X-RAY FLASHES FROM OFF-AXIS GAMMA-RAY BURSTS

RYO YAMAZAKI
Department of Physics, Kyoto University, Kyoto 606-8502, Japan; yamazaki@tap.scphys.kyoto-u.ac.jp

KUNIHITO IOKA
Department of Earth and Space Science, Osaka University, Toyonaka 560-0043, Japan; ioka@vega.ess.sci.osaka-u.ac.jp

AND

TAKASHI NAKAMURA¹
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan; takashi@yukawa.kyoto-u.ac.jp

Received 2002 March 14; accepted 2002 April 16; published 2002 April 25

ABSTRACT

K. Ioka and T. Nakamura proposed a simple jet model that is compatible with the peak luminosity–spectral lag relation, the peak luminosity–variability relation, and various other relations in the gamma-ray bursts. If the viewing angle is much larger than the collimation angle of the jet in the model by Ioka and Nakamura, for appropriate model parameters we obtain the observational characteristics of the X-ray flashes, such as the peak flux ratio and the fluence ratio between the γ-ray (50–300 keV) and the X-ray (2–10 keV) band, the X-ray photon index, the typical duration, and the event rate, ~100 yr⁻¹. In our model, if the distance to the X-ray flashes is much larger than ~1 Gpc (or z ≥ 0.2) they are too dim to be observed, so the spatial distribution of the X-ray flashes should be homogeneous and isotropic.

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

1 INTRODUCTION

Recently, a new class of X-ray transients has been recognized. The Wide Field Cameras (WFCs) on BeppoSAX in the X-ray range 2–25 keV have detected some fast X-ray transients (FXTs) with a duration less than ~10⁻³ s, which are not triggered and not detected by the Gamma-Ray Burst Monitor (GRBM) in the γ-ray range 40–700 keV (Heise et al. 2001; see also Strohmayer et al. 1998; Gotthelf, Hamilton, & Helfand 1996; Hamilton, Gotthelf, & Helfand 1996). In Heise et al. (2001), these FXTs are defined as X-ray flashes (XRFs). This definition of XRFs excludes the X-ray counterparts of the typical gamma-ray bursts (GRBs) including X-ray–rich GRBs. Seventeen XRFs have been observed in the WFCs on BeppoSAX in about 5 yr, while 49 GRB counterparts have been observed in the same period.

XRFs have the following properties (Heise et al. 2001): (1) The peak flux of the XRFs ranges between 10⁻⁹ and 10⁻⁷ ergs s⁻¹ cm⁻² (Fig. 2 of Heise et al. 2001). The mean peak flux of the XRFs is about a factor of 3 smaller than that of the GRBs. Nine out of 17 XRFs are detected in either the lowest or the lowest two BATSE energy channels (25–50 and 50–100 keV; Kippen et al. 2001). (2) The ratio of the peak flux and the fluence in the X-ray range (2–10 keV) and the γ-ray range (50–300 keV) for nine XRFs are shown in Fig. 3 of Heise et al. (2001). The peak flux ratio extends up to a factor of 100, and the fluence ratio extends up to a factor of 20. (3) The energy spectrum in the range 2–25 keV fits with a single power law with the photon index between 1.2 and 3 and the mean of about 2, while the mean photon index of 36 GRBs in the same X-ray band is about 1, with the range between 0.5 and 3. (4) The duration of the XRFs ranges between 10 and 200 s, which is the same order as that of the GRBs. (5) The event rate of the XRFs is estimated as ~100 yr⁻¹ since the WFCs observed ~3 yr⁻¹ with the covering 40° × 40° (full width to zero response). (6) The sky distribution is consistent with being isotropic. The spatial distribution is consistent with being homogeneous in Euclidean space since (V/Vₘₚ) = 0.56 ± 0.12 (J. Heise, J. in ‘t Zand, R. M. Kippen, R. D. Preece, P. M. Woods, & M. Briggs 2000, unpublished; Schmidt, Higdon, & Huter 1988).

