SHORT DURATION GAMMA-RAY BURST WITH EXTENDED EMISSION

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Abstract. Assuming that the extended emission (EE) with broad dynamic range is a common property of short duration bursts, we propose a two-jet model which can describe both short main episode of hard spectra emission, specific for short bursts, and softer spectra EE by the different off axis position of the observer. The model involves a short-duration jet, which is powered by heating due to $\nu\bar{\nu}$ annihilation, and a long-lived Blandford–Znajek (BZ) jet with a significantly narrow opening angle. We also discuss observational tests of two-jet model.

1 Introduction

Prompt gamma-ray emission of SGRB consists of a short main episode, sometimes resolved into substructure of short pulses, which we call the Initial Pulse Complex (IPC). The duration, T_{90} , of the IPC of the short bursts is usually less than ~ 2 s. However, in the sum of light curves of many short bursts, aligned relative to the main peak of the IPC, significant extended emission (EE) has been observed up to ~ 100 s in different experiments and energy bands (*e.g.* Fig. 1, left).

Extended emission has actually been observed in individual light curves of some SGRB, confirmed with KONUS, BAT/Swift, BATSE, SPI-ACS/INTEGRAL. Despite the T_{90} of some bursts being less than 2 seconds, those the EE are significantly detected. Otherwise some long bursts ($T_{90} > 2$ s) could be classified as short bursts with EE. Finally, the ultimate example of an apparently long burst (Fig. 1, right) with all signatures of short bursts is Swift GRB 060614 (Gehrels *et al.* 2006).

Usually the EE has a peak flux much smaller than the analog parameters of the IPC. The ratio of the fluences of the EE and IPC can vary in a wide range. While the spectrum of EE is softer than in IPC, the EE poses the absence of spectral lag (when it can be measured due to statistical reason) which is compatible with the lag

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Fig. 1. *Left:* light curve in 50 – 300 keV energy band for 100 short (<1 s), summed, background subtracted, BATSE bursts after peak alignment, with peak time suppressed. Adapted from Connaughton 2002. *Right:* light curve of GRB 060614 in 15 – 150 keV energy band as recorded with BAT/Swift, time bin is 64 ms.

properties of IPC. Additionally, variability of the EE is not negligible. Certainly the EE can be a manifestation of prolonged activity of the central engine.

Thus one could suggest that short duration bursts have a distinctive feature, such as extended emission with very broad dynamic range of flux and fluence of the EE. We propose that EE is an inherent property of short bursts, and an observable property of the EE can be explained by the different angular position of the observer with respect to the axis of the coaxial jets (Fig. 2).

2 The model

In our model (Barkov & Pozanenko 2011), we assume the merging of two NSs or a NS+BH system which can lead to the formation of a fast-rotating black-hole ($a = J/M_{BH}^2$, where a is the dimensionless BH spin parameter). Simulations of the merging of a BH+BH or BH+NS give final values of a in the range $0.3 \leq a \leq 0.65$ (Baker *et al.* 2008), and in our calculations, we will assume $a = 0.5$, the formation of a relatively massive $M_d \sim 0.001 - 0.2 M_\odot$ and compact $R_d \sim 10^7$ cm, accretion disk.

To explain the EE of SGRBs, we suggest a two-component model with neutrino heating and an electromagnetic Blandford-Znajek (BZ) mechanism. A short main episode (IPC) of SGRB is the result of a fast accretion period, which launches a neutrino-powered jet. After a few seconds, neutrino heating becomes ineffective, however, the lower accretion rate can keep the central engine active for a longer time due to the BZ mechanism. The duration of the BZ-powered jet will depend on the mass in the accretion disk.

The accretion time of the main mass of the compact disk with radius $R_d \sim 10^7$ cm is short 0.1 – 1 s. Following Metzger *et al.* (2008), the accretion rate can be estimated as

$$\dot{M}_d \approx f M_d / t_{visc}, \quad (2.1)$$

Fig. 2. An observer will register different flux of IPC (S_1) and EE (S_2) depending on the angle of view against the axis of the jets.

where $t_{visc} = R_d^2/\nu$ is the viscosity time scale and ν is the viscosity, and the factor $f \approx 1.6$. For the viscosity we have used an α -prescription, $\nu = \alpha c_s H$, where $c_s = (P/\rho)^{1/2}$ is the isothermal sound speed and H is the half-thickness of the disc. The initial viscosity time scale is

$$t_{visc,0} \approx 0.02 \alpha_{-1}^{-1} M_{0.5}^{-1/2} R_{d,7}^{3/2} \left(\frac{H}{R_d} \right)^{-2} \text{ s}, \quad (2.2)$$

where $M_{0.5} = M/10^{0.5} M_\odot$ is the mass of the BH, $\alpha_{-1} = \alpha/0.1$ is the standard dimensionless viscosity, $R_{d,7} = R_d/10^7$ cm is the radius of the accretion disk.

We assume that only a fraction $\sim (R/R_d)^p$ of the available material is accreted onto the BH (Blandford & Begelman 1999). The rest of the mass will be lost to an outflow, and the parameter “p”, can vary from 0 (no wind) up to 1 (powerful wind). The mass accretion rate will depend on the time as $\dot{M} \sim t^{-4/3}$ and $\dot{M} \sim t^{-8/3}$ for $p = 0$, and $p = 1$, respectively. Consequently, a luminosity is linearly dependent on the accretion rate and will be influenced by magnetic flux evolution.

