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The study of the mechanisms of X-ray generation in binary X-ray systems using the example of Cygnus X-1 within the framework of the statistical Memory Functions Formalism

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In this work, we study the mechanisms of radiation generation in double X-ray systems based on the Memory Functions Formalism. The method was applied to estimate the temporal parameters of the X-ray emission of Cygnus X-1 by constructing the frequency components of autocorrelators and their derivatives. Analysis of the functions and measures of statistical memory demonstrates the internal structural heterogeneity of the accretion disk generating X-ray radiation and the low rate of transformation of matter. The time periods corresponding to the most significant changes in the total X-ray flux and characterizing the main evolution of the binary system are equal to several hundred days. Possible ways to study the effects of synchronization and cross-correlations in the signals of accreting binary systems recorded at different frequency ranges are indicated.

Keywords: Physics of complex systems, binary X-ray systems, Cygnus X-1, Memory Functions Formalism, statistical memory effects, accretion.

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X-ray binary systems are close systems containing a black hole or a neutron star, as well as a companion star, which can be either a low-mass or a large object. In such systems, a compact object is accreting the matter from its companion star. The first candidate X-ray source for black holes was Cygnus X-1 (Cyg X-1), discovered in 1964 during a suborbital flight [1]. Cygnus X-1 is part of a binary system and has a mass of about 14.8 solar. The binary system, located at a distance of approximately 6 070 light-years from the Sun, also includes a blue supergiant with variable brightness with a mass of about 19 times the mass of the Sun [2]. Recent studies using a very long baseline interferometer demonstrate that a black hole in this system can be located at a distance of seven thousand light-years from Earth, while Cygnus X-1 mass is about 20 times the mass of the Sun, which makes this object one of the largest black holes [3].

The previously obtained results of studying the evolution of the binary system are supplemented with X-ray studies using data from the space missions. Contemporary studies of X-ray objects show their complex structure and the dynamics of radiation processes. For further description, methods are required that can analyze the basic parameters of such systems depending on the interaction and influence of components in the composition of the whole. For this purpose, the present study provides a multiparametric statistical analysis method — a Memory Functions Formalism (MFF), based on which it is shown that signal processing of total X-ray flux from Cyg X-1 makes it possible to establish some long-term features of accretion processes against the background of rapid variability in X-ray activity. The purpose of this paper is to study correlations and statistical memory effects in the activity of Cygnus X-1 X-ray source in order to establish dynamic and spectral patterns of disk accretion and X-ray generation of the specified object.

Experimental data were recorded by a surveillance camera All-Sky Monitor (ASM) of the orbital X-ray station Rossi X-Ray Timing Explorer (RXTE) [4]. The experimental data are the exposed values of 90-second observations of the total X-ray flux S (1.5−12 keV) in the camera's own units. The full flux of the Crab Nebula within the range of 2−10 keV makes 75 ASM counts/s [4].

MFF — the finite-difference generalization of Zwanzig−Mori projection formalism [5,6] adapted for analysis of discrete dynamics of complex systems [7,8]. Here we do not stop at the mathematical relations introduced within the framework of MFF, but give only a brief description of it. This method is based on representation of temporal dynamics of the studied process in the form of a multidimensional vector of state obeying the motion equation expressed in discrete form. Using Zwanzig−Mori projection technique and the procedures of Gramm−Schmidt orthogonalization allows making the description brief. Within the method, a chain of finite-difference interlocking kinetic equations of Zwanzig−Mori type is constructed for the studied time series designed for the time correlation function (TCF) and statistical memory functions for interrelated variables. The method provides a wide range of characteristics: time dependences of orthogonal dynamic variables, phase portraits of dynamic variables combinations, relaxation and kinetic parameters, statistical memory functions and

