ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2021, Vol. 57, No. 10, pp. 1308–1321. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Geofizicheskie Protsessy i Biosfera, 2021, Vol. 20, No. 3, pp. 76–90.

Synchronization of Activity–Rest Cycle Indicators in Mice with Geomagnetic Field Variations in the Millihertz Frequency Range

V. B. Dorokhov[a], *, G. N. Arseniev[a], **, D. S. Sakharov[a], *, O. N. Tkachenko[a], ****, M. E. Diatroptov[b], *****, and T. A. Zenchenko[c, d], ******

[a] *Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences, Moscow, 117485 Russia*
[b] *Severtsov Institute of Ecology and Evolution, Russian Academy of Sciences, Moscow, 119071 Russia*
[c] *Institute of Theoretical and Experimental Biophysics, Russian Academy of Sciences, Pushchino, Moscow oblast, 142290 Russia*
[d] *Space Research Institute, Russian Academy of Sciences, Moscow, 117997 Russia*

**e-mail: vbdorokhov@mail.ru*
***e-mail: byron100z@gmail.com*
****e-mail: sakharovdm@yandex.ru*
*****e-mail: tkachenkoon@gmail.com*
******e-mail: diatrom@inbox.ru*
*******e-mail: zench@mail.ru*

Received April 22, 2021; revised July 5, 2021; accepted July 19, 2021

Abstract—The synchronization of mice motor activity, which reflects the activity–rest cycle, with variations in the *X* component of the geomagnetic field vector (BOXX) in the range of fluctuations from 10 to 120 min has been studied. The percentage of pixels on the video recording that changed their intensity within 10 s is used as an indicator of motor activity. The experiment was performed simultaneously on 16 males of the C57BL/6 line in October 2019 in Moscow. The mice were kept single in a plastic box (t = 22–26°C) under an artificial 12-h light regime and free access to water and food. The degree of similarity of the rhythm of biological and BOXX indicators is analyzed for each animal by evaluating the degree of similarity of their Fourier spectra for each 12-h day and night intervals. An analysis of the time series averaged over the group showed that almost all harmonics in the interval of 50–120 min correspond to equal harmonics of the BOXX. The cross-correlation function of two series has a statistically significant absolute maximum with a zero time lag between the series. On average, 18% of individual segments show statistically significant correlation between the spectra of activity–rest cycle and BOXX. This result indicates the adjustment of the biological rhythm for the variations of the geophysical one, which corresponds to the effect of adjusting the rhythms of heart and brain human activity to an external rhythm generator, the geomagnetic field.

Keywords: biological rhythms, magnetic sensitivity, oscillation synchronization
DOI: 10.1134/S0001433821100029

INTRODUCTION

One widely known manifestation of solar–biospheric interactions is the presence of solar rhythm in various biological processes. This phenomenon is observed on different spatiotemporal scales (see reviews (Temuryants et al., 1992; Vladimirskii and Temuryants, 2000; Breus et al., 2016; Zenchenko and Breus, 2021)).

Thus, the 11-year rhythm of solar activity could be detected in the emergence of epidemics (Chizhevskii, 1976; Hayes, 2010; Gumarova et al., 2013; Qu, 2016; Wickramasinghe, 2020), high mortality outbreaks (Vieira et al., 2018), and noncommunicable diseases such as cardiovascular diseases (Halberg et al., 2000; Cornelissen et al., 2002) or mental diseases (Davis and Lowell, 2006).

Infradian rhythms present in the dynamics of the solar wind and the disturbance of the geomagnetic field (GMF) (28, 14, 9, 6.8, 5.4, 4.5 days, etc.) have been repeatedly observed in the diurnal dynamics of population indicators (such as an increase in complications of cardiovascular diseases, an increase in the number of suicides, etc.) (Cornelissen et al., 2002; Breus et al., 2016), as well as in the individual rhythms of a number of physiological indicators of humans (Halberg et al., 1991; Breus et al., 1995; Kornelissen et al., 1998) and animals (Komarov et al., 1994), including protozoa (Schweiger et al., 1986; Kuznetsov, 1992).

Recently, the manifestation of synchronization of geophysical and biological rhythmics at the intraday time scale is gaining more and more attention from researchers. Such synchronization is shown for rhythmic processes in the human brain and heart. Thus, the indicators of the total spectral power of the EEG, averaged over a group of healthy volunteers, change synchronously with the changes in the intensity of the first mode of Schumann resonances (8 Hz), and this synchronization increases with an increase in the general level of solar activity (Pobachenko et al., 2006; Saroka et al., 2016). The individual sensitivity of the rhythm-generating structures of the human brain in the high-frequency (14–35 Hz) and low-frequency (up to 4 Hz) parts of the EEG spectrum turned out to be associated with variations in the horizontal component of the GMF (Poskotinova et al., 2018).

A number of studies analyzed long multiday heart rate records in groups of healthy volunteers and compared these data with the dynamics of the intensity of Schumann resonances and variations in the total GMF vector (Alabdulgade et al., 2015, 2018; McCraty et al., 2017; Timofejeva et al., 2017).

Another series of studies shows that, in a healthy person at rest, the heart rate adjusts to synchronous variations in the geomagnetic field vector in the range of oscillation periods from 3 to 30 min (millihertz frequency range 0.56–5.56 mHz, close to the frequencies of geomagnetic pulsations PC5-6) (Zenchenko et al., 2013, 2014, 2015). This effect was observed in about 60% of 230 individual ECG recordings and did not depend on the geographical point of observation.

No significant shifts in the average values of cardiac parameters beyond the physiological norm were recorded in these studies. This suggests that the synchronization of the heart rhythm is observed during the normal functioning of the studied body systems.

The authors of the studies also analyzed individual characteristics of rhythmics. They emphasize that characteristics of the reaction such as the amplitude of oscillations and the phase shift differ in different individuals (Zenchenko et al., 2013, 2014; Alabdulgade et al., 2015; Timofejeva et al., 2017; Poskotinova et al., 2018). Thus, group-averaged results of studies on magnetobiological synchronization confirm the fundamental existence of the effect and the individual ones show significant interindividual variability. Thus, it can be concluded that averaging over the group largely smooths the severity of the effect.

Studies on animals indicate the presence of synchronization between physiological rhythms in the range of periods of 10–120 min (0.14–1.67 mHz) in different individuals, even at a considerable distance from each other (Dzalilova et al., 2019; Diatroptov et al., 2020a, 2020b). This effect makes it possible to assume the presence of an external rhythm sensor; however, in these studies, no direct synchronization with any specific geophysical rhythms have been established.

The effect of synchronization is manifested in the processes associated with the central and autonomic nervous system. Therefore, it can be assumed that a similar "rhythm seizure" can also be manifested in the activity–rest cycle. The study of this effect is important for assessing the possible contribution of the geomagnetic factor to human well-being. It has been previously shown (Ohayon et al., 2019; Dorokhov et al., 2020) that weak artificial electromagnetic fields of ultra low frequency have a positive effect on human sleep.

Small rodents, including mice, are characterized by frequently alternating periods of rest and activity. It is believed that the brain dopaminergic system is involved in the formation of such cycles (Bourguignon and Storch, 2017). This statement is based on the fact that fluctuations in the dopamine level in the structures of the corpus striatum are synchronous with the ultradian cycles of motor activity. A mutation in the Slc6a3$^{-/-}$ dopamine transporter gene leads to an increase in the period of the ultradian rhythm of motor activity (Blum et al., 2014).

The aim of this work is to detect and then conduct a preliminary study of the possible effect of biogeophysical synchronization in animals in relation to the rhythm of motor activity reflecting the activity–rest cycle.

We have set and solved three tasks:

(i) Develop a method for detecting synchronization taking into account the specifics of biological and geophysical data (such studies have not been conducted before);

(ii) Reveal the effect of synchronization on the test group of animals in the middle-group and individual analysis;

(iii) A preliminary study of the characteristics of the effect, namely, its distribution within a group of animals in time and the presence or absence of preferential frequencies.

MATERIALS AND METHODS

Experiment Design and Data Collection

For the analysis, we used data on the intensity of locomotor activity, continuously recorded simultaneously in 16 mice (line C57BL/6, males) from October 7 (night from 6 to 7 October) to October 22 (day), 2019. An automated device for recording the motor activity of mice consisted of two sound-insulated ventilated chambers with an internal size of 110 × 45 × 70 cm each. The mice were kept single in a transparent plastic box measuring 16 × 16 × 40 cm; each chamber contained 8 boxes. The chambers were kept at a constant temperature of 22–26°C with an artificial 12-h light regime (08:01–20:00 bright white light; 20:01–08:00 weak red light), water and food ad libitum.

The illumination uniformity was provided by LED strips with SMD 3528 LEDs. Daylight illumination had a color temperature of 3200 K (warm white light). The illumination at the location of a mouse was about 100 Lx. Night illumination was provided by 900 K LED lamps (red light). The illumination measured at the location of a mouse was about 15 Lx. A Smart Sensor AR823 luxometer was used. It is known that mice are the least sensitive to the red part of the spectrum and illumination less than 20 Lx does not disrupt their sleep–wake cycle (Zhang et al., 2017).

