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Gamma Ray Burst: A Model

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Abstract. In this paper we present a simple model which can give us basic parameters of Gamma-ray bursts in the second phase. The model is based on the interactions of ultra-relativistic shock waves, where the slower shock is catched by the faster one. We specified basic equation for shock wave evolution and used the gaussian function for density disturbance to simulate another, the slower, shock. By using this method, we can change the width and height of gaussian function, as well as, the other parameters of the incoming faster shock wave, and fit the light and spectral curves. We also take that radiation mechanism is mostly based on the synchrotron emission ignoring the inverse Compton radiation. Moreover, we fitted several gamma ray light curves in order to demonstrate the ability of the model.

1 Introduction

Gamma Ray Bursts (GRB) are short and violent ejection of radiation in broad energy band. This phenomena present a long time mystery of modern astrophysics. It was discovered accidently by the American military satelite (Vela) in the time of cold war, while try to monitor the nuclear arm testing by the opposite block. The discovery was confirmed by the Soviet Konus satelites of the same kind, but it was keeped secret until 1973. This date mark the biggining of the era of Gamma Ray Bursts.

Until present days, much of this strange phenomena has been revealed [1, 2]. First of all we have very important observational results acquired by the *Compton Gamma Ray Observatory* (CGRO), which carring onboard the *Burst and Transient Source Experiment* (BATSE) [3, 4]. This satelite was able to record light and spectral curves as well as to pinpoint location of each GRBs. The results are presented in the Figure 1. and can be easily simplified in one sentence. *The Gamma Ray Bursts present a nongalactic phenomena*. This conclusion even worse that time understanding of GRB phenomena, because it predict galactic distances and enormous energies.

To explain this unusual behavior researches form the so called fireball theory [7], which in its core have ultrarelativisticly expanding ball of ejected material. What

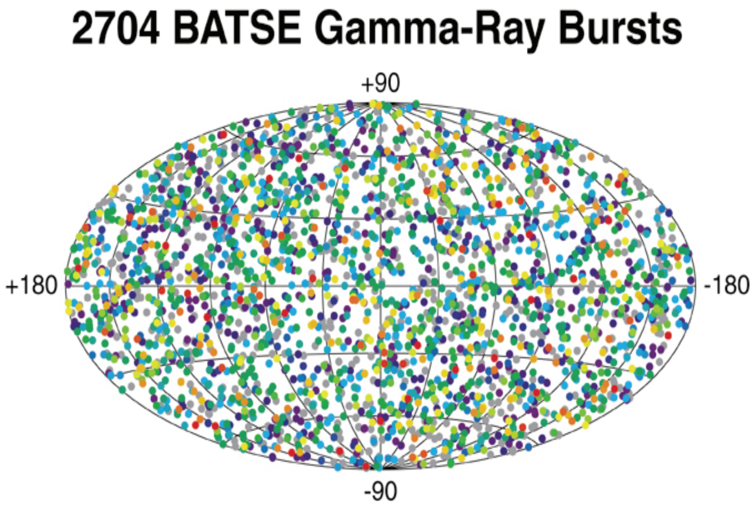

Figure 1. Homogenous distribution of Gamma Ray Bursts on the sky, means non galactic origin of this phenomena.

cause this violent event has left unclear until present days. The theory also predict that the dimension and mass of this fireball must be relatively small (solar like), in order to satisfy the variability expressed in the light curve. Such a fast and hot plasma moves throughtout the Interstellar Medium (ISM) consisted of a charged particles, which immediately generate strong magnetic field in comoving reference frame. As a consequence, we have the synchrotron radiation as the main mechanism of cooling the particles of ejecta. A small part of total radiation at the highest energies covering the Inverse Compton cooling.

The fireball theory also predict radiation at lower energies (the afterglow), like X-ray, optical or radio band, generated by the cooled shock wave. Confirmation of this prediction has achieve the Italian-Duch satelite (BeppoSAX) first observing the afterglow of the GRB970228 (see Figure 2) [5, 6].

However, the advance in understanding the external of this phenomena has not give us the true nature of the GRBs. The association of GRBs with star forming regions and the indication that GRBs follow the star formation rate, suggest that GRBs are related to stellar death, namely to Supernovae [8]. Additionally there is some direct evidence of association of GRB with supernovae. First such indication of an association was found when SN98bw was discovered within the error box of GRB98425 [9].

