Research Article

Systematic Spectral Lag Analysis of Swift Known- z GRBs

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The difference of photon arrival time, which is known as spectral lag, is well known characteristics of gamma-ray bursts (GRBs). In particular, long duration GRBs show a soft lag which means that high energy photons arrive earlier than soft photons. The lag-luminosity relation is the empirical relationship between the isotropic peak luminosity and the spectral lag. We calculated the spectral lags for 40 known redshift GRBs observed by *Swift* addition to the previous 31 GRB samples. We confirmed that most of our samples follow the lag-luminosity relation. However, we noticed that there are some GRBs which show a significant scatter from the relation. We also confirm that the relationship between the break time and the luminosity of the X-ray afterglow (so-called Dainotti relation) extends up to the lag-luminosity relation.

1. Introduction

The time variability and the spectral evolution seen in the prompt emission of gamma-ray bursts (GRBs) are not well understood despite the large data samples collected by various GRB instruments. However, there are some clues to understand temporal and spectral variations seen in the prompt emission. The spectral lag which is known as the difference of an arrival time between high energy photons and low energy photons is one of such clues. It is known that high energy photons arrive earlier than low energy photons for long duration GRBs (hereafter long GRBs) [1, 2], while short duration GRBs (hereafter short GRBs), which have a duration shorter than 2 seconds, have a smaller or a negligible lag than that of long GRBs [3, 4].

There is an empirical relation between a spectral lag and an isotropic peak luminosity which is called lag-luminosity relation [5]. The relation is discovered based on the analysis of only 6 known- z GRBs using the BATSE samples. Recently, Ukwatta et al. [6] calculated the spectral lag for 31 *Swift* known- z GRBs. They found that the *Swift* GRBs follow the lag-luminosity relation with a significant scatter in their samples from the best fit relation.

Many theoretical models suggested explaining the lag-luminosity relation. Salmonson [7] suggests that this relation

is caused by the variation in line-of-sight velocity of GRBs. Ioka and Nakamura [8] proposed that an observer's viewing angle to the jet causes this relation, while Schaefer [9] suggested that a lag and a peak luminosity are related to a cooling time of a pulse. Although there are many theoretical models that have been proposed to explain the lag-luminosity relation, physical origin of this relation is still unclear.

On the other hand, Dainotti et al. [10] discovered the empirical relation between an X-ray break time and an X-ray luminosity from the *Swift* X-ray afterglow samples (hereafter Dainotti relation). The break time from a shallow to a normal decay in the X-ray afterglow light curve (e.g., [11]) is anticorrelated with the luminosity at the break time. The theoretical interpretations of this relation include long-term behavior of an external accretion disk [12] and a prior emission model for X-ray plateau phase [13]. Furthermore, Sultana et al. [14] suggested that the lag-luminosity relation at the prompt emission nicely connects to the Dainotti relation found from the X-ray afterglow data. Also, they proposed that both relations might be explained individually by the same kinematic effect, which is viewing the jet at “off-beam” line of sight [8, 15]. If viewing angle is large, an isotropic luminosity and a spectral lag are large in a prompt emission following Ioka and Nakamura [8]. Also, Eichler and Granot [15] proposed that the viewing angle which is slightly larger

than an opening angle makes a long plateau and a low flux emission in an afterglow. Therefore, if this finding is true, we are probably seeing a clear physical connection between the prompt and the afterglow emission. However, since those findings are still based on a small number of GRBs, it is important to investigate using rich GRB samples.

The number of *Swift* known- z GRBs is increasing and becoming large samples. We analyzed additional 40 *Swift* known- z GRBs following the method described in Ukwatta et al. 2010 [6]. Our paper is organized as follows. The analysis method is described in Section 2. The results of analysis and application to the lag-luminosity relation are shown in Section 3. We discussed our results in Section 4. We concluded and summarized our results in Section 5.

