ALTERNATIVE AMPLITUDES OF THE MAGNETIC CYCLES OF THE SUN

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We propose a scenario to explain the observed phenomenon of amplitude alternation of adjacent 11-year solar activity cycles. It is shown that a noticeable radial gradient of angular velocity in the radiant zone (calculated by us on the basis of helioseismological experiments), acting on a weak relict radial magnetic field, generates a powerful deep toroidal magnetic field of constant direction (the deep Ω-effect of radiant zone). As a result of magnetic buoyancy, this field gradually penetrates from below to the turbulent layers of the SCZ, where the dynamo mechanism operates, responsible for the 11-year cyclical activity of the solar activity. Continuous "feeding" of the magnetic flux in the SCZ due to the additional toroidal flux emerging from below leads to variations in the power of the total toroidal field in adjacent cycles. The total toroidal field, rising on the solar surface, causes the observed alternation of the amplitude of adjacent solar 11-year activity cycles.

Key words: Sun; radiant zone; relic magnetic field; helioseismological experiments; inner rotation of the Sun; magnetic buoyancy; convective zone; turbulent dynamo; 11-year cycle of solar activity.

Deep magnetism is involved by researchers to explain the many observed phenomena in the Sun, although the origin of powerful magnetic fields in the solar subsoil has not been sufficiently studied, and in some works it is generally beyond the field of view of researchers. Taking into account this, we have studied the evolution of the deep toroidal field which is excited by radial differential rotation in the radiant zone filled with the primary (relic) poloidal field. The results obtained are used to construct a scenario of alternating amplitudes of neighboring 11-year solar cycles.

Asymmetry of solar cycles.

G. Turner in 1925 noticed a trend [1] that the intensity of the odd 11-years cycles of solar activity, as a rule, turns out to be slightly higher than the intensity of even cycles. Later M.N. Gnevyshev and A.I. Ol [2] found that solar cycles, in which the intensity alternates, are grouped in pairs: paired - unpaired cycles (the Gnevyshev-Ol principle). A significant difference between the amplitudes of even and odd cycles (bimodality) was convincingly confirmed by R.M. Wilson [3].

In order to explain the detected asymmetry of cyclicity in papers [4-6], a mechanism was proposed, according to which the alternation of the heights of adjacent 11-years cycles occurs due to the fact that the deep primary poloidal magnetic field of the Sun penetrates into the solar convection zone (SCZ), and thus influences the dynamo process here. According to this approach, the poloidal field $\mathbf{B}_P$ in the dynamo region in the SCZ consists of the sum of two components. The first component is the alternating poloidal field $\mathbf{B}_P^{(c)}$, associated with the dynamo process in the convective zone. It is excited by the α-effect and therefore changes its direction from one 11-year cycle to another. The second component is the primary poloidal field $\mathbf{B}_P^{(r)}$ of the radiant zone, which has a constant direction and penetrates from the radiant zone up into the turbulent layers of the convective zone. Based on this, the total poloidal field in the dynamo region in the SCZ should oscillate from cycle to cycle: in one 11-year cycle, its intensity will be higher, and in the next cycle, its intensity will be lower. As a result of this, a toroidal field that is excited from the poloidal field due to differential rotation (Ω-effect) should also change its intensity in neighboring cycles. Thus, within the framework of this approach, the primary field takes part in the formation of a toroidal field in the SCZ (along with the dynamo field), which leads to the alternation of the intensity of neighboring 11-year cycles.

In contrast to the authors' idea [4-6], we believe that the primary poloidal magnetic field $\mathbf{B}_P^{(r)}$ is involved in the generation of the toroidal field _not only in the SCZ, but also in deeper layers – in the area of radiant energy transfer_. Our assumption is based on the data of helioseismological experiments on the internal rotation of the Sun, according to which the radial gradient of the angular velocity extends deeper than the SCZ into the layers of the radiant zone [7-9].

