Quasi-periodic oscillation of the $\gamma$-ray burst GRB 190114C

V A Dranevich and P B Dmitriyev
Ioffe Institute, 26 Politekhnicheskaya, St. Petersburg, 194021, Russia
E-mail: v.dranevich@mail.ioffe.ru

Abstract. The data obtained by the BAT $\gamma$-ray telescope on board the SWIFT satellite in the energy range of 15-350 keV with a time resolution of 64 ms were used to study the temporal structure of the $\gamma$-ray burst GRB 190114C emission by means a modified spectral analysis technique. The analysis revealed quasi-periodic fluctuations with main periods of 3.84 s and 2.24 s. Both oscillations start simultaneously, continue throughout of the burst, and are equally modulated. Based on this evidence, it can be argued that all three episodes of the burst were controlled by one “central engine”.

1. Introduction

The $\gamma$-ray burst GRB190114C is one of the brightest $\gamma$-ray bursts detected to date. This event is interesting in that photons were recorded in the energy range from units of keV to hundreds of GeV [1]. Later the detection of photons with energy of several TeV was reported [2]. The evolution of the burst energy spectra from prompt to the afterglow, as well as possible radiation mechanisms, were discussed in many papers, see for example [3]. Based on such analysis of the burst, Ruffini et al. [4] proposed a scenario according to which the source of the burst was a binary system located at a distance corresponding to the redshift $z = 0.425$ [5] and consisting of a massive star with carbon-oxygen nucleus and neutron star. In the explosion of a massive star, like a supernova, hyper accretion of the material of its shell on a neutron star caused the collapse of the latter with the formation of a black hole. A supernova explosion was later recorded [6].

No less informative is the analysis of the dynamics of light curves of $\gamma$-ray bursts in the time and frequency domains. So, it was shown [7, 8] that the averaged power spectrum of light curves of long $\gamma$-ray bursts up to a frequency of 1 Hz obeys a power law with an exponent of -5/3. Since this slope value coincides with the Kolmogorov spectrum of velocity fluctuations in a turbulent medium, it was concluded that the radiation region is concentrated in a completely turbulent relativistic jet. At higher frequencies, the average exponent becomes -2.15, which may indicate a violation of the Kolmogorov distribution at these time scales [9]. On the other hand, the shape of the spectrum and the magnitude of the exponent can be determined by the shape of the dominant pulses [10, 11].

The second area of research into the temporal structure of $\gamma$-ray bursts is the search for quasiperiodic signals. This task is complicated by the fact that $\gamma$-ray bursts have a finite duration. In addition, the stochastic component is of great importance. A systematic analysis of light curves for 2203 bursts recorded in the BATSE experiment, carried out in [12], did not reveal events with quasiperiodic oscillations in the frequency range 400 - 2500 Hz typical of neutron stars. However, in the light curves of some $\gamma$-ray bursts, quasiperiodic oscillations were detected with varying degrees of confidence in the subhertz frequency range. In the light curve of the $\gamma$-ray burst GRB 771029 the
period of 4.2 s was detected [13] and for the light curve of GRB 790113 was detected the period 5.7 s [14]. Using a Fourier analysis the period of 5.9 s was detected in a powerful burst of GRB 830801 [15]. The oscillation with a period of 2.2 s was detected in GRB 840805 [16] and one was detected with a period of 9 s in a GRB 060614 light curve [17]. Quasiperiodic oscillations with period of 13.8 s for GRB 970110 [18] and 6.4 s for GRB 930905 [19] were detected also in the background after the short γ-ray bursts. Separately it is worth mentioning the detection of quasiperiodic oscillations with a period of 7.2 min for a burst of GRB 050922C [20] and with a period of 8.7 s for GRB 080319B [21] in the optical range. Here and further all values are given in the observer’s rest frame. Despite the numerous data obtained to date little attention has been paid to studies of the temporal structure (frequency spectra) of γ-ray bursts.

Ruffini et al. [22] suggested that each stage of the developed scenario corresponds to its own episode of the γ-ray burst light curve. Episode (1) is the beginning of a supernova explosion, episode (2) is the formation of a black hole from a neutron star, and episode (3) is radiation when the cavity which is carved out of the supernova ejecta by neutron star collapses (Figure 1). If so, then each episode may have its own characteristics in the time and frequency domains. Therefore, the study of the structure of the light curve of the unique event GRB 190114C is of particular relevance.