Definitive proof of the supernova link, at least in the case of those GRBs with an afterglow, came on March 29, 2003, when a relatively nearby burst, GRB030329 produced an afterglow whose optical spectrum was nearly identical to a super-

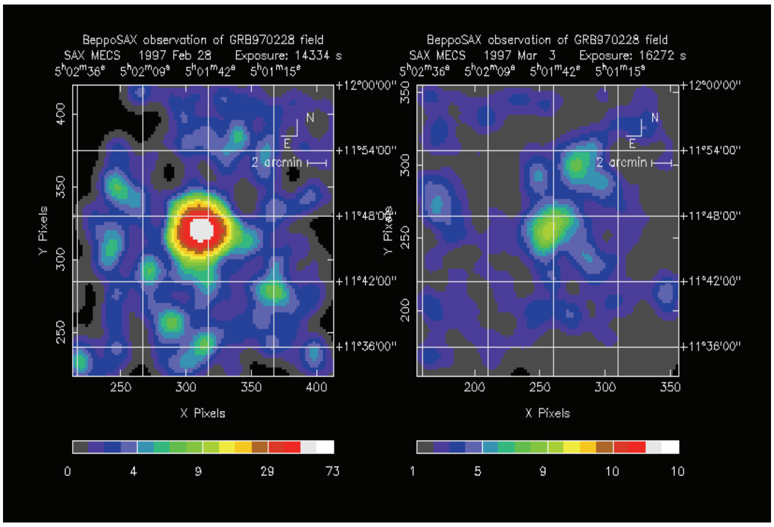

Figure 2. Afterglow observation of the GRB970228 by the BeppoSaX.

nova [10, 11]. X-ray observations also showed a signature associated with oxygen heated to high temperatures. Such a light pattern occurs when the supernova blast wave excites oxygen atoms in the close vicinity of the star. These observations constituted the "smoking gun", providing even more solid evidence than GRB980425.

2 The Model

Light curve of the ordinary GRB is far from smooth, but rather very changeable, consisted of some number of sharp peaks, which in some cases have recognizable *fast-rise slow-decay* shape or better known as FRED (*fast-rise exponential-decay*) (see Figure 3). It is widely accepted that peaks in the light curve arise in the moment when two shock wave of different velocities collide. We have developed the simple model in order to study this shocks and to extract some of their basic parameters. Now we give short description of the model.

In the first phase of the explosion, the central engine creates a large number of small mass highly collimated shocks, isotropically distributed with respect to the central engine. These shocks have high but non-uniform Lorentz factors, such that the faster shocks can catch the slower ones – this is known as the internal model [1, 12–14]. When an interaction occurs, a number of radiating particles of the faster shock increases sharply, as well as the velocity of particles, creating a pulse in the GRB light curve. The duration of the pulse depends on the width of the shock waves and on their Lorentz factors, with a typical values

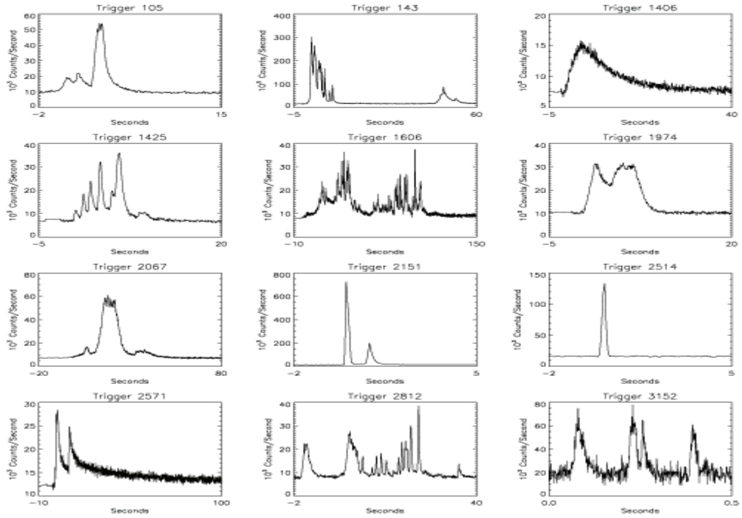

Figure 3. Light curve of some tipical gamma ray bursts.

of ~ 1 sec. The overall GRB light curve presents a series of pulses produced by the collisions of shock waves with different basic parameters.

Since the mass of the shocks are relatively low (a few orders of magnitude lower than the mass of the afterglow shock), they have short life-times and quickly disappear in the surrounding media. But, the central engine continuously creates new small mass shocks that cause the flow of shock waves with different initial parameters. With time, they are able to accelerate particles of the Inter-Stellar Medium (ISM) surrounding the GRB and to accumulate in another, massive shock wave which continues to spread with lower velocity. Then, the second phase of the GRB event starts, with the creation of the afterglow.

