# Investigation of the dynamics of the oscillations of the light curve of the $\gamma$-burst GRB 240825A

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As a result of studying the temporal structure of the light curve of the GRB 240825A $\gamma$-ray burst, recorded by Swift satellite equipment in the energy range of 15−350 keV, for the presence of quasi-periodic components, oscillations with periods of 0.384, 0.768, 1.224 and 1.536 s were detected. Moreover the oscillation with a period of 1.536 s turned out to be modulated with the same period. Assuming that the modulation is caused by the relativistic Doppler effect during the orbital motion of the emitting object around a more massive central body, the orbital parameters of the emitting object and the mass of the central body were calculated in the classical approximation.

**Keywords:** periodogramanalysis, quasiperiodicities, model - amplitude-frequency modulation.

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The search for quasi-periodic signals is one of the directions of studying the temporal structure of $\gamma$-ray bursts. This task is complicated by the fact that $\gamma$-ray bursts are short-lived and last from a few milliseconds to several hundred seconds. Thus, a systematic analysis of the light curves of 2203 bursts recorded in the BATSE (Burst and Transient Sources Experiment) experiment from 1991 to 2000 [1] did not reveal events with quasi-periodic oscillations characteristic of neutron stars, but quasi-periodic oscillations were nevertheless detected in case of some $\gamma$-bursts in the recorded fluxes of their radiation with varying degrees of reliability. The periods of such oscillations for long $\gamma$-bursts ($> 2$ s) are usually several seconds. A detailed review of more recent observations of $\gamma$-bursts (from 2004 to 2015) can be found in Ref. [2], where 1160 light curves of long $\gamma$-bursts observed by the Swift Space Observatory are analyzed. In this work, the wavelet analysis method revealed 34 events with one, two, and even three quasi-periodic oscillations. The temporal structure of the light curve of $\gamma$-burst GRB 190114C attributed to the supernova explosion [3] was studied in Ref. [4,5], and two quasi-periodic components with time-varying periods were detected. An oscillation with a period of $\sim 0.05$ s was also detected in the precursor of the long $\gamma$-burst GRB 211211A, the cause of which was explained in Ref. [6] by the possible existence of a „black hole“ or „magnetar“. Consequently, the study of $\gamma$-bursts from the point of view of the presence of quasi-periodic components in their radiation structure is currently of urgent importance in the theory of stellar evolution and, especially, „close binary systems“. Therefore, in this paper, we have attempted to study the light curve of $\gamma$-ray burst GRB 240825A for the presence of quasi-periodic components in its temporal structure.

The burst GRB 240825A was detected by the BAT telescope (Burst Alert Telescope) installed on the Swift spacecraft on August 25, 2024 at $15^{\text{h}}\,52^{\text{m}}\,59^{\text{s}}$ UTC [7], and the redshift of the source was estimated as $Z = 0.659$ [8]. The duration of the event was 57.2 s, while its explosive phase, consisting of a series of consecutive peaks, had a duration of only about 10 s [9]. To analyze the temporal structure of the light curve of the studied $\gamma$-ray burst in the electronic archive [10], data obtained by the BAT telescope in the energy range of 15−350 keV with temporal resolution of $\Delta_t = 0.064$ s were taken which were processed for the presence of quasi-harmonic components using a technique specially developed for such studies. The method is based on the construction of a Combined Spectral Periodogram (CSP), the meaning of which is as follows. The main element of the CSP is the Normalized Spectral Density (NSD) [11], calculated for a time series depending not on frequency, but on the trial period. Besides, the initial time series is exposed to the preliminary high-frequency filtering [12] with the pre-set „cut-off“ frequency at the half of the signal power that in the time region is compliant with the value of the „separating“ period $T_f$. The input data are filtered to remove the trend and more powerful low-frequency components. Then for each parameter $T_f$ of the high frequency component filtered with its specific value, the NSD of the period is again calculated, and all these estimates calculated for the various values of parameter $T_f$ are imposed one onto another in the same field of the curve to form a CSP. The method is described in more detail in Ref. [13]. The total length of the processed sampled $\gamma$-ray burst from the archived data was 82.4 s ($1288\Delta_t$): 35 s ($547\Delta_t$) before the burst, 14.08 s ($220\Delta_t$) during the intense part of the burst and 33.34 s ($521\Delta_t$) after its active phase.

