IL NUOVO CIMENTO Vol. 28 C, N. 3 Maggio-Giugno 2005
DOI 10.1393/ncc/i2005-10081-9

A possible origin of bimodal duration distribution of gamma-ray bursts(*)

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

Summary. — We study the distribution of the durations of gamma-ray bursts (GRBs) in the unified model of short and long GRBs recently proposed by Yamazaki, Ioka, and Nakamura. Monte Carlo simulations show clear bimodal distributions, with lognormal-like shapes for both short and long GRBs, in a power law as well as a Gaussian angular distribution of the subjets. We find that the bimodality comes from the existence of the discrete emission regions (subjets or patchy shells) in the GRB jet.

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

1. – Introduction

The durations of gamma-ray bursts (GRBs) observed by BATSE show a bimodal distribution, which has led to a classification of GRBs into two groups: bursts with T_{90} durations $< 2\,\mathrm{s}$ are called short GRBs, and those with durations $> 2\,\mathrm{s}$ are called long GRBs [1,2]. If T_{90} directly reflects the active time of the progenitor of the GRB, different origins of short and long bursts are implied, such that the former arise from the binary neutron star mergers while the latter arise from the collapse of massive stars.

The short and long bursts roughly consist of 25% and 75%, respectively, of the total BATSE GRB population. We should regard these fractions as comparable, considering possible instrumental effects on the statistics. If these two phenomena arise from essentially different origins, the similar number of events is just by chance. However, some observations have suggested that the short GRBs are similar to the long GRBs [3-7]. Motivated by these facts, Yamazaki, Ioka, and Nakamura (2004) ([8]; see also these proceedings) proposed a unified model of short and long GRBs, even including X-ray flashes (XRFs) and X-ray–rich GRBs (XRRs), and showed that it is possible to attribute the

(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.
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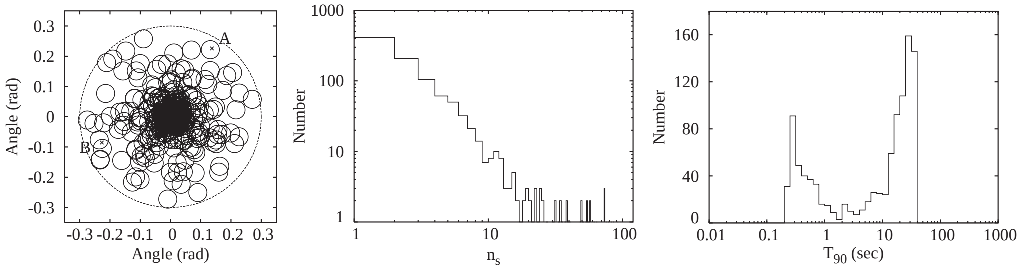

Fig. 1. – Left: Angular distribution of 350 subjets confined in the whole GRB jet in our simulation. The effective angular size of the subjets are represented by the solid circles, while the whole jet is represented by the dashed circle. The examples of lines of sight A and B are shown in the figure, while C is located at (−0.04 rad, 0.04 rad), and D is close to the center of the whole jet. Center: Distribution of multiplicity n_s for the angular distribution of the subjets of the left panel. Right: T_{90} duration distribution in the 50–300 keV band of hard events. All sources are located at $z = 1$.

apparent differences of the light curves and spectra of these four kinds of events to the different viewing angles of the same GRB jet. See also [9].