The LED strips and fans were powered by a 12 V DC network. Four A4Tech PK333E webcams (with integral infrared illumination) were used for video recording of motor activity. Each of the webcams provided simultaneous video recording of the activity of four mice in four quadrants of the field of view of the video camera. In each quadrant, every second, the analysis program quantified the ratio of the proportion of changed and unchanged pixels and averaged these data over 10 s (Manolov et al., 2016). Then this data was recorded to a file individually for each mouse.

Geophysical Data for Analysis

As geophysical indicators, 1-m values of the horizontal *X* component of the GMF vector (BOXX) were selected according to the data of the Borok geomagnetic station (58°04′ N, 38°14′ E), nearest to the measurement point (Moscow, 55°45′ N, 37°37′ E). Data were taken from INTERMAGNET (International Real-time Magnetic Observatory Network, http://ottawa.intermagnet.org/Welcom_e.php). We chose the *X* component because in the investigated frequency range it spreads over considerable distances without distortions. Earlier, we determined that during quiet times the data for the Borok station coincide with the data for the Kiev station (Zenchenko et al., 2014).

The geomagnetic activity during the entire period of measurements was calm ($Kp < 4$); no geomagnetic storms were observed.

Analysis Methods

Filtration. In this work we were interested in the possible synchronization of oscillations with periods from 10 to 120 min (0.14–1.67 mHz); so, to exclude diurnal variations, trends, and low-frequency components to biological and geomagnetic time series, we preliminarily applied a Blackman–Harris window. The specific parameters of the bandpass filter (lower f_1 and upper f_2 cutoff frequencies (from the Nyquist frequency) and filter length l_f) are listed below for each result.

Similarity assessment methods. Since, as was mentioned above, group-averaging can lead to a significant decrease in the severity of the effect and even results in its total vanishing, we used both the mean-group and individual approaches.

Mean-group analysis. In the mean-group analysis, first, the activity values averaged over each minute were calculated for all 16 animals. A series with a total length of 23278 points was filtered with a low-frequency filter (see above), then divided into sequential 12-h intervals corresponding to day and night observation intervals. In total there were 32 intervals consisting of 720 points (16 day and 16 night). For each 12-h interval, a cross-correlation function between the biological and the synchronous geophysical interval of the time series was determined.

Individual analysis. Individual time series of 1-min activity values for each animal were transformed into 3-min ones, then divided into 12-h intervals (240 points each). A total of 32 time intervals were obtained for each animal; in total for the whole group of 16 animals, there were 512 individual time intervals. After the abovementioned low-frequency filtering, the Fourier spectra of the time series of variations in the geomagnetic vector and 16 individual biological activity series were calculated for each of the 12-h intervals.

A conclusion about the similarity of the biological and geomagnetic series for each animal at each of the 12-h intervals was made on the basis of the correlation analysis of their Fourier spectra. Intervals from the 5th to the 72nd harmonics (periods from 10 to 144 min, 0.12–1.67 mHz) were separated from each spectrum, the spectra were normalized to the maximum power value of this spectrum interval, a linear trend was excluded to prevent excessive contribution large periods, the Spearman *r*-correlation coefficients (nonparametric method) for synchronous time intervals were calculated, and the level of statistical significance of the correlation (*p*) was estimated.

Results of the individual analysis. The values of the *r*-correlation coefficients were converted to the form of indices:

$$K = -\operatorname{sgn} r \times \log p. \tag{1}$$

This representation is more convenient for analyzing large arrays or tables of results than the traditional one in the form of pairs of *r* and *p* values. The *K* value uniquely depends on *r* and *p* and contains information about the sign of the correlation coefficient (it is reflected by the function sign *r*) and about the degree of connection between the two series ($-\log p$). Since the value of the $-\log p$ function increases with an increase in the level of statistical significance, the *K* value also increases, while the *p*-value decreases.

The traditionally accepted first level of statistical significance $p < 0.05$ corresponds to the values $|K| > 1.3$, since $-\log 0.05 = 1.3$. Similarly, $p < 0.01$ corresponds to $|K| > 2$ and $p < 0.001$ to $|K| > 3$. $|K| < 1.3$ means that there is no statistical relationship between the tested series.

RESULTS

Mean Group Analysis

For the mean group analysis of animal activity, the series of biological and geophysical data were preliminarily filtered with filter parameters $f_1 = 0.007$, $f_2 = 0.9995$, and $l_f = 7500$. Figure 1 shows the Fourier spec-

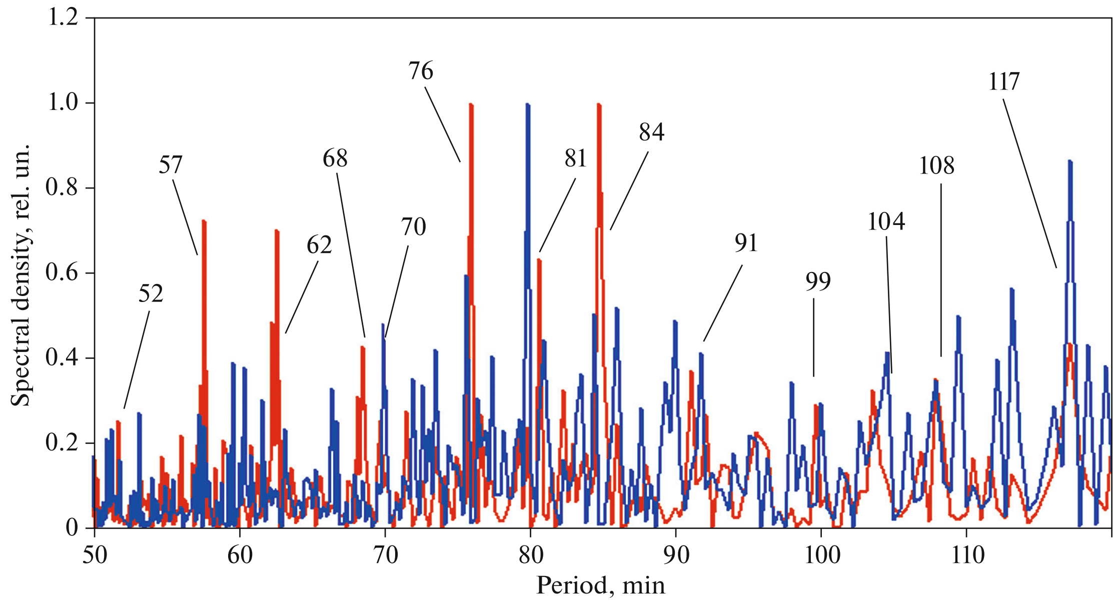

Fig. 1. Fourier spectra of the mean-group biological and geophysical 1-min time series. The row length is 23 278 points, $f_1 = 0.007$, $f_2 = 0.9995$, and $l_f = 7500$. The values of the spectral power are normalized to the maximum value.

tra of two series in the range of periods of 50–120 min (0.14–0.33 mHz). It can be seen that, for 11 of the 13 most pronounced harmonics of the activity series of animals (the values of the periods are indicated in the figure), there are corresponding harmonics of the geophysical series that coincide exactly with them in magnitude.

Spearman's nonparametric correlation coefficient calculated for the biological and geophysical series was low ($r = 0.053$); however, due to the very large length of the series (23 278 points) the level of statistical significance was $p < 10^{-15}$. Then the series was divided into 12-h intervals; for each of the 32 intervals (day and night data for 16 mice), a cross-correlation function was calculated between the animal activity values and BOXX values at time shifts of ±200 min. The distributions of the correlation coefficients over the time lag in the form of the median, as well as the first and third quartiles, are shown in Fig. 2. It can be seen that the absolute maximum of the distribution corresponds to a zero shift between the rows.

Individual Analysis

The first step of the individual analysis was to develop a method for identifying the effect.

Figure 3 shows examples of two 12-h intervals of the activity of a certain animal and synchronous variations of the horizontal GMF component (initial and after applying a band-pass filter ($f_1 = 0.1$, $f_2 = 0.95$, $l_f = 79$)). It can be seen that, in the initial series, the daily variation of the GMF vector has large amplitude, which practically hides fluctuations with shorter periods. After the filtering procedure, they become more pronounced.

The data (Fig. 3) also show the nature of the synchronization effect: cyclic oscillations with periods of 40–100 min (0.17–0.42 mHz) are observed both in the geophysical and biological time series. Their amplitude and phase vary significantly. In these examples, 17–20 cycles fit into a 12-h observation period. If the observed quasiperiodic oscillations were independent and the phase coincidence in a certain area was random, then a significant desynchronization of the oscillation phases would occur during the chosen observation time. However, Figs. 3a, II and 3b, II show that the coincidence of the extrema in the two series persists throughout the entire observation period, despite the variability of the cycle length.

