Postprint on the Spectral Lag and Flare Properties of GRB051117A

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Abstract

Margutti et al. found that for 8 gamma-ray bursts, the spectral lag of flares exhibits a strong correlation with flare characteristic parameters (peak time, width, rise time, decay time), and with time, flares become wider and the spectral lag increases. We employ the discrete cross-correlation function (DCF) to investigate the spectral lag of a multi-flare gamma-ray burst (GRB051117A) with 10 flares, and find that inside GRB051117A, the spectral lag also exhibits a strong correlation with the peak time, width, rise time, and decay time of flares, i.e., lag t_{peak}, w, t_{rise}, t_{decay}. Flares within a gamma-ray burst also evolve temporally, i.e., with time, flares become broader and the spectral lag increases. This work extends the relationship between spectral lag and flare characteristic parameters that exists among gamma-ray bursts to the interior of individual gamma-ray bursts, which can facilitate a deeper understanding of multi-flare gamma-ray bursts. Moreover, the correlations among flare characteristic parameters within GRB051117A are highly similar to those found among multiple gamma-ray bursts and even prompt emission pulses, which also provides support for X-ray flares and prompt emission pulses having the same physical origin.

Full Text

Study on the Spectral Lag and Flare Characteristics of GRB051117A

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Abstract

Margutti et al. discovered a strong correlation between the spectral lag of flares and their characteristic parameters (peak time, width, rise time, and decay time) in eight gamma-ray bursts (GRBs), finding that flares become wider and their spectral lags increase over time. Using the discrete correlation function (DCF), we investigate the spectral lag properties of a multi-flare GRB (GRB051117A) containing ten flares. We find that within GRB051117A, the spectral lag is also strongly correlated with the peak time, width, rise time, and decay time of flares, following the relations lag   t_{peak}, w, t_{rise}, t_{decay}. Flares within a GRB also evolve over time: as time progresses, flares become wider and their spectral lags become larger. This work extends the relationship between spectral lag and flare characteristic parameters from inter-GRB comparisons to within individual GRBs, providing deeper insight into multi-flare GRBs. Moreover, the correlations between flare characteristic parameters within GRB051117A are highly similar to those found between different GRBs and even prompt emission pulses, supporting the hypothesis that X-ray flares and prompt emission pulses may share the same physical origin.

Keywords: gamma-ray bursts; X-ray flares; DCF; spectral lag

1. Introduction

Gamma-ray bursts (GRBs) are among the most violent astronomical phenomena observed in recent decades, consisting of two components: prompt emission and afterglow. Research on the spectral lags of GRBs has continued for decades. Spectral lag refers to the time difference between the arrival of high-energy and low-energy photons from a GRB. Typically, high-energy photons arrive earlier than low-energy photons, producing a positive lag; if low-energy photons arrive earlier, a negative lag is produced. Studying GRB spectral lags is of great significance for understanding GRB origins and cosmology [?, ?]. Common methods for calculating GRB spectral lags include light curve fitting and cross-correlation function (CCF) techniques.

The CCF method is widely used to estimate GRB spectral lags [?, ?]. Norris et al. [?] discovered an anti-correlation between GRB spectral lag and luminosity. Ukwatta et al. [?] obtained similar results by expanding the sample, enabling redshift estimation from the lag-luminosity relation and allowing exploration of GRB cosmology from the perspective of spectral lags. Hakklia et al. [?] statistically analyzed the spectral lags of over 2000 GRBs from the BATSE database and provided the ratio of positive to negative lags. Yi et al. [?, ?] compared long and short bursts, finding that long bursts show a positive correlation between spectral lag and duration, while short bursts do not. They also compared the distribution of relative spectral lag $R = \tau/\Delta T$, finding similar distribution shapes but different magnitudes between long and short bursts. Roychoudhury et al. [?] analyzed a multi-pulse GRB (GRB060814) and found that pulses 1, 2, and 4 showed positive lags while pulse 3 showed negative lag, with all pulses exhibiting similar spectral evolution trends. Although the physical origin of GRB spectral lags remains unclear, spectral evolution [?] and curvature effects [?] are widely accepted explanations, with some suggesting that spectral lags result from the combined action of both mechanisms [?].