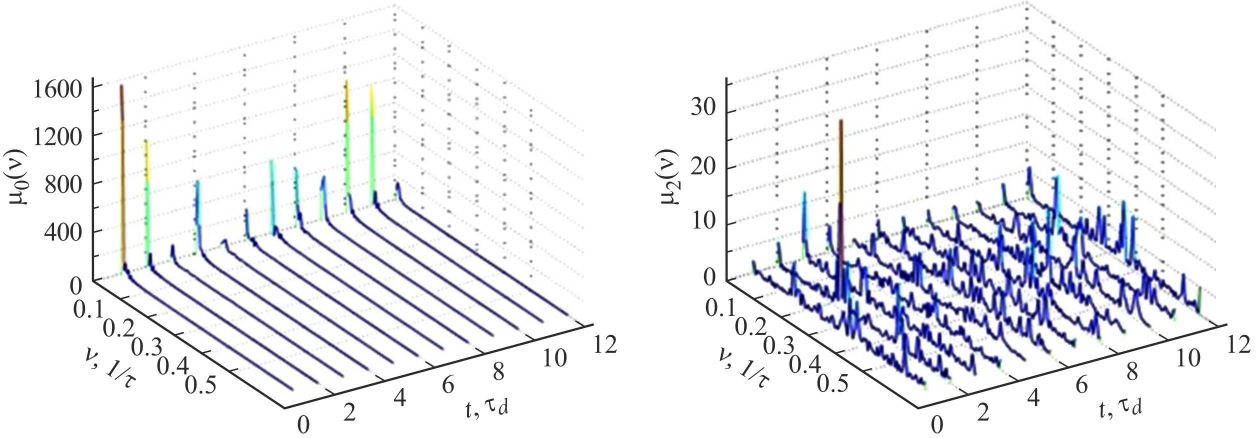

Figure 1. Window-time representation of the power spectra of time correlation function $\mu_0(\nu)$, second-order memory function $\mu_2(\nu)$ by dividing the daily averaged X-ray activity data of Cyg X-1 system into separate intervals. The spectra are plotted separately in the linear scale for each window.

their power spectra, frequency dependences of statistical memory measures calculated directly from sequences of dynamic variables [9,10].

Analysis of power spectra of TCF $\mu_0(\nu)$ and three first memory functions $\mu_i(\nu)$, where $i = 1, 2, 3$, for the averaged values of X-ray radiation of Cyg X-1 enables us to set a low-frequency band $\sim 10^{-3}$ f.un. (frequency units, 1 f.un. $= 1/\tau$, $\tau = 1$ days, τ — sampling rate) where a series of spectral spikes is observed. The period of ~ 1000 days corresponds to the time during which self-similar features of Cyg X-1 X-ray radiation occur [11]. Significant spikes are observed on the power spectra of memory functions at frequencies ~ 0.18 f.un., defining the orbital period of $P = 5.6$ days in the binary system. In the middle and high frequency band, periodic processes of varying amplitude and duration appear on the spectra of memory functions. The combination of these processes leads to a rather complex configuration of small-scale fluctuations in the time sequence of Cyg X-1 X-ray activity, with strong variability over short time intervals (up to milliseconds).

A localization procedure is used to clarify the periodic patterns found on the power spectra of TCF and memory functions of Cyg X-1 X-ray activity. Its essence consists in dividing the time signal into windows of equal length and constructing the studied frequency characteristics for them. The description of choosing the optimal length of the local window is outlined in papers [12,13]. Optimization was performed by incrementally increasing the length of the local window (by one step of sampling rate) until the calculated parameters became relatively constant.

Temporal representation of the power spectra of TCF $\mu_0(\nu)$ and second-order memory function $\mu_2(\nu)$ in windows allows to demonstrate the findings on existence of long intervals (~ 3 years) of self-similarity and to identify the orbital period in Cyg X-1 X-ray source activity (Fig. 1). In the window-time behavior of the frequency dependence $\mu_0(\nu)$ the intensity of spikes in the low-frequency region significantly exceeds all others. The most significant spike in $\mu_2(\nu)$ power spectrum corresponds to the orbital period of Cyg X-1 binary system (the second time window). Periodic processes of varying duration and intensity can be distinguished in the power spectrum of the memory function $\mu_2(\nu)$.