Thus, at least in some cases, in the biological series of the activity–rest cycle, the oscillations are close in frequency and phase to similar oscillations in the BOXX dynamics. If we assume that this relationship is not accidental, then the most appropriate method for assessing their similarity degree is the method for assessing the proximity of the Fourier spectra of these series.

Development of a Method for Analyzing the Similarity of Individual Fourier Spectra

Table 1 provides a correlation coefficients between 12-h intervals of biological (separately for each animal) and synchronous geophysical series. The traditionally accepted level of statistical significance $p < 0.05$ ($K > 1.3$) in Table 1 satisfies 172 out of 512 coefficients, i.e., 34% (in bold).

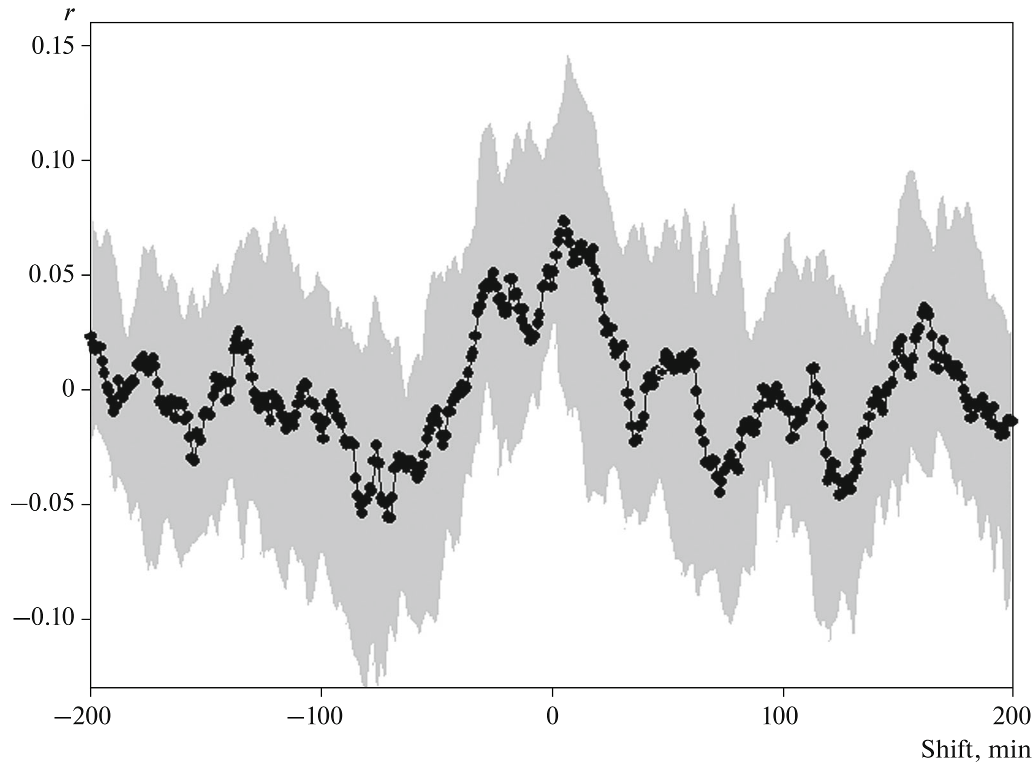

Fig. 2. Value of the cross-correlation function between the mean-group biological and geophysical series averaged over 32 consecutive 12-h intervals. The filtering parameters are the same as in Fig. 1.

However, in this case, the traditional criterion $p < 0.05$ turns out to be too weak, since we are not interested in the probability of a random coincidence of the spectra, but in their similarity. Therefore, it is necessary to conduct additional research and determine the limits of the correlation coefficients that are sufficient to consider the spectra similar.

The compared spectra segments can be considered space vectors (in this case, the dimension $n = 68$), and their scalar product, similar to the linear correlation coefficient, can serve as a measure of their proximity.

The distribution of the significance levels (K) of the correlation coefficients obtained in accordance with formula (1) for 512 time intervals is represented in Fig. 4. It can be seen that this distribution is asymmetric and shifted relative to zero (the mode is 0.5). If we assume that the distribution of features of the two coincidentally random spectra follow the normal probability law (shown in the figure by the solid line), then the observed anomalously large values (in this case, for $K > 2.5$) can be considered outlets of the random distribution.

Figure 5a presents examples of spectra estimated as dissimilar; Fig. 5b presents them as similar according to the chosen similarity boundary, $K > 2.5$ (which corresponds to $r > 0.354$). It can be seen that the chosen criterion is quite strict. It excludes as dissimilar not only the cases with great differences of the main peak frequencies (if it is one) (see Figs. 5a, 5b; K = −1.43, $K = 0.47$), but also such cases when the frequencies are close, but do not coincide (Figs. 5c, 5d; $K = 1.56$, $K = 1.77$). According to the criterion, in the case of multiplicity of high-amplitude peaks, a small frequency discrepancy of one of them turns out to be admissible (Figs. 5e, 5f; $K = 2.59–2.62$).

Thus, the examples of the spectra shown in Fig. 5 confirm the validity of the K value chosen as the limit value of distribution for all sample values (see Fig. 4): the spectra for which $K > 2.5$ do indeed have similar values of the main presented periods, while the spectra with $K < 2.5$ differ.

This criterion is much more rigorous than the traditional $p < 0.05$ ($K > 1.3$) and even $p < 0.01$ ($K > 2$). However, in the sample of correlation coefficients, it corresponds to 18% of the values.

Thus, according to the similarity criterion for Fourier spectra, which we developed on the basis of standard methods of statistical, correlation, and spectral analyses, there is a significant number of cases that go beyond the boundaries of random coincidence.

Characteristics of the Synchronization Effect

Distribution features for individual animals and days of observation. Figure 6 presents the results of the analysis of the table data for individual animals (see Fig. 6a)

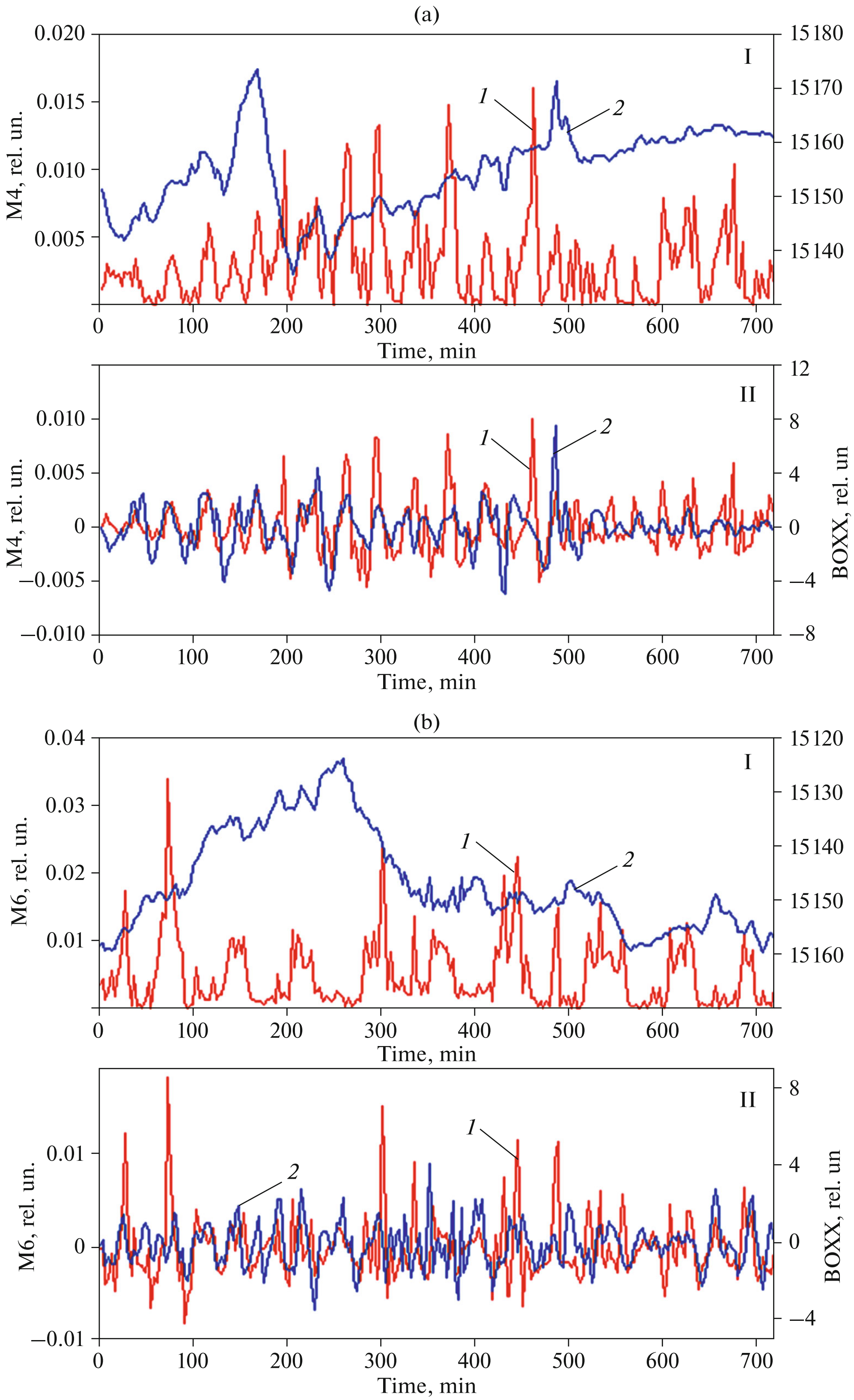

Fig. 3. Examples of series of 3-min values of animal activity (*1*) and the value of the horizontal component of the geomagnetic vector BOXX (*2*): initial (I) and after applying a band-pass filter (II). (a) October 14, 2019, night, M4 mouse; (b) October 17, 2019, day, mouse M6.

