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A UNIFIED MODEL OF SHORT AND LONG GAMMA-RAY BURSTS, X-RAY–RICH GAMMA-RAY BURSTS, AND X-RAY FLASHES

Ryo Yamazaki,[1] Kunihito Ioka,[2] and Takashi Nakamura[1]
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ABSTRACT

Taking into account the recent suggestion that a short gamma-ray burst (GRB) looks like the first 1 s of a long GRB, we propose that the jet of a GRB consists of multiple subjets or subshells (i.e., an inhomogeneous jet model). The multiplicity of the subjets 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 is small (~ 1) the event looks like a short GRB. If our line of sight is off-axis to any subjets, the event looks like an X-ray flash or an X-ray–rich GRB. The lognormal distribution of durations of short and long GRBs are also suggested in the same model.

Subject headings: gamma rays: bursts — gamma rays: theory

1. INTRODUCTION

For long gamma-ray bursts (GRBs), the cosmological distance, the collimated jet, the massive star progenitor, and the association with the supernova are almost established or strongly suggested (e.g., Mészáros 2002; Zhang & Mészáros 2004). However, for short GRBs, little is known since no afterglow has been observed. The origin of X-ray flashes (XRFs) also remains unclear, although many models have been proposed (see Yamazaki et al. 2004 and references therein). The observed event rate of short GRBs is about a third of long GRBs, while the observed event rate of XRFs is also about a third (Heise et al. 2001; Kippen et al. 2003; Lamb et al. 2004). Although there may be a possible bias effect to these statistics, in an astrophysical sense, these numbers are the same or comparable. If these three phenomena arise from essentially different origins, the similar number of events is just by chance. If these three phenomena are related like Seyfert 1 and 2 galaxies, the similar number of events is natural and the ratio of the event rate tells us something about the geometry of the central engine (Awaki et al. 1991; Antonucci 1993; Urry & Padovani 1995). In this Letter, 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.

2. UNIFIED MODEL

It has been suggested that short GRBs are similar to the first 1 s of long GRBs (Ghirlanda et al. 2003). Although short GRBs are harder than long GRBs (Kouveliotou et al. 1993), this difference is mainly due to the difference in the low-energy spectral slope while the peak energy is similar (Ghirlanda et al. 2003). Other properties, such as $\langle V/V_{\max}\rangle$, the angular distribution, the energy dependence of the duration, and the hard-to-soft spectral evolution of short GRBs, are also similar to those of long GRBs (Lamb et al. 2002). If short GRBs also obey the peak energy–luminosity relation found for long GRBs (Yonetoku et al. 2004), it is suggested that short and long GRBs have a similar redshift distribution (Ghirlanda et al. 2003).[3]

These similarities suggest that the difference between short and long GRBs is just the number of pulses, and each pulse is essentially the same (Ramirez-Ruiz & Fenimore 2000). As shown in Figure 1, using the BATSE 4B Catalog (Paciesas et al. 1999), the fluence is roughly in proportion to the duration in the range of 0.01–1000 s (see also Balázs et al. 2003). Thus, we may consider that each pulse is produced by essentially the same unit or the subjet, and the GRB jet consists of many subjets. If many subjets point to our line of sight, the event looks like a long GRB, while if a single subjet 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 a different number of subjets depending on the distribution of subjets within the GRB jet. Since the angular size of a causally connected region is also $\gamma^{-1} < 0.01$, the opening half-angle of a subjet can be much smaller than that of the whole GRB jet ($\sim$0.1), say $\sim$0.02.

XRFs also appear to be related to GRBs. Softer and dimmer GRBs smoothly extend to the XRFs (Heise et al. 2001; Kippen et al. 2003; Lamb et al. 2004; Watson et al. 2004), while the peak energy–isotropic luminosity/energy relations hold for GRBs as well as XRFs (Sakamoto et al. 2004; Yonetoku et al. 2004; Amati et al. 2002). The total energy including the radio afterglow of XRF 020903, which has a measured redshift, might be similar to that of GRBs (Soderberg et al. 2004). Other properties, such as the duration, the temporal structure, and the Band spectrum of XRFs are also similar to those of GRBs, suggesting that XRFs are in fact soft and dim GRBs. In the subjet model, XRFs are naturally expected when our line of sight is off-axis to any subjets (Nakamura 2000; Ioka & Nakamura 2001; Yamazaki et al. 2002, 2003b, 2004).

