a moderate specific star formation rate ($R_{\text{Host}} \approx 2M_y^{-1}(L^*)^{-1}$, $M_{v,\text{Host}} \approx -15.5$ [Fynbo et al., 2006; Della Valle et al., 2006], and the spectral lag in its light curves is very small or absent (Gehrels et al., 2006), and these are typical features of the short bursts. Moreover, the morphology of this source is very similar to the one of many recently observed short GRBs with afterglow (in particular GRB 050724, Zhang et al., 2007).

N.2. The lack of any bright Ib/c Supernova

In the standard scenario, long duration GRBs are thought to be produced during the collapse of massive stars and a broad-lined and luminous type Ib/c core collapse supernova should accompany these events (Woosley and Bloom, 2006). For nearby GRBs ($z \leq 1$) the SN emission must be visible. Until last year there were only four cases of long GRBs at low redshift and all confirmed this association (GRB 980425-SN 1998bw, GRB 030329-SN 2003dh, GRB 031203- SN 2003lw, GRB 060218- SN 2006aj). GRB 060614 is the first clear example of a near, long burst without SN emission observed. It has been estimated that, if present, the SN-component should be about 80/100 times fainter than the archetypal SN 1998bw associated to GRB 980425; moreover, it would also be strongly fainter than any Ic supernova not associated to GRBs ever observed, with $M_v \geq -13.5$ (Della Valle et al., 2006). To account for this new situation many different hypothesis have been proposed: ruling out the chance superposition with a galaxy at low redshift (Gal-Yam et al., 2006) and the strong dust obscuration and extinction (Della Valle et al., 2006), it is likely that this burst should be associated to a TypeII SN (Della Valle et al., 2006) or, in a different scenario, that is the result of the merger of a neutron star and a massive white dwarf (Davies et al., 2007).

This case of long duration GRB without any bright Supernova associated confirms our hypothesis according to which these two astrophysical phenomena are not “intrinsically” correlated (see section G).

By the analysis of GRB 060614 we obtained some preliminary results and, although we are still working on this source, we are able to find a first interpretation of it within our theoretical model.

N.3. Analysis of the prompt emission: a progress report

We realized a detailed analysis of the observational data in the 15 – 150 keV energy band, corresponding to the Gamma-Ray emission (data observed from
N. Application to GRB 060614

Figure N.2.: The BAT 15 – 25 KeV and 25 – 50 KeV light curves (blue points) are compared with the respective theoretical curves (red lines); their onset is at the end of the P-GRB. While for the first energy band we have a good correspondence between data and theoretical results, for the second one the theoretical curve presents an evident excess with respect to the observations. At the end of the curve the radial approximation falls down (see text).

Figure N.3.: The BAT 50 – 100 KeV and 100 – 150 keV light curves (blue points) are compared with the respective theoretical curves (red line); their onset is at the end of the P-GRB. Also in this case, the first energy band presents a good agreement between data and theoretical results, while the theoretical curve of the other one shows a strong defect with respect to the observations. At the end of the curve the radial approximation falls down (see text).
Theoretical curve 25-50 keV U 100-150 keV
BAT data 25-50 keV U 100-150 keV

Figure N.4.: Here the union of the two energy bands $25 - 50 \cup 100 - 150$ keV light curves (blue points) is compared with the respective theoretical curve (red line). The opposite trend of the separated light curves are now compensated and we found a good agreement between the observational data and the theoretical results.
the BAT telescope on the Swift satellite). Initially, we made separated fit for four different energy bands: 15 – 25 keV, 25 – 50 keV, 50 – 100 keV, 100 – 150 keV (see N.2, N.3). Looking at the figures you can see that the theoretical curves obtained for the 25 – 50 keV and the 100 – 150 keV energy bands presented, respectively, an excess and a defect with respect to the observational data. It’s clearly a problem of distribution of the total energy in the different channels and it is probably due to the spectral models used. In fact, in our model we suppose thermal emission (in the comoving frame) while the reduction of the observational data we analized has been made with different assumptions, so with different spectral model (Mangano et al., 2007). In N.4 we compact the two energy bands, so that the opposite contribution compared themselves and we succeeded to reproduce a theoretical curve in a good approximation with the data.

We reproduced the theoretical curves of the Afterglow phase only, determining univocally the energy and the baryon loading and finding appropriate circum burst densities, so the fit starts after the P-GRB.

Looking at the figures with our results we can observe that the general feature agree; the very good correspondence between the observational data and our theoretical curves seems to confirm our canonical interpretation.

We have seen that the “canonical” GRB light curve consists of two different parts:

- an hard, spikelike component that corresponds to the Proper-GRB (P-GRB).
- the strongly hard to soft, multiwavelenght component that corresponds to the Afterglow phase. In particular, the Gamma-Ray emission, in the literature Prompt Emission is just the peak of the Afterglow.