Table 1. Values $K = -\text{sgn}\, r \times \log p$ for estimates of the similarity of the spectra of biological series with variations in the X component of the GMF vector

Observation date	Time of the day (1, day; 2, night)	Study Subjects (Mice)															
		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16
October 7, 2019	2	1.33	**2.69**	0.14	0.49	–0.19	–0.27	0.41	1.48	**2.84**	–1.09	0.83	0.97	–0.05	2.09	0.16	**3.78**
	1	0.74	0.96	1.11	–0.11	1.04	0.81	2.04	2.08	2.10	**2.98**	0.03	–1.42	–0.01	**3.13**	0.74	0.93
October 8, 2019	2	1.90	0.22	0.98	0.18	**3.79**	–0.22	**3.41**	0.29	**2.84**	0.01	0.28	1.70	–0.25	2.34	0.10	0.13
	1	0.29	0.04	0.08	–0.03	0.44	1.78	**5.56**	**5.94**	**4.59**	1.92	**3.43**	0.32	1.29	–0.13	0.24	**5.59**
October 9, 2019	2	0.41	**3.86**	**5.78**	1.57	0.09	**2.52**	–0.03	–0.12	0.38	1.59	0.59	0.32	–0.48	1.61	**3.36**	0.50
	1	0.68	1.43	1.00	0.86	0.05	1.03	0.36	0.65	0.16	–0.76	2.16	1.64	1.95	1.25	1.19	1.32
October 10, 2019	2	1.75	1.75	–1.53	0.03	1.45	2.26	0.09	0.29	0.04	1.66	1.94	0.92	–1.06	–0.18	–1.12	–0.64
	1	0.12	–0.08	0.95	0.10	1.57	0.12	0.14	0.41	0.55	0.61	**2.53**	1.11	0.30	–0.23	1.46	0.55
October 11, 2019	2	**11.73**	**4.63**	1.35	**4.60**	1.83	–0.27	**3.03**	0.19	0.85	0.89	0.84	0.29	0.83	–0.02	0.36	0.21
	1	0.10	1.27	**3.37**	**2.69**	0.62	**3.17**	2.28	**3.28**	**12.95**	1.11	0.91	1.11	**3.60**	1.69	0.43	**14.42**
October 12, 2019	2	1.81	1.08	0.96	–0.27	–0.24	**2.51**	1.31	2.31	**5.06**	–0.56	2.42	0.73	0.04	2.00	**4.18**	–0.06
	1	1.12	0.08	0.59	1.62	0.31	**3.70**	0.47	–0.41	0.13	–0.69	2.39	1.75	**4.27**	0.68	–0.19	1.99
October 13, 2019	2	1.00	–0.49	1.77	–0.23	1.67	–0.40	0.75	1.83	1.21	**3.22**	–0.49	**2.89**	0.93	0.25	0.79	1.80
	1	–0.38	–2.19	0.20	0.62	–0.17	0.05	0.33	–0.09	0.00	–0.94	–0.09	–0.38	0.08	–0.14	–0.23	–2.09
October 14, 2019	2	**4.74**	–0.23	–0.47	–0.18	0.21	–0.13	1.53	–0.04	0.99	0.38	0.23	–0.15	0.56	0.02	0.91	**2.84**
	1	0.70	–0.24	**6.59**	–0.29	0.43	0.16	0.51	–0.24	–0.42	0.75	0.15	0.21	–0.19	0.52	1.85	0.36
October 15, 2019	2	**3.16**	–0.03	**2.70**	0.02	0.07	**6.15**	1.40	1.52	**4.20**	0.24	1.51	**3.21**	1.56	1.63	**5.22**	1.36
	1	1.48	–0.34	1.26	1.70	**2.99**	0.44	0.19	0.88	**7.06**	1.13	–0.08	0.87	0.86	1.25	2.43	0.83
October 16, 2019	2	–0.16	–1.45	0.05	–0.77	–0.10	–0.01	–0.02	–0.96	–0.87	–0.82	–0.57	0.17	0.02	–1.40	–1.44	–0.65
	1	–0.14	0.75	0.55	–0.25	–0.18	0.28	–0.15	0.18	–2.15	0.37	–1.35	–0.05	0.60	0.57	–0.14	2.01
October 17, 2019	2	1.07	0.83	0.15	1.05	2.45	0.43	**6.50**	1.72	0.67	1.74	**2.68**	1.11	1.04	**3.87**	–0.11	**6.01**
	1	**4.21**	**4.33**	1.82	0.72	–0.13	**5.32**	–0.62	**10.14**	0.47	**14.53**	0.69	–0.02	0.97	**8.32**	**7.91**	0.08
October 18, 2019	2	0.31	0.94	**4.70**	**4.26**	0.89	**4.81**	0.83	**3.03**	–0.06	1.64	**8.16**	1.00	0.71	1.14	0.23	0.98
	1	0.33	2.01	**4.71**	1.66	**5.39**	**5.32**	0.26	0.22	0.68	0.04	–0.15	0.05	0.84	1.08	**3.37**	1.01
October 19, 2019	2	0.39	2.01	1.00	**5.91**	1.40	0.10	**3.05**	**8.64**	0.86	**4.95**	–0.21	2.08	0.04	**4.03**	0.35	–0.36
	1	1.19	–0.18	1.40	0.07	–1.06	–0.71	**2.70**	0.80	**3.04**	1.13	0.25	–0.13	**5.76**	–1.07	0.47	**2.59**
October 20, 2019	2	0.40	–0.03	–0.68	1.55	0.50	–0.15	0.44	–1.42	1.56	**5.76**	0.06	–0.44	**10.67**	–0.51	–0.42	–0.24
	1	0.35	0.16	1.70	**5.99**	**4.21**	–1.00	0.08	0.48	–1.43	1.84	0.58	0.86	0.15	–0.30	0.42	2.20
October 21, 2019	2	–0.08	**6.11**	**3.53**	–0.11	**6.16**	–0.19	1.42	–0.23	0.76	–0.10	–0.07	1.07	0.79	–0.14	–0.87	0.87
	1	–0.53	0.23	0.86	–0.33	1.64	–0.76	**2.93**	1.12	0.50	0.91	0.70	–0.55	0.34	–0.05	**4.49**	–0.16
October 22, 2019	2	–1.14	**4.25**	**4.67**	0.39	**5.59**	2.20	**2.56**	**2.82**	**5.91**	**2.58**	0.64	0.42	2.37	1.32	1.81	**3.09**
	1	–1.34	–0.38	–1.22	–0.10	1.55	–0.35	–0.10	–0.22	–0.29	0.07	0.26	0.03	0.02	0.19	–0.85	0.16

The values corresponding to the level of statistical significance $p < 0.05$ are in bold. The spectra were considered to be similar at $K > 2.5$.

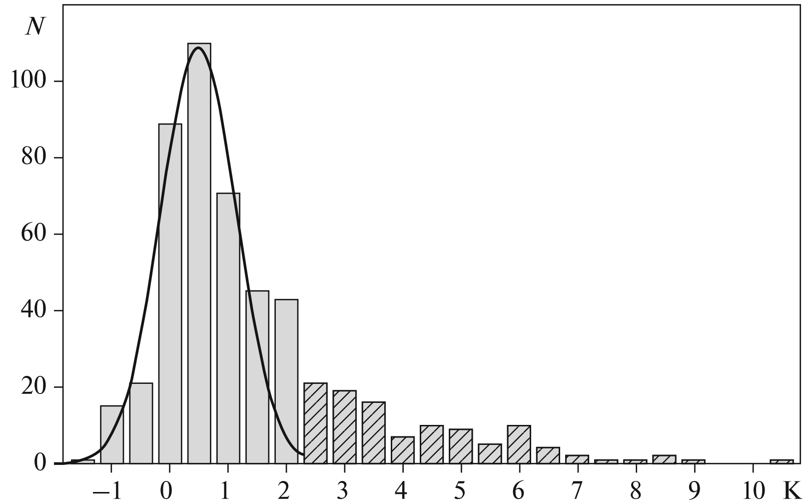

Fig. 4. Distribution of coefficients $K = -\text{sgn}r \times \log p$ correlations of Fourier spectra of individual biological series with the GMF X component over the entire sample of results. Solid line designates the approximation of the distribution by the Gaussian function.

