An Off-Axis Jet Model For GRB 980425 and Low Energy Gamma-Ray Bursts

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ABSTRACT

Using a simple off-axis jet model of GRBs, we can reproduce the observed unusual properties of the prompt emission of GRB 980425, such as the extremely low isotropic equivalent $\gamma$-ray energy, the low peak energy, the high fluence ratio, and the long spectral lag when the jet with the standard energy of $\sim 10^{51}$ ergs and the opening half-angle of $10^\circ \lesssim \Delta \theta \lesssim 30^\circ$ is seen from the off-axis viewing angle $\theta_v \sim \Delta \theta + 10\gamma^{-1}$, where $\gamma$ is a Lorentz factor of the jet. For our adopted fiducial parameters, if the jet that caused GRB 980425 is viewed from the on-axis direction, the intrinsic peak energy $E_p(1+z)$ is $\sim 2.0$–$4.0$ MeV, which corresponds to those of GRB 990123 and GRB 021004. We also discuss the connection of GRB 980425 in our model with the X-ray flash, and the origin of a class of GRBs with small $E_\gamma$.

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

1. INTRODUCTION

Recently, a very luminous gamma-ray burst (GRB), GRB 030329 at the distance of 0.8 Gpc ($z = 0.1685$) was confirmed to be associated with supernova SN 2003dh (Stanek et al. 2003; Uemura et al. 2003; Price et al. 2003; Hjorth et al. 2003). The geometrically corrected $\gamma$-ray energy $E_\gamma$ of this event $\sim 5 \times 10^{49}$ergs is a factor 20 smaller than the standard value, if the jet break time of $\sim 0.48$ days is assumed (Vanderspek et al. 2003; Price et al.

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GRB 980425 was the first GRB associated with a supernova (SN) event, SN 1998bw at $z = 0.0085$ (36 Mpc) (Galama et al. 1998; Kulkarni et al. 1998; Woosley et al. 1998; Pian et al. 2000, 2003). There are some other events that might be associated with supernovae (Della Valle et al. 2003; Wang & Wheeler 1998; Germany et al. 2000; Rigon et al. 2003). Therefore the association of the long duration GRBs with supernovae is strongly suggested and at least some GRBs arise from the collapse of a massive star.

In this context, it is important to investigate whether GRB 980425/SN 1998bw is similar to more or less typical long duration GRBs like GRB 030329/SN 2003dh. However, GRB 980425 showed unusual observational properties. The isotropic equivalent $\gamma$-ray energy is $E_{\text{iso}} = 6 \times 10^{47}$ ergs and the geometrically corrected energy is $E_{\gamma} \sim 3 \times 10^{46}$ ergs ($\Delta \theta/0.3)^2$, where $\Delta \theta$ is the unknown jet opening half-angle. These energies are much smaller than the typical values of GRBs $E_{\gamma} \sim 1 \times 10^{51}$ ergs (Bloom et al. 2003; Frail et al. 2001). Bloom et al. (2003) claim that there should be some events with small $E_{\gamma}$ such as GRB 980519 and GRB 980326 and that GRB 980425 might be a member of this class. The other properties of GRB 980425 are also unusual; the large low energy flux, the long spectral lag, the low variability, and the slowly decaying X-ray luminosity of its counterpart detected and monitored by BeppoSAX and by XMM-Newton (Frontera et al. 2000a; Norris, Marani, & Bonnell, 2000; Fenimore & Ramirez-Ruiz 2000; Pian et al. 2000, 2003).

