Spectral Lags Obtained by CCF of Smoothed Light Curves

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ABSTRACT. We present a new technique to calculate the spectral lags of gamma-ray bursts (GRBs). Unlike previous processing methods, we first smooth the light curves of gamma-ray bursts in high- and low-energy bands using the “Loess” filter, then we directly define the spectral lags as such to maximize the cross-correlation function (CCF) between two smoothed light curves. This method is suitable for various shapes of CCF; it effectively avoids the errors caused by manual selections for the fitting function and fitting interval. Using the method, we have carefully measured the spectral lags of individual pulses contained in Swift BAT gamma-ray bursts with known redshifts and confirmed the anticorrelation between the spectral lag and the isotropic luminosity. The distribution of spectral lags can be well fitted by four Gaussian components, with the centroids at 0.03 s, 0.09 s, 0.15 s, and 0.21 s, respectively. We find that some spectral lags of the multipeak GRBs seem to evolve with time.

Online material: extended tables

1. INTRODUCTION

Observationally, the shape of a light curve of gamma-ray burst (GRB) is quite complex. It contains one or several pulses characterized by a fast rise followed by an exponential decay (FRED) profile (e.g., Fishman et al. 1994; Fenimore 1999). The majority of light curves do not present periodic variations. Light curves in different energy bands differ in many aspects, such as the widths. The widths of the pulses in the higher-energy bands are usually smaller than those in the lower ones (Fenimore et al. 1995; Norris et al. 2005). The time delay among different energy photons is called spectral lag. As has been suspected, the spectral lags of GRBs and their evolution are vital for probing the physics of GRBs (Schaefer 2007). Many statistical works have been done (Band 1997; Norris et al. 2000; Chen et al. 2005). By using cross-correlation function, Norris et al. (2000) estimated spectral lags of six GRBs with known redshifts, concluding that the pulse peak luminosity and the spectral lag in time lag are anticorrelated and can be well fitted with a power law \( L \sim \tau_{\text{lag}}^{–1.14} \). Schaefer (2004) explained the relation and also demonstrated that the isotropic luminosity and the spectral lag should meet \( L \sim \tau_{\text{lag}}^{–1} \). Shen et al. (2005) interpreted the spectral lag as the curvature effect of relativistic motion of GRB shells. Interestingly, Chen et al. (2005) examined the spectral lags of GRBs with multipulse, and found that there seemed to be no apparent correlation between spectral lags and luminosity in general for pulses within a given long GRB. Since Swift launched successfully, many GRBs have been measured with redshifts (Gehrels et al. 2004). With larger samples, this anticorrelation was checked carefully. The results show that the lag-luminosity correlation does exist, but with a larger scatter (Schaefer 2007; Xiao & Schaefer 2009; Ukwatta et al. 2010). The spectral lags in long and short GRBs are quite different. Generally, short GRBs have nearly zero lags and long GRBs have large positive lags (corresponding to a temporal lead by higher-energy \( \gamma \)-ray photons; Band 1997). From this point of view, the spectral lags can be used as one of the observational parameters to classify the GRBs.

The procedure for estimating spectral lags of GRBs using a cross-correlation function (CCF) has been widely adopted (e.g., Link et al. 1993; Fenimore et al. 1995; Norris et al. 2000). The CCF of \( x_1(t) \) and \( x_2(t) \) for a GRB, where \( x_1(t) \) and \( x_2(t) \) are the respective light curves in two different \( \gamma \)-ray photon energy bands, is simply defined as

\[
\text{CCF}_{\text{Std}}(\tau; \nu_1, \nu_2) = \frac{\langle \nu_1(t+\tau)\nu_2(t) \rangle}{\sigma_{\nu_1}\sigma_{\nu_2}},
\]

