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ELEMENTARY PARTICLES AND FIELDS
Theory

Approximately 2400-Year Cycle in the Concentration of Cosmogenic Radionuclides: Sources of Variations

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Abstract—Cosmogenic isotopes, including ^{14}C, ^{10}Be, and ^{7}Be, are produced in the Earth's atmosphere under the effect of cosmic rays. The rate of their production is determined by several factors, such as the intensity of primary galactic cosmic rays, the level of solar activity, and the strength of the Earth's magnetic field. Changes in the isotope concentrations and distributions receive contributions from mixing processes proceeding in the surrounding medium: the atmosphere, biosphere, and oceans. The isotopes ^{14}C and ^{10}Be are the most important for studying solar activity and climate. Investigation of isotope concentrations reveal that there are both long-term trends and cyclic components. As for ^{14}C, the long-term component caused by the change in the magnetic dipole moment of the Earth with a characteristic time of about 10^4 years is the most commonly known. It is well known that the concentrations of cosmogenic isotopes change cyclically with time. The $\sim$2400-year cycle (Hallstatt cycle) and the $\sim$210-year cycle (de Vries cycle) are the most famous. In the present article, we discuss the possible origin of the $\sim$2400-year cycle.

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INTRODUCTION

The cosmogenic isotopes ^{14}C and ^{10}Be are produced in the Earth's atmosphere under the effect of galactic cosmic rays (GCR). The rate of isotope production is affected by the intensity of primary GCR, the level of solar activity, and the magnetic dipole moment of the Earth. Changes in the isotope concentrations and distributions also receive contributions from mixing processes in environment: the atmosphere, biosphere, and oceans.

In early studies devoted to exploring the influence of the geomagnetic field on the production of cosmogenic isotopes, it was assumed that the geomagnetic field has a dipole character. Elsasser and his coauthors [1], Hofmann and Sauer [2], and O'Brien [3] used Stoermer's geomagnetic-cutoff rigidities to estimate variations in the rate of radiocarbon (^{14}C) production because of the change in the magnetic dipole moment of the Earth. The influence of solar activity on the rate of ^{14}C production was discussed in detail earlier in [4–6].

The parameters of the radiocarbon exchange reservoir were considered in [7–9]. In [10, 11], the solar activity, production rate for cosmogenic isotopes, and solar radiation were reconstructed on the basis of the radiocarbon exchange reservoir.

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Radiocarbon, which propagates in the atmosphere, is captured by plants. Of great interest is ^{14}C in tree rings, which form a chronological sequence (dendrochronology) making it possible to establish the date of wood-substance fragments to a precision of one year.

The INTCAL13 radiocarbon chronology of length 50 thousand years has been obtained to date [12].

BASIC PROPERTIES OF THE RADIOCARBON SEQUENCE

Let us now consider basic properties of the radiocarbon sequence according to INTCAL13 data. The relative radiocarbon concentration (Δ^{14}C) is the parameter which we are interested. In Fig. 1 the $R_{\rm C}$ curve represents Δ^{14}C as a function of time. The smooth curve singles out a cyclic trend around which small-scale fluctuations of the ^{14}C concentration occur. The cyclic change in the radiocarbon concentration is due to the quasiperiodic change in the Earth's magnetic field (see D_M curve).

A careful examination of fluctuations of the ^{14}C concentration with respect to the trend shows that outliers appear from time to time. This can clearly be seen when removing the trend from radiocarbon data (see Fig. 2). Anomalous deviations from the trend are appeared at nearly regular time intervals. The average value of the time interval is 2300 years. Earlier, this quasiperiod was found in the spectral analysis of the

