IL NUOVO CIMENTO Vol. 28 C, N. 3 Maggio-Giugno 2005
DOI 10.1393/ncc/i2005-10084-6

A unified model of short and long gamma-ray bursts, X-ray–rich gamma-ray bursts, and X-ray flashes(*)

R. Yamazaki(1)(**), K. Ioka(2), T. Nakamura(3) and K. Toma(3)

(1) *Department of Earth and Space Science, Osaka University - Japan*
(2) *Physics Department and Center for Gravitational Wave Physics Pennsylvania State University - PA, USA*
(3) *Department of Physics, Kyoto University - Japan*

(ricevuto il 23 Maggio 2005; pubblicato online il 15 Settembre 2005)

Summary. — We propose a possible unified model of short and long gamma-ray bursts (GRBs), X-ray–rich GRBs, and X-ray flashes. The jet of a GRB is assumed to consist of many emitting sub-shells, that is called sub-jet emissions (*i.e.*, an inhomogeneous jet model). The multiplicity of the sub-jets along a line of sight n_s is an important parameter. If n_s is large ($\gg 1$) the event looks like a long GRB, while if $n_s = 1$, the event looks like a short GRB. Finally, when $n_s = 0$, the event looks like an X-ray flash or an X-ray–rich GRB.

PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

While the association with the supernova is almost established or strongly suggested for the long gamma-ray bursts (GRBs) [1,2], the origins of short GRBs and X-ray flashes (XRFs) remain unclear. The observed event rate of short GRBs is about a third of the long GRBs, while the observed event rate of XRFs is comparable to that of long GRBs. Although there may be a possible bias effect to these statistics, these numbers are, in an astrophysical sense, the same or comparable. If these phenomena arise from essentially different origins, the similar number of events is just by chance. On the other hand, if they are related, the similar number of events is natural and the ratio of the event rate tells us something about the geometry of the central engine. We propose a unified model in which the central engine of short GRBs, long GRBs and XRFs is the same and the apparent differences come essentially from different viewing angles. For details, see [3].

(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.
(**) E-mail: ryo@vega.ess.sci.osaka-u.ac.jp

© Società Italiana di Fisica

2. – Unified model

Roughly speaking, short GRBs are similar to the first 1 s of long GRBs [4], which suggests that the difference between short and long GRBs is just the number of pulses, and each pulse is essentially the same. Thus, we may consider that each pulse is produced by essentially the same unit or the sub-jet, and the GRB jet consists of many sub-jets. If many sub-jets point to our line of sight, the event looks like the long GRB while if a single sub-jet points to us, the event looks like a short GRB. Since we can observe only the angular size of $\sim \gamma^{-1}$ within the GRB jet with the Lorentz factor γ, different observers will see different number of sub-jets depending on the distribution of sub-jets within the GRB jet.

XRFs also appear to be related to GRBs. Softer and dimmer GRBs smoothly extend to the XRFs [5-7]. Other properties of the XRFs are also similar to those of the GRBs, suggesting that XRFs are in fact soft and dim GRBs. In the sub-jet model, XRFs are naturally expected when our line of sight is off-axis to any sub-jets [8-13].

In the following, we show a numerical simulation to demonstrate how the event looks so different depending on the viewing angle in our unified model [3]. The whole jet, with an opening half-angle of $\Delta\theta_{\rm tot} \sim 0.2$ rad, consists of 350 sub-jets. All sub-jets are assumed to have the same intrinsic properties, *e.g.*, the opening half-angle $\Delta\theta^{(j)}_{\rm sub} = 0.02$ rad, and so on. We consider the case in which the angular distribution of sub-jets is given by $P(\vartheta^{(j)}) \propto \exp[-(\vartheta^{(j)}/\vartheta_c)^2/2]$, where we adopt $\vartheta_c = 0.1$ rad [14]. In this case, sub-jets are concentrated on the central region. For our adopted parameters, isolated sub-jets exist near the edge of the whole jet with the multiplicity $n_s = 1$ and there exists a viewing angle where no sub-jets are launched. The left, middle, and right panels of fig. 1 show the angular distributions of sub-jets and the directions of three selected lines of sight, the observed light curves in the γ-ray bands, and the observed time-integrated spectra, respectively.

Long GRB: When we observe the source from the $\vartheta = 0$ axis (case "A"; see the figure caption), we see spiky temporal structures (the upper-middle panel of fig. 1) and $E_p \sim 300$ keV which are typical for the long GRBs. We may identify case "A" as long GRBs.

