Висновки. Виявлені на сьогодні всі Троянці Нептуна та нумеровані Троянці Юпітера навряд чи можуть перейти в популяцію Кентаврів у найближчі кілька сотень тисяч років за рахунок лише гравітаційних збурень.

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О ВОЗМОЖНОСТИ ПЕРЕХОДА ТРОЯНЦЕВ ПЛАНЕТ К КЕНТАВРАМ

Из каталога Международного центра малых планет на 2020 год отобраны Троянцы Юпитера и Нептуна. Проведены числовые расчеты эволюции орбит на интервалы до 1 млн лет. Установлено, что обнаруженные на сегодня все Троянцы Нептуна и нумерованные Троянцы Юпитера вряд ли могут переходить в популяцию Кентавров в ближайшие сотни тысяч лет.
Ключевые слова: Троянцы, Кентавры, орбиты.

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ON A POSSIBILITY OF TRANSFER OF THE PLANET TROYANS TO CENTAURS

Jupiter Trojans and Neptune Trojans have been selected from the Minor Planet center catalog for 2020. Numerical calculations of the evolution of orbits on intervals of up to 1 million years have been carried out. It has been established that all discovered by today Neptune Trojans and the numbered Jupiter Trojans are unlikely to transfer into the Centaur population during the next hundreds of thousands of years.
Keywords: Trojans, Centaurs, orbits.

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ON SUNSPOT "ROYAL ZONE" AND TWO MAXIMA OF SOLAR CYCLE

Cyclic regeneration of the large-scale magnetic field of the Sun underlies all the phenomena known collectively as "solar activity". The sunspot cycle is arguably the best known manifestation of the solar magnetic cycle. We outlined here the scenario of reconstructing of toroidal magnetic field in the solar convection zone (SCZ), which, on our opinion, may help to understand why magnetic fields rise to the solar surface only in the sunspot "royal zone" and what is reason of the phenomenon of double maximum of sunspots cycle. The effect of magnetic pumping (advection) caused by radial inhomogeneity of matter with taking into account Sun's rotation [28], in conjunction with deep meridional circulation, play a key role in proposed scenario. Magnetic buoyancy constrains the magnitude of toroidal field produced by the Ω effect near the bottom of the SCZ. Therefore, we examined two "antibuoyancy" effects: macroscopic turbulent diamagnetism and magnetic advection caused by radial inhomogeneity of fluid density in the SCZ, which we call as the $\nabla\rho$ effect. The Sun's rotation substantially modifies the $\nabla\rho$ effect. The reconstructing of the toroidal field was examined assuming the balance between mean-field magnetic buoyancy, turbulent diamagnetism and the rotationally modified $\nabla\rho$ effect. We found that the reconstructing of large-scale magnetism develops differently in the near-polar and equatorial domains of the SCZ. In the near-polar domain, two downward pumping effects (macroscopic diamagnetism and rotational pumping) act against magnetic buoyancy and, as a result, they neutralize magnetic buoyancy and block the toroidal field (which is generated by the Ω effect) near the tachocline. Therefore, these two antibuoyancy effects might be the reason why sunspots at the near-polar zones are never observed. In other words, strong deep-seated fields at high latitudes may well be there, but they not produce sunspots. At the same time, in the deep layers of the equatorial domain, the rotational turbulent pumping due to the latitudinal convection anisotropy changes its direction to the opposite one (from downward to upward), thereby facilitating the migration of the field to the surface. We call this transport as first (upward) magnetic advection surge. The fragments of this floating up field can be observed after a while as sunspots at latitudes of the "royal zone". Meanwhile, a deep equator-ward meridional flow ensures transporting of deep-seated toroidal field, which is blocked near pole in tachocline, from high latitudes to low ones where are favourable conditions for the floating up of the strong field. Here this belated strong field is transported upward to solar surface (the second upward magnetic advection surge). Ultimately, two time-delayed upward magnetic surges may cause on the surface in the "royal zone" the first and second maxima of sunspots cycle.
Keywords: Sunspots, "royal zone", solar cycle, magnetic fields, turbulent convection, magnetic buoyancy, turbulent magnetic pumping, meridional circulation.