2. – Unified model of short and long GRBs

We assume that the GRB jet is not uniform but made up of multiple subjets, and that each subjet causes a spike in the observed light curve. This is an extreme case of an inhomogeneous jet model [10, 11]. The crucial parameter in our model is the multiplicity (n_s) of the subjets along a line of sight. Events with high n_s are long GRBs, while events with $n_s = 1$ are short GRBs. Specifically, we suppose that 350 subjets are launched from the central engine of the GRB randomly in time and directions, being confined in the whole jet with opening half-angle $\Delta\theta_{\rm tot} = 0.3$ rad. The departure time of each subjet $t_{\rm dep}^{(j)}$ is assumed to be homogeneously random between $t = 0$ and $t = t_{\rm dur}$, where $t_{\rm dur}$ is the active time of the central engine measured in its own frame and is set to $t_{\rm dur} = 20$ s. The emission model for each subjet is the same as the uniform jet model in [12]. For simplicity, all the subjets are assumed to have the same intrinsic properties (*e.g.*, the opening half-angle $\Delta\theta_{\rm sub}^{(j)} = 0.02$ rad). We randomly spread the subjets following the angular distribution function $\mathrm{d}N/\mathrm{d}\Omega = n_c(\vartheta/\vartheta_c)^{-2}$ for $\vartheta_c < \vartheta < \Delta\theta_{\rm tot} - \Delta\theta_{\rm sub}$, while for $0 < \vartheta < \vartheta_c$ $\mathrm{d}N/\mathrm{d}\Omega = n_c$, and adopt $\vartheta_c = 0.02$ rad. Figure 1 (*left*) shows an example of the angular distribution of *effective* emission regions of the subjets whose angular size is $\Delta\theta_{\rm sub} + \gamma^{-1}$. When the viewing angle θ_v is larger than this angular size, the subjet emission is dim and soft because of relativistic effects [13].

3. – Distribution of T_{90} durations of GRBs

We perform Monte Carlo simulations to show that our unified model can explain the observed bimodal distribution of T_{90} durations of GRBs. We fix the subjets' configuration as in fig. 1 (*left*). We generate 2000 lines of sight with $0 < \vartheta_{\rm obs} < 0.35$ rad according to the probability distribution of $\sin\vartheta_{\rm obs}\, d\vartheta_{\rm obs}\, d\varphi_{\rm obs}$, and calculate the T_{90} duration for each observer in the 50–300 keV band. We then select only hard events, whose observed hardness ratio is $S(2\text{–}30\,\mathrm{keV})/S(30\text{–}400\,\mathrm{keV}) < 10^{-0.5}$, following the definition of GRBs by HETE team. The other soft events are classified as XRFs or XRRs, which are observed

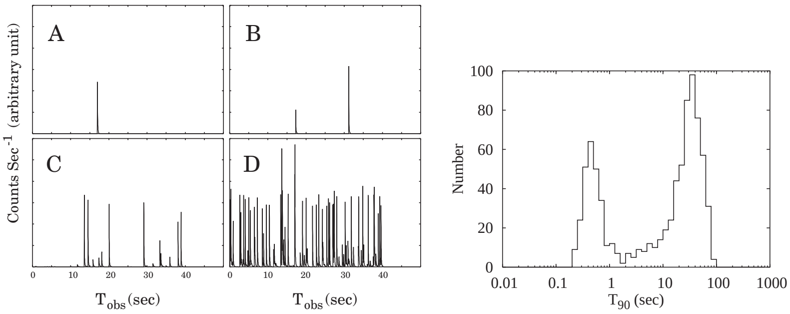

Fig. 2. – Left: Observed light curves in the 50–300 keV band for the lines of sight shown in fig. 1 (*left*): A with $n_s = 1$ (*upper left*), B with $n_s = 2$ (*upper right*), C with $n_s = 15$ (*lower left*), and D with $n_s = 97$ (*lower right*). The sources are located at $z = 1$. The T_{90} durations are 0.25 s for A, 14.1 s for B, 25.4 s for C, and 37.8 s for D. Right: Same as fig. 1 (*right*), but the source redshifts are varied according to the cosmic star formation rate (see text for details).

when all subjets are viewed off-axis [12]. Figure 1 (*center*) shows the distribution of n_s in our simulation. We first consider the T_{90} distribution in the case in which the redshifts of all the sources are fixed at $z = 1$ for simplicity. The result is shown in fig. 1 (*right*). One can see a bimodal distribution of T_{90} clearly.