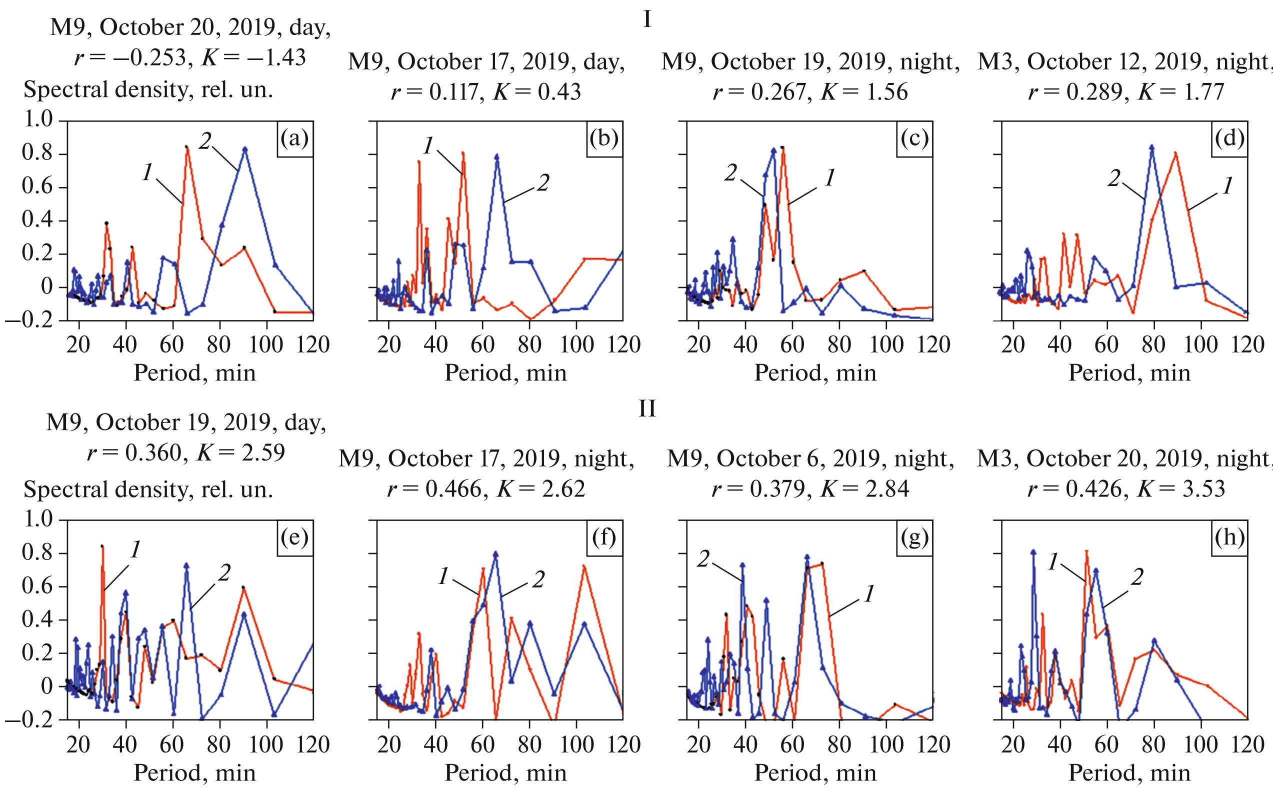

Fig. 5. Examples of spectra recognized as dissimilar according to the criterion $K < 2.5$ (I) and recognized as similar according to the criterion $K > 2.5$ (II). (*1*) Biological series; (*2*) geophysical series. Spectra are normalized to the maximum value.

and for the observation time (see Fig. 6b). The distribution of the number of cases N in which the Fourier spectra were found to be similar ($r > 0.354$ or, consequently, $K > 2.5$) is shown. The presented data (Fig. 6a) show that, for different animals, the number of such cases varies from 2 to 9 (or from 6 to 28%; 18% on average for the entire sample of animals). With the exception of the animal M12, for which only two cases of similarity of spectra were noted, we failed to discover objective criteria by which the mice could be divided into "magnetically sensitive" and "magnetically insensitive." If we consider the limit values of this distribution, then the similarity of the spectra in more than 20% of cases (7–9 cases) was found for animals

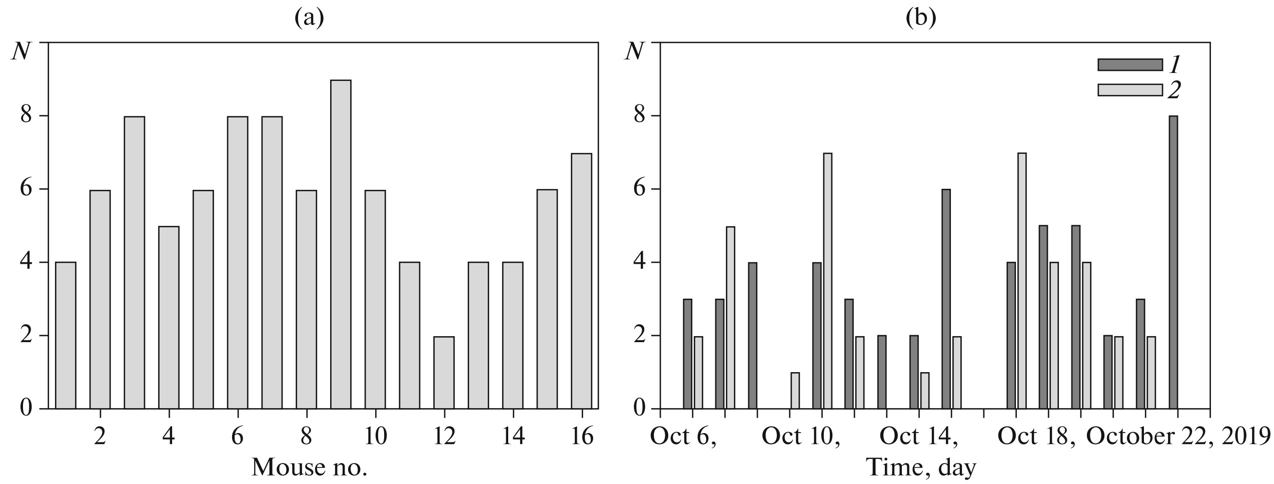

Fig. 6. Distribution of the number of cases of similarity ($K > 2.5$) between the Fourier spectra of biological and geomagnetic time series for 16 mice (a) and for each observation interval (b). (b) (*1*) Night; (*2*) day.

M3, M6, M7, M9, and M16; less than 15% (2–4 cases) was found for M1 and M11– M14 animals.

Figure 6b shows the distribution according to observation days separately for day and night intervals. For day intervals, 39 matches were noted (in total for all animals); for night intervals, 54 were noted.

The number of cases varies considerably by day, from a complete lack of coincidences (October 16) to 9–11 cases per day, which is 28–34% (October 11 or October 17–19). More research is needed to identify the reasons for these differences.

A comparison of the specific features of the day and night intervals shows that, over 4 days (October 8, 10, 11, and 17), the daytime value of the number of coincidences exceeded the nighttime one, and on the other days it was the opposite. Thus, there is a certain trend towards an increase in the percentage of coincidences at night; however, the comparison of the samples of the obtained day and night values of the number of coincidences turns out to be indistinguishable according to the nonparametric Wilcoxon test ($r = 0.14$, $p > 0.05$). For a more accurate answer to the question of whether there is a predominant coincidence of the spectra at night intervals in comparison to day intervals, it is necessary to increase the sample number of animals and analyzed intervals, which is a task for future studies.

Peculiarities of Spectrum Frequency Distribution

To explain the reasons for the effect of the similarity of biological and geomagnetic periods, two mechanisms can be proposed.

1. In geophysical and biological series, there is a definite endogenous rhythm with a constant set of characteristic periods. A correlation between the series is recorded in time intervals when the values of these internal periods are close, although the causal relationship may be completely absent.

2. The biological rhythm adjusts to the vibrations that are present at a given moment in the geomagnetic field. Therefore, at each separate moment of time, a predominance of different frequencies can be observed.

To determine which of the proposed mechanisms is more probable, we analyzed the features of the spectra for various samples of experimental animals. Figure 7a shows the total spectra of the BOXX time series (separately for the day and night intervals of the experiment); Figs. 7b–7d show the total spectra for the following samples: (b) all 16 animals in total, (c) 5 animals (M3, M6, M7, M9, and M16) with the highest frequency of similarity, and (d) 5 animals (M1, M11–M14) with the lowest frequency of similarity.

