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A Close Correlation between the Spectral Lags and Redshifts of Gamma-Ray Bursts *

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Abstract Based on nine BATSE GRBs with known redshifts, we found that the maximum spectral lag of all the pulses in a gamma-ray burst (GRB) appears to be anti-correlated with the redshift of the burst. In order to confirm this finding, we analyzed 10 GRBs detected by HETE-2 with known redshifts and found a similar relation. Using the relation, we estimated the redshifts of 878 long GRBs in the BATSE catalog, then we investigated the distributions of the redshifts and 869 $E_{\rm iso}$ of these GRBs. The distribution of the estimated redshifts is concentrated at $z = 1.4$ and the distribution of $E_{\rm iso}$ peaks at $10^{52.5}$ erg. The underlying physics of the correlation is unclear at present.

Key words: gamma-rays: bursts — gamma-rays: observations — methods: statistical

1 INTRODUCTION

In 1997, the optical counterparts and host galaxies of gamma-ray bursts (GRBs) were first discovered (van Paradijs et al. 1997). Since then many ground-based telescopes have observed a number of optical afterglows of GRBs and their redshifts have been measured, making possible the study of the intrinsic properties of this challenging astrophysical phenomena (see review of Cheng & Lu 2001; Mészáros 2002; Zhang & Mészáros 2004; Piran 2005). Especially, in the Swift era, the X-ray and optical afterglows were extensively investigated (Zhang et al. 2006a; Panaitescu et al. 2006; O'Brien et al. 2006; Dai et al. 2006; Gao & Fan 2006; Liang et al. 2006; Liang & Zhang 2006; Wei 2007; and see review of Mészáros 2006; Fox & Mészáros 2006; Zhang 2007). However, the number of GRBs with known redshift is only a fraction of all GRBs detected with BATSE, BeppoSAX, HETE-2, INTEGRAL and Swift satellites. Hence, an effective method that can estimate the redshifts from X-ray/gamma-ray light curves alone would be a great help.

Papers on the estimation of the GRB redshifts have been written by several authors (Fenimore & Ramirez-Ruiz 2000; Norris et al. 2000; Atteia 2003; Yonetoku et al. 2004; Yang et al. 2005; Amati 2006; Zhang et al. 2006b). Fenimore & Ramirez-Ruiz (2000) and Reichart et al. (2001) obtained a linear relation between the intrinsic peak-luminosity of the GRB and its so called "variability". Similarly, Norris et al. (2000) found a relation between the spectral lag and the peak-luminosity that would allow an estimation of the redshifts of long GRBs. Later, based on a spectral analysis of the BeppoSAX data alone, Amati et al. (2002) found a correlation between the total isotropic energy, $E_{\rm iso}$, radiated in the gamma-ray band, and the energy $E_{\rm p}$, at the peak of the νF_ν spectrum. Atteia (2003) suggested possibly using this relation as an empirical redshift indicator. Amati (2006) confirmed this relation with the data of the subsequent observations.

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However, there is a redshift degeneracy in the $E_{\rm iso}$-$E_{\rm p}$ relation of GRBs (Li 2007). So the $E_{\rm iso}$-$E_{\rm p}$ relation is not good for determining the GRB distance, when $z > 1.4$ (Schaefer & Collazzi 2007). Yonetoku et al. (2004) estimated the redshifts of the GRBs based on a relation between the spectral peak energy and the peak luminosity. The empirical relations used in the previous studies, however, are not quite reliable and are still under debate.

In this paper, we use a new relation, the $\tau_{\rm max}$-z relation, to estimate the redshifts. With this, we estimate the redshifts of 878 long BATSE GRBs and then we calculate $E_{\rm iso}$ for 869 BATSE GRBs using our estimated redshifts and available fluences. Throughout this paper we assume a flat-isotropic universe with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 65\,{\rm km\,s^{-1}\ Mpc^{-1}}$.