where \( \nu_i(t) \equiv x_i(t) - \langle x_i(t) \rangle \) is the light curve of zero mean and \( \sigma_{\nu_i} = \langle \nu_i^2 \rangle^{1/2} \) is the standard deviation from the mean. The spectral lag \( \tau_{\text{lag}} \) is defined as such that it maximizes CCF \((\tau; \nu_1, \nu_2)\). Because of the Poisson noise, \( \tau_{\text{lag}} \) has to be evaluated through fitting the maximum of CCF with a polynomial function (model I) or a Gaussian function with a linear term representing a background (model II). For a faint burst, the CCF often displays asymmetry, or even multiple peaks. Therefore, using model II to fit the CCF maximum will introduce a systematic bias, whereas it is difficult to determine the degree of polynomial to fit CCF with model I. In both models, fitting the interval of CCF will influence the result.

In order to reduce those man-made biases, we introduce a smoothing technique. In § 2, we smooth the light curves of different energy bands with the “Loess method” and then calculate
the CCF of two smoothed curves. Finally, we directly select the maximum point of CCF as the spectral lag. The Monte Carlo simulation is implemented to confirm the smoothing factor $\alpha$. The algorithm looks simple and reasonable. In §3, we apply this procedure to 121 GRBs detected by Swift and compare the results with a traditional algorithm. The lag-luminosity correlation and lag/pulse-width correlation are also carefully analyzed in the third section. Finally, we analyze the results and give some brief discussions in §4.

2. PROCEDURE OF ANALYSIS

2.1. Smoothing the Light-Curves First

We use a moving-Loess (Cleveland 1979; Cleveland & Devlin 1988) filter to smooth the GRB light curves. The Loess filter is a local regression model, determined by only one parameter: the smoothing factor, $\alpha$, which gives a percentage ($0 \leq \alpha \leq 1$). This means to take $\alpha \times 100\%$ of the whole number of data as the smooth span. For example, supposing a light curve contains 110 data points, $x_1, \ldots, x_{110}$, taking $\alpha = 0.1$, then a smoothed value of $x_3$ is generated by a regression using linear least squares with 11 data points $x_3, x_4, \ldots, x_{13}$ and a second-degree polynomial model. Obviously, the $\alpha$ is smaller, the light curve is less smoothed, and vice versa. Specifically, when $\alpha = 0$, no smoothing has been applied. On the other hand, if $\alpha$ is too large, then the smoothed light curve becomes very flat, i.e., $\alpha = 1$, and the smooth span is the interval of entire points.

Figure 1 displays the smoothing results of GRB 081222 with different $\alpha$. It is easy to see that $\alpha = 0.2$ has a stronger smoothing effect than $\alpha = 0.05$.

In this article, the smoothing procedure is as follows: Suppose we have a single-pulse GRB. First, we select an interval to cover the peak of the GRB light curve (e.g., T90, the duration over which a burst emits from 5% of its total fluence to 95%) as the time range for calculating spectral lag. Then we choose an appropriate smoothing factor $\alpha$, which is determined by Monte Carlo simulations, taking each $x_i$ as the center of its smoothing span. We then use a second-order polynomial model to fit all data points in the span, and we replace $x_i$ by its fitted value. Obviously, this is a moving-average filter.

Ukwatta et al. (2010) suggested that CCFStd may not recover the artificial lag at times. So in this article, we adopt the CCF defined by Band (1997):

$$\text{CCF}_{x,y}(d) = \min(N,N-d) \sum_{i=\max(1,1-d)} x_i y_{i+d} \sqrt{\sum_{i} x_i^2 \sum_{i} y_i^2}. \quad (2)$$

Here, $x_i$ and $y_i$, for $i = 0, \ldots, (N - 1)$, denote the data of respective smoothed light curves in two different energy bands. The spectral lag is defined by $\tau_{\text{lag}} = d \times t_b$, where $d$ is the maximum of CCF, and $t_b$ is the size of a time bin.