XRF and X-ray–rich GRB: When the line of sight is away from any sub-jets (case "B"), soft and dim prompt emission, *i.e.* XRFs or X-ray–rich GRBs are observed with $E_p =$ 10–20 keV and ~ 4 orders of magnitude smaller fluence than that of case "A" (the right panel of fig. 1). The burst duration is comparable to that in case "A". These are quite similar to the characteristics of XRFs. We may identify the case "B" as XRFs or X-ray–rich GRBs.

Short GRB: If the line of sight is inside an isolated sub-jet (case "C"), its observed pulse duration is ~ 50 times smaller than in case "A". Contributions to the observed light curve from the other sub-jets are negligible, so that the fluence is about a hundredth of that of case "A". These are quite similar to the characteristics of short GRBs. However the hardness ratio ($= S(100\text{–}300\,\text{keV})/S(50\text{–}100\,\text{keV})$) is about 3 which is smaller than the mean hardness of short GRBs (~ 6). It is suggested that the hardness of short GRBs is due to the large low-energy photon index $\alpha_B \sim -0.58$ [4] so that if the central engine launches $\alpha_B \sim -0.58$ sub-jets to the periphery of the core where n_s is small, we may identify case "C" as the short-hard GRBs. In other words, the hardness of 3 comes from $\alpha_B = -1$ in our simulation so that if $\alpha_B \sim -0.58$, the hardness will be 6 or so. We suggest here that not only the isotropic energy but also the photon index may depend on ϑ. Another possibility is that if short GRBs are the first 1 s of the activity of the central

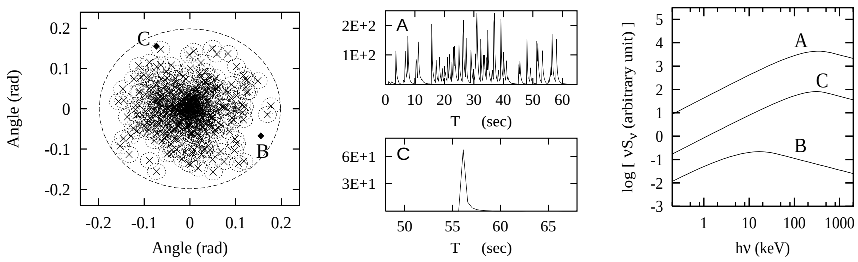

Fig. 1. – Left: The angular distribution of 350 sub-jets confined in the whole GRB jet in our simulation. The whole jet has an opening half-angle of $\Delta\theta_{\rm tot} = 0.2$ rad. The sub-jets have the same properties. The axes and the angular size of sub-jets are represented by crosses and dotted circles, respectively. "A" represents the center of the whole jet and is hidden by the lines of sub-jets. Middle: The observed γ-ray light curves, corresponding to cases "A"and "C" in the left panel. Right: Time-integrated energy spectrum of the emission from the multiple sub-jets for the observers denoted by "A", "B", and "C". The source is located at $z = 1$.

engine, the spectrum in the early time might be $\alpha_B \sim -0.58$ for both the sub-jets in the core and the envelope. This is consistent with a high KS test probability for E_p and α_B [4]. These possibilities may have something to do with the origin of $\alpha_B \sim -1$ for the long GRBs.

3. – Discussions

Let $\Delta\theta_{\rm sub}$, ϑ_c and $\bar{n}_s$ be the typical opening half-angle of the sub-jet, the core size of the whole jet and the mean multiplicity in the core. Then the total number of the sub-jets ($N_{\rm tot}$) is estimated as $N_{\rm tot} = \bar{n}_s(\vartheta_c/\Delta\theta_{\rm sub})^2 \sim 10^3$, so that the total energy of each sub-jet is $\sim 10^{48}$ erg. In our model, the event rate of long GRBs is in proportion to ϑ_c^2. Let M be the number of sub-jets in the envelope of the core with a multiplicity $n_s = 1$. Then the event rate of short GRBs is in proportion to $M\Delta\theta_{\rm sub}^2$, so that $M \sim 10$ is enough to explain the event rate of short GRBs.

In this paper, we have not discussed the origin of the sub-jets, but argued the implications of the sub-jet model. The origin of sub-jets is not yet clear. They may arise from relativistically outflowing blobs generated by various fluid instabilities like Kelvin-Helmholtz, Rayleigh-Taylor instability, and so on [15-17].

