Testing a new luminosity/redshift indicator for γ-ray bursts

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ABSTRACT

We have tested a relative spectral lag (RSL) method suggested earlier as a luminosity/redshift (or distance) estimator, using the generalized method by Schaefer & Collazzi. We find the derivations from the luminosity/redshift-RSL (L/R-RSL) relation are comparable with the corresponding observations. Applying the luminosity-RSL relation to two different GRB samples, we find that there exist no violators from the generalized test, namely the Nakar & Piran test and Li tests. We also find that about 36 per cent of Schaefer’s sample are outliers for the L/R-RSL relation within 1σ confidence level, but no violators at 3σ level within the current precision of L/R-RSL relation. An analysis of several potential outliers for other luminosity relations shows they can match the L/R-RSL relation well within an acceptable uncertainty. All the coincident results seem to suggest that this relation could be a potential tool for cosmological study.

Key words: gamma ray: bursts — gamma rays: observations — cosmology: theory

1 INTRODUCTION

Gamma-ray bursts (GRBs) have been found to have several empirical correlations based on the properties of light curves and spectra (e.g., Norris, Marani & Bonnell 2000; Lloyd, Petrosian & Mallozzi 2000; Fenimore & Ramirez-Ruiz 2000; Chang et al. 2002; Schaefer 2003a; Amati et al. 2002; Ghirlanda et al. 2004; Schaefer 2002; Firmani et al. 2006). It has been proposed that the relations can be used as “standard candle” for cosmological applications (e.g., Ghirlanda et al. 2006 and Schaefer 2007 for reviews; see also Friedman & Bloom 2005; Bertolami & Silva 2006; Oguri & Takahashi 2006; Li 2007b) thanks to the feature of the standard energy release from the central engine (Fraiil et al. 2001; Bloom et al. 2003). However, as pointed by Schaefer & Collazzi (2007), these empirical relations can return the luminosities with a diverse level of accuracy. That is, the derived luminosity is highly dependent on the estimator or relation. It is therefore need to inspect these estimators by comparing the derived and observed luminosities directly.

Following the tests of Nakar & Piran (2005) and Li (2007a), Schaefer & Collazzi (2007) gave a generalized test (Section 2) simultaneously to the eight luminosity relations. As a result, all the eight luminosity relations passed the generalized test successfully. For the $E_p - E_{γ,iso}$ relation (Amati et al. 2002), they found that ~44% of 69 GRBs in their sample including pre-Swift and Swift sources were violators. However, they explained that this was a natural consequence resulting from both systematic and observational errors (due to the small fluctuations of < 1σ deviations). By analyzing a BATSE sample, Band & Preece (2005) otherwise found ~88% of pre-Swift bursts were inconsistent with the $E_p - E_{γ,iso}$ relation. Further investigations (Cabrera et al. 2007; Butler et al. 2007) show the “Amati relation” does exist in the Swift sample but is already inconsistent with its pre-Swift form (Lamb 2004). Recently, Butler et al. (2007) systematically investigated the properties of temporal and spectral parameters for 218 Swift bursts and pointed out the $E_p - E_{γ,iso}$ relation, as well as most other pre-Swift relations proposed by Yonetoku et al. (2004), Atteia (2003) and Firmani et al. (2006), may not be true but pseudo since they are correlated with an unavoidable threshold effect (namely Malmquist bias). In this case, some previous empirical relations will meet a serious challenge on whether they are reliable for cosmological applications or not.

Recently, Zhang et al. (2006a) put forward a new redshift/luminosity estimator of relative spectral lag (RSL, $τ_{rel,31}$), which is defined as the ratio of spectral lags between light curves observed in energy channels 1 and 3 to the full width at half maximum ($FWHM$) of the light curve in channel 1. Based on analyzing the RSL for 9 long BATSE GRBs with known redshift, they found that the RSLs are also tightly correlated with the redshift or luminosity, as follows:

$$logz = a - br_{τ_{rel,31}}$$ (1)
logL = \eta - \xi \tau_{\text{rel},31} \tag{2}