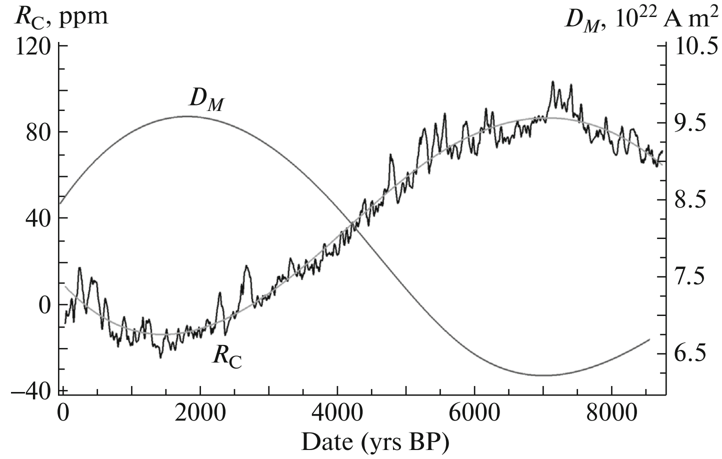

Fig. 1. Radiocarbon sequence according to INTCAL13 data (R_C curve). The time is reckoned from 1950 toward the past. The relative concentration of ^{14}C is plotted along the left ordinate. The smooth curve represents a cyclic trend. The D_M curve is the smoothed curve for the magnetic dipole moment of the Earth [13]. BP stands for "before present" and means the number of years reckoned from 1950 AD toward the past.

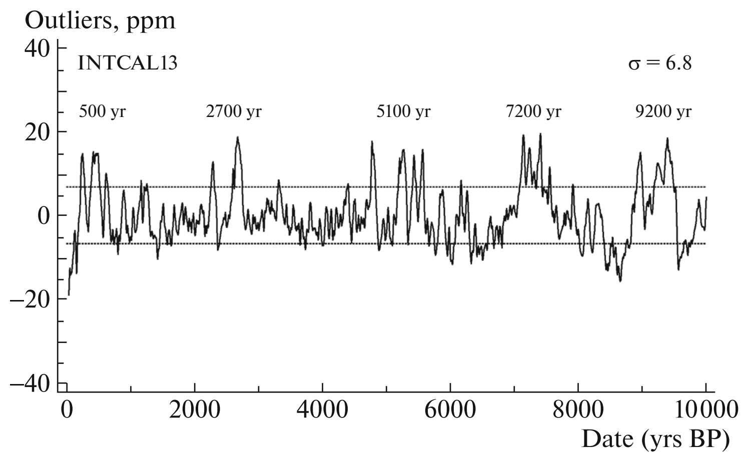

Fig. 2. Radiocarbon data after the removal of the trend. The horizontal dashed lines are drawn at the level of one standard deviation (1σ). Large outliers are observed at time intervals of about 2300 years. The dates of the appearance of anomalous deviations from the trend are indicated.

power spectrum and in a visual examination of various radiocarbon sequences [14–15].

The power spectrum for the present-day radiocarbon sequence [12] is shown in Fig. 3. The significance of periodogram peaks was determined by a method based on the red-noise model [16]. Peaks in the periodogram that have a significance in excess of 0.95 include ∼2400-year, 350-year, and ∼200-year peaks. In the following, we will discuss the ∼200-year cycle, which is of importance for the ensuing conclusions.

An extensive analysis aimed at clarifying the nature of the ∼2400-year cycle has been performed to date. Basically, considered three reasons for its emergence. These are (i) the change in the climate, (ii) solar activity, and (iii) variations of the geomagnetic field.

QUASI-MILLENNIAL CYCLES AND CLIMATIC PHENOMENA

In connection with studies of the ∼2400-year radiocarbon cycle, there arose interest in the existence of quasi-millennial climatic cycles.

Bray [17] put forth the idea that a 2600-year climatic cycle exists. His conclusions relied on the discovery of periodic advances and retreats of glaciers within the holocene. If the phenomenon that Bray observed was due to climatic processes, then it is important to find other signatures of these changes. A change in the parameters of radiocarbon exchange

