The study of frequency-phase synchronization in the dynamics of solar activity indices using non-equilibrium statistical physics methods

© D.E. Averkiev, S.A. Demin, O.Yu. Panischev

Kazan Federal University,
420008 Kazan, Russia
e-mail: aver263@gmail.com

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Using the Memory Functions Formalism, we parameterize correlations and effects of frequency-phase synchronization, which are revealed in the Zurich series of Wolf numbers and a set of radio frequency signals in the meter range, to understand the physico-chemical processes occurring in the convective zone and the outer layers of the Solar atmosphere. We have calculated the power spectra characteristics of cross-correlation functions and memory functions, which allow us to determine the degree of frequency-phase synchronization between these signals. We have determined the types of statistical memory and spatio-temporal characteristics in simultaneously recorded signals. The results obtained will be of interest to specialists who study the mechanisms of self-organization of magnetized plasma in the Solar atmosphere and the formation of stable magnetic solar structures.

Keywords: Solar activity, Memory Functions Formalism, cross-correlations, frequency-phase synchronization, effects of statistical memory, radio emission.

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Solar activity and cosmic radiation are the subject of study in many sciences, including astrophysics, astronomy, and the sciences of complex systems. Data reflecting the activity of solar and cosmic radiation can be presented in various forms, including Wolf numbers (solar activity index, relative number of sunspots), different frequency ranges of radio waves (for example, solar activity index F10.7), as well as energy characteristics associated with the flow of elementary particles from distant objects and solar plasma emissions [1,2]. Previously, scientists using spectral analysis of Wolf numbers established that the Sun's magnetic cycle is unstable and has a period of 22.3 years [3]. In study [4] the authors have developed a method for digitizing very high-energy signals (Cherenkov radiation) emitted by astrophysical objects. In paper [5] a study was conducted on the correlations of time series of Wolf numbers and their derivatives, during which the relationship between sunspots and magnetic energy was established.

Cosmic radiation may be related to solar activity indices. Thus, in paper jcite6, using a mathematical method, a high correlation was established between the intensity of cosmic rays and the number of spots on the Sun, which may indicate the influence of solar activity on the cosmic ray flux. A high correlation of signals is also observed between different frequencies of the Sun's radio emission. In paper [7] it was shown that correlation between signals at frequencies of 161 and 2800 MHz, 245 and 2800 MHz is higher than at frequencies of 161 and 245 MHz. The possibility to estimate solar radiation power at a frequency of 2800 MHz based on the flux magnitude at lower frequencies was studied in paper [8].

The purpose of this study is to analyze the cross-correlations and frequency-phase synchronization between dynamic variables in simultaneously detected astrophysical signals, such as Wolf numbers (W) and radio emission detected at various frequencies in VHF band. Frequency-phase synchronization is understood as a manifestation of certain relationships between the characteristic amplitudes, frequencies and phases of excitations of time signals generated by the upper layers of the Sun's atmosphere. The analysis of solar activity indicators synchronization effects is a prerequisite for studying the mechanisms of self-organization and collective processes in the formation of solar structures. Experimental data on solar activity were taken from open Internet sources (database of the National Center for Environmental Information — NCEI). The signals recorded daily from 2007 to 2015, during the 24th cycle of solar activity, were studied.

The analysis was performed within the framework of the author's theoretical approach for analyzing time signals of complex systems of a non-Hamiltonian nature — Memory Functions Formalism. The method is a finite-difference analogue of the kinetic Zwanzig-Mori equations, which relate the normalized cross-correlation function (CCF) to the statistical memory functions [9,10]. 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 for the studied time series X and Y — simultaneously fixed solar activity indices, a chain of finite-difference interlocking kinetic equations of Zwanzig-Mori type for CCF and statistical memory functions is constructed. Directly from experimental data we may calculate the phase portraits of dynamic variables

