CHANGES IN THE SOLAR MODULATION PARAMETER IN THE HOLOCENE AND THE GEOMAGNETIC DIPOLE INCLINATION

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Received February 03, 2025

Revised April 06, 2025

Accepted June 17, 2025

Abstract. Knowledge of solar activity in the past is important for predicting solar activity in the future. One of the main quantities characterizing solar activity is the solar modulation parameter (SMP), which parameterizes solar activity using the equation describing the propagation of cosmic rays in the solar system. The SMP for the last few decades has been determined using neutron monitors. Cosmogenic isotopes are commonly used to obtain information on PSM beyond the instrumental period.

We applied data on the formation rate of ^{10}Ve for the last 9.5 thousand years. According to Kovaltsov and Usoskin [2010], there is an unambiguous relationship between the rate of ^{10}Ve production, geomagnetic field strength, and PSM. We used this relationship to determine the solar modulation parameter for the Holocene.

The time dependence of the PSM was shown to be nonstationary. For further analysis, we used the empirical mode decomposition method [Huang et al., 2003]. When analyzing the obtained modes, it was found that among the younger modes there are cycles with a period of 710 years and 208 years. The latter mode is a manifestation of the De Fries cycle known in the analysis of cosmogenic isotopes. The existence of the cycle with a period of 710 years does not find an explanation within the standard concepts of cosmogenic isotopes. We associated the existence of the 710-year cycle with fluctuations in the tilt of the Earth's magnetic dipole.

Taking into account the influence of fluctuations of the dipole tilt on the cosmogenic isotope formation rate showed that the De Fries cycle in the Holocene was a dominant low-frequency cycle with a period of about a hundred years. As the wavelet analysis showed, its amplitude practically did not change for 9.5 thousand years.

The aim of the paper is to investigate the cyclicity of solar activity taking into account the existence of fluctuations of the Earth's magnetic dipole tilt.

DOI: 10.31857/S00167940250704e4

1. INTRODUCTION

1.1 Cosmic ray propagation in the Solar System

The rate of formation of cosmogenic radionuclides depends on the intensity of penetration of galactic cosmic rays (GCRs) into the Earth's atmosphere. Before reaching the Earth, GCRs must cross the heliosphere, where they are affected by solar modulation. The propagation of GCRs through the heliosphere is described by the cosmic ray transport equation formulated by Parker [1965]. The GCR spectra and, consequently, the formation rate of cosmogenic radionuclides depend on the local interstellar cosmic ray spectrum J_{LIS} and the solar modulation parameter F. Different approaches to the determination of J_{LIS} are described by Herbst et al. [2010].

1.2 Formation of cosmogenic isotope ^{10}Be in the Earth's atmosphere

Protons and neutrons from cosmic rays penetrating the atmosphere interact with nitrogen and oxygen to form ^{10}Be by reactions:

$$^{14}N + n(p) \Rightarrow {}^{10}Be + 3p(4p) + 2n(1n)$$
$$^{16}O + n(p) \Rightarrow {}^{10}Be + 4p(5p) + 3n(2n)$$

The rate of isotope formation depends on the cosmic ray flux incident on the atmosphere, which varies due to the modulating effects of the solar wind and the Earth's magnetic field.

1.3 Earth's magnetic field

The Earth's magnetic field is essentially dipole-like. The Earth's past magnetic field has been determined from archaeomagnetic data. The dipole moment D for the Holocene has been studied in detail by McElhinny and Senanayake [1982], as well as Yang et al. [2000], Knudsen et al. [2008], who used a large amount of archaeomagnetic data. Another approach was used by Constable et al. [2016], who developed a spherical harmonic field model to estimate dipole moment changes based on archaeomagnetic data. Figure 1 shows the Earth's dipole moments for the last 10 thousand years obtained by some of the above researchers.

1.4. Synchronization of the series ^{10}Be and ^{14}C

Variations in galactic cosmic rays reaching the Earth's atmosphere cause synchronous changes in the rate of cosmogenic radionuclide formation. Muscheler et al. [2014] compared the radiocarbon timescale with the ^{10}Be timescale over the last 14,000 years, identifying and synchronizing common short-term changes in the annual ring records of ^{10}Be and ^{14}C.

1.5 Solar Modulation Parameter

The formation rate of cosmogenic isotopes Q, such as ^{10}Be or^{14}C , is affected by the local cosmic ray spectrum in the Earth's neighborhood J_{LIS}, the geomagnetic field strength, and the solar modulation parameter Φ. Typically, numerical methods are used to calculate Q. Details of this approach can be found in Masarik and Beer [1999] and Kovaltsov and Usoskin [2010].

2. METHODS AND RESULTS

2.1 A real-world approach to the calculation of the solar modulation parameter Φ

In calculating the present-day expression for Φ, we used data on the formation rate of the cosmogenic isotope ^{10}Be, synchronized with the radiocarbon scale (Muscheler et al., [2014]), as well as up-to-date data on the Earth's dipole moment [Constable et al., 2016]. To calculate F, we used the relation obtained by Kovaltsov and Usoskin [2010], an illustration of which is shown in Fig. 2.