The origin of subjets is not yet clear. In this Letter, we do not discuss the origin of the subjets but argue the implications of the subjet model.

3. AN EXAMPLE OF A NUMERICAL SIMULATION OF OUR UNIFIED MODEL

We first show a numerical simulation to demonstrate how an event looks so different depending on the viewing angle in our unified model. Let us consider $N_{\rm tot} = 350$ subjets, for simplicity, confined in the whole GRB jet whose axis is the same as a $\vartheta = 0$ axis. For each subjet, the emission model is the same as in Yamazaki et al. (2003b). Let the opening half-angle of the jth subjet ($j = 1, \ldots, N_{\rm tot}$) be $\Delta\theta_{\rm sub}^{(j)}$, while the opening half-angle of the whole jet is $\Delta\theta_{\rm tot}$. The direction of the observer and the axis

[1] Department of Physics, Kyoto University, Kyoto 606-8502, Japan.

[2] Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan.

[3] Even if the afterglows of the short and long GRBs have a similar mechanism, the current limits are still consistent with the lack of afterglows for short GRBs (Hurley et al. 2002; Lamb et al. 2002; Klotz et al. 2003).

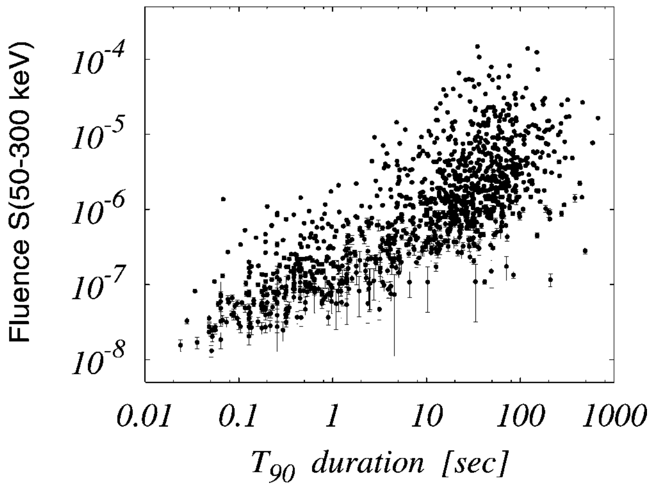

FIG. 1.—Fluence S(50–300 keV) as a function of T_{90} duration for BATSE bursts from the BATSE 4B Catalog (courtesy of S. Michikoshi and T. Suyama).

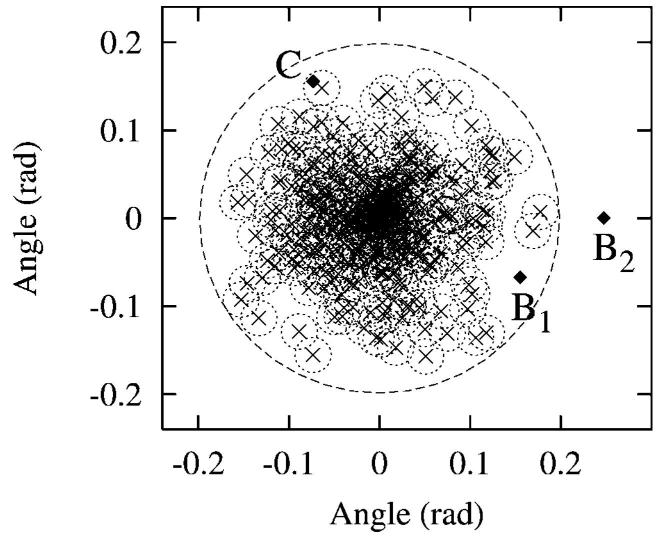

FIG. 2.—Angular distribution of $N_{\rm tot} = 350$ subjets confined in the whole GRB jet in our simulation. The whole jet has the opening half-angle of $\Delta\theta_{\rm tot} = 0.2$ rad. The subjets have the same intrinsic luminosity, opening half-angles $\Delta\theta_{\rm sub} = 0.02$ rad, and other properties: $\gamma = 100$, $r = 10^{14}$ cm, $\alpha_B = -1$, $\beta_B = -2.5$, $h\gamma\nu' = 500$ keV. The axes and the angular size of subjets are represented by crosses and dotted circles, respectively. "A" represents the center of the whole jet and is hidden by the lines of subjets.