Let us consider a moving, highly collimated shell, which is assumed to be a part of sphere. The shell front area is given by $2\pi R^2(1-\cos\theta)$, while its width is $R\big/\Gamma^2$ in highly relativistic case [15]. Then, the mass of the shell is given by $m_s = 2\pi n m_p(1-\cos\theta)R^3/\Gamma^2$, where n is a number density of the shell, θ is the angle of collimation, m_p is the proton mass, R is the distance of the shell from the center of the GRB and Γ is the Lorentz factor. We assumed that the number density of the shell (n) is connected with a number density of the ISM n_0, as $n = n_0(4\Gamma+3)$ [15].

We will use here the equations for R and Γ given by [17] (their Eqs. (3) and (8)), and derive the equation for a shock shell with mass m_s. The complete system of differential equations we use is:

$$\frac{dR}{dt} = c\sqrt{\Gamma^2 - 1}\Big[\Gamma + \sqrt{\Gamma^2 - 1}\Big], \tag{1}$$

$$\frac{d\Gamma}{dm_s} = -\frac{\Gamma^2 - 1}{M_{ej} + 2(1-\varepsilon)\Gamma m_s + \varepsilon m_s}, \tag{2}$$

$$\frac{dm_s}{dt} = 2\pi n m_p (1 - \cos\theta)\frac{R^2}{\Gamma^3}\left(3\Gamma\frac{dR}{dt} - 2R\frac{d\Gamma}{dt}\right), \tag{3}$$

where the parameter ε takes values from 0 for the adiabatic expansion, to 1 which describes a fully radiative case, and M_{ej} is the mass of a primary ejected material. Eqs. (1)–(3) are derived for an observer reference frame, and they have to be solved simultaneously, together with the density equation. Initial values of parameters and variables are highly dependent on the properties of the shocks.

The emission mechanism of shock waves is mainly based on synchrotron radiation, but for higher energy bands additional flux can be gained by the inverse Compton (IC) radiation (see [1]). To calculate the intensity of the radiation by particles in the shock wave we will use the formulae given by [16], then the total emitted flux can be calculated as *e.g.* in [17]. Also, we should note that the shock waves contains relativistic electrons and barions which contribute to the synchrotronic radiation, but taking into account the difference in velocities of these constituents, one can neglect the contribution of barions to the total emitted flux.

We also assume that the radiation is homogeneous across the spherical shell surface. We can take that from an infinitesimal small surface of the spherical shell, $ds = 2\pi R^2(\cos\theta_m)^2 \tan\theta d\theta$, the photons arrive at the same time to the observer. Then in the comoving reference frame the total flux is:

$$P_\nu^{'} = A \cdot \int_0^{\theta_m} \tan\theta d\theta \int_{\gamma_{emin}}^{\gamma_{emax}} \gamma_e^{-(p+1)} F(\nu^{'}/\nu_c^{'}) d\gamma_e \tag{4}$$

where A is:

$$A = \frac{\sqrt{3}e^3 B^{'}}{m_e c^2}\frac{m_s}{m_p}\frac{C_1}{\ln(\cos(\theta_m))} \tag{5}$$

and $F(x) = \int_x^\infty K_{5/3}(x)dx$ where $K_{5/3}^{'}$ is the Bessel function of the second order. Here, $\nu_c^{'}$ is the critical frequency of the radiation expressed by $\nu_c^{'} = 3\gamma_e^2 e B^{'}/4\pi m_e c$.

The magnetic field has been calculated in a standard way, by assuming that the energy of the magnetic field is a certain fraction, ξ_b, of the total energy of the shock wave. In the comoving reference frame the expression for the magnetic field is taken as:

$$B = \sqrt{8\pi\xi_b n_0 \Gamma m_p c^2 (4\Gamma + 3)\left(\frac{R_0}{R}\right)^s \left(1 + a \cdot e^{-\left(\frac{R-R_c}{b}\right)^2}\right)}. \tag{6}$$

Using Eqs. (1)–(6) in the next section we will first simulate a GRB light curve, after that we will fit observed GRBs in one BATSE channel, in order to demonstrate the applicability of the model. Also, we will apply this model for the rest of the BATSE channels to produce the spectral curve for all tree GRBs.

3 Results and Discussion

In order to demonstrate the ability of the model to reproduce observed pulse shapes from a GRB light curve, we fitted three isolated pulses with different shapes; GRB 020508, GRB 911104 and GRB 911117. The observations with BATSE instrument were used (3rd channel, $E = 100 - 300$ keV, for the light curve). The light curves of these gamma-ray bursts do not have a standard form, *i.e.* the shape of pulses does not always follow the FRED behavior. To find a fit of the pulses we specify different values of the parameters for the faster and slower shock waves. As one can see in Figure 4 the shapes of the light and energy curves can be very well described by the model. In Table 1, the parameters of the best fits are given.