The results of the calculation of the solar modulation parameter F are presented in Fig. 3.

A series is called stationary if such statistical characteristics of the time series as its mathematical expectation, variance, and covariance do not depend on the time instant. Obviously, the obtained series for Φ is not stationary, which makes it difficult to analyze by classical methods. A number of methods have been developed to analyze nonstationary series, the most popular of which are secular spectral analysis and empirical mode decomposition (EMD), Huang et al. [2003]

In the application of EMD, the series X(t) under consideration must be oscillatory. It is possible for the amplitude or frequency of the series to vary with time. The essential feature in performing EMD is the construction of envelopes passing through maxima (upper envelope) and minima (lower envelope). To determine the first component of the eigenfunctions (IMF), denoted as C_1, we need to find the average of the two envelopes, m(t). Then C_1(t) is defined by the expression:

$$X(t)-m(t)=C_1(t)\,. \tag{1}$$

Details of the process for obtaining the C_1component can be found in Huang et al. [2003, Section 2]. After finding C_1, this component should be subtracted from the X(t) series, and the residual should be analyzed in the same way as the original series. The process continues until the residual is no longer oscillatory. As a result, we obtain the following representation for the original series:

$$X(t)=\sum_{i=1}^{n} C_i + r_n\,, \tag{2}$$

where r_n is the non-oscillating residual (trend). It is essential that the components of C_i are orthogonal (see Huang et al. [2003]), i.e.

$$\left\langle C_i, C_j \right\rangle = 0,\ \text{если}\ i \neq j\,. \tag{3}$$

An EMD decomposition was applied to analyze the solar modulation parameter data, Huang et al. [2003]. As a result of the standard procedure, the data can be represented as a combination of several oscillating components and a trend. Fig. 4 shows the result of the decomposition of the solar modulation parameter into oscillating modes. The first two modes, IMF1 and IMF2, are quasi oscillatory components. The oscillation period of the first component is ~208 years. In the study of cosmogenic isotopes, this cycle is known as the De Fries cycle, see Grootes et al. [2022]. The second mode, IMF2, shows oscillations with a period of ~710 years. The power spectrum of the first two components is presented in Fig. 5.

Fluctuations with the discussed period of about 710 years were not observed in the analysis of cosmogenic isotopes. There are no such variations in the data on the variation of the dipole geomagnetic moment either. We have drawn attention to a possible connection of these fluctuations with the change in the tilt of the Earth's dipole moment in time.

2.2 Fluctuations in the position of the north geomagnetic pole and the 710-year cycle

Nilsson et al. [2011] investigated the tilt of the geomagnetic dipole in the Holocene using paleomagnetic data. They showed that the latitude of the northern geomagnetic pole varies cyclically with periods of 2700 and 1350 years. Our analysis confirms Nielson's conclusions. The data on the position of the northern geomagnetic pole of Korte and Mandea [2008] were considered. A spectral analysis of the fluctuations of the longitude of the north magnetic pole for the last several thousand years was carried out. It was shown that the obtained periodogram contains spectral lines with periods of ~2700, ~1350, and ~710 years (see Fig. 6)

2.3 Influence of the magnetic dipole inclination on F

The effect of the Earth's magnetic dipole tilt on Φ is almost entirely determined by the second component (IMF2) in the EMD decomposition of the solar modulation parameter. We excluded this component by summing all others in the EMD decomposition. Fig. 7 shows the corrected solar modulation parameter F_{cor}, free from the influence of the variation of the magnetic dipole tilt.

F_{cor}varies differently in the first and second halves of the considered time interval. In the interval from 5000 years to the present, the parameter fluctuates with different amplitude. The maximum amplitude is reached around 2500 years A.D. At earlier times, from 9.5 thousand years to 5000 years A.D., the picture of changes is more complicated.

2.4 Wavelet analysis of the solar modulation parameter F_{cor}

The corrected solar modulation parameter F_{cor} (Fig. 7) does not give a complete picture of the behavior of the modulation parameter of the frequency region of interest for the study of solar activity. The application of wavelet analysis facilitates the study of frequency-time behavior of the parameter. Figure 8 shows the result of wavelet analysis of the parameter F_{cor} for the last 9.5 thousand years. It can be seen that the behavior of the parameter is nonstationary: both spectral behavior and amplitude change with the temporal shift from the beginning of the Holocene to the present time.

It is significant that the main contribution in the frequency region of ~100 years is made by the De Fries cycle (period ~208 years), the behavior of which is stable. The cycle with a period of ~710 years for the nearest time is practically not observed. The amplitude of the Hallstatt cycle (period ~2400 years) changes significantly: for the early Holocene, being very large, it becomes insignificant when approaching the present time.