In this scenario, the “anomalous” GRB 060614 is naturally interpreted as a canonical GRB: the first, hard, spikelike emission is the P-GRB and the long, softer Gamma-Ray tail is the peak of the Afterglow (see N.1).

At about the end of the light curve, the good agreement between the observational data and the fit seems to vanish: this is because, as the Lorentz Gamma Factor decreases, the maximum viewing angle enhances, breaking the radial approximation we use (Ruffini et al., 2002a). To overcome this problem it is necessary to introduce the three-dimensional structure of the circum burst medium to avoid an over-estimated effective area of emission. We are still working on this issue (Caito et al., in press). From our analysis we found the values of the parameters: $E_{\text{tot}} = 2.94 \times 10^{51}$ erg, still now in excellent agreement with the observed one, and $B = 2.8 \times 10^{-3}$. We also found $E_{\text{P-GRB}} = 1.15 \times 10^{50}$ erg, the time-integrated energy of the P-GRB, once again in a good approximation with the observed one; the Lorentz Gamma Factor at the transparency is $\gamma_t = 3.46 \times 10^2$. We collected a set of values for
$n_{\text{CBM}}$ and $R$, from which we extracted the average values: $\langle n_{\text{CBM}} \rangle = 4.45 \times 10^{-4}$ part cm$^{-3}$, $\langle n_{\text{CBM}} \rangle_{\text{weight}} = 2.25 \times 10^{-5}$ part cm$^{-3}$, $\langle R \rangle = 1.72 \times 10^{-8}$.

Evidently, the density is small. If we consider the energies involved, we immediately note that the total time integrated energy of the afterglow is larger than the one of the P-GRB of about one order of magnitude. However, the morphology of the light curve manifests an opposite trend: a high, hard P-GRB and a much lower afterglow emission. This is just due to the smallness of the density of the CBM, that produces a deflation of the afterglow with a misleading lowering of its peak energy. Considering the high baryon loading of this burst and its peculiar morphology associated with the very small density of the environment, it seems clear that GRB 060614 is one of the above mentioned case of “fake” bursts, of which GRB 970228 is a prototype (Bernardini et al., 2007a). This would be consistent with the merger of a neutron star and a massive white dwarf (or another neutron star), for the amount of energies involved in the process (Davies et al., 2007) and for the absence of any clear bright hypernova emission.

**N.4. Conclusions**

Finally, up today, from the results of our preliminary analysis, we are able to conclude that the peculiar source GRB 060614 finds a natural interpretation in our canonical GRB scenario: two sharply different components in the phenomenon, the hard P-GRB and the softer Afterglow. In fact, the theoretical curves we obtained by the application of our model are in good agreement with the observational data in the $15 - 150$ keV energy band.

In particular, GRB 060614 belongs to the class of the “fake” short bursts: a very low surrounding density ($\approx 10^{-3}$ part cm$^{-3}$) produces the pronounced deflation of the Afterglow in contrast with an high value of the peak energy of the P-GRB. The total energy of the Afterglow, integrated in time, remains larger than the P-GRB one.

Our attention is now turned on the late afterglow tail, the XRT $0.3 - 10$ keV energy band, and on the study of this source in comparisons with other GRBs yet analyzed by our group to find eventual analogies and new hints of investigation.
N. Application to GRB 060614
Bibliography

AMATI, L.
≪The $e_{p,i}$-$e_{iso}$ correlation in gamma-ray bursts: updated observational status, re-analysis and main implications≫.

AMATI, L.

≪Intrinsic spectra and energetics of bepposax gamma-ray bursts with known redshifts≫.

≪Grb 050904: photometric redshift.≫
GRB Coordinates Network (GCN), 3924 (2005).

ATKINSON, R.D. AND HOUTERMANS, F.G.
≪Zur quantenmechanik der $\alpha$-strahlung≫.
Zeitschrift fur Physik, 58, pp. 478–496 (1929a).

ATKINSON, R.D.E. AND HOUTERMANS, F.G.
≪Zur frage der aufbaumöglichkeit der elemente in sternen≫.

≪Batse observations of gamma-ray burst spectra. i - spectral diversity≫.

≪Preliminary refined analysis of the swift-bat trigger 191157.≫
BARTHELMY, S.D.


BARTHELMY, S.D., CHINCARINI, G., BURROWS, D.N., GEHRELS, N., COVINO, S., MORETTI, A., ROMANO, P., O’BRIEN, P.T., SARAZIN, C.L., KOUVIELIOTOU, C. ET AL.

BELL, S.J. AND Hewish, A.

BERGER, E., SHIN, M.S., MULCHAEG, J.S. AND JELTEMA, T.E.

BERNARDINI, M.G., BIANCO, C.L., CAITO, L., DAINOTTI, M.G., GUIDA, R. AND RUFFINI, R.

BERNARDINI, M.G., BIANCO, C.L., CAITO, L., DAINOTTI, M.G., GUIDA, R. AND RUFFINI, R.

BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F., RUFFINI, R. AND XUE, S.S.
BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F.,
RUFFINI, R. AND XUE, S.S.
«Theoretical interpretation of the luminosity and spectral properties of grb
031203».  

BERNARDINI, M.G., BIANCO, C.L., RUFFINI, R., XUE, S.S., CHARDONNET,
P. AND FRASCHETTI, F.
«General features of grb 030329 in the embh model».
In M. Novello, S. Perez Bergliaffa and R. Ruffini (eds.), *The Tenth Marcel
Grossmann Meeting. On recent developments in theoretical and experimental
general relativity, gravitation and relativistic field theories*, p. 2459 (Singapore:

BETHE, H.A.
«Energy production in stars».

BIANCO, C.L. AND RUFFINI, R.
«Exact versus approximate equitemporal surfaces in gamma-ray burst af-
terglows».

BIANCO, C.L. AND RUFFINI, R.
«Exact versus approximate solutions in gamma-ray burst afterglows».

BIANCO, C.L. AND RUFFINI, R.
«On the exact analytic expressions for the equitemporal surfaces in
gamma-ray burst afterglows».

BIANCO, C.L. AND RUFFINI, R.
«Exact versus approximate beaming formulae in gamma-ray burst after-
glows».

BIANCO, C.L., RUFFINI, R., VERESHCHAGIN, G. AND XUE, S.S.
«Equations of motion and initial and boundary conditions for gamma-ray
burst».

BIANCO, C.L., RUFFINI, R. AND XUE, S.S.
«The elementary spike produced by a pure $e^+e^-$ pair-electromagnetic
pulse from a black hole: The pem pulse».
Bini, D., Cherubini, C., Jantzen, R.T. and Ruffini, R.
«Teukolsky master equation—de Rham wave equation for the gravitational and electromagnetic fields in vacuum—». 

Bini, D., Geralico, A. and Ruffini, R.
«Charged massive particle at rest in the field of a Reissner-Nordström black hole». 

Bini, D., Geralico, A. and Ruffini, R.
«On the equilibrium of a charged massive particle in the field of a Reissner-Nordström black hole». 

Bisnovatyi-Kogan, G.S. and Murzina, M.V.A.
«Early stages of relativistic fireball expansion». 

Blandford, R.D. and McKee, C.F.
«Fluid dynamics of relativistic blast waves». 

Blinnikov, S.I., Kozyreva, A.V. and Panchenko, I.E.
«Gamma-ray bursts: When does a blackbody spectrum look non-thermal?» 

Bloom, J.S., Djorgovski, S.G. and Kulkarni, S.R.
«The redshift and the ordinary host galaxy of GRB 970228». 

Born, M.
«On the quantum theory of the electromagnetic field». 

Burbidge, E.M., Burbidge, G.R., Fowler, W.A. and Hoyle, F.
«Synthesis of the elements in stars». 

Burrows, A. and Lattimer, J.M.
«The birth of neutron stars». 

Bibliography

«The swift x-ray telescope».

«The swift x-ray telescope».

Caito, L., Bernardini, M.G., Bianco, C.L., Dainotti, M.G., Guida, R. and Ruffini, R.
«Grb 060614: a progress report».

Caito, L., Bernardini, M.G., Bianco, C.L., Dainotti, M.G., Guida, R. and Ruffini, R.

«The association of grb 060218 with a supernova and the evolution of the shock wave».

Campana, S., Tagliaferri, G., Lazzati, D., Chincarini, G., Covino, S., Page, K., Romano, P., Moretti, A., Cusumano, G., Mangano, V. et al.
«The x-ray afterglow of the short gamma ray burst 050724».

Canuto, V.
«Neutron stars».

Carter, B.
«Global structure of the kerr family of gravitational fields».

Carter, B.
Cavallo, G. and Horstman, H.M.  
«Spectrum of cosmic fireballs».  

Cavallo, G. and Rees, M.J.  
«A qualitative study of cosmic fireballs and gamma-ray bursts».  

Chiang, J. and Dermer, C.D.  
«Synchrotron and synchrotron self-compton emission and the blast-wave model of gamma-ray bursts».  

Chincarini, G., Moretti, A., Romano, P., Falcone, A.D., Morris, D., Racusin, J., Campana, S., Guidorzi, C., Tagliaferri, G., Burrows, D.N. et al.  
«The first survey of x-ray flares from gamma ray bursts observed by swift: Temporal properties and morphology».  

Christodoulou, D. and Ruffini, R.  
«Reversible transformations of a charged black hole.»  

Cobb, B.E., Bailyn, C.D., van Dokkum, P.G. and Natarajan, P.  
«Sn 2006aj and the nature of low-luminosity gamma-ray bursts».  

«Discovery of an x-ray afterglow associated with the γ-ray burst of 28 february 1997».  

«Evolution of the low-energy photon spectral in gamma-ray bursts».  

