Cosmological X-Ray Flashes from Off-Axis Jets

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Abstract. The $\langle V/V_{\rm max}\rangle$ of the cosmological X-ray flashes detected by WFC/*BeppoSAX* is calculated theoretically in a simple jet model. The total emission energy from the jet is assumed to be constant. We find that if the jet opening half-angle is smaller than 0.03 radian, off-axis emission from sources at $z \leq 4$ can be seen. The theoretical $\langle V/V_{\rm max}\rangle$ is less than 0.4, which is consistent with the observational result of 0.27 ± 0.16 at the 1 σ level. This suggests that the off-axis GRB jet with the small opening half-angle at the cosmological distance can be identified as the cosmological X-ray flash.

INTRODUCTION

The X-ray flash (XRF) is a class of X-ray transients, whose peak energy of νF_ν spectra is small but the other properties are roughly similar to those of GRBs [4, 7, 8]. The observational value of $\langle V/V_{\rm max}\rangle$ has been updated from 0.56 ± 0.12 [3] to 0.27 ± 0.16 [5]. The updated value of $\langle V/V_{\rm max}\rangle$ suggests that XRFs take place at a cosmological distance. Various models accounting for the nature of the XRFs have been proposed (see [13] and references therein; see also [9, 10]). In our *off-axis jet model*, if we observe the GRB jet with a large viewing angle, it looks like an XRF [12, 13]. In Yamazaki et al. [12], the value of the jet opening half-angle was adopted as $\Delta\theta = 0.1$. Then the distance to the farthest XRF ever detected is about 2 Gpc ($z \sim 0.4$) so that the cosmological effect is small and $\langle V/V_{\rm max}\rangle \sim 0.5$. Recent observations suggest that GRBs with relatively small opening angle exist, while the distribution of $\Delta\theta$ is not yet clear [11]. If we assume the total emission energy to be constant, the intrinsic luminosity is larger for the smaller $\Delta\theta$ Such GRBs at the cosmological distance observed from off-axis viewing angle may be seen as XRFs and $\langle V/V_{\rm max}\rangle$ is expected to be smaller than 0.5.

In this paper, we will show that our off-axis model has a possibility of accounting for the observational value of $\langle V/V_{\rm max}\rangle$ if we change some of the model parameters used in Yamazaki et al. [12].

CALCULATION OF $\langle V/V_{\rm max}\rangle$

We consider a simple jet model of XRFs [12, 13] taking into account the cosmological effect. The uniform jet with sharp edges is assumed. See Yamazaki et al. [13] for details. In order to study the dependence on the viewing angle θ_v and the jet opening half-angle $\Delta\theta$, we fix the other parameters as $\alpha_B = -1$, $\beta_B = -3$, $\gamma\nu'_0 = 200\,{\rm keV}$,

TABLE 1. Results of calculation for fixed $\Delta\theta$

$\Delta\theta$	A_0*	$\theta_{v,p}$†	$z_{\rm max}(\theta_{v,p})$	$z_{\rm min}(\theta_{v,p})$	$\langle V/V_{\rm max}\rangle_{\Delta\theta}$**
0.10	0.84	0.103	2.8	1.5	0.46
0.09	1.0	0.095	2.9	1.4	0.45
0.08	1.3	0.086	3.0	1.4	0.44
0.07	1.7	0.077	3.1	1.3	0.44
0.06	2.3	0.068	3.3	1.2	0.44
0.05	3.4	0.060	3.5	1.2	0.44
0.04	5.2	0.052	3.6	1.1	0.43
0.03	9.3	0.045	3.8	0.99	0.40
0.02	22	0.038	4.0	0.89	0.38
0.01	109	0.034	4.1	0.77	0.35

* In units of erg $\rm cm^{-2}\ Hz^{-1}$
† The viewing angle where $W(\theta_v)$ becomes maximum.
** For the XRFs detected by WFCs on BeppoSAX.

$r_0/c\beta\gamma^2 = 10\,$s, and $\gamma = 100$. We fix the amplitude A_0 so that the isotropic γ-ray energy $E_{\rm iso} = 4\pi d_L^2(1+z)^{-1}S_\gamma$ satisfies $(\Delta\theta)^2 E_{\rm iso}/2 = 0.5\times10^{51}$ ergs, when $\theta_v = 0$ and $z = 1$ [1]. The values of A_0 for different opening angles are summarized in Table 1. When the jet opening half-angle $\Delta\theta$ becomes smaller, A_0 becomes larger.