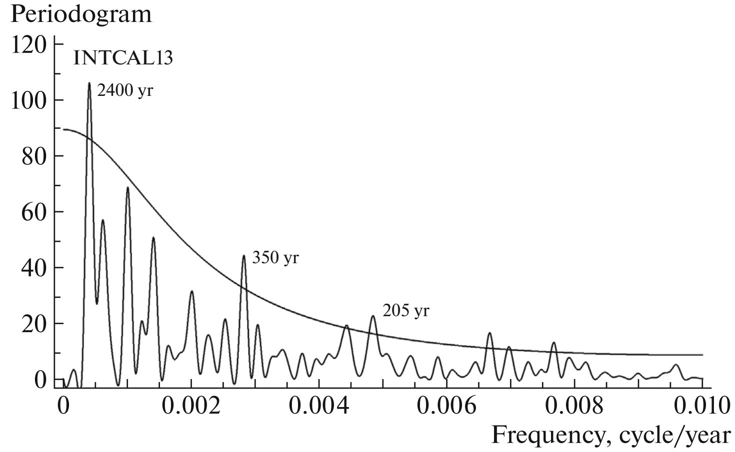

Fig. 3. Lomb–Scargle periodogram for the $\Delta^{14}C$ sequence. The smooth curve delimits amplitudes whose confidence level does not exceed 0.95.

between the atmosphere and ocean may be a consequence of a global climatic cycle, and this would lead to a change in the concentration $\Delta^{14}C$ in the atmosphere. It is the most natural to seek these signatures in the change of the concentration $\Delta^{14}C$ in tree rings.

The results of studying the dendrochronology of oak-tree rings in Central Europe [18, p. 378] exemplify the existence of climate variations with a period of 2300 to 2400 years.

The atmosphere temperature change is reflected by the changes of $^{18}O/^{16}O$ ratio of concentrations from rainfalls Polar ice formed by rainfalls carries important information about the change in temperature.

O'Brien [19] described the results of a geochemical analysis of the Greenland ice core. According to these results, a colder climatic period begins approximately every 2600 years.

An ∼2500-year climatic period was also mentioned in [20, 21].

Recently, Usoskin and his coauthors [22] applied a singular spectral analysis (SSA) in comparing ^{14}C and ^{10}Be data fixed in natural archives (tree rings and polar ice) as the result of various climatic processes. In accordance with the difference in the way of formation, the first SSA components do not correlate. As for the second components, their variations are similar. These components are quite consistent. Second components of SSA are dominated by an ∼2400-year periodicity. In all probability, the second components are formed under the effect of general processes. These results rule out the climatic nature of the ∼2400-year cycle.

AMPLITUDE MODULATION OF THE ∼200-YEAR CYCLE

Solar activity and fluctuations of the geomagnetic field may be other possible sources of such variations. In the early 1990s, the geomagnetic nature of quasiperiodicity in the concentration $\Delta^{14}C$ thought to be hardly probable, because variations in the magnetic dipole moment that have the required amplitude and a period of about 2400 yr were not known at that time [18]. Since then, however, modern data on variations in the magnetic dipole moment of Earth appeared [13], permitting a fresh look at the problem.

For the ensuing analysis of the ∼2400-year cycle, we highlight the following important property of ∼200-year variations of radiocarbon. As was indicated in [4, 9], ∼200-year variations in the radiocarbon sequence likely are of the solar origin, since they correlate with epochs of Grand solar-activity minima. Figure 4 shows the rate of ^{14}C production over the past 1000 years. Given in this figure are both the original radiocarbon-production rate [10] and the rate filtered in the vicinity of the 210-year line. One can see that the curve at ∼200-year years correlates with the rate of ^{14}C production in the atmosphere. Figure 4 also shows that, in the era of Grand solar-activity minima, the production rate for cosmogenic isotopes grows; also, the amplitude of the ∼210-year wave grows synchronously. It follows that the ∼210-year cycle is of the solar origin.

Table 1 lists the known Grand solar-activity minima of the last millennium. More comprehensive information can be found in [22].

In order to clarify the nature of the ∼2400-year cycle, it is important to bear in mind that there is an amplitude modulation (AM) of ∼210-year variations of the concentration $\Delta^{14}C$. Earlier, the modulation of ∼210-year variations against the background of

