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Dynamics of quasi-periodic oscillations in the light curve of the GRB 190114C γ-ray burst

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Abstract. Based on the γ-ray Burst Monitor data of the Fermi space observatory, the light curve time structure of the γ-ray burst GRB 190114C in the energy range from 5 keV to 50 MeV was investigated. It was found that the temporal structure of the emission of this γ-ray burst contains quasi-periodic components with periods of 0.768 s, 1.28 s, 2.24 s, and 3.84 s, determined with an accuracy of up to ±0.064 s where the original data time bin is 0.064 s. We also analyzed the evolution of these quasi-period values during the background radiation intensity, which was recorded within 137 s before and within 354 s after the event. As a result, a systematic decrease with time in the value of the quasi-period of 3.84 s was found, while the value of the quasi-period of 0.768 s at the same time gradually increases. A similar unambiguous result for the quasi-periods of 1.28 s and 2.24 s was not obtained. According to the above estimates, it should be noted that the γ-ray burst itself is located within the time interval when oscillations with quasi-periods of 2.24 s and 3.84 s are in a multiple ratio of ~3/5. Such coincidence can serve as an indication of the significant role of resonance phenomena in the process of formation and flow of a γ-ray burst.

Keywords: Gamma-Ray Bursts, GRB 190114C, quasi-periodic oscillations

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Динамика квазипериодических колебаний кривой блеска γ-всплеска GRB 190114C

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Аннотация. По данным прибора Gamma-ray Burst Monitor космической обсерватории «Fermi» была исследована временная структура световой кривой γ-всплеска GRB 190114C в энергетическом диапазоне от 5 кэВ до 50 МэВ. Было обнаружено, что во временной структуре излучения данного γ-всплеска присутствуют квазипериодические компоненты с периодами 0,768 с, 1,28 с, 2,24 с и 3,84 с. Также была проанализирована эволюция значений этих квазипериодов на протяжении «фоновой» части записи интенсивности излучения длительностью 137 с до и 354 с после события.

Ключевые слова: гамма-всплески, GRB 190114C, квазипериодические колебания

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Introduction

The question of whether γ-ray bursts are purely stochastic processes, or whether they contain quasi-periodic components, has long been discussed in the scientific literature. From time to time, papers appear in which results are presented on the presence of quasi-periodic oscillations in the structure of the light curves of γ-ray bursts. The periods of these oscillations are usually several seconds [1–7], and quasi-periodic oscillations are observed in a wide energy range from the γ-range up to the visible light one. A detailed review of such observations can be found in [8], where 1160 light curves of γ-ray bursts with duration of more than 3.2 s were analyzed, obtained during observations on the Swift spacecraft. Thanks to these observations, by means of the wavelet analysis method, 34 events with similar oscillations were detected, of which in 21 cases during the events the oscillation period did not change in time, in 10 cases the oscillation frequency increased, and in 3 cases it decreased with time. In 8 events, the simultaneous existence of 2 oscillations was noted, and in 3 events, the simultaneous existence of 3 oscillations, and in each of these events, the oscillation periods were related as integers.

In particular, the authors of [9] studied the light curve of the γ-ray burst GRB 190114C associated with the explosion of a Supernova [10] located at a cosmological distance z equal to 0.425 [11]. Based on the data obtained as a result of observations of this γ-ray burst with the Swift spacecraft, it was found that in the time structure of the light curve of the GRB 190114C exist with a reliability of more than 3σ the quasi-periodic components with periods of 2.24 s and 3.84 s and with a lower confidence value 2σ the quasi-harmonic components with periods of 1.28 s and 0.768 s. The periods of the first two components are related as ~ 3/5 or 7/12, and the two second oscillations can probably be considered as the third harmonics of the first two. A discussion of possible mechanisms for the appearance of quasi-periodic oscillations in the structure of the light curves of γ-ray bursts can be found in [10, 12]. In order to determine which process is responsible for oscillations, it is necessary to know whether they appear during the development of the burst, or whether oscillations that previously existed in the radiation source amplify during the burst. Therefore, in this work, we continued the study of the temporal structure of the GRB 190114C in order to study the behavior of the quasi-harmonic components with time, which were previously identified based on the Swift data [9], but with the involvement of data from a wider energy range obtained by the Fermi spacecraft. To do this, the behavior of the quasi-harmonic oscillations detected during the burst was investigated in the background parts of the radiation intensity record before and after the event.