Taking this into account, we believe that already in the deep layers of the radiant zone (below the turbulent dynamo region), the deep Ω-effect begins to work: radial differential rotation acts on the relic poloidal field, the lifetime of which is comparable with the lifetime of the Sun, and thereby creates a stationary toroidal field constant direction over time. Due to magnetic buoyancy, this deep toroidal field rises and gradually penetrates the overlying layers of the SCZ, where the turbulent dynamo operates. Obviously, here an additional toroidal field should somehow influence the processes of magnetism restructuring, which lead to solar cyclicity.

The inner rotation of the Sun.

According to the data of helioseismological experiments, a noticeable radial gradient of angular velocity $\partial\Omega/\partial r$ is stored in the bowels deeper than the convective zone and tachocline [7-9]. Figure 1 presents radial profiles of the frequency of internal rotation for three solar latitudes, obtained as a result of inversions of the data of helioseismological observations [8].

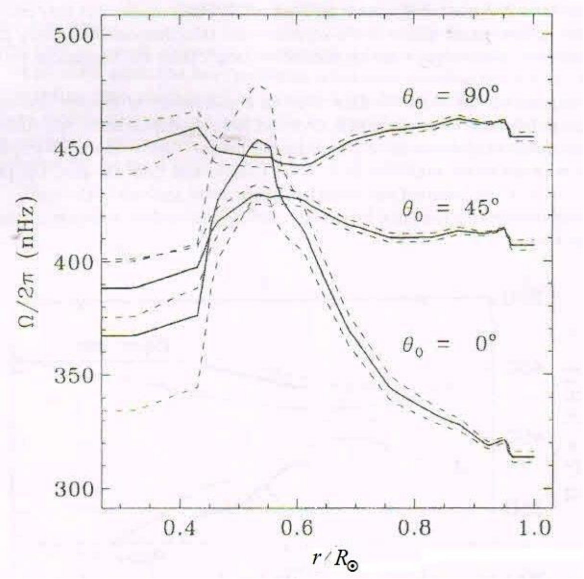

Fig.1. Radial velocity profiles of the Sun's internal rotation for three polar angles (latitudes) θ_0: $\Omega/2\pi$ is the frequency of internal rotation in nanoHertz, $r/R_\odot$ is the relative heliocentric radius. The figure is taken from paper [8]

It is seen that the latitudinal differential rotation is stored in the full volume of the convective zone in the depth range $(0{,}7 \div 1{,}0)\, r/R_\odot$, and it decreases to the minimum value in the tachocline layer $(0{,}63 \div 0{,}7)\, r/R_\odot$ ($R_\odot$ is the Sun's radius). At the same time, inside the SCZ at each fixed solar latitude the magnitude of the angular velocity of rotation changes substantially along the radius r. And it is extremely important that _the noticeable radial inhomogeneity of the angular velocity $\partial\Omega(r)/\partial r$ persists below the tachocline, penetrating the upper part of the stable radiant zone._ This radial gradient of angular velocity $\partial\Omega/\partial r$ undoubtedly acts on the relict (primary) magnetic field, which will lead to the restructuring of deep magnetism (the deep Ω-effect).

We believe that the primary magnetic field of the radiant zone has a dipole structure whose maximum intensity is reached at latitudes ±45°. Therefore, we next take into account the radial variation of the angular velocity at latitude 45°. As follows from Fig.1 the jump of internal rotation frequency $\Delta\Omega/2\pi$ at this solar latitude in the depth range $(0{,}3 \div 0{,}7)\, r/R_\odot$ is

≈ 35 nHz. It corresponds to our calculated value of the radial gradient of the angular velocity $\partial\Omega/\partial r \approx \Delta\Omega/\Delta r \approx 7\cdot10^{-18}$ rad/s·cm. We believe that the specified radial angular velocity gradient will affect the primary poloidal field, thereby exciting the toroidal field of the radiant zone below the SCZ.

Evolution of the toroidal field in the radiant zone.

