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THE EARTH'S MAGNETIC FIELD AND THE LARGE-SCALE MAGNETIC FIELD OF THE SUN: THE SOLAR-TERRESTRIAL CONNECTION

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ABSTRACT. The paper presents the results of a joint analysis of the Earth's main magnetic field (core field) B_{IGRF} and the large-scale magnetic field (LSMF) of the Sun. Selected 11- and 22-year periods of LSMF and B_{IGRF} variations are well manifested in both fields and are usually modulated by solar activity. Even 11-year cycles for which the direction of the Sun's magnetic field coincides with the direction of the Earth's magnetic field are characterized by the minimum values of sanspot numbers, and odd cycles with opposite directions of magnetic fields have larger values of sunspot numbers. The rotation rate of two- and four-sector structure of the Sun source of LSMF varied with about 11-year and 22-year cycle. Longer changes in the magnetic fields of the Sun and the Earth with a period of about 75 years have also been revealed.

The rotation periods of the Sun source global field (28,0-28,5 days) were maximum at the middle of the 20th century in the period 1940÷1960 years. This maximum of solar activity corresponds to temporal gradient of geomagnetic field. It is shown that the gradient of the geomagnetic field B_{IGRF} depends on the rate of change in the length of the day. So, according to the results of the study, the rotation modes of the Sun and the Earth cause different periodic changes in their magnetic fields.

Keywords: geomagnetic field, solar activity, magnetic field of the Sun, space weather.

АНОТАЦІЯ. У статті представлені результати спільного аналізу основного магнітного поля Землі (поля ядра) B_{IGRF} і великомасштабного магнітного поля Сонця (ВМПС). При цьому 11- та 22-річні періоди варіацій ВМПС і B_{IGRF} добре проявляються в обох полях і зазвичай модулюються сонячною активністю. Парні 11-річні цикли, для яких напрямок магнітного поля Сонця збігається з напрямком магнітного поля Землі, характеризуються мінімальними значеннями чисел сонячних плям, а непарні цикли з протилежними напрямками магнітних полів мають більші значення чисел сонячних плям. Швидкість обертання дво- та чотирисекторної структури сонячних джерел ВМПС змінювалася з приблизно 11-річним та 22-річним циклом. Виявлено також більш тривалі зміни магнітних полів Сонця і Землі з періодом близько 75 років. Період обертання джерел ВМПС (28,0-28,5 доби) був максимальним в середині 20 століття в 1940÷1960 роках. Цей максимум сонячної активності відповідає часовому градієнту геомагнітного поля. Показано, що градієнт геомагнітного поля B_{IGRF} залежить від швидкості зміни тривалості дня. Отже, згідно з результатами дослідження ротаційні режими Сонця та Землі зумовлюють різноперіодні зміни їх магнітних полів.

Ключові слова: геомагнітне поле, сонячна активність, магнітне поле Сонця, космічна погода

1. Introduction

The study of solar-terrestrial relations is a determining condition for forecasting short-term and long-term changes in space weather. One of the main factors of space weather, which affects a number of terrestrial systems, including the biosphere, is the perturbation of the geomagnetic field. The majority of works in this direction are aimed at studying the relationship between geomagnetic and solar activity in a relatively short-period frequency range (Georgieva et al., 2022; Du, 2011; Sukharev et al., 2022). In this regard, the authors performed an analysis of the long-term changes of the B_{IGRF} magnetic field of the Earth with the large-scale magnetic field of the Sun and solar activity and proposed a mechanism of their potential relationship.

2. Data and methodology

Digital data from sites (DGRF/IGRF…: Solar Cycle…) and graphical data (Obridko et al., 2021; Matsakis, McCarthy, 2023), which were partially generated into digital data, were used for the research. For a joint analysis of temporal changes of the B_{IGRF}, day length, LSMF and Solar activity trend and variation components of long-term and short-term changes were selected using statistical analysis methods.