Current research on GRB spectral lags primarily focuses on data from CGRO/BATSE, Swift BAT, and Fermi, concentrating mainly on prompt emission pulses in the gamma-ray band. Studies of spectral lags in X-ray afterglow flares are relatively scarce. However, the common origin of X-ray afterglow flares and prompt emission pulses is widely accepted. Burrows [?] proposed that flares are produced at late times by internal shocks, requiring reactivation of the GRB central engine, a conclusion supported by many researchers [?]. Chincarini et al. [?] studied the temporal evolution of flare characteristics across different X-ray energy bands using 113 flares from the Swift XRT database. Spectral lags are also present in X-ray flares. Margutti et al. [?] investigated spectral lags in eight GRBs (containing nine flares) observed by Swift XRT, finding positive correlations between spectral lag and flare characteristic parameters, and obtained a lag-luminosity relation similar to that found in prompt emission pulses, concluding that flares and prompt emission pulses share the same origin mechanism. Sonbas et al. [?] also supported a common origin for X-ray flares and prompt emission pulses. However, they did not conduct detailed studies of the spectral lag properties within individual multi-flare GRBs.

GRB051117A is a multi-flare GRB with a complex light curve structure, containing at least ten flares in the first 2000 seconds of observation. Goad et al. [?] studied this bright GRB across multiple wavelengths, finding significant correlations between point source intensity and spectral parameters such as photon index, hardness ratio, and break energy. Chincarini et al. [?] also investigated correlations between flare characteristic and spectral parameters for this burst. However, they did not systematically discuss its spectral lag properties. Therefore, we aim to study the multi-flare GRB GRB051117A from the perspective of spectral lags.

We estimated the lags of all flares and analyzed correlations between flare characteristic parameters, comparing them with the correlations found by Margutti et al. [?] for nine flares across eight GRBs. We also discuss the correlations between flare characteristic parameters within GRB051117A, making direct comparisons with prompt emission pulses to gain deeper insight into this multi-flare GRB.

2. Sample Processing and Analysis Methods

XRT data were processed using the HEASOFT software package v6.26.1 with corresponding calibration files. The 0.3–10 keV X-ray afterglow light curve for this burst was obtained from the Swift/XRT website [?, ?] (https://www.swift.ac.uk/), which provides data for both the 0.3–1.5 keV and 1.5–10 keV energy channels. When the GRB source brightness exceeds a few counts per second, data are processed in Windowed Timing (WT) mode; when the source brightness decreases, the spacecraft automatically switches to Photon Counting (PC) mode for observations. To ensure we selected bright flares, we used the light curve from GRB051117A in WT mode, as shown in Figure 1 [Figure 1: see original paper].

Chincarini et al. [?] fitted the ten flares of this burst using the Norris function [?], which can provide flare characteristic parameters such as rise time, decay time, peak time, width, and asymmetry. The Norris function [?] is defined as:

$$I(t) = A\lambda \exp\left[-\frac{(t-t_s)}{\tau_1} - \frac{\tau_2}{(t-t_s)}\right] \quad \text{for } t > t_s \tag{1}$$

where $\lambda = \exp(2\mu)$, $\mu = (\tau_1/\tau_2)^{1/2}$, and t_s is the flare start time (see Norris et al. [?] for specific definitions). The flare peak parameter is:

$$t_{\text{peak}} = t_s + (\tau_1 \tau_2)^{1/2} \tag{2}$$

The flare width is defined as the distance between the two intensity points at the start and end of the flare:

$$w = t_{\text{decay}} + t_{\text{rise}} = \tau_2 \left(\sqrt{1+4\mu} - 1\right) \tag{3}$$

The flare asymmetry is defined as the distance at $1/e$:

$$\frac{t_{\text{decay}}}{t_{\text{rise}}} = \frac{\sqrt{1+4\mu} - 1}{2\mu} \tag{4}$$

The rise time t_{rise} and decay time t_{decay} are expressed in terms of w and k as:

$$t_{\text{decay, rise}} = \frac{w}{2}(1 \pm k) \tag{5}$$

Since Swift XRT data are discrete, we can only use the discrete correlation function (DCF) to estimate spectral lags. The DCF shares the same principle as the CCF. Due to the complex structure of the GRB051117A light curve, the DCF method is more suitable than light curve fitting for estimating spectral lags in this burst. We obtained flare characteristic parameter data for GRB051117A from Chincarini et al. [?] and used the DCF to estimate the spectral lag for each flare. The results are shown in Table 1 .