Here it is necessary to explain the structure of the time axis, which describes the results obtained, and its relation to real time. Instrument data for specific $\gamma$-bursts are archived at discrete points in the elapsed time of the Swift mission in seconds with a time step of $\Delta_t = 0.064$ s. During further data processing, these time points are set by a natural series of numbers, which are counted from the moment the BAT telescope starts recording this $\gamma$-burst. Inside this data array, there is a mark for the start of recording the intense phase of the outbreak, which is indicated at the time in UTC. For GRB 240825A, this time point 14043 in the natural scale of the data archive falls on 2024.08.25 15:52:59.832 UTC.

Fig. 1, *a* shows the results of processing the light curve of the $\gamma$-ray burst over the entire sample of 82.4 s (Fig. 1, *b*), and Fig. 2, *a* — CSP built on its explosive phase with a length of 14.08 s (Fig. 2, *c*) for trial periods from 3 to 43$\Delta_t$ (0.192–2.752 s) in increments of $\Delta_t$. When the CSP was calculated, the values of the „separating“ period $T_f$ of the high-frequency filter were assumed as follows: $T_f$ = 5, 11, 17, 23, 31, 41, 47, 53$\Delta_t$. Therefore, each peak on CSP is „outlined “ by nine curves: eight from high-frequency components and one more curve from the original time series. „Peaks“ of quasi-periods 6, 12, 18, 23 and 24$\Delta_t$ are distinguished on the CSP (Fig. 2, *a*). The two fluctuations with the shortest periods are probably the second and fourth overtones of the oscillation with the period 24$\Delta_t$. To determine whether the identified periods are constant during the burst, a dynamic diagram of changes in their values was constructed (Fig. 1, *a*) throughout the entire data sample $\gamma$-burst lasting 1288$\Delta_t$ (Fig. 1, *b*), which are the NSD values calculated in the „sliding time window“ with a width of 143$\Delta_t$ (9.152 s) for trial periods from 3 to 43$\Delta_t$, and the time window shift it was performed with the same step as the discrete data step $\Delta_t$.

In this diagram (Fig. 1, *a*) and in more detail in its highlighted part for the explosive phase of the event (Fig. 2, *b*), the following oscillation feature with a period of 24$\Delta_t$ was found: the frequency of this oscillation during the explosive phase of the burst periodically varies with the same period as the period of the oscillation itself, and at least three cycles of such fluctuations are observed in Fig. 2, *b*. This effect is not an artifact that occurs due to a certain length of the „sliding window“, since when repeated similar calculations with other sizes of the „sliding window“: 91, 121 and 221$\Delta_t$ — the same result was obtained. Thus, it can be argued that an oscillation with a period of 24$\Delta_t$ is frequency-modulated (or phase-modulated). In this case, the reason for the similar radiation structure of the $\gamma$-ray burst may be the orbital rotation of a radiating object with the same period, for example, a bright spot of a relativistic accretion disk rotating around the central „body“. Then the Doppler effect is most likely the reason for this feature of radiation. To confirm or refute this assumption, we will calculate the radiation from a similarly moving object, for simplicity of presentation, within the framework of classical concepts. To minimize the number of free parameters, we will neglect the effects of general relativity, the possible inclination of the accretion disk to the line of sight, the size of the emitting object, etc. Then, as a result of this