3. Spatio-temporal structure of the geomagnetic field induction B_{IGRF}

The maximum values of the main magnetic field B_{IGRF} of the Earth for 2020 are characteristic for the negative magnetic pole ($B_{IGRF,1950}$ = 69 000 nT, $B_{IGRF,2020}$ = 66 900 nT) (located near the Earth's geographical North Pole) and positive (located near the Antarctic coast opposite Australia), and the minimum ones for the near-equatorial regions of the South Atlantic (the so-called South Atlantic Anomaly) ($B_{IGRF,\ 1950}$ = 24 500 nT, $B_{IGRF,\ 2020}$ = 22 300 nT) (see Fig. 1 *a*, *b*) (Orlyuk & Romenets, 2020; 2022].

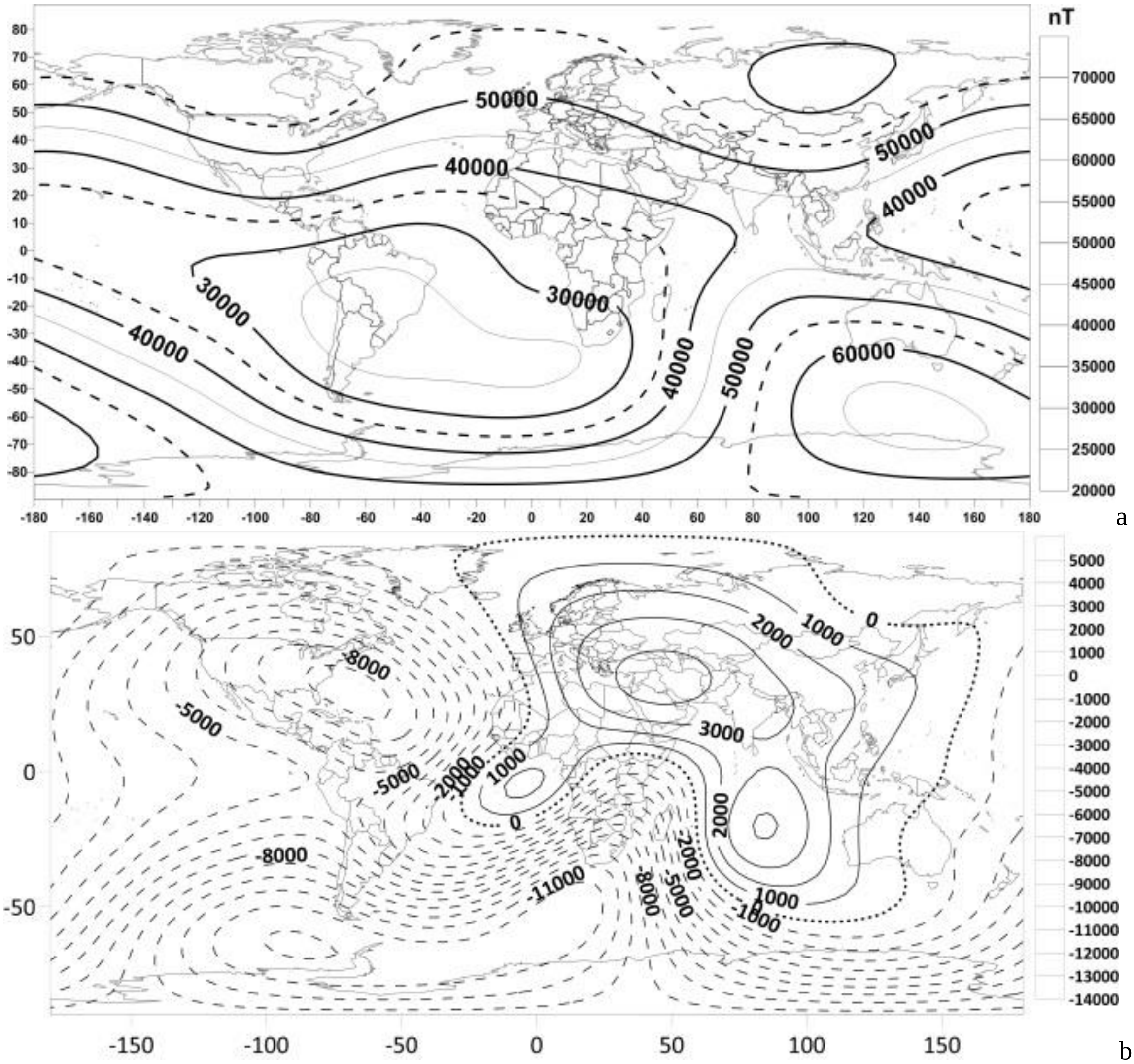

Figure 1: The normal component of the geomagnetic field B_{IGRF} value for 2020 (*a*), and for 1950-2020-time interval temporal changes (*b*)

