GRB 980425 in the Off-Axis Jet Model of the Standard GRBs

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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 γ-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 \( 10^\circ \leq \Delta \theta \leq 30^\circ \) 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. Our model might be able to explain the other unusual properties of this event. 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 \( E_\gamma \) such as GRB 030329.

INTRODUCTION

There are some GRBs that were thought to be associated with SNe [4, 17]. GRB 980425 / SN 1998bw, located at \( z = 0.0085 \) (36 Mpc), was the first event of such class [7, 11, 15, 16]. It is important to investigate whether GRB 980425 is similar to more or less typical long duration GRBs. However, GRB 980425 showed unusual observational properties. The isotropic equivalent γ-ray energy is \( E_{\text{iso}} \sim 6 \times 10^{47} \) ergs and the geometrically corrected energy is \( E_\gamma = (\Delta \theta)^2 E_{\text{iso}} / 2 \sim 3 \times 10^{46} \) 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. The other properties of GRB 980425 are also unusual; the large low-energy flux [6], the low variability [5], the long spectral lag [14], and the slowly decaying X-ray afterglow [15, 16].

Previous works suggest that the above peculiar observed properties may be explained if the standard jet is seen from the off-axis viewing angle (e.g.[9, 13]). Following this scenario, the relativistic beaming effect reduces \( E_{\text{iso}} \) and hence \( E_\gamma \). In this paper, in order to explain all of the observed properties of GRB 980425, we reconsider the prompt emission of this event using our simple jet model [21, 22, 23, 24].

SPECTRAL ANALYSIS OF GRB 980425 USING BATSE DATA

We argue the time-averaged observed spectral properties of GRB 980425. Using the BATSE data of GRB 980425, we analyze the spectrum within the time of FWHM of the peak flux in the light curve of BATSE channel 2. We fit the observed spectrum
with the Band function. The best-fit values are $\alpha = -1.0 \pm 0.3$, $\beta = -2.1 \pm 0.1$, and $E_p = 54.6 \pm 20.9$ keV, which are consistent with those derived by the previous works [6, 7]. This spectral property is similar to one of the recently identified class of the X-ray flash (XRF) [8, 10]. The observed fluence of the entire emission is $S(20–2000$ keV) = $(4.0 \pm 0.74) \times 10^{-6}$ erg cm$^{-2}$, thus we find $E_{\text{iso}} = (6.4 \pm 1.2) \times 10^{57}$ ergs. The fluence ratio is $R_v = S(20–50$ keV)/$S(50–320$ keV) = $0.34 \pm 0.036$.

**MODEL OF PROMPT EMISSION OF GRB 980425**

We use a simple jet model of prompt emission of GRBs, where an instantaneous emission of infinitesimally thin shell is adopted [9, 21, 22, 23, 24]. See Yamazaki et al. [24] for details. We fix model parameters as $\alpha_B = -1$, $\beta_B = -2.1$, $\gamma v_0^2 = 2600$ keV, and $\gamma = 100$. Normalization of emitted luminosity is determined so that $F_0$ be observationally preferred value of $1.15 \times 10^{51} \pm 0.35 (h/0.7)^{-2}$ ergs [3] when we see the jet from the on-axis viewing angle $\theta_v = 0$. Our calculations show that on-axis intrinsic peak energy becomes $E_p(\theta_v = 0) (1 + z) \sim 1.54 \gamma v_0^2 \sim 4.0$ MeV, in order to reproduce the observed quantities of GRB 980425. Indeed, there are some GRBs with higher intrinsic $E_p$; for example, $E_p(1 + z) \sim 2.0$ MeV for GRB 990123 and $3.6$ MeV for GRB 021004 [1, 2].

The left panel of Figure 1 shows $E_{\text{iso}}$ as a function of the viewing angle $\theta_v$. When $\theta_v \leq \Delta \theta$, $E_{\text{iso}}$ is constant, while for $\theta_v \geq \Delta \theta$, $E_{\text{iso}}$ is considerably smaller than the typical value of $\sim 10^{51–53}$ ergs because of the relativistic beaming effect.

We next calculated $E_p$ and $R_v$ for the set of $\Delta \theta$ and $\theta_v$ that reproduces the observed $E_{\text{iso}}$ of GRB 980425. For our parameters, $\Delta \theta$ 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 observation results. Thorough discussions on the right panel of Figure 1 is found in [24].

**DISCUSSION**

We have found that 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. Observed low variability can be explained since only subsets at the edge of the cone contribute to the observed quantities [21]. If the time unit parameter $n_0/c\beta \gamma^2$ is about 3 sec, which is in the reasonable parameter range, the spectral-lag of GRB 980425 can be also explained.

