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The canonical GRB scenario

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Summary. — The canonical GRB scenario implied by the fireshell model is briefly summarized.

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1. – Introduction

The first systematic analysis on a large sample of GRBs was made possible by the BATSE instrument on board the Compton Gamma-Ray Observer (CGRO) satellite [1]. One of the main outcomes of this early analysis was the evidence of a bi-modal temporal distribution in the T_{90} observed duration of the GRB prompt emission. The T_{90} duration is defined as the time interval over which 90% of the total background-subtracted counts is observed, with the interval starting when 5% of the total counts has been observed. The "long" and "short" GRBs were defined as being longer or shorter than $T_{90} = 2\,\mathrm{s}$. The observed spectra of the "short" GRBs have appeared also to be systematically harder than the ones of the "long" [2-5]. This dichotomy led to an idea of different progenitors: respectively, the explosion of very massive stars for long GRBs (see *e.g.* the collapsar model by [6] and the merger of compact objects for short GRBs [7, 8]).

After BATSE, a fundamental progress was achieved with the discovery by Beppo-SAX of a prolonged soft X-ray emission, following the traditional hard X-ray emission observed by BATSE [9]. The Beppo-SAX observed soft X-ray emission, lasting from few days to months, was named the "afterglow", while the BATSE observations were referred to as the "prompt emission". The afterglow allowed to pinpoint more accurately the GRB position in the sky with narrow field instruments and permitted the identification of their optical counterpart by space and ground-based telescopes. This has allowed to measure their redshift, confirming their cosmological nature [10].

In recent years, the observations by the Swift satellite [11] evidenced the existence of a possible third class of bursts presenting hybrid properties between the short and the long ones: the Norris-Bonnell sources [12]. The prompt emission of these sources is characterized by an initial short spike-like emission lasting a few seconds, followed by a prolonged softer extended emission lasting up to some hundred seconds. They were initially indicated in the literature as "short GRBs with an extended emission".

In parallel the theoretical progress in the Fireshell model of GRBs (see [13-15]) has led to an alternative explanation of the Norris-Bonnell sources as "disguised short bursts": canonical long bursts exploding in a low density circum burst medium (CBM) typical of galactic halos [16-23]. In the Fireshell model GRBs originate from an optically thick $e^{\pm}$ plasma created by vacuum polarization processes in the gravitational collapse to a black hole [24] in the Kerr-Newman geometry (for a recent review, see [25]). The dynamics of such a plasma in the optically thick phase is described by its total energy $E^{\rm tot}_{e^{\pm}}$ and by the amount of the engulfed baryons, the baryon load $B = M_B c^2/E^{\rm tot}_{e^{\pm}}$, where M_B is the mass of the engulfed baryons. The canonical GRBs light curve is characterized by a first emission due to the transparency of the $e^{\pm}$-photon-baryon-plasma, defined as Proper-GRB (P-GRB), followed by an extended afterglow due to the collisions, in a fully radiative regime, between the accelerated baryons and the CBM, with density n_{CBM} (see sect. **2**). From these theoretical considerations, it has become clear that the Norris-Bonnell sources belong to a new class of GRBs which have been defined "disguised" short GRBs [16-23]. The initial short spike-like emission is identified as the characteristic emission of the P-GRB. The prolonged soft emission is the extended afterglow occurring in a particularly low average density CBM, $\langle n_{CBM}\rangle \approx 10^{-3}$ particles/cm^3, typical of a galactic halo environment (see sect. **3**).

The search for the class of GRBs which we defined "genuine short GRBs", theoretically predicted by the Fireshell model [14, 26], is still open. This class of canonical GRBs is characterized by severely small values of the Baryon load, $B \lesssim 10^{-5}$. The energy emitted in the P-GRB is predominant and the characteristic duration is expected to be shorter than a fraction of a second (see sect. **4**).