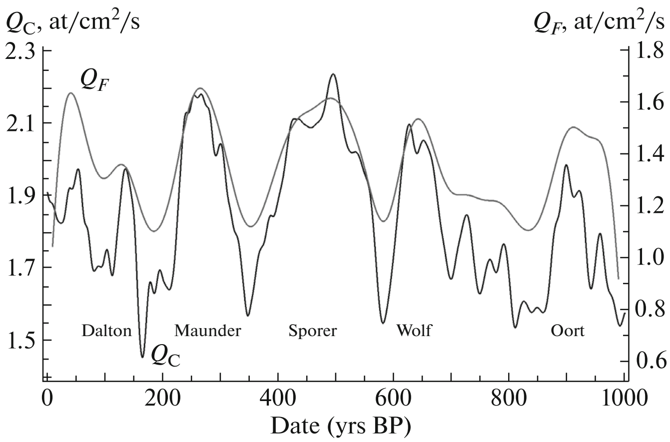

Fig. 4. Global rate of ^{14}C production over 1000 years (Q_C curve). The legend shows the positions of Grand solar-activity minima. The Q_F curve represents data of the Q_C sequence that were filtered in the vicinity of the frequency of 0.0047 yr^{-1} (period of about 210 years).

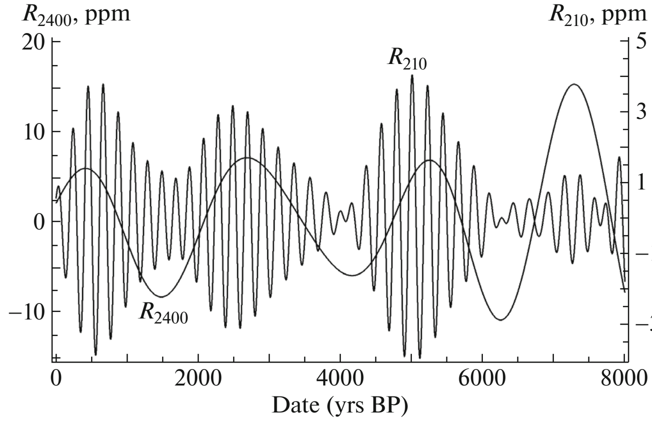

Fig. 5. Results of filtering radiocarbon-sequence data. The amplitudes after a low-frequency filtration (period of about 2400 years) R_{2400} and a band filtration (period of about 210 years) R_{210} are plotted along, respectively, the left and the right ordinate.

$\sim$2400-year changes in the radiocarbon concentration was studied in [23, 15].

A formal AM model can be represented in the form

$$\Delta^{14}C_{\rm mod} = \Delta^{14}C_0(1 + a\sin\omega_M t)(1 + b\sin\omega_c t),$$

where ω_M is the frequency of the modulating signal and ω_c is the frequency of the modulated signal.

In Fig. 5, data of low-frequency filtration (wavelengths of more than 1600 years) are compared with data of band filtration (a wavelength of about 210 years). One can see that the amplitude of $\sim$200-year variations grows synchronously with the amplitude of the $\sim$2400-year wave. High-frequency variations of the concentration Δ^{14}C behave with respect to $\sim$2400-year variations in just the same way as the change in the production rate for radiocarbon (^{14}C) behaves with respect to the change in the solar activity (see Fig. 4). Does this mean that the nature of the 2400-year variations is of the solar origin?

A sufficiently effective empirical method for determining source of quasi-millennial variations in the rate of production of cosmogenic isotopes was proposed earlier in [24]. Following this method, we will consider two versions of the origin of the amplitude modulation of $\sim$200-year variations of the concentration in the radiocarbon sequence. According to the first version, it is due exclusively to processes initiated by interaction of solar wind with primary GCR. The solar-modulation parameter (SMP) characterizes the strength of this interaction. For the first version, we will consider the modulation of $\sim$200-year fluctuations of the radiocarbon production rate by low-frequency, $\sim$2400-year, variations of the geomagnetic field. In order to obtain a more realistic picture of AM, we will make use of the results of a simulation of the rate of ^{14}C production in the Earth's atmosphere [25–27].

Radiocarbon is produced in the atmosphere upon thermal-neutron interaction with nitrogen via the reaction $n(^{14}\mathrm{N}, {}^{14}\mathrm{C})p$. The efficiency of ^{14}C production depends on the local spectrum of cosmic rays penetrated to the atmosphere. The local spectrum of cosmic rays is determined by the solar-activity level and is parameterizes in terms of SMP [28, 10]. On the other hand, the efficiency of ^{14}C production depends on the magnetic dipole moment screening the atmosphere from cosmic rays [3].