2 DATA ANALYSIS

The four-channel spectral GRB data (Concatenated 64-ms Burst Data in ASCII Format) observed by BATSE are available via anonymous ftp on the website *ftp://cossc.gsfc.nasa.gov/compton/data/batse/*.

Spectral lag is the interval between the arrival times at two different energy bands. The method for estimating spectral lags of GRBs using cross-correlation function (CCF) has been widely adopted (Link et al. 1993; Cheng et al. 1995; Band 1997; Norris et al. 2000, 2005; Chen et al. 2005; Yi et al. 2006). We use the data to calculate the pulse spectral lags between the first channel ($25-55\,{\rm keV}$) and third channel ($110-300\,{\rm keV}$) using the CCF. A positive spectral lag in our analysis corresponds to an earlier arrival of the higher energy gamma-ray photons. To reduce the scattering by noise, we use a Gaussian function to fit the part around the peak of the CCF. The uncertainties of the lags are determined via the fitting parameters (Chen et al. 2005). Using the above method, we analyze 10 GRBs in the BATSE archive with known redshifts (GRB 970508, GRB 971214, GRB 980329, GRB 980425, GRB 980519, GRB 980703, GRB 990123, GRB 990506, GRB 990510, and GRB 991216). We calculate the spectral lags of all the pulses in these bursts that have enough signal-to-noise ratio for the CCF analysis. The results are summarized in Table 1. We also use this same method on some HETE-2 GRBs with known redshifts available. The HETE-2 results are also included in Table 1.

Table 1 Redshift (z) and the Maximum Spectral Lag ($\tau_{\rm max}$) of the GRBs with Known-redshifts (Friedman & Bloom 2005). $\tau_{\rm max}$ is in units of second.

BATSE	z	$\tau_{\rm max}$	HETE-2	z	$\tau_{\rm max}$
GRB 970508	0.8349	0.296	GRB 010921	0.4509	0.586
GRB 971214	3.418	0.016	GRB 020124	3.198	0.253
GRB 980329	[2.95]*	0.027	GRB 020813	1.254	0.329
GRB 980425	0.0085	2.608	GRB 021004	2.3351	0.777
GRB 980519	[2.50]*	0.057	GRB 021211	1.006	0.620
GRB 980703	0.9662	0.307	GRB 030115	[2.20]*	0.209
GRB 990123	1.6004	0.110	GRB 030324	< 2.70	0.387
GRB 990506	1.3066	0.049	GRB 030328	1.52	0.547
GRB 990510	1.6187	0.124	GRB 030329	0.1685	1.076
GRB 991216	1.02	0.114	GRB 030528	< 1.00	11.759

*z is the mean value of the upper and lower limits.

3 RELATIONSHIP BETWEEN MAXIMUM SPECTRAL LAG AND REDSHIFT

The maximum spectral lag, $\tau_{\rm max}$, is defined as the largest lag of all the pulses in one burst. By analyzing the BASTE GRBs, we find a new anti-correlation between $\tau_{\rm max}$ and z, as shown in panel (a) of Figure 1. We excluded GRB 980425 because it is not clear whether which is associated with SN 1998bw. We obtained a correlation coefficient $R = -0.89$ and a chance probability $p = 2.4\times10^{-3}$. When we adopt the power-law model to the $\tau_{\rm max}$-z relation, the best-fit function is

$$\log z = (-0.28 \pm 0.11) + (-0.44 \pm 0.10) \log \tau_{\rm max}. \quad (1)$$

To further confirm the $\tau_{\rm max}$-z relation, we looked at the available HETE-2 GRB data, and found indeed a similar anti-correlation ($R = -0.68$, $P = 6.4\times10^{-2}$) with a different slope ($k = -1.16$). See panel (b) of Figure 1. GRB 030324 and GRB 030528 are not included in the correction analysis, because they only have