The maximum field decreases from 1950 to 2020 (from –5500 to –7400 nT, from –80 to –100 nT/year) are located near the Atlantic coast of Central America, as well as in the region the Drake Strait and between Africa and Antarctica. Field increase maxima (2100÷3500 nT, 40÷60 nT/year) are typical for Europe and the Indian Ocean (see Fig. 1*b*)

For the period from 1950 to 2020 the average B_{IGRF} value on the planet's surface decreased by 1797 nT (from 47 603 to 45 806 nT).

The time trend of these changes seems interesting, namely: against the background of a general decrease in the field (at a rate of about –25 nT/year), its sharp jumps are observed (up to –45 nT/year in 1960—1965; –58 nT/year in 1980—1985; –32 nT/year in 2000—2005) after which over the next 15 years there was a less intensive decrease in its changes (to –18 nT/year in 1975; –12 nT/year in 1995; –2 nT/year in 2015). From all this it can be concluded that, starting from 1985 to the present, there is a slowdown in the geomagnetic field decrease (Orlyuk & Romenets, 2022).

More significant changes in the B_{IGRF} geomagnetic field are observed for the time interval 1900-2020. The average value of geomagnetic field induction in the epoch of 1900 is B_{IGRF}=49140 nT, and in the epoch of 2020 – B_{IGRF}=45803 nT. For 120 years, the main magnetic field decreased by 3337 nT (Fig. 2) (Orlyuk & Romenets, 2023).

4. Comparison of temporal changes of the geomagnetic field and length of day

For the time interval 1900-2022, 3 regional extremes can be distinguished regarding changes in the geomagnetic field and the length of the day. The extremes of changes in the B_{IGRF} geomagnetic field fall on the following years: 1917.5±2.5 (-90 nT/year); 1945.5±2.5 (-25 nT/year); 1982.5±2.5 (-70 nT/year) (Fig. 2). The regional extremes of the change in the length of day (relative to the norm) fall on 1905.0±2.5 (4 msec/year; 1936±2.5 (0.3 msec/year); 1972.5 ±2.5 (3 msec/year). An anti-correlation between the extreme values of changes in the geomagnetic field and the length of the day was revealed.