In order to determine a reasonable value of $\alpha$, we calculated the lags between the simulated light curves of high- and low-energy bands. We selected the following equation to model a pair of GRB light curves $F_h(t)$ (high-energy band) and $F_l(t)$ (low-energy band; Abdo et al. 2009):

$$F(t) = C_0 + p_0 \left[ \frac{0}{\rho} \exp\left( -\frac{t-t_0}{\rho} \right), \quad t < t_0 \right]$$

where $C_0$ is the background counts rate, $t_0$ is the trigger time, and $p_0$ and $\rho$ represent the amplitude and the width of the light curves, respectively. Our light curves were background-subtracted; therefore, $C_0 = 0$. The observational facts tell us that the light curves of higher-energy bands have smaller $p_0$ and narrower widths. In fact, the spectral lag obtained from the CCF has no relation to $p_0$. So we just need to consider the width ratios between two energy bands. In this article, we choose width ratios as 1.05. For a given width, we calculated the theoretical lags with equation (2). Then we added a noise $X(t)$ on both $F_h(t)$ and $F_l(t)$, where $X(t)$ is a normally distributed random variable with expectation 0 and standard deviation $\sigma$. Obviously, a larger $\sigma$ corresponds to a lower signal-to-noise ratio (S/N). By adjusting the value of $\sigma$, we obtain the light curves with different S/N from 5 to 10. After smoothing, we achieved the simulation spectral lags of noisy light curves. We shift $\alpha$ from 0.01 to 0.1 (step = 0.01) to examine which $\alpha$ can fit the theoretical lags best. Figure 2 illustrates the simulating results of “lag vs. $\alpha$.” Each panel of Figure 2 contains a dashed line and six solid curves. The dashed line shows the value of the theoretical lag, and the rest of the solid curves are the lags obtained from six different S/N, with higher S/N indicating shorter error bars. All the curves reveal a similar trend: the curves are mildly flattened and show a slight spread;

![Image](https://example.com/image.png)
2.2. Uncertainty Estimation

The Monte Carlo simulation is applied to estimate the uncertainty of spectral lags. For a pair of given light curves of high- and low-energy bands,

\[
\begin{align*}
(x_1, x_2, \ldots, x_n) & \quad (y_1, y_2, \ldots, y_n),
\end{align*}
\]

where \(x_i\) and \(y_i\) are count rates of high- and low-energy bands, with measurement errors \(\epsilon_i\) and \(\epsilon_j\), respectively. Based on the data, we constructed a pair of simulated light curves \((x'_1, x'_2, \ldots, x'_n)\) and \((y'_1, y'_2, \ldots, y'_n)\) by taking \(x'_i \sim N(x_i, \epsilon_i^2)\) and \(y'_i \sim N(y_i, \epsilon_j^2)\) for \(i = 1, \ldots, n\). Here, \(x'_i\) is a normally distributed random variable with expectation \(x_i\) and standard deviation \(\epsilon_i\) for \(i = 1, \ldots, n\). The explanation is similar to \(y'_i\). In this work, we constructed 1000 \((x'_i, y'_i)\) for each pair of observed \(x_i\) and \(y_i\). We simulated 1000 light curves and derived the standard deviation of 1000 lags as the uncertainty estimate of the lag.

2.3. Determine the S/N and the Duration of a GRB Pulse

The ratio between the maximum of a pulse and the standard deviation of its background is defined as the S/N. Here, the background is an interval taken before or after the pulse region. Many works have been done to determine the duration of GRB (Scargle 1998; Hakkila et al. 2003). In this work, we still use the smoothing skill. In Figure 3, we utilize GRB 061007 as an example to represent the procedure of the duration of GRB pulses. We smooth the GRB light curve for energy band 15–150 keV with \(\alpha = 0.1\). The smoothed light curve may contain a few local maximum values. The lags in which the pulse peaks exceed \(1\sigma\) background are returned. There are two ways to determine the width of individual pulse. First, when the pulse peak has local minimums on both sides, the pulse duration is the interval between the low minimums. Second, when the pulse peak is missing a local minimum on one side (or both sides), we drew a horizontal line for which the height is equal to the global minimum of smoothed light curve with \(0.1\sigma\) background added, and then the intersection points between the horizontal line and the smoothed light curve are considered as the start or end point of the pulse.

