

# Detailed study of the GRB 190114C spectral lags in the energy range of 5 keV – 2 MeV

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**Abstract.** The spectral lags of gamma ray bursts are defined as the difference in the registration time of the same radiation pulse in different energy channels of the recording device. This parameter can characterize both the mechanism of radiation generation by the source and the physical conditions of radiation propagation from the source to the observer. In this paper, the dependence of the arrival time of photons on their energy for the gamma ray burst GRB 190114C is obtained from the data of the Gamma ray Burst Monitor (NaI detectors) of the Fermi Gamma ray Space Telescope. It is shown that this dependence is mainly due to the back edges of the light curve pulses. The spectral lags of the leading edges of the pulses are small and comparable in magnitude to the measurement errors. The observed anomaly in the energy range from 5 to 20 keV is probably related to the quasi-thermal radiation of the source.

## 1. Introduction

Spectral lags are one of the ways to describe changes in the energy spectra of gamma ray bursts over time. The spectral lags are considered positive if the higher-energy photons arrive earlier than the lower-energy photons, and negative if the sequence is reversed. You can specify several reasons for changing the energy spectra. There are also various ways to determine delays.

The standard model of particle physics assumes that the speed of light is a Lorentz-invariant quantity. However, many modern physical theories that lie outside the standard model suggest that there may be a Lorentz invariance violation (LIV) in the region of high energies, of the order of the Planck energy ( $\sim 1.22 \cdot 10^{19}$  GeV), i.e. the speed of light may depend on the energy of photons. In this case, if two photons with energies  $E_1$  and  $E_2$  are emitted simultaneously from the source, the arrival time delay  $\tau(E_1, E_2)$  for each such pair of values should be the same both for any elements of the time structure and for the entire light curve [1]. The study of the light curves of gamma ray bursts has been repeatedly used to estimate the parameters of such a model. An analysis of the results of several dozen studies on the search for LIV effects, conducted in [2, 3], showed that the totality of the results does not allow us to draw a definite conclusion about the presence of LIV in these data.

An alternative hypothesis about the influence of LIV is the natural assumption that the spectral lag is determined by the conditions of generation and propagation of radiation in the source region. This assumption is supported by the fact that the delay value correlates with the isotropic peak luminosity of the gamma ray bursts [4, 5]. The spectral lags depend on the evolution of the energy spectrum of the radiation source during the burst time [6, 7]. It is also noted that the spectral lag is related to the pulse width on the light curves of the gamma ray bursts [8]. This feature is used as a tool for classifying bursts into long and short ones [9, 10, 11]. In the paper [12], it was suggested that the



spectral lags of long gamma ray bursts are a consequence of the evolution of pulses, and not a property of GRB in general. This assumption was confirmed by analyzing the data from the «INTEGRAL» satellite in [13]. Obviously, the delay for a given pair of values  $E_1$  and  $E_2$  will not necessarily be the same for any elements of the time structure of the light curves.

Several methods are used to calculate the values of the spectral lags of light curves. The main difference between these methods is the choice of which elements of the time structure of the light curves to look for this time shift. You can monitor the position of the maxima of the strongest peaks [8, 14, 15]. However, not all gamma ray bursts have a pronounced impulse structure. In addition, the spectral lags of individual pulses of the same burst measured in this way may differ due to changes in the rate of evolution of the energy spectrum [7]. Most often, the method of constructing cross-correlation functions (CCF) is used to calculate the spectral lags of light curves for two energy channels [16]. The delay value is determined by fitting the CCF maximum with the Gaussian function. The value of the difference in the arrival time of photons in two different energy channels obtained in this way determines the delay averaged over the entire burst. In multi-channel observations, the energy channel with the lowest energy is usually chosen as a reference and the dependence of the photon arrival time on the energy is constructed. Note that the application of CCF could give accurate values of the time shift if the light curves in different energy channels had the same shape. Otherwise, we get an estimate of the time shift for the centroids of the light curves. To date, the reason for the appearance of spectral lags is not fully clear.