The $\langle V/V_{\rm max}\rangle$ for fixed opening half-angle $\Delta\theta$ is calculated as

$$\langle V/V_{\rm max}\rangle_{\Delta\theta} = \frac{\int \langle V/V_{\rm max}\rangle_{\Delta\theta,\,\theta_v} W(\theta_v)\,d\theta_v}{\int W(\theta_v)\,d\theta_v}\ , \tag{1}$$

where $\langle V/V_{\rm max}\rangle_{\Delta\theta,\,\theta_v}$ is for fixed $\Delta\theta$ and θ_v (See Yamazaki et al. [13] for details). The weight function $W(\theta_v)$ is the product of the solid angle factor and the volume factor:

$$W(\theta_v) = 2\pi\sin\theta_v \int_{z_{\rm min}(\theta_v)}^{z_{\rm max}(\theta_v)} dz\,\frac{n(z)}{1+z}\,4\pi\left(\frac{d_L}{1+z}\right)^2 \frac{d}{dz}\left(\frac{d_L}{1+z}\right)\ , \tag{2}$$

where $n(z)$ and d_L are the comoving GRB rate density and the luminosity distance, respectively. Here $z_{\rm max}$ ($z_{\rm min}$) is the maximum (minimum) redshift of the XRF for given $\Delta\theta$ and θ_v. In determining $z_{\rm min}$ and $z_{\rm max}$, we should note that the operational definition of the *BeppoSAX*-XRF is the fast X-ray transient with duration less than $\sim 10^3$ seconds which is detected by WFCs and not detected by the GRBM [4]. Therefore, if the sources are nearby such that $z < z_{\rm min}$, they are observed as GRBs because the observed fluence in the γ-ray band becomes larger than the limiting sensitivity of GRBM ($\sim 3\times10^{-6}$ergs $\rm cm^{-2}$). If the sources are too far such that $z > z_{\rm max}$, they cannot be observed by WFCs with a limiting sensitivity of about 4×10^{-7}ergs $\rm cm^{-2}$. The behavior of $z_{\rm max}$, $z_{\rm min}$, $\langle V/V_{\rm max}\rangle_{\Delta\theta,\,\theta_v}$, and $W(\theta_v)$ for $\Delta\theta = 0.03$ are shown in Figure 1.

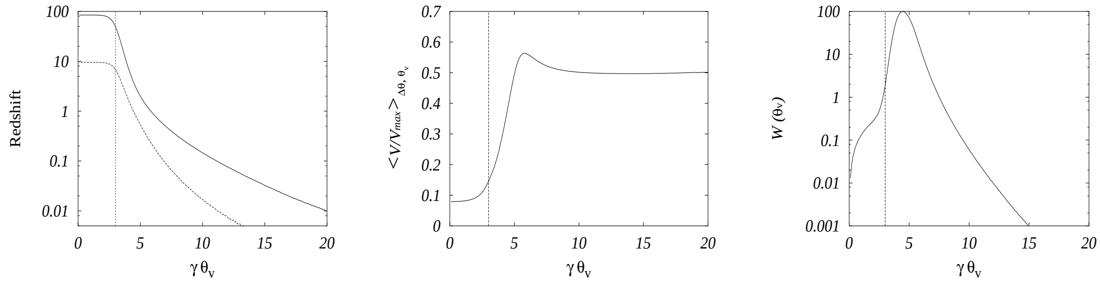

FIGURE 1. (Left panel): The maximum (minimum) redshift, $z_{\rm max}$ ($z_{\rm min}$), of the XRF as a function of the viewing angle $\gamma\theta_v$ is shown as the solid line (dashed line). The jet emission is observed as the XRF if the source has a redshift z in the range $z_{min} < z < z_{max}$. (Midle panel): $\langle V/V_{\rm max}\rangle_{\Delta\theta,\,\theta_v}$ for the XRF detected by the WFCs/*BeppoSAX* is shown as a function of $\gamma\theta_v$. (Right panel): The weight function $W(\theta_v)$ (arbitrary normalization), which is the relative observed event rate, is shown as a function of $\gamma\theta_v$. All figures are for the case of $\Delta\theta = 0.03$. The vertical dashed lines represent $\theta_v = \Delta\theta = 0.03$.