2.5 Discussion

To study solar activity, it is necessary to know the parameters characterizing its variability. At the time closest to us, the XIX-XX centuries AD, we can use data on changes in geomagnetic activity and neutron monitor data available since 1951, characterizing changes in galactic cosmic rays under the influence of solar activity. For more distant times, since 1700 AD, sunspot data closely related to solar activity are available [WDC-SILSO, http://www.wdcb.ru/stp/solar/sunspots.html].

For earlier times, the so-called pre-instrumental era, solar activity is studied using cosmogenic isotopes, typically ^{10}Be and ^{14}C. Data on ^{10}Be are obtained from ice cores from Greenland and Antarctica. The cosmogenic isotope ^{10}Be is formed in the Earth's atmosphere and then precipitates to the Earth's surface with a short delay [Finkel and Nishiizumi, 1997]. The rate of precipitation varies with climate. However, there was little climate change during the Holocene, so the concentration of ^{10}Be in ice cores roughly corresponds to the rate of formation in the atmosphere [Johnsen et al., 1989; Mayewski et al., 1997]. The rate of formation of cosmogenic radionuclides depends on the intensity of galactic cosmic rays (GCRs) in the immediate vicinity of the Earth. Before reaching the Earth, GCRs pass through near-solar space (heliosphere), where they undergo solar modulation. The propagation of GCRs in the heliosphere is described by Parker's equation [Parker, 1965]. This equation can only be solved numerically. Under some simplifying assumptions, Gleeson and Axford [1968] derived the so-called force field equation:

$$J(E_p) = J_{LIS}(E_p + \Phi)\frac{E_p\left(E_p + 2m_pc^2\right)}{\left(E_p + \Phi\right)\left(E_p + 2m_pc^2 + \Phi\right)} \tag{4}$$

where $J_{LIS}$is the local flux of interstellar cosmic rays, $E_P$is the kinetic energy of the proton (MeV), F is the solar modulation parameter (MeV),,*c* is the speed of light, and m_pc^2 is the proton's rest energy , which is 938 MeV. This equation relates the intensity of GCR with energy E_P, $J(E_P)$ considered for a distance of 1 a.u. (astronomical unit = $149.6\times\ 10^6$ km) from the Sun, to the intensity of GCR with energy EP + F in the local interstellar region, $J_{(LIS)}$ (E_P+ F). The modulation parameter F, which formally determines the energy loss, changes the shape of the differential energy spectrum of the GCL particles.

Equation (4) shows that the GCR spectra and, consequently, the cosmogenic radionuclide formation rate depend on the local flux of interstellar cosmic rays J_{LIS} and the modulation parameter Φ. Different approaches to the determination of J_{LIS} were described by Herbst et al. [2010].

The solar modulation parameter is determined by the magnitude of the Earth's dipole moment and the cosmogenic isotope formation rate ^{10}Be, Kovaltsov and Usoskin [2010].

As shown in Nilsson et al. [2011], the tilt of the Earth's dipole changes, and these changes have a periodic character. The latitude of the northern geomagnetic pole changes cyclically with a period of 1350 years. Our analysis confirms Nielson's conclusions (see Fig. 6). If the tilt of the dipole did not change with time, the changes in the solar modulation parameter would reflect the modulation activity of the GCR.

The question arises as to the nature of the change in the dipole moment. The magnetic field arises from fluid convection in the outer part of the core, which is rich in liquid iron [Tauxe, 2021]. Now, at the Earth's surface, the field is a geocentric dipole field tilted about 11° from the axis of rotation. A detailed analysis of the influence of convection at the core-mantle boundary on the change of the dipole moment can be found in the study by Amit and Olson [2008].

The paper shows that in the last 9.5 thousand years, the solar modulation in the region of periods of the order of hundreds of years has a predominantly cyclic character, with a period of ~210 years. A wavelet analysis of the corrected series for PSM has been carried out. A ~2000-year cyclicity is found in the PSM data, the amplitude of which varies in time.

Similar issues were discussed in Kudryavtsev, Dergachev, and Nagovitsyn [Kudryavtsev et al., 2022], where the reconstruction of the heliospheric modulation potential characterizing the solar activity variations over the last 20,000 years based on radiocarbon data is considered. The reconstruction process takes into account variations in global temperature and carbon dioxide content in the Earth's atmosphere.

3. CONCLUSIONS

The study focuses on the reconstruction of the solar modulation parameter F based on the ^{10}Be formation rate and the value of the Earth's magnetic dipole moment over the last 9.5 thousand years. Cyclic variations in the dipole tilt make an additional contribution to the estimate of F that is not related to solar activity. Using empirical mode decomposition (EMD), we were able to isolate the signal associated with dipole tilt changes and generate a signal that characterizes solar activity over 9.5 thousand years.