It is easily seen that the spectra of the BOXX day and night intervals (Fig. 7a) differ significantly: the period of 45–48 min (0.35–0.37 mHZ) dominates in the day intervals and there are also periods of 65 and 80 min (0.21–0.26 mHZ), while at night the maximum frequency of occurrence shifts to periods of 65 and 80 min (0.26 and 0.21 mHZ, respectively) and there are practically no periods of 45 min (0.37 mHZ). The period of 72 min (0.23 mHZ) corresponds to a local minimum both in the day and night spectra.

Distributions of spectrum amplitudes of biological series look almost the same both in the daytime and at night within each of the three samples and for different samples. There are no clearly defined extrema. This fact testifies in favor of the assumption that stable (monochromatic) endogenous frequencies are not present in the rhythm of the studied biological parameter.

At the same time, an analysis of the individual characteristics of the frequency distribution in the spectra of biological series shows that in a number of cases there is still a change in the characteristics of the rhythm depending on the time of day, and these

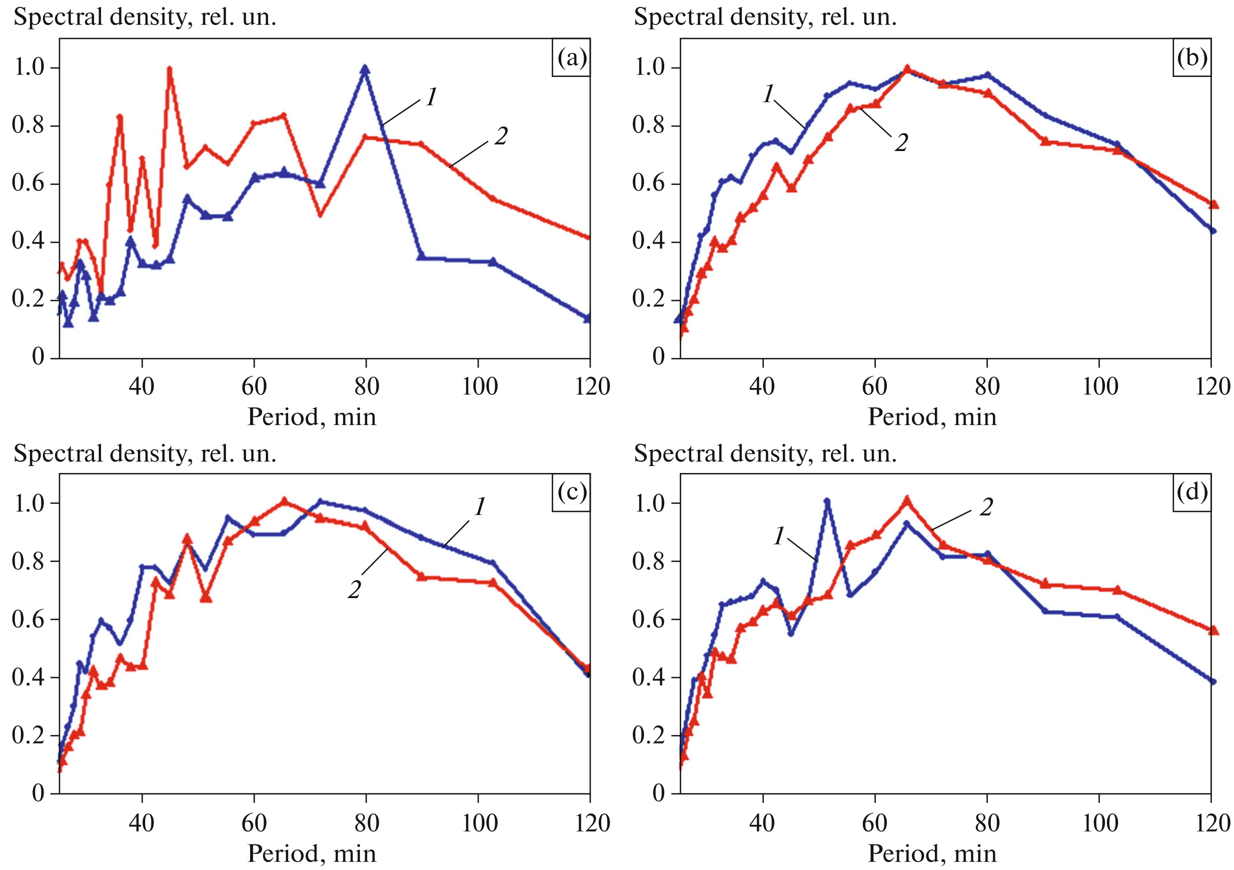

Fig. 7. Total spectra of the investigated geophysical and biological time series separately for night (*1*) and day (*2*) observation intervals. (a) BOXX, (b) all animals, (c) 5 animals with the highest frequency of similarity, and (d) 5 animals with the lowest frequency of similarity.

changes are similar to the features observed in the geophysical series. Thus, Fig. 8 shows the time-frequency distribution of the presented periods sequentially for 16 night (Fig. 8a) and day (Fig. 8b) observation intervals of the BOXX series and the reactions of animals M3 and M5. Each horizontal line displays the spectrum of a certain day; the intensity of the periods is reflected by the intensity of the red color.

A comparison of the data presented in Fig. 8 shows that the highest frequency of the maximum intensity periods in biological series in the daytime corresponds to 60 min (0.28 mHZ) and, at night, to 80 min (0.21 mHZ). In the figure these intervals are limited by vertical lines. This behavior of the spectral rhythm suggests that the averaged spectra shown in Fig. 7 do not fully reflect the peculiarities of biological rhythm, and there is not enough material for the final choice in favor of any of the hypotheses formulated above.

DISCUSSION

In this study, the following tasks were set and solved.

1. On the basis of traditional methods of statistical and correlation analysis, we developed a method to reveal the effect of synchronization of variations in the GMF vector and time series of motor activity in laboratory mice, which in these animals is largely determined by the activity–rest cycle.

2. It has been shown that the coincidence of spectra on 12-h intervals of the time series occurs many times more often than is possible with a random coincidence; i.e., for the activity–rest cycle in mice, the effect of the frequency adjustment of biological rhythm to the vibrations present in the geomagnetic spectrum has been observed.

3. A primary assessment of the characteristics of the effect, namely, the peculiarities of its variations over individual animals, days of observation, and certain frequencies of the spectrum, has been made.

It was found that the distribution of correlation coefficients calculated for 512 time intervals of biological and geomagnetic series is highly asymmetric. Approximately 18% of anomalously high values are outside the boundaries of random distribution, which corresponds to cases of significant proximity of the compared spectra.

The distribution of such cases of spectrum similarity by individual animals and by days of observation