of the jth subjet are specified by $(\vartheta_{\rm obs}, \varphi_{\rm obs})$ and $(\vartheta^{(j)}, \varphi^{(j)})$, respectively. We assume the jth subjet departs at time $t^{(j)}_{\rm dep}$ from the central engine and emits at radius $r = r^{(j)}$ and time $t = t^{(j)} \equiv t^{(j)}_{\rm dep} + r^{(j)}/\beta^{(j)}c$, where t and r are measured in the central engine frame and we set $t^{(j=1)}_{\rm dep} = 0$. For simplicity, all subjets are assumed to have the same intrinsic properties, that is, $\Delta\theta^{(j)}_{\rm sub} = 0.02$ rad, $\gamma^{(j)} = 100$, $r^{(j)} = 10^{14}$ cm, $\alpha^{(j)}_B = -1$, $\beta^{(j)}_B = -2.5$, $\gamma h\nu'^{(j)}_0 = 500$ keV, and amplitude $A^{(j)} =$ const for all j. The departure time of each subjet, $t^{(j)}_{\rm dep}$, is randomly distributed 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 set to $t_{\rm dur} = 30$ s. The opening half-angle of the whole jet is set to $\Delta\theta_{\rm tot} = 0.2$ rad as a typical value. We consider the case in which the angular distribution of subjets is given by $P(\vartheta^{(j)}, \varphi^{(j)})d\vartheta^{(j)}\,d\varphi^{(j)} \propto \exp\,[-(\vartheta^{(j)}/\vartheta_c)^2/2]d\vartheta^{(j)}\,d\varphi^{(j)}$ for $\vartheta^{(j)} < \Delta\theta_{\rm tot} - \Delta\theta_{\rm sub}$, where we adopt $\vartheta_c = 0.1$ rad (Zhang et al. 2004a). In this case, subjets are concentrated on the $\vartheta = 0$ axis (i.e., the multiplicity in the center $n_s \sim 10$). For our adopted parameters, subjets are sparsely distributed in the range $\vartheta_c \lesssim \vartheta \lesssim \Delta\theta_{\rm tot}$; however, the whole jet would be entirely filled if the subjets were uniformly distributed (i.e., the mean multiplicity $n_s \sim 3$). Therefore, isolated subjets exist near the edge of the whole jet with the multiplicity $n_s \ll 1$, and there exists a viewing angle where no subjets are launched. Figures 2, 3, and 4 show the angular distributions of subjets and the directions of four selected lines of sight, the observed time-integrated spectra, and the observed light curves in the X-ray and γ-ray bands, respectively. Note that in Figure 2, "A" represents the center of the whole jet and is hidden by the lines of subjets.

Long GRB.—When we observe the source from the $\vartheta = 0$ axis (case A), we see spiky temporal structures (Fig. 3) and $E_p \sim 300$ keV, which are typical for 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 subjets (cases B_1 and B_2), 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 (Fig. 2). The burst duration is comparable to that in case A. These are quite similar to the characteristics of XRFs. We may identify cases B_1 and B_2 as XRFs or X-ray–rich GRBs.

Short GRB.—If the line of sight is inside an isolated subjet (case C), its observed pulse duration is ∼50 times smaller than case A (Fig. 3). Contributions to the observed light curve from the other subjets are negligible so that the fluence is about a hundredth of case A. These are quite similar to the characteristics of short GRBs. However, the hardness ratio [$=S$(100–300 keV)/S(50–100 keV)] is about 3, which is smaller than the mean hardness of short GRBs (∼6). Ghirlanda et al. (2003) suggested that the hardness of short GRBs is due to the large low-energy photon index $\alpha_B \sim -0.58$ so that if the central engine launches $\alpha_B \sim -0.58$ subjets 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 engine, the spectrum in the early time might be $\alpha_B \sim -0.58$ for both the subjets in the core and the envelope. This is consistent with a high Kolmogorov-Smirnov test probability for E_p and α_B (Ghirlanda et al. 2003). These possibilities may have something to do with the origin of $\alpha_B \sim -1$ for long GRBs.

X-ray pre-/postcursor.—It is quite interesting that in Figure 4, we see the X-ray precursor at $T_{\rm obs} \sim 60$ s in case B_2 and the postcursor at $T_{\rm obs} \sim 65$–75 s in case B_1. These can be understood by the model proposed by Nakamura (2000).