Previous works suggest that the above peculiar observed properties of GRB 980425 might be explained if the standard jet is seen from the off-axis viewing angle (Ioka & Nakamura 2001; Nakamura 1999; Nakamura 2001; see also Maeda et al. 2002; Iwamoto 1999; Dado, Dar, & De Rújula 2003; Dar & De Rújula 2000). Following this scenario, the relativistic beaming effect reduces $E_{\text{iso}}$ and hence $E_{\gamma}$. The quantity $E_{\text{iso}}$ is roughly proportional to $\delta^{2-3}$ for the typical observed spectrum, where $\delta = [\gamma(1 - \beta \cos(\theta_v - \Delta \theta))]^{-1}$ is the Doppler factor and $\theta_v$ is the viewing angle (Yamazaki, Ioka, & Nakamura 2002). Since $E_{\text{iso}} \sim 10^{45-5}$ times smaller than the standard value, $\delta$ should be $20 \sim 10^2$ times smaller than the usual value. Then the peak energy $E_p (\propto \delta)$ becomes $20 \sim 10^2$ times smaller than on-axis $E_p$, that is measured when the jet is seen from the on-axis viewing angle. However, the observed $E_p$ of GRB 980425 ($\sim 50$ keV) is only a factor 4 or 5 smaller than the typical value of $\sim 250$ keV. Therefore, one might consider that GRB 980425 belongs to a different class of GRBs.

It is well known that the distribution of $E_p$ is log-normal with the mean of $\langle E_p \rangle \sim 250$ keV (Preece et al. 2000). Ioka & Nakamura (2002) showed that if the distribution of intrinsic $E_p$ (i.e. $E_p(1 + z)$) is log-normal, the redshifted one is also log-normal under the assumption that the redshifts of the observed GRBs are random. Therefore, $\langle E_p(1 + z) \rangle \sim 570$ keV since the mean value of the measured redshifts is $\sim 1.3$ (Bloom et al. 2003). There are some GRBs with even higher intrinsic peak energy; for example, $E_p(1 + z) \sim 2.0$ MeV.
for GRB 990123 (Amati et al. 2002) and $E_p(1 + z) \sim 3.6$ MeV for GRB 021004 (Barraud et al. 2003). Furthermore, Fig. 3 of Schaefer et al. (2003) shows that the highest value of $E_p(1 + z)$ detected by BATSE is about 4 MeV. Since GRB 980425 is the nearest GRB, the redshift factor is not important. In this sense, the peak energy of GRB 980425 is at least a factor $\sim 10$ smaller than the usual one of $\sim 570$ keV. Suppose that the intrinsic $E_p$ of GRB 980425 is similar to that of GRB 990123 and GRB 021004 when the jet of GRB 980425 is seen from the on-axis viewing angle. Then, the observed $E_p$ of GRB 980425 is $\sim 10^2$ times smaller than the intrinsic $E_p$ of GRB 990123 and GRB 021004. This is the reason why we incline to reconsider the off-axis jet model for GRB 980425.

In this Letter, assuming the rather large on-axis $E_p$, we reconsider the prompt emission of GRB 980425 using the simple model in Yamazaki, Ioka, & Nakamura (2002, 2003b) to reproduce its unusual observed quantities. In § 2, in order to extract the observational properties that should be compared with our theoretical model for prompt emission of the GRB, we analyze the BATSE data of GRB 980425. In § 3, we describe a simple jet model including the cosmological effect. We assume a uniform jet with a sharp edge. Numerical results are shown in § 4. Section 5 is devoted to discussions. Throughout this paper, we adopt the flat universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$.

2. SPECTRAL ANALYSIS FOR PROMPT EMISSION OF GRB 980425 USING BATSE DATA

In our simple jet model of GRBs, the time-dependence of spectral indices is not treated, while it is known that the spectral parameters of GRB 980425 changed in time (Galama et al. 1998; Frontera et al. 2000a). Hence, we should discuss the time-averaged observed spectral properties of GRB 980425 before we apply our model to them.

Using the BATSE data of GRB 980425, we analyze the spectrum within the time of Full-Width at Half-Maximum of the peak flux in the light curve of BATSE channel 2 (50–110 keV). This time interval approximately corresponds to portions “B” and “C” in Frontera et al. (2000a), when most of photons arrived at the detector and the spectral shape was approximately constant with time. We fit the observed spectrum with smoothly broken power-law function given by Band et al. (1993), that is characterized by the energy at the spectral break $E_0$, and the low- and high-energy photon index $\alpha$ and $\beta$, respectively. For the case of $\beta < -2$, the peak energy is derived as $E_p = (2 + \alpha)E_0$. The best-fit spectral parameters are

$$\alpha = -1.0 \pm 0.3$$
\[ \beta = -2.1 \pm 0.1 \]
\[ E_p = 54.6 \pm 20.9 \text{ keV}. \]

The reduced chi square is 1.10 for 31 degree of freedom. These results are consistent with those derived by the previous works (Frontera et al. 2000a; Galama et al. 1998). Although the photon indices are the typical values of GRBs, \( E_p \) is lower than the typical values of GRBs (Preece et al. 2000). This spectral property is similar to one of the recently identified class of the X-ray flash (Kippen et al. 2002; Heise et al. 2001).

