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Letter to the Editor

Lightcurves of cosmological gamma-ray bursts

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Abstract. It is shown that in a typical fireball of cosmological GRB a neutron component is initially present and has the energy of the order of the proton-electron component. Free neutrons change essentially the dynamics of a relativistic shock formed by the ejected material in the surrounding medium. The neutron flow may decouple from the proton one or may not. Also, neutrons may decay before the shock of proton origin decelerates significantly or after that. According to these possibilities there are four types of bursts possessing lightcurves with different global appearance. We point out a number of lightcurve features expected to be correlated. For example, the height, delay time and duration of the secondary pulse are related to each other. We show that two-peaked lightcurves may be as common as single-peaked ones.

Key words: gamma rays: bursts – ISM: jets and outflows – shock waves

1. Introduction

The lightcurves of gamma-ray bursts (GRBs) and their subsequent X-ray to radio afterglows are thought to reflect the rise and the fall of a relativistic shock which emerges when the fireball material runs into the surrounding medium (Rees & Mészáros 1992, Paczyński & Rhoads 1993, Mészáros & Rees 1997). The latter process would, in the simplest case, lead to a smooth single peak of the standard shape. However, the observed diversity of lightcurves does not harmonise with this poor picture (e.g., Fishman et al. 1994). Apart from rapid gamma-ray flux variations seen on the timescales down to a fraction of millisecond, there are deviations of the entire lightcurve, such as deformation of the main peak or presence of the second peak. In the present paper we focus on the global features of GRB lightcurves, leaving aside their short-term variability.

A number of hypotheses were put forward to explain why the time behaviour of gamma-ray fluxes is so different while an underlying physical phenomenon is common for all GRBs. These explanations include non-monotonous changes of the Lorentz factor during a burst (faster shells ejected between slower ones) (Kobayashi, Piran & Sari 1997), delayed activity of a GRB source (Dai & Lu 1998), modification of shock geometry (for jet sources) when a Lorentz factor of decelerating shock becomes smaller than an inverse opening angle of the jet (Mészáros, Rees & Wijers 1998). The last two proposals are aimed primarily at the afterglow stage, and the principal outcome of the first one is that any particular lightcurve is a unique signature of that very GRB and no specific correlations can be predicted as far as there is no detailed model.

In any stellar-type model of cosmological GRBs, as it is demonstrated below, a neutron flow must be present in addition to the proton-electron one. We suggest that the collection of GRB lightcurves may partially owe its complexity to the interplay between the proton and neutron components of relativistic ejecta. This phenomenon should take place in every burst on the routine basis, thus allowing several definite predictions to be made. In particular, we find it possible to classify (theoretically) all GRB bolometric lightcurves into four separate groups, according to their global properties. If it is the proton-neutron interplay which is responsible for the observed diversity of GRBs, then there must be a number of correlations inside the groups as well as between them.

In the following section we discuss the origin of free neutrons in a fireball and determine what condition guarantees that they do not recombine with protons. Then we present the classification of GRB lightcurves and describe the main relations between empirical parameters.

2. Free neutrons in a fireball

If one assumes a nucleon-loaded fireball as the generic way of the energy extraction from a GRB central engine, then there are two possibilities: nucleons are either free or assembled into nuclei. With an increase of the source temperature, T_0, helium nuclei are the last to dissociate, and it happens when the temperature is about 0.7 MeV, low by GRB standards. Dissociation of helium and heavier elements results in nearly equal amounts of neutrons and protons. Neutrons become the dominant dissociation product if a GRB progenitor is a neutron star.

Should a GRB arise not from a neutron star or a white dwarf, but from a non-degenerate star composed mainly of hydrogen, another process will come into play. Before protons get into a fireball they are "cooked" for a while in a thermal bath of electron-positron plasma, where some of them are converted to neutrons: $p+e^- \to n+\nu$. The equilibrium densities of protons and neutrons are roughly the same provided the temperature of a GRB source is well above 1 MeV. However, it takes quite a long time for weak interaction to reach an equilibrium (Shapiro & Teukolsky 1983):

$$t_{\rm w} \sim \frac{60\pi^3\hbar^7c^6}{Q^5G_{\rm F}^2(1+3g_{\rm A}^2)} \simeq 3.25\times10^{-2}\,{\rm s}\left(\frac{Q}{10\,{\rm MeV}}\right)^{-5}. \quad (1)$$

Here $G_{\rm F} \simeq 10^{-49}$ erg$\cdot$ cm^3 is the Fermi constant, Q the energy of interacting particles ($Q \simeq 3\,T_0$ for thermal Fermi distribution), $g_{\rm A} \simeq 1.25$, c the velocity of light.