The change in the toroidal field in the radiant zone is determined by the induction equation [10]:

$$\partial\mathbf{B}_\mathrm{T}/\partial t = r\sin\theta\,(\mathbf{B}_\mathrm{r}\nabla)\,\mathbf{\Omega}\,\mathbf{i}_\varphi + \mathrm{rot}\,[\mathbf{U}_\mathrm{B}\times\mathbf{B}_\mathrm{T}] + \nu_\mathrm{m}\Delta\mathbf{B}_\mathrm{T}. \qquad (1)$$

The first term on the right-hand side of equation (1) describes the generation of a toroidal field $\mathbf{B}_\mathrm{T} = B_\varphi\mathbf{i}_\varphi$ (B_φ is the azimuthal component of the field, $\mathbf{i}_\varphi$ is the azimuthal unit vector in the spherical coordinate system) under the influence of the radial gradient of the angular velocity $\partial\mathbf{\Omega}/\partial r$ on the radial component $\mathbf{B}_\mathrm{r}$ of the primary poloidal field (the deep Ω-effect). The second term of the equation is responsible for the loss of the magnetic flux of the toroidal field due to its magnetic buoyancy with the velocity $\mathbf{U}_\mathrm{B}$, and the third one describes the ohmic dissipation of the field due to the magnetic viscosity $\nu_\mathrm{m} = c^2/4\pi\sigma$ (σ is gas-kinetic electrical conductivity).

As T. Cowling [11] showed for the first time, the time of ohmic attenuation of a relict magnetic field entrapped by a substance in the formation of the Sun, due to the high plasma conductivity in the deep bowels ($\sigma \approx 3\cdot10^{17}$ CGSE) is extremely long – comparable to evolutionary of the Sun. Therefore, in the following we will not consider the third term on the right in equation (1) and focus on considering the processes of field generation in the radiant zone and its transfer by magnetic buoyancy from the radiant zone in the SCZ.

In order to analyze the restructuring of magnetism in the radiant zone, we will evaluate the evolution of the magnetic field over time separately for these two processes.

The rate of increase of the toroidal field is determined by the measure of the deep differential rotation $G \equiv r\partial\Omega/\partial r$ (r is the distance from the center of the Sun) and the value of the primary radial field B_r

$$\left|\frac{\partial B_\varphi}{\partial t}\right|_\Gamma = O\,(GB_\mathrm{r}) \equiv O\,(\Gamma)\cdot \qquad (2)$$

Here $\Gamma \equiv GB_\mathrm{r} = (r\partial\Omega/\partial r)B_\mathrm{r}$ is the parameter of generation (the intensity of deep Ω-effect); it is also taken into account that $\sin\theta = O(1)$ for $\theta = 45°$.

According to E. Parker [12], any magnetic field B of the radiant zone, which is concentrated into magnetic force tubes (MFT), is transported upward in the direction of SCZ due to magnetic buoyancy. The magnitude of the rate of rise of the field is determined by the expression

$$U_\mathrm{B} \approx u_\mathrm{T}\,(\lambda_\mathrm{T}/a)^2\,(B^2/8\pi P), \qquad (3)$$

where u_T is the average rate of heat transfer upwards, λ_T is the height temperature scale, a is the transverse radius of the MFT, P is the gas pressure outside the MFT. From this, the rate of loss of the growing field B_φ with the characteristic scale L due to magnetic buoyancy is proportional to the third degree of magnitude of the field

$$\left|\frac{\partial B_\varphi}{\partial t}\right|_\gamma = O\,\left(\frac{U_\mathrm{B}}{L}B_\varphi\right) \equiv O\left(\gamma B_\varphi^3\right)\cdot \qquad (4)$$

Here $\gamma_\mathrm{b} = (U_\mathrm{B}/\,LB_\varphi^2) \equiv (u_\mathrm{T}/8\pi PL)(\lambda_\mathrm{T}/a)^2$ is the parameter of loss of magnetic flux due to buoyancy.