2. Method

We calculated a spectral lag following the method described by Ukwatta et al., 2010 [6], using the data of *Swift* Burst Alert Telescope (BAT [16]). First, we made the mask-weighted (background subtracted) light curves using the BAT event data for four energy bands (15–25 keV, 25–50 keV, 50–100 keV, and 100–200 keV). We made 1000 simulated light curves for each energy band. Those simulated light curve bins are calculated by

$$LC_{\text{sim}}^{\text{bin}} = LC_{\text{real}}^{\text{bin}} + \xi LC_{\text{error}}^{\text{bin}}, \quad (1)$$

where ξ is a random number from the standard normal distribution. We calculated cross correlation function (CCF) for all 6 combinations of energy bands and determined spectral lags. We used the Band's CCF formula (Band 1997 [17]) which is expressed as

$$CCF_{\text{Band}}(d, x, y) = \frac{\sum_{i=\max(1, 1-d)}^{\min(N, N-d)} x_i y_{i+d}}{\sqrt{\sum_i x_i^2 \sum_i y_i^2}} \quad (2)$$

for two series x_i and y_i with a delay d , where $i = 0, 1, 2, \dots, N - 1$. We fitted CCF with the Gaussian function to

determine the CCF peak for each 1000 CCFs generated from simulated light curves. Then, we made the histogram of the CCF peaks and determined the center value as the best fit value of a lag and its standard deviation as an error of a lag.

To cross-check the validity of our code, we analyzed 5 GRBs whose lags have been reported in Ukwatta et al. 2010 [6]. The results of this cross-check are shown in Figure 1. The figure clearly shows that our lag values are consistent with those of Ukwatta et al. 2010 [6], including the size of the errors.

We selected 229 long GRB samples from *Swift* known- z GRBs between March 2005 and May 2013 at the beginning. Three selections were applied for the initial samples. As the first selection, we selected 198 GRBs of which spectral lags have not been calculated in Ukwatta et al., 2010 [6]. In the second selection, the 92 GRBs are selected based on the peak flux threshold (≥ 1.5 peak photon flux in the 15–150 keV band). In the third selection, the GRBs which are possible to estimate the peak energy (E_{peak}) using the relationship between E_{peak} and the photon index of the simple power-law fit to the BAT spectral data [18] are selected from the samples. Finally, our samples became 40 GRBs. There are 14 GRBs between 2005 and 2009 which are selected in our samples but not in Ukwatta et al. The difference between our samples and Ukwatta's sample is that our samples include darker GRBs than Ukwatta's samples. Those weak samples are needed in order to confirm the lag-luminosity relation for GRBs which have the low luminosities. The average peak flux of Ukwatta's samples is ~ 13 counts/sec/cm² in 15–150 keV, whereas the averaged peak flux of our 14 GRBs is ~ 5 counts/sec/cm².

We used T_{100} time interval as the time range of the analysis. We examined the time bin of the light curve from 1 ms to 1024 ms and reported the lag as the reliable lag values if the average CCF_{max} is greater than ~ 0.5 . This value corresponds to a reasonable signal to noise level in a light curve in this analysis. The validity of the correspondence between a CCF_{max} and a signal to noise level is studied in Ukwatta et al. 2010 [6].

Most of the GRB spectra can be fitted by the Band function [19] which has four parameters (normalization, E_{peak} , and power-law photon indices α and β):

$$N(E) = \begin{cases} A \left(\frac{E}{100 \text{ keV}} \right)^\alpha e^{-(2+\alpha)E/E_{\text{peak}}} & E \leq \left(\frac{\alpha - \beta}{2 + \alpha} \right) E_{\text{peak}} \\ A \left(\frac{E}{100 \text{ keV}} \right)^\beta \left[\frac{(\alpha - \beta) E_{\text{peak}}}{(2 + \alpha) 100 \text{ keV}} \right]^{\alpha - \beta} e^{\beta - \alpha} & \text{(otherwise).} \end{cases} \quad (3)$$

We calculated the following equation to determine a normalization A :

$$A = \frac{f_{\text{obs}}}{\int_{15 \text{ keV}}^{150 \text{ keV}} N'(E) dE}, \quad (4)$$

where f_{obs} is 1 sec peak photon flux in the 15–150 keV band and N' is $N(E)$ when $A = 1$. The flux in the source frame energy band 1–10000 keV is calculated by

$$f_{\text{obs}}^{\text{new}} = \int_{1.0 \text{ keV}/(1+z)}^{10000 \text{ keV}/(1+z)} N(E) E dE. \quad (5)$$

FIGURE 1: The relationship between the lag reported in Ukwatta et al., 2010, and the lag based on our work for common GRBs. The dotted line shows $y = x$.