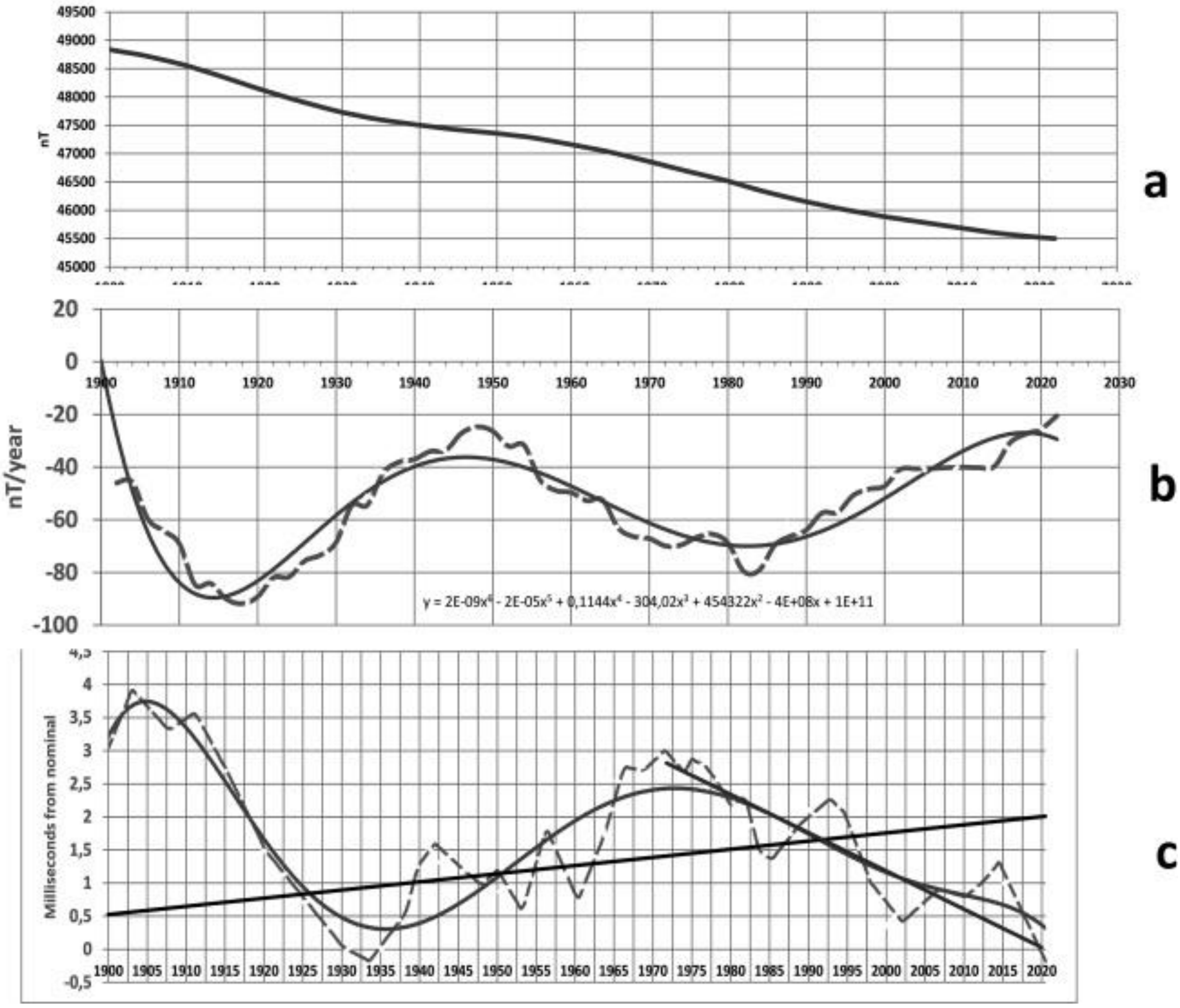

Figure 2: Changes in the average values of the geomagnetic field (a) on the Earth's surface, its temporal gradient (dashed line – raw data; solid line – polynomial approximation)(b) and length of day for the time interval 1900-2022 year (dashed line – raw data, solid line – polynomial approximation and trend (Matsakis & McCarthy, 2023))(c).

The extremes of the change in the length of day precede the extremes of the change in the geomagnetic field by approximately: 12.5 years (1917.5-1905) for the first extreme; 9.5 years (1945.5-1936) – the second; 10.0 years (1982.5-1972.5) – for the third.

Taking into account the accuracy of the determination of the peaks of the corresponding extremes, it is possible to assume an 11-year cycle of their alternation (correlation coefficient r=-0.93 when the curve of length of the day is shifted 11 years ahead).

5. The structure of the large-scale magnetic field of the Sun

Solar and interplanetary large-scale magnetic fields (LSMF) are observed in the form of the sector structure (SS) (Fisk, 2001; Bandic et al., 2023).

5.1 Solar background magnetic field (SBMF)

The rotation rate of two-sector structure of SBMF varied with about 11-year cycle. Four-sector structure had about 22-year cycle of the rotation period. The maximal rotation rate of four-sector structure was observed during maximum of even cycles (14, 16, 18, 20, 22) and minimal rate of the rotation was observed during maximum of odd cycles (15, 17, 19, 21) (Leiko, 2005).

5.2 Interplanetary magnetic field.

The main rotation period (about 27-day period) of the two-sector structure of IMF varied with about 22-year cycle: maximal value of the rotation period of IMF was during about 1952–1956, 1976, 1997 (Leiko, 2005).