Introduction. Sunspots, the most noticeable and observable manifestation of solar activity, do not appear on the entire disk of the Sun, but only in heliolatitude belts located at a distance of about 40° ÷ 45° on both sides of the solar equator. Near the equator itself, up to latitudes ± 5º, spots also appear very rarely. Christopher Scheiner, one of the four telescopic discoverers of sunspots, called these latitudinal belts as "royal zone" (Scheiner's "Rosa Ursina sive Sol", published in 1630). After the discovery of 11-year cyclic variations in the number of sunspots (Schwabe-Wolf law, 1843, 1848), it turned out that the location of latitudinal zones of sunspots changes with the phase of the cycle. This circumstance attracted the attention of the English researcher R. Carrington in 1858 [4], who also discovered the differential rotation of the solar surface. Subsequently, the German scientist G. Spörer studied in detail the changes with the phase of the cycle in the distribution of sunspots over heliolatitude [58]. At the beginning of each new cycle, spots appear mainly at the polar edges of the "royal latitudes of activity", and later at ever lower latitudes. The maximum coverage of the solar surface by spots is achieved at approximately 15º latitude. The law established by Spörer reflects the frequency of the emergence of new groups of sunspots, which consists in a monotonic displacement to the equator of the latitudinal zone of sunspot formation during the cycle. Visually, Spörer's law is illustrated by the diagram of latitude – time, first built by E. Maunder in 1913 [46]. The discovered latitudinal distribution of spots with a cycle phase was later called the "Maunder butterflies" diagram (Fig. 1).

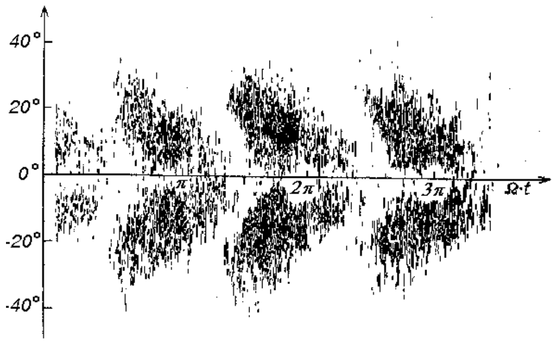

Fig. 1. Diagram of the "Maunder butterflies" [46], according to observations from 1874 to 1913, this shows the areas of existence of sunspots depending on the heliographic latitude (in the "royal zone") and phase of the solar cycle, Ωt

The nature of sunspots was unknown till 1908, when J. Hale [16] observed Zeeman splitting in the light coming from sunspots on the Sun and concluded that sunspots are highly magnetic structures on the solar surface with magnetic fields of the order of 1000 G. Another major breakthrough came in 1913, when J. Hale [17] proposed that the Sun has a general magnetic field similar to the field of a uniformly magnetized sphere, the axis of which is slightly inclined to the axis of rotation of the Sun. Its one now called the global magnetic field. A little later (1919) Hale's celebrated polarity laws [18] established the existence of a well-organized toroidal magnetic flux system, residing somewhere in the solar interior, as the source of sunspots. In the same year (1919) J. Larmor suggested [44] the inductive action of fluid motions as one of a few possible explanations for the origin of this magnetic field, thus opening the path to contemporary solar cycle modeling. Larmor's suggestion fitted nicely with Hale's polarity laws, in that the inferred equatorial antisymmetry of the solar internal toroidal fields is precisely what one would expect from the shearing of a large-scale poloidal magnetic field by an axisymmetric and equatorially symmetric differential rotation pervading the solar interior. Later in 1959, as a result of magnetographic measurements on the Sun, weak magnetic fields were revealed near its poles. It soon became clear that the magnetic field lines of these fields are directed along the meridians and correspond to a dipole configuration.