At present, the origin of the XRFs is not known. Heise et al. (2001) have proposed that XRFs could be GRBs at large redshift, z > 5, when γ-rays would be shifted into the X-ray range. However, as they have pointed out in their paper, one cannot explain the duration distribution since no time dilation due to cosmological expansion is observed. There is also a possibility that the XRFs could be dirty fireballs or failed GRBs (e.g., Dermer, Chiang, & Böttcher 1999; Heise et al. 2001; Huang, Dai, & Lu 2002).

Ioka & Nakamura (2001) have proposed that the XRFs could be GRBs observed from the large viewing angle as shown in Figure 1 (see also Nakamura 2000). They computed the kinematical dependence of the peak luminosity, the pulse width, and the spectral lag of the peak luminosity on the viewing angle θ of a jet. For appropriate model parameters, they obtained a peak luminosity–spectral lag relation similar to the observed one. They suggested that the viewing angle of the jet might cause various relations in GRBs, such as the peak luminosity–variability relation and the luminosity-width relation.

Very recently, several authors have also suggested that the viewing angle is the key parameter to understanding the various properties of the GRBs (Zhang & Mészaros 2001; Rossi, Lazzati, & Rees 2002; Salmonson & Galama 2002). In this circumstance, it is meaningful to study the off-axis GRB model for the XRFs by Ioka & Nakamura (2001) in more detail.

In this Letter, we will show that the GRBs observed from the large viewing angle possess the above-mentioned properties 1–6 of the XRFs. In § 2, we describe a simple jet model for the XRFs. In § 3, we consider the peak flux ratio and the fluence ratio (property 2). In § 4, we consider the peak flux, the photon index, and the event rate (properties 1, 3, and 5). Section 5 is devoted to a discussion (properties 4 and 6).
where \( \alpha_g (\beta_g) \) is the low- (high-) energy power-law index and \( s \) describes the smoothness of the transition between the high and low energy. In the GRBs, \( \alpha_g \approx -1 \) and \( \beta_g \approx -3 \) are typical values (Preece et al. 2000). Equations (1) and (2) are the basic equations to calculate the flux of a single pulse, which depends on 10 parameters for \( \gamma \gg 1 \), \( \theta_s \ll 1 \), and \( \Delta \theta \ll 1 \): \( \gamma \nu'_0 \), \( \gamma \theta_s \), \( \gamma \Delta \theta \), \( r_0/c \beta_0 \gamma^2 \), \( T_0 \), \( \alpha_g \), \( \beta_g \), \( s \), \( D \), and \( \gamma' A_0 \).

In order to study the dependence on the viewing angle \( \theta_s \), we fix parameters as \( \gamma \Delta \theta = 10 \), \( \alpha_g = -1 \), \( \gamma \nu'_0 = 300 \) keV, \( r_0/c \beta_0 \gamma^2 = 10 \) s, and \( s = 1 \), since typical GRBs have a break energy of \( \sim 300 \) keV (Preece et al. 2000) and a pulse duration of \( \sim 10 \) s. Other parameters, i.e., the viewing angle \( \gamma \theta_s \), the high-energy power-law index \( \beta_g \), and the distance \( D \), are varied depending on circumstances.

We fix the amplitude \( \gamma' A_0 \), so that the isotropic \( \gamma \)-ray energy \( \mathcal{E}_{iso} = 4\pi D^2 S(20–2000 \text{ keV}) \) equals \( 10^{53} \) ergs when \( \beta_g = -3.0 \) and \( \gamma \theta_s = 0 \). Here \( S(\nu_1–\nu_2) = \int_{\nu_1}^{\nu_2} F(T; \nu) d\nu \) is the fluence in the energy range \( \nu_1–\nu_2 \) and \( F(T; \nu) = \left[ \frac{\gamma}{\nu \theta_s} \right] \nu^{\gamma-1} d\nu \) is the flux in the same energy range. The result is

\[
A_0 = 1.2 \text{ ergs cm}^{-2} \text{ Hz}^{-1} \frac{\mathcal{E}_{iso}}{10^{53} \text{ ergs}} \left( \frac{r_0/c \beta_0 \gamma^2}{10 \text{ s}} \right)^{-2} \left( \frac{\gamma}{100} \right)^{-4}.
\]  

Note that when we adopt \( \gamma = 100 \), the opening half-angle of the jet is similar to the observed one, \( \Delta \theta \sim 0.1 \), and the total energy corrected for geometry is comparable to the observed value, \( \mathcal{E}_{iso} \sim 10^{51} \) ergs (Frail et al. 2001).