4. LOGNORMAL DISTRIBUTIONS

The total duration of long and short GRBs are consistent with the lognormal distributions (McBreen et al. 1994). In our subjet model, these distributions may be naturally expected as a result of the central limit theorem. Suppose a certain quantity q is expressed by a product of random variables $q = x_1 x_2 \ldots x_n$. Then $\log q = \log x_1 + \log x_2 + \ldots + \log x_n$. When the individual distributions of $\log x_i$ satisfy certain weak conditions, the distribution of $\log q$ obeys the normal distribution in the limit

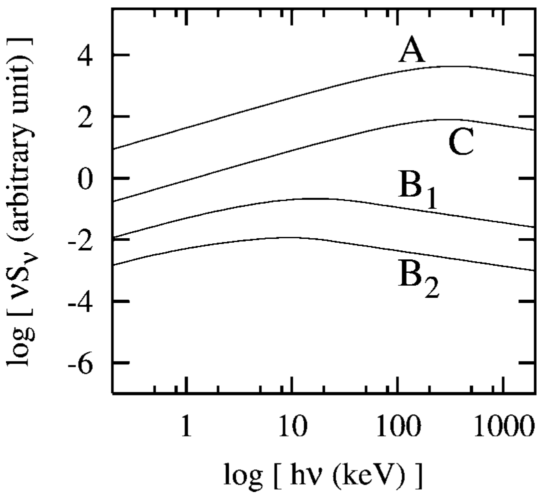

FIG. 3.—Time-integrated energy spectrum of the emission from the multiple subjets for the observers denoted by "A," "B_1," "B_2," and "C" in Fig. 2. The source is located at $z = 1$.

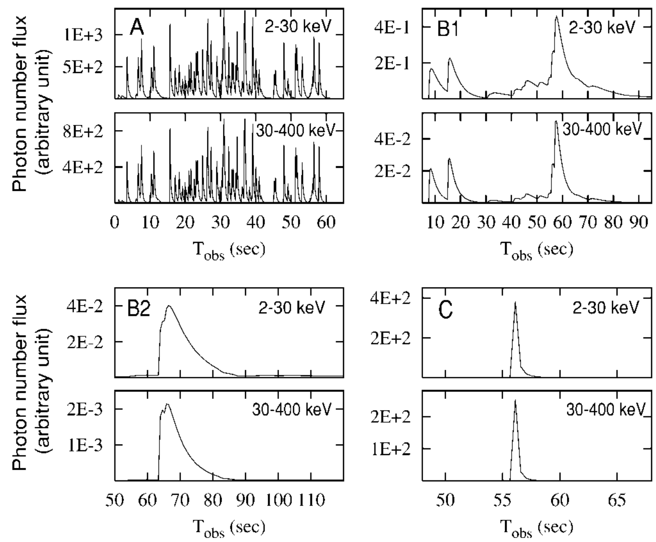

FIG. 4.—Observed X-ray and γ-ray light curves from the multiple subjets, corresponding to cases A (*upper left*), B_1 (*upper right*), B_2 (*lower left*), and C (*lower right*) in Fig. 2. The sources are located at $z = 1$.

of $n \to \infty$ by the central limit theorem. However, in some cases the lognormal distributions can be achieved only by a few variables (Ioka & Nakamura 2002). Thus, we might say, "Astrophysically, not $n \to \infty$ but $n = 3$ gives the lognormal distribution in practice!" This argument may apply to the lognormal distributions of the peak energy, the pulse fluence, and the pulse duration of GRBs (Ioka & Nakamura 2002).

In our subjet model, short GRBs are due to a single subjet. The pulse duration of a single subjet is mainly determined by the angular spreading timescale and is given by the product of four variables in the internal shock model (Ioka & Nakamura 2002) as $\Delta T_{\rm short} \sim (1 + z)(L/c)(\gamma_s/\gamma_m)^2$, where L, γ_s, and γ_m are the separation of two shells and the Lorentz factor of the slow and merged shell in the internal shock model, respectively. Therefore, the lognormal distribution of the duration of short GRBs may be a natural result of the central limit theorem.

In our unified model, the duration of long GRBs is determined by the interval between pulses $\Delta t = L/c$ times the multiplicity of the subjets n_s. For a GRB at redshift z, the observed duration is given by the product of three random variables, $\Delta T_{\rm long} \sim (1 + z)(L/c)n_s$. Therefore, the lognormal distribution of the duration of long GRBs may be realized. The ratio of the duration of long GRBs to short GRBs is given by $n_s(\gamma_m/\gamma_s)^2 \sim 10^2$. Since in the internal shock model the relative Lorentz factor is not large, this equation suggests that $n_s = 10$–30, which is compatible with the observed number of spikes of long GRBs.