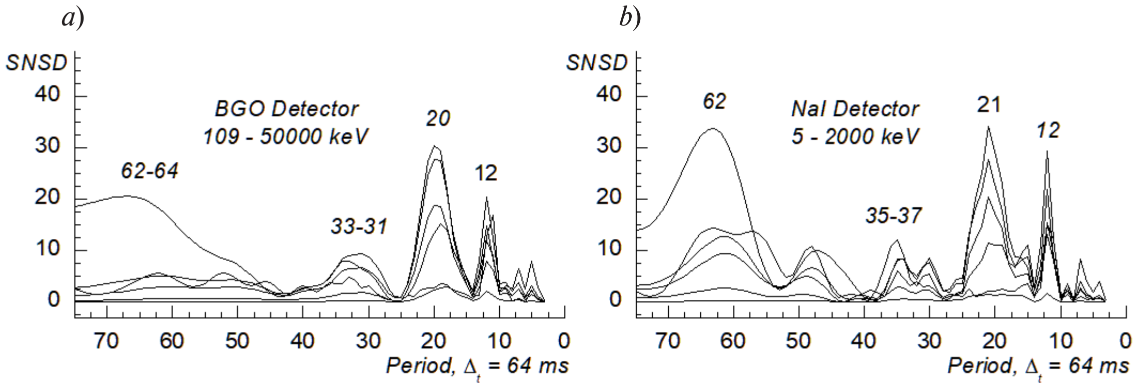

Fig. 1. CSP of the main stage of the GRB 190114C light curve and of light curve high-frequency components with different cutoff parameters (T_f = 7, 17, 29, 37, and 57 Δ_t = 64 ms) for the BGO (*a*) and the NaI (*b*) detectors

Experimental data and analysis technique

To study the dynamics of quasi-periodic oscillations, data from the Gamma-ray Burst Monitor (GMB) located on board the Fermi space Observatory were used, which are available on the NASA High Energy Astrophysics Science Archive Research Center server [13]. Data from detectors based on NaI crystals (detectors n7 and n8, energy range from 5 to 2000 keV) and BGO crystals (detectors b0 and b1, energy range from 109 keV to 50 MeV) were analyzed. The data files of γ-ray quantum streams of each detector, recorded in the TTE format, were recalculated into even time series in 64 ms increments. Such a time step was chosen according to the sampling value of the time series used to process Swift telescope data [9]. Further, for the convenience of presentation and graphical representation of the source data and the results obtained, the time scale will be displayed, and the time itself will be counted, in units of sampling of the source data: Δ_t = 64 ms (or 1 bin). Thus, the length of each time series was 8064 Δ_t or 8064 bins (516.096 s). Fig. 2,*a* and 2,*f* shows graphs of γ-ray quantum fluxes (counts/0.064 s) recorded by detectors based on BGO and NaI crystals within their respective integral energy ranges on the time scale described above. To increase the signal-to-noise ratio, data from two NaI detectors were summed into one row. Similarly, data from two BGO detectors were combined. Further, the records of the time series of observations were divided into two background sections: 2144 bins before and 5522 bins after the burst; and the burst itself, 398 bins long. Then, the section before the burst was divided into seven identical segments with a duration of 536 bins so that each subsequent segment half overlapped the previous one. The section after the burst was divided into nine with duration of 1110 bins in the same way. The power spectrum for each section was calculated separately. For this purpose, the method of constructing a combined spectral periodogram (CSP) was used, which is a modification of the classical spectral analysis method.

A modification of the traditional method of spectral analysis was as follows. A sample normalized spectral density (SNSD) (the Fourier transform of the autocorrelation function of the original signal [14]), of the initial time series was calculated depending on the trial period, which is caused by the formulation of the problem of revealing the hidden periodicity in the initial data [15]. In addition, the initial time series was subjected to preliminary high-frequency filtering [16] with a predetermined filter cut off frequency at half the signal power, which corresponds to the "separation" period T_f in the time domain. The initial data is filtered to eliminate the trend and more powerful low-frequency components from them. Then, for each high-frequency component T_f filtered with its specific value of the parameter T_f, the normalized spectral density estimate from the period was again calculated, and all these estimates calculated for different values of the T_f parameter were superimposed on each other on the same field of the graph, forming combined spectral periodogram (CSP). More details about this method can be found in [10, 13].

To assess the statistical significance of the assumed oscillations, a model was constructed that includes 4 sinusoidal oscillations with periods 12, 20, 36, and 60 bins, As a result of calculating the model parameters, the amplitude and statistical significance of each component were estimated.