Our result might be able to explain the slowly decaying X-ray afterglow of GRB 980425. If we assume the density profile of ambient matter as $n = n_0(r/r_{\text{ext}})^{-2}$ with $n_0 r_{\text{ext}}^2 = 4 \times 10^{17}$ cm$^{-2}$, the break in the afterglow light curve should occur at $t_b = 3.1 \times 10^2$ days $E_{51}(\Theta/0.4$ rad)$^2$, where $\Theta$ is defined by $\Theta^2 = (\Delta \theta)^2 + \theta_v^2$, and $E$ is the total energy in the collimated jet [12, 13]. Since our calculation suggests $\Theta$ should range between 0.4 and 0.67 rad, $t_b$ is consistent with the observation [13]. Up to the break time, one can estimate the flux in the X-ray band as $F(2–10$ keV) $\propto t^{-0.2}$, where we assume $\theta_v \gg \Delta \theta$ and the spectral index of accelerated electrons as $p = 2.2$ [12, 13]. This result is also consistent with the observation [15, 16]. Furthermore,
FIGURE 1. (Left panel): the isotropic equivalent $\gamma$-ray energy $E_{iso}$ 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. Horizontal dashed line represents the observed value of GRB 980425. (Right panel): 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 $R^*_s = R^{(\theta = \theta^*_v)}$ and the peak energy $E^*_p = E^{(\theta = \theta^*_v)}$, respectively. Solid lines correspond to the fiducial case. 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. 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.

the adopted value of $n_0 r_{ext}^2$ corresponds to the mass loss rate of the progenitor star $M = 1.3 \times 10^{-6} M_\odot \text{yr}^{-1}$ ($\nu_\text{W}/10^3 \text{km s}^{-1}$), which might be able to explain the radio data (see [20]).

The observed quantities of small $E_p$ and large fluence ratio $R_s$ are the typical values of the XRF [3, 8, 10]. The operational definition of the BeppoSAX-XRF is a fast X-ray transient with duration less than $\sim 10^3$ s which is detected by WFCs and not detected by the GRBM. If the distance to the source of GRB 980425 were larger than $\sim 90$ Mpc, the observed flux in the $\gamma$-ray band would have been less than the limiting sensitivity of GRBM, so that the event would have been detected as an XRF.

We might be able to explain the origin of a class with low $E_{\gamma}$ such as GRB 980326 and GRB 981226 [8], and GRB 030329 whose $E_{\gamma}$ is about $\sim 5 \times 10^{49}$ ergs if the jet break time of $\sim 0.48$ days is assumed [18, 19]. 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. 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 the above three bursts are less than $\sim 70$ keV. In our model the fraction of low-$E_{\gamma}$ GRBs becomes $2/(\gamma \Delta \theta) \sim 0.1$ since the mean value of $\Delta \theta \sim 0.2$, while a few of them are observed in $\sim 30$ samples [3]. In later phase, the Lorentz factor of afterglow emitting shock $\gamma_f$ is smaller than $\gamma_i$, so that $\theta_v \sim \Delta \theta + \gamma_f^{-1}$. Then, the observed properties of afterglow may
be similar to the on-axis case $\theta_r \ll \Delta \theta$; hence the observational estimation of the jet break time and the jet opening angle remains the same.

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**REFERENCES**

1. Amati, L., et al. 2002, A&A, 390, 81
2. Barraud, C., et al. 2003, A&A, 400, 1021
3. Bloom, J.S., et al. 2003, ApJ, 594, 674
4. Della Valle, M. et al. 2003, A&A, 406, L33
5. Fenimore, E. E. & Ramirez-Ruiz. E., 2000, astro-ph/0004176
6. Frontera, F. et al. 2000a, ApJS, 127, 59
7. Galama, T.J., et al. 1998, Nature, 395, 670
8. Heise, J., et al. 2001, in Proc. 2nd Rome Workshop: GRBs in the Afterglow Era, astro-ph/0111246
9. Ioka, K., & Nakamura, T. 2001, ApJ, 554, L163
10. Kippen, R. M., et al. 2002, in Proc. Woods Hole Gamma-Ray Burst Workshop, astro-ph/0203114
11. Kulkarni, S.R., et al. 1998, Nature, 395, 663
12. Nakamura, T. 1999, ApJ, 522, L101
13. Nakamura, T. 2001, Prog. Theor. Phys. Suppl, 143, 50
14. Norris, J.P., Marani, G.F., & Bonnell. J.T. 2000, ApJ, 534, 248
15. Pian, E. et al, 2000, ApJ, 536, 778
16. Pian, E. et al, 2003, astro-ph/0304521
17. Stanek, K.Z., et al. 2003, ApJ, 591, L71
18. Tamagawa, T. et al. 2003, in this proceeding
19. Vanderspek, R. et al. 2003, GCN circ. 1997
20. Waxman, E. 2003, astro-ph/0310320
21. Yamazaki, R., Ioka, K., & Nakamura, T. 2002, ApJ, 571, L31
22. Yamazaki, R., Ioka, K., & Nakamura, T. 2003a, ApJ, 591, 283
23. Yamazaki, R., Ioka, K., & Nakamura, T. 2003b, ApJ, 593, 941
24. Yamazaki, R., Yonetoku, D., & Nakamura, T. 2003, ApJ, 594, L79