Curves, B.G.L.  

«Grb 060218: Swift-bat detection of a possible burst.»  
Dainotti, M.G., Bernardini, M.G., Bianco, C.L., Caito, L., Guida, R. and Ruffini, R.
«Grb 060218 and grbs associated with supernovae ib/c». 

Damour, T. and Ruffini, R.
«Quantum electrodynamical effects in kerr-newman geometries.»

«Progenitors of long gamma-ray bursts».

Della Valle, M.
«Supernova and grb connection: Observations and questions».

Della Valle, M., Chincarini, G., Panagia, N., Tagliaferri, G., Malesani, D., Testa, V., Fugazza, D., Campana, S., Covino, S., Mangano, V. et al.
«An enigmatic long-lasting γ-ray burst not accompanied by a bright supernova».

Dermer, C.D.
«On spectral and temporal variability in blazars and gamma-ray bursts».

Dermer, C.D., Böttcher, M. and Chiang, J.
«The external shock model of gamma-ray bursts: Three predictions and a paradox resolved».

Dermer, C.D. and Mitman, K.E.
«Short-timescale variability in the external shock model of gamma-ray bursts».

«Short cosmic events - a subset of classical grbs?»

**EDDINGTON, A.S.**


**EDEROCLITE, A., MASON, E., DELLA VALLE, M., GILMOZZI, R., WILLIAMS, R.E., GERMANY, L., SAVIANE, I., MATTEUCCI, F., SCHAEFEER, B.E., WALTER, F. ET AL.**


**EINSTEIN, A.**


**FAN, Y.Z., PIRAN, T. AND XU, D.**


**FATKHULLIN, T.A., SOKOLOV, V.V., MOISEEV, A.V., GUZIY, S. AND CASTRO-TIRADO, A.J.**


**FENIMORE, E.E.**


**FENIMORE, E.E., COOPER, C., RAMIREZ-RUIZ, E., SUMNER, M.C., YOSHIDA, A. AND NAMIKI, M.**


**FENIMORE, E.E., MADRAS, C.D. AND NAYAKSHIN, S.**


**FERMI, E.**
FERRERO, P., PALAZZI, E., PIAN, E. AND SAVAGLIO, S.
«Optical observations of grb 060218/sn 2006aj and its host galaxy».

FINZI, A. AND WOLF, R.A.
«Early-type magnetic stars».

FIRMANI, C., GHISELLINI, G., AVILA-REESE, V. AND GHIRLANDA, G.
«Discovery of a tight correlation among the prompt emission properties of long gamma-ray bursts».

FIRMANI, C., GHISELLINI, G., GHIRLANDA, G. AND AVILA-REESE, V.
«A new method optimized to use gamma-ray bursts as cosmic rulers».

«The afterglow of grb 050709 and the nature of the short-hard γ-ray bursts».

«Beaming in gamma-ray bursts: Evidence for a standard energy reservoir».

FRAIL, D.A., WAXMAN, E. AND KULKARNI, S.R.
«A 450 day light curve of the radio afterglow of grb 970508: Fireball calorimetry».

«Prompt and delayed emission properties of gamma-ray bursts observed with bepposax».
FRONTERA, F., COSTA, E., PIRO, L., MULLER, J.M., AMATI, L., FEROCI, M., 
FIORE, F., PIZZICCHINI, G., TAVANI, M., CASTRO-TIRADO, A. ET AL.
«Spectral properties of the prompt x-ray emission and afterglow from the 
gamma-ray burst of 1997 february 28».  

FYNBO, J.P.U., WATSON, D., THÖNE, C.C., SOLLERMAN, J., BLOOM, J.S., 
«No supernovae associated with two long-duration γ-ray bursts».  

LEONARD, D.C., SODERBERG, A.M., SCHMIDT, B.P., LEWIS, K.M., PETERSON, B.A. ET AL.
«A novel explosive process is required for the γ-ray burst grb 060614».  

GALAMA, T.J., TANVIR, N., VREESWIJK, P.M., WIJERS, R.A.M.J., GROOT, P.J., 
ROL, E., VAN PARADIJS, J., KOUVELIOTOU, C., FRUCHTER, A.S., 
MASETTI, N. ET AL.
«Evidence for a supernova in reanalyzed optical and near-infrared images 
of grb 970228».  

GALAMA, T.J., VREESWIJK, P.M., VAN PARADIJS, J., KOUVELIOTOU, C., AUGUSTEIJN, T., 
«An unusual supernova in the error box of the γ-ray burst of 25 april 
1998».  

GAMOW, G.

GAMOW, G.

GAMOW, G. AND HOUTERMANS, F.G.
«Zur quantenmechanik des radioaktiven kerns».  
Zeitschrift fur Physik, 52, pp. 496–509 (1929).

GAMOW, G. AND SCHOENBERG, M.
«Neutrino theory of stellar collapse».  
«The swift gamma-ray burst mission».