Data processing results

The burst flux CSP constructed for the NaI and BGO detector data are shown in Fig. 1. These results, up to the resolution of the CSP (±1 bin), confirm the conclusions made in [9] about the presence of quasi-periodic oscillations with the quasi-periods 12, 20, 35, and 60 bins in the GRB 190114C light curve time structure. The analysis of the periodograms of the background sections of the photon flux recordings was carried out as follows. Starting from the time interval corresponding to the γ-ray burst, the interval in which the periodogram was constructed shifted to the beginning of the analyzed series in increments of 268 bins or to the end of the analyzed data series in increments of 555 bins. Since the time intervals overlapped by half, the signal spectrum of each subsequent section contained elements of the spectrum of the previous section, and therefore, it was possible to trace the evolution of each component of the periodogram. This procedure was repeated until the beginning or the end of the original row was reached. When analyzing the photon background fluxes, it was assumed that the values of the quasi-periods of the existing oscillations would remain unchanged, or would change insignificantly and rather slowly [8]. Therefore, the value corresponding to the peak that was closest to one of the values of the quasi-periods: 12, 20, 35, and 60 bins was chosen from the CSP values of the background data sections. The results obtained are presented in Fig. 2. It was assumed that the quasi-oscillation periods do not depend on the photon energy and therefore the data from the NaI and BGO detectors are plotted on the same field of the graph. It should be noted that in these graphs, only one point on the time axis corresponds to the length of the 398-bin γ-burst stage.

This method of revealing hidden periodicities in the treatment time series makes it possible to determine the values of the periods of quasi-oscillations only with an accuracy of ±1 bin, and the presence of the cosmic radiation noise component increases the error in estimating these values. Therefore, in order to find out the trend in the behavior of changes in the values of each of the four quasi-periods identified during the burst over the background sections of the light curve before and after the event, the values of the quasi-oscillation periods calculated by the method described above (Fig. 2) were approximated by a linear dependence: $P = A + Bt$, where P are the values of the quasi-periods, t is the time. The results of this linear fit are shown in the table, from which one can notice a systematic decrease with time in the period of the 60 bins oscillation, while the 12 bins oscillation tends to increase in period values. A similar unambiguous result for oscillations with periods of 35 bins and 20 bins was not obtained. It should be noted that the γ-ray burst itself is located inside the time interval when, according to the estimates, fluctuations with quasi-periods 35 bins and 60 bins are in a multiple ratio of 3/5.

To estimate the amplitudes, initial phases and their standards (assuming their normal distribution) of oscillations, a model consisting of 4 sinusoidal oscillations with periods of 12, 20, 36, and 60 bins was constructed. The amplitude, initial phase and standards of each component were estimated as a result of calculating the parameters of the model under consideration. As a result of such processing the following very unexpected result was revealed. Before the γ-ray burst, there is an increase in the amplitudes (and, accordingly, their standards) of the oscillations characteristic of the main stage of the burst. At the same time, the average value of the background component remained almost unchanged. This is especially noticeable for fluctuations with a period of 12 and 20 bins. During the burst, the amplitude of the first harmonic of the analyzed oscillations increases by more than 2 orders of magnitude. After the main stage of the burst, the amplitude of the oscillations decreases sharply. Then there is a long process of a slow fall in the amplitudes of these oscillations. As noted in [17, 18] in this time interval the energy flux of γ-radiation decreases according to a power law with an exponent of about 1, which is typical for GRB afterglows. At the end of the time series (5000–8064 bins), the analyzed oscillations do not stand out among other noise components of the signal.

At the point of ~6200 bins, an eclipse of the GRB 190114C radiation source occurs by the Earth [17]. At the same time at a time interval of 5000 – 8064 bins we do not see significant changes in the signal spectrum. It should be noted that at the moment of the beginning of the eclipse the average value of the photon flux recorded by the GBM device does not change either.

Table

Parameters of linear approximation of oscillation periods versus the time: $P = A + Bt$

P, Δ_t	Energy range			
	5 – 50000 keV		109 – 2000 keV	
	A, Δ_t	$B*10^4$	A, Δ_t	$B*10^4$
12	11.96 ± 0.33	0.91 ± 0.78	11.79 ± 0.30	0.27 ± 0.73
20	21.11 ± 0.65	-1.27 ± 1.59	19.50 ± 0.46	1.11 ± 1.12
35	36.10 ± 0.65	-2.13 ± 1.59	34.53 ± 0.74	2.86 ± 1.81
60	60.18 ± 0.88	-3.82 ± 2.13	61.35 ± 1.08	-4.44 ± 2.57
Position of the resonance point 3/5	380 Δ_t		4116 Δ_t	