If you use estimates (2) and (4), then the induction equation (1) can be rewritten (taking into account the signs of change of the magnetic field) in the following simplified form:

$$\partial B_\varphi/\partial t \approx \Gamma - \gamma B_\varphi^3. \qquad (5)$$

From the stationarity condition $B_\varphi/\partial t = 0$, when the deep Ω-effect compensates for the field losses caused by magnetic buoyancy, we obtain a formula for estimating the maximum magnitude of the toroidal magnetic field, which can be maintained in the radiant zone for a long time,

$$\max\left|B_{\varphi}\right| \equiv B_{\varphi}^{\circ} = O\left(\left[\frac{\Gamma}{\gamma_{\text{b}}}\right]^{1/3}\right) = O\left(\left[GB_{\text{r}}\frac{8\pi PL}{u_{\text{T}}}\left(\frac{a}{\lambda_{\text{T}}}\right)^{2}\right]^{1/3}\right). \quad \textbf{(6)}$$

It is seen that magnetic buoyancy (parameter γ_b) limits the intensity of the excited field (parameter Γ) at the stationary level B_{φ}°. A typical time to reach this value is

$$\tau_o \approx B_{\varphi}^{\circ}/\Gamma = (1/\gamma_b\Gamma^2)^{1/3}. \quad (7)$$

At a sufficiently powerful source of generation ($\Gamma > \gamma_b$) fields, that are larger than the stationary value B_{φ}°, are brought to the surface. The characteristic time of the toroidal field B to rise from a certain depth in the radiant zone up to the lower base of the convective zone can be estimated by the expression

$$\tau_B \approx d/U_B = 8\pi Pd\,/u_T B^2\,(\lambda_T/a)^2, \quad (8)$$

where $d = r_{rz} - r_{scz}$ (r_{rz} is the solar radius corresponding to the depth in the radiant zone from which the field floating up begins, r_{scz} is the radius of the lower base of the SCZ).

Calculations of the parameters of the restructuring of magnetism.

Let us proceed to the numerical analysis of the evolution of the deep magnetism of the Sun, taking into account the calculated value of the radial gradient of the angular velocity based on the data of helioseismological experiments ($\partial\Omega/\partial r \approx \Delta\Omega/\Delta r \approx 7 \cdot 10^{-18}$ rad/s·sm) and considered above effects of exciting and loss of magnetic flux of the toroidal field. The necessary physical parameters (P and u_T for calculations are taken from the standard model of the Sun [13]. According to papers [14, 15], the value of the radial component B_r of the poloidal field in the radiating zone lies in the range of $0{,}1 \div 10$ G. Therefore we used three values of B_r for the estimates: 0,1 G; 1 G and 10 G. Following Parker [12], we considered the optimal variant of restructuring magnetism, when the characteristic magnitude of the change in the magnetic field L and the temperature scale of the height are equal to the transverse radius a of the magnetic force tube, the value of which is taken to be $0{,}1\,R_{\odot} = 7 \cdot 10^{10}$ cm. The results of the calculations of the parameters of the restructuring of magnetism are given in the Table. It can be seen that as a result of the deep Ω-effect a quasi-stationary toroidal magnetic field can be excited in the radiant zone, whose power varies (depending on the accepted value of the radial field $B_r = 0{,}1 \div 10$ G) in the range of values from $5 \cdot 10^7 \div 2 \cdot 10^8$ G near the core of the Sun ($r/R_{\odot} = 0{,}3$) to $5 \cdot 10^6 \div 2 \cdot 10^7$ G at the top of a stable section located directly below the lower base of the SCZ ($r/R_{\odot} = 0{,}7$). The latter estimate is consistent with the order of magnitude with the determination of the toroidal magnetic field at the boundary of the radiant zone and the SCZ from the decoding of the data of helioseismological experiments [16, 17], as well as with theoretical calculations within the diffuse models of the solar cycle [18, 19]. The characteristic time τ_0 of reaching these field values B_{φ}° according to the estimates of expression (7) varies accordingly in the range from $1 \cdot 10^8 \div 5 \cdot 10^6$ years to $5 \cdot 10^6 \div 2 \cdot 10^5$ years. The time intervals τ_0 obtained for the output of the exciting of field to a steady-state level (when the order of several megaGauss is reached) are in agreement with the order of magnitude with the estimates τ_0 within the diffusion model [18]. Due to magnetic buoyancy, the toroidal fields, whose magnitude outweighs the regular values B_{φ}°, are gradually pushed out of the radiant zone (where there is no convection) into the turbulent SCZ layers where the dynamo mechanism operates. The calculations by the expression (8) of the time τ_B of the magnetic field removal from the bowels of the Sun to the lower base of the SCZ ($r/R_{\odot} = 0{,}7$) give the following estimates: $\tau_B \approx 4 \cdot 10^8 \div 2 \cdot 10^6$ years when the field emerges from depth $r/R_{\odot} = 0{,}3$ ($d = 0{,}4\,R_{\odot}$); and $\tau_B \approx 10^7 \div 4 \cdot 10^5$ years when rising from the depth $r/R_{\odot} = 0{,}6$ ($d = 0{,}1\,R_{\odot}$). From our estimates, it can be seen that the characteristic time τ_0 of reaching the magnitude of the field due to the deep Ω-effect is shorter than the time τ_B of the field removal from the radiant zone to the SCZ due to magnetic buoyancy. Therefore, a regular field of constant direction B_φ° can be maintained in a radiant zone for a long time, despite the permanent loss of magnetic flux due to buoyancy.