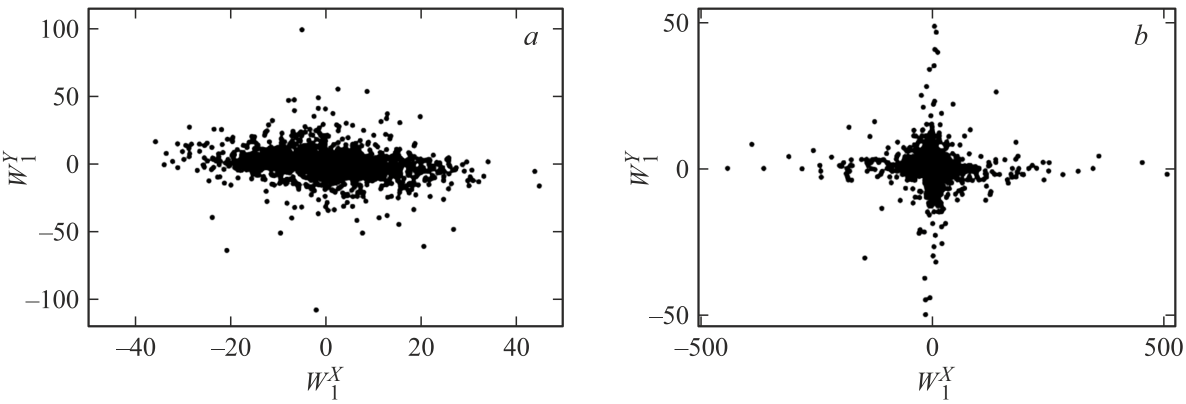

Figure 1. Phase portraits made through a combination of orthogonal dynamic variable solar activity indices: Wolf number and radio signal at frequency of 4995 MHz (a), radio signals at frequencies 15 400 and 610 MHz (b).

describing the spatiotemporal structure of time signals: deviations from the average values of the detected parameter leads to a deformed phase portrait; power spectra of CCF and statistical memory functions allowing to identify periodic regularities, as well as manifestation degree of the frequency-phase synchronization effects between X and Y signals; frequency dependence of the cross-correlation non-Markov behavior parameter characterizing the extent of manifestation of statistical memory. The mathematical ratios for calculation of the specified characteristics are provided in papers [9,10].

In this paper, we consider a large set of experimental data — combinations of various solar activity indices, as a result of which only derivatives of the calculated characteristics are given: maximum values of the memory cross-correlation functions spectra and the values of the non-Markov parameter at zero frequency. In addition, we present representative phase portraits demonstrating the main types of spatiotemporal structure of the analyzed signals.

The features of the signals spatiotemporal structure were investigated on the basis of phase portraits composed by a combination of orthogonal dynamic variables [9,10]. As an example in Fig. 1 we may see the phase portraits for the following signals: Wolf numbers and radio signal at a frequency of 4995 MHz (Fig. 1, a), radio signals at frequencies 15 400 and 610 MHz (Fig. 1, b). The study of the entire set of phase portraits showed that such forms are the most common ones; differences were found only in the spatial dimensions and angles of inclination of the portraits relative to the axes. It can also be noted that there is no stratification into several parts in the structure of the portraits, which may indicate a high correlation between the signals.

The analysis of the effects of solar activity signals synchronization is based on the study of the power spectra for the corresponding CCF and statistical memory functions [9,10]. During the analysis of the entire set of power spectra of memory functions, it was found that synchronization of two signals can occur both, over the entire frequency range and in low-, medium- or high-frequency regions. Power spectra are also characterized by the presence of one or more resonant frequencies, which are complemented by additional periodic processes. Fig. 2, a–c illustrates maximal values of spectral power density — i.e. level of the frequency-phase synchronization in the memory functions of the 1-st (Fig. 2, a), 2-d (Fig. 2, b), 3-d (Fig. 2, c) orders for the solar activity indices X and Y in logarithmic scale. During the analysis of the maximum synchronization values, it was found that, on average, it tends to increase with decreasing radio emission frequencies. The most significant synchronization is also observed between the sequence of Wolf numbers and low-frequency signals (245, 410MHz). This was found not only for interaction of index X with Y (in the left part of the graphs with respect to the diagonal, when X and Y coincide — autocorrelation case), but also for the interaction of index Y with X (in the right part of the graphs with respect to the diagonal).

The quantitative characteristics of the statistical memory effects of the analyzed signals were determined using the cross-correlation non-Markov behavior parameter [9,10]. The non-Markov behavior parameter initially was used as a simple quantitative measure that allows us to compare the relaxation times of CCF and statistical memory functions. In papers [9,10] we propose the frequency dependence of the non-Markov behavior parameter calculated based on the spectral power density of CCF and memory functions. To quantify the memory effects manifestation in signals X and Y the parameter values at zero frequency $\varepsilon = \varepsilon_1^{XY}(0)$ are calculated. Depending on the values of the specified parameter, processes with strong statistical memory $\varepsilon \sim 1$ (non-Markovian processes), moderate memory $\varepsilon \sim 1$, short memory $\varepsilon \gg 1$ (Markovian processes) are identified. Fig. 2, d illustrates the values of the first point of non-Markov parameter at zero frequency for the combination of solar activity indices. Due to the three-dimensional representation we may determine which type of statistical memory is displayed for a certain combination