The isotropic peak luminosity L_{iso} is

$$L_{\text{iso}} = 4\pi d_L^2 f_{\text{obs}}^{\text{new}}, \quad (6)$$

where d_L is the luminosity distance:

$$d_L = \frac{(1+z)c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M(1+z')^3 + \Omega_L}}, \quad (7)$$

where H_0 is Hubble constant. We assumed that $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} = 2.268 \times 10^{-18} \text{ s}^{-1}$, $\Omega_M = 0.27$, $\Omega_L = 0.73$. The error of L_{iso} was estimated by performing the L_{iso} calculations for 1000 times taking into account the uncertainties in spectral parameters. We used reported Band function parameters E_{peak} , α , β , flux, and their errors from the BAT analysis (e.g., [20], GCN circulars) as the input parameters. However, if E_{peak} , α , and β are not constrained, we estimated E_{peak} from a photon index based on a single power-law fit [18]. In this case, α and β are used from the distributions by BATSE where $\alpha = -0.87 \pm 0.33$ and $\beta = -2.36 \pm 0.31$ [21].

3. Results

We calculated spectral lags for 40 known- z GRBs. Table 1 shows the results of spectral lag analysis and calculation of L_{iso} . The columns “LC st” and “LC et” are the start time and the end time of the light curve. The “CCF fit range min” and “CCF fit range max” are the fitting range of the CCF to the Gaussian function. The channel numbers from 1 to 4 correspond to the following energy bands: 15–25 keV, 25–50 keV, 50–100 keV, and 100–200 keV, respectively. We called two pieces of light curve data which are cross-correlated to calculate a lag in the channel numbers. For example, “Lag₃₁”

means the lag value obtained by cross-correlating the light curves between the 50–100 keV and the 15–20 keV band. We calculated spectral lags for all 6 combinations. However, if an average of 1000 CCF_{max} is not larger than ~ 0.5 in the 1 ms to 1024 ms time binning, we did not report the lags. A few GRBs show the lags which have large errors or negative lags. Since the light curves of those GRBs generally have low statistics, we believe the lags were not measured with a good accuracy.

Figures 2 and 3 shows the relationship between lags and luminosities of 71 known- z *Swift* GRBs based on the BAT data. Table 2 summarized linear correlation coefficients between the lag measured by different combinations of channels and the luminosity. We used a maximum likelihood method which was used to analyze a peak luminosity and variability correlation by Guidorzi et al. 2006 [22]. This method accounts for X and Y errors and samples variance [23]. The parameters are the normalization and index of the power-law and the variance of L_{iso} ($\sigma_{L_{\text{iso}}}$). Table 3 shows the results of fittings. In the calculation and fittings, the results of GRB060614A were not used. This is because GRB060614A has smaller lag than that expected from the lag-luminosity relation [24]. The results show that an isotropic peak luminosity negatively correlates with a spectral lag for all combinations of the channels. The best fit power-law index of the lag between the 50–100 keV band and the 15–25 keV band and the luminosity is -0.46 ± 0.04 with logarithm variance $\sigma_{L_{\text{iso}}}$ of 0.78. The linear correlation coefficient in this case is -0.40 with sample size of 62 (null probability of 0.2%). Therefore, we concluded that there is a correlation between the lag and the luminosity with the *Swift* GRB samples.

Figure 4 shows the lag-luminosity relation overlaid with the break time and the luminosity of the X-ray afterglow [14]. We used the results of Lag31 for the plot. This is because the lags between consecutive energy bands show low significant values. Also, the sample size of the lags between channel 4 and other channels is small due to a low signal to noise in the light curve of channel 4 in general.