![Fig. 2.—Lag vs. \(\alpha\). The width ratio is 1.05 and the theoretical lags are 32 ms, 64 ms, 128 ms, and 240 ms, respectively. For each panel, the horizontal dotted line shows the theoretical lag. The horizontal axis represents \(\alpha\), and the vertical axis represents lag. The spectral lags and corresponding error bars of light curves are displayed, with S/N changing from 5 to 10.](image)

![Fig. 3.—Determining the pulse duration of GRB. The rectangle region is considered as the GRB background, where the standard derivation is denoted as \(\sigma\). The height of the horizontal dashed line is the minimum of the smoothed light curve plus \(\sigma\), and only the local maximum of the solid line above the dashed line is regarded as pulse. The vertical dot-dashed lines represent the local minimums, and the pulse duration is the interval between the two dot-dashed lines (w1, w2, and w3 are the durations for the three pulses). The height of the horizontal solid line is the minimum of the smoothed light curve plus 0.1\(\sigma\). When the local maximum misses the local minimum on one side or both sides, the intersection points between the solid line and the smoothed light curve are considered as the start or end time of the pulse.](image)
3. THE GRB SAMPLE AND THE RESULTS

3.1. Description of the GRB Sample

Since the successful launch of the Swift satellite in 2004 November (Gehrels et al. 2004), over 600 GRBs have been detected. Swift is a multiwavelength satellite that can detect the gamma-ray transient source and accurately locate the source within less than 100 s. Swift observations have played an inconceivably important role in GRB research.

The energy band of the Swift Burst Alert Telescope (BAT) is 15–350 keV. In practice, we only choose photons between 15 and 150 keV, because the BAT is transparent to high-energy photons over 150 keV. In previous works, GRB light curves were extracted by specifying GRB positions that were detected by BAT. Here, we use a slightly different method. The X-Ray Telescope (XRT) can improve GRB position in both accuracy and precision by using the Ultra-Violet/Optical Telescope (UVOT) to accurately determine Swift’s position (Goad et al. 2007; Evans et al. 2009). So

![Comparison between Gaussian fitting and Loess filter methods for GRB 080413B](image1)

![Comparison between Gaussian fitting and Loess filter methods for GRB 071020](image2)

![Comparison between Gaussian fitting and Loess filter methods for GRB 080413B](image1)

![Comparison between Gaussian fitting and Loess filter methods for GRB 071020](image2)

**TABLE 1**

| GRB   | Peak no. | Start time (s) | Stop time (s) | lag$_{G}$ (s) | $\alpha = 0.1$ (s) | $\alpha = 0.05$ (s) |
|-------|----------|---------------|--------------|---------------|-------------------|-------------------|
| 050318 ... | ... | 24.52 | 32.392 | 0.06 ± 0.05 | 0 ± 0.05 | 0.11 ± 0.06 |
| 050401 ... | ... | 22.968 | 33.992 | 0.44 ± 0.1 | 0.27 ± 0.13 | 0.14 ± 0.05 |
| 050416A ... | ... | −1.648 | 3.856 | 0.49 ± 0.1 | 0.69 ± 0.14 | 0.64 ± 0.1 |
| 050603 ... | ... | −3.24 | 3.560 | 0.06 ± 0.02 | 0.06 ± 0.02 | 0.05 ± 0.02 |
| 050922C ... | ... | −3.624 | 4.152 | 0.21 ± 0.02 | 0.16 ± 0.02 | 0.27 ± 0.11 |
| 051111 ... | ... | −8.88 | 12.304 | 1.1 ± 0.4 | 0.51 ± 0.44 | 0.48 ± 0.2 |
| 060206 ... | ... | −1.976 | 8.856 | 0.44 ± 0.07 | 0.45 ± 0.08 | 0.43 ± 0.2 |
| 060210 ... | ... | −5.032 | 9.304 | 0.51 ± 0.2 | 0.43 ± 0.2 | 0.34 ± 0.1 |
| 060418 ... | ... | 23.104 | 34.848 | 0.08 ± 0.2 | 0 ± 0.2 | 0.02 ± 0.02 |
| 060526 ... | ... | −5.040 | 16.192 | 0.25 ± 0.06 | 0.16 ± 0.06 | 0.21 ± 0.08 |