### 3. Peak Flux Ratio and Fluence Ratio

In this section, we calculate the peak flux ratio \( R_{peak} = F_{peak}(2–10 \text{ keV})/F_{peak}(50–300 \text{ keV}) \) and the fluence ratio \( R_{fluence} = S(2–10 \text{ keV})/S(50–300 \text{ keV}) \) and compare the results with observations.

Figure 2 shows the peak flux ratio \( R_{peak} \) and the fluence ratio \( R_{fluence} \) as a function of the viewing angle \( \gamma \theta_s \). When the viewing angle \( \theta_s \) is larger than the opening half-angle \( \Delta \theta \), both the peak flux ratio \( R_{peak} \) and the fluence ratio \( R_{fluence} \) increase as the viewing angle \( \gamma \theta_s \) increases. The ratios, \( R_{peak} \) and \( R_{fluence} \), increase as the high-energy index \( \beta_g \) decreases.

We can understand this behavior as follows. As shown in the Appendix, the maximum frequency \( \nu_{max} \) at which most of the radiation energy is emitted is estimated as \( \nu_{max} \sim \nu_{\nu_2} \), where \( \delta = \gamma [1 - \beta \cos \theta] / (\Delta \theta) \approx 1 + \frac{\gamma \theta_s}{2} \gamma' \Delta \theta / 2 \) is the Doppler factor and \( \theta_s > \Delta \theta \). Thus, the maximum frequency \( \nu_{max} \) decreases as the viewing angle increases. In the following, we consider two observation bands: the lower energy band, \( \nu_1–\nu_2 \) keV, and the higher energy band, \( \nu_2–\nu_{\nu_2} \) keV. The maximum frequency \( \nu_{max} \) is larger than the highest observed energy \( \nu_{\nu_2} \) (=300 keV in the present case) when \( \gamma \theta_s < \gamma \theta_{s*} \equiv \gamma \Delta \theta + \sqrt{(2 \gamma \theta_s \nu_2^2 – 1)/2} \). In this case, we observe the low-energy part of the Band spectrum in equation (2). Since the low-energy power-law index is \( \alpha_g = -1 \), the peak flux ratio \( R_{peak} = F_{peak}(\nu_1–\nu_2 \text{ keV})/F_{peak}(\nu_2–\nu_{\nu_2} \text{ keV}) \) and the fluence ratio \( R_{fluence} = S(\nu_1–\nu_2 \text{ keV})/S(\nu_2–\nu_{\nu_2} \text{ keV}) \) are given by \( R_{peak} \sim R_{fluence} \sim (\nu_2/\nu_1)^{2-s/\gamma} \), where \( \alpha_g > -2 \). Similarly, when the maximum frequency \( \nu_{max} \)
is smaller than the lowest observed energy \( \nu_1 = 2 \) keV, i.e., 
\[ \gamma^{(4)}_\theta \equiv \gamma \Delta \theta + (2 \nu_\gamma/\nu_1 - 1)^{1/2}, \]
the peak flux ratio and the fluence ratio are given by 
\[ R_{\text{peak}} \sim R_{\text{fluence}} \sim (\nu_\gamma/\nu_1)^{2 + \beta_\nu}, \]
where \( \beta_\nu < -2 \).

We compare Figure 2 with observations. Observed peak flux ratios extend up to a factor of 100, and observed fluence ratios extend up to a factor of 20 (Fig. 3 of Heise et al. 2001). One can see that when \( \gamma \Delta \theta = 10 \) \( \gamma \theta_\nu \leq \gamma^{(3)} \) \( \gamma \Delta \theta \), and 
\[ -4 \leq \beta_\nu \leq -2, \]
the two solid curves in Figure 2 are nearly equal (\( \nu_\gamma/\nu_1 \sim 100 \)), as shown by the long-dashed lines.