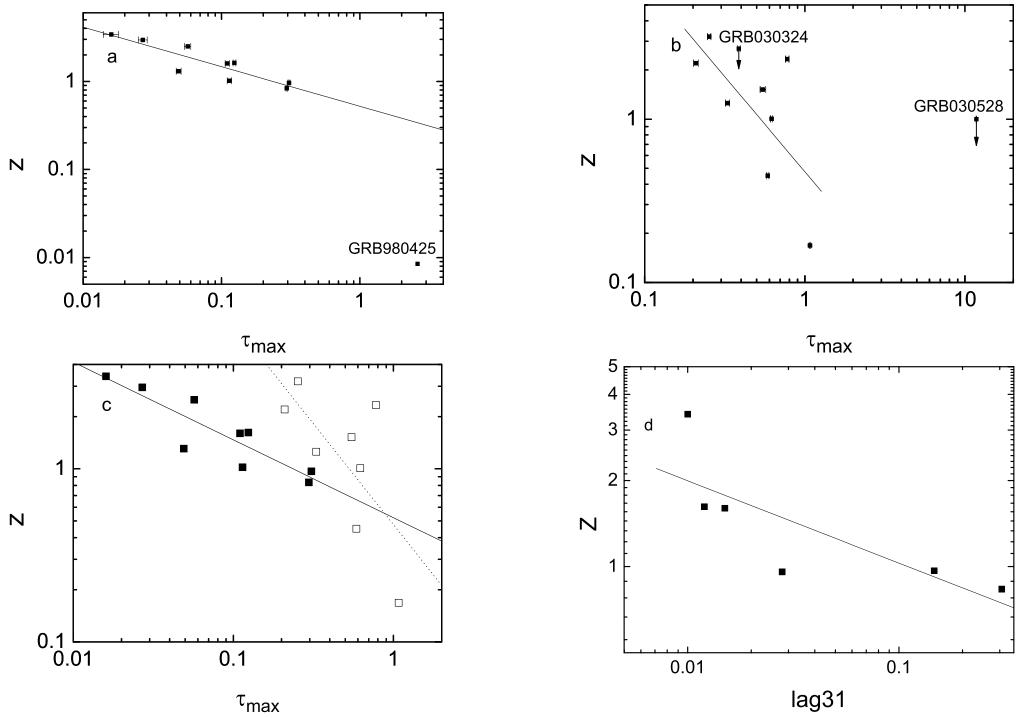

Fig. 1 Relation between the maximum spectral lag and redshift for the BATSE GRBs (panel (a)) and HETE-2 GRBs (panel (b)). In panel (a), the linear correlation coefficient is $R = -0.89$, and the chance probability is $P = 0.001$. Panels (b) and (d) show similar anti-correlations, with $R = -0.68$ and $P = 0.064$ for HETE-2 GRBs, and $R = -0.78$ and $P = 0.065$ for Norris' data (panel d). Panel (c) displays the results of BATSE (filled squares) and HETE-2 GRBs (open squares) (GRB 980425, GRB 030324 and GRB 030528 are not included). The lags are in units of second.

upper limits of redshifts. For HETE-2, the spectral lags were calculated for the light curves in $4 - 70$ keV and $30 - 400$ keV bands, which are different from the BATSE energy bands. The spectral lag is energy-band-dependent (Norris et al. 2000), this may be why the two relations in panel (c) of Figure 1, have different slopes. For further comparison, using the data in Table 1 of Norris et al. (2000), we show another similar anti-correlation ($k = -0.29$, $R = -0.78$, $P = 6.5 \times 10^{-2}$) in panel (d) of Figure 1. This result further confirms the anti-correlation. Unfortunately, the Swift GRBs with known redshifts have not enough high signal-to-noise ratios for the CCF calculation. It is unclear that whether or not this anti-correlation is present also in the Swift GRBs .