The burst GRB 190114C is one of the brightest bursts on record. The temporal structure of the light curve consists of powerful pulses, which creates favorable conditions for evaluating and studying the effect of spectral lags of radiation. It was previously noted that this impulse activity has a quasi-periodic character [17]. The purpose of this work is to determine which elements of the light curves are responsible for the appearance of spectral lags. To isolate the individual components of the light curves, the original data was filtered in both the frequency and time domains [18]. When studying the spectral lags of the light curves, the dependence of the arrival time of the photons on the energy was constructed. To estimate the magnitude of delays, the method of constructing CCF was used. To compensate for the asymmetry of the CCF, the fragment of the curve on which the approximation was performed was chosen to be asymmetric with respect to the maximum.

## 2. Experimental data and analysis technique

Data from the Fermi Gamma ray Space Telescope Gamma ray Burst Monitor were used to analyze the GRB 190114C gamma ray burst. Only the NaI scintillator data of the n7 and n8 detectors were analyzed. From the NASA's High Energy Astrophysics Science Archive Research Center server at: [https://heasarc.gsfc.nasa.gov/dbperl/W3Browse/w3table.pl?tablehead=name%3Dfermigbrst&Action=More + Options](https://heasarc.gsfc.nasa.gov/dbperl/W3Browse/w3table.pl?tablehead=name%3Dfermigbrst&Action=More+Options) TTE files were obtained with data on the measurement of the gamma ray flux of the GRB 190114C burst in 128 energy channels covering the energy range from 5 to 2000 keV. These data were recalculated in even series with a step of 64 ms and distributed over 16 energy channels, the parameters of which are shown in the table 1. The boundaries of these channels were chosen so that the average energy values of the channels were located approximately evenly on the logarithmic scale. To construct the spectral delays, the main episode of the GRB 190114C burst was selected, in which the radiation flux was observed in the entire energy range from 5 to 2000 keV, that is, in all 16 formed energy channels (figure 1). Due to the strong overlap of the pulses of the GRB 190114C light curves, it is very difficult to study the behavior of individual pulses. On the other hand, most works on the study of spectral delays provide data on calculations for the whole event. In order to compare our results with most of the previously obtained similar results, we will follow this method in this article.

In the study of spectral lags by the method of constructing CCF, the channel with the lowest energy is usually used as a reference channel [19, 20 and 21]. However, this choice is not necessary, since any other energy channel can be used as a reference channel. If the light curves in different energy channels had the same shape and differed from each other only in amplitude and displacement along the time axis, then the function  $\tau(E)$  calculated relative to the second channel would differ from the

function calculated relative to the first channel by a constant value equal to the spectral delay between these channels. This statement will be true for any pair of reference channels. In real cases this principle of additivity is violated both because of the change in the signal shape from one energy channel to another, and because of the different contribution of the noise component. Therefore, the curves  $\tau(E)$  calculated when choosing different reference energy channels differ somewhat in shape.

For GRB 190114C, the dependence  $\tau(E)$  was calculated for each of the 16 reference channels. Since all the reference channels are equal, we calculated the average values of the function  $\tau(E)$ . When plotting the graphs, the channel, in which the photons arrive first, was chosen as the reference channel [22]. The arrival time of photons in all other channels will be positive values. The use of the above technique allows us to exclude random errors associated with any fluctuation in the reference channels and increases the signal-to-noise ratio at the stage of constructing the dependence  $\tau(E)$  and provides a visual comparison of different results. All the dependencies given later in this paper were obtained using this technique.