4. PEAK FLUX, PHOTON INDEX, AND EVENT RATE

We calculate the peak flux and the photon index in the energy band 2–25 keV as a function of the viewing angle \( \gamma \theta_\nu \), and plot it in the peak flux–photon index plane. Figure 3 shows the results for \( \beta_\nu = -3 \). The distance is varied from \( D = 0.01 \) Gpc to \( D = 2.1 \) Gpc for our parameters. One can see that the photon index increases and the peak flux decreases as the viewing angle \( \gamma \theta_\nu \) increases.

As discussed in § 3, we observe the low- (high-) energy part of the Band spectrum in equation (2) when \( \gamma \theta_\nu < \gamma^{(3)} \) (\( \gamma \theta_\nu > \gamma^{(3)} \)), where \( \nu_2 = 25 \) keV and \( \nu_1 = 2 \) keV. Therefore, the photon index in the energy range 2–25 keV is nearly equal to the low- (high-) energy spectral index \( \alpha_n = 1 \) (\( \alpha_n = 3 \) when \( \beta_\nu = 3 \).

When we consider the effect of cosmology (\( \Omega_m = 0.3, \Omega_\Lambda = 0.7, \) and \( h = 0.7 \), \( D \sim 2 \) Gpc corresponds to \( z \sim 0.4 \). This does not affect our argument qualitatively but alters the quantitative results up to a factor of 2.

![Figure 3](image-url)
X-RAY FLASHES FROM OFF-AXIS GRBs
Vol. 571

and such events are observed as GRBs, not as XRFs. The vertical dashed line represents the limiting sensitivity of WFCs (~3 × 10^-3 ergs s^-1 cm^-2). Therefore, the observed data of the XRFs sit in a fairly narrow region surrounded by two dashed lines.

The distance to the farthest XRF $D_{\text{XRF}}$ gives the observed event rate of the XRFs. The observed event rate $R_{\text{XRF}}$ can be estimated as $R_{\text{XRF}} = \frac{\gamma}{4\pi}D_{\text{XRF}}^3/(f_{\text{XRF}}/f_{\text{GRB}})$, where $r_{\text{GRB}}$ and $n_1$ are the event rate of the GRBs and the number density of galaxies, respectively. The quantity $f_{\text{XRF}}/f_{\text{GRB}}$ is the solid angle subtended by the direction to which the source is observed as the XRF (GRB). From previous discussions, one can find that the emitting thin shell with opening half-angle $\Delta \theta$ is observed as the XRF (GRB). Let the viewing angle of each subjet be $\theta_j$. The observed flux ($\nu_{\text{obs}}$), the flux normalization factor is invariant, $\nu_{\text{obs}} \propto D_{\text{obs}} = \nu_{\text{max}}$ when the viewing angle is within $\Delta \theta \leq \theta_j \leq \theta_j^{\text{max}} \sim 3\Delta \theta (0 \leq \theta_j \leq \Delta \theta)$. Therefore, the ratio of each solid angle is estimated as $f_{\text{XRF}}/f_{\text{GRB}} \sim (3^{2} - 1^{2})/1^{2} \approx 8$. Using this value, we obtain

$$R_{\text{XRF}} \sim 10^{2} \text{ events yr}^{-1} \times \left(\frac{D_{\text{XRF}}}{2 \text{ Gpc}}\right)^{3} \frac{r_{\text{GRB}}}{5 \times 10^{-3} \text{ events yr}^{-1} \text{ galaxy}^{-1}} \times \frac{n_{1}f_{\text{XRF}}/f_{\text{GRB}}}{10^{-2} \text{ galaxies} \text{ Mpc}^{-3}}.$$ (5)

which is comparable to the observation.

5. DISCUSSION

We have shown that the observed data of XRFs can be reproduced by a simple jet model of GRBs. This suggests that XRFs are identical to GRBs. We may say that in the context of our model, nearby GRBs are observed as XRFs when we see them from the off-axis viewing angle. If the distance to the XRFs is much larger than a few gigaparsecs, they cannot be observed since the observed flux is low. This is consistent with the observed value of $(V/V_{\text{max}}) \sim 0.5$ since the nearby sources distribute homogeneously in Euclidean space.