2. – The canonical long GRBs

In the Fireshell scenario, the GRBs originate from the process of vacuum polarization occurring in the formation of a black hole, resulting in pair creation [24, 25]. The formed $e^{\pm}$ plasma, with total energy $E^{\rm tot}_{e^{\pm}}$, reaches the thermal equilibrium almost instantaneously [27]. The annihilation of these pairs occurs gradually and it is confined in an expanding shell, called *fireshell*, which self-accelerates up to ultrarelativistic velocities [28], and engulfs the baryonic matter (of mass M_B) left over in the process of collapse, which thermalizes with the pairs due to the large optical depth [29]. The baryon load is measured by the dimensionless parameter $B = M_B c^2/E^{\rm tot}_{e^{\pm}}$. The fireshell continues to self-accelerate until it reaches the transparency condition and a first flash of radiation, the P-GRB, is emitted [14]. The radius at which the transparency occurs and the theoretical temperature, the Lorentz factor as well as the amount of the energy emitted in the P-GRB are functions of $E^{\rm tot}_{e^{\pm}}$ and B (see fig. 1). The residual expanding plasma of leptons and baryons interacts with the CBM and, due to these collisions, starts to slow down giving rise to a multi-wavelength emission: the extended afterglow. Assuming a fully radiative condition, the structures observed in the extended afterglow of a GRB

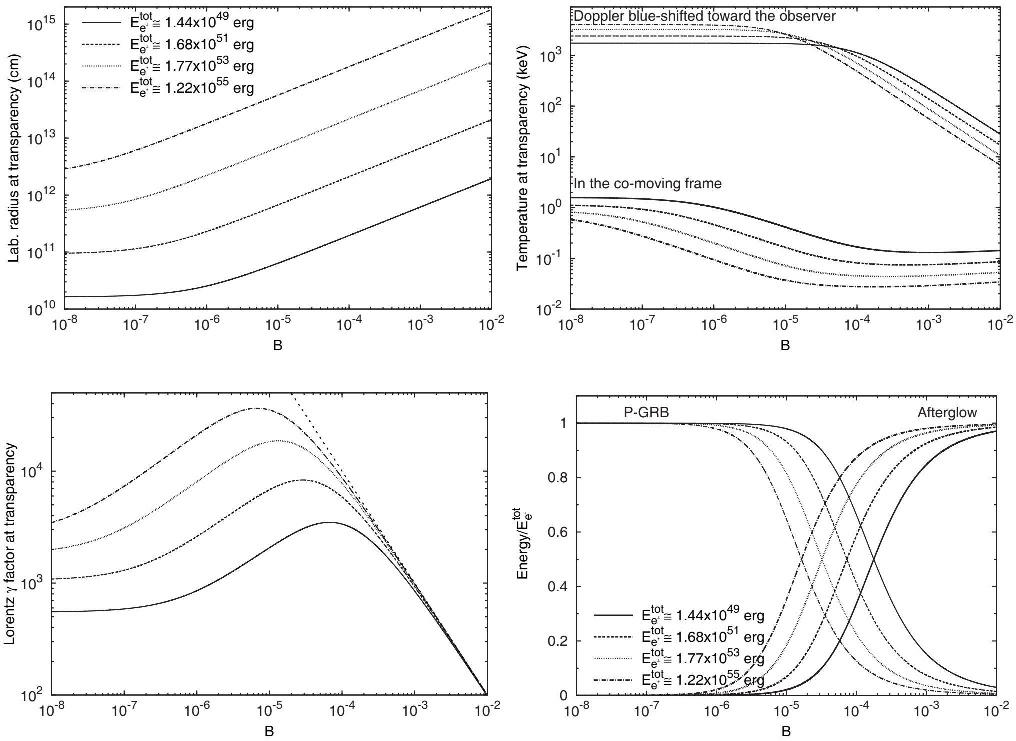

Fig. 1. – The main quantities of the Fireshell model at the transparency for selected values of $E^{\rm tot}_{e^\pm}$: the radius in the laboratory frame, the co-moving frame and blue-shifted toward the observer temperatures of the plasma, the Lorentz Γ factor, and the fraction of energy radiated in the P-GRB and in the extended afterglow as functions of B. In this last plot, the crossing point, corresponding to the condition $E_{P\text{-}GRB} \equiv 50\% E^{\rm tot}_{e^\pm}$, marks the division between the region of the parameter space pertaining to genuine short GRBs (on the left of the crossing) and the one pertaining to disguised short and long GRBs (on the right). Its exact position is a function of $E^{\rm tot}_{e^\pm}$. In these simulations a sudden transition between the optically thick adiabatic phase and the fully radiative condition at the transparency has been assumed.

are described by two quantities associated with the environment: the CBM density profile n_{CBM}, which determines the temporal behavior of the light curve, and the fireshell surface filling factor $\mathcal{R} = A_{\rm eff}/A_{\rm vis}$, in which $A_{\rm eff}$ is the effective emitting area of the fireshell and $A_{\rm vis}$ its total visible area [26,30]. This second parameter takes into account the inhomogeneities in the CBM and its filamentary structure [31]. The emission process of the collision between the baryons and the CBM has been assumed in the comoving frame of the shell as a modified black body spectrum [32-34], given by

$$\frac{{\rm d}N_\gamma}{{\rm d}V{\rm d}\epsilon} = \frac{8\pi}{h^3c^3}\left(\frac{\epsilon}{kT}\right)^\alpha \frac{\epsilon^2}{\exp(\epsilon/kT)-1}\,, \tag{1}$$

where α is a phenomenological parameter.