We increased the samples which have both the lag and the luminosity values of the prompt emission, and the X-ray afterglow properties by combining our results and the latest report by Dianotti et al. 2013 [25]. As a result of power-law fitting, best fit parameters are

$$\log(L_{\text{iso}}) = (-1.05 \pm 0.03) \times \log\left(\frac{\text{Lag}_{31}}{(1+z)}\right) + (54.46 \pm 0.11) \quad (8)$$

with $\sigma_{L_{\text{iso}}} = 0.82 \pm 0.18$. The correlation coefficient is -0.96 with a sample size of 32. We confirmed that the two relations are connected with a power-law index of -1 as suggested by Sultana et al. 2012 [14], with larger samples.

4. Discussion

Our large known- z samples confirmed that the isotropic luminosity negatively correlates with the spectral lag (Figures 2 and 3). The linear correlation coefficients are between -0.4 and -0.5 . These results suggest that the most

TABLE 1: Summary of spectral lag analysis.

GRB name	Redshift	L_{iso} [erg/s]	LC st [s]	LC et [s]	Time bin [ms]	CCF fit range min [s]	CCF fit range max [s]	LagXX [ms]
050315	1.949	$8.07e + 51 \pm 5.11e + 51$	-56.108	125.288	256	-10	10	877 ± 528 (Lag21)
					512	-10	10	2458 ± 722 (Lag31)
					512	-10	10	1168 ± 484 (Lag32)
050318	1.44	$4.76e + 51 \pm 0.37e + 51$	-56.108	125.288	64	-1	1	-2 ± 39 (Lag21)
					64	-1	1	40 ± 50 (Lag31)
					64	-1	1	56 ± 38 (Lag32)
050319	3.14	$2.16e + 52 \pm 6.16e + 51$	-134.040	28.952	1024	-3	3	22 ± 409 (Lag21)
050505	4.27	$8.50e + 52 \pm 2.06e + 52$	-10.064	52.492	1024	-20	20	-492 ± 1217 (Lag21)
					1024	-20	20	-371 ± 984 (Lag31)
					1024	-20	20	-298 ± 640 (Lag32)
050802	1.71	$1.11e + 52 \pm 4.25e + 51$	-2.92	34.08	512	-7	10	545 ± 636 (Lag21)
					512	-7	7	1311 ± 602 (Lag31)
					512	-5	5	575 ± 359 (Lag32)
					1024	-10	10	1467 ± 893 (Lag41)
					1024	-10	10	1261 ± 812 (Lag42)
					1024	-5	5	-93 ± 517 (Lag43)
					1024	-20	20	1769 ± 522 (Lag21)
060502A	1.51	$5.33e + 51 \pm 1.80e + 51$	-5.644	38.984	128	-15	15	3252 ± 549 (Lag31)
					128	-10	20	1371 ± 362 (Lag32)
					512	-10	20	5914 ± 733 (Lag41)
					512	-10	15	3793 ± 574 (Lag42)
					512	-10	15	2577 ± 542 (Lag43)
060614	0.13	$7.87e + 49 \pm 5.86e + 49$	-1.496	176.472	16	-0.3	0.3	23 ± 15 (Lag21)
					32	-0.5	0.5	78 ± 22 (Lag31)
					32	-0.5	0.5	58 ± 18 (Lag32)
060814	0.84	$4.93e + 51 \pm 1.76e + 51$	-11.688	218.608	128	-4	4	272 ± 101 (Lag21)
					128	-4	4	495 ± 101 (Lag31)
					128	-4	4	226 ± 79 (Lag32)
					32	-5	5	980 ± 196 (Lag41)
					32	-5	5	674 ± 167 (Lag42)
060906	3.685	$4.25e + 52 \pm 1.30e + 52$	-41.796	47.666	32	-4	4	320 ± 152 (Lag43)
					512	-30	30	1497 ± 928 (Lag21)
					1024	-30	30	3042 ± 1165 (Lag31)
060912A	0.94	$6.41e + 51 \pm 3.03e + 51$	-0.564	6.116	1024	-30	30	1111 ± 1091 (Lag32)
					16	-1	1	134 ± 40 (Lag21)
					16	-1	1.5	294 ± 46 (Lag31)
070508	0.82	$1.86e + 52 \pm 1.45e + 52$	-13.756	33.112	16	-1	1	130 ± 39 (Lag32)
					4	-0.3	0.3	36 ± 8 (Lag21)
					4	-0.3	0.3	58 ± 8 (Lag31)
					2	-0.2	0.2	20 ± 4 (Lag32)
					8	-0.3	0.3	83 ± 14 (Lag41)
					8	-0.2	0.2	39 ± 8 (Lag42)
					8	-0.2	0.2	16 ± 5 (Lag43)

TABLE 1: Continued.