The sunspot butterfly diagram, Hale's polarity law, Joy's law of the tilt angles of bipolar sunspot groups, synoptic magnetograms, and the shape of the solar corona at and around solar activity minimum jointly suggest that, to a tolerably good first approximation, the large-scale solar magnetic field is axisymmetric about the Sun's rotation axis, as well as antisymmetric about the equatorial plane. According to modern understanding [36, 49, 61, 65] the axially symmetric global magnetic field of the Sun consists of two components. The first component is a weak poloidal field B_P. The lines of force of the poloidal field, coming out on the solar surface, form background magnetic fields, in particular, polar magnetic fields. The second magnetic component is a deep toroidal field B_T hidden from observers. The magnetic flux tubes of this field have opposite directions in the northern and southern hemispheres. Sunspots appear when deep-seated toroidal flux ropes due to magnetic buoyancy rise through the SCZ and emerge at the photosphere [48, 49]. Assuming that they rise radially and are formed where the magnetic field is the strongest, the sunspot butterfly diagram can be interpreted as a spatio-temporal "map" of the internal, large-scale toroidal field.

When observing, we see only local fragments of the toroidal field caused by magnetic buoyancy, which appear in the "royal zone" in the form of bipolar magnetic groups of sunspots. The strong magnetic field of bipolar spots first appears near heliolatitudes ± 40°÷ 45° and migrates towards low latitudes during about 11 years. Ultimately, the magnetic field of the spots near the equator is neutralized by the penetration of the field of the opposite sign from the other hemisphere, decreases and disappears. Therefore, it becomes clear that the "butterflies diagram" reflects the places of concentration of the deep toroidal magnetic field in the sub-photospheric layers and determines the rate of its migration to the equator [48].

M. Gnevyshev [12], and A.Antalova and M. Gnevyshev [1] studied the distribution of the average yearly total area of sunspot groups in the "royal zone heliolatitudes". As a result, they discovered the phenomenon of the so-called the double maximum of the sunspot cycle, the essence of which is as follows. It was found that there were two maxima of yearly total area of sunspots in each cycle. The first maximum was centered at the latitude 25°. It coincided in time with the main maximum of the 11-year cycle of Wolf numbers, while the second maximum appeared later (about two years) at low latitudes (10°÷15°).

In the last few decades, researchers have made a lot of effort to clarify the described observed spatio-temporal features of sunspot activity [2, 8, 11, 13, 14, 15, 26, 30, 51, 57, 68, 69]. However, no definitive explanation of the problem of the "royal zone" and double sunspots maximum has been received. Therefore, in this paper we attempted to outline the scheme of the reconstructing of magnetism in the solar convection zone (SCZ), which may help to understand why magnetic fields rise to the solar surface only in the "royal zone", and how may to explain the double peak sunspot cycle. The processes of turbulent radial magnetic pumping and deep meridional flow play a key role in the proposed scenario of the reconstructing of the toroidal magnetic field. To explain the physics behind the proposed scenario, we briefly review the effects involved in the proposed reconstructing scheme.

Global magnetic field, solar dynamo and magnetic buoyancy. It is well known today, that the poloidal (polar) magnetic field flips its orientation every 11 years with a 90º phase lag with the sunspot cycle [19]. A typical sunspot cycle starts with a strong polar magnetic field while there are hardly any sunspots. As time progresses, the number of sunspots increases while the polar field strength decreases gradually, until it becomes zero during the sunspot maximum. As the cycle progresses further, the sunspot number starts to decline and a polar magnetic field of opposite polarity starts building up and as the sunspot cycle reaches its end, the new polarl field is fully formed. Thus, one sunspot cycle corresponds to one half of the solar magnetic cycle, with the full cycle having a period of roughly 22 years.