The DCF is defined as [?, ?]:

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

where x_i and y_i are the photon counts in the i-th time bin of two light curves, N is the number of time bins, and d is the offset value of light curve y relative to light curve x. The DCF is a function of d. We obtained the DCF curve as a function of d and fitted it with a Gaussian function. When the light curve morphologies in the two energy channels differ significantly, more complex functions such as higher-order polynomials or the Norris function [**?**] are needed to fit the DCF curve. In our sample, a Gaussian function provides a good fit, so we uniformly used Gaussian functions to fit the DCF curves. The peak of the Gaussian fitting curve represents the point of best correlation between the two light curves, which we denote as d'. The spectral lag is then defined as:

$$\mathrm{lag} = d' \times \Delta t, \quad \Delta t = T/N$$

where T is the total length of the time series. This method essentially calculates the integrated lag over the entire flare.

We used Monte Carlo simulations to estimate the lag errors. The procedure is as follows: we assumed that the error in photon count rate for each time bin follows a normal distribution with mean 0 and variance 1. From this distribution, we randomly sampled photon count rates for each time bin to generate a simulated light curve, then used the DCF to estimate its spectral lag. Repeating this process 1000 times yielded 1000 lag values. The standard deviation of these 1000 values was taken as the spectral lag error [**?**].

3.1 Correlation Between Spectral Lag and Flare Characteristic Parameters

The lag results for the ten flares of GRB051117A are shown in Table 1. The fifth flare is considered to have zero lag within the error margins. The relationships between the spectral lags of the other nine flares and their characteristic parameters are shown in Figure 2 [Figure 2: see original paper]. In this figure, red points represent the nine flares of GRB051117A, while blue triangles, black squares, and green asterisks represent pulses from different energy channels in Norris et al. (2005) [**?**] (hereafter N05), which used BATSE/CGRO data. We define $\mathrm{lag}_{i1} = t_{\mathrm{peak}}(1) - t_{\mathrm{peak}}(i)$ for $i = 2, 3, 4$, allowing us to calculate the spectral lags between the second (50-100 keV), third (100-300 keV), and fourth ($>$ 300 keV) energy channels relative to the first (25-50 keV) channel. Since the N05 sample consists of long-lag bursts (with lag_{31} typically 1-2 s), our calculated spectral lags are concentrated in the range of 10^{-1}-10^{1} seconds. We then investigated their correlations with the pulse characteristic parameters of the first energy channel and compared these with the relationships found in flares, providing evidence that flares and pulses may share a common origin.

The upper left panel of Figure 2 shows the relationship between spectral lag and flare peak time in GRB051117A. The best-fit relation is $t_{\mathrm{peak}} = 10^{2.64\pm0.18}\mathrm{lag}^{0.33\pm0.35}$, with a Spearman correlation coefficient of 0.45 ($p = 2.2 \times 10^{-1}$), indicating that spectral lags increase over time.

The upper right panel shows the relationship between spectral lag and peak width. The best-fit relation is $w = 10^{1.85\pm0.1}\mathrm{lag}^{0.52\pm0.2}$, with a Spearman correlation coefficient of 0.57 ($p = 1.2 \times 10^{-1}$). In multi-flare GRBs, the magnitude of spectral lag is proportional to flare width—wider flares have larger lags.

We find that the median spectral lag of these nine flares is 2.01 s, with a mean of 3.55 s and a mean width of 130 s. In our previous study of 48 multi-flare GRBs (containing 137 flares), we found that among 123 positive-lag flares, the median lag was 3.55 s, the mean lag was 5.18 s, and the mean duration was 185.5 s. The positive correlation between lag and duration/width in flares is well established [**?**]. The relatively small lags in GRB051117A are due to its smaller durations/widths.

The lower left and lower right panels of Figure 2 show the relationships between rise time and decay time with spectral lag, respectively. Both rise time and decay time affect the magnitude of spectral lag. The correlation between rise time and spectral lag is $t_{\mathrm{rise}} = 10^{1.4\pm0.09}\mathrm{lag}^{0.49\pm0.18}$ (Spearman coefficient 0.8, $p = 1.3 \times 10^{-2}$), while the correlation between decay time and spectral lag is $t_{\mathrm{decay}} = 10^{1.64\pm0.13}\mathrm{lag}^{0.55\pm0.24}$ (Spearman coefficient 0.6, $p = 9.68 \times 10^{-2}$). In GRB051117A, larger rise and decay times correspond to larger spectral lags, consistent with the relationships found across multiple GRBs [**?**].

Figure 2 demonstrates that prompt emission pulses exhibit similar correlations between lag and characteristic parameters as those found in GRB051117A flares, with the general relationships lag $\ t_{\mathrm{peak}}, w, t_{\mathrm{rise}}, t_{\mathrm{decay}}$ being common in prompt emission pulses. This provides support for the hypothesis that X-ray flares and prompt emission pulses share a common physical origin.