FUNDING

The work was financially supported by the Russian Academy of Sciences under the state assignment FFUG-2024-0002.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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FIGURE CAPTIONS

Fig. 1. Earth's dipole moment over the last 10 thousand years, according to Yang et al. [2000], Knudsen et al. [2008] and Constable et al. [2016]. The gray bar shows the uncertainty in the data from the study of Knudsen et al. [2008]. The time is counted in years and the dipole moment is in units of $10^{22} Am^2$.

Fig. 2. Relationship between the solar modulation parameter F, the dipole moment of the geomagnetic field D (in units of the present-day value), and the formation rate of ^{10}Be in the Earth's atmosphere Q, according to Kovaltsov and Usoskin [2010].

Fig. 3. Solar modulation parameter Φ for the last 9.5 thousand years. The vertical axis shows the non-normalized value of the parameter, and the horizontal axis shows the time counted back in time.

Fig. 4. Results of the solar modulation parameter F analyzed using empirical mode decomposition. The eigenfunctions (IMF) are shown here. The partial amplitudes of the eigenfunctions (MeV) are plotted on the vertical axis. The values of the backward-looking dates are plotted on the horizontal axis.

Fig. 5. Power spectrum of IMF1 and IMF2 components in arbitrary units.

Fig. 6. Periodogram of longitude fluctuations of the north geomagnetic pole. The periodogram shows lines with periods of ~2700, 1350, and ~710 years. The smooth curve limits the amplitudes whose significance does not exceed 0.95.

Fig. 7. The corrected solar modulation parameter F_{cor}, free from the influence of the magnetic dipole tilt variation.

Fig. 8. Results of wavelet analysis of the corrected solar modulation parameter F_{cor}. Dotted lines mark the levels of periods (from bottom to top): 208 years (De Fries cycle), 710 years, 2000 and 2500 years.

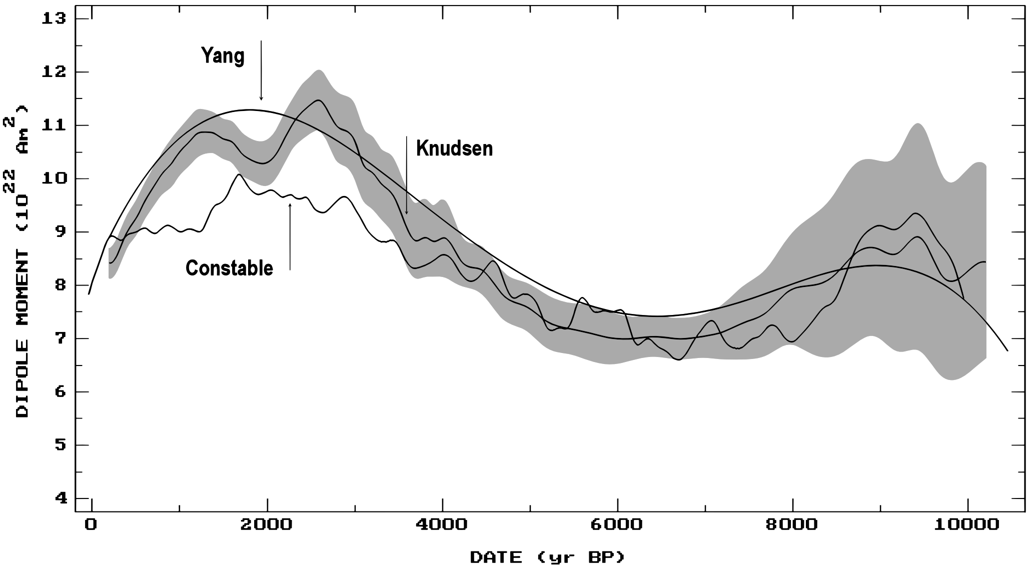

Yang
Knudsen
Constable
DIPOLE MOMENT (10^22 Am^2)
DATE (yr BP)
0
2000
4000
6000
8000
10000
4
5
6
7
8
9
10
11
12
13

Fig. 1.