The origin of solar activity with its 11-year magnetic cycle is generally understood in terms of an oscillatory hydrodynamic dynamo inside the Sun [5]. A toroidal magnetic field is generated from a poloidal field through differential rotation: the angular velocity radial gradient $\partial\Omega/\partial r$ acts in the solar high-conducting interior on the large-scale poloidal field B_P to transform the latter into a toroidal field B_T. This process is called the Ω-effect. The essence of the global dynamo is the regeneration of the poloidal field B_P from the toroidal one B_T through interaction with helicity turbulent convection in the rotating Sun (α-effect). The systematic twisting due to the Coriolis force generates an N–S dipole moment from the originally E–W oriented toroidal field. This dipole moment spreads by turbulent diffusion to reverse the old global poloidal field and replace it with a new one of opposite sign, thereby closing the solar cycle ($\alpha\Omega$-dynamo model of the solar cycle). Nowadays we know that sunspots represent proxies for the underlying toroidal the magnetic field, strong flux ropes of which float to the surface. The solar dynamo operates in the Sun's interior, which is not accessible to direct observations (except indirectly through helioseismology). At the surface of the Sun, the main directly observable signatures of the dynamo are the bipolar magnetic regions (sunspots, ephemeral active regions, and the still smaller intra-network fields), which represent magnetic flux that has emerged from the interior. It is usually assumed that the most favourable place for the generation of a toroidal field is the deep layers near the SCZ bottom, in the vicinity of the tachocline. This is due to the fact that the efficiency of magnetic buoyancy is the lowest here.

The buoyancy mechanism of magnetic tubes with plasma in the gravitational field was proposed by E. Parker [48] and, independently, by E. Jensen [25]. According to E. Parker [48], the magnitude of the buoyancy velocity of the magnetic field B is determined by the expression $U_B\,(B,\rho) \approx B/(4\pi\rho)^{1/2}$. Near the solar surface, where the plasma density ρ is sufficiently small, the buoyant velocity U_B is very high, while in the deep dense layers the effectiveness of buoyancy is much lower. However, even in the deep layers of the SCZ it is difficult to keep flux tubes with strong magnetic field for a long time against magnetic buoyancy [49].

Constrains on magnitude of the excited fields were reduced substantially when the magnetic buoyancy effect was derived within framework of the mean-field magneto-hydrodynamics by L.Kitchatinov and V.Pipin [32, 33]. In the field case $\beta < 1$, which is typical for almost all bulk of the SCZ, the effective buoyant velocity for the smoothed field is determined by the equation

$$U_B(\beta) = \left(\frac{l}{H_P}\right)\left(\frac{u}{\gamma}\right)\frac{\beta^2}{15}, \quad (1)$$

where parameter $\beta = B/B_{eq}$ is the field strength normalized to the energy equipartition value $B_{eq} \approx (4\pi\rho)^{1/2}u$, l and u are the mixing length and the r.m.s. velocity of the convective turbulent motions, ρ is the fluid density, H_P is the pressure scale height and $\gamma = 5/3$ is the adiabaticity index. Calculations by L. Kitchatinov and V. Pipin [32, 33] showed that the buoyancy velocity for the smoothed field is noticeably less than the magnetic buoyancy velocity determined by Parker expression.

For the effective Ω-process it is necessary that magnetic field be held for a long time in the region of the field generation. As noted above, the best place for the localization of the toroidal field generation mechanism is the deep SCZ layers near the tachocline. However, even with a low of buoyant velocity for the smoothed field (1) it is difficult to achieve a significant magnetic field strength and retain it over a time comparable to the period of the solar cycle. The reason is that strong fields due to the magnetic buoyancy are quickly evacuated from the generation zone. In this regard, there is an urgent need to search for mechanisms of magnetic anti-buoyancy (negative magnetic buoyancy) compensating for the fast rise of the fields. The below described effects of turbulent reconstructing of large-scale magnetism can play the role of the necessary anti-buoyancy mechanisms.