Our view of XRFs is different from that of Heise et al. (2001). They have proposed that XRFs could be GRBs at large redshift, $z > 5$, when $\gamma$-rays would be shifted into the X-ray range. However, the observed total duration $T_{90}^{\text{tot}}$ cannot be explained. In our model, $\gamma$-rays are shifted into the X-ray range by the relativistic beaming effect. The total duration is equal to the lifetime of the central engine and thus does not depend on the viewing angle $\theta_j$. Hence, the total duration of the XRFs may be similar to that of the GRBs in our model.

We can calculate $T_{90}$, the observed duration of a single pulse in the X-ray band (2–25 keV). When the viewing angle ranges from $\gamma \theta_j = 10$ to $\gamma \theta_j = 30$, the pulse duration is about $T_{90} \sim 30–3000$ s ($r_{\text{GRB}}/c\beta\gamma^{2}$)/10 s. This value is comparable but a little bit inconsistent with the observation since the observed pulse duration $T_{90}$, which is on the order of the angular spreading timescale, should be less than the total duration $T_{90}^{\text{tot}} \sim 10–200$ s, which is the time interval between the first and the last emission. This contradiction can be resolved as follows. So far, we have assumed the isotropic energy of the instantaneous emission $E_{\text{iso}} \sim 10^{53}$ ergs and the time unit $r_{\text{GRB}}/c\beta\gamma^{2} \sim 10$ s. The effect of changing the values of these two parameters appears only in the flux normalization $(\gamma A_{\nu})/(r_{\text{GRB}}/c\beta\gamma^{2})$ in equation (1). However, one can see that from equation (3), if one rescales these parameters as $E_{\text{iso}} \rightarrow E_{\text{iso}}^{\text{new}} = 10^{53}N^{-1}$ ergs and $r_{\text{GRB}}/c\beta\gamma^{2} \rightarrow (r_{\text{GRB}}/c\beta\gamma^{2})^{\prime} = 10^{-1} N^{-1}$ s, the flux normalization factor is invariant, $(\gamma A_{\nu}(r_{\text{GRB}}/c\beta\gamma^{2} ))^{\prime} = [(\gamma A_{\nu}(r_{\text{GRB}}/c\beta\gamma^{2} ))]$’ which implies that the result is unchanged. The value of $N$ is the number of instantaneous emissions, since we fix the total emission energy as $E_{\text{iso}}^{\text{new}} = 10^{50}$ ergs. If we adopt $N \approx 15$, $T_{90}$ of each emission can be less than $T_{90}^{\text{tot}}$.

Ioka & Nakamura (2001) showed that the variability of GRBs is small for a large viewing angle. In addition, our model predicts that the number of pulses of XRFs is smaller than that of typical GRBs. This can be expected from the following discussion. In this Letter, we consider the time-averaged emissions, which means that successive emissions from multiple subjets with the opening half-angle $\Delta \theta^{j} \sim \gamma^{-1} \sim \Delta \theta / 10$ are approximated by one spontaneous emission caused by a single jet with the viewing angle $\theta_j$ and the opening half-angle $\Delta \theta$. Let the viewing angle of each subjet be $\theta_j^{(m)}$. The observed flux (or fluence) in the X-ray band due to the subjets with $\theta_j^{(m)} \approx \theta_j + \Delta \theta$ is much smaller than that with $\theta_j^{(m)} \approx \theta_j - \Delta \theta$ and hence negligible. We have confirmed this in the practical calculation. If $\theta_j \sim \Delta \theta$, the emissions of subjets with $\theta_j^{(m)} \approx \theta_j - \Delta \theta$ dominates, while if $\theta_j \sim 0$, in the GRB case, the emissions from almost all subjets may be detected.

We are grateful to the referee for useful comments. This work was supported in part by Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Culture, Sports, Science and Technology 00660 (K. I.), 11640274 (T . N.), 09NP0801 (T. N.), 14047212 (T. N.), and 14204024 (T. N.).