where \( a = 1.56 \pm 0.24, b = 9.66 \pm 1.86, \eta = 55.44 \pm 0.63, \xi = 23.07 \pm 4.88 \) and \( \tau_{\text{rel},31} \) is normally distributed with a mean value of \( \mu = 0.102 \) and a standard error of \( \sigma = 0.045 \). The spearman rank-order correlation coefficients of the two relations are -0.88 (\( \rho \sim 1.5 \times 10^{-3} \)) and -0.83 (\( \rho \sim 5 \times 10^{-3} \)) respectively, indicating the RSL could be a redshift/luminosity indicator (see Zhang et al. 2006a for the details and Peng et al. 2007 for further studies). Among the nine sources in Zhang et al. (2006a), eight redshifts are estimated from the \( L_p - E_p \) relation by Yonetoku et al. (2004) (assumed the derived redshifts are comparable with the observed ones no matter whether the \( L_p - E_p \) relation is artificial). Strictly speaking, the redshifts should be measured from spectroscopy rather than some empirical relations. Meanwhile, we see the RSL is an unique and intrinsic quantity since such definition can reduce both Doppler and cosmological time dilation effects on the observations owing to \( \tau_{\text{tag}} \propto \Gamma^{-2} (1 + z) \) and \( \text{FWHM} \propto \Gamma^{-2} (1 + z) \) (Zhang et al. 2005, 2006b; Norris et al. 2000; Kocevski & Liang 2006). On the other hand, the RSL is independent of energy bands because \( \tau_{\text{tag}} \) and \( \text{FWHM} \) are roughly proportional to \( E^{-0.4} \) respectively (e.g. Fenimore et al. 1995; Norris et al. 1996; Reichart et al. 2001; Zhang et al. 2007). In such case, the RSL is also independent of energy bands, implying that the measurement of RSL is not influenced by different instruments with distinct energy sensitivity.

Therefore, the primary task of this work is to check if the luminosity/redshift-RSL (hereafter L/R-RSL) relation can pass the so-called generalized test here. In addition, we investigate what we can get from the RSL relations within its current precision level. Finally, we focus our study on whether there are outliers violating from the new L/R-RSL relation and compare them with the observations. We list the results of the generalized test for two different GRB samples. In particular, we adopt another test to examine whether there are outliers violating the L/R-RSL relation in comparison to other luminosity estimators.

2 METHODOLOGY

We adopt the same method proposed by Schaefer & Collazzi (2007) to test the L-RSL relation. According to their unified expression, the luminosity in our empirical relation can be written as

\[
L = A[\kappa(1 + z)^{Q}]^m \tag{3}
\]

where the parameters \( A, Q, m \) and \( \kappa \) are usually determined by empirical relations. In particular, the power index \( Q \) represents the cosmological time dilation effect to the observation. We take \( Q = 0 \) because the RSL already eliminated the cosmological effect. By comparing Eq. (3) with Eq. (2), we let \( \kappa = 10^{-\tau_{\text{rel},31}} \) and rewrite the Eq. (3) as

\[
\log L = \log A + m\tau_{\text{rel},31} \tag{4}
\]

Combining Eqs. (2) and (4), we easily have \( A = 10^9 \text{ erg s}^{-1} \) and \( m = -\xi \).

On the other hand, the luminosity can also be obtained from the following expression if the redshift and bolometric peak flux are given

\[
L = 4\pi d_i^2 \psi (1 + z)^{-B} \tag{5}
\]

where \( \psi \) and \( B \) denote bolometric peak flux and cosmological correction for time dilation, respectively. In this equation, we have \( \psi = P_{\text{bol}}(z) \) and \( B = 0 \) for a burst with measured spectral parameters (namely \( \alpha, \beta \) and \( E_p \) for Band spectrum (Band et al. 1993)). The luminosity distance \( d_i \) is calculated throughout this paper with respect to the unchanged parameters \( H_0=100h \text{ km s}^{-1}\text{Mpc}^{-1} (h = 0.71), \Omega_M = 0 \) for a flat universe, \( \Omega_M = 0.27 \) and \( \Omega_\Lambda = 0.73 \) (Dai et al. 2004). Meanwhile, we suppose the unchanged cosmological constant of \( w = -1 \) in advance and take the speed of light as \( c = 3 \times 10^5 \text{ km s}^{-1} \).