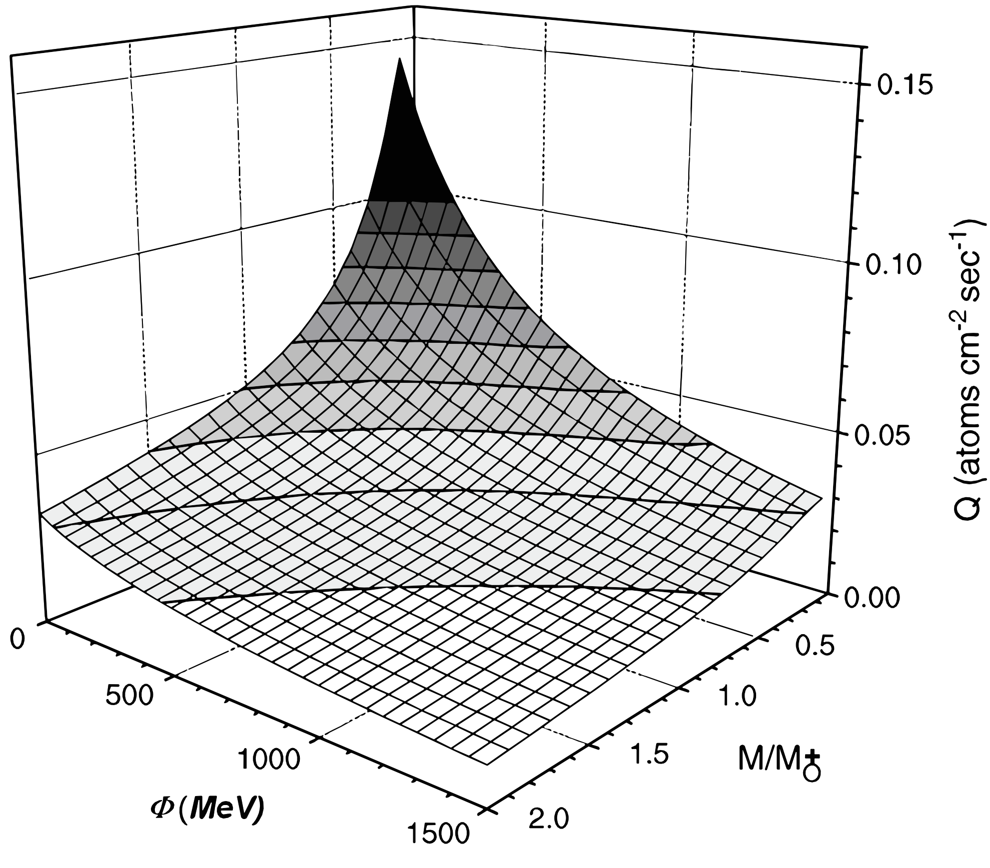
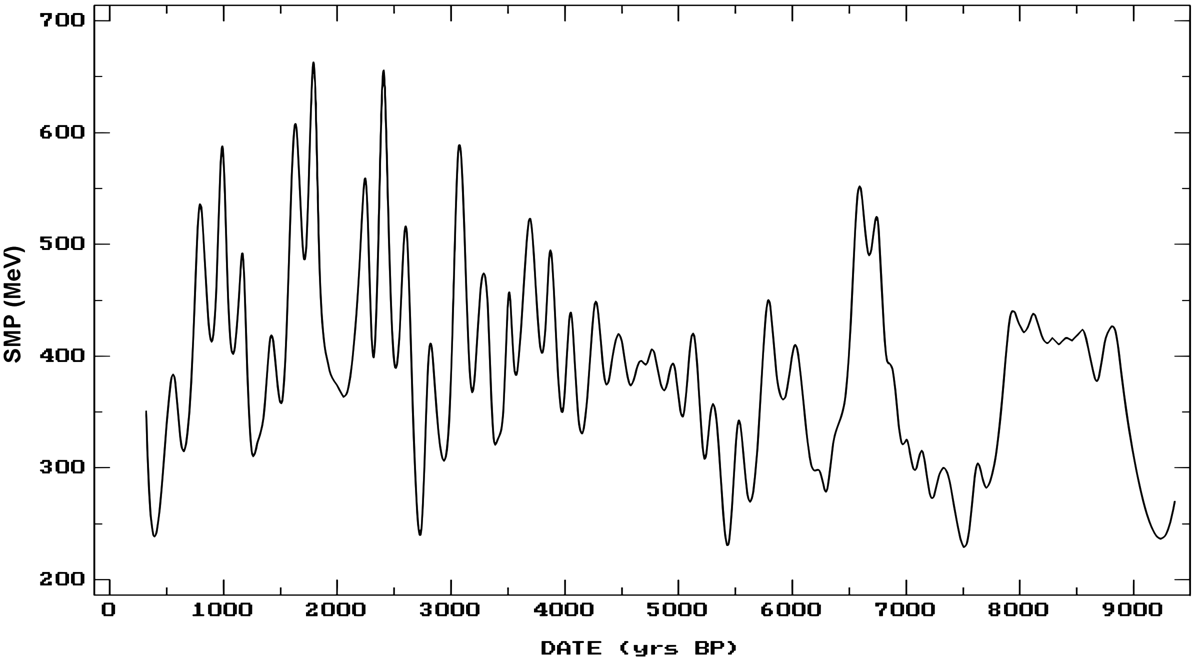

Q (atoms cm^-2 sec^-1)
0.15
0.10
0.05
0.00
0
500
1000
1500
Φ(MeV)
0.5
1.0
1.5
2.0
M/M⊕

Fig. 2.


700
600
500
400
300
200
SMP (MeV)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
DATE (yrs BP)
Fig. 3.