APPENDIX A

ANALYTICAL ESTIMATES

$n_{\text{GRB}}$ and $(\nu S_{\nu})_{\text{max}}$—In equation (1), the typical value of $\theta(T) \sim (\theta_j - \Delta \theta) / \theta_j$ when $\theta_j > \Delta \theta$ since the flux peaks soon after the jet edge becomes visible. Since the function $\nu^\prime(\nu^\prime)$ in equation (2) takes a maximum at $\nu^\prime_{\text{max}} = \nu^\prime / \delta \sim \delta^{-1}$, where $\delta \equiv \gamma[1 - \beta \cos(\theta_j - \Delta \theta)] \sim [1 + \gamma^2(\theta_j - \Delta \theta)^2]/2\gamma$ and $S_{\nu} = \int_{T_{\text{start}}}^{T_{\text{end}}} F_{\nu}(T) dT$. At $\nu_{\text{max}}$, $F_{\nu}$ in equation (1) is proportional to $\delta^{-2}$ so that we expect $(\nu S_{\nu})_{\text{max}} \sim \delta^{-1}$ (Ioka & Nakamura 2001). Note here that $\Delta \phi(T)/dT$ depends on $\theta_j$ and $\delta$ very weakly.

The peak duration $T_{\text{peak}}$ can be estimated as $T_{\text{peak}} \sim (T_{\text{end}} - T_{\text{start}}) \sim \Delta \theta / \theta_j$ for $\theta_j > \Delta \theta$. The peak flux $F_{\text{peak}}$ can be estimated from the relation $F_{\text{peak}} \sim S \sim \delta^{-1 + \alpha}(\delta^{-1 + \beta})^{-\alpha}$ when the maximum frequency $\nu_{\text{max}}$ is higher (lower) than the observed frequency.

REFERENCES

Band, D., et al. 1993, ApJ, 413, 281
Dermer, C. D., Chiang, J., & Böttcher, M. 1999, ApJ, 513, 656
Fenimore, E. E., Madras, C. D., & Nayakshin, S. 1996, ApJ, 473, 998
Frail, D. A., et al. 2001, ApJ, 562, L55
Gottfried, E. V., Hamilton, T. T., & Helfand, D. J. 1996, ApJ, 466, 779
Granot, J., Piran, T., & Sari, R. 1999, ApJ, 513, 679
Hamilton, T. T., Gotthelf, E. V., & Helfand, D. J. 1996, ApJ, 466, 795
Heise, J., in 't Zand, J., Kippen, R. M., & Woods, P. M. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 16
Huang, Y. F., Dai, Z. G., & Lu, T. 2002, MNRAS, 332, 735
Ioka, K., & Nakamura, T. 2001, ApJ, 554, L163
Katz, J. I. 1997, ApJ, 490, 633
Kippen, R. M., Woods, P. M., Heise, J., in 't Zand, J. J. M., Briggs, M. S., & Preece, R. D. 2002, preprint (astro-ph/0203114)
Kippen, R. M., Woods, P. M., Heise, J., in 't Zand, J. J. M., Preece, R. D., & Briggs, M. S. 2001, in Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 22
Kobayashi, S., Piran, T., & Sari, R. 1997, ApJ, 490, 92
Nakamura, T. 2000, ApJ, 534, L159
Piran, T. 1999, Phys. Rep., 314, 575
Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., & Band, D. L. 2000, ApJS, 126, 19
Rossi, E., Lazzati, D., & Rees, M. J. 2002, MNRAS, in press (astro-ph/0112083)
Salmonson, J. D., & Galama, T. J. 2002, ApJ, in press (astro-ph/0112298)
Sari, R., Narayan, R., & Piran, T. 1996, ApJ, 473, 204
Schmidt, M., Higdon, J. C., & Hueter, G. 1988, ApJ, 329, L85
Strohmayer, T. E., Fenimore, E. E., Murakami, T., & Yoshida, A. 1998, ApJ, 500, 873
Woods, E., & Loeb, A. 1999, ApJ, 523, 187
Zhang, B., & Meszaros, P. 2001, AAS Meeting, 199, 12.01