«A new γ-ray burst classification scheme from grb060614».

Ghirlanda, G., Celotti, A. and Ghisellini, G.
«Time resolved spectral analysis of bright gamma ray bursts».

Ghirlanda, G., Ghisellini, G. and Lazzati, D.
«The collimation-corrected gamma-ray burst energies correlate with the peak energy of their $v f_\nu$ spectrum».

Ghisellini, G., Ghirlanda, G., Mereghetti, S., Bosnjak, Z., Tavecchio, F. and Firmani, C.
«Are grb980425 and grb031203 real outliers or twins of grb060218?»

Giacconi, R., Ruffini, R., Giacconi, R. and Ruffini, R. (eds.).
*Physics and astrophysics of neutron stars and black holes* (1978).

Gold, T.
«Rotating neutron stars as the origin of the pulsating radio sources».

Gold, T.
«Rotating neutron stars and the nature of pulsars».

«Grb 011121: A collimated outflow into wind-blown surroundings».

Guetta, D.
«Short grbs: Rates and luminosity function implications».
GUETTA, D. AND DELLA VALLE, M.
«On the rates of gamma-ray bursts and type Ib/c supernovae».

HALPERN, J.P., UGLESICH, R., MIRABAL, N., KASSIN, S., THORSTENSEN, J.,
KEEL, W.C., DIERCKS, A., BLOOM, J.S., HARRISON, F., MATTOX, J. ET AL.
«Grb 991216 joins the jet set: Discovery and monitoring of its optical after-
glow».

HANNI, R.S. AND RUFFINI, R.
«Lines of force of a point charge near a schwarzschild black hole.»

HEISENBERG, W. AND EULER, H.
«Folgerungen aus der diracschen theorie des positrons».

HORSTMAN, H.M. AND CAVALLO, G.
«The energy spectrum of cosmic fireballs».

INFANTE, L., GARNAVICH, P.M., STANEK, K.Z. AND WYRZYKOWSKI, L.
«Grb011121: possible redshift, continued decay.»
GRB Coordinates Network (GCN), 1152 (2001).

IWAMOTO, K., MAZZALI, P.A., NOMOTO, K., UMEDA, H., NAKAMURA,
T., PATAT, F., DANZIGER, I.J., YOUNG, T.R., SUZUKI, T., SHIGEYAMA,
T. ET AL.
«A hypernova model for the supernova associated with the γ-ray burst of
25 april 1998».

KANEKO, Y., RAMIREZ-RUIZ, E., GRANOT, J., KOUVELIOTOU, C.,
WOOSLEY, S.E., PATEL, S.K., ROL, E., ZAND, J.J.M.I., VAN DER HORST,
A.J., WIJERS, R.A.M.J. ET AL.
«Prompt and afterglow emission properties of gamma-ray bursts with spectroscopically identified supernovae».

KAWAI, N., YAMADA, T., KOSUGI, G., HATTORI, T. AND AOKI, K.
«Grb 050904: Subaru optical spectroscopy.»
GRB Coordinates Network (GCN), 3937 (2005).

KELSON, D. AND BERGER, E.
«Grb 050315: absorption redshift.»
GRB Coordinates Network (GCN), 3101 (2005).
KENNEA, J.A., BURROWS, D.N., CUSUMANO, G. AND TAGLIAFERRI, G.
≪Subject: Grb 060218: Swift xrt position.≫

KERR, R.P.
≪Gravitational field of a spinning mass as an example of algebraically special metrics≫.

KLEBESADEL, R.W.
≪The durations of gamma-ray bursts≫.

≪Identification of two classes of gamma-ray bursts≫.

≪Chandra observations of the x-ray environs of sn 1998bw/grb 980425≫.

KRAMER, M.

≪Radio emission from the unusual supernova 1998bw and its association with the $\gamma$-ray burst of 25 april 1998≫.

LANDAU, L.D. AND LIFSHITZ, E.M.

LATTIMER, J.M., VAN RIPER, K.A., PRAKASH, M. AND PRAKASH, M.
≪Rapid cooling and the structure of neutron stars≫.

LEACH, R.W. AND RUFFINI, R.
≪On the masses of x-ray sources≫.
**Bibliography**


**Lewis, A.D., Buote, D.A. and Stocke, J.T.**
«Chandra observations of a2029: The dark matter profile down to below 0.01r_{vir} in an unusually relaxed cluster».  

**Li, L.X.**
«Shock breakout in type icb supernovae and application to grb 060218/sn 2006aj».  

**Liang, E. and Zhang, B.**
«Model-independent multivariable gamma-ray burst luminosity indicator and its possible cosmological implications».  

**Liang, E., Zhang, B., Virgili, F. and Dai, Z.G.**
«Low-luminosity gamma-ray bursts as a unique population: Luminosity function, local rate, and beaming factor».  

«Temporal profiles and spectral lags of xrf 060218».  