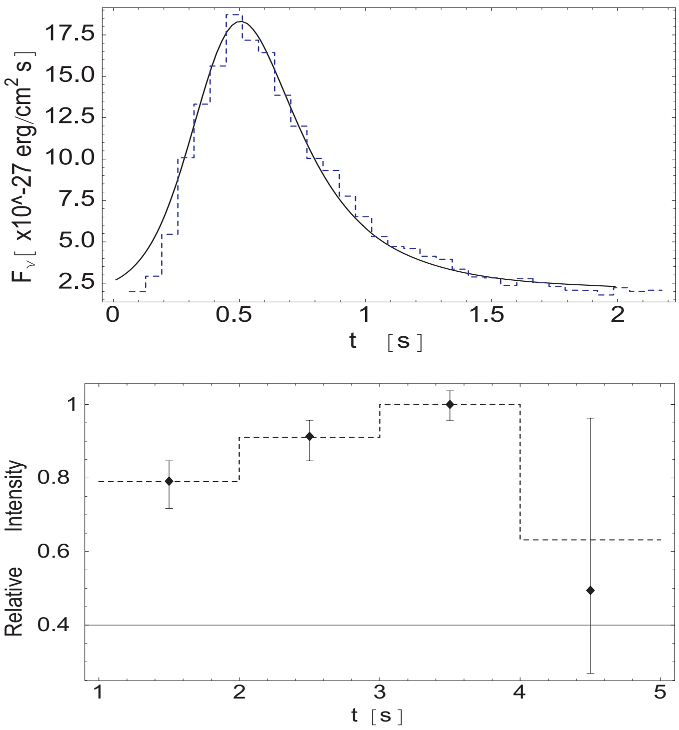

Figure 4. The light and spectral curves of pulse of GRB 911104 fitted with the model.

Table 1. Extracted parameters for all tree GRB's. The error is calculated as a deviation of parameter at the 90 % of the minimal rms value.

param.	units	GRB 911104	GRB 911117	GRB 020508
ξ	-	0.12±0.03	0.14±0.01	0.01±0.007
ξ_e	-	0.2±0.004	0.18±0.02	0.2±0.01
ξ_b	-	0.2±0.008	0.2±0.04	0.2±0.02
p	-	2.5±0.025	2.5±0.15	2.5±0.09
n_0	cm^{-3}	10.8±0.9	5.0±1.0	10±2.5
Γ_0	-	40±0.4	78.7±1.5	30±0.3
M_{ej}	$M_\odot$	$(0.26\pm0.005)\cdot10^{-10}$	$(0.1\pm0.006)\cdot10^{-10}$	$(3\pm0.18)\cdot10^{-10}$
θ_m	rad	0.08±0.024	0.057±0.016	0.23±0.007
R_c	cm	$(1.4\pm0.01)\cdot10^{14}$	$(1.22\pm0.012)\cdot10^{14}$	$(2.5\pm0.025)\cdot10^{14}$
n_b	cm^{-3}	$(5.3\pm0.08)\cdot10^{7}$	$(4.6\pm0.06)\cdot10^{7}$	$(3.0\pm0.03)\cdot10^{8}$
ΔR	cm	$(6.6\pm0.08)\cdot10^{13}$	$(3.5\pm0.2)\cdot10^{13}$	$(1.0\pm0.02)\cdot10^{14}$

Taking into account that we have 11 free parameters in our fitting procedure, we tested the sensitivity of the parameters using root minimal square (rms). We were changing one by one parameter fixing the rest of them and measure rms. This gives us the sensitivity of the model with respect of different parameters as well as a possibility to estimate the error-bars of the parameters. The error-bars are taken to be at 90% of rms deviation (in both directions).

In general, comparing the obtained values of parameters (Table 1) for different GRBs, one can conclude that there is no huge differences between them even when the shapes and lasting of GRB pulses are different. This suggests that the nature of these three GRBs is similar and that there should not be big differences between the physical conditions of GRB progenitors. On the other hand, we note here that the density shape of a shock wave can differ from the Gaussian one assumed here, and it may reflect the values of basic parameters. But in any case, one can expect that density distribution of a shock wave has to be taken into account in the shock model.

4 Conclusions

In order to test the model we fit the light and spectral curves of three different GRBs observed with BATSE. From this we can conclude:

(i) the model can successfully fit the observed light and spectral curves.

(ii) the obtained basic parameters from the fit of the GRBs are in good agreement with expected values from different literature sources.

(iii) no huge differences between the same parameters for different GRBs. That indicates the similar nature of GRB generator for the considered three GRBs.

Acknowledgments

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