2. Experimental data and analysis technique

For the analysis of the GRB 190114C light curve, data from the Swift spacecraft were used. The γ-ray telescope BAT aboard the Swift satellite detects radiation with γ-ray energies from 15 to 350 keV. The measurement series with a temporal resolution of 64 ms over four energy channels (15-25, 25-50, 50-100 and 100-350 keV) are stored in the archive at https://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/2019_01/00883832000/bat/rate/sw00883832000brtms.lc.gz. The recording includes 640 s of the background before the burst, the burst itself 361.5 s, and lasts up to 2100.8 s. The main portion of the GRB 190114C light curves in these energy ranges is shown in Figure 1.

To study the light curve of GRB 190114C, a modified spectral analysis method was used. 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 [23]), 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 [24]. In addition, the initial time series was subjected to preliminary high-frequency filtering [25] 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 parameter $T_f$ were superimposed on each other on the same field of the graph, forming combined spectral periodogram (CSP).

To filter the light curves of γ-ray bursts, a high-pass filter with modified Blackman – Tukey weights was used [25]. The values of the separation period were: $T_f = 7, 17, 29, 37, 59, 63, 97$ and 127 bins, where one bin is the temporal resolution of the light curves (0.064 s). These values of the parameter $T_f$ were used to process the data of all energy channels. The modification of the generally accepted method of spectral analysis described above allows us to investigate the stability of the position of the detected period on the periodogram, since the filtration changes the length of the filtered component, compared to the length of the initial series, and it is different for different values of the parameter $T_f$. In addition, this modification makes it possible to detect shorter periods with small amplitudes in the original signal. This is due to the elimination of the trend from the original signal and more powerful long-period components that make the main contribution to the signal dispersion. Therefore, only weak short-period components contribute to the dispersion of the filtered high-frequency component of the signal and due to normalization of the spectral power, the contribution from these components to the combined periodogram becomes comparable with the contribution from longer and more powerful signal components. Then, the values of the amplitudes
and their standards of the signal polyharmonic model are estimated, which consists of a finite number of harmonics with the values of the revealed quasi-periods [24]. Based on the ratio of the values of the harmonic amplitudes and their standards, the probability of the existence of harmonics in the original signal is determined in accordance with the normal distribution. A more detailed description of the method can be found in [26]. The results of calculation for the four energy channels are shown in Figure 2.

**Figure 1.** Light curve of GRB 190114C on four energy channels: (a) – 15 – 25, (b) – 25 – 50, (c) – 50 – 100 and (d) – 100 – 350, keV.

**Figure 2.** The CSPs on four energy channels of GRB 190114C light curve: (a) – 15 – 25, (b) – 25 – 50, (c) – 50 – 100 and (d) – 100 – 350, keV.

The SNSD was also calculated in a sliding window. The window width was 211 bins (13.5 s), and the slip step was one bin (0.064 s). The calculation results for the four energy channels are shown in Figure 3 - Figure 6. The right panel (a) of each figure shows the light curve for the corresponding energy channel. On the top panel (b) is the SNSD of the entire event. The central panel (c) shows the change in the SNSD of the signal over time. The time is for the centre point of the sliding window. Note the rapid variation of the amplitudes of the harmonics.