3.2 Correlations Between Flare Characteristic Parameters

Our investigation of the relationship between spectral lag and flare characteristic parameters in the ten flares of GRB051117A suggests that correlations found between different GRBs can be extended to within individual GRBs. This section discusses correlations between flare characteristic parameters within multi-flare GRBs, comparing them with those found between different GRBs and in prompt emission pulses to provide a more comprehensive understanding of multi-flare GRBs.

We obtained flare characteristic parameter data from Margutti et al. (2010) [**?**] (hereafter M10) for nine flares and from N05 for 115 pulses. The N05 pulses were divided into four energy channels, and we calculated their rise times (t_{rise}) and decay times (t_{decay}) using Equation (5). See Norris et al. [**?**] (2005) for specific definitions.

The upper left panel of Figure 3 [Figure 3: see original paper] shows the correlation between flare/pulse rise time and decay time. The best-fit relation for GRB051117A flares is $t_{\mathrm{decay}} = 10^{0.36\pm0.41}t_{\mathrm{rise}}^{0.98\pm0.26}$, with a Spearman correlation coefficient of 0.75 ($p = 1.84 \times 10^{-2}$). In GRB051117A, M10, and N05, rise time is positively correlated with decay time, with all points following $t_{\text{decay}} > t_{\text{rise}}$. In GRB051117A, $t_{\text{decay}} \sim 1.9 t_{\text{rise}}$, similar to previous results [**?**, **?**] showing that t_{decay} in flares is approximately twice t_{rise}.

The upper right panel shows the correlation between peak time and width. The best-fit relation for GRB051117A is $t_{\text{peak}} = 10^{0.58\pm0.54} w^{0.53\pm0.19}$, with a Spearman coefficient of 0.73 ($p = 2.12 \times 10^{-2}$). In GRB051117A, flare peak time is positively correlated with flare width—as the afterglow progresses, newly produced flares become wider, which may explain why spectral lags increase over time. Combined with Figures 2 and 3, our analysis shows that flares in GRB051117A evolve over time: later flares are wider and have larger spectral lags, supporting the conclusions of Margutti et al. [**?**]. Similar positive correlations between pulse peak time and width exist in prompt emission pulses, though the relationship is more dispersed in pulses compared to the more concentrated relationship in flares—a phenomenon worthy of future investigation.

The lower left and lower right panels show the relationships of peak time with rise time and decay time, respectively. For GRB051117A, the best-fit relations are $t_{\text{rise}} = 10^{0.15\pm0.38} t_{\text{peak}}^{0.52\pm0.17}$ (Spearman coefficient 0.78, $p = 1.17 \times 10^{-2}$) and $t_{\text{decay}} = 10^{0.35\pm0.64} t_{\text{peak}}^{0.55\pm0.23}$ (Spearman coefficient 0.7, $p = 3.11 \times 10^{-2}$). Both M10 and N05 samples show similar relationships to those in GRB051117A. Flare rise time t_{rise} and decay time t_{decay} are both strongly correlated with peak time t_{peak}, jointly influencing it. In GRB051117A, $t_{\text{rise}} \sim 0.06 t_{\text{peak}}$ and $t_{\text{decay}} \sim 0.12 t_{\text{peak}}$. Chincarini [**?**] found that in 113 flares, $t_{\text{rise}} \sim 0.05 t_{\text{peak}}$ and $t_{\text{decay}} \sim 0.14 t_{\text{peak}}$, showing that GRB051117A exhibits similar behavior.

Figure 4 [Figure 4: see original paper] shows the correlations between width and rise/decay times. The best-fit relations for GRB051117A are $w = 10^{-0.17\pm0.31} t_{\text{rise}}^{0.83\pm0.15}$ (Spearman coefficient 0.79, $p = 9.8 \times 10^{-3}$) and $w = 10^{-0.39\pm0.15} t_{\text{decay}}^{1.1\pm0.07}$ (Spearman coefficient 0.98, $p \sim 0$). Width shows a very strong correlation with rise time, similar to relationships found in prompt emission pulses—for example, Kocevski et al. [**?**] (2003) showed a strong positive correlation between pulse rise time and pulse half-width in their Figure 10. We find that similar correlations between width and rise/decay times exist across flares between GRBs, flares within GRBs, and prompt emission pulses.

Figure 5 [Figure 5: see original paper] shows scatter plots of characteristic parameters (t_{peak}, w, t_{rise}, t_{decay}) versus asymmetry k, where larger k indicates greater asymmetry. No correlations are found between asymmetry and other characteristic parameters in prompt emission pulses, inter-GRB flares, or intra-GRB flares, suggesting that asymmetry appears to be independent of other parameters.