In papers [7,9] we propose the frequency dependence of the non-Markov behavior parameter $\varepsilon_i(\nu)$ calculated based on the spectral power density of TCF and memory functions. To quantify the memory effects manifestation, the value of the non-Markov behavior parameter at zero frequency $\varepsilon = \varepsilon_1(0)$ is used. Depending on the values of the specified parameter, processes with strong statistical memory $\varepsilon \sim 1$ (non-Markovian processes), moderate memory $\varepsilon > 1$, and short memory $\varepsilon \gg 1$ (Markovian processes) are distinguished. Fig. 2 illustrates the frequency dependence of the first three points of the non-Markov behavior parameter — statistical memory measures $\varepsilon_i(\nu)$, $i = 1, 2, 3$. The numerical value of parameter $\varepsilon_1(0) = 18.23$ characterizes a moderate degree of intensity of the manifestation of statistical memory. The rate of correlation bonds losses and significant relaxation times indicate the heterogeneity of the inner layers of the accretion disk structure, where mainly X-rays are generated, and also indicate rather slow rate of the matter transfer into them. Spectral spikes corresponding to the period of variation of the radial velocity of the optical star in Cyg X-1 binary system, i.e. the orbital period, are detected at the frequency dependences $\varepsilon_2(\nu)$ and $\varepsilon_3(\nu)$.

Our findings indicate a rather complex stochastic nature and interrelation of the physical processes that determine the mechanisms of X-ray generation in Cyg X-1 binary system. In particular, the analysis of the power spectra of statistical memory functions constructed for daily averaged Cyg X-1 X-ray activity data allowed us to estimate the heterogeneity of the accretion disk inner layers. At the same time, the time intervals characterizing the most significant stepwise changes in the evolution of an Object are several

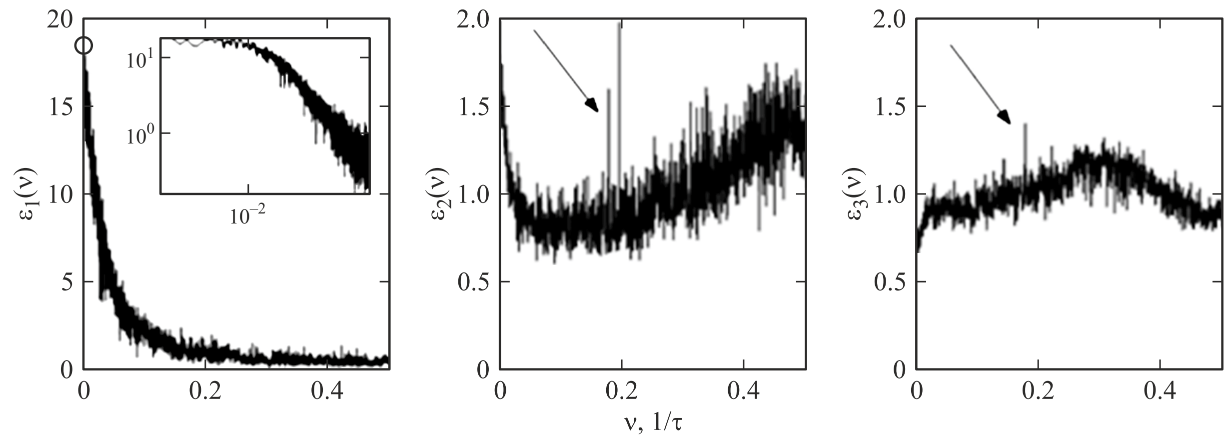

Figure 2. Frequency dependence of the first three points of non-Markov behavior — measures of statistical memory $\varepsilon_i(\nu)$, where $i = 1, 2, 3$ for the daily averaged values of X-ray activity of Cyg X-1 binary system. Insert window — a low-frequency domain of $\varepsilon_1(\nu)$ dependence represented in the log-log scale.

hundred days (up to 3 years). The obtained results were supplemented by studying the spectral features of the total X-ray flux at separate time intervals (based on the window-time representation of the power spectra of memory functions). Significant relaxation times obtained from the frequency dependences of statistical memory measures indicate certain mechanisms of disk accretion of the specified Object — changes in disk density and accretion rate which mainly determined by the slow rate of matter transfer.

Finally, it should be noted that the complex nature of the accretion of matter in binary star systems and the mechanisms of X-ray generation determines the areas of further analysis: analysis of cross-correlations and identification of the frequency-phase synchronization effects for simultaneously recorded radiation signals from astrophysical objects in different frequency bands [14–16]; detection of dual X-ray systems of low-frequency (resonant frequencies, natural and induced) and high-frequency (noise) components in the X-ray activity [17]. In particular, in paper [17] for GRS $1915 + 105$ X-ray source, the authors managed not only to find the information about correlation dependencies contained in chaotic signals, but also to indicate ways to extract the necessary part of it, depending on the type of irregularities: spikes, jumps, discontinuities of derivatives, as well as specific frequencies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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