3. Discussion

Many processes determine the light curve of γ-ray bursts. Dynamic processes in a plasma jet can produce different power spectra for different energy ranges of γ-ray bursts. We believe that the possible periodicity of processes in the internal engine will lead to relatively similar features in the signal power spectrum. The light curve of GRB 190114C consists of three episodes each of which has many local peaks. The time interval between the maxima of the first and last episode is 240 bins (15.36 s) and between the maxima of the first and second about 60 bins (3.84 s). These values are multiples of each other. Therefore, we can consider the light curve as consisting of a periodic process with a period of 60 bins, modulated by oscillation with a period of 240 bins. On the periodograms (Figure 2) a peak corresponding to a period of 60 bins is visible in all energy ranges. For amplitude modulation of a harmonic with a frequency $f_S$ harmonic with a frequency $f_M$ (where $f_S > f_M$) the amplitude-modulated oscillation is the sum of three sinusoidal oscillations with frequencies: $f_S$, $f_S + f_M$ и $f_S - f_M$. The frequency $f_S$ is the “carrier”, and the frequencies $f_{S1} = f_S + f_M$ and $f_{S2} = f_S - f_M$ are lateral.
In this case, for the values of the corresponding periods: \( T_M = f_M^{-1} \), \( T_S = f_S^{-1} \) and \( T_{SI} = f_{SI}^{-1} \), \( T_{S2} = f_{S2}^{-1} \) the following expressions will be valid: \( T_{SI} = T_SM(T_M - T_{SI})^{-1} \) and \( T_{S2} = T_SM(T_M + T_{SI})^{-1} \). At \( T_S = 60 \) bins and \( T_M = 240 \) bins, the periods of the lateral oscillations are 48 bins (3.072 s) and 80 bins (5.12 s). A satellite with a period of 48 bins is actually observed, while a satellite of 80 bins is outside the graphs. A triplet with a main period of 35 bins (2.24 s) and side bands of 30 bins (1.92 s) and 40 bins (2.56 s) has a similar structure. Oscillations with periods of 19 bins (1.216 s) and 12 bins (0.768 s) may be the second and third harmonics of these oscillations. Note that the presence of multiple dips on the light curve of the 50-100 keV channel does not significantly affect the position of the spectrum maxima for periods longer than 25 bins.

To assess the statistical significance of the assumed oscillations, a model was constructed that includes 11 sinusoidal oscillations with periods 9, 12, 15, 19, 21, 24, 31, 35, 40, 49, and 60 bins. As a result of calculating the model parameters, the amplitude and statistical significance of each component were estimated. For the time interval from the beginning of episode (1) to the end of episode (2), the calculations showed that the statistical significance of the three higher harmonics exceeded 2\( \sigma \), while for the rest it was on the order of 1\( \sigma \). However, for the entire event, the statistical significance of fluctuations with periods of 35, 40, 49, and 60 bins are in range from 3 to 4 \( \sigma \). A time interval of 25.5 s before the start of episode (1) was also investigated. The statistical significance of sinusoidal oscillations ranged from 2\( \sigma \) to 4\( \sigma \). It turned out that the amplitude of sideband vibrations for carriers with a period of 35 and 60 bins are approximately equal to the amplitude of the carriers themselves. Such situation occurs when the modulation coefficient is equal to 1. The statistical significance of the signal with a period of 35 and 60 bins at the exponential decay stage after episode (3) was 1\( \sigma \) and 2\( \sigma \) respectively.

**Figure 3.** (a) - Light curve of the GRB 190114C in the energy channel 15 - 25 keV and SNSD of this light curve, calculated: (b) - over the entire burst duration; (c) - in a sliding time window of size 13.5 s

**Figure 4.** (a) - Light curve of the GRB 190114C in the energy channel 25 - 50 keV and SNSD of this light curve, calculated: (b) - over the entire burst duration; (c) - in a sliding time window of size 13.5 s
Figure 5. (a) - Light curve of the GRB 190114C in the energy channel 50 - 100 keV and SNSD of this light curve, calculated: (b) - over the entire burst duration; (c) - in a sliding time window of size 13.5 s

Figure 6. (a) - Light curve of the GRB 190114C in the energy channel 100 - 350 keV and SNSD of this light curve, calculated: (b) - over the entire burst duration; (c) - in a sliding time window of size 13.5 s

Oscillations with period of 60 and 35 bins are easy tracked on light curves. In Figure 1 we have indicated the position of the calculated oscillations maxima with period of 60 (red lines) and 35 (blue lines) bins. All of them coincide with actual local maxima of the light curves. Both oscillations have a common started point.

We suggested above that each episode in the Ruffini’s model [4] may have its own features in time and frequency domain. However, we found that there are at least two modes of oscillation observed throughout the entire burst. It imposes strong restriction on the model. The consistent nature of radiation from different sources suggests that there is a kind of resonant connection between them. If this is somehow possible in a tight binary system, then the probability that the plasma shell has the necessary parameters to ensure that the cavity collapse at the right time seems very small.