**NOTES.**—Col. (1): GRB trigger number. Col. (2): Peak number of GRBs. Col. (3): Start time of individual pulse relative to the GRB trigger time. Col. (4): Stop time of individual pulse relative to the GRB trigger time. Col. (5): Spectral lags plus errors between 15–25 keV and 50–100 keV by fitting with Gaussian plus linear equation. Col. (6): Spectral lags plus errors calculated by smoothing method with $\alpha = 0.1$. Col. (7): Spectral lags plus errors calculated by smoothing method with $\alpha = 0.05$. Table 1 is published in its entirety in the electronic edition of the PASP. A portion is shown here for guidance regarding its form and content.
we apply enhanced XRT position to the procedures `batmaskw` and `batbinevt` and extract background-subtracted 15–25 keV and 50–100 keV light curves with a time-bin size of 16 ms for spectral lag calculating.

Obviously, when we apply this procedure to a low-S/N GRB, it can produce unendurable error. So we select the GRBs with S/N larger than 5 in the 15–25 keV energy range.

Our sample contains 121 long GRBs detected by `Swift` BAT from 2004 to 2010, and 54 of them have measured redshifts.

3.2. Results

For a given spectral lag in advance, Ukwatta et al. (2010) simulated a group of light curves with the profile of a FRED pulse superposed on a background of different noise levels and fitted the peaks of CCF by a Gaussian function. The calculated lag was consistent with the value given previously. Through calculation we find that the CCF shows a symmetrical peak when the simulated light curves have FRED-like pulse shapes. Obviously, Gaussian curve is appropriate for fitting such a maximum. The raw light curves, however, are much more complicated than the simulated ones, and it is difficult to get a good fitting with Gaussian function. As for our samples, the shapes of the CCF can be roughly classified into three categories: (1) Gaussian-like profile, (2) asymmetric peak, and (3) multipeak. As expected, it is easy to fit the first kind of CCF with a Gaussian function, but difficult for the other two kinds. We will compare the two methods with various shapes of CCF.

We choose GRB 080413B and GRB 071020 as examples. In Figure 4, the CCF between 15–25 keV and 50–100 keV of GRB 080413B shows a Gaussian-like pulse. We fit the maximum of CCF with a Gaussian function plus a linear function and obtain the spectral lag and error, $\tau = 0.14 \pm 0.02$ s.

In Figure 5, the CCF (circle) between 15–25 keV and 50–100 keV of GRB 071020 displays an asymmetry peak. There is an offset between A and B. If we change the fitting interval, point A will move, while the location of B is not related to the fitting interval. Although using a smaller fitting interval that contains the maximum of the CCF may yield similar lags, it will increase the lag uncertainty. Figure 5 shows the smoothing method (dashed line) is better for finding the maximum of CCF.

We list 121 spectral lags and pulse widths of GRBs in Tables 1 and 2. For GRBs with multiple pulses, we calculate each pulse of spectral lag. In this article, the spectral lags with smoothing factor $\alpha = 0.1$ and $\alpha = 0.05$ are utilized for analysis.

3.3. The Results Analysis

3.3.1. Comparison between Gaussian Curve-Fitting and Smoothing Methods

From Tables 1 and 2, we note that the correlation coefficient between $\text{lag}_G$ and $\text{lag}_L$ is 0.9, which implies that the results of the two methods have high correlation. The $\text{lag}_G$–$\text{lag}_L$ relation in Figure 6 is fitted by a linear function $\text{lag}_L(s) = (0.75 \pm 0.05) \text{lag}_G(s) + (0.005 \pm 0.03)$. Hence, $\text{lag}_G$ is systematically larger than $\text{lag}_L$ by a factor of 4/3.