GRB name	Redshift	L_{iso} [erg/s]	LC st [s]	LC et [s]	Time bin [ms]	CCF fit range min [s]	CCF fit range max [s]	LagXX [ms]
070810A	2.17	$1.03e + 52 \pm 3.43e + 51$	-3.072	14.264	128	-10	10	509 ± 276 (Lag21)
					256	-10	10	969 ± 404 (Lag31)
					256	-10	10	564 ± 337 (Lag32)
080810	3.35	$5.28e + 52 \pm 1.09e + 52$	-21.192	111.436	256	-3	3	-49 ± 133 (Lag21)
					256	-3	3	-175 ± 145 (Lag31)
					128	-2	2	-107 ± 99 (Lag32)
					1024	-4	4	97 ± 476 (Lag41)
					512	-2	2	78 ± 266 (Lag42)
					512	-3	3	132 ± 343 (Lag43)
090423	8.0	$2.79e + 53 \pm 3.76e + 52$	-0.668	11.74	64	-2	2	79 ± 137 (Lag21)
					128	-2	2	132 ± 150 (Lag31)
					128	-3	3	123 ± 227 (Lag32)
090926B	1.24	$5.81e + 51 \pm 1.84e + 51$	-21.612	130.34	256	-0.7	0.7	47 ± 48 (Lag21)
					256	-0.7	0.7	96 ± 93 (Lag31)
					128	-0.7	0.7	45 ± 22 (Lag32)
091020	1.71	$1.71e + 52 \pm 6.21e + 51$	-8.476	48.264	64	-10	10	53 ± 266 (Lag21)
					128	-5	5	48 ± 250 (Lag31)
					64	-5	5	-14 ± 163 (Lag32)
					256	-5	5	-413 ± 416 (Lag41)
					256	-5	5	-356 ± 320 (Lag42)
					256	-5	5	-340 ± 323 (Lag43)
091127	0.49034	$5.82e + 51 \pm 3.01e + 51$	-0.372	7.196	16	-0.3	0.3	17 ± 20 (Lag21)
					16	-0.3	0.3	28 ± 24 (Lag31)
					16	-0.3	0.3	4 ± 22 (Lag32)
					128	-0.3	0.3	26 ± 59 (Lag41)
					64	-0.3	0.3	3 ± 47 (Lag42)
					64	-0.3	0.3	10 ± 57 (Lag43)
100615A	1.398	$1.05e + 52 \pm 4.23e + 51$	-0.044	47.408	16	-1.5	1.5	202 ± 43 (Lag21)
					32	-1	1.5	408 ± 44 (Lag31)
					16	-1.5	1.5	210 ± 38 (Lag32)
					256	-2	2	620 ± 143 (Lag41)
					256	-2	2	376 ± 132 (Lag42)
					128	-1	1.5	185 ± 101 (Lag43)
100621A	0.542	$2.26e + 51 \pm 1.22e + 51$	-6.1	204.192	8	-12	3	682 ± 63 (Lag21)
					16	-1	3	1432 ± 85 (Lag31)
					8	-2	3	776 ± 59 (Lag32)

TABLE I: Continued.