Table 1. Positions of Grand solar-activity minima in the past millennium

Center, yr AD	Duration, yr	Name	Center, yr, BP
1810	40	Dalton	140
1680	80	Maunder	270
1470	160	Spörer	480
1310	80	Wolf	640
1030	80	Oort	920

BP stands for before present and means the number of years reckoned from 1950 AD toward the past.

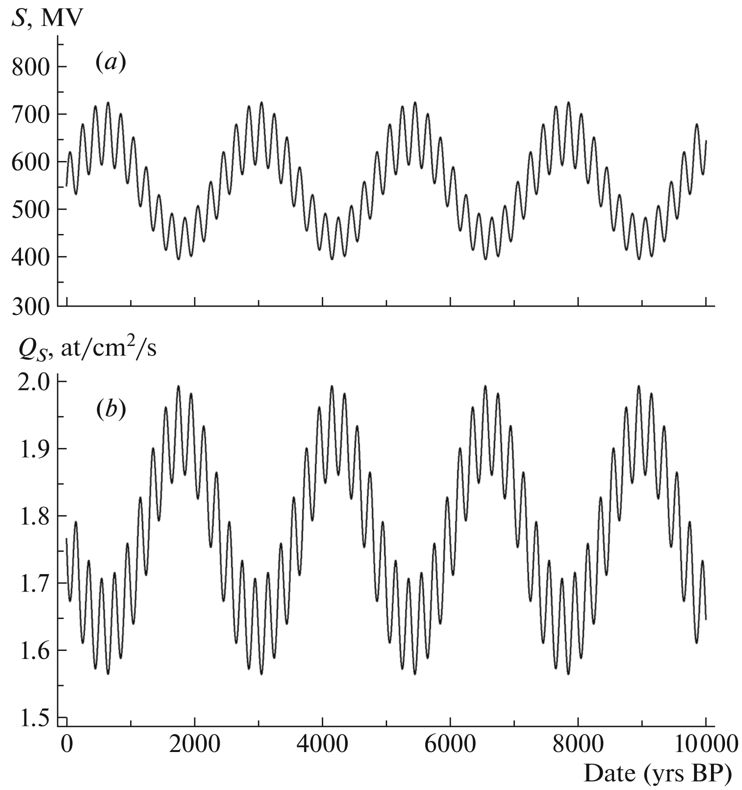

Fig. 6. Solar-modulation parameter S according to the AM 1 model (a) and global rate of ^{14}C production Q_s according the AM 1 model (b). The results reported in [27] were used in the calculations. The magnetic dipole moment was assumed to be constant.

SIMULATION OF AMPLITUDE MODULATION

We will simulate the above versions via which there arises an amplitude modulation in the radiocarbon sequence.

In the first version (AM 1), the amplitude modulation is due exclusively to the change in SMP (S) according to the law

$$S = (1 + a_s \sin\omega_M t)(1 + b_s \sin\omega_c t), \qquad (1)$$

where a_s and ω_M are, respectively, the amplitude and frequency of the ∼2400-year modulation, while b_s and ω_c are those of the ∼200-year signal. Expression (1) was used to calculate the ^{14}C production rate at a constant value of the magnetic dipole moment.

Figure 6 shows that, within the AM 1 model, the amplitude of the ∼200-year variations is independent of the phase of ∼2400-year modulations. A comparison of this picture with the result of filtration of the radiocarbon sequence (see Fig. 5) indicates that the AM 1 model is inconsistent with radiocarbon data.

Let us consider the second amplitude-modulation model (AM 2). In that case, ∼200-year SMP variations occur, as one can observe this in the radiocarbon sequence (see Fig. 5). In addition, we admit the existence of ∼2400-year variations of the magnetic dipole moment; that is,

$$\begin{cases} S = S_0\,(1 + b_d \sin(\omega_c t)) \\ D = D_0\,(1 + a_d \sin(\omega_M t)) \end{cases} \qquad (2)$$

where S_0 and D_0 are the average values of, respectively, SMP and the magnetic dipole moment of the Earth.