On the other hand, it is possible episode (1) is not limited to the time frame specified in the work [4], and the burst of a supernova in binary system is reflected on the light curve of the entire burst. Under this assumption, a third source of radiation is hardly necessary.

The simplest way to explain the features of the GRB 190114C light curves is to assume that there is only one source. In this case, it is easy to explain the simultaneous onset of both quasi-periodic oscillation with a period of 3.84 s and 2.24 s, as well the same amplitude modulation.

4. Conclusion
The study of the temporal characteristics of the light curves of the γ-ray burst GRB190114C allowed us to establish some interesting features. The γ-ray burst GRB 190114C is not completely stochastic process. It turns out that the light curves of the burst in energy range of 15 -350 keV have quasi-periodic oscillations with a period of 3.84 s and 2.24 s. Both oscillations start simultaneously, continue
throughout of the burst, and are equally modulated. Based on this, we assume that there is only one and not three “central engine” that controls the $\gamma$-ray burst. The presence of two modes of vibrations may indicate a possible geometry of the “central engine”.

References

[1] Mirzoyan R et al. 2019 GCN Circular #23701
[2] Acciari V et al. 2020 Nature 575 455-8
[3] Ajello M et al. 2020 Astrophys. J. 890 9
[4] Ruffini R, Melon Fuksman J and Vereshchagin G 2019 Astrophys. J. 883 191
[5] Selsing J et al. 2019 GCN Circular #2395
[6] Melandri A et al. 2019, GCN Circular #23983
[7] Beloborodov A, Stern B and Svensson R 1998 Astrophys. J. 508 L25-7
[8] Beloborodov A, Stern B and Svensson R 2000 Astrophys. J. 535 158-66
[9] Pozanenko A and Loznikov V 2002 Lighthouses of the Universe: The Most Luminous Celestial Objects and their use for Cosmology eds. by M Gilfanov, R Sunyaev and E Churazov (Garching Germany: Springer-Verlag) p 194-6
[10] Chang H-Y and Yi I 2000 Astrophys. J. 542 L17-20
[11] Suzuki M, Morikawa M and Joichi I 2002 Lighthouses of the Universe: The Most Luminous Celestial Objects and their use for Cosmology eds. by M Gilfanov, R Sunyaev and E Churazov (Garching Germany: Springer-Verlag) p 201-3
[12] Kruger T, Loredo T and Wasserman I 2002 Astrophys. J. 576 932-41
[13] Wood K et al. 1981 Astrophys. J. 247 632
[14] Barat C et al. 1984 Astrophys. J. 286 L5
[15] Kuznetsov A, Sunyaev R, Tereshkov O, Boer M, Hurley K, Niel M and Vedenne G 1987 Sov. Astron. Lett. 13 444-6
[16] Kouveliotou C et al. 1988 Astrophys. J. 330 L101-5
[17] Gehrels N et al. 2006 Nature 444 1044-6
[18] Crider A 2006 AIP Conf. Proc. 836 64
[19] Pozanenko A, Loznikov V and Preece R 2006 Proc. of the XLith Rencontres de Moriond, series: Moriond Particle Physics meet. eds. by J Dumarchez and J T T Van p 253
[20] Zhilyaev B, Andreev M, Sergeev A and Petkov V 2007 Detection of an oscillatory phenomenon in optical transient counterpart of GRB 090522C from observations on peak Terskol preprint astro-ph/0711.0038
[21] Beskin G, Karpov S, Bondar S, Greco G, Guarnieri A, Bartolmi C and Piccioni A 2010 Astrophys. J. 719 L10-4
[22] Ruffini R et al. 2019 Self-similarity and power-laws in GRB190114C preprint astro-ph/1904.04162
[23] Jenkins J and Watts D 1971 Spectral Analysis and its Application (Amsterdam: Holden-Day) p 525
[24] Serebrennikov M and Pervozvansky A 1965 Hidden Periodicity Determination (Moscow: Nauka) p 244
[25] Alavi A and Jenkins G 1965 Appl. Statist. 14 70
[26] Dergachev V, Tyasto M and Dmitriev P 2016 Adv. Sp. Res. 57 1118