The observed fluence of the entire emission between 20 to 2000 keV is \( S(20-2000 \text{ keV}) = (4.0 \pm 0.74) \times 10^{-6} \text{ erg cm}^{-2} \), so the isotropic equivalent \( \gamma \)-ray energy becomes \( E_{iso} = (6.4 \pm 1.2) \times 10^{47} \text{ ergs} \). The fluence ratio is \( R_s = S(20-50 \text{ keV})/S(50-320 \text{ keV}) = 0.34 \pm 0.036 \). In the following sections, we reproduce the above results using our prompt emission model.

### 3. MODEL OF PROMPT EMISSION OF GRBs

We use a simple jet model of prompt emission of GRBs adopted in Yamazaki et al. (2003b), where the cosmological effect is included (see also Yamazaki et al. 2002, 2003a; Ioka & Nakamura 2001). We adopt an instantaneous emission of infinitesimally thin shell at \( t = t_0 \) and \( r = r_0 \). Then the observed flux of a single pulse is given by

\[
F_{\nu}(T) = \frac{2(1+z)r_0 c A_0 \Delta \phi(T)f[\nu \gamma(1 - \beta \cos \theta(T))]}{d_L^2 \gamma(1 - \beta \cos \theta(T))^2},
\]  

(1)

where, \( 1 - \beta \cos \theta(T) = (1+z)^{-1}(c/\beta r_0)(T-T_0) \) and \( A_0 \) determines the normalization of the emissivity. Detailed derivation of Eq. (1) and the definition of \( \Delta \phi(T) \) are found in Yamazaki et al. (2003b). In order to have a spectral shape similar to that derived by the previous section, we adopt the following form of the spectrum in the comoving frame,

\[
f(\nu') = \begin{cases} 
(\nu'/\nu_0^\gamma)^{1+\alpha_B} \exp(-\nu'/\nu_0^\gamma) & \text{for } \nu'/\nu_0^\gamma \leq \alpha_B - \beta_B \\
(\nu'/\nu_0^\gamma)^{1+\beta_B} (\alpha_B - \beta_B)^{\alpha_B - \beta_B} \exp(\beta_B - \alpha_B) & \text{for } \nu'/\nu_0^\gamma \geq \alpha_B - \beta_B
\end{cases},
\]  

(2)

with \( \alpha_B = -1 \) and \( \beta_B = -2.1 \). Equations (1) and (2) are the basic equations to calculate the flux of a single pulse, which depends on the following parameters; \( \gamma \), \( \gamma \nu_0', \theta_v \), \( \Delta \theta \), \( r_0/c \beta \gamma^2 \), \( z \), and \( A_0 \). In the next section, the viewing angle \( \theta_v \) and the jet opening half angle \( \Delta \theta \) are mainly varied. The other parameters are fixed as follows; the quantity \( \gamma \) is fixed as \( \gamma = 100 \). The isotropic \( \gamma \)-ray energy is calculated as \( E_{iso} = 4\pi(1+z)^{-1}d_L^2 S(20-2000 \text{ keV}) \), where \( S(\nu_1 - \nu_2) \) is the observed fluence in the energy range \( h\nu_1 - h\nu_2 \text{ keV} \). We fix the amplitude \( A_0 \) so that the geometrically-corrected \( \gamma \)-ray energy \( E_\gamma = (\Delta \theta)^2 E_{iso}/2 \) be observationally preferred value when we see the jet from the on-axis viewing angle \( \theta_v = 0 \). It is shown that
\( E_{\gamma} \) is tightly clustering about a standard energy \( \mathcal{E}_{\gamma} \) of \( \sim 10^{51} \) ergs (Bloom et al. 2003; see also Frail et al. 2001; Panaitescu & Kumar 2002). Bloom et al. (2003) derived this energy as