The regional component of the rotation speed of the large-scale magnetic field of the Sun changes from 27.5 days for

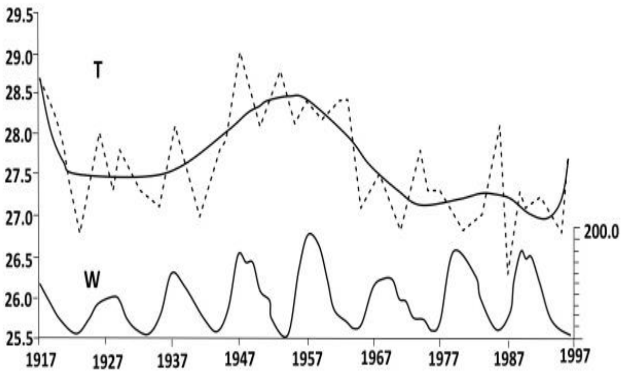

Figure 3: The rotation period (T) as a function of the 11-year cycle (W) (Obridko et al., 2021).

the time interval 1920-1940 to 27.0 days in 1965-1990. During 1945-1965 the speed of rotation was 28.0-28.5 days (Fig. 3).

An analysis of the spectrums of the whole cycles showed that during the 20th–23rd cycles the rotation period of IMF and SMMF was greater in even cycles and smaller in odd cycles. During the 18th–19th cycles the rotation period of IMF was greater during odd cycle and smaller during even cycle. Possibly, this fact is indicative of a change of the rotation regime of IMF in the middle of the 20th century, and this is an indirect confirmation of the Sun’s rotation change. The rotation of the source surface global field decelerates as the activity of the local fields grows during both the 11-year and longer cycles. The rotation periods were maximum at the middle of the 20th century, i.e., in the period of the high cycles 18 and 19. At the minimum of the cycle, the frequency increases, i.e., the rotation rate increases (Fig. 3).

22-year Hale cycle of the solar activity starts at the maximum odd 11-year cycles and the change of the LSMF sign in the maxima of even cycles. Hale cycle begins at the maximum activity of an odd 11-year cycle LSMF at the north pole of the directed from the Sun (positive during the decline phase of the odd cycle and during the growth phase of the activity of the 11-year cycle). The direction of the LSMF is defined as positive when the magnetic field in the northern hemisphere is directed away from the Sun, and negative – towards the Sun (Sumaruk T. & Sumaruk P., 2020). At the cycle minimum, the heliospheric current sheet lies in the plane of the solar equator, while at the maximum, it can be tilted up to 90° (Obridko et al., 2021).

Hale cycles are characterized by the following regularity: negative III (1957-1979) and V (2000-2021 (?)) cycles have one low-intensity cycle in its middle (20 and 24), and positive cycle IV is characterized by an intense 11-year cycle (22). Accordingly, the odd Hale cycles are characterized by the minimum values of the time gradient of the B_{IGRF} field (see Fig. 4) (Orlyuk & Romenets, 2022).

6. Discussion of results

According to the above, cyclical changes of the LSMF and the induction module of the main magnetic field of the Earth B_{IGRF} are observed. First of all, we note that the LSMF changes both in direction and in amplitude and the B_{IGRF} field has a constant direction of the induction vector (negative in the northern hemisphere) and an uneven nature of its rate of decrease (see Fig. 5). Selected 11- and 22-year periods of LSMF and B_{IGRF} variations are well manifested in both fields and are usually modulated by solar activity (see Figs. 3, 4). Therefore, the dependence of solar activity on the ratio of the direction of the LSMF and B_{IGRF} is observed. As can be seen from Fig.5, even 11-year cycles for which the direction of the Sun's magnetic field coincides with the direction of the Earth's magnetic field are characterized by the minimum values of sanspot numbers, and odd cycles with opposite directions of magnetic fields have larger values of sunspot numbers. Odd cycles of polarity change LSMF are characterized by a wider spectrum of values of sunspot numbers.

Longer changes in the magnetic fields of the Sun and the Earth with a period of about 75 years have also been revealed.

The analysis of different periodic variations of magnetic fields indicates their potential connection with the rotational regime of the Earth and the Sun (Lesur et al., 2022; Obridko et al., 2021).