DISCUSSION

The results of the numerical integration are summarized in Table 1. For each $\Delta\theta$, $z_{\rm max}(\theta_{v,\,p})$ $[z_{\rm min}(\theta_{v,\,p})]$ means the maximum (minimum) redshift where $W(\theta_v)$ takes the maximum value. If we take the jet opening half-angle as $\Delta\theta \leq 0.03$, $\langle V/V_{\rm max}\rangle_{\Delta\theta}$ is smaller than ~ 0.4, which is consistent with the observational result at the $1\,\sigma$ level. The value of $\Delta\theta \sim 0.03$ is as low as the minimum of those having ever been inferred from afterglow light curve. The jet break time is given by $t_j \sim 13\,{\rm min}\,(\Delta\theta/0.01)^{8/3}$ [1] and so it requires fast localization to observe the jet break for a narrow jet. Therefore, at present, the small number of GRBs with small $\Delta\theta$ may come from the observational selection effect. In the context of this scenario, we might be able to account for the fact that afterglows of XRFs have been rarely observed since the afterglow at a fixed time gets dimmer for an earlier break time. Furthermore, some "dark GRBs" might be such a small opening angle jet observed with an on-axis viewing angle for the same reason.

Table 1 shows that the sources with the viewing angle $\theta_{v,\,p} \sim \Delta\theta + 0.02$, where $W(\theta_v)$ takes maximum, are the most frequent class of the XRFs in the population for $\Delta\theta \leq 0.03$. The typical observed photon energy is estimated as [12, 13]

$$E_p \sim 2\gamma\nu_0'(1+z)^{-1}[1+(\gamma\theta_{v,\,p}-\gamma\Delta\theta)^2]^{-1} \sim 30\ {\rm keV}\ [(1+z)/2.5]^{-1}\,, \qquad (3)$$

which is the typical observed peak energy of the XRFs [8]. We can propose from our argument that the emissions from the jets with a small opening half-angle such as $\Delta\theta \leq 0.03$ are observed as XRFs when they are seen from off-axis viewing angle. If one can detect the afterglow of the XRF, which has the maximum flux at about several hours after the XRF, the fitting of light curve may give us the key information about the jet opening angle [2]. For example, the light curve of afterglow of XRF 030723 was unusual in early epoch, which can be well explained if the jet is seen from off-axis viewing angle [6].

We can estimate the observed event rate of the XRF for fixed $\Delta\theta$ as $R^{\rm XRF}_{\Delta\theta} = (1/4\pi)\int W(\theta_v)\,d\theta_v$. For a reasonable proportionality constant, we derive $R^{\rm XRF}_{\Delta\theta=0.03} \sim 10^2$ events yr^{-1}, which is consistent with the observation. The value of $R^{\rm XRF}_{\Delta\theta}$ remains unchanged within a factor of 2 when we vary $\Delta\theta$ from 0.01 to 0.07.

When the jet opening half-angle $\Delta\theta$ has a distribution $f_{\Delta\theta}$, we integrate $\langle V/V_{\rm max}\rangle_{\Delta\theta}$ and $R_{\Delta\theta}^{\rm XRF}$ over the distribution of $\Delta\theta$ as

$$\langle V/V_{\rm max}\rangle \propto \int d(\Delta\theta)\, f_{\Delta\theta}\, R_{\Delta\theta}^{\rm XRF}\, \langle V/V_{\rm max}\rangle_{\Delta\theta} \ , \tag{4}$$

$$R_{\rm XRF} \propto \int d(\Delta\theta)\, f_{\Delta\theta}\, R_{\Delta\theta}^{\rm XRF} \ , \tag{5}$$

respectively [13]. When we adopt a power-low distribution as $f_{\Delta\theta} \propto (\Delta\theta)^{-q}$, with $q = 4.54$ [1] and integrate over $\Delta\theta$ from 0.01 to 0.2 rad, we find $\langle V/V_{\rm max}\rangle = 0.36$ and $R_{\rm XRF} \sim 10^2$ events yr^{-1}. These values mainly depend on the lower cut-off of $f_{\Delta\theta}$. For example, we obtain $\langle V/V_{\rm max}\rangle = 0.43$ and $R_{\rm XRF} \sim 3$ events yr^{-1} if the integration is done over $\Delta\theta$ from 0.03 to 0.2 rad. Hence, we might be able to determine the lower cut-off if the other uncertain factors are fixed by other arguments. Since the statistics of the observational data will increase in the near future owing to instruments such as *HETE-2* and *Swift*, we will be able to say more than above discussion, including more accurate functional form of $f_{\Delta\theta}$ than that we have considered above, as well as the relation to the GRB event rate.

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