Alternation of amplitude of solar magnetic cycles.

Due to the magnetic buoyancy, the deep toroidal field, excited by the deep Ω-effect in the radiant zone, is carried upward and gradually penetrates into the turbulent layers of the SCZ, where the turbulent dynamo operates. In view of this, the total toroidal (azimuthal) magnetic field B_φ in the SCZ consists of two components: cyclic $B_\varphi^C(t)$, changing with time, and quasi-stationary (regular) B_φ°:

$$B_\varphi(t) = B_\varphi^C(t) + B_\varphi^\circ. \tag{9}$$

The first magnetic component $B_\varphi^C(t)$, excited by the αΩ-dynamo process, changes its direction (polarity) with a period of 11 years, thereby causing the observed cyclicality of solar activity [20-22]. At the same time, the second additional component of constant direction, which, due to magnetic buoyancy, penetrates into the SCZ from below from the radiant zone, plays here the role of a source of stable magnetic "feeding", which affects the power of the total magnetic flux of the toroidal field. Therefore, in a certain cycle, when the directions of the two magnetic components coincide, the total magnetic flux will be more powerful than in adjacent cycles in which the directions of the two components are opposite. Rising on the solar surface, the total toroidal field, characterized by these cyclic variations in its magnitude, will cause corresponding variations in the intensity of the formation of the sunspots, which should eventually lead to the observed alternation of the amplitude of adjacent (even and odd) cycles.

Conclusion.

A scenario is proposed to explain the observed phenomenon of amplitude alternation of adjacent 11-year solar activity cycles. It is shown that a noticeable radial gradient of angular velocity in the radiant zone (calculated by us on the basis of helioseismological experiments), acting on a weak relict radial magnetic field, generates a powerful deep toroidal magnetic field of constant direction (the deep Ω-effect of radiant zone). As a result of magnetic buoyancy, this field gradually penetrates from below to the turbulent layers of the SCZ, where the dynamo mechanism operates, responsible for the 11-year cyclical activity of the solar activity. Continuous "feeding" of the magnetic flux in the SCZ due to the additional toroidal flux emerging from below leads to variations in the power of the total toroidal field in adjacent cycles. The total toroidal field, rising on the solar surface, causes the observed alternation of the amplitude of adjacent solar 11-year activity cycles.