With given parameters value, after eliminating \( L \) from Eqs. (3) and (5), we derive the separate variable functions (SVFs) as follows

\[
F(\kappa, \psi) = \left[(H_0/c)^2/4\pi\right](A\kappa^m/\psi) \tag{6}
\]

\[
F(\zeta) = (H_0/c)^2 d_i^2 \tag{7}
\]

Here, note that Eq. (6) instead of Eq. (7) is determined by the L-RSL relation. An ideal luminosity relation should be expected to approach \( F(\kappa, \psi) = F(\zeta) \) in term of statistical principium. Therefore, we use these relations to investigate whether a GRB sample can be described by the L-RSL relation.

3 RESULTS

In this section, we list the derivations from the L/R-RSL relation and compare them with the observations. We list the results of the generalized test for two different GRB samples. In particular, we adopt another test to examine whether there are outliers violating the L/R-RSL relation in comparison to other luminosity estimators.

3.1 RSL Distribution

Measuring the cosmological redshift of GRBs is important for estimating the energy output, the distance and intrinsic parameters including jet angles (e.g. Sari et al. 1999; Frail et al. 2001), the Lorentz factor of ejection (e.g. Dermer et al. 1999; Panaitescu & Kumar 2002; Molinari et al. 2006; Zhang et al. 2006), the medium density etc (see Piran 2005 and Mészáros 2006 for reviews). A redshift distribution for GRBs has been adopted to calculate an evolving star formation rate and to explore a GRB rate evolution especially in the high redshift Universe (see Bromm & Loeb 2002, 2006; Natarajan et al. 2005; Lloyd-Ronning, Fryer & Ramirez-Ruiz 2002; Daigne et al. 2006; Le & Dermer 2006; Salvaterra et al. 2007; see also Coward 2007 for a review). However, it is difficult to accurately determine the distribution because of present incomplete samples (Tanvir & Jakobsson 2007). Nonetheless, statistical approach to the distribution is still important, for instance, to probe the efficiency of GRB production (Daigne et al. 2006).
which are close to the corresponding values of $\sigma = 0.045$ and $\mu = 0.102$ in Zhang et al. (2006a). The small discrepancy comes from the statistical fluctuation and thus is not significant. It is an interesting result since the different instruments with distinguishing energy sensitivity can present the same normal distribution of RSLs. The fact demonstrates that the RSL is independent of energy bands, at least insensitive to energy channels.

### 3.2 Luminosity Function

We already know the observed luminosity is usually calculated from Eq. (5) through the measurements of redshift and peak flux for an assumed cosmology. Apart from this, eliminating $\tau_{\text{rel,31}}$ from Eqs. (1) and (2) one can estimate the luminosity using the following relation

$$\log L = \eta - \xi(a - \log z)/b,$$

where the luminosity only depends on the redshift measurement. Besides, this relation allows us to conveniently estimate the luminosity of each burst once its redshift has been measured. It needs to be pointed out that both luminosity calculations are relevant to a special cosmology. In theory, the empirical Eq. (8) can match the observed values well if it is reliable to estimate the luminosity.

Fortunately, large amount of high-quality data have resulted in the determination of cosmological parameters with a rather good precision (Balbi 2006). This means different luminosity relations depend not too much on an assumed standard cosmology but on themselves. We apply Eqs. (5) and (8) to the Schaefer’s sample respectively and compare the observed luminosities with the estimated ones in Figure 2, from which we see that they both follow an analogous trend with the increase of redshift, which supports the result of Wei & Gao (2003) obtained from the luminosity-variability relation. In addition, we find both of them have a very close median value, i.e., $1.89 \times 10^{52}$ erg s$^{-1}$ and $1.64 \times 10^{52}$ erg s$^{-1}$ for the observed and estimated luminosities, respectively. To evaluate the degree of consistency, we put the lines of upper and lower limits on $\log L$ (1 $\sigma$ confidence level) arising from the L-RSL relation. Note that $\sigma = [(\sum_{i=1}^{\text{max}}(y_{o,i} - y_i))/\text{max}(N - 1)]^{1/2}$ whose $y_{o,i}$ and $y_i$ respectively stand for the observational and theoretical (or derivative) quantities. As can be seen in figure 2, both pre-Swift and Swift bursts follow the empirical luminosity relation robustly. Quantitatively, the L/R-RSL relation can account for about 72% sources in Schaefer’s sample within 1 $\sigma$ level. For larger confidence levels, say 3$\sigma$, no sources are found to violate the relation. Moreover, we notice that most data points exist within the range of redshift from $z \sim 0.5$ to 4, indicating that the current GRB sample lacks much more sources with lower and higher redshifts.