\[
\log \mathcal{E}_{\gamma} = \log \left( 1.15 \times 10^{51} (h/0.7)^{-2} \right) \pm 0.07 ,
\]

so that \( \mathcal{E}_{\gamma} = (0.98–1.35) \times 10^{51} \) ergs, at the 1 \( \sigma \) level while \( \mathcal{E}_{\gamma} = (0.51–2.57) \times 10^{51} \) ergs, at 5 \( \sigma \) level. Note that the smaller jet opening half-angle \( \Delta \theta \) corresponds to the larger \( A_0 \) (Yamazaki et al. 2003b).

Practical calculations show that when the jet with \( \alpha_B = -1 \) and \( \beta_B = -2.1 \) is seen from the on-axis viewing angle \( \theta_v = 0 \), the observed peak energy becomes \( E_p(\theta_v=0) \sim 1.54 \gamma \nu_0'(1+z)^{-1} \), which is independent on \( \Delta \theta \) larger than \( \sim \gamma^{-1} \). In order to reproduce the observed quantities of GRB 980425, we adopt the value \( \gamma \nu_0' = 2600 \) keV, which yields \( E_p(\theta_v=0)(1+z) \sim 4.0 \) MeV. For comparison, we consider another case of \( \gamma \nu_0' = 1300 \) keV, which reads \( E_p(\theta_v=0)(1+z) \sim 2.0 \) MeV. These values correspond to the intrinsic \( E_p \) of GRB 021004 and GRB 990123, respectively. Note here that in our jet model the quantities that will be calculated in the next section do not depend on \( r_0/c\beta\gamma^2 \); for example, \( E_{iso} \propto A_0 (r_0/c\beta\gamma^2)^2 \propto (r_0/c\beta\gamma^2)^0 \) since \( A_0 \propto (r_0/c\beta\gamma^2)^{-2} \). The value of \( r_0/c\beta\gamma^2 \) will be determined when we discuss the spectral lag in § 5.

\section{4. ISOTROPIC ENERGY, PEAK ENERGY, AND FLUENCE RATIO}

We now calculate the isotropic equivalent \( \gamma \)-ray energy \( E_{iso} \) as a function of \( \theta_v \) and \( \Delta \theta \). Then, the peak energy \( E_p \) and the fluence ratio \( R_s = S(20–50 \) keV)\()/S(50–320 \) keV) are computed for the set of \( \Delta \theta \) and \( \theta_v \) that reproduces the observed \( E_{iso} \) of GRB 980425.

For fixed \( \Delta \theta \) and \( \mathcal{E}_{\gamma} \), \( E_{iso} \) is calculated as a function of the viewing angle \( \theta_v \). The result is shown in Fig. 1. When \( \theta_v \lesssim \Delta \theta \), \( E_{iso} \) is essentially constant, while for \( \theta_v \gtrsim \Delta \theta \), \( E_{iso} \) is considerably smaller than the typical value of \( \sim 10^{51–53} \) ergs because of the relativistic beaming effect. In order to explain the observation, \( \theta_v \) should be \( \sim 21^\circ \) in the case of \( \Delta \theta = 15^\circ \), while \( \theta_v \sim 25^\circ \) in the case of \( \Delta \theta = 20^\circ \). This result does not depend on \( \gamma \nu_0' \) so much.