Effects of turbulent reconstructing of large-scale magnetism

Macroscopic turbulent diamagnetism. In an inhomogeneous fluid flow, the statistics of the velocity field depend on the coordinate along the inhomogeneous direction **g**. If we thread such a flow with a large-scale magnetic field, then the latter will be expelled from the regions of higher turbulence intensity to the regions of lower turbulent intensity. In a stratified turbulent fluid layer in particular, rms value of velocity u_{ms} usually decreases along **g** as density increases, and therefore the magnetic field can be expect to transport downwards. Yakov Zeldovich [64] studied the process of turbulent reconstructing of magnetic fields, which was latter called the macroscopic diamagnetic effect [52]. While this effect is not inducing magnetic field on its own, it can contribute to the large-scale transport of the field, and may notably lead to its accumulation deep into solar interiors. The physical sense of macroscopic turbulent diamagnetism of a plasma [36, 49, 61, 65] is the displacement of the mean (large-scale) magnetic field B along the gradient of turbulent diffusivity, $\nu_T \approx (1/3)\,ul \approx (1/3)\,u^2\tau$, with an effective velocity of $\mathbf{U}_\mu = -\nabla\nu_T/2$ ($\tau \approx l/u$ is the characteristic time of turbulent pulsations).

Since the parameters of turbulent convection on the Sun vary substantially along the depth, then in the SCZ are favourable conditions for macroscopic diamagnetism. We used the SCZ model computed by M.Stix [59] with $l = 2H_p$ (see Table) for our calculations.

Table

Physical parameters (ρ, *u*, τ) from the SCZ model by M. Stix [59].
Coriolis numbers ω(*z*) and the rotational functions $\varphi_1[\omega(z)]$ and $\varphi_2[\omega(z)]$ are received by our calculating.
Value $\theta_0^* = 90° - \theta_0$ is calculated boundary latitude, where radial ∇ρ-pumping changes its sign from positive sign to negative one

z, km	ρ, g/cm^3	*u*, cm/s	τ, s	ω	$\varphi_1[\omega(z)]$	$\varphi_2[\omega(z)]$	**θ*,°**
5,84 (3)	2,33 (-04)	4,34 (4)	1,45 (4)	8,70 (-2)	0,0005	0,1665	
1,12 (4)	1,08 (-03)	3,15(4)	3,71 (4)	2,15 (-2)	0,0046	0,1640	
3,17 (4)	8,12 (-03)	1,64 (4)	1,92 (5)	1,10 (0)	0,0383	0,1186	
5,08 (4)	1,86 (-02)	1,31 (4)	3,91 (5)	2,27 (0)	0,0565	0,0758	
5,95 (4)	2,45 (-02)	1,21 (4)	4,96 (5)	2,88 (0)	0,0562	0,0625	
6,98 (4)	3,23 (-02)	1,11 (4)	6,32 (5)	3,67 (0)	0,0525	0,0503	17,2
8,83 (4)	4,88 (-02)	9,83 (3)	9,02 (5)	5,23 (0)	0,0458	0,0363	21,1
9,54 (4)	5,61 (-02)	9,43 (3)	1,02 (6)	5,92 (0)	0,0427	0,0323	29,6
1,03 (5)	6,44 (-02)	9,05 (3)	1,14 (6)	6,60 (0)	0,0403	0,0292	31,7
1,11 (5)	7,39 (-02)	8,68 (3)	1,29 (6)	7,48 (0)	0,0372	0,0258	33,6
1,20 (5)	8,49 (-02)	8,30 (3)	1,45 (6)	8,41 (0)	0,0344	0,0231	35,0
1,29 (5)	9,75 (-02)	7,93 (3)	1,64 (6)	9,51 (0)	0,0315	0,0204	36,4
1,39 (5)	1,20 (-01)	7,53 (3)	1,85 (6)	1,07 (1)	0,0287	0,0181	37,4
1,49 (5)	1,29 (-01)	7,12 (3)	2,11 (6)	1,22 (1)	0,0261	0,0160	38,5
1,60 (5)	1,48 (-01)	6,60 (3)	2,44 (6)	1,42 (1)	0,0231	0,0138	39,3
1,72 (5)	1,70 (-01)	5,93 (3)	2,90 (6)	1,68 (1)	0,0200	0,0116	40,4
1,84 (5)	1,95 (-01)	4,91 (3)	3,78 (6)	2,19 (1)	0,0161	0,0090	41,6
1,98 (5)	2,26 (-01)	8,63 (2)	2,30 (7)	1,33 (2)	0,0030	0,0015	45,0