In Zhang et al. (2006a), if building a relation of $\tau_{\text{rel,31}}$ with $1 + z$, we can rewrite Eq. (1) as $\log (1 + z) = (1.37 \pm 0.19) - (6.54 \pm 1.46)\tau_{\text{rel,31}}$ with probability $P = 0.002$. Combining this relation with Eq. (2), one can get a rough luminosity function $L \propto (1 + z)^{3.52 \pm 1.08}$. The power law index is significantly different with that of either $\sim 1.4$ drawn by Lloyd-Ronning et al. (2002) from the luminosity-variability relation or $\sim 1.7$ gotten by Kocevski & Liang (2006) from the luminosity-lag relation. However, our luminosity function is more close to $L \propto (1 + z)^{3.70 \pm 0.60}$ up to $z \sim 6$, which is based on the suggestion that GRBs perfectly matches the history of cosmological star-formation (Hopkins 2004). This implies that the L/R-RSL relation might favor a higher redshift estimation.

### 3.3 SVF Curve and Violator Test

From Eq. (7), we get the theoretical SVF curve for the measured redshift ($z$) and the given cosmological parameters. Here, we likewise let $z_{\text{max}} = 20$ in order to make a direct comparison with the Schaefer’s results. Then one can acquire the maximum value $F_{\text{max}}(z) \sim 3002$ at $z = z_{\text{max}} = 20$ (Bromm & Loeb 2002). Figure 3 shows the normalized SVF curve, from which we find it behaves same as that of the $L - N_p$ relation plotted by Schaefer & Collazzi (2007). The reason for the agreement is that both RSL and $N_p$ are intrinsic variables and uninfluenced by the cosmological correction.
the luminosity relations. A source passes the Nakar & Piran test because the SVF increases monotonically with redshift in its reasonable range.

In general, we name some special sources violating one given law as violators or outliers. The violators as a ruler in any effective tests usually reflect the validity of anyone of the luminosity relations. A source passes the Nakar & Piran (2005) test means it locates in the region of $F/F_{\text{max}} < 1$.

To examine if there are some bursts violating the L-RSL relation, we apply this method to the two different GRB samples: one is taken from Zhang et al. (2006a), in which 9 single-pulsed bursts holding both long spectral lags and wide widths are included (hereafter Zhang’s sample); Another is Schaefer’s sample of 69 sources as mentioned above. The motivation of this selection is to exclude the hopeless effect of sample selection on our results. At the same time, we also need to diagnose the degree of the derived data points according with the L/R-RSL relation in a quite different manner.

We use the spectral indices ($\alpha$, $\beta$, and $E_p$) presented in Zhang et al. (2006a) to calculate the bolometric peak flux $P_{\text{bolo}}$ in the unit of erg cm$^{-2}$ s$^{-1}$ (where the energy range $E_{\text{min}} = 50$ keV and $E_{\text{max}} = 300$ keV is selected for the BATSE instrument; see Schaefer 2007 for the details). With the measured $\tau_{\text{rel,31}}$ and $P_{\text{bolo}}$, for 9 bursts, we obtain the SVF values of $F(\kappa, \psi)$ from Eq. (6) and the corresponding deviations within 1σ error, as shown in Figure 4. In addition, a theoretical SVF curve (Eq. (7)) that is proportional to luminosity distance squared is plotted to compare with the data points in the Zhang’s sample. We find $\simeq 33\%$ sources are marginally present as violators at 1σ level. It is also found within a larger uncertainty limit (namely $\geq 2\sigma$) all the data points are well consistent with the theoretical curve. It is obviously seen that all the derived data points distribute in the region of $\log(F/F_{\text{max}}) < 0$, indicates no sources violate the Nakar & Piran test.