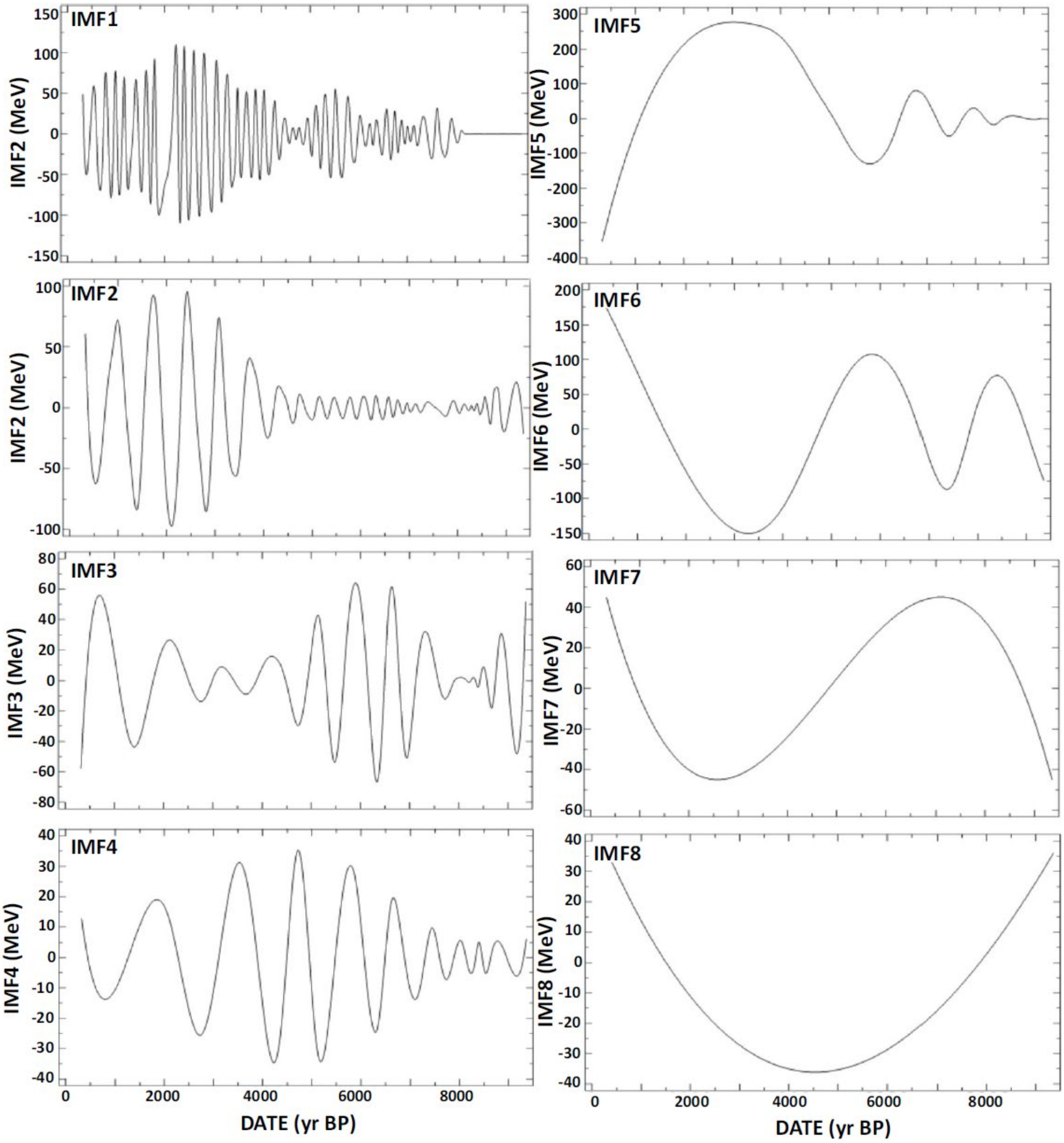
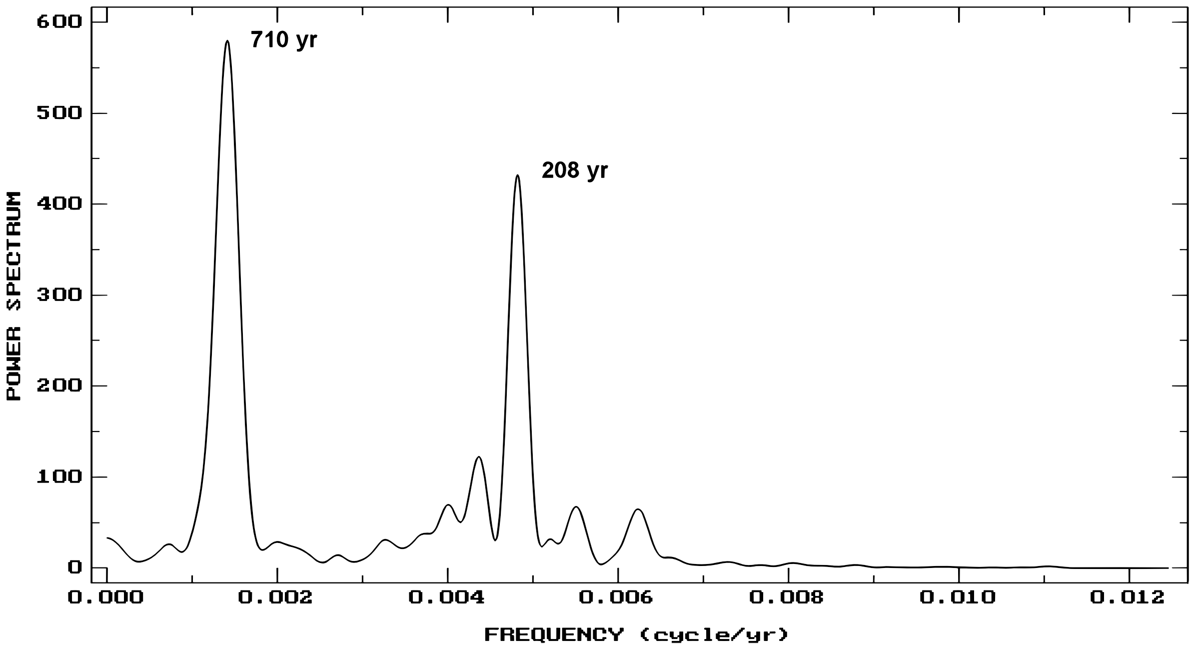