The rotation rate of two- and four-sector structure of the Sun source of LSMF varied with about 11-year and 22-year cycle. The maximal rotation rate of four-sector structure was observed during maximum of even cycles and minimal rate of the rotation was observed during maximum of odd cycles. Such a manifestation of the dependence of the speed of rotation of LSMF sources on solar activity can be explained by the effect of "skating rotation".

The rotation periods of the Sun source global field (28,0-28,5 days) were maximum at the middle of the 20th century in the period 1940÷1960 years. This maximum of solar activity corresponds to temporal gradient geomagnetic field dB_{IGRF}/dt =35-40 nT/year. For this reason, it is worth paying attention to the close connection of the temporal gradient of the geomagnetic field with the change in the gradient of LOD (correlation coefficient r=0.72), i.e. with the change in the rotation mode of the Earth (see Fig. 5). According to the (Orlyuk & Romenets, 2022), the twentieth cycle is the axis of a kind of symmetry with respect to changes in solar and geomagnetic activity, and length of day, namely, cycles 21, 22, 23 and 24 are almost a mirror image of cycles 19, 18, 17 and 16 of solar and geomagnetic activity. Therefore, it can be assumed that the 25th cycle should be similar to the 15th cycle.

Figure 5 shows the 15th cycle of solar activity as a dotted line, which in terms of morphology and intensity corresponds to the solar activity of the 25th cycle.

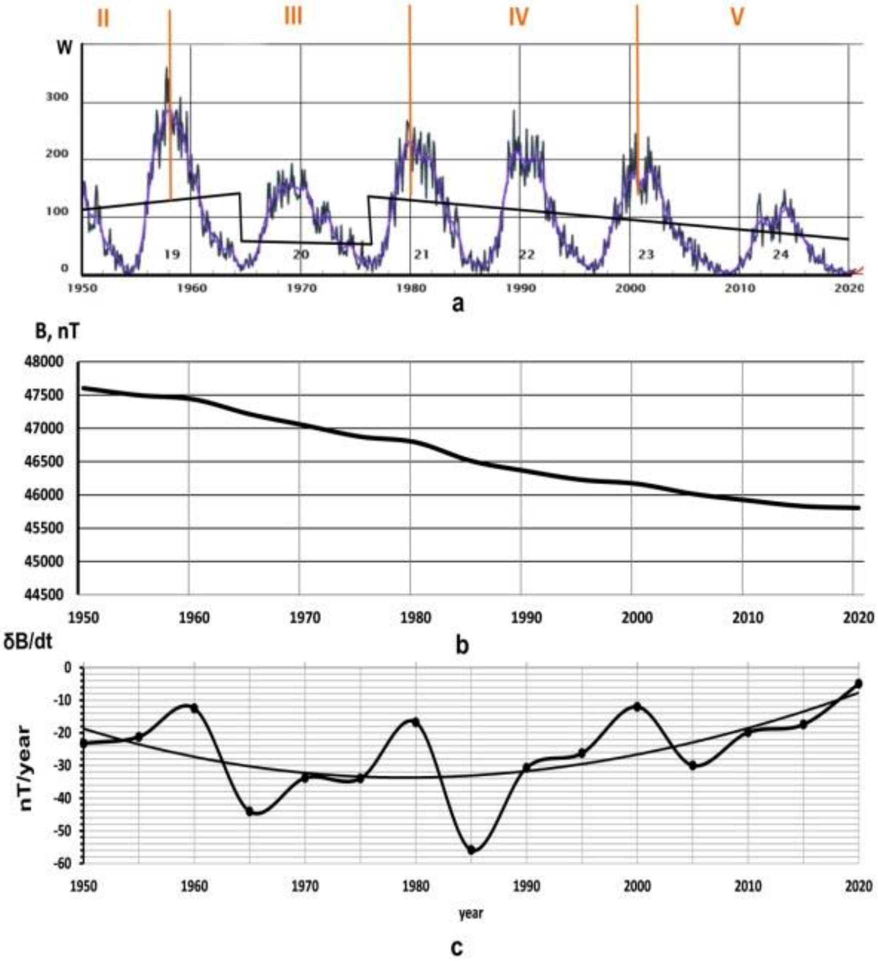

Figure 4: Comparison of 19-24 cycles of solar activity (a) with changes in the average values of the geomagnetic field (b) on the Earth's surface and its time gradient (c) for the time interval 1950÷2020.