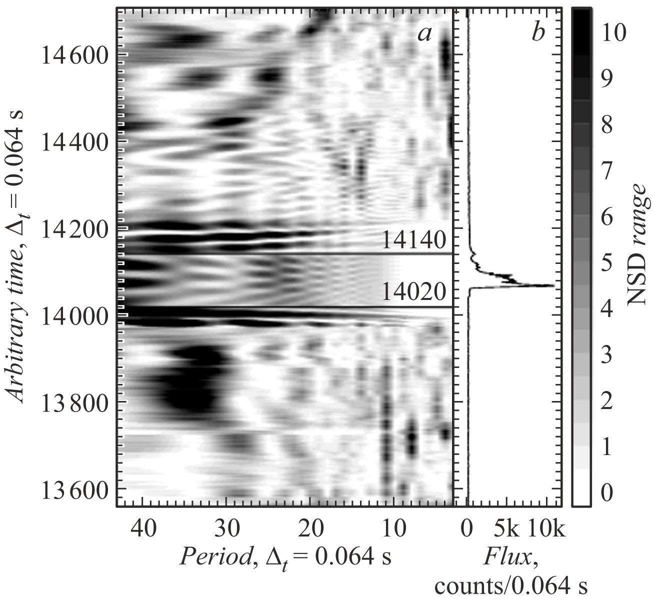


**Figure 1.** *a* — NSD, constructed from the values of the light curve of $\gamma$-burst GRB 240825A (*b*) over a time interval of 1288$\Delta_t$ in a sliding time window with a width of 143$\Delta_t$ for trial periods from 3 to 43$\Delta_t$. The discrete time scale along the ordinate axis is constructed with a step of $\Delta_t$ equal to 0.064 s, from the moment the BAT telescope starts recording the $\gamma$ data of the burst. The time point 14043 of this scale falls on 2024.08.25 15:52:59.832 UTC.

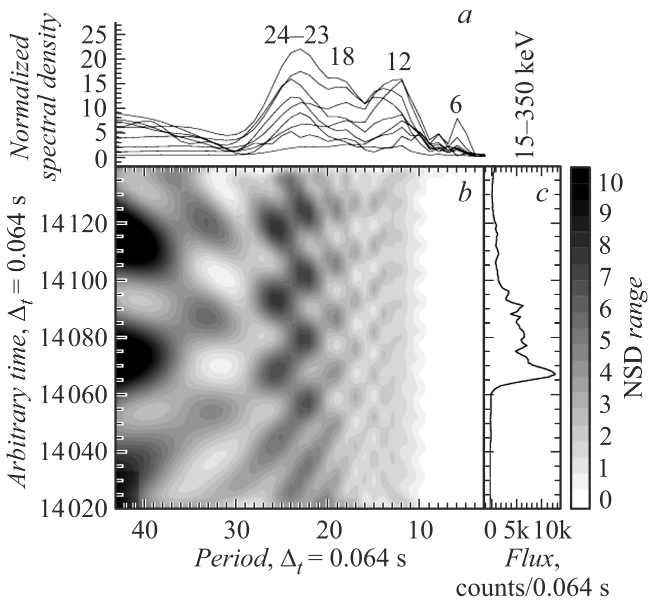


**Figure 2.** *a* — CSP plotted based on the data of the $\gamma$-ray burst over time interval 14036–14256$\Delta_t$ with the length of 221$\Delta_t$, for trial periods from 3 to 43$\Delta_t$; *b* — highlighted part of NSD (Fig. 1, *a*) providing a more detailed illustration of the explosive phase of the event (*c*).

simplification, there remains only one fitting parameter — the linear velocity of the orbital motion.

Let us consider the following simple model. Let a body rotate around a central object at a speed $V$ along a circle with a radius $R$, completing a complete revolution in a certain time $T$. The observer and the central object are stationary relative to each other, and the observer is in the plane of the orbit, and at some point in time the angle between the velocity vector and the direction of the observer is $\varphi$. Then the radius of the orbit will be $R = VT/(2\pi)$, and the mass of the central object will be $M = (\beta^3 c^3 T)/(2\pi G)$ where $\beta = V/c$, $c$ is the speed of light, and $G$ is the universal gravitation constant.