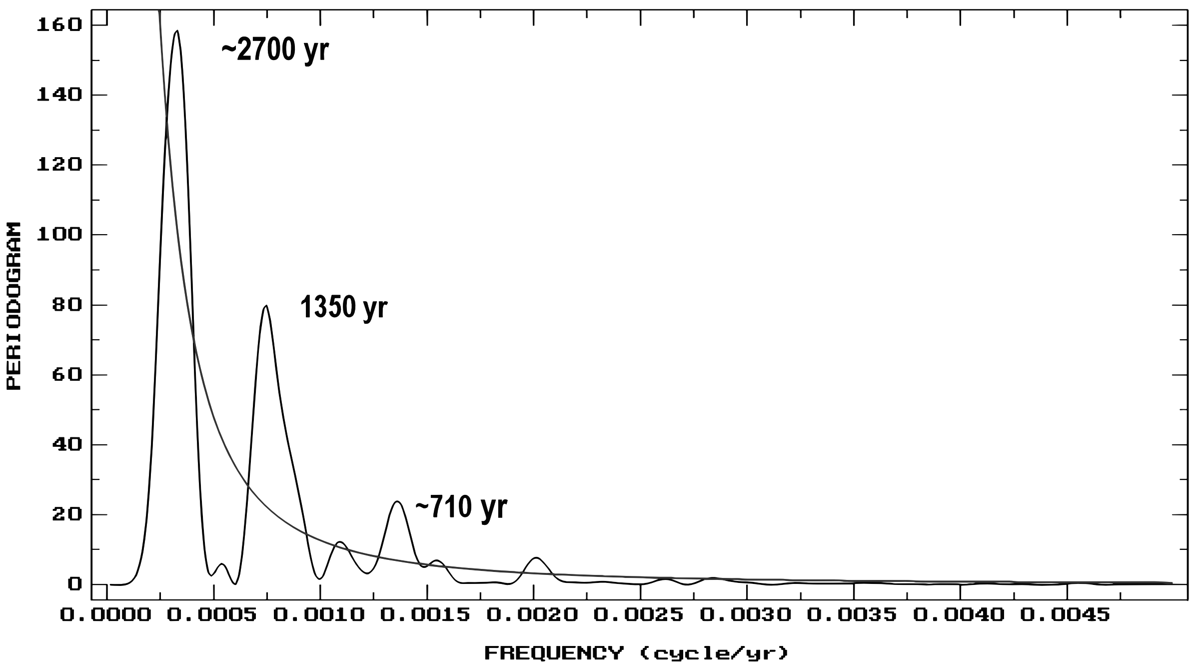