Note. Numbers in parentheses are an exponent of ten.

As we had showed [37, 38] the radial profile of turbulent diffusivity $\nu_T(z)$ is a smooth convex function with a maximum value, $\nu_T \approx 10^{13}$ см^2/с, approximately in the middle of the SCZ at a depth of $z \approx 130\times10^3$ km (Fig. 2) (see also [48]).

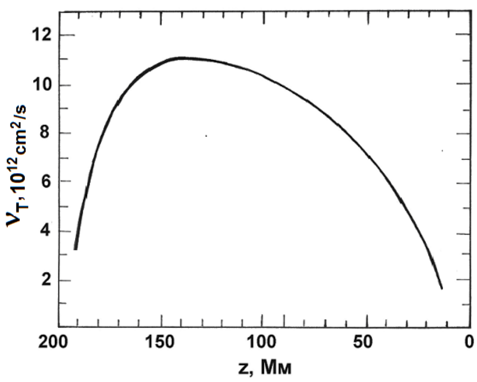

Fig. 2. The distribution by depth z in the SCZ of the value of the coefficient of turbulent diffusion $\nu_T \approx (1/3)\, ul \approx (1/3)\, u^2\tau$ calculated in the approximation of the theory of mixing length. The parameters *u* and τ are taken from the model by M. Stix [59]

The radial inhomogeneity of turbulent diffusivity suggests that the turbulent solar plasma has strong diamagnetic properties. According to our calculations [38, 42] the velocity of the diamagnetic pumping U_μ significantly varies along solar radius. The turbulent diamagnetism in the upper bulk of the SCZ manifests itself in the same way as magnetic buoyancy. However, in the lower half of the SCZ the intensity of turbulent convection falls to zero, so here macroscopic diamagnetism counteracts to magnetic buoyancy and, thus, plays the role of negative magnetic buoyancy, or anti-buoyancy effect. Due to sharp decreasing of the turbulent diffusivity near the bottom of the SCZ the velocity of the diamagnetic pumping U_μ here ($z \approx 184\times10^3$ km) reaches $\approx 1{,}6\times10^3$ cm/s (Fig. 3).

At the same time, one should bear in mind that the magnetic field in deep layers will suppress turbulent convection. Therefore, in the non-linear regime, the expression for the velocity of diamagnetic field pumping takes the next form [34]

$$\mathbf{U}_D(\beta) = 6\,\mathbf{U}_\mu \Psi_D(\beta), \qquad (2)$$

where $\Psi_D(\beta)$ is the function of magnetic suppression of the kinematic turbulent diamagnetic pumping (so called quenching function). In the weak field case (β < 1), which is characteristic for almost all bulk of the SCZ, quenching function is defined by the equation

$$\Psi_D(\beta) \approx \Psi_0 - \beta^2/5 = (1/6) - \beta^2/5, \qquad (3)$$

and it is normalized to $\Psi_0 = 1/6$ at β = 0.