Now, we apply this test to the Schaefer’s sample with the measured redshift and $P_{\text{bolo}}$. Using Eq. (1), one can estimate the RSL for each burst. As seen in figure 1, the derived RSLs are normally distributed. Substituting the estimated RSLs to Eq. (6), one can then obtain the $F(\kappa, \psi)$ values of 69 bursts. Similarly, our L/R-RSL relation is also found to pass the Nakar & Piran test because all data points have evidently small values of $F/F_{\text{max}} < 1$ (Figure 5). It is worthwhile to emphasize that within 1σ errors 64% data points estimated from both pre-Swift and Swift bursts match the theoretical curve well. That is to say, the fraction of potential outliers for L/R-RSL relation is $\sim 36\%$. However, a higher confidence interval of 99.8% (3σ) for the selective Schaefer’s sample reports that no violators deviate from the theoretical line under the current precision level of the L/R-RSL relation.

3.4 Comparison with other estimators

In principle, the real outliers should be basically the same for all the unbiased luminosity estimators. Unfortunately, people usually give different even opposite judgements on the same burst. For example, some previous works claimed all but two bursts (GRB 980425 and GRB 031203) were...
consistent with the Amati relation (Amati et al. 2002) as well as the Ghirlanda relation (namely the $E_p - E_\gamma$ relation) (Ghirlanda et al. 2004; see also Ghisellini et al. 2006). This is a very strong contrast with the result of 88% being outliers reported by Nakar & Piran (2005) for the Amati relation. According to Butler et al.’s (2007) interpretations, the Amati relation is likely caused by threshold effect and thus artificial. Panaitescu (2007) suggests the Ghirlanda relation is probably a consequence of the Amati relation and can not work for GRB 050416A. Rizzuto et al. (2007) find GRB 050416A is also an outlier of luminosity-variability relation. In addition, Campana et al. (2007) argued that at least five bursts (including GRB 050416A) are outliers of the $E_p - E_\gamma$ relation. Another analysis shows it is not the case (Ghirlanda et al. 2007). The outlier identification is a crucial target to judge the practicability of any luminosity relations for cosmological studies. However, the important topic is still controversial or uncertain for most previous luminosity relations.

It is therefore necessary to examine if these potential outliers (Table 1) exist in the same manner for the L/R-RSL relation. We select 10 bursts in this study, in which 7 outliers (Table 1) exist in the same manner for the L/R-RSL relation. We stress that GRB 050416A (marked with star) is a typical outlier for both $L - V$ and $E_p - E_\gamma$ relations, but good consistent with the L/R-RSL relation here. Surprisingly, we also see GRB 980425 fully matches and GRB 031203 is marginally consistent with the relation within 1 $\sigma$ region. GRB 060218 is also found to follow the L/R-RSL relation well within 3 $\sigma$ levels. These potential outliers for other luminosity relations do not violate the L/R-relation. The interesting results seem in turn to show the L/R-RSL relation is potentially an expected cosmological tool.

4 DISCUSSION AND SUMMARY

As mentioned in §3.3, the agreement between SVF curve in Figure 3 and that of the $L - N_p$ relation provides us an indirect clue that the L-RSL relation is expectantly true. Likewise, we have shown in Figure 4 that the 9 data points derived from the L/R-RSL relation match well with the theoretical SVF curve, which in turn proves both $L_p - E_p$ and L/R-RSL relations are equally reliable because the data are actually related with the $L_p - E_p$ relation. Besides, the R-RSL relation can be used to estimate redshift without constraints by theoretical cosmological models.