The upper panels of Fig. 2 and 3 show \( \theta_v^* \), for which \( E_{iso} \) becomes equal to the observed values, as a function of \( \Delta \theta \) in the case of \( \gamma \nu_0' = 2600 \) keV and 1300 keV, respectively. Since the emissivity (\( \propto A_0 \)) of the jet is small for large \( \Delta \theta \), the relativistic beaming effect should be weak for large \( \Delta \theta \). Therefore, the value of \( \theta_v^* - \Delta \theta \) is a decreasing function of \( \Delta \theta \). For such \( \theta_v^* \), we calculate the fluence ratio \( R_s^* = R_s(\theta_v=\theta_v^*) \) and the peak energy \( E_p^* = E_p(\theta_v=\theta_v^*) \). The middle and the lower panels of Figs. 2 and 3 show the results. The quantity \( E_p^* \) is proportional to
the Doppler factor $\delta \sim [\gamma (1 - \beta \cos(\theta_v^* - \Delta \theta))]^{-1}$. Therefore, when $\Delta \theta$ increases, $\theta_v^* - \Delta \theta$ decreases so that $E_p^*$ increases. Since we fix spectral indices $\alpha_B$ and $\beta_B$, $R_s^*$ depends only on $E_p^*$. Hence, if $E_p^*$ is large, the spectrum is hard and $R_s^*$ is small. For the fiducial parameters of $\gamma \nu_0' = 2600$ keV, $E_\gamma = 1.15 \times 10^{51}$ ergs, and $E_{iso} = 6.4 \times 10^{47}$ ergs, $\Delta \theta$ should be between $\sim 18^\circ$ and $\sim 31^\circ$, and then $\theta_v^*$ ranges between $\sim 24^\circ$ and $\sim 35^\circ$ in order to reproduce the observed values of $R_s$ and $E_p$. When $E_\gamma$ is varied from $0.51 \times 10^{51}$ to $2.6 \times 10^{51}$ ergs (at 5 $\sigma$ level), the allowed region with $20^\circ \lesssim \Delta \theta \lesssim 30^\circ$ can exist even in the case of $\gamma \nu_0' = 1300$ keV.

Note that $\gamma$ does not affect our results for observed $R_s^*$ and $E_p^*$. When $\gamma$ is large, $\theta_v^*$ becomes small because the observed flux for fixed $\theta_v$ becomes small due to stronger relativistic beaming effect. However, we can see that $\gamma (\theta_v^* - \Delta \theta)$ remains almost unchanged even if $\gamma$ is varied. Then for fixed $\gamma \nu_0'$, $E_p^*$ remains constant since $E_p^* \propto \nu_0'^{2} \sim 2 \nu_0'[1 + (\gamma (\theta_v^* - \Delta \theta))]^{-1}$. The quantity $R_s^*$ depends only on $E_p^*$ so that $\gamma$ does not affect the estimate of $R_s^*$.

5. DISCUSSION

We considered the time-averaged emissions, which means that successive emissions from multiple subjets (or shells) are approximated by one spontaneous emission caused by a single jet (Yamazaki et al. 2002). We choose $\alpha_B = -1$, $\beta_B = -2.1$, $\gamma = 100$, and $\gamma \nu_0' = 2600$ keV for the canonical set of parameters. As a result, when the jet of opening half-angle of $\Delta \theta \sim 10$–30$^\circ$ is seen from the off axis viewing angle of $\theta_v \sim \Delta \theta + 6^\circ$, observed quantities can be well explained. Derived $\theta_v$ and $\Delta \theta$ are consistent with those suggested in Nakamura 2001, Nakamura 1999, and Maeda et al. 2002. We may also be able to explain observed low variability since only subjets at the edge of the cone contribute to the observed quantities (see the discussion of Yamazaki et al. 2002). If the jet is seen from an on-axis viewing angle (i.e. $\theta_v < \Delta \theta$), the intrinsic peak energy $E_p(1 + z)$ is $\sim 4.0$ MeV, which is almost the same as the highest one (Schaefer 2003; Amati et al. 2002; Barraud et al. 2003).

As we have mentioned in § 3, $E_{iso}$, $E_p^*$, and $R_s^*$ do not depend on the parameter $r_0/\beta c \gamma^2$. In order to estimate the value of $r_0/\beta c \gamma^2$, we discuss the spectral lag of GRB 980425 (Ioka & Nakamura 2001). In our model, we can calculate the spectral lag $\Delta T$, which is defined, for simplicity, as the difference of the peak time between BATSE energy channel 1 and 3. We obtain $\Delta T/(r_0/c \beta \gamma^2)$ = 0.97–1.34. Therefore, the observed value of $\Delta T = 3$ s (Norris et al. 2000) can be explained when $r_0/c \beta \gamma^2 = (2.2$–3.1) sec, which is in the reasonable parameter range.