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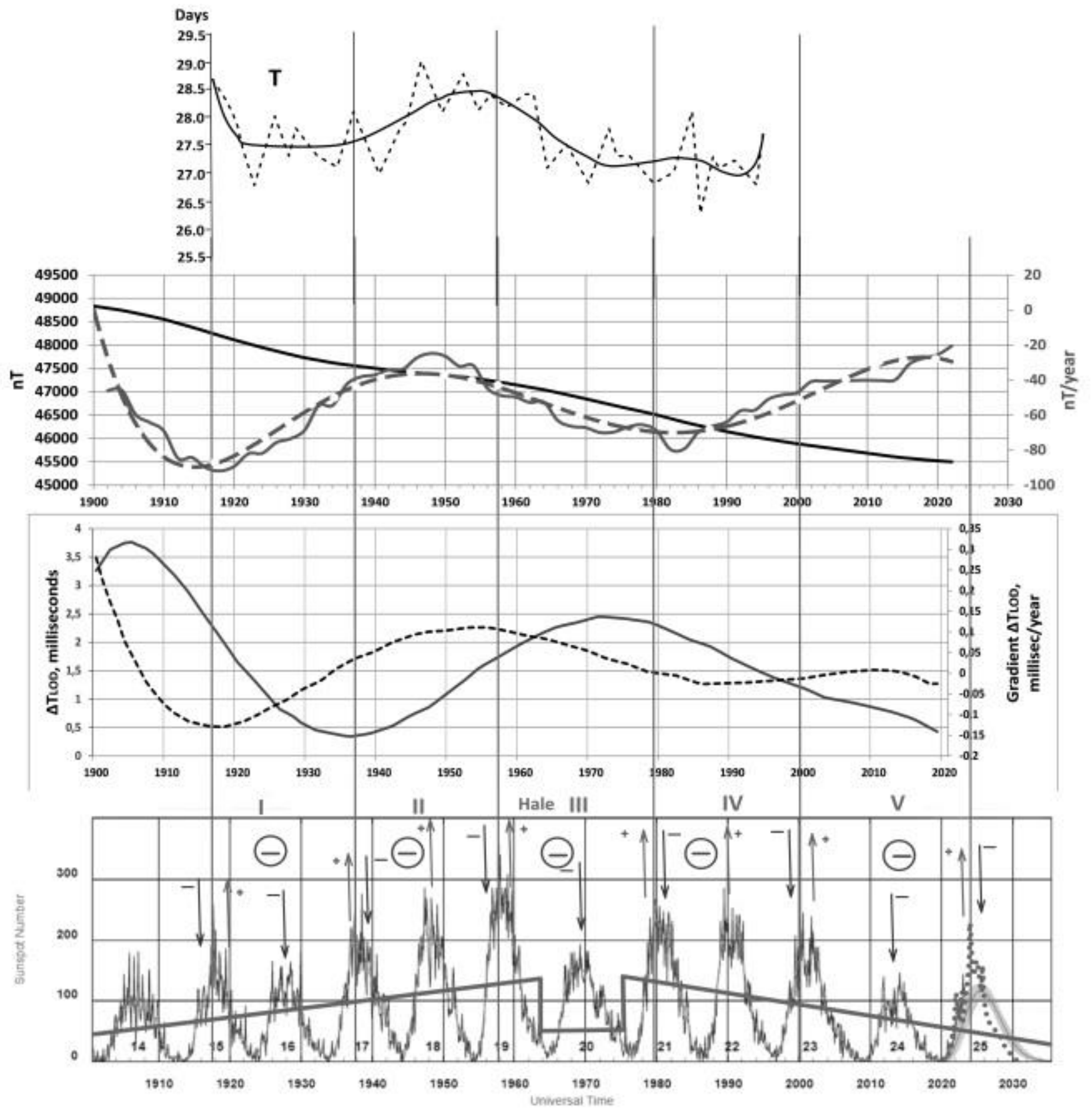

Figure 5: Dynamics of the large-scale field of the Sun and the Earth's magnetic field in connection with their rotation mode and solar activity.

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