Although many luminosity/redshift estimators have been constructed so far to obtain either a synthetic redshift or luminosity distance, it is still difficult to answer which one is the best. In theory, a powerful estimator should be applicable to both lower and higher redshift sources without producing an obvious evolutionary effect for fitted parameters in a statistical point of view. Besides, the empirical data points from this estimator should be distributed along the smooth theoretical SVF curve shown in Figure 4. However, some factors involving the systematic and measurement errors and the gravitational lensing effects (Oguri & Takahashi 2006) can cause additional uncertainties that make the observations to deviate largely from the expected curve. Another different effect is the Malmquist biases (Schaefer 2007; Butler et al. 2007) that lead the estimated data points to approach the SVF curve. Note that the L/R-RSL relation is built with only 9 long bursts. To get more precise RSL relations, calibration as well as an in-depth test required, especially for many but several bursts with measured redshifts.

We summarize our results as follows: (1) We have clarified that the RSLs have a Gaussian distribution; (2) Our calculations for RSLs and luminosities (or redshifts) are comparable with those of observations, indicating that the L/R-RSL relation may be a potential tool for cosmological study; (3) The behavior of luminosity increasing with redshift confirms the result of Wei & Gao obtained from the luminosity-variability relation; (4) We have tested the L/R-RSL relation for two different GRB samples and found that there exist 36 per cent of Schaefer’s sample are outliers within 1 $\sigma$ confidence level, but no violators at 3$\sigma$ regions within the current precision of L/R-RSL relation; and (5) The potential outliers for other luminosity relations can match the L/R-RSL relation well.

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Table 1. Special bursts as the potential candidates of “outlier” for luminosity relations

| GRB     | Instrument | z     | LogLobs | LogLder | Log[F(e, γ)/Fmax] | Relation               | Ref. |
|---------|------------|-------|---------|---------|-------------------|------------------------|------|
| 050401* | Swift      | 2.9   | 53.19   | 52.82   | -2.31±0.72        | E_p - E_γ            | 1    |
| 050416A*| Swift      | 0.653 | 50.99   | 51.27   | -3.26±1.08        | E_p - E_γ            | 1, 2 |
| 050603  | Swift      | 2.821 | 53.83   | 52.79   | -3.00±0.84        | E_p - E_γ            | 1    |
| 050922C*| Swift      | 2.199 | 52.87   | 52.53   | -2.58±0.88        | E_p - E_γ            | 1    |
| 051109A | Swift      | 2.346 | 52.54   | 52.59   | -2.10±0.87        | E_p - E_γ            | 1    |
| 060206* | Swift      | 4.05  | 52.86   | 53.17   | -1.29±0.79        | E_p - E_γ            | 1    |
| 060256* | Swift      | 3.21  | 52.35   | 52.92   | -1.26±0.70        | E_p - E_γ            | 1    |
| 060218* | Swift      | 0.033 | 46.69   | 46.18   | -4.93±2.25        | ?                     | —    |
| 060208A | BeppoSAX   | 0.0085| 47.11   | 46.77   | -7.42±5.62        | E_p - E_isoe        | 4, 5, 6 |
| 031203* | INTEGRAL   | 0.106 | 48.56   | 49.39   | -4.53±1.93        | E_p - E_γ            | 4, 5, 6 |

Note.—Col. (1) and (3) are respectively the burst name and redshift; Col. (2) stands for the exploring instrument; Col. (4) and (5) represent the observed and derived logarithmic luminosities (erg s^{-1}), respectively; Col. (6) denotes the references of the outliers for luminosity relations marked in col. (7); Col (6) are the derived SVF values in logarithmetic form.

Refs.— 1. Campana et al. 2007; 2. Panaitescu 2007; 3. Rizzuto et al. 2007; 4. Ghisellini et al. 2006; 5. Ghirlanda, Ghisellini & Lazzati 2004; 6. Amati et al. 2007.
* Ghirlanda et al. (2007) argued these source were not outliers for the $E_p - E_\gamma$ relation.
* The three bursts are associated with supernova and belong to low luminosity burst class. Unlike GRB 980425 and GRB 031203, GRB 060218 is however in excellent agreement with the Amati relation (Ghisellini et al. 2006; Amati et al. 2007). Meanwhile, this burst has a similar energy output with GRB 031203. Ghisellini et al. (2006) suggest GRB 980425 and GRB 031203 as a twin of GRB 060218 might be correlated with the $L - E_p - T_{0.45}$ (Firmani et al. 2006).

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