The afterglow could have a different behavior between the core-envelope sub-jet model and the uniform jet model. In the uniform jet model, the afterglows of XRFs should resemble the orphan afterglows that initially have a rising light curve [18,19]. An orphan afterglow may be actually observed in XRF 030723 [20], but the light curve may peak too early [14]. The optical afterglow of XRF 020903 is not observed initially (< 0.9 days) but may not be consistent with the orphan afterglow [21]. These problems could be overcome by introducing a Gaussian tail with a high Lorentz factor around the uniform jet [14] because the energy redistribution effects may bring the rising light curve to earlier times [14, 22]. Therefore, as long as the observer points within or slightly off-axis to the whole jet, the late phase properties of XRF afterglow may be similar to those of long GRBs. On the other hand, when the whole jet is viewed far from the edge of the jet, such that $\vartheta_{\rm obs} \gg \Delta\theta_{\rm tot}$, XRF afterglows may resemble the orphan afterglow (*e.g.*, see the upper-left panel of fig. 5 in ref [22]). Because of the relativistic beaming effect, the latter are dimmer than the former in both the prompt and afterglow phase, so that they may be rarely observed, but we believe XRF 030723 is a member of such a class. The afterglow of a short GRB may be difficult to predict since it could resemble both the orphan and normal afterglow depending on the sub-jet configuration within the envelope.

It is also found that our model can reproduce the bimodal distribution of T_{90} duration of GRBs observed by BATSE [23] (see also these proceedings). It has commonly been said that the observed bimodal distribution of T_{90} durations of BATSE bursts shows the different origins of short and long GRBs. However, the bimodal distribution is also available as a natural consequence of our unified model of short and long GRBs. A clear prediction of our unified model is that short GRBs should be associated with energetic SNe.

Interestingly, our model has predicted short XRFs or short X-ray–rich GRBs [3]. They are observed when isolated sub-jets are viewed slightly off-axis. The observed short XRF 040924 may be a kind of these bursts [24].

* * *

This work was supported in part by a Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science and Technology, No.05008 (RY), No.14047212 (TN), and No.14204024 (TN).

REFERENCES

[1] Stanek K. Z. *et al.*, *ApJ*, **591** (2003) L17.
[2] Hjorth J. *et al.*, *Nature*, **423** (2003) 847.
[3] Yamazaki R. *et al.*, *ApJL*, **607** (2004) L103.
[4] Ghirlanda G. *et al.*, *A&A*, **422** (2004) L55.
[5] Heise J. *et al.*, *2nd Rome Workshop: Gamma-Ray Bursts in the Afterglow Era*, edited by Costa E., Frontera F. and Hjorth J. (Berlin, Springer) 2001, p. 16.
[6] Kippen R. *et al.*, *AIP Conf. Proc.*, **662** (2002) 244.
[7] Sakamoto T. *et al.*, *ApJ*, **602** (2004) 875.
[8] Nakamura T., *ApJL*, **534** (2000) L159.
[9] Ioka K. and Nakamura T., *ApJL*, **554** (2001) L163.
[10] Yamazaki R. *et al.*, *ApJL*, **571** (2002) L31.
[11] Yamazaki R. *et al.*, *ApJ*, **593** (2003) 941.
[12] Yamazaki R. *et al.*, *ApJL*, **594** (2003) L79.
[13] Yamazaki R. *et al.*, *ApJL*, **606** (2004) L33.
[14] Zhang B. *et al.*, *ApJL*, **601** (2004) L119.
[15] Aloy M. A. *et al.*, *A&A*, **396** (2002) 693.
[16] Zhang W. *et al.*, *ApJ*, **608** (2004) 365.
[17] Gomez E. *et al.*, preprint astro-ph/0311134.
[18] Yamazaki R. *et al.*, *ApJ*, **591** (2003) 283.
[19] Granot J. *et al.*, *ApJL*, **570** (2002) L61.
[20] Fynbo J. P. U. *et al.*, *ApJ*, **609** (2004) 962.
[21] Soderberg A. M. *et al.*, *ApJ*, **606** (2004) 994.
[22] Kumar P. and Granot J., *ApJ*, **591** (2003) 1075.
[23] Toma K. *et al.*, *ApJ*, **620** (2005) 835.
[24] Fenimore E. *et al.*, GCN Circ. 2735 (2004).