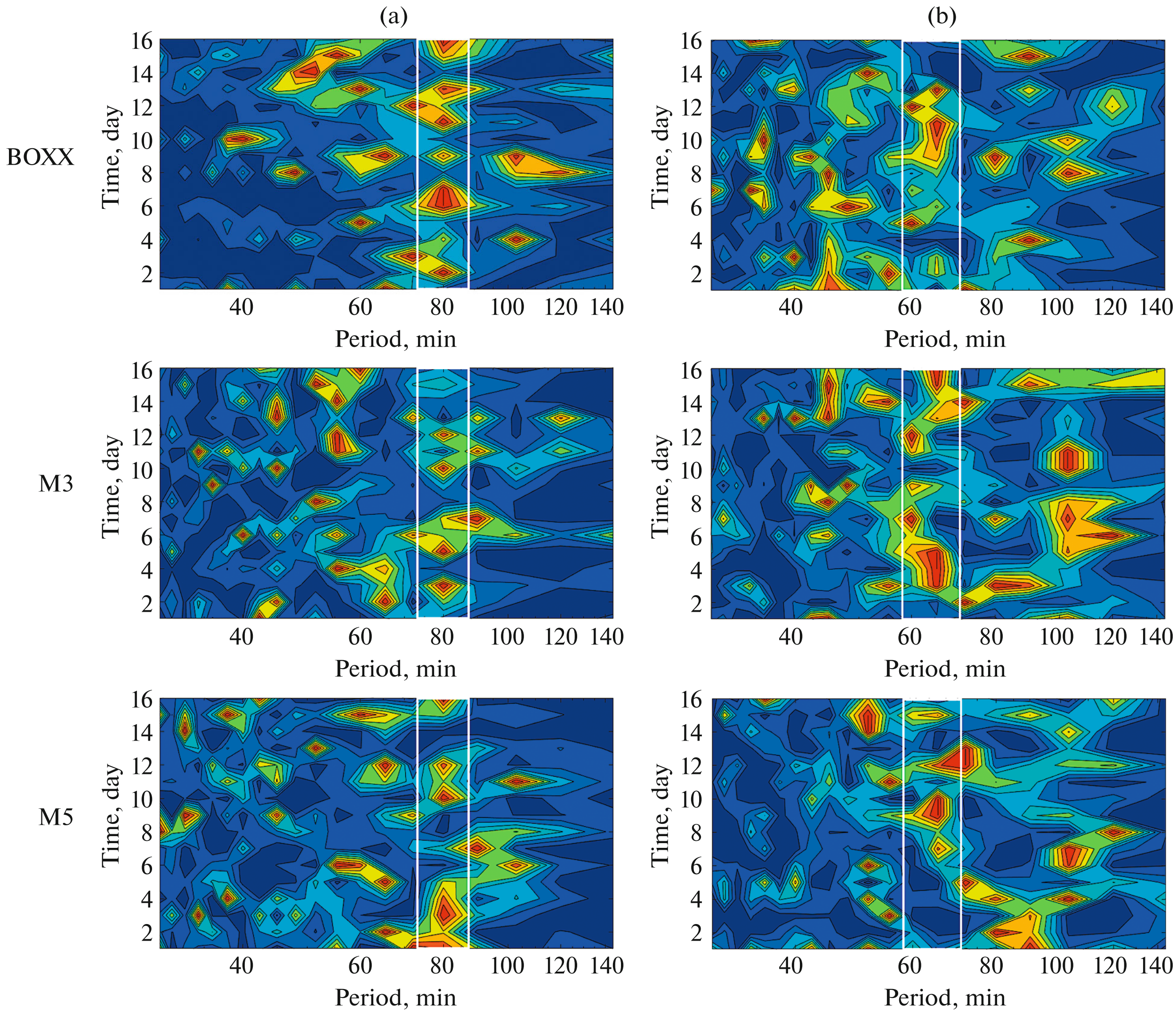

Fig. 8. Spectra of sequential 16 night (a) and day (b) intervals of time series. See text for explanations.

does not provide reasons for dividing the group of experimental animals into magnetically sensitive and magnetically insensitive, since the number of cases of similarity varies smoothly from 2 to 9 for different animals. This is similar to the effect of synchronization of the heart rate with variations in the geomagnetic field (Alabdulgade et al., 2015; Timofejeva et al., 2017): it was not possible to divide the participants of the study into certain groups of stably magnetically sensitive or stably magnetically insensitive persons.

It was found that the number of cases of similarity varies greatly from day to day, with a slight predominance of the number of cases at night. To date, no data have been found in the literature on the symmetry or asymmetry of the sensitivity distribution at different day periods, but this issue is extremely important for understanding the mechanism of the effect. The database we used in our work may simply not be sufficient to evaluate such differences.

It was also shown that, in different individual time intervals, synchronization is found at different values of the main fluctuation periods. This result testifies in favor of the assumption about the adjustment of the biological rhythm to the variations of the geophysical rhythm. Consequently, the revealed association of changes in the activity of animals and GMF variations is determined not simply by a random coincidence of the period characteristics of these studied parameters. This conclusion is consistent with the results obtained earlier in the studies on synchronization of the human heart rate with GMF variations (Zenchenko et al., 2013, 2014) and the physiological rhythms of animals in the range of periods of 10–120 min (0.14–1.67 mHz) in different individuals, even at a considerable distance from each other (Dzalilova et al., 2019; Diatroptov et al., 2020a, 2020b).

However, further experimental studies are needed to conclude that it is the fluctuations of the magnetic field, not related to their formation other physical factors, that affect the rhythm of the activity of animals, particularly the activity–rest cycle. There are two reasons to explain the complexity of such studies.

1. The mechanism of magnetic-field reception in organisms is tuned precisely to the registration of extremely weak variations in magnetic fields, which are comparable in amplitude to the GMF oscillations. The ability of the body's cells to respond to ultraweak magnetic fields during distant intercellular interactions has also been mentioned earlier (Kaznacheev et al., 1981). Consequently, more intense artificially generated signals may not be perceived by the organisms.

2. Passive magnetic shielding does not provide the complete elimination of GMF variations in the investigated ultra-low-frequency range. If the body has a highly sensitive mechanism of magnetoreception, even a significant decrease in the signal amplitude does not always cause a corresponding decrease in the response in the rhythm of the activity–rest cycle, since we observe precisely the phenomenon of synchronization and not the direct activating/inhibiting effect of geomagnetic pulsations.

CONCLUSIONS

(1) The existence of the synchronization effect in the geophysical and biological time series shows that the degree of sensitivity of various animals changes smoothly and varies over time. A more accurate determination of the prevalence of the effect in the population and in time requires larger experimental samples and duration of observations.

(2) In some cases, the mean group and individual analysis reveal synchronization effect in the geophysical and biological time series: observed fluctuations are close in frequency and phase to similar fluctuations in the dynamics of the geomagnetic field vector with periods of 40–100 min (0.17–0.42 mHz), the amplitude and phase of which vary; distribution of the obtained correlation coefficients over the time lag in the form of a median shows that the maximum corresponds to a zero shift between the series.

(3) The BOXX spectra of the day and night intervals differ: the period of 45–48 min (0.35–0.37 mHz) dominates in the day intervals and there are also periods of 65 and 80 min (0.21–0.26 mHz) (with a lower amplitude), while at night the maximum frequency of occurrence shifts to periods of 65 and 80 min (0.26 and 0.21 mHz, respectively), and there are practically no periods of 45 min (0.37 mHz). The period of 72 min (0.23 mHz) corresponds to a local minimum in both the day and night spectra. The distribution of amplitudes in the spectra of biological series also looks similar and there are no clearly pronounced extrema.

ACKNOWLEDGMENTS

The results presented in this article are based on data collected from magnetic observatories. We thank the national institutions supporting the observatories and the leadership of the INTERMAGNET international network for promoting the high standards of practice in magnetic observatories (www.intermagnet.org).

FUNDING

This study was supported by the state budget and partly with financial support from the Russian Foundation for Basic Research, project no. 20-013-00603a.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

Alabdulgade, A., McCraty, R., Atkinson, M., Vainoras, A., Berškienė, K., Mauricienė, V., Navickas, Z., Šmidtaitė, R., Landauskas, M., and Daunoravičienė, A., Human heart rhythm sensitivity to earth local magnetic field fluctuations, *J. Vibroeng.*, 2015, vol. 17, pp. 3271–3278.

Alabdulgade, A., McCraty, R., Atkinson, M., Dobyns, Y., Stolc, V., and Ragulskis, M., Long-term study of heart rate variability responses to changes in the solar and geomagnetic environment, *Sci. Rep.*, 2018, vol. 8, no. 1, p. 2663. https://doi.org/10.1038/s41598-018-20932-x

Blum, I.D., Zhu, L., Moquin, L., Kokoeva, M.V., Gratton, A., Giros, B., and Storch, K.F., A highly tunable dopaminergic oscillator generates ultradian rhythms of behavioral arousal, *Elife*, 2014, vol. 3, p. e05105. https://doi.org/10.7554/eLife.05105

Bourguignon, C. and Storch, K.F., Control of rest: Activity by a dopaminergic ultradian oscillator and the circadian clock, *Front Neurol.*, 2017, vol. 8, p. 614. https://doi.org/10.3389/fneur.2017.00614

Breus, T.K., Halberg, F., and Cornélissen, G., Effect of solar activity on the physiological rhythms of biological systems, *Biofizika*, 1995, vol. 40, no. 4, pp. 737–747.

Breus, T.K., Binhi, V.N., and Petrukovich, A.A., Magnetic factor of the solar terrestrial relations and its impact on the human body: physical problems and prospects for research, *Phys.-Usp.*, 2016, vol. 59, no. 5, pp. 502–510.

Chizhevsky, A.L., *Zemnoe ekho solnechnykh bur'* (The Terrestrial Echo of Solar Storms), Moscow: Mysl', 1976.

Cornélissen, G., Halberg, F., Breus, T.K., Watanabe, Y., Sothern, R., Haus, E., Kleitman, E., Wendt, H.W., and Bingham, C., The possible origin of the biological week inferred from the human heart rate variations over the solar activity cycle, *Biophysics*, 1998, vol. 43, no. 4, pp. 628–631.

Cornélissen, G., Halberg, F., Breus, T.K., Syutkina, E.V., Baevsky, R.M., Weydahl, A., Watanabe, Y., Otsuka, K., Siegelova, J., Fiser, B., and Bakken, E.E., Non-photic solar associations of heart rate variability and myocardial infarction, *J. Atmos. Sol.-Terr. Phys.*, 2002, vol. 64, pp. 707–728.

Davis, G.E. and Lowell, W.E., Solar cycles and their relationship to human disease and adaptability, *Med. Hypotheses*, 2006, vol. 67, pp. 447–461. https://doi.org/10.1016/j.mehy.2006.03.011

Diatroptov, M.E., Diatroptova, M.A., Aleksankina, V.V., and Kosyreva, A.M., Intraday biorhythms of body temperature dynamics in c57bl/6 mice under constant illumination and natural photoperiod, *Byull. Eksp. Biol. Med.*, 2020a, vol. 169, no. 3, pp. 361–365.

Diatroptov, M.E., Rutovskaya, M.V., and Surov, A.V., The phenomenon of synchronous food intake in starlings (*Sturnus vulgaris*) under the conditions of isolation from each other, *Dokl. Biol. Sci.*, 2020b, vol. 492, no. 1, pp. 99–102.