The results of calculating the radii of the orbits and masses of the central object using these formulas for the value of the quasi-period $24\Delta_t$ revealed in the time structure of the GRB 240825A light curve, depending on the value of the parameter $\beta$ are presented in the table, where $M_{sun}$ and $R_g$ is the mass of the Sun ($1.99 \cdot 10^{30}$ kg) and the Schwarzschild radius of an object with a mass $M$, respectively. Considering that the central object is located at the cosmological distance $Z = 0.659$ [8], we obtain the absolute upper limit ($\beta = 1$) of the mass of the central object $5.97 \cdot 10^{34}$ kg, i.e. 30 000 Solar masses. At $\beta > 0.7$, the central object can only be a Kerr black hole. Let us proceed as follows to get a more realistic value of the parameter $\beta$. For different $\beta$ values, we calculate the theoretical light curves as an observer would see them, and then compare the results with the observational data. At the same time, we will take into account the influence of the following additional factors on the received signal.

The Lorentz factor for a body at an arbitrary point in a circular orbit can be written as $\gamma = \sqrt{1-\beta^2}/(1-\beta\cos\varphi)$, and the energy spectrum of the $\gamma$-ray burst GRB 240825A in the energy range of 15–350 keV can be written as a power-law spectrum with the exponent $\alpha = 1.2$ ($dN/dE = KE^{-\alpha}$) based on the study in Ref. [12]. Then the number of photons detected by the receiver in the energy range of $[E_{\min}; E_{\max}]$ keV will be determined by the expression: $N_{obs} = K(E_{\max}^{1-\alpha} - E_{\min}^{1-\alpha})/(1-\alpha)$. In order for photons to be registered at the receiver, the source, taking into account the Lorentz factor, must emit in the energy range of $[15\gamma;\ 350\gamma]$ keV. Then the number of photons emitted by the source in this energy range, provided that the spectrum is preserved, will be equal to: $N_{rad} = K\gamma^{1-\alpha}(E_{\max}^{1-\alpha} - E_{\min}^{1-\alpha})/(1-\alpha)$. Therefore, the coefficient $K$ in the expression for $N_{obs}$ should change proportionally to $\gamma^{\alpha-1}$ when the body moves in orbit, i.e. there should be an amplitude modulation of the light curve. Further, with relativistic circular motion, the radiation pattern is not isotropic. It is extended forward in the direction of the velocity vector. In the plane of the orbit, the dependence on the angle $\varphi$ for electrons is expressed by the formula: $P = q^2\beta^2/(4\pi c(1-\beta\cos\varphi)^3)$, where $q$ is the charge of the electron. Finally, we take into account the correction for the delay in the time of photon registration in the receiver, depending on the position of the emitting body in orbit: $\Delta t = \beta T \sin\varphi/(2\pi)$, which introduces frequency (or phase) modulation with an inversion period of $T$ into the temporal structure of the detected radiation. Taking into account this correction leads to the fact that instead of the calculated points equidistant from each other in time in the coordinate system of the central object, the points in the coordinate system of the receiver will be located at different distances, and the applied spectral analysis method requires equal time intervals between the points. Therefore, in order to obtain the calculated function values at evenly spaced points, the calculated function values were linearly interpolated.

The shape and amplitude of the model light curves constructed according to the above relations strongly depend on the parameter $\beta$. The light curve is similar to a sinusoid

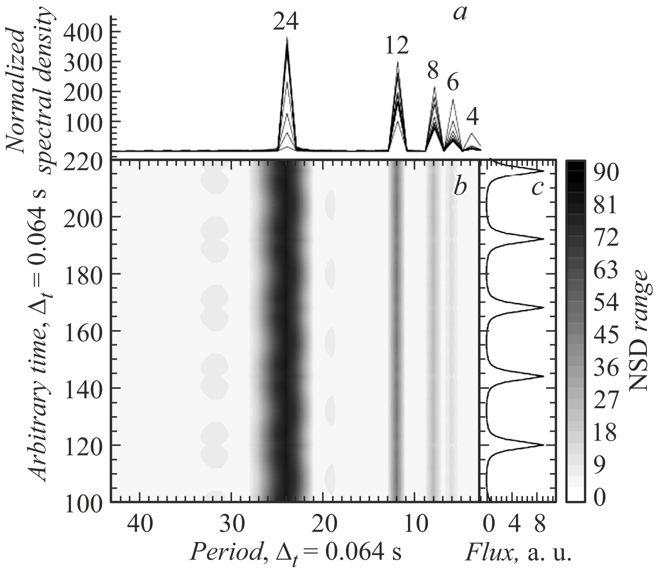


**Figure 3.** $a$ — CSP, $b$ — NSD, constructed for a stationary pulse signal ($c$) calculated using the proposed $\gamma$-ray burst model with the parameter $\beta = 0.5$, on a time domain of length and with a time step similar to Fig. 2.