For the accretion of a thick disk, the maximum luminosity due to BZ mechanism can be estimated following Komissarov & Barkov (2010). The pressure of the magnetic field can be a fraction, $\beta = 8\pi P_g/B^2$, of the gas pressure in the disk at MSO, from MSO magnetic field accretes to the BH horizon. In such a way, the luminosity of the BZ mechanism becomes a weak function of the BH spin parameter, a (if $0.5 \leq a \leq 1$) and can be estimated as

$$L_{BZ} \approx \frac{0.05}{\alpha_{-1}\beta_1} \dot{M}_{in} c^2 \approx 10^{48} \alpha_{-1}^{-1} \beta_1^{-1} \dot{M}_{in,-5} \text{ erg s}^{-1}, \quad (2.3)$$

where $\beta_1 = \beta/10$.

The main source of the neutrino heating is the neutrino annihilation reaction $\nu\bar{\nu} \rightarrow e^+e^-$. The heating rate can be described by Zalamea & Beloborodov (2010)

$$L_{\nu\bar{\nu}} \approx 3 \times 10^{50} X^{-4.7} M_{BH,0.5}^{-3/2} \dot{M}_{in,0}^{9/4} \text{ ergs s}^{-1}, \quad (2.4)$$

where $X \equiv R_{\text{mso}}/4R_g$. This formula is valid when the accretion rate is higher than $\sim 0.05\alpha_{-1}^{5/3} M_\odot \text{ s}^{-1}$, this critical value of the accretion rate is a function of a . As the accretion rate becomes lower, the efficiency of neutrino heating drops dramatically and becomes negligible.

In our model, the distribution of SGRBs in the intensity of the EE is a selection effect due to different angular positions of the observer (Fig. 2) with respect to the axis of coaxial jets and a dispersion of opening angles of the $\nu\bar{\nu}$ and BZ jets. The $\nu\bar{\nu}$ -powered jet has the opening angle $\theta_{\nu\bar{\nu}} \sim 0.1$ and can be significantly wider than the opening angle of the jet powered by the BZ mechanism, $\theta_{BZ} \sim 1/\Gamma$.

3 Observational tests

There are other models of the EE (MacFadyen *et al.* 2005; Metzger *et al.* 2008; Lazatti *et al.* 2010). However we can suggest some tests to discern between models and find possible parameter of the two-jet model.

In our model the opening angle $\theta_{\nu\bar{\nu}}$ is wider than the opening angle θ_{BZ} . Actually, the ratio of $\theta_{BZ}/\theta_{\nu\bar{\nu}}$ calculated from the fluence ratio of the EE and IPC, is always less than 1 (Bostanci *et al.* 2013). Indeed, the ratio $\theta_{BZ}/\theta_{\nu\bar{\nu}}$ was calculated with a-priori suggestions about the jet luminosity.

Another test of the BZ-jet properties is a type of functional dependency of the EE with time. Luminosity is linearly dependent on the accretion rate which is described by a power law. There is a signature that the EE decay part may be described by the power law (Minaev *et al.* 2010). Indeed, the decay part of observed EE might be investigated to restrict the wind parameter p .

A further possible test might be the absence/presence of a jet break in an afterglow light curve. Jet-breaks could be observed if $1/\Gamma$ (where Γ is bulk motion Lorentz factor) less than the opening angle of the jet cone. Meanwhile, the opening angle of the jet powered by the BZ mechanism is $\theta_{BZ} \sim 1/\Gamma$. Would the nature of the GRB afterglow be only BZ-jet interacting with the ISM, we could not observe any jet break. One can suggest that if the fluence of the EE is greater than the fluence of the IPC the jet break will not occur. Other consequence of the two-jet model might be re-brightening (or second peak) in an afterglow light curve.

Since in our model $\theta_{BZ} < \theta_{\nu\bar{\nu}}$ a number density of burst with less pronounced EE is more than with EE comparable with the IPC. It is really true if we take the fluence ratio of the EE and IPC of BATSE bursts with the EE (Fig. 3). The best parameter for number density estimation is the ratio of the peak flux of EE and peak flux of IPC since peak flux is directly related with the luminosity in Equations (2.3) and (2.4).

Finally, there is a problem of dichotomy of short bursts with EE. In our model each short burst has to be accompanied by EE. However, the more off-axis the observer is placed, the less will be the intensity of EE and hence the less will be the ratio of peak fluxes of EE and IPC. The ratio tends to zero continuously. In statistical analysis of SPI-ACS/INTEGRAL short bursts without individual EE in each particular event, the EE was found in the averaged light curve (Minaev *et al.* 2010). Contrary, Norris *et al.* (2010) investigating BAT/Swift short burst

Fig. 3. Number of SGRB *vs.* fluence ratio of EE and IPC (Bostanci *et al.* 2013).

found no EE on average in an ensemble of 39 GRBs without EE in each individual event.

Finally, the occurrence of the BZ-jet depends on the initial parameters of the accretion disc (mass, radius, spin parameter; see Barkov & Pozanenko 2011). So it is not fully prohibited that in some combinations of initial parameters the BZ-jet could not be started and hence there will be no prolonged activity of the central engine. In this case the EE would be fully suppressed.

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