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ЧЕРГУВАННЯ АМПЛІТУДИ МАГНІТНИХ ЦИКЛІВ СОНЦЯ

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Запропоновано сценарій, що пояснює спостережене явище чергування амплітуди сусідніх 11-річних циклів сонячної активності. Показано, що помітний радіальний градієнт кутової швидкості в променистій зоні (розрахований нами на підставі даних геліосейсмологічних експериментів), діючи на слабке реліктове радіальне магнітне поле, генерує потужне глибинне тороїдальне магнітне поле постійного спрямування (глибинний Ω-ефект променистої зони). Внаслідок магнітного спливання це поле поступово проникає знизу в турбулізовані шари сонячної конвективної зони (СКЗ), де працює механізм динамо, відповідальний за 11 - річну циклічність сонячної активності. Неперервне «підживлення» магнітного потоку в СКЗ за рахунок спливаючого знизу додаткового тороїдального потоку приводить до варіацій потужності сумарного тороїдального поля в суміжних циклах. Останнє, спливаючи на сонячну поверхню, викликає спостережене чергування амплітуди сусідніх сонячних 11-річних циклів активності.

Ключові слова: Сонце; промениста зона; реліктове магнітне поле; геліосейсмологічні експерименти; внутрішнє обертання; магнітна плавучість; конвективна зона; турбулентне динамо; 11 - річний цикл сонячної активності.

НАЙБЛИЖЧІ ПЕРСПЕКТИВИ КОСМІЧНОЇ ПРОГРАМИ «ARTEMIS»

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В даній статті проаналізовано програму місії «Artemis», описані основні етапи її реалізації, охарактеризовано нинішній стан окремих виконаних етапів та висвітлені майбутні перспективи космічної місії.

Ключові слова: *Artemis, космічна місія, космічна програма, Місяць, Марс, дослідження космосу.*

Після висадок на природній супутник Землі астронавти робили фотознімки, проводили експерименти, встановили декілька прапорів і взявши зразки ґрунту, поверталися додому. Та це тижневе перебування не поклало початок тривалій присутності людини на Місяці.

Через 48 років після останньої місії «Аполлон-17» (в грудні 1972 року), яка передбачала посадку на Місяць, з'явилася потреба у подальшому дослідженні супутника Землі для створення постійної бази.

Науковці вважають, що база на Місяці може перетворитися на відправний пункт для польотів у дальній космос; на ньому можна встановлювати космічні телескопи, які працюватимуть на нових принципах; місячна база допоможе в освоєнні Марсу та створить додаткові можливості щодо вирішення наукових таємниць про формування Землі та Місяця. Така база, навіть, може стати економічно вигідною завдяки космічному туризму.

Колишній астронавт Кріс Хадфілд вважає, що постійна дослідницька станція на Місяці − це наступний логічний крок у дослідженні космосу.

Також багато експертів вважають, що найбільші перешкоди для подальших місій на Місяць мають банальні причини. Найбільша перешкода для будь-якої програми, яка передбачає космічні польоти, особливо з людьми, – це велика вартість проекту. Проте бюджет – не єдина причина, через яку людство не повернулося на Місяць. На його поверхні чимало кратерів та валунів, які загрожують безпечній висадці.

Але зважаючи на різні причини, NASA знову озвучує інформацію про запуск нової програми. Вона увібрала у себе напрацювання скасованих програм «Сузір'я» та «Asteroid Redirect Mission». Ця програма отримала назву «Artemis» («Артеміда»), вона пов'язана із назвою попередньої програми NASA «Аполлон». Ці імена належать грецьким богам. У Аполлона існує сестра-близнюк на ім'я Артеміда, яка є богинею Місяця. Тобто, назва програми цілком логічна, якщо керуватися давньою міфологією [1].

«Artemis» – програма NASA у кооперації із приватними компаніями та ЄКА щодо розвитку пілотованих космічних польотів. Її метою є відправлення людей на поверхню Місяця у 2024 році та створення тамтешньої інфраструктури із подальшими планами доправити астронавтів на Марс.

За багато років підготовки місячна програма «Artemis» об'єднала відразу кілька розробок. У польоті братиме участь жінка та чоловіки-астронавти. Точкою «примісячення» швидше за все буде територія південного полюса Місяця.

Ця програма є амбіційним місячним проектом згідно з яким будуть виконані: 37 запусків з Землі, 5 посадок на поверхню з екіпажем, створення першої місячної бази.