The observed quantities of small $E_p$ and large fluence ratio $R_s$ (see also Frontera et al. 2000a) are the typical values of the X-ray flash (Heise et al. 2001; Kippen et al. 2002; see
also Barraud et al. 2003; Arefiev, Priedhorsky & Borozdin 2003). The operational definition of the X-ray flash detected by BeppoSAX is a fast X-ray transient with duration less than $\sim 10^3$ seconds which is detected by WFCs and not detected by the GRBM (Heise et al. 2001). If the distance to the source of GRB 980425 that has an opening half-angle of $\Delta \theta = 20^\circ$ were larger than $\sim 86$ Mpc, the observed flux in the $\gamma$-ray band would have been less than the limiting sensitivity of GRBM $\sim 5 \times 10^{-7}$ erg cm$^{-2}$ in 40–700 keV band (Band 2003), so that the event would have been detected as an X-ray flash.

We might be able to explain the origin of a class with low $E_\gamma$, pointed by Bloom et al. (2003). Let us consider the jet seen from a viewing angle $\theta_v \sim \Delta \theta + \gamma_i^{-1}$, where $\gamma_i$ is the Lorentz factor of a prompt $\gamma$-ray emitting shell. Due to the relativistic beaming effect, observed $E_\gamma$ of such a jet becomes an order of magnitude smaller than the standard energy (see Fig. 1). At the same time, the observed peak energy $E_p$ is small because of the relativistic Doppler effect. In fact, the observed $E_p$ of GRB 980326 and GRB 981226 are $\sim 35$ keV and $\sim 60$ keV, respectively (Amati et al. 2002; Frontera et al. 2000b). In our model the fraction of GRBs with low $E_\gamma$ becomes $2/(\gamma_i \Delta \theta) \sim 0.1$ since the mean value of $\Delta \theta \sim 0.2$, while a few GRBs with low $E_\gamma$ are observed in $\sim 30$ samples (Bloom et al. 2003). In later phase, the Lorentz factor of afterglow emitting shock $\gamma_f$ is smaller than $\gamma_i$, so that $\theta_v < \Delta \theta + \gamma_f^{-1}$. Then, the observed properties of afterglow may be similar to the on-axis case $\theta_v \ll \Delta \theta$; hence the observational estimation of the jet break time and the jet opening angle remains the same.

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REFERENCES

Amati, L., et al. 2002, A&A, 390, 81
Arefiev, V.A., Priedhorsky, W.C., & Borozdin, K.N. 2003, ApJ, 586, 1238
Band, D.L., 2003, ApJ, 588, 945
Band, D., et al. 1993, ApJ, 413, 281
Barraud, C., et al. 2003, A&A, 400, 1021
Bloom, J.S., et al. 2003, ApJ, 594, 674
Dado, S., Dar, A., & De Rújula, A. 2003, A&A, 401, 243
Dar, A. & De Rújula, A. 2000, astro-ph/0008474
Della Valle, M. et al. 2003, A&A, 406, L33
Fenimore, E. E. & Ramirez-Ruiz. E., 2000, astro-ph/0004176
Frail, D., A., et al. 2001, ApJ, 562, L55
Frontera, F. et al. 2000a, ApJS, 127, 59
Frontera, F. et al. 2000b, ApJ, 540, 697
Galama, T.J., et al. 1998, Nature, 395, 670
Germany, L.M., Reiss, D.J., Sadler, E.M., Schmidt, B.P., & Stubbs, C.W. 2000, ApJ, 533, 320
Heise, J., in ’t Zand, J., Kippen, R. M., & Woods, P. M. 2001, in Proc. Second Rome Workshop: Gamma-Ray Bursts in the Afterglow Era, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 16
Hjorth, J. et al., 2003, Nature, 423, 847
Ioka, K., & Nakamura, T. 2001, ApJ, 554, L163
Ioka, K., & Nakamura, T. 2002, ApJ, 570, L21
Iwamoto, K., 1999, ApJ, 512, L47
Kippen, R. M., et al. 2002, in Proc. Woods Hole Gamma-Ray Burst Workshop, astro-ph/0203114
Kulkarni, S.R., et al. 1998, Nature, 395, 663
Maeda, K., et al. 2002, ApJ, 565, 405
Nakamura, T. 1999, ApJ, 522, L101
Nakamura, T. 2001, Prog. Theor. Phys. Suppl, 143, 50
Norris, J.P., Marani, G.F., & Bonnell, J.T. 2000, ApJ, 534, 248
Panaitescu, A. & Kumar, P. 2002, ApJ, 571, 779
Pian, E. et al., 2000, ApJ, 536, 778
Pian, E. et al., 2003, astro-ph/0304521
Preece, R. D., Briggs, M. S., Mallozzi, R. S., Pendleton, G. N., Paciesas, W. S., & Band, D. L.
2000, ApJS, 126, 19
Price, P.A. et al., 2003, Nature, 423, 844
Rigon, L. et al. 2003, MNRAS, 340, 191
Schaefer, B.E. et al., 2003, ApJ, 583, L71
Stanek, K.Z. et al. 2003, ApJ, 591, L71
Uemura, M. et al. 2003, Nature, 423, 843
Vanderspek, R. et al. 2003, GCN circ. 1997
Wang, L. & Wheeler, J.C. 1998, ApJ, 504, L87
Woosley, S. E., Eastman, R.G., & Schmidt, B.P. 1999, ApJ, 516, 788
Yamazaki, R., Ioka, K., & Nakamura, T. 2002, ApJ, 571, L31
Yamazaki, R., Ioka, K., & Nakamura, T. 2003a, ApJ, 591, 283
Yamazaki, R., Ioka, K., & Nakamura, T. 2003b, ApJ, 593, 941