### Table 2

| GRB      | Peak no. | Start time (s) | Stop time (s) | $\text{lag}_G$ (s) | $\alpha = 0.1$ (s) | $\alpha = 0.05$ (s) |
|----------|----------|---------------|--------------|-------------------|-------------------|-------------------|
| 041220   | ...      | $-2.608$      | $8.096$      | $0.21 \pm 0.05$   | $0.08 \pm 0.05$   | $0.18 \pm 0.08$   |
| 041224   | ...      | $16.032$      | $41.568$     | $0.49 \pm 0.2$    | $0.62 \pm 0.2$    | $0.77 \pm 0.4$    |
| 050124   | ...      | $-6.264$      | $6.904$      | $0.03 \pm 0.02$   | $0.08 \pm 0.02$   | $0.05 \pm 0.02$   |
| 050219B  | 1        | $-6.376$      | $5.432$      | $0.23 \pm 0.06$   | $0.05 \pm 0.06$   | $0.03 \pm 0.02$   |
| 050219B  | 2        | $-5.976$      | $15.896$     | $0.32 \pm 0.05$   | $0.29 \pm 0.05$   | $0.10 \pm 0.03$   |
| 050326   | 1        | $-2.736$      | $13.392$     | $0.03 \pm 0.02$   | $0.02 \pm 0.02$   | $0.02 \pm 0.02$   |
| 050326   | 2        | $15.52$       | $30.560$     | $0.09 \pm 0.02$   | $0.06 \pm 0.02$   | $0.06 \pm 0.02$   |
| 050418   | ...      | $-25.416$     | $31.000$     | $0.44 \pm 0.09$   | $0.50 \pm 0.1$    | $0.42 \pm 0.2$    |
| 050509A  | ...      | $-8.664$      | $8.680$      | $0.06 \pm 0.03$   | $0.14 \pm 0.04$   | $0.06 \pm 0.02$   |
| 050701   | ...      | $2.968$       | $13.384$     | $0.21 \pm 0.05$   | $0.14 \pm 0.06$   | $0.29 \pm 0.2$    |

Note.—Col. (1): GRB trigger number. Col. (2): Peak number of GRBs. Col. (3): Start time of individual pulse relative to the GRB trigger time. Col. (4): Stop time of individual pulse relative to the GRB trigger time. Col. (5): Spectral lags plus errors between 15–25 keV and 50–100 keV by fitting with Gaussian plus linear equation. Col. (6): Spectral lags plus errors calculated by smoothing method with $\alpha = 0.1$. Col. (7): Spectral lags plus errors calculated by smoothing method with $\alpha = 0.05$. Table 1 is published in its entirety in the electronic edition of the PASP. A portion is shown here for guidance regarding its form and content.
3.3.2. The Distribution of Spectral Lags with Smoothing Method

Distribution of the lags can be obtained as follows: Assume that each spectral lag obeys a normal distribution with the mean equal to itself and the standard deviation equal to its uncertainty. In principle, the uncertainty of a lag should be larger than its temporal resolution, 0.016 s. Therefore, if a simulated uncertainty is smaller than 0.016 s, we set it to 0.016 s. In Figure 7, we add all probability density functions (PDFs) together and normalize the result. As shown in Figure 7, the PDF of spectral lags has four components that locate at $0.028 \pm 0.001$ s, $0.091 \pm 0.003$ s, $0.151 \pm 0.01$ s, and $0.21 \pm 0.01$ s. Obvi-
ously, most GRBs have positive spectral lags, which is consistent with the high-energy photons arriving earlier than those with low-energy photons in long GRBs.