«Sn 2006aj associated with xrf 060218 at late phases: Nucleosynthesis signature of a neutron star-driven explosion».  

**Majumdar, S.D.**
«A class of exact solutions of einstein’s field equations».  

«Swift observations of grb 060614: an anomalous burst with a well-behaved afterglow».  

**Mathews, G.J. and Wilson, J.R.**
«Relativistic induced compression of neutron stars and white dwarfs».  

296

MAZZALI, P.


«A neutron-star-driven x-ray flash associated with supernova sn 2006aj».


MEREGHETTI, S. AND GOTZ, D.

«Grb 031203: further analysis of integral data.»

GRB Coordinates Network (GCN), **2460** (2003).

MÉSZÁROS, P.

«Theories of gamma-ray bursts».


MÉSZAROS, P.

«Gamma-ray bursts.»


MÉSZAROS, P., LAGUNA, P. AND REES, M.J.

«Gasdynamics of relativistically expanding gamma-ray burst sources - kinematics, energetics, magnetic fields, and efficiency».  

MÉSZÁROS, P. AND REES, M.J.

«Collapsar jets, bubbles, and Fe lines».


MIRABAL, N., HALPERN, J.P., AN, D., THORSTENSEN, J.R. AND TERNDRUP, D.M.

«Grb 060218/sn 2006aj: A gamma-ray burst and prompt supernova at z = 0.0335».


MIRABEL, I.F. AND RODRIGUEZ, L.F.

«A superluminal source in the galaxy».


MISNER, C.W., THORNE, K.S. AND WHEELER, J.A.

MODJAZ, M., STANEK, K.Z., GARNAVICH, P.M., BERLIND, P., BLONDIN, S., BROWN, W., CALKINS, M., CHALLIS, P., DIAMOND-STANIC, A.M., HAO, H. ET AL.
«Early-time photometry and spectroscopy of the fast evolving sn 2006aj associated with grb 060218».

NAVA, L., GHISELLINI, G., GHIRLANDA, G., TAVECCHIO, F. AND FIRMANI, C.
«On the interpretation of spectral-energy correlations in long gamma-ray bursts».

NEWMAN, E.T., COUCH, E., CHINNAPARED, K., EXTON, A., PRAKASH, A. AND TORRENCE, R.
«Metric of a rotating, charged mass».

NOMOTO, K., TOMINAGA, N., TANAKA, M., MAEDA, K., SUZUKI, T., DENG, J.S. AND MAZZALI, P.A.
«Diversity of the supernova - gamma-ray burst connection».

NORRIS, J.P. AND BONNELL, J.T.
«Short gamma-ray bursts with extended emission».

«Evidence for a canonical gamma-ray burst afterglow light curve in the swift xrt data».

OPPENHEIMER, J.R. AND SERBER, R.
«On the stability of stellar neutron cores».

OPPENHEIMER, J.R. AND SNYDER, H.
«On continued gravitational contraction».

OPPENHEIMER, J.R. AND VOLKOFF, G.M.
«On massive neutron cores».
«The fourth batse gamma-ray burst catalog (revised)».  

PACINI, F.
«Rotating neutron stars, pulsars and supernova remnants».  

PACZYNSKI, B.
«Are gamma-ray bursts in star-forming regions?»  

PACZYNSKI, B. AND XU, G.
«Neutrino bursts from gamma-ray bursts».  

PANAITESCU, A.
«The energetics and environment of the short-grb afterglows 050709 and 050724».  

PANAITESCU, A. AND MESZAROS, P.
«Simulations of gamma-ray bursts from external shocks: Time variability and spectral correlations».  

PANAITESCU, A., MESZÁROS, P., GEHRELS, N., BURROWS, D. AND NOUSEK, J.
«Analysis of the x-ray emission of nine swift afterglows».  

PAPAPETROU, A.  
Proceedings of the Royal Irish Academy, 51, p. 191 (1945).

PARKER, L., RUFINI, R. AND WILKINS, D.
«Metric of two spinning charged sources in equilibrium».  

«Swift-bat detection of grb 050315.»  
GRB Coordinates Network (GCN), 3094 (2005).
PERRIN, J.B.

«Bepposax observations of grb 980425: Detection of the prompt event and monitoring of the error box».

PIAN, E., GIOMMI, P., AMATI, L., COSTA, E., DANTZIGER, J., FEROCI, M., FIOCCHI, M.T., FRONTERA, F., KOUVELIOTOU, C., MASETTI, N. ET AL.
«Xmm-newton observations of the field of γ-ray burst 980425».

«An optical supernova associated with the x-ray flash xrf 060218».

PIRAN, T.
«Gamma-ray bursts and the fireball model».

PIRAN, T.
«Gamma-ray bursts - a puzzle being resolved.»

PIRAN, T.
«Gamma-ray bursts-when theory meets observations (plenary talk)».