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Fig. 1.— The isotropic equivalent $\gamma$-ray energy $E_{\text{iso}}$ is shown as a function of the viewing angle $\theta_v$ for a fixed jet opening half-angle $\Delta \theta$. The source is located at $z = 0.0085$. The values of $\Delta \theta$ are shown in parentheses. Solid lines correspond to the case of $\gamma \nu_0' = 2600$ keV, while dotted lines $\gamma \nu_0' = 1300$ keV. Other parameters are fixed as $\alpha_B = -1$, $\beta_B = -2.1$, $\gamma = 100$, and $\mathcal{E}_\gamma = 1.15 \times 10^{51}$ ergs. Horizontal dashed line represents the observed value of GRB 980425 $E_{\text{iso}} = 6.4 \times 10^{47}$ ergs. The value of $E_{\text{iso}}$ in the on-axis case $\theta_v < \Delta \theta$ is slightly smaller for $\gamma \nu_0' = 2600$ keV than for $\gamma \nu_0' = 1300$ keV. This is because the amplitude $A_0$ is fixed so that we should observe constant $E_\gamma$ from the source at $z = 1$, and the K-correction is larger for $\gamma \nu_0' = 1300$ keV than for $\gamma \nu_0' = 2600$ keV.
Fig. 2.— The upper panel shows $\theta^*_v$ for which $E_{iso}$ is the observed value of GRB 980425, while the middle and the lower panels represent the fluence ratio $R^*_s = R_s^{(\theta_v=\theta^*_v)}$ and the peak energy $E^*_p = E_p^{(\theta_v=\theta^*_v)}$, respectively. Solid lines correspond to the fiducial case of $E_{iso} = 6.4 \times 10^{47}$ ergs and $E_\gamma = 1.15 \times 10^{51}$ ergs. The dotted lines represent regions where $E_{iso}$ becomes $(6.4 \pm 1.2) \times 10^{47}$ ergs when $E_\gamma$ is in 1 $\sigma$ and 5 $\sigma$ level around the fiducial value, respectively. Other parameters are fixed as $\alpha_B = -1$, $\beta_B = -2.1$, $\gamma = 100$, and $\gamma_0' = 2600$ keV. The dot-dashed line in the upper panel represents $\theta^*_v = \Delta \theta$. Horizontal dashed lines in the middle and the lower panels represent the observational bounds $R_s = 0.42 \pm 0.13$ and $E_p = 54.6 \pm 20.9$ keV, respectively.
Fig. 3.— Same as Fig. 2 but for $\gamma'_{0} = 1300$ keV.