The results of the simulation are presented in Fig. 7. In contrast to what we had for the AM 1 model, the amplitude of ∼200-year variations of the ^{14}C production rate depends in this case on the phase of ∼2400-year variations in the magnetic dipole moment of the Earth. Comparing Figs. 5 and 7, we can see qualitative agreement in the behavior of the amplitudes in the AM 2 model and the filtered radiocarbon sequence (Fig. 5).

ESTIMATION OF THE AMPLITUDES OF ∼200-YEAR VARIATIONS

Let us now perform analytic estimations of the amplitude of ∼200-year variations for the two amplitude-modulation models formulated above. We will

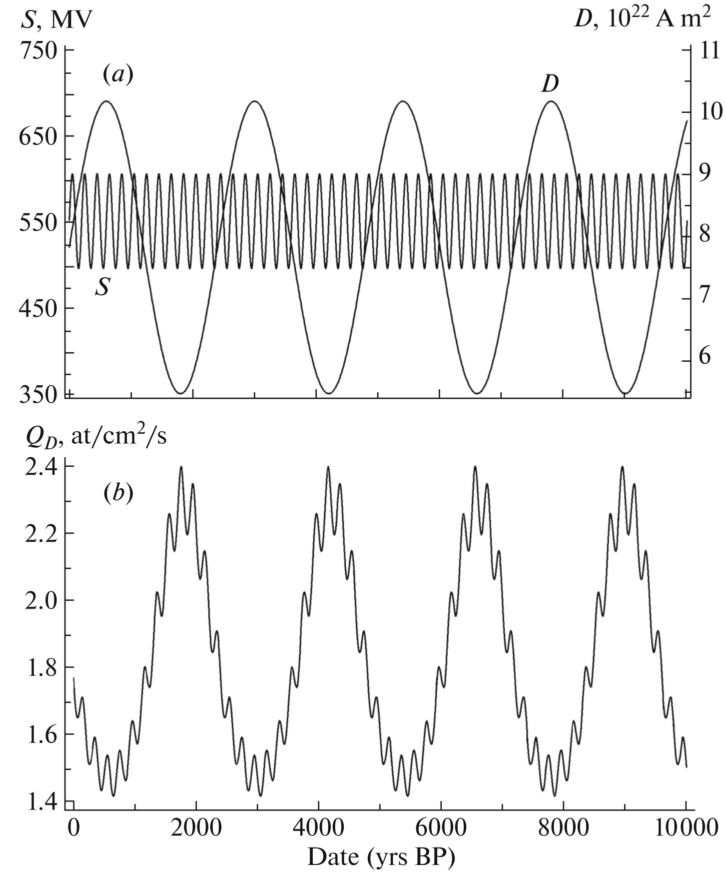

Fig. 7. ~200-year variations of the solar-modulation parameter S (left ordinate) and ~2400-year changes in the magnetic dipole moment D (right ordinate) according to the AM 2 model (a) and global rate of ^{14}C production (Q_D) according to the AM 2 model (b). The results reported in [27] were used.

consider the radiocarbon production rate Q as a function of SMP S and the magnetic dipole moment D—that is, $Q = Q(S, D)$, where the values of $Q(S, D)$ are given in Table 2 (see also the note under this table).

In view of the smallness of deviations of S from the average value of this parameter, S_0, it is sufficient to confine oneself, in analyzing the amplitude-modulation model specified by Eq. (1), only by the linear term in the expansion of Q in a power series in $S - S_0$. The relative change in the amplitude of ~200-year variations, ΔQ_S, in the opposite phases of the ~2400-year cycle will then be $\Delta Q_S = \partial \ln Q/\partial \ln S \times a_s$, where a_s is the modulation amplitude in the AM 1 model. Making use of the data in Table 2 for $Q = Q(S, D)$, we find the relation $\Delta Q_S \approx -0.4a_s$ at the average values S_0 and D_0 ($S_0 = 550$ MV and $D_0 = 7.8 \times 10^{22}$ A m^2). One can see that, for $a_s < 1$, the change in the amplitude versus the modulation phase is insignificant.