Dorokhov, V.B., Taranov, A.O., Sakharov, D.S., Gruzdeva, S.S., Tkachenko, O.N., Arseniev, G.N., Ligun, N.V., Sveshnikov, D.S., Bakaeva, Z.B., Dementienko, V.V., and Puchkova, A.N., Effects of exposures to weak 2 Hz vs. 8 Hz electromagnetic fields on spectral characteristics of the electroencephalogram in afternoon nap, *Biol. Rhythm Res.*, 2020. https://doi.org/10.1080/09291016.2020.1857936

Dzalilova, D.S., Diatroptova, M.A., Mkhitarov, V.A., and Diatroptov, M.E., Infradian rhythms of resistance to a dissociative anesthetic in wistar male rats under normal conditions and after surgical removal of the adrenal glands and testes, *Bull. Exp. Biol. Med.*, 2019, vol. 166, no. 3, pp. 413–416.

Gumarova, L., Cornélissen, G., Hillman, D., and Halberg, F., Geographically selective assortment of cycles in pandemics: Meta-analysis of data collected by Chizhevsky, *Epidemiol. Infect.*, 2013, vol. 141, no. 10, pp. 2173–2184. https://doi.org/10.1017/S0950268812002804

Halberg, F., Breus, T.K., Cornélissen, G., Bingham, C., Hillman, D.C., Rigatuso, J., Delmore, P., and Bakken, E., International womb-to-tomb chronome initiative group, in *Chronobiology in Space: Keynote of 37th Annual Meeting of Japan Society for Aerospace and Environmental Medicine, Nagoya, Japan, November 8–9, 1991*, Minneapolis: Univ. of Minnesota, 1991.

Halberg, F., Cornélissen, G., Otsuka, K., Watanabe, Y., et al., Cross-spectrally coherent ~ 10.5- and 21-year biological and physical cycles, magnetic storms and myocardial infarctions, *Neuroendocrinol. Lett.*, 2000, vol. 21, no. 3, pp. 233–258.

Hayes, D.P., Influenza pandemics, solar activity cycles, and vitamin D, *Med. Hypotheses*, 2010, vol. 74, no. 5, pp. 831–834. https://doi.org/10.1016/j.mehy.2009.12.002

Kaznacheev, V.P. and Mikhailova, L.P., *Sverkhslabye izlucheniya v mezhkletochnykh vzaimodeistviyakh* (Ultraweak Radiation in Intercellular Interactions), Novosibirsk: Nauka, 1981.

Komarov, F.I., Breus, T.K., Rapoport, S.I., Oraevskii, V.N., Gurfinkel', Yu.I., Halberg, F., and Cornélissen, G., Medical and biological effects of solar activity, *Vestn. Akad. Med. Nauk*, 1994, no. 11, pp. 37–50.

Kuznetsov, A.E., Synchronization of the biosynthetic activity of microbial producers of rhythms of cosmophysical original, *Biofizika*, 1992, vol. 37, no. 4, pp. 772–784.

Manolov, A.I., Dolgikh, V.V., Ukraintseva, Yu.V., Zavalko, I.M., Revishchin, A.V., Pavlova, G.V., Pronina, T.S., Ugryumov, M.V., Dorokhov, V.B., and Koval'zon, V.M., Changes in motor activity and the sleep-waking cycle in an MPTP model of Parkinson's disease in mice, *Neurosci. Behav. Physiol.*, 2016, vol. 46, no. 4, pp. 467–471.

McCraty, R., Atkinson, M., Stolc, V., Alabdulgader, A.A., Vainoras, A., and Ragulskis, M., Synchronization of human autonomic nervous system rhythms with geomagnetic activity in human subjects, *Int. J. Environ. Res. Public Health*, 2017, vol. 14, no. 7, p. 770. https://doi.org/10.3390/ijerph14070770

Ohayon, M.M., Stolc, V., Freund, F.T., Milesi, C., and Sullivan, S.S., The potential for impact of man-made super low and extremely low frequency electromagnetic fields on sleep, *Sleep. Med. Rev.*, 2019, vol. 47, pp. 28–38. https://doi.org/10.1016/j.smrv.2019.06.001

Pobachenko, S.V., Kolesnik, A.G., Borodin, A.S., and Kalyuzhin, V.V., The contingency of parameters of human encephalograms and Schumann resonance electromagnetic fields revealed in monitoring studies, *Biophysics*, 2006, vol. 51, no. 3, pp. 480–483. https://doi.org/10.1134/S0006350906030225

Poskotinova, L.V., Zenchenko, T.A., Krivonogova, E.V., and Demin, D.B. Methodological aspects of the monitoring of individual reactions of the brain bioelectrical activity under variations in the geomagnetic field in the Arctic, *Vestn. Ural. Med. Akad. Nauk*, 2018, vol. 15, no. 2, pp. 316–323. https://doi.org/10.22138/2500-0918-2018-15-2-316-323

Qu, J., Is sunspot activity a factor in influenza pandemics?, *Rev. Med. Virol.*, 2016, vol. 26, no. 5, pp. 309–313. https://doi.org/10.1002/rmv.1887

Saroka, K.S., Vares, D.E., and Persinger, M.A., Similar spectral power densities within the Schumann resonance and a large population of quantitative electroencephalographic profiles: Supportive evidence for Koenig and Pobachenko, *PLoS One*, 2016, vol. 11, p. e0146595. https://doi.org/10.1371/journal.pone.0146595

Schweiger, H.-G., Berger, S., Kretschmer, H., Morler, H., Halberg, E., Sothern, R.B., and Halberg, F., Evidence of a circaseptan and circasemiseptan growth response to light/darkness cycle shifts in nucleated and enucleated Acetabularia cells respectively, *Proc. Natl. Acad. Sci. U.S.A.*, 1986, no. 83, pp. 8619–8623.

Temur'yants, N.A., Vladimirskii, B.M., and Tishkin, O.G., *Sverkhnizkochastotnye elektromagnitnye signaly v biologicheskom mire* (ELF Electromagnetic Signals in the Biological World), Kiev: Naukova Dumka, 1992.

Timofejeva, I., McCraty, R., Atkinson, M., Joffe, R., Vainoras, A., Alabdulgader, A., and Ragulskis, M., Identification of a group's physiological synchronization with Earth's magnetic field, *Int. J. Environ. Res. Public Health*, 2017, vol. 14, no. 9, p. 998. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5615535/.

Vieira, C.L.Z., Janot-Pacheco, E., Lage, C., Pacini, A., Koutrakis, P., Cury, P.R., and Shaodan, H., Pereira, L.A., and Saldiva, P.H.N., Long-term association between the intensity of cosmic rays and mortality rates in the city of Sao Paulo, *Environ. Res. Lett.*, 2018, vol. 13, p. 024009. https://doi.org/10.1088/1748-9326/aaa27a

Vladimirskii, B.M. and Temuryants, N.A., *Vliyanie solnechnoi aktivnosti na biosferu–noosferu* (Solar Activity Effect on the Biosphere–Noosphere), Moscow: MNEPU, 2000.

Wickramasinghe, N.C., Is the 2019 novel coronavirus related to a spike of cosmic rays?, *Adv. Genet.*, 2020, vol. 106, pp. 119–122. https://doi.org/10.1016/bs.adgen.2020.06.003

Zenchenko, T.A. and Breus, T.K., The possible effect of space weather factors on various physiological systems of the human organism, *Atmosphere*, 2021, vol. 12, p. 346. https://doi.org/10.3390/atmos12030346

Zenchenko, T.A., Medvedeva, A.A., Khorseva, N.I., and Breus, T.K., Synchronization of human heart-rate indicators and geomagnetic field variations in the frequency range of 0.5–3.0 mHz, *Izv., Atmos. Ocean. Phys.*, 2014a, vol. 50, no. 7, pp. 736–744.

Zenchenko, T.A., Jordanova, M., Poskotinova, L.V., Medvedeva, A.A., Alenikova, A.E., Khorseva, N.I., Synchronization between human heart rate dynamics and Pc5 geomagnetic pulsations at different latitudes, *Biophysics*, 2014b, vol. 59, no. 6, pp. 965–972.

Zenchenko, T.A., Medvedeva, A.A., Potolitsina, N.N., Parshukova, O.I., and Boiko, E.R., Correlation of the dynamics of minute-scale heart rate oscillations and biochemical parameters of the blood in healthy subjects to Pc5–6 geomagnetic pulsations, *Biophysics*, 2015, vol. 60, no. 2, pp. 309–316.

Zhang, Z., Wang, H.J., Wang, D.R., Qu, W.M., and Huang, Z.L., Red light at intensities above 10 Lx alters sleep-wake behavior in mice, *Light Sci. Appl.*, 2017, vol. 6, p. e16231. https://doi.org/10.1038/lsa.2016.231

Translated by T. Kuznetsova