3.3.3. The Relation between the Peak Isotropic Luminosity and the Lag of Primary Peak

Ukwatta et al. (2010) calculated spectral lags within the entire burst region for the “gold sample” of GRBs detected by Swift, confirming the correlation between the peak isotropic luminosity and the lag of primary peak, albeit with a larger scatter in the relation. Hakkila et al. (2008) argued that it is reasonable to calculate individual-pulse spectral lag instead of a burst range. From Tables 1 and 2, our results support that each pulse

![Fig. 6.—The lag$_G$–lag$_L$ relation. The solid line shows the best fit between lag$_G$ and lag$_L$. The dashed line displays the diagonal. The 1σ simulation uncertainties are used for error bars.](image)

![Fig. 7.—PDF of Loess spectral lags. The PDF is fitted by four Gauss components that locate $0.028 \pm 0.001$ s (dashed line), $0.091 \pm 0.003$ s (dotted line), $0.15 \pm 0.01$ s (dash-dotted line), and $0.21 \pm 0.01$ s (double-dot-dashed line), respectively.](image)

![Fig. 8.—Log-log relation between isotropic luminosity and spectral lag. The factor $(1+z)^{-1}$ corrects for the time-dilation effect.](image)

![Fig. 9.—Lag/pulse-duration relation in the rest frame of GRBs. Both axes are in units of second. The factor $(1+z)^{-1}$ corrects for the time-dilation effect. Each duration error is set as 10% of its value.](image)
3.3.4. The Lag/Pulse-Duration Relation

Hakkila et al. (2008) reported a correlation between the spectral lag and pulse duration of GRBs with a high correlation coefficient ($R = 0.97$); i.e., the shorter the duration of the pulse, the smaller the lag and the higher the luminosity, and vice versa. We calculated the time duration and pulse spectral lag of each pulse in the samples. In Figure 9, the lag-duration relation in the rest frame of GRBs is still established, but with a smaller correlation coefficient, $R = 0.6$.

3.3.5. The Evolution of the Lag with Time

Most GRB light curves in the sample have multipeak structure; we show the lag corresponding to each peak in Tables 1 and 2. We find that different pulses in one GRB generally have different spectral lags, meaning that the lags evolve with time. Some GRBs (GRB 060927, GRB 061222A, GRB 080413A, GRB 080603B, GRB 090404, and GRB 100615A) even have different signs from different pulses; i.e., during a multipeak burst, one pulse has a positive lag, while the other may have a negative one. It may be due to the time evolution of peak energy, which can produce negative lags (Peng et al. 2011; Ukwatta et al. 2011).

4. CONCLUSION

In this work, we develop a new method to calculate the spectral lags. Our method does not require the choice of fitting function and intervals, thus avoiding the human-selection effects in traditional CCF-fitting methods. The Monte Carlo simulation is utilized to determine the smoothing factor $\alpha$. The results show that our method obtains the introduced lags appropriately, as long as $\alpha$ is between 0.05 and 0.1. Using the method, we assign $\alpha = 0.05$ and $\alpha = 0.1$ to calculate the spectral lags of GRBs detected by Swift BAT, respectively. The Gaussian fitting and smoothing methods for spectral lags are listed in Tables 1 and 2. For two smoothing factors, most of the spectral lags cover each other well. From Figure 6, we see that the spectral lags fitted by model II (i.e., Gauss and line) are strongly correlated with the smoothing method results, which demonstrates that our method is reasonable. It is worth noting that lags measured by our new method are systematically smaller than those calculated by the traditional method. Figure 2 shows us that this is not caused by smoothing. We also verify the isotropic-luminosity/spectral-lag relation, which is consistent with the work of Norris et al. (2000) and Ukwatta et al. (2010). By calculating multipeak GRB spectral lag, we find that lags evolve with time, with a weak tendency. Finally, Hakkila et al. (2008) reported the lag/pulse-duration relation with an extremely high correlation coefficient. Our sample does not show this behavior.

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