Let us now proceed to consider the AM 2 amplitude-modulation model. In just the same way as in the preceding case, we restrict ourselves to expansion $Q = Q(S, D)$ in a power series in the small parameters $S - S_0$ and $D - D_0$. The relative difference of the amplitudes of ~200-year variations of ΔQ_D in the opposite phases of the ~2400-year cycle can then be estimated as $\Delta Q_D = \partial\,(\ln Q_s)/\partial \ln D$, where $Q_s = \partial Q/\partial \ln S$. Making use of the data in Table 2 for $Q(S, D)$, we obtain the relation $\Delta Q_D = 8.3a_d$ at the average parameter values S_0 and D_0. Thus, even for a small value of the parameter a_d, a considerable difference in the amplitude of the 200-year variations in the opposite phases of the 2400-year cycle will be observed. At the same time, the increase in the amplitude being considered correlates with the increase in the amplitude of the ~2400-year wave (see Fig. 5).

CONCLUSIONS

We will briefly touch upon the question, what variations of the geomagnetic field may exist. Fluctuations of the geomagnetic field are observed over a broad range of time scales [29]. Times about 10^8

Table 2. Rate of ^{14}C production (in at./cm^2/s units) [27]

D	S					
	300	400	500	600	700	800
5	2.77	2.52	2.32	2.14	1.99	1.86
5.2	2.71	2.47	2.27	2.1	1.95	1.82
5.4	2.66	2.42	2.23	2.06	1.91	1.79
5.6	2.61	2.38	2.19	2.02	1.88	1.76
5.8	2.56	2.33	2.15	1.99	1.85	1.73
6	2.51	2.29	2.11	1.95	1.82	1.7
6.2	2.47	2.26	2.08	1.92	1.79	1.67
6.4	2.43	2.22	2.04	1.89	1.76	1.65
6.6	2.39	2.18	2.01	1.86	1.73	1.62
6.8	2.35	2.15	1.98	1.83	1.71	1.6
7	2.31	2.11	1.95	1.8	1.68	1.57
7.2	2.28	2.08	1.92	1.78	1.65	1.55
7.4	2.24	2.05	1.89	1.75	1.63	1.53
7.6	2.21	2.02	1.86	1.73	1.61	1.51
7.8	2.18	1.99	1.84	1.7	1.59	1.49
8	2.15	1.96	1.81	1.68	1.57	1.47
8.2	2.12	1.94	1.79	1.66	1.55	1.45
8.4	2.09	1.91	1.76	1.64	1.53	1.43
8.6	2.07	1.89	1.74	1.62	1.51	1.41
8.8	2.04	1.87	1.72	1.6	1.49	1.4
9	2.01	1.84	1.7	1.58	1.47	1.38
9.2	1.99	1.82	1.68	1.56	1.45	1.36
9.4	1.97	1.8	1.66	1.54	1.44	1.35
9.6	1.94	1.78	1.64	1.52	1.42	1.33
9.8	1.92	1.76	1.62	1.51	1.41	1.32
10	1.9	1.74	1.6	1.49	1.39	1.3
10.2	1.88	1.72	1.59	1.47	1.37	1.29
10.4	1.86	1.7	1.57	1.46	1.36	1.28
10.6	1.84	1.68	1.55	1.44	1.35	1.26
10.8	1.82	1.66	1.54	1.43	1.33	1.25
11	1.8	1.65	1.52	1.41	1.32	1.24

S is the solar-modulation parameter (in MV units), and D is the magnetic dipole moment of the Earth (in 10^{22} A m^2 units).

years are characteristic of a slow convective motion in the Earth's mantle (see, for example, [30]). Dynamo processes in the liquid core are associated with faster changes in the geomagnetic field. Dynamic processes may modify the magnetic field of the Earth's core over 10^2 years [31], whereas the dipole decay time is about 10^4 years [32]. Waves with periods 10^1 to 10^3 years can make a nontrivial contribution to variations of the geomagnetic field [33–35].

The above analysis of the AM 1 and AM 2 amplitude-modulation models gives sufficient grounds to assume that variations in magnetic dipole moment of the geomagnetic field are responsible for the observed 2400-year variations of the radiocarbon concentration.

Quantitative estimations based on the analysis of data on the magnetic dipole moment and radiocarbon production rate are required for drawing a definitive conclusion.

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