4 ESTIMATIONS OF REDSHIFTS AND ISOTROPIC ENERGIES

In this section, using the $\tau_{\max}$-z relation, we try to estimate the redshifts and $E_{\rm iso}$ of the BATSE long GRBs. First, besides the 10 BATSE GRBs in Table 1, we examined 2032 GRBs from the BATSE catalog, and found 1380 of these have sufficiently high signal-to-noise ratios for the CCF analysis. Of the 1380 GRBs, 218 have negative $\tau_{\max}$, giving no solutions of Equation (1), and 1162 have positive $\tau_{\max}$. For these, we estimated their redshifts using Equation (1). Of our estimated redshifts, 1141 are within the range $0 < z < 6$ and 21 are beyond 6. Of the 1141 GRBs, 1082 have their T_{90} durations available from the website (*http://cossc.gsfc.nasa.gov/docs/cgro/batse/BATSE_Ctlg/duration.html*), of these, 878 are long GRBs and 204 are short GRBs. Here, we just consider the long GRBs, because the 10 BATSE GRBs are all long GRBs. Also, since the highest known redshift of GRBs is about 6, we did not consider the few GRBs with redshifts beyond 6. The distribution of redshifts for these 878 long GRBs is shown in the left panel of Figure 2.

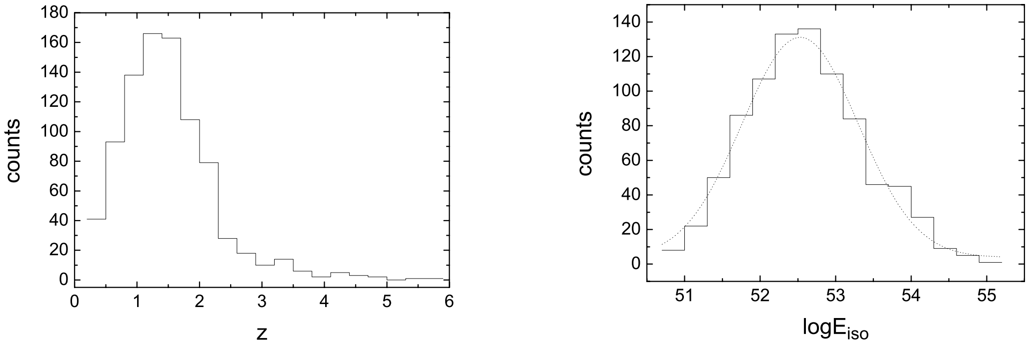

Fig. 2 Distributions of the redshifts (left) and the isotropic equivalent energies (right) of 878 long BATSE GRBs. The redshift distribution is concentrated around $z = 1.4$. The Gaussian fit of the isotropic equivalent energy distribution peaks at $\log E_{\rm iso} = 52.5$ erg.

The isotropic energy is defined as $E_{\rm iso} = 4\pi F d_L^2 (1+z)^{-1}$ (Frail et al. 2001; Bloom et al. 2001), where F is the fluence of the burst, z the redshift, and d_L the luminosity distance. In the 878 long GRBs, 869 GRBs have fluences obtained from the website (*http://cossc.gsfc.nasa.gov/docs/cgro/batse/BATSE_Ctlg/flux.html*). We estimated the isotropic energies of the 869 long GRBs. The resulting distribution of $E_{\rm iso}$ is shown in the right panel of Figure 2. The mean value of $E_{\rm iso}$ for these GRBs is $10^{52.6}$ erg, and the Gaussian fit peaks at $10^{52.5}$ erg.