GRB name	Redshift	L_{iso} [erg/s]	LC st [s]	LC et [s]	Time bin [ms]	CCF fit range min [s]	CCF fit range max [s]	LagXX [ms]
100704A	3.6	$9.03e + 52 \pm 1.98e + 52$	-62.226	202.304	256	-5	5	599 ± 181 (Lag21)
					256	-3	4	1154 ± 183 (Lag31)
					256	-3	4	735 ± 129 (Lag32)
					1024	-3	5	1576 ± 316 (Lag41)
					512	-3	5	1120 ± 196 (Lag42)
100728B	2.106	$2.35e + 52 \pm 6.89e + 51$	-1.744	13.2	512	-3	3	425 ± 205 (Lag43)
					256	-2	2	73 ± 294 (Lag21)
					256	-4	3	514 ± 319 (Lag31)
					256	-3	3	183 ± 218 (Lag32)
					128	-3	3	338 ± 189 (Lag21)
100814A	1.44	$7.16e + 51 \pm 2.53e + 51$	-3.204	234.644	256	-3	4	914 ± 218 (Lag31)
					64	-3	4	920 ± 137 (Lag32)
					16	-1	1	213 ± 64 (Lag21)
					16	-1	1.5	397 ± 71 (Lag31)
					16	-1	1	89 ± 59 (Lag32)
100906A	1.727	$3.28e + 52 \pm 1.42e + 52$	-0.192	130.456	128	-1.5	3	834 ± 126 (Lag41)
					64	-2.5	2.5	432 ± 98 (Lag42)
					64	-2	2	302 ± 101 (Lag43)
					256	-5	5	-21 ± 194 (Lag21)
					256	-5	5	-18 ± 201 (Lag31)
110205A	2.22	$2.27e + 52 \pm 6.73e + 51$	-129.78	377.232	256	-2	2	83 ± 126 (Lag32)
					8	-1	1	97 ± 62 (Lag21)
					8	-1	1	166 ± 62 (Lag31)
					4	-0.5	0.5	38 ± 26 (Lag32)
					32	-2	2	272 ± 85 (Lag21)
110503A	1.613	$1.25e + 53 \pm 3.70e + 52$	-6.584	16.296	32	-1	1.5	456 ± 87 (Lag31)
					16	-1	1.5	293 ± 55 (Lag32)
					128	-1	2	575 ± 131 (Lag41)
					64	-2	3	464 ± 105 (Lag42)
					64	-2	2	99 ± 93 (Lag43)
110715A	0.82	$3.21e + 52 \pm 1.26e + 52$	-3.144	20.856	2	-1	1	70 ± 16 (Lag21)
					2	-1	1.2	107 ± 17 (Lag31)
					1	-0.5	0.5	41 ± 13 (Lag32)
					8	-0.5	0.7	132 ± 30 (Lag41)
					4	-0.5	0.7	105 ± 19 (Lag42)
111008A	4.9898	$3.04e + 53 \pm 5.17e + 52$	-2.636	72.464	4	-0.5	0.5	52 ± 15 (Lag43)
					128	-1	1	12 ± 100 (Lag21)
					256	-2	2	113 ± 213 (Lag31)
					128	-1	1	93 ± 114 (Lag32)
					128	-1	1	93 ± 114 (Lag32)

TABLE I: Continued.