PIRAN, T.
«The physics of gamma-ray bursts».

PIRAN, T., SHEMI, A. AND NARAYAN, R.
«Hydrodynamics of relativistic fireballs».

PIRO, L.
«Bepposax grb011121.»
*GRB Coordinates Network (GCN)*, **1147** (2001).
«The x-ray afterglow of the gamma-ray burst of 1997 may 8:spectral variability and possible evidence of an iron line». 

«Probing the environment in gamma-ray bursts: The case of an x-ray pre-cursor, afterglow late onset, and wind versus constant density profile in grb 011121 and grb 011211».

POZDNIAKOV, L.A., SOBOL, I.M. and SIUNIAEV, R.A.
«Comptonization and the shaping of x-ray source spectra - monte carlo calculations».

PREECE, R.D., BRIGGS, M.S., MALLOZZI, R.S., PENDLETON, G.N., PACIESAS, W.S. and BAND, D.L.
«The synchrotron shock model confronts a “line of death” in the batse gamma-ray burst data».

PREPARATA, G., RUFINI, R. and XUE, S.S.
«The dyadosphere of black holes and gamma-ray bursts».

PRICE, P.A., BERGER, E. and FOX, D.B.
«Grb 060614: redshift.»

«Grb 011121: A massive star progenitor». 

«The host galaxy of grb 031203: Implications of its low metallicity, low redshift, and starburst nature».

REES, M., RUFINI, R. and WHEELER, J.A.

REES, M.J.
«Appearance of relativistically expanding radio sources».

REES, M.J. AND MESZAROS, P.
«Unsteady outflow models for cosmological gamma-ray bursts».

«A possible cepheid-like luminosity estimator for the long gamma-ray bursts».

RESPONSE, B.R.B.

RHOADES, C.E. AND RUFFINI, R.
«Maximum mass of a neutron star.»

ROMANI, R.W.
«Model atmospheres for cooling neutron stars».

RUFFINI, R.
«On the energetics of black holes.»

RUFFINI, R.
«Beyond the critical mass: The dyadosphere of black holes».

RUFFINI, R.
«Analogies, new paradigms and observational data as growing factors of relativistic astrophysics».

RUFFINI, R.
RUFFINI, R.

RUFFINI, R.
«The ergosphere and dyadosphere of black holes».

«The blackhole energy and the canonical gamma-ray burst».

«The role of grb 031203 in clarifying the astrophysical grb scenario».
volume 622 of ESA Special Publication (in press).

RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F., GUIDA, R. AND XUE, S.S.
«Grb 050315: A step toward the uniqueness of the overall grb structure».

RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F., GUIDA, R. AND XUE, S.S.
«Grb 050315: A step toward understanding the uniqueness of the overall gamma-ray burst structure».

RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F., GUZADYAN, V., VITAGLIANO, L. AND XUE, S.S.
«The blackhole energy: long and short gamma-ray bursts (new perspectives in physics and astrophysics from the theoretical understanding of gamma-ray bursts, ii)».

RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F. AND XUE, S.S.
«Grb 980425, sn1998bw and the embh model».
Bibliography


RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F. AND XUE, S.S.
«Evidence for isotropic emission in grb991216».

RUFFINI, R., BERNARDINI, M.G., BIANCO, C.L., VITAGLIANO, L., XUE, S.S., CHARDONNET, P., FRASCHETTI, F. AND GURZADYAN, V.
«Black hole physics and astrophysics: The grb-supernova connection and urca-1 - urca-2».

RUFFINI, R., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F., VITAGLIANO, L. AND XUE, S.S.
«New perspectives in physics and astrophysics from the theoretical understanding of gamma-ray bursts».

RUFFINI, R., BIANCO, C.L., CHARDONNET, P., FRASCHETTI, F. AND XUE, S.S.
«On the structures in the afterglow peak emission of gamma-ray bursts».

RUFFINI, R., BIANCO, C.L., FRASCHETTI, F., XUE, S.S. AND CHARDONNET, P.
«On a possible gamma-ray burst-supernova time sequence».

RUFFINI, R., BIANCO, C.L., FRASCHETTI, F., XUE, S.S. AND CHARDONNET, P.
«On the interpretation of the burst structure of gamma-ray bursts».

RUFFINI, R., BIANCO, C.L., FRASCHETTI, F., XUE, S.S. AND CHARDONNET, P.
«Relative spacetime transformations in gamma-ray bursts».

RUFFINI, R., BIANCO, C.L., XUE, S.S., CHARDONNET, P., FRASCHETTI, F. AND GURZADYAN, V.
«On the instantaneous spectrum of gamma-ray bursts». 

«Emergence of a filamentary structure in the fireball from grb spectra». 

**Ruffini, R., Chardonnet, P., Bianco, C.L., Xue, S.S. and Fraschetti, F.**
«Les sursaut gamma». 

**Ruffini, R., Fraschetti, F., Vitagliano, L. and Xue, S.S.**
«Observational signatures of an electromagnetic overcritical gravitational collapse». 