**Table 1.** The GRB 190114C gamma burst spectral lags in the energy range 5 - 2000 keV.

Channel No.	Energy (keV)			Spectral lags (ms)		
	$E_{\min}$	$E_{\max}$	$E_{\text{mean}}$	$\tau$	$\tau_{\text{rise}}$	$\tau_{\text{decline}}$
1	4.64	7.83	6.03	$120.1 \pm 7.8$	$40 \pm 10$	$126 \pm 23$
2	7.83	19.4	12.3	$212 \pm 10$	$-7.8 \pm 6.5$	$291 \pm 19$
3	19.4	32.0	24.9	$170.7 \pm 5.3$	$59.0 \pm 4.1$	$251 \pm 9.3$
4	32.0	42.0	36.7	$150.8 \pm 5.6$	$45.6 \pm 7.0$	$210 \pm 11$
5	42.0	56.6	48.8	$127.2 \pm 5.5$	$18.4 \pm 5.5$	$192 \pm 8.5$
6	56.6	76.6	65.9	$111.6 \pm 4.3$	$30.1 \pm 4.4$	$167 \pm 13$
7	76.6	99.1	87.2	$100.1 \pm 5.9$	$23.2 \pm 4.9$	$147 \pm 13$
8	99.1	127	112	$91.5 \pm 5.3$	$24.1 \pm 4.5$	$116 \pm 12$
9	127	169	146	$82.3 \pm 5.7$	$20.8 \pm 4.3$	$109 \pm 11$
10	169	236	200	$68.1 \pm 5.4$	$17.6 \pm 4.3$	$87 \pm 11$
11	236	332	280	$56.0 \pm 7.1$	$24.5 \pm 5.1$	$76 \pm 12$
12	332	443	383	$49.1 \pm 7.1$	$17.1 \pm 4.2$	$62 \pm 15$
13	443	572	503	$34.1 \pm 7.0$	$9.8 \pm 5.1$	$35 \pm 17$
14	572	746	653	$28.8 \pm 9.3$	$11.3 \pm 8.1$	$43 \pm 14$
15	746	970	850	$11.6 \pm 8.2$	$0 \pm 11$	$22 \pm 12$
16	970	2000	1393	$0 \pm 9.0$	$18 \pm 10$	$0 \pm 28$

### 3. Discussion

The result of calculating the photon arrival time  $\tau(E)$  for the initial light curves of the GRB 190114C burst is shown in the figure 2 and in the table 1. Here and further on, all values are given in the observer's rest frame. The dependence of  $\tau(E)$  in the energy range 25 - 2000 keV can be approximated by both a first order [20] and a second order ( $\tau = \tau_0 + A_1 \exp(-E/E_1) + A_2 \exp(-E/E_2)$ ) exponent [22]. However, in the first case, the correlation coefficients are lower (0.95 vs. 0.998). The inflection of the  $\tau(E)$  dependence in the low-energy region is observed in many gamma-ray bursts. In the article [13], this behavior is explained by the difference in the properties of individual pulses in a multi-pulse event. In the work [22], it was assumed that this feature arises due to additional quasi-thermal emission. The results of the study of the energy spectrum of GRB 190114C [23] showed that such a component of radiation is actually present in the energy spectrum of this burst.

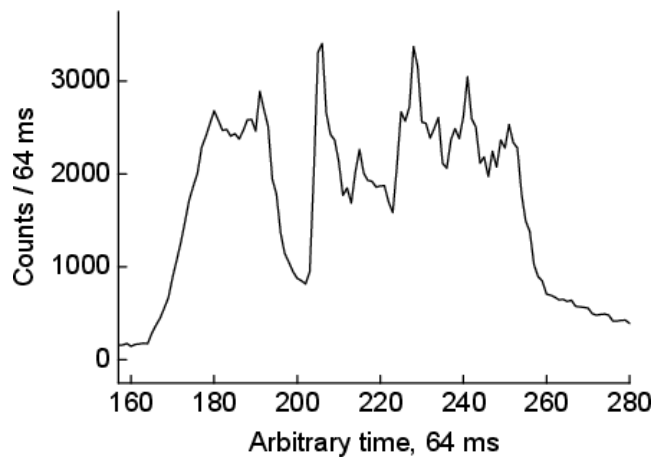
In the work [17], it was shown that the light curves of the GRB 190114C gamma ray burst have quasi-periodic oscillations with periods from 3.84 to 0.77 s. In order to understand how these