The time (1) must be compared with the lifetime of a central engine. At present, the latter cannot be measured directly. Instead, we estimate the minimum burst duration as the Keplerian time for a source,

$$t_{\rm k} = \sqrt{2\pi R_{\rm src}^3/GM_{\rm src}}\,, \quad (2)$$

which is the smallest global dynamical timescale. Here $R_{\rm src}$ and $M_{\rm src}$ are the size and the mass of a source, $G \simeq 6.67\times 10^{-8}$ cm^{3}g^{-1} s^{-2} is the gravitational constant. In jet sources, the mass and radius of the core, $M_{\rm c}$ and R_0, may be significantly smaller than $M_{\rm src}$ and $R_{\rm src}$.

The condition $t_{\rm w} < t_{\rm k}$ implies $T_0 > 8$ MeV if the source is a neutron star. At the same time, the temperature of a blackbody – which has the largest possible luminosity – must be higher in order to fulfil the energy requirements of cosmological GRBs, at least 10^{51} ergs assuming isotropic emission. So, the equilibrium is reached in this case.

Alternatively, a GRB source could evolve from a non-degenerate hydrogen star, which undergoes compression to a density above 10^6 g/cm^3 as imposed by the need to have the Keplerian time smaller than a typical GRB duration, say, 5 s. During compression, the temperature rises approaching the virial value and, by any means, it is much higher than the electron Fermi energy in the degenerate gas of that density, i.e., $T_0 \gg 0.5$ MeV. On the other hand, the condition $t_{\rm w} < t_{\rm k}$ yields that $T_0 > 1$ MeV is sufficient to set up the equilibrium. Thus, the neutron and proton densities appear to be balanced in this case also.

The same process of thermal relaxation could cause the opposite result. If the equilibrium were maintained down to the temperature significantly below $(m_{\rm n}-m_{\rm p})c^2 \simeq 1$ MeV, the ratio of neutron density to proton one would become exponentially small. Actually, in an expanding fireball this ratio is frozen starting from higher temperatures $T \gtrsim 1$ MeV, when $t_{\rm w}$ grows larger than the expansion timescale of relativistic wind, $R_0/c \lesssim 10^{-2}$ s. The last expression is valid at the linear acceleration stage where the Lorentz factor of an outflow, Γ, is proportional to radius. In a fireball of cosmological GRB, which should have a terminal Lorentz factor $\Gamma_{\rm p}$ greater than 100 (Baring & Harding 1995), the temperature above 1 MeV can exist only at this stage.

We will not discuss cosmological GRB models based on non-stellar sources, because there is no observational evidence in favour of them. However, basically the same arguments may be applied to these models as well. The general conclusion is that free neutrons form in the sources of cosmological GRBs, get into relativistic wind and survive there despite the temperature in the local comoving frame of expanding fireball drops below 1 MeV.

Following subsequent decrease of temperature, neutrons may be lost due to recombination with protons. Such a recombination proceeds in several ways:

$$d+d\to t+p, \quad t+d\to {}^4He+n\,; \quad (3)$$

$$d+d\to {}^3He+n, \quad {}^3He+d\to {}^4He+p\,; \quad (4)$$

$$d+d\to {}^3He+n, \quad {}^3He+n\to t+p, \quad t+d\to {}^4He+n. \quad (5)$$

Here d and t mean deuterium and tritium. All these reaction chains allow cumulative representation, $3d \to {}^4He+p+n$, and begin with the formation of deuterium, $p+n\to d+\gamma$, which is relatively slow and hence limits the overall rate of recombination. The latter does not start until the formation of deuterium prevails over its thermal destruction, i.e., until the temperature in the local comoving frame is below $T_{\rm rec} \simeq 70\,$keV. The exact value of $T_{\rm rec}$, a bit larger than the temperature of dissociation, has a weak logarithmic dependence on the nucleon density, which we ignore in the following discussion. We take the reference nucleon density $\rho_{\rm rec} \sim 10\,$g/cm^3, i.e., close to the radiation density at the temperature $T_{\rm rec}$.