GRB name	Redshift	L_{iso} [erg/s]	LC st [s]	LC et [s]	Time bin [ms]	CCF fit range min [s]	CCF fit range max [s]	LagXX [ms]
111228A	0.71627	$4.21e + 51 \pm 2.15e + 51$			32	-0.5	0.5	24 ± 22 (Lag21)
					64	-0.5	0.7	60 ± 30 (Lag31)
					64	-0.5	0.5	21 ± 21 (Lag32)
120119A	1.728	$4.95e + 52 \pm 1.33e + 52$	-13.216	361.888	32	-3	3	476 ± 101 (Lag21)
					32	-3	3	957 ± 123 (Lag31)
					32	-1	1	58 ± 44 (Lag32)
					256	-3	5	1647 ± 209 (Lag41)
					128	-3	3	620 ± 125 (Lag42)
					128	-3	3	240 ± 116 (Lag43)
120326A	1.798	$1.53e + 52 \pm 6.46e + 51$	-679	22.564	32	-3	3	386 ± 81 (Lag21)
					64	-2	4	766 ± 108 (Lag31)
					64	-3	4	367 ± 94 (Lag32)
120327A	2.813	$5.59e + 52 \pm 1.35e + 52$	-15.788	74.576	128	-1	1.5	144 ± 116 (Lag21)
					128	-2	2.5	247 ± 126 (Lag31)
					64	-1.5	1.5	119 ± 80 (Lag32)
					512	-1.5	2.5	565 ± 238 (Lag41)
					256	-3	4	432 ± 168 (Lag42)
					256	-2	2	244 ± 177 (Lag43)
120712A	4.1745	$1.03e + 53 \pm 1.83e + 52$	-4.572	16.528	128	-5	5	558 ± 327 (Lag21)
					128	-5	7	809 ± 325 (Lag31)
					64	-1	1	-88 ± 99 (Lag32)
					512	-10	10	1137 ± 757 (Lag41)
					512	-7	7	534 ± 602 (Lag42)
					512	-7	7	352 ± 573 (Lag43)
120802A	3.796	$7.32e + 52 \pm 1.73e + 52$	-35.680	28.016	128	-3	3	5 ± 156 (Lag21)
					256	-2	3	685 ± 203 (Lag31)
					256	-2	3	504 ± 131 (Lag32)
					1024	-3	4	1231 ± 598 (Lag41)
120907A	0.970	$2.58e + 51 \pm 1.06e + 51$	-0.024	8.136	1024	-3	4	915 ± 463 (Lag42)
					128	-2	2	129 ± 142 (Lag21)
					256	-1.5	2	196 ± 120 (Lag31)
					256	-1	1	173 ± 124 (Lag32)
121128A	2.20	$7.83e + 52 \pm 2.51e + 52$	-0.04	41.688	8	-0.5	0.5	18 ± 16 (Lag21)
					16	-0.5	0.5	38 ± 21 (Lag31)
					8	-0.4	0.4	23 ± 10 (Lag32)
					256	-1	1	102 ± 104 (Lag41)
					128	-1	1	96 ± 71 (Lag42)
					128	-0.5	0.5	46 ± 34 (Lag43)

TABLE 1: Continued.

GRB name	Redshift	L_{iso} [erg/s]	LC st [s]	LC et [s]	Time bin [ms]	CCF fit range min [s]	CCF fit range max [s]	LagXX [ms]
130215A	0.597	$7.22e + 50 \pm 3.27e + 50$	-5.832	73.384	1024	-20	20	458 ± 1663 (Lag21)
					1024	-20	20	-1235 ± 2013 (Lag31)
					1024	-20	20	-1527 ± 1448 (Lag32)
130420A	1.297	$5.14e + 51 \pm 2.15e + 51$	-14.988	188.128	64	-10	10	334 ± 274 (Lag21)
					128	-10	10	890 ± 347 (Lag31)
					128	-10	10	515 ± 277 (Lag32)
130427B	2.78	$4.13e + 52 \pm 1.06e + 52$	-0.616	36.808	256	-3	3	-10 ± 269 (Lag21)
					512	-3	1.5	-279 ± 252 (Lag31)
					256	-3	3	89 ± 204 (Lag32)
130514A	3.6	$6.06e + 52 \pm 1.23e + 52$	-7.088	257.932	128	-10	10	1522 ± 462 (Lag21)
					256	-10	15	3214 ± 531 (Lag31)
					256	-10	10	1123 ± 400 (Lag32)

FIGURE 2: The lag versus isotropic peak luminosity. The blue points are our results. The red points are the results which are reported in Ukwatta et al. 2010. The blue lines are best fit values of power-law fitting. The black dotted lines show the region corresponding to variance $\sigma_{L_{\text{iso}}}$. (a) Between 25–50 keV and 15–25 keV, (b) between 50–100 keV and 15–25 keV, (c) between 50–100 keV and 25–50 keV, and (d) between 100–200 keV and 15–25 keV.

of the long GRBs are consistent with the lag-luminosity relation. However, the results of fitting show the samples variance $\sigma_{L_{\text{iso}}}$ between 0.7 and 0.9. This suggests that samples show a significant scatter from the best fit line.

Even if we considered scatter, GRB060614A is far away from the best fit line. Our result confirmed that GRB 060614 is a real outlier to the relation [24].

Combining the fact that the duration itself might not be sufficient enough to distinguish the different classes of GRBs [26], we think multiple aspects of the prompt and

the afterglow properties are needed to investigate and classify GRBs appropriately.