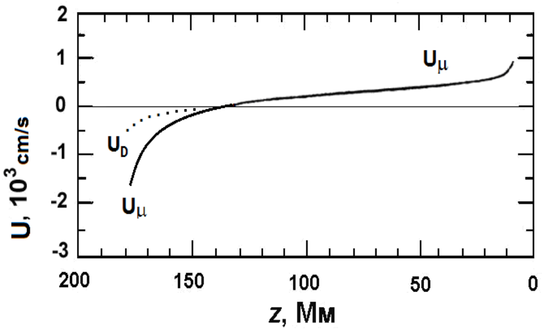

Fig. 3. Distributions of the velocities of macroscopic diamagnetic transport with depth, *z*, in the SCZ. The velocity $U_\mu = -\nabla\nu_T/2$ results from the kinematic approach (solid curve), while, $U_D(\beta_s) = 6\,U_\mu\Psi_D(\beta_s)$ is supplied by a nonlinear theory (dotted curve). Negative values of velocity correspond to downwards transport

When the rotation of the Sun is taken into account, the diamagnetic properties of the turbulized plasma manifest themselves differently with respect to the toroidal and poloidal fields [31]. The toroidal field is transported only along the radius, while at the pumping velocity of the poloidal field, in addition to the radial component, an equatorial meridional component also appears. However, we will only take into account the pumping of the toroidal field, since the reconstructing of this field is the subject of our study.

Magnetic pumping in a density-inhomogeneous turbulent medium. Besides the turbulent diamagnetism, another macroscopic transport of large-scale magnetic field results from magnetic fluctuations in the stratified turbulent plasma. E. Drobyshevskij [9] and S. Vainshtein [60] had found that in density-inhomogeneous turbulent plasma small-scale magnetic pulsations **b** lead to a change in the spatial distribution of a large-scale magnetic field **B**. The magnetic transport effect can be interpreted as follows (see [27]). The amplitude of the magnetic fluctuations, ***b***, produced by turbulent pulsations, ***u***, is increasing in the direction of the gradient of the fluid density, $b^2 \approx 4\pi\rho u^2$. At the same time, the random electric currents, $\mathbf{j} = (c/4\pi)\,\mathrm{rot}\,\mathbf{b}$, also are increasing in this direction. These modified currents change the initial distribution of the large-scale field ***B***. The resulting magnetic reconstructing can be represented as the transport (advection) of large-scale field **B** along the density gradient $\nabla\rho$. In the non-linear regime, the net distribution of the global magnetic field is equivalent to its transport with the effective velocity [27]

$$U_\rho = (1/6)\tau b^2\nabla\rho/4\pi\rho \approx (1/6)\,\tau\, u^2\, \nabla\rho/\rho, \quad (4)$$

where τ is the characteristic time of turbulent pulsations. To emphasize the role of the density plasma gradient in the magnetic advection effect, we call it as the **∇ρ-effect** of magnetized turbulent stratified plasma [39, 40, 42].

The density of the solar stratified substance increases from the photospheric layers to the lower base of the SCZ by almost six orders of magnitude [59] (see also as illustration Fig. 4). Therefore, there must be a noticeable radial downward magnetic flux **U**ρ. Indeed, our calculations [39, 40, 42] showed that the effective velocity of this downward flux, U_ρ, varies along solar radius from $\approx 2 \times 10^3$ cm/s near the bottom of the SCZ to $\approx 7 \times 10^3$ cm/s in the near-surface layers (Fig. 5). Thus, the ∇ρ-effect in the SCZ acts (similar to turbulent diamagnetism in the deep layers) as an anti-buoyancy (downward turbulent drift) transport.