Which type of burst is observed, long or short, depends on n_s, and the distribution of n_s is unimodal. Then why does the distribution of the duration become bimodal? We explain the reason for the scarcity of the events for $1 < T_{90} < 10\,\mathrm{s}$, using the examples of the lightcurves in the 50–300 keV band presented in fig. 2 (*left*). The lightcurves correspond to the line of sights A, B, C, and D shown in fig. 1 (*left*), respectively. Let us first consider the event with $n_s = 1$. In this case the T_{90} duration does not vary significantly around $\sim 0.25\,\mathrm{s}$ when $\theta_v < \Delta\theta_{\mathrm{sub}}$, which is determined by the angular spreading time of a subjet. As the viewing angle increases, T_{90} increases [13]. When $\theta_v > \Delta\theta_{\mathrm{sub}} + \gamma^{-1}$, however, the emission becomes soft and dim, so that the event will not be detected as a GRB [12]. The T_{90} takes a maximum value of $\sim 0.75\,\mathrm{s}$ when $\theta_v \sim \Delta\theta_{\mathrm{sub}} + \gamma^{-1}$. We confirm that $n_s = 1$ for almost all $T_{90} < 1\,\mathrm{s}$ events. Next let us consider the $n_s = 2$ case. The example of the light curve for this case is fig. 2 (*left*) B, and the T_{90} is 14.1 s. The T_{90} duration is roughly given by the interval between the arrival times of two pulses. Since the two pulses arrive sometime in the range $0 < T_{\mathrm{obs}} < T_{\mathrm{dur}}$, where T_{dur} is the active time of the central engine measured in the observer's frame, $T_{\mathrm{dur}} = (1 + z)t_{\mathrm{dur}} = 40\,\mathrm{s}$, the mean interval is $40/3 = 13.3\,\mathrm{s}$. This means that the duration of the $n_s = 2$ event is much longer than that for $n_s = 1$. For $n_s \geq 3$, the mean duration is longer than 13.3 s. The typical example is fig. 2 (*left*) C for $n_s = 15$, with $T_{90} = 25.4\,\mathrm{s}$. This is the reason we have few events for $1 < T_{90} < 10\,\mathrm{s}$. The maximum value of T_{90} is $\sim T_{\mathrm{dur}}$, which can be seen in the example D.

The ratio of events of the short GRBs and the long GRBs is about 2 : 5, which can be explained as follows [8]. The event rate of the long GRBs is in proportion to the effective angular size of the central core ${\vartheta_{c,eff}}^2 \sim (0.15\,\mathrm{rad})^2$, where $n_s \geq 2$. The event rate of the short GRBs is in proportion to $M(\Delta\theta_{\mathrm{sub}} + \gamma^{-1})^2$, where M is the number of isolated subjets in the envelope of the core and $M \sim 10$ in our present case. Then the ratio of event rates of the short and long GRBs becomes $M(\Delta\theta_{\mathrm{sub}} + \gamma^{-1})^2 : {\vartheta_{c,eff}}^2 \sim 2 : 5$.

In reality, we should take into account the source redshift distribution. We assume that the rate of GRBs is in proportion to the cosmic star formation rate. We adopt the model SF2 in [14], in which we take the standard cosmological parameters of $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. The result (fig. 2; *right*) is again clearly bimodal, and the shapes of the short and long GRBs look like lognormal distributions (see [15]).

4. – Conclusion

We have investigated the T_{90} duration distribution of GRBs under the unified model of short and long GRBs proposed by [8], and found that the model can reproduce the bimodal distribution observed by BATSE. In our model, the crucial parameter is the multiplicity (n_s) of the subjets in the direction of the observer. The duration of an $n_s = 1$ burst is determined by the angular spreading time of one subjet emission, while that of an $n_s \geq 2$ burst is determined by the time interval between the observed first pulse and the last one. These two different time scales naturally lead to a division of the burst T_{90} durations into the short and long ones. We also performed a similar calculation for a Gaussian distribution, $\mathrm{d}N/\mathrm{d}\Omega = n_c \exp\left[-(\vartheta/\vartheta_c)^2/2\right]$, and found that the T_{90} duration distribution is bimodal in the same way as for the power law subjet model.

At present we assume that a subjet produces one pulse and all the subjets have the same intrinsic properties for simple calculations. In reality, there are more complicated temporal properties of short and long GRBs; *e.g.*, according to the analysis of temporal profiles of short GRBs with 2 ms resolution, they also consist of several pulses [5] (see also [9]). We hope that in the future more sophisticated modeling will reproduce such properties.

It has commonly been said that the observed bimodal distribution of the 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. The clear prediction of our unified model is that short GRBs are associated with energetic supernovae (SNe). Indeed, one of the short GRBs shows possible association with a SN [3].

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This work was supported in part by a Grant-in-Aid for the 21st Century COE "Center for Diversity and University in Physics" and also by Grants-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science, and Technology 05008 (R. Y.), 14047212 (T. N.), and 14204024 (T. N.).

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