The observed GRB non-thermal spectral shape is then produced by the convolution of a very large number of modified thermal spectra with different temperatures and different Lorentz and Doppler factors. This convolution is performed over the surfaces of constant arrival time for the photons at the detector (EQuiTemporal Surfaces, EQTS [35, 36])

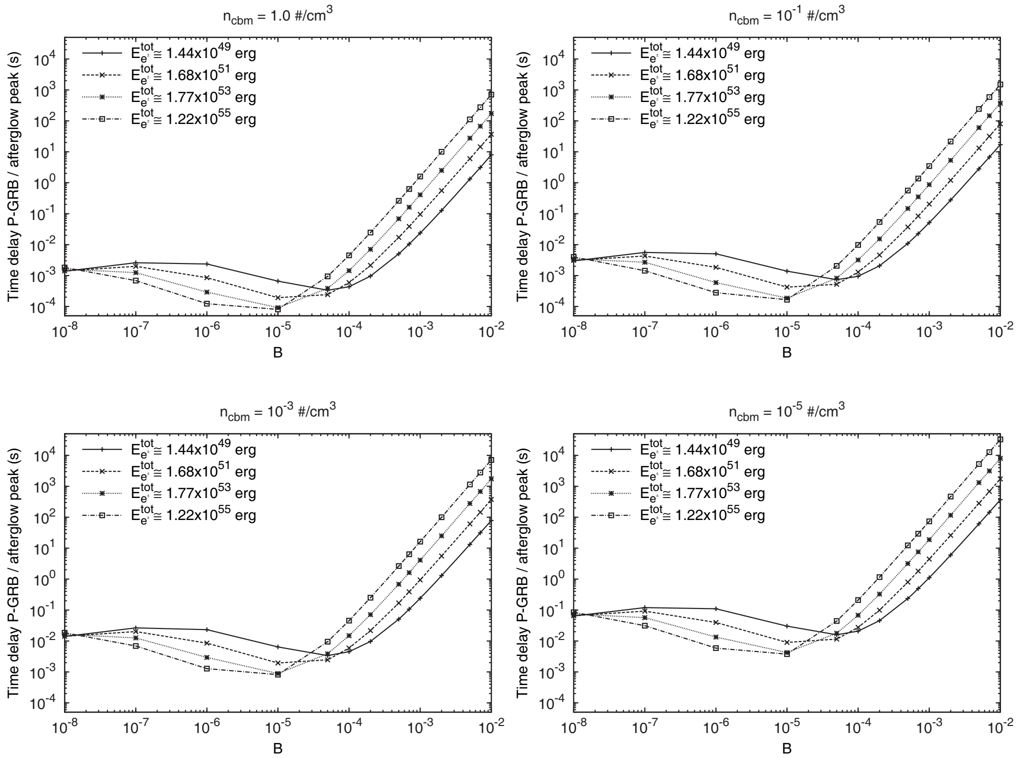

Fig. 2. – Plots of the arrival time separation Δt_a between the P-GRB and the peak of the extended afterglow as function of B for four different values of $E^{\rm tot}_{e^\pm}$, measured in the source cosmological rest frame. This computation has been performed assuming four constant CBM density $n_{CBM} = 1.0$, 1.0×10^{-1}, 1.0×10^{-3}, 1.0×10^{-5} particles/cm^3.

encompassing the total observation time. The observed hard-to-soft spectral variation comes out naturally from the decrease with time of the comoving temperature and of the bulk Lorentz Γ factor. This effect is amplified by the curvature effect originated by the EQTS, which produce the observed time lag in the majority of the GRBs.