4. Summary and Discussion

We analyzed the spectral lag properties of the multi-flare GRB051117A using the DCF method. We find that within GRB051117A, spectral lag magnitude is positively correlated with flare peak time, showing an overall increasing trend over time. The primary factor affecting spectral lag magnitude in GRB051117A is flare width—wider flares have larger spectral lags. This supports the conclusion of Margutti et al. [?] that flares evolve over time, becoming wider with larger spectral lags as time progresses.

Norris et al. (2005) [?] showed in their Figure 4 that prompt emission pulses also exhibit positive correlations between spectral lag and pulse width, as well as between width and pulse peak time. In prompt emission pulses, pulse width and spectral lag also increase over time. Our Figure 2 further demonstrates that pulses and flares share similar correlations between lag and characteristic parameters, providing support for the hypothesis that prompt emission pulses and X-ray afterglow flares may have similar production mechanisms.

However, we find that although X-ray flares have larger widths, rise times, and decay times than the pulses from N05, their spectral lags are not significantly different. Two possible reasons may explain this: (1) Sample selection effects—the N05 sample consists of large-lag pulses with average lags greater than 1-2 s, while the flares in GRB051117A are relatively narrow with small spectral lags; (2) Different energy channel selections—the energy channels used to calculate X-ray flare spectral lags are adjacent (0.3-1.5 keV and 1.5-10 keV), whereas those for prompt emission pulses are not adjacent. Typically, spectral lags calculated from adjacent energy channels are smaller. However, as shown in Figure 2, even when including GRBs with small lags, prompt emission pulses are not simply an extension of X-ray flares, suggesting that X-ray flares in GRB051117A and large-lag pulses may be produced under different physical conditions—though this could also be due to sample selection effects, requiring larger samples for more in-depth future studies.

In GRB051117A, spectral lag is positively correlated with both flare rise time and decay time, with both parameters jointly influencing lag magnitude. These results are similar to Figure 7 in Margutti et al. [?]. The positive correlation between flare rise time and decay time in GRB051117A, with $t_{\rm decay} \sim 1.9 t_{\rm rise}$, is consistent with the results from Chincarini et al. [?] based on 113 flares. Through our investigation of the relationship between spectral lag and flare characteristic parameters in GRB051117A, we conclude that the correlations between spectral lag and flare parameters found across multiple GRBs also exist within individual multi-flare GRBs.

The various correlations between flare characteristic parameters within GRB051117A are highly similar to those found between different GRBs by Margutti et al. [?] and to those in prompt emission pulses, providing evidence that prompt emission pulses and X-ray afterglow flares may share the same physical origin.

The spectral lags we estimated for GRB051117A are smaller than those given by Margutti et al. [?] for nine flares in eight GRBs. While the correlations between spectral lag and width, peak time, rise time, and decay time are consistent, the slopes we obtain differ significantly from those in Figure 7 of Margutti et al. [?]. Possible reasons include: (1) Differences in sample processing signal-to-noise ratio and energy channel selection—our sample has a signal-to-noise ratio of 2.4, while Margutti et al. [?] used a ratio of 4, which would inevitably introduce biases in lag results. Our energy channels (0.3–1.5 keV and 1.5–10 keV) are adjacent, producing smaller spectral lags than the non-adjacent channels (0.3–1 keV and 2–3 keV) used by Margutti et al. [?]. (2) Different methods for calculating spectral lag—we used the DCF method, while Margutti et al. [?] used light curve fitting to compare differences in t_{peak}. While these two methods should produce similar lag magnitudes, for a multi-flare GRB like GRB051117A with extremely complex structure, the goodness-of-fit cannot be guaranteed when using the Norris model to fit flares, leading to inaccurate determination of t_{peak} and consequently inaccurate spectral lag calculations. Using DCF to calculate the integrated lag over the entire flare avoids this issue. However, because Swift XRT data are discrete, DCF can only estimate flare lags, with accuracy depending on the data quality. While fitting DCF curves with Gaussian models can remove noise interference, the stability of time binning in the light curve data is also crucial for DCF accuracy. For example, if the time binning is stable at ~2 s during the flare rise but suddenly increases to ~10 s during the decay, DCF lag estimates will be compromised. Selecting different methods for calculating spectral lags based on different samples ensures more rigorous and accurate lag studies.

Acknowledgments

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Note: Figure translations are in progress. See original paper for figures.