We estimated the bulk Lorentz factor Γ from the averaged Lag31 value of ~ 0.6 seconds following the argument of Lu et al. [27]:

$$\text{lag} = \begin{cases} aE & \text{if } E \leq E_s \\ aE_s & \text{if } E \geq E_s, \end{cases} \quad (9)$$

FIGURE 3: The lag versus isotropic peak luminosity. The blue points are our results. The red points are the results which are reported in Ukwatta et al. 2010. The blue lines are best fit values of power-law fitting. The black dotted lines show the region corresponding to variance $\sigma_{L_{\text{iso}}}$. (a) Between 100–200 keV and 25–50 keV and (b) between 100–200 keV and 50–100 keV.

FIGURE 4: The lag between 50–100 keV and 15–25 keV versus isotropic peak luminosity with X-ray break time versus X-ray luminosity. The blue points are lag-luminosity results. The data reported in Dainotti et al. 2013 are shown in red. The blue lines are best fit values of power-law fitting. The black dotted lines show the region corresponding to variance $\sigma_{L_{\text{iso}}}$. The correlation coefficient is -0.96 with sample size of 32.

where $E_s = 1.67E_{\text{peak}}$ and a is shown by

$$a = 10^{-2.4} \left(\frac{\Gamma}{100} \right)^{-2.8} [\text{s/keV}]. \quad (10)$$

The bulk Lorentz factor is estimated to be 115 assuming a source frame peak energy E_{peak} of 240 keV (typical observed

peak energy of 80 keV for the *Swift* GRBs), a source frame energy E of 75 keV, and redshift of 2.

Figure 4 suggests the clear extension of the lag-luminosity relation to the Dainotti relation. Although the connection of those two relations is still puzzling, this might imply an important clue to understand the physical relationship between the prompt and the X-ray afterglow emission.

TABLE 2: Correlation coefficient between lag and isotopic luminosity.

Channel XX	Correlation coefficient	Sample size	Null probability
Channel 21	-0.42	61	0.1%
Channel 31	-0.40	62	0.2%
Channel 32	-0.52	62	0.1%
Channel 41	-0.50	45	0.1%
Channel 42	-0.50	45	0.1%
Channel 43	-0.56	41	0.1%

TABLE 3: Fit parameters.

Channel XX	Best fit	$\sigma_{L_{\text{iso}}}$	Sample size
Channel 21	$\log(L_{\text{iso}}) = (-0.30 \pm 0.05) \times \log(\text{Lag}_{21}/(1+z)) + (52.99 \pm 0.08)$	0.90 ± 0.12	61
Channel 31	$\log(L_{\text{iso}}) = (-0.46 \pm 0.04) \times \log(\text{Lag}_{31}/(1+z)) + (53.37 \pm 0.16)$	0.91 ± 0.12	62
Channel 32	$\log(L_{\text{iso}}) = (-0.61 \pm 0.04) \times \log(\text{Lag}_{32}/(1+z)) + (53.45 \pm 0.08)$	0.78 ± 0.10	62
Channel 41	$\log(L_{\text{iso}}) = (-0.60 \pm 0.04) \times \log(\text{Lag}_{41}/(1+z)) + (53.87 \pm 0.09)$	0.82 ± 0.13	45
Channel 42	$\log(L_{\text{iso}}) = (-0.69 \pm 0.04) \times \log(\text{Lag}_{42}/(1+z)) + (53.95 \pm 0.08)$	0.72 ± 0.12	45
Channel 43	$\log(L_{\text{iso}}) = (-0.75 \pm 0.05) \times \log(\text{Lag}_{43}/(1+z)) + (53.87 \pm 0.09)$	0.68 ± 0.13	41

5. Conclusion and Summary

We calculated spectral lags of 40 known- z *Swift* GRBs in addition to the previously calculated 31 GRBs. We found that most of our samples follow the lag-luminosity relation with a scatter of samples. We also confirmed that the negative relation between the break time and the luminosity in the X-ray afterglow extends nicely to the lag-luminosity relation of the prompt emission.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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