oscillations affect the appearance of the function  $\tau(E)$ , high-frequency Fourier filtering of the source data was performed using a rectangular filter in the frequency domain. The filter cut off frequency was selected to sequentially cut off periods longer than 2.3 s, 1.28 s, and 0.77 s. As a result of such filtering of the initial data, it turned out that fluctuations with periods of more than 1.28 seconds do not actually affect the values of the spectral lags. Significant changes in the value of the spectral lags occur after the removal of all frequencies less than one hertz from the spectrum. Figure 3 shows an example of the change in the spectral lag between energy channels with an average energy of 49 and 383 keV, depending on the filter cut off frequency.

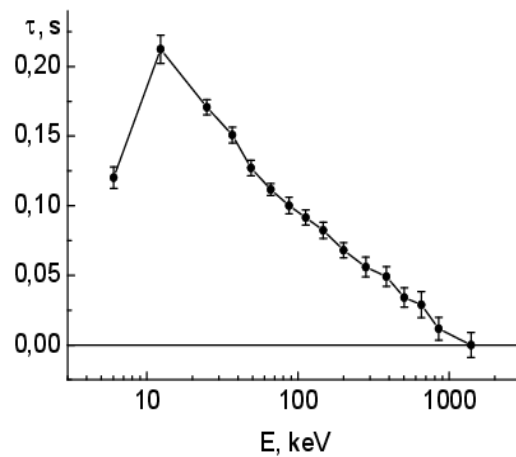
**Table 2.** Spectral lag exponential approximation of the initial curve (figure 2) and of the back pulse edges (figure 4 (b)).

Approximation parameter	Figure 2		Figure 4 (b)	
	First order	Second order	First order	Second order
$\tau_0$ , s	$0.025 \pm 0.005$	$-0.008 \pm 0.015$	$0.038 \pm 0.007$	$-0.075 \pm 0.031$
$A_1$ , s	$0.158 \pm 0.006$	$0.117 \pm 0.117$	$0.248 \pm 0.012$	$0.135 \pm 0.031$
$E_1$ , keV	$137 \pm 13.5$	$504.6 \pm 178$	$111.7 \pm 13.7$	$550 \pm 545$
$A_2$ , s	-	$0.153 \pm 0.027$	-	$0.218 \pm 0.034$
$E_2$ , keV	-	$31 \pm 8.7$	-	$46.1 \pm 16.5$
$R^2$	0.95	0.998	0.97	0.995
$\chi^2/\text{DoF}$	3.89	0.198	1.186	0.246

The period of one second is comparable to the duration of the main powerful pulses on the light curves of the GRB 190114C gamma ray burst. After processing the initial data with high-frequency filters, the pulses do not disappear, since the high-frequency component of the Fourier decomposition of the pulses themselves remains. Therefore the pulses become much narrower. Consequently, the spectral lags are mainly due to the shape of the powerful radiation pulses. Then the next question immediately arises – how does the shape of these pulses affect the value of the calculated values of the spectral lags?