The necessary condition for preserving neutrons free is defined by the optical depth for their capture on protons:

$$\tau_{\rm c} = \int_{R_{\rm rec}}^{\infty} \frac{2}{3}\,\langle\sigma_{\rm d}v\rangle\, n_{\rm p} dt_0 \,<1. \quad (6)$$

Here $dt_0 = dR/c\Gamma$ is the time interval and $n_{\rm p}$ is the proton number density, both in the local comoving frame, the radius $R_{\rm rec}$ corresponds to the onset of the recombination. The rate of deuterium formation is virtually constant at the temperature $T_{\rm rec}$ and below it, $\langle\sigma_{\rm d}v\rangle \simeq 5\times10^{-20}$ cm^3 s^{-1}; two-thirds of this value is taken in Eq. (6) because three deutrons fuse to form only one helium nucleus. The remaining fraction of free neutrons is about $(\tau_{\rm c}+1)^{-1}$, so that elimination of the neutron component implies $\tau_{\rm c} \gtrsim 10$.

To estimate the integral (6) we assume a simple model in which the Lorentz factor of a fireball grows linearly at $R<R_{\rm s}$ and is practically equal to its terminal value $\Gamma_{\rm p}$ at $R>R_{\rm s}$. The temperature at the saturation radius $R_{\rm s}$ is approximately equal to $T_0/\Gamma_{\rm p}$, and reasonable assumptions $T_0 < 10$ MeV and $\Gamma_{\rm p} > 150$ lead to the conclusion that $T_{\rm rec} > T_0/\Gamma_{\rm p}$, i.e., the recombination takes place at the linear acceleration stage. When $\Gamma \propto R$ and consequently $n_{\rm p} \propto R^{-3}$, Eq. (6) gives $\tau_{\rm c} \simeq (10^{-20}\,{\rm cm^3\,s^{-1}})(R_{\rm rec}/\Gamma_{\rm rec}c)n_{\rm p}(R_{\rm rec})$, where $\Gamma_{\rm rec} = \Gamma(R_{\rm rec}) \simeq T_0/70$ keV. The value of $n_{\rm p}(R_{\rm rec})$ may be represented as $\rho_{\rm nuc}/2m$ ($\rho_{\rm nuc}$ is the density of nucleons, m their mass), $\rho_{\rm nuc}$, in turn, constitutes $4\Gamma_{\rm rec}/3(\Gamma_{\rm p}-\Gamma_{\rm rec})$ fraction of the radiation density at the same point, and finally, the latter is determined by fixing the recombination temperature $T_{\rm rec}$. When the above considerations are consequently applied, we get

$$\tau_{\rm c} \simeq 5\times10^{-7}\,{\rm cm}^{-1}\frac{R_{\rm rec}}{\Gamma_{\rm rec}}\frac{T_0}{70\,{\rm keV}\Gamma_{\rm p}} \simeq \frac{R_0}{1\,{\rm km}}\frac{T_0}{1.5\,{\rm MeV}}\frac{1}{\Gamma_{\rm p}}. \quad (7)$$

Here we substitute an effective radius of the source $R_{\rm rec}/\Gamma_{\rm rec}$ by R_0; two values are nearly the same for the radiation-driven fireball, and in the case of MHD-wind the effective radius may be considerably smaller than the actual one.

It is usually thought that ultrarelativistic winds trace their origin down to $\sim 3R_{\rm g}$ (here $R_{\rm g}$ is Schwarzschild radius of the core) from the compact central engine. Suppose $R_0 = 3R_{\rm g}$, then Eq. (7) provides a link between the presence of free neutrons in a fireball and the mass of a central engine. For more or less standard GRB models with $\Gamma_{\rm p} = 200$–500 and $T_0 \sim 10$ MeV, neutrons remain free if the mass of the core $M_{\rm c} \lesssim 3$–$8M_\odot$, and the elimination of free neutrons requires $M_{\rm c} \gtrsim 30$–$80M_\odot$.

The net outcome is that free neutrons, which must form in GRB sources, can usually escape capturing on protons unless the core of stellar-type source is very massive and generates a fireball with low (by GRB standards) Lorentz factor. It should be noted that GRB progenitors of the latter kind can hardly account for short (a few seconds or shorter) bursts.