IMF1
IMF2 (MeV)
IMF2
IMF2 (MeV)
IMF3
IMF3 (MeV)
IMF4
IMF4 (MeV)
DATE (yr BP)
IMF5
IMF5 (MeV)
IMF6
IMF6 (MeV)
IMF7
IMF7 (MeV)
IMF8
IMF8 (MeV)
DATE (yr BP)

Fig. 4.



710 yr
208 yr
POWER SPECTRUM
600
500
400
300
200
100
0
0.000
0.002
0.004
0.006
0.008
0.010
0.012
FREQUENCY (cycle/yr)

Fig. 5.



~2700 yr
1350 yr
~710 yr
PERIODOGRAM
160
140
120
100
80
60
40
20
0
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
0.0045
FREQUENCY (cycle/yr)

Fig. 6.

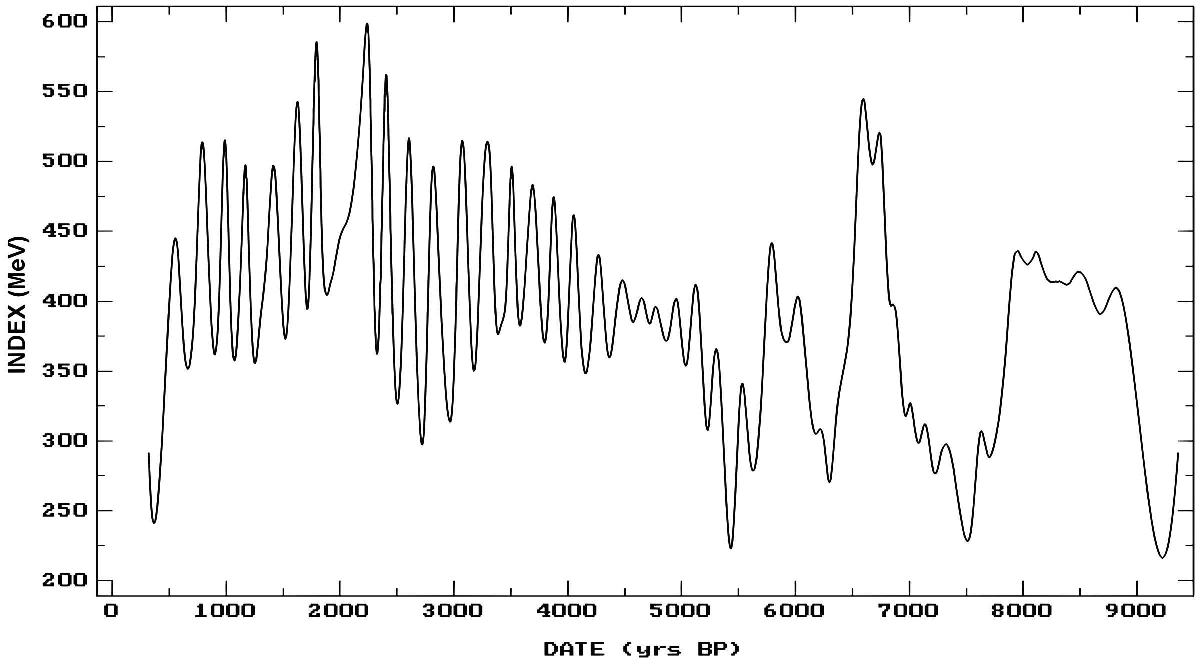

INDEX (MeV)
600
550
500
450
400
350
300
250
200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
DATE (yrs BP)

Fig. 7.

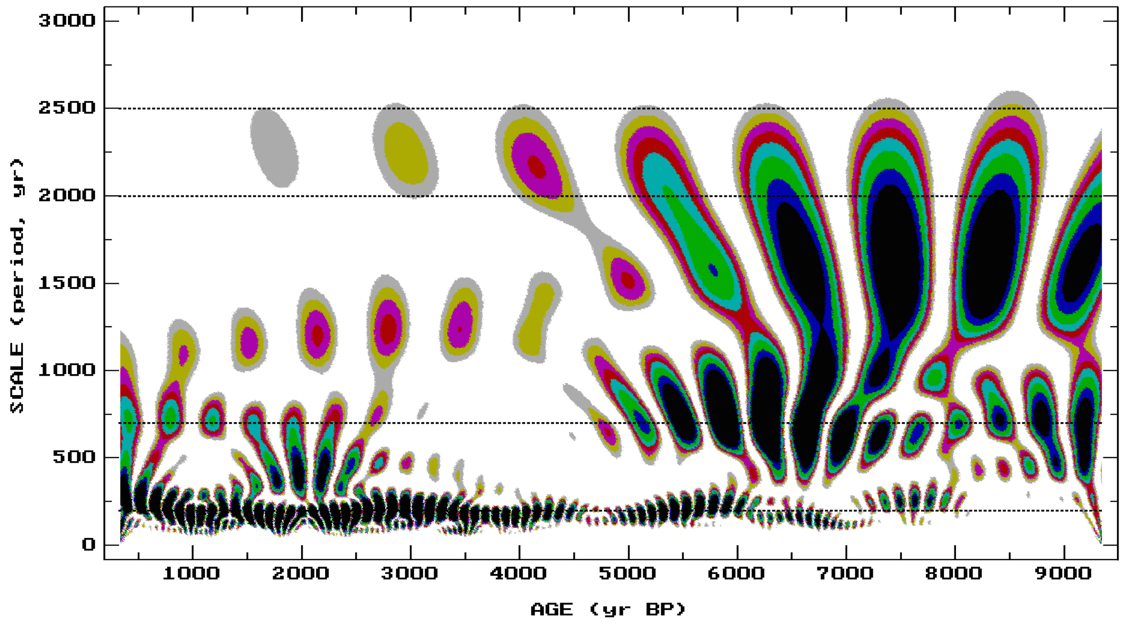

SCALE (period, yr)
3000
2500
2000
1500
1000
500
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
AGE (yr BP)

Fig. 8.