5 DISCUSSION AND CONCLUSIONS

We investigated the spectral properties of BATSE GRBs with known redshifts and found a new correlation, one between $\tau_{\rm max}$ and z. To correct for the cosmological effect $\tau_{\rm max}$ was corrected by the factor $(1+z)^{-1}$. For the correlation, we obtained, for the BATSE GRBs, slope $k = -0.37$, correlation coefficient $R = -0.93$ and chance probability $p = 2.4 \times 10^{-4}$; for the HETE2 GRBs, $k = -0.94$, $R = -0.88$ and $p = 3.6 \times 10^{-3}$; and for the Norris data, $k = -0.27$, $R = -0.85$ and $p = 2.9 \times 10^{-2}$. See Figure 3. Zhang et al. (2006b) obtained a similar relation by using relative spectral lags and the estimated redshifts taken from Yonetoku et al. (2004). Several mechanisms have been proposed to explain the spectral lag, such as an intrinsic cooling effect of radiating electrons (e.g., Zhang et al. 2002) and the relativistic curvature effects of the fireball (Shen et al. 2005; Lu et al. 2006). Recently, Zhang et al. (2007) argued that the spectral lag may come from a joint contribution of both the hydrodynamic processes of the outflows and the curvature effect, but no GRB scenarios have ever predicted a $\tau_{\rm max}$-z relation. The physical mechanism underlying this relation is unclear at present.

We estimated the redshifts of 878 long BATSE GRBs using the $\tau_{\rm max}$-z relation. Because we do not have enough information about the $\tau_{\rm max}$-z relation for GRBs with very high redshift values, we just consider the redshifts below 6.0. As shown in Figure 2 the distribution of our estimated redshifts is concentrated at about 1.4. For comparison, we analyze the distributions of the known redshifts and the redshifts estimated by Yonetoku et al. (2004). In Figure 4, the distributions of 48 pre-Swift GRBs (Friedman & Bloom 2005), 71 Swift GRBs (updated to April 10, 2007), 119 GRBs combined with 48

Table 2 Features of the Distributions for Five Redshift Samples and the Significance Level $P_{\rm ks}$ of K-S Test

Sample	Number	$z_{\rm mean}$	$z_{\rm median}$	$P_{\rm ks-Yi}$	$P_{\rm ks-Yonetoku}$
pre-Swift	48	1.4	1.1	4.5×10^{-2}	2.5×10^{-10}
Swift	71	2.1	1.8	1.4×10^{-7}	2.2×10^{-4}
pre-Swift&Swift	119	1.8	1.5	1.6×10^{-5}	3.3×10^{-11}
Yonetoku et at.	689	4.0	3.0	0.0	
Yi et al.	878	1.5	1.4		0.0

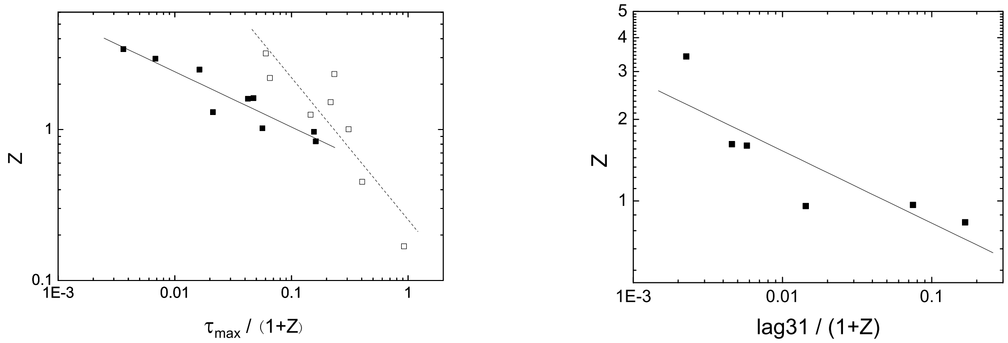

Fig. 3 The left panel shows the relation between redshift and spectral lag corrected by the factor $(1+z)^{-1}$ for the BATSE GRBs (filled squares) and HETE-2 GRBs (open squares), excluding GRB 980425, GRB 030324 and GRB 030528. The right panel shows the same relation between the corrected Norris' lag31 and redshifts.