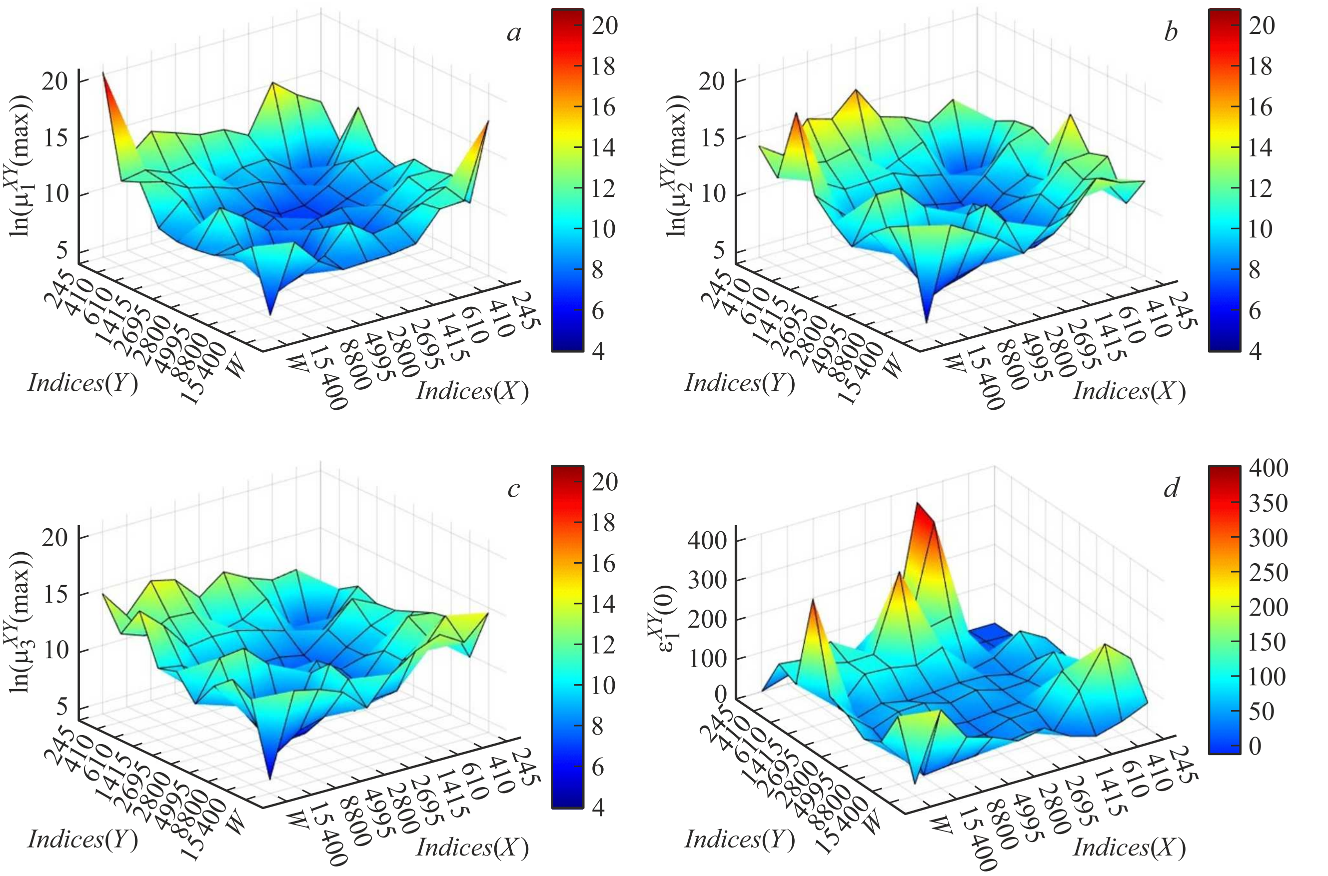

Figure 2. Maximal values of spectral power density — level of the frequency-phase synchronization of memory functions of $\mu_i^{XY}(\max)$ 1-st (a), 2-d (b), 3-d (c) order for the solar activity indices X and Y in logarithmic scale (W — dimensionless Wolf number, units of measurement of other indices — MHz); values of the non-Markov behavior parameter at zero frequency $\varepsilon_1^{XY}(0)$ for the appropriate signals (d).

of signals. Analysis of this parameter showed that in most cases, non-Markov effects and moderate memory prevail in the mutual dynamics of the studied signals (for example, in the dynamics of signals at frequencies of 410 and 245 MHz, 610 and 24 MHz).

Thus, the effects of frequency-phase synchronization were studied, as well as the nature of manifestation of statistical memory in simultaneously detected astrophysical signals — characteristics of solar activity. The results of the analysis of CCF power spectra, memory functions, phase portraits, and the frequency-dependent non-Markov behavior parameter are presented.

The results obtained after further verification (for example, they can be supplemented by a study of the frequency-phase synchronization of the considered solar activity indices within flicker-noise spectroscopy [11,12]) will provide information about the structure and physical properties of the solar atmosphere [13], as well as about collective phenomena associated with solar flares. The study of radio emission in a wide frequency band can be used to predict active phenomena (flares, spots) on the surface of the Sun.

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Conflict of interest

The authors declare that they have no conflict of interest.

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