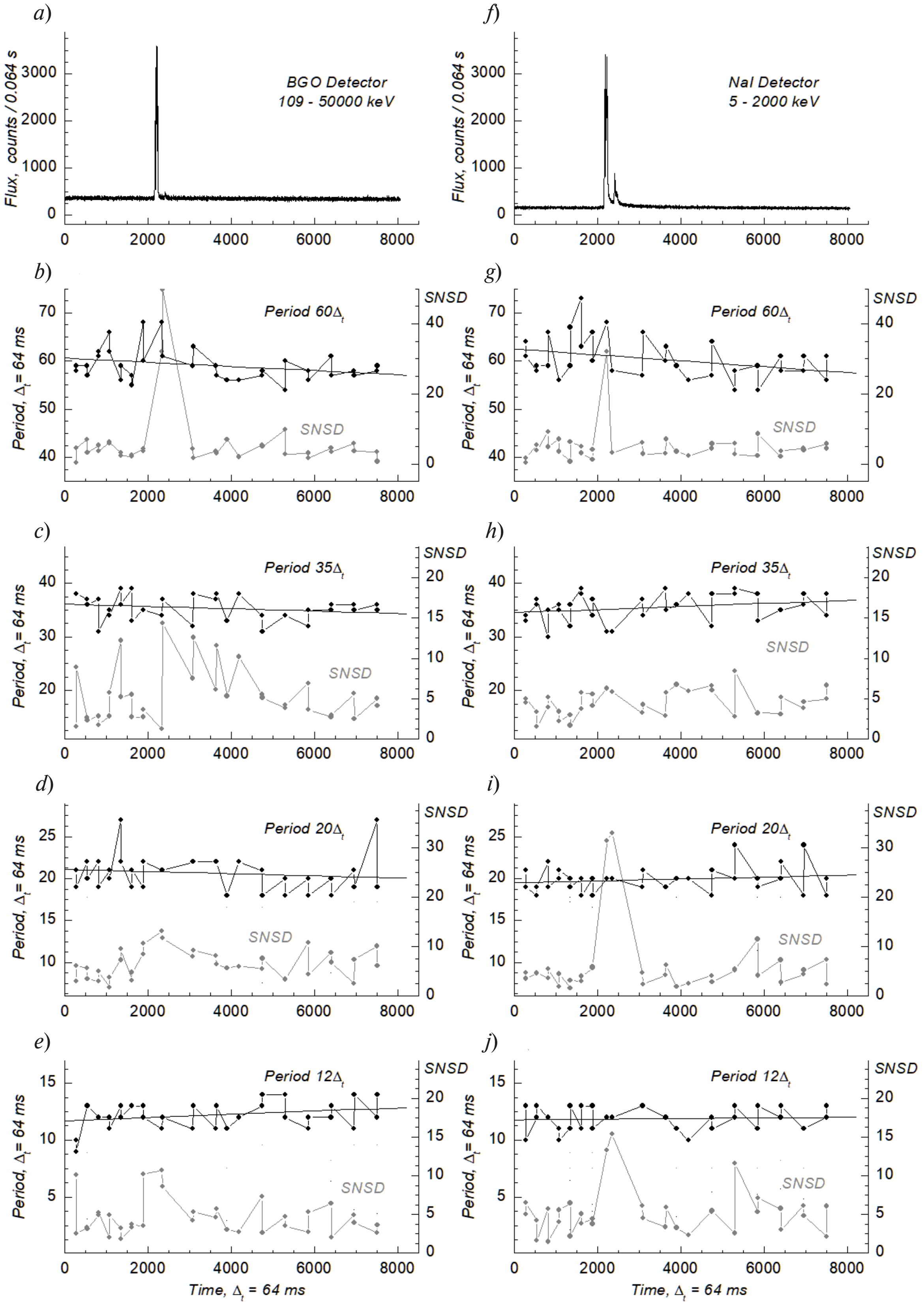

Fig. 2. Change of the oscillation period value and corresponding SNSD value over time for periods: 60 bins (*b*, *g*); 35 bins (*c*, *h*); 20 bins (*d*, *i*), and12 bins (*e*, *j*). The curves on the graphs (*b*–*e*) correspond to the energy range 5–50000 keV, and on the graphs (*g*–*j*) to the energy range 109–2000 keV

Based on the above observations, we can propose the following scenario for the formation of a γ-ray burst GRB 190114C. After a supernova explosion, an accretion disk and jet form around the collapsing core. The oscillation periods of this disk change over time. When the resonance of the oscillations occurs, the amplitude of the oscillations increases significantly, this leads to a significant increase in the flow of matter to the collapsing core. Jet parameters change and conditions arise for generating a γ-ray burst. Such a scenario makes it possible to explain the presence of quasi-periodic fluctuations before the trigger time and after the burst. In this case, the temporal structure of the γ-ray emission reflects the dynamics of the space-time structure of the accretion disk.

Conclusion

As a result of this work, it has been established that the oscillatory processes detected on the GRB 190114C light curve also occur in the background areas of this event recordings by the GBM monitor of the Fermi spacecraft. It was hypothesized that the γ-ray burst of GRB 190114C arose due to the resonance of oscillations in the accretion disk around the collapsing Supernova core.

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