**Ruffini, R., Salmonson, J.D., Wilson, J.R. and Xue, S.S.**
«On the pair electromagnetic pulse of a black hole with electromagnetic structure». 

**Ruffini, R., Salmonson, J.D., Wilson, J.R. and Xue, S.S.**
«On the pair-electromagnetic pulse from an electromagnetic black hole surrounded by a baryonic remnant». 

**Ruffini, R., Vitagliano, L. and Xue, S.S.**

**Ruffini, R. and Wheeler, J.A.**
«Introducing the black hole.» 

«The optical counterpart to γ-ray burst grb970228 observed using the hubble space telescope». 

«Grb 060218/sn 2006aj: Swift-bat fluence and peak flux.» 
SARI, R. AND PIRAN, T.
«Variability in gamma-ray bursts: A clue».

SAZONOV, S.Y., LUTOVINOV, A.A. AND SUNYAEV, R.A.
«An apparently normal $\gamma$-ray burst with an unusually low luminosity».

SAZONOV, S., LUTOVINOV, A. AND SUNYAEV, R.
Private communication (2004b).

SCHWARZSCHILD, M.

SCHWINGER, J.
«On gauge invariance and vacuum polarization».

SHEMI, A. AND PIRAN, T.
«The appearance of cosmic fireballs».

SODERBERG, A.M., BERGER, E. AND SCHMIDT, B.P.
«Grb060218: optical spectroscopy of grb-sn.»
*GRB Coordinates Network (GCN)*, **4804** (2006a).

«The sub-energetic $\gamma$-ray burst grb 031203 as a cosmic analogue to the nearby grb 980425».

«Relativistic ejecta from x-ray flash xrf 060218 and the rate of cosmic explosions».

«Supernova 2006aj and the associated x-ray flash 060218».

STRONG, I.B.
«Cosmic gamma-ray bursts».
Bibliography


TAVANI, M.
«Euclidean versus non-euclidean gamma-ray bursts».  

TIENGO, A., MEREGHETTI, S., GHISELLINI, G., ROSSI, E., GHIRLANDA, G. AND SCHARTEL, N.  
«The x-ray afterglow of grb 030329».  

TIENGO, A., MEREGHETTI, S., GHISELLINI, G., TAVECCHIO, F. AND GHIRLANDA, G.  
«Late evolution of the x-ray afterglow of grb 030329».  

TOMA, K., IOKA, K., SAKAMOTO, T. AND NAKAMURA, T.  
«Low-luminosity grb 060218: A collapsar jet from a neutron star, leaving a magnetar as a remnant?»  

TRÜMPER, J.E.  
«Observations of cooling neutron stars».  

TSURUTA, S.  

TSURUTA, S.  
«Thermal properties and detectability of neutron stars. i. cooling and heating of neutron stars.»  

TSURUTA, S. AND CAMERON, A.G.W.  
«Cooling and detectability of neutron stars».  

TSURUTA, S., TETER, M.A., TAKATSUKA, T., TATSUMI, T. AND TAMAGAKI, R.  
«Confronting neutron star cooling theories with new observations».  
Bibliography

«Transient optical emission from the error box of the γ-ray burst of 28
february 1997».

VAN RIPER, K.A.
«Magnetic neutron star atmospheres».

VAN RIPER, K.A.
«Neutron star thermal evolution».

«Swift observations of the x-ray-bright grb 050315».

«Discovery of the short γ-ray burst grb 050709».

VON WEIZSÄCKR, C.F.

VON WEIZSÄCKR, C.F.

«Are short γ-ray bursts collimated? grb 050709, a flare but no break».

«A very low luminosity x-ray flash: Xmm-newton observations of grb 031203».
«The soft x-ray blast in the apparently subluminous grb 031203».

Weinberg, S.

«The nature of the dwarf starforming galaxy associated with grb 060218/sn 2006aj».

Wilson, J.R., Salmonson, J.D. and Mathews, G.J.
«A binary neutron star grb model».

Wilson, J.R., Salmonson, J.D. and Mathews, G.J.
«A gamma ray burst model».

Woosley, S.E. and Bloom, J.S.
«The supernova gamma-ray burst connection».

Yakovlev, D.G. and Pethick, C.J.
«Neutron star cooling».

Yonetoku, D., Murakami, T., Nakamura, T., Yamazaki, R., Inoue, A.K. and Ioka, K.
«Gamma-ray burst formation rate inferred from the spectral peak energy-peak luminosity relation».

«Physical processes shaping gamma-ray burst x-ray afterglow light curves: Theoretical implications from the swift x-ray telescope observations».
Zhang, B., Zhang, B.B., Liang, E.W., Gehrels, N., Burrows, D.N. and Mészáros, P.
«Making a short gamma-ray burst from a long one: Implications for the nature of grb 060614».