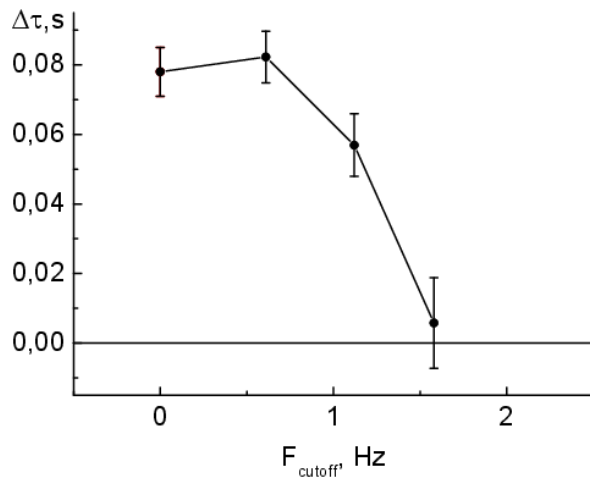


**Figure 1.** Main episode of GRB 190114C light curve within the energy range 5 - 2000 keV.

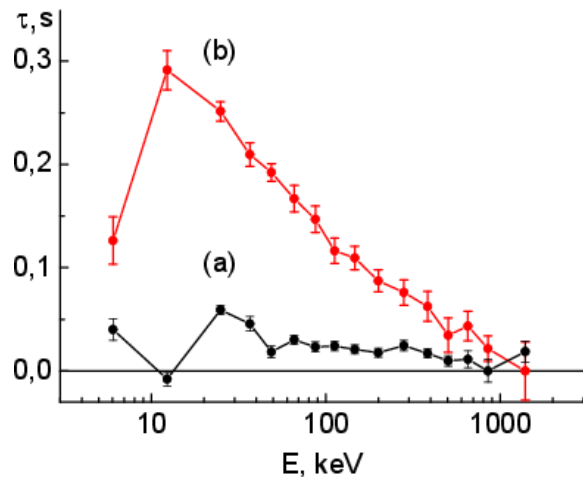


**Figure 2.** The spectral lags depending on quantum energy. The energy channel in which the photons arrived first is chosen as a reference.

To answer this question, the rise and decay stages of light curves were considered separately. These elements were distinguished by calculating the derivatives of the light curves. By putting negative values equal to zero the leading edges of the pulses can be distinguished, and by putting their positive values equal to zero, the stages of pulse decline can be distinguished. The arrival time curves plotted for the leading and trailing edges of GRB 190114C pulses selected in this way are shown in figure 4. Note that in this case, the values of the function  $\tau(E)$  correspond to real points on the light curves, namely, the inflection points.



**Figure 3.** The spectral lag of the filtered signal between the 5 and 12 channels depends on the cut off frequency of the rectangular filter.



**Figure 4.** The photon spectral lags depending on quantum energy for the leading (a) and the back (b) edges of pulses.

It follows from this figure that the leading edges of the pulses come almost simultaneously, and the photons in the quasi-thermal emission region are slightly ahead of all the others. The curve of the arrival time of the trailing edges of the pulses gives larger values than the similar curve for the original data (figure 2). Approximation of the dependence for the trailing edges of the pulses (figure 4b) in the energy range 25–2000 keV by a first order and second order exponents gives the following results: the correlation coefficients are 0.97 and 0.995, respectively. Hence, it can be assumed that the decay stages of the GRB 190114C pulses are controlled by two different physical processes.

#### 4. Conclusion

In the work [12], it was suggested that the spectral lags of long gamma ray bursts are a consequence of the evolution of pulses, and not a property of the entire GRB. Observations on an “INTEGRAL” satellite [13] have shown that there is a correlation between spectral lags and characteristic pulse decay times. This assumption for GRB 190114C was confirmed and clarified in this paper.

The spectral lags of the GRB 190114C burst are a consequence of the pulses evolution at the exponential decay stage. Highly likely that this stage of pulses in gamma ray bursts is controlled by two processes.

The spectral lags of the leading edges of the pulses are several times smaller. It can be assumed that this feature will be observed for all gamma-ray bursts with a pronounced pulsed structure of the light curve. This will allow us to study the possible effects of LIV with much greater accuracy.

The dependencies  $\tau(E)$  for all the constructed curves are not monotonic. The characteristic features in the region of the lowest energies can be explained either by the presence of an additional quasi-thermal component [21], or by the difference in the properties of individual pulses in a multi-pulse event [13]. This feature is reflected in the arrival time of photons both at the growth stage and at the pulses decay stage.

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