Assuming the spherical symmetry of the system, the isotropic energy emitted in the burst, $E_{\rm iso}$, is equal to the energy of the $e^\pm$ plasma, $E^{\rm tot}_{e^\pm}$, and the GRB bolometric light curve is composed of the P-GRB and the extended afterglow. Their relative energetics and observed time separation are functions of the energy $E^{\rm tot}_{e^\pm}$, of the baryon load B, and of the CBM density distribution n_{CBM} (see fig. 2). In particular, for B decreasing, the extended afterglow light curve "squeezes" itself on the P-GRB and the P-GRB peak luminosity increases (see fig. 3).

To reproduce the shape of the light curve we have to infer for each CBM clump the filling factor $\mathcal{R}$, which fixes the effective temperature in the comoving frame and the corresponding peak energy of the spectrum, and of the CBM density n_{CBM}, which affects the temporal behavior of the light curve. It is clear that, since the EQTS encompass emission processes occurring at different comoving times weighted by their Lorentz and Doppler factors, the fit of a single spike is not only a function of the properties of the specific CBM clump but of the entire previous history of the source. Due to the

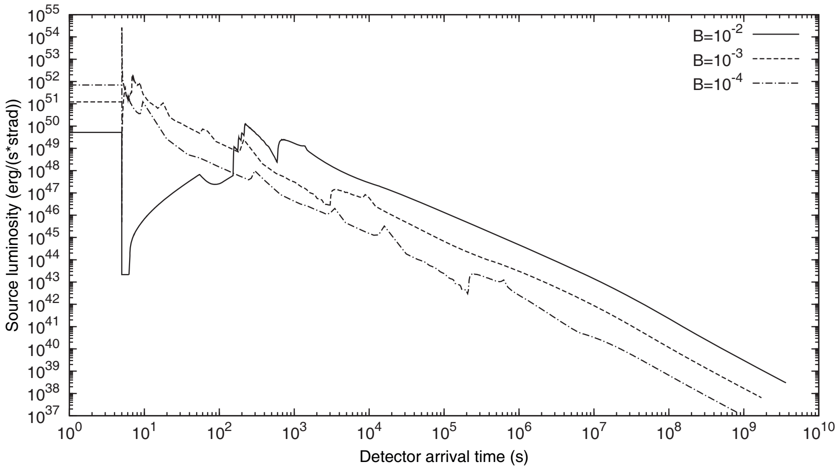

Fig. 3. – The dependence of the shape of the light curve on B. The computations have been performed assuming $E^{\rm tot}_{e^\pm} = 4.83 \times 10^{53}$ ergs, $\langle n_{CBM} \rangle = 1.0$ particles/cm^3, three different values of the Baryon load $B = 10^{-2}, 10^{-3}, 10^{-4}$ and the P-GRBs duration fixed, *i.e.* 5 s. For B decreasing, the extended afterglow light curve squeezes itself on the P-GRB and the peak becomes sharper and higher.

non-linearity of the system and to the EQTS, any change in the simulation produces observable effects up to a much later time. This leads to an extremely complex procedure by trial and error in the data simulation to reach the uniqueness.

According to this theory, when $3.0 \times 10^{-4} \lesssim B \leq 10^{-2}$ and the CBM average density is $\langle n_{CBM} \rangle \approx 1$ particle/cm^3, the extended afterglow peak luminosity is predominant with respect to the P-GRB one, giving rise to the long GRBs (see fig. 1).

3. – The disguised short GRBs

After the observations by Swift of GRB 050509B [11], which was declared in the literature as the first short GRB with an afterglow ever observed, it has become clear that such sources are actually disguised short GRBs [23]. It is very probable that also a large fraction of the declared short duration GRBs in the BATSE catalog, observed before the discovery of the afterglow, are members of this class. In the case of the disguised short GRBs the Baryon load varies in the same range of the long bursts, while the CBM density is of the order of 10^{-3} particles/cm^3. As a consequence, the extended afterglow results in a "deflated" emission that can be exceeded in peak luminosity by the P-GRB [16, 21-23]. Indeed the total energy emitted over the entire extended afterglow is much larger than the one of the P-GRB (see fig. 1), as expected for long GRBs. With these understandings long and disguised short GRBs are interpreted in terms of long GRBs exploding, respectively, in a typical galactic density or in a galactic halo density.

These sources have given the first evidence of GRBs originating from binary mergers, formed by two neutron stars and/or white dwarfs in all possible combinations, that have spiraled out from their host galaxies into the halos [16, 17, 21-23]. This interpretation has been supported by direct optical observations of GRBs located in the outskirts of the host galaxies [10, 37-42].