3. Classification of lightcurves

Specific influence of the neutron component of relativistic wind on the shock formed by its plasma component largely depends on whether the two flows decouple or not. The effect of decoupling (Derishev, Kocharovsky & Kocharovsky 1999) may be described as follows. Free neutrons, which come out from a GRB source, are accelerated only via collisions with protons (or heavier ions, if present). With expansion of a fireball, the collision rate decreases and at some radius becomes so small that the majority of neutrons can escape to infinity without further collisions. If this "neutronosphere" is closer to the source than the saturation radius, the terminal Lorentz factor of the neutron flow, $\Gamma_{\rm n}$, is smaller than that of the plasma (proton) flow. *Decoupling* occurs when velocity difference between protons and neutrons grows up to a relativistic value, $\simeq 0.5\,c$. This has an important consequences for the shape of a function $\Gamma_{\rm n}(\Gamma_{\rm p})$ at given luminosity. With decreasing baryon load, i.e., with increasing $\Gamma_{\rm p}$, the Lorentz factor of the neutron flow grows at first, reaches maximum near the decoupling threshold, and then declines. The latter is evident: very low baryon load means smaller density of nucleons, so that neutrons rarer collide with protons and decouple at smaller radius, i.e., reach smaller Lorentz factor. For radiation-driven fireballs, decoupling is possible when $T_0/\Gamma_{\rm p} < 5$ keV. From the above principles one may deduce analogous condition for MHD-driven wind.

Below we assume that a GRB source generates a fireball with comparable fluxes of protons (ions) and neutrons having either equal or different Lorentz factors, $\Gamma_{\rm p}$ and $\Gamma_{\rm n}$. We also assume that the fireball ejection lasts for a time period much shorter than a GRB duration.

The plasma component of a fireball pushes the surrounding medium and forms a shock at the interface, while neutrons propagate freely until they decay into charged particles. There are two independent alternatives: (i) the neutron flow may decouple from the proton one or may not, and (ii) the lifetime of a free neutron, $t_{\rm n}$, either exceeds or is smaller than the deceleration time of the proton shock, $t_{\rm p}$. A source satisfying the condition of decoupling will be a typical GRB representative. The apparent lifetime of free neutrons, ~ 900 s $/\Gamma_{\rm n}$, also appears to be comparable with duration of an ordinary burst. Therefore, the above two alternatives produce four combinations; each one gives rise to a distinct type of lightcurves.

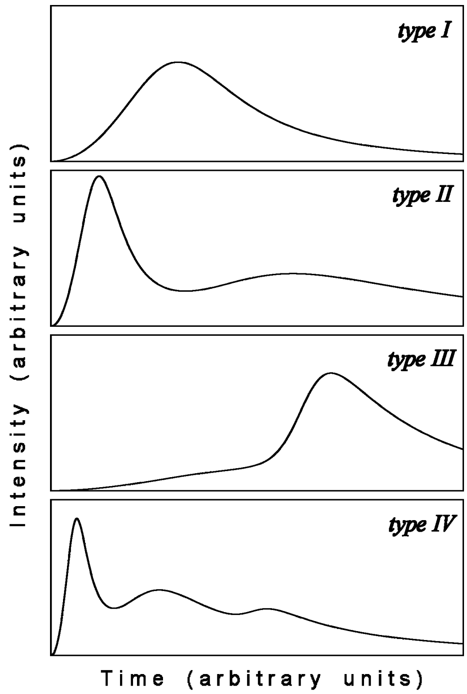

Fig. 1. Four types of GRB bolometric lightcurves. Proportions are not exactly maintained.

First case: $t_{\rm n} < t_{\rm p}$, no decoupling. It is the simplest case, which is practically indistinguishable from the standard GRB model considering a shock formed by one-component fireball (Mészáros, Laguna & Rees 1993). Assuming the radiative regime of shock deceleration, when all the energy of the swept up interstellar gas is immediately radiated, one has:

$$\frac{\Gamma+1}{\Gamma-1} = \frac{\Gamma_{\rm p}+1}{\Gamma_{\rm p}-1}\left(\frac{M}{M_0}\right)^2 . \qquad (8)$$

Here Γ and M are the Lorentz factor and the mass of the shock ($\Gamma_{\rm p}$, M_0 are the initial values). The resulting type I lightcurve has a single peak, and its rise time and decay time are comparable with the total duration of burst.

Second case: $t_{\rm n} < t_{\rm p}$, neutron flow decouples. The proton shock moves ahead of slower neutrons and gradually decelerates. Neutrons have decayed before their decay products approach the sufficiently decelerated primary shock. Two shells collide at a radius defined by the equation $\int_0^{R_{\rm c}} \beta\, dR = \beta_{\rm n} R$, where β is (decreasing with radius) velocity of the proton shock, $\beta_{\rm n}$ is (constant) velocity of neutrons. As may be shown with the help of Eq. (8), at the radius $R_{\rm c}$ the Lorentz factors of protons and neutrons satisfy the relation $\Gamma_{\rm n}^2/\Gamma^2 \simeq 7$ (in the case of adiabatic deceleration it will be $\Gamma_{\rm n}^2/\Gamma^2 \simeq 4$). Faster inner shell transfers its energy to GRB envelope, thus forming a secondary shock. The bulk Lorentz factor of GRB envelope is boosted to significantly higher values, what causes another peak on the lightcurve. As the second pulse reaches its maximum, the intensity rises by approximately 7 times. The delay time of the second pulse is $\simeq (7\Gamma_{\rm p}^2/\Gamma_{\rm n}^2)^{7/6}$ times larger than the duration of the main peak.