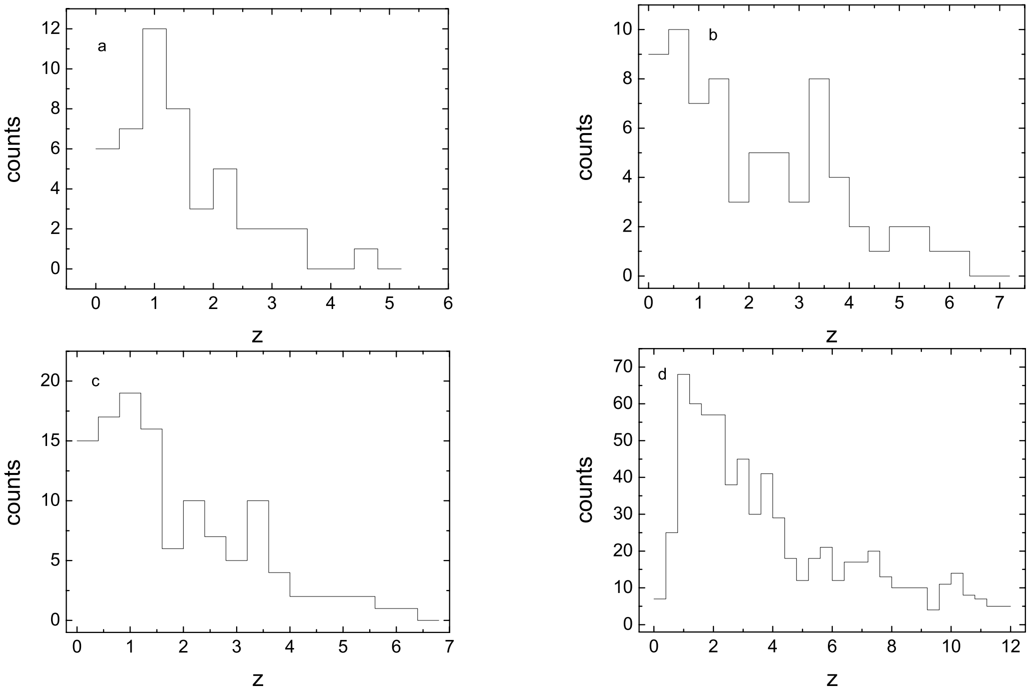

Fig. 4 Distributions of redshifts: (a) 48 pre-Swift GRBs (Friedman & Bloom 2005); (b) 71 Swift GRBs; (c) 48 pre-Swift GRBs and 71 Swift GRBs; (d) 689 GRBs, which have redshifts estimated by Yonetoku (2004).

pre-Swift ones and 71 Swift ones, 689 GRBs with redshifts estimated by Yonetoku (2004) are shown in panels (a), (b), (c) and (d), respectively. The redshifts of the 71 Swift GRBs are taken from the website: *http://swiftsc.gsfc.nasa.gov/docs/swift/archive/grb_table/*. We summarized the features of these distributions in Table 2. Whether these samples have the same distribution are checked by the Kolmogorov-Smirnov (K-S) test, and the results are also given in Table 2. From Figure 4 and Table 2, one can find that the distributions of redshifts for our 878 GRBs and pre-Swift GRBs are more similar than among the others. As shown in the right panel of Figure 2, the distribution of $E_{\rm iso}$ of 869 long BATSE GRBs is concentrated at

$E_{\rm iso} = 10^{52.5}$ erg and the mean value is $10^{52.6}$, this result is consistent with $E_{\rm iso} = 10^{52.7}$ erg, which is the mean value of 44 GRBs with known redshifts (Amati 2006).

There are several well studied short GRBs with known redshifts at present. However, the redshifts of short BATSE GRBs have not been measured. Our nine GRBs for the $\tau_{\rm max}$-z relation all are long BATSE GRBs, so we would like to know whether the relation also holds for the short GRBs. The spectral lag of short GRBs is generally smaller than that of long GRBs (Yi et al. 2006), so the short GRBs with small spectral lags should have large redshifts. This is not be consistent with the current observation of short GRB redshifts. So, it may be that the $\tau_{\rm max}$-z relation is only applicable to long GRBs.

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