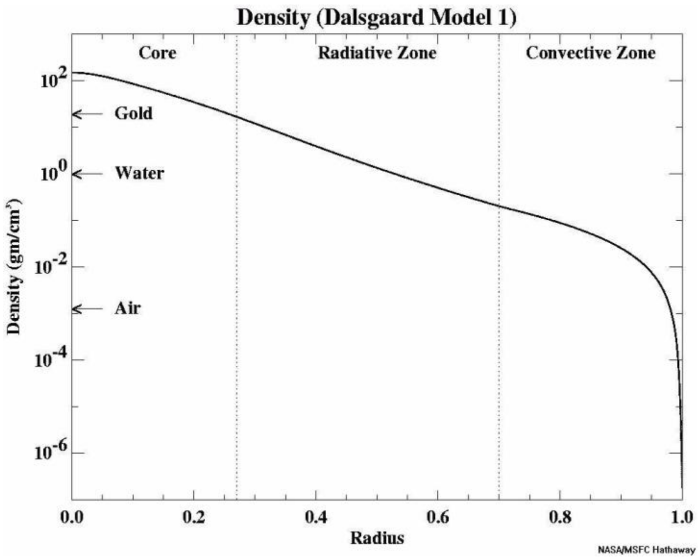

Fig. 4. Dependence of the density of solar plasma on the radius of the Sun [http://solarscience.msfc.nasa.gov/interior.shtml]

Rotational ∇ρ-effect. The Sun's rotation originates the convection anisotropy, which adds new properties to the ∇ρ-effect [28]. The degree of perturbation of convection by rotation depend on the anisotropy parameter – the Coriolis number $\omega = 2\tau\Omega$, where Ω is angular velocity ($\omega = Ro^{-1}$ is the inverse Rossby number). The strongest change occurs at moderate rotation ($\omega \approx 1 \div 10$) because very fast rotation suppresses the convection as well as the field advection. It is known that the effect of rotation leads to a relative increase in the scale of convective pulsations along the axis of rotation. Therefore, it is obvious that the transformation of the $\nabla\rho$ effect will depend on the angular distance from the poles. If at the poles the density gradient $\nabla\rho$ is parallel to the axis of rotation, then when approaching the middle and low latitudes, the $\nabla\rho$ gradually changes its direction, so that at the equator it becomes already perpendicular to the axis of rotation. Ultimately the $\nabla\rho$-effect, combined with rotation, performs the "fields' selection", as a result of which the toroidal and poloidal magnetic components are transported independently in the radial and meridional directions [28]. We called this modified turbulent magnetic pumping as the **rotational ∇ρ-effect**.

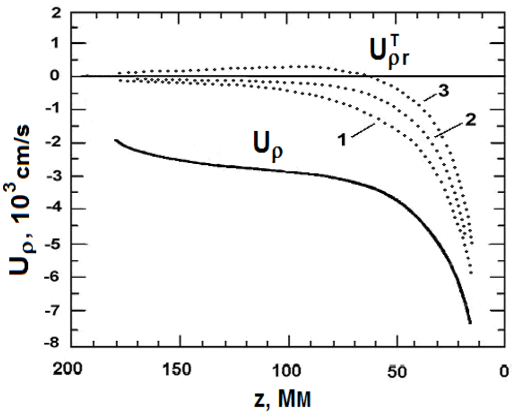

Fig. 5. Distributions of the magnetic pumping velocity $U_\rho \approx (1/6)\,\tau u^2\,\nabla\rho/\rho$ (solid line) with depth, z, in the SCZ; and the radial velocity of magnetic advection of toroidal field $U_{\rho r}^{T}$ for different co-latitudes θ (dotted lines: 1 – θ = 0° (pole), 2 – θ = 45°, 3 – θ = 90° (equator)). Negative velocities correspond to downwards transport. Plasma density ρ was taken from the SCZ model by M.Stix [59]. The rotation of the Sun causes a rotational modification of the $\nabla\rho$ effect, which depends on the angular distance from the poles. At the poles and in the middle latitudes, the $\nabla\rho$-pumping acts against magnetic buoyancy (curves 1 and 2, $U_{\rho r}^{T}$). However, in the equatorial plane in the lower half of the SCZ ($z \approx 60 \div 184$ Mm) the rotational pumping is directed upwards (curve 3)

We will take into account only the radial transport of the toroidal field B_T, because this field is involved in production of sunspots on the surface. The toroidal field radial transport directions (downward or upward) are dependent on the depth z, polar angle θ (co-latitude), and Coriolis number ω [28, 42]:

$$\mathbf{U}_{\rho r}^{T}(z,\theta,\omega) = 