5. DISCUSSION

Let $\Delta\theta_{\rm sub}$, ϑ_c, and $\bar{n}_s$ be the typical opening half-angle of the subjet, the core size of the whole jet, and the mean multiplicity in the core. Then the total number of the subjets ($N_{\rm tot}$) 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 subjet is $\sim 10^{48}$ ergs. In our model, the event rate of long GRBs is proportional to ϑ_c^2. Let M be the number of subjets in the envelope of the core with a small multiplicity $n_s \ll 1$. Then the event rate of short GRBs is proportional to $M\Delta\theta_{\rm sub}^2$ so that $M \sim 10$ is enough to explain the event rate of short GRBs.

Of course, the above numerical values are typical ones and should have a dispersion (Lloyd-Ronning et al. 2004). Our core-envelope subjet model can have a similar structure to the two-component jet model (Berger et al. 2003; Huang et al. 2004; Zhang et al. 2004b; Ramirez-Ruiz et al. 2002) if we vary parameters such as $\bar{n}_s$ and M. However, the distribution of subjets could also have other possibilities, e.g., a hollow-cone distribution like a pulsar, a power-law distribution, a Gaussian distribution (Zhang & Mészáros 2002; Rossi et al. 2002; Zhang et al. 2004a), and so on.

Some observers could see a cold spot with small n_s in the core to have a small geometrically corrected energy even if the total energy of the GRBs is the same. Thus, our model may be compatible with the recent claim that the total kinetic energy has smaller dispersion than the geometrically corrected γ-ray energy (Berger et al. 2003; Bloom et al. 2003). The X-ray pre-/postcursor is also expected if off-axis subjets are ejected earlier (for precursor) or later (for postcursor) than the main subjets (Nakamura 2000). The viewing angle of the subjets may also cause the luminosity-lag/variability/width relations of the GRBs including GRB 980425 (Yamazaki et al. 2003c; Ioka & Nakamura 2001). This multiple subjet model is an extreme case of the inhomogeneous or patchy shell model (Kumar & Piran 2000; Nakamura 2000). The afterglow variabilities, such as in GRB 021004, may arise from the angular energy fluctuations within the GRB jet (Nakar & Piran 2003; Piran et al. 2003), which might correspond to the inhomogeneous n_s.

Since the core may be regarded as a uniform jet, our model for XRFs is analogous to the off-axis uniform jet model (Yamazaki et al. 2002, 2003b, 2004). However, the afterglow could have a different behavior between the core-envelope subjet 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 (e.g., Yamazaki et al. 2003a; Granot et al. 2002). An orphan afterglow may be actually observed in XRF 030723 (Huang et al. 2004), but the light curve may peak too early (Zhang et al. 2004a). The optical afterglow of XRF 020903 is not observed initially (<0.9 days) but may not be consistent with the orphan afterglow (Soderberg et al. 2004). These problems could be overcome by introducing a Gaussian tail with a high Lorentz factor around the uniform jet (Zhang et al. 2004a) since the energy redistribution effects may bring the rising light curve to earlier times (Zhang et al. 2004a; Kumar & Granot 2003). The afterglow of a short GRB is difficult to predict since it could resemble both the orphan and normal afterglow depending on the subjet configuration within the envelope.

Since all bursts have the same progenitor, our model suggests that short GRBs and XRFs are also associated with supernovae. The radio calorimetry will also give a similar energy to long GRBs because of the same reason. Our unified model will be refuted if the locations of short GRBs are mainly in the halo of the galaxy, as in the coalescing binary neutron star model (Bloom et al. 2002).

Interestingly, our model also predicts off-axis short GRBs or short XRFs. However, these bursts will be difficult to detect since short XRFs, which have a multiplicity of $n_s \sim 1$, will be ∼30 times dimmer than XRFs with $n_s \sim 30$. Note that short XRFs will be longer than short GRBs since the pulse duration grows as the viewing angle increases (Ioka & Nakamura 2001; Yamazaki et al. 2002). The event rate of short XRFs will depend on the configuration of the subjets in the envelope. Further observations are necessary to determine the envelope structure.

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