Values of the parameters of the model of a radiating object located at a cosmological distance $Z = 0.659$, which rotates around a massive central body of mass $M$ in a circular orbit of radius $R$ with a constant velocity $V$ and fixed period $1.536/(1+Z)$ s

| $V/c$ | $M$, $10^{32}$ kg | $M/M_{sun}$ | $R$, $10^5$ m | $R_g$, $10^5$ m | $R/R_g$ | $\tau$,s |
|---|---|---|---|---|---|---|
| 0.05 | 0.0746 | 3.75 | 22.1 | 0.11 | 201 | 0.70 |
| 0.1 | 0.597 | 30 | 44.2 | 0.985 | 44.9 | 0.62 |
| 0.2 | 4.77 | 240 | 88.4 | 7.06 | 12.5 | 0.48 |
| 0.3 | 16.1 | 809 | 133 | 23.9 | 5.57 | 0.37 |
| 0.4 | 38.1 | 1915 | 177 | 56.5 | 3.13 | 0.27 |
| 0.5 | 74.6 | 3749 | 221 | 110 | 2.01 | 0.19 |
| 0.6 | 129 | 6482 | 265 | 197 | 1.35 | 0.13 |
| 0.7 | 206 | 10352 | 309 | 304 | 1.02 | 0.076 |
| 0.8 | 305 | 15327 | 354 | 451 | 0.785 | — |
| 0.9 | 435 | 21859 | 398 | 645 | 0.617 | — |
| 0.95 | 511 | 25678 | 420 | 757 | 0.555 | — |

at $\beta = 0.05$. Its pulses with the profile of the $\delta$-function are periodically repeated at $\beta = 0.95$. Therefore, to determine a more realistic value of $\beta$, a criterion such as the width of the pulse at half its height was used (the value of the parameter $\tau$, measured in seconds). For the pulses of the GRB 240825A light curve, the value of $\tau$ is $(3 \pm 0.5)\Delta_t$. Hence, the range of values of $\beta$ $0.46 - 0.55$ was determined based on the calculated dependence of $\tau$ on $\beta$, and the mass of the central object $M = (2.8{-}5) \cdot 10^3 M_{sun}$ and the radius of the orbit $R = (2.37{-}1.66)\ R_g$ were obtained from the values given in the table. Fig. 3 shows the CSP (Fig. 3, $a$) and the dynamic NSD diagram (Fig. 3, $b$) for the pulse sequence modeled with the parameter value $\beta = 0.5$ (Fig. 3, $c$). It can be seen from this figure that the spectral characteristics of such a simplified model satisfactorily reflect the dynamics of real oscillations with a period of $24\Delta_t$ during the explosive phase of the $\gamma$-ray burst.

So, summing up this study, it is possible to highlight the following main points. A quasi-periodic oscillation with a period of 1.536 s was detected by the method of modified spectral analysis at the „explosive“ phase of the $\gamma$-ray burst GRB 240825A. To explain the cause of such pulsations, it was hypothesized that it could be radiation from a bright spot in the accretion disk. Therefore, the simplest case was considered: what can an observer see when the observer's „viewpoint“ lies in the plane of the accretion disk. When constructing the mathematical model, the relativistic Doppler effect, the amplitude and frequency (or phase) modulation of the signal due to the motion of the bright spot in orbit, and the radiation pattern were taken into account. By comparing the parameters of the pulses on the light curve and the radiation pulses of the model obtained as a result of calculations, the possible values of the emitter orbit and the mass of the central object were estimated. This object should be a black hole with a mass in the range of 2800–5000 solar masses and, therefore, it should belong to the class of „hypothetical“ black holes with intermediate mass.

### Conflict of interest

The authors declare that they have no conflict of interest.

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