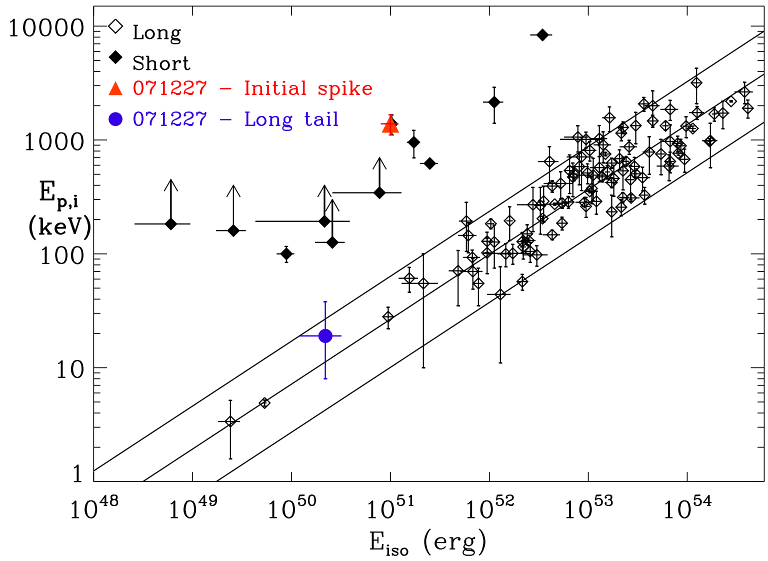

Fig. 4. – Location of the initial short spike and soft long tail of GRB 071227 in the $E_{p,i}$-$E_{\rm iso}$ plane. The continuous lines show the best-fit power law and the 2σ confidence region of the correlation. Details in ref. [22].

4. – The class of genuine short GRBs

In the Fireshell model the genuine short GRBs occur in the limit of very low baryon load, *e.g.* $B \lesssim 10^{-5}$ with the P-GRB energetically predominant with respect to the extended afterglow. For such small values of B the afterglow peak emission shrinks over the P-GRB (see fig. 3).

Since the thermalization of photon-pairs plasma is reached on a very short timescale at the beginning of the expansion phase and the thermal equilibrium is implemented during the entire phase of the expansion [27], the spectrum of these genuine short GRBs is expected to be characterized by a significant thermal-like emission. Due to the small values of the baryon load, in addition to the predominant role of the P-GRB, a non-thermal component originating from the extended afterglow is expected.

We face however a difficulty in identifying a "genuine" short GRB. A selection effect is at work: a genuine short GRB must have a very weak extended afterglow (see figs. 1, 3); consequently, it is very difficult to determine its redshift.

5. – Implications for the Amati relation

The most effective tool for determining the nature and, then, interpreting the different classes of GRBs, is the Amati relation [43-45]. This empirical spectrum-energy correlation states that the isotropic-equivalent radiated energy of the prompt emission $E_{\rm iso}$ is correlated with the cosmological rest-frame νF_ν spectrum peak energy $E_{p,i}$: $E_{p,i} \propto (E_{\rm iso})^a$, where $a \approx 0.5$ and the dispersion is $\sigma(\log_{E_p}) \sim 0.2$. The Amati relation holds only for long duration bursts, while short ones, as it has been possible to prove after the "afterglow revolution" and the measurement of their redshift, are inconsistent with it [44, 45].

This dichotomy can naturally be explained by the fireshell model. As we recalled above, within this theoretical framework the prompt emission of long GRBs is dominated by the peak of the extended afterglow, while that of the short GRBs is dominated by the P-GRB. Only the extended afterglow emission follows the Amati relation (see [46, 22]). Therefore, all GRBs in which the P-GRB provides a negligible contribution to the prompt emission (namely the long ones, where the P-GRB is at most a small precursor) fulfill the Amati relation, while all GRBs in which the extended afterglow provides a negligible contribution to the prompt emission (namely the short ones) do not (see [16-23]). As a consequence, for disguised short bursts the two components of the prompt emission must be analyzed separately. The first spikelike emission alone, which is identified with the P-GRB, should not follow the Amati relation; the prolonged soft tail, which is identified with the peak of the extended afterglow, should instead follow the Amati relation. This has been confirmed in many cases [18, 19, 21-23] see also fig. 4.

We are currently analyzing the implications on this scenario of the correlation recently found by Bernardini *et al.* [47] see also ref. [48].

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