This situation bears similarity with the model of one-flow fireball which assumes sharp and large variations of the Lorentz factor. The advantage of the proton-neutron decoupling mechanism is that it can give sharply separated shells with different Lorentz factors under more realistic assumption of a smooth variation of baryon load, and even in the case when a source evolves from decoupling to non-decoupling regime or vice versa[1]. The main properties expected for type II GRBs are: (i) the delay time of the beginning of the second pulse is approximately equal to the duration of its leading edge and (ii) the peak flux of the second pulse correlates with the flux reconstructed from the back slope of the first pulse. One more thing to be mentioned is that the second pulse may appear at the afterglow stage if the ratio $\Gamma_{\rm p}/\Gamma_{\rm n}$ is large.

Third case: $t_{\rm n} > t_{\rm p}$, no decoupling. Chargeless neutrons overtake and surpass a shock initiated by protons and then some of them decay producing secondary protons. The latter push interstellar gas ahead and hence prolong the deceleration of the primary shock till all neutrons have decayed. Decay products do not carry frozen-in magnetic field, so that the expansion of the secondary shock (which is in front of the primary one in this case) starts in the adiabatic regime and continues in the radiative regime when magnetic field grows up.

The final result of proton-neutron interplay in type III GRBs is a single-peaked lightcurve with slow rise followed by relatively sharp outburst, which occurs when the radiative regime of the shock deceleration establishes.

Fourth case: $t_{\rm n} > t_{\rm p}$, neutron flow decouples. Type IV GRBs generate the most sophisticated lightcurves, which may be considered as a hybrid of types II and III. At the beginning, the primary shock moves faster than neutrons. Neutrons surpass the primary shock when it slows down. Those of them that have already decayed by this time boost the GRB envelope and produce the second pulse, while others pass through the shock creating the geometry characteristic for type III bursts. After that point type IV GRBs follow the scenario for the third case, which predicts one more peak on the lightcurve when secondary protons form a radiative shock. So, a three-peaked lightcurve should be observed in this case and the relative heights and widths of the second and third pulses depend on the ratio $\Gamma_{\rm n}/\Gamma_{\rm p}$ and exact relationship between $t_{\rm n}$ and $t_{\rm p}$.

Clearly, there are no sharp boundaries between type I and type III bursts as well as between type II and type IV. However, lightcurves of first and second class are expected only in short GRBs with duration $\lesssim 10$ s, while longer bursts should possess lightcurves of third and forth class.

4. Final remarks

We have shown that free neutrons are very likely to be present in the fireballs of cosmological GRBs and that interaction of primary and secondary shocks may result in rather complex time histories even if the source has only one period of activity. Two separate episodes of relativistic wind ejection may already yield a lightcurve having up to seven peaks. It is clear that two-flow model of a fireball can easily account for very complicated lightcurves, though, like the hypotheses based on variations of the Lorentz factor during source's activity cycles, it cannot explain short-term variability. The latter, however, often renders the lightcurve appearance unrecognizable, so that any statistical analysis aimed to support or disprove the model must exclude from consideration all flares with steep leading and/or trailing fronts. Such methods are to be developed.

Some cosmological GRBs, perhaps as many as ten per cent, must be gravitationally lensed events. Generally speaking, lensing distorts the actual time history, so that lensed GRBs are not good candidates for studying the effects of proton-neutron interplay.

Finally, we note that decoupling of neutron flow is accompanied by emission $\sim 10^{-3}$ of the total GRB energy budget in the form of 50–100 GeV photons, which may be detected by ground-based telescopes (Derishev, Kocharovsky & Kocharovsky 1999). Since it is decoupling that separates type I and III from type II and IV bursts, there must be a correlation between an observation of a flash of energetic quanta and the shape of the lightcurve.

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[1] Such a transition means that the Lorentz factor of neutrons grows, approaches a maximum, $\Gamma_{\rm max}$, and falls again. This gives a mass distribution of ejected neutrons over their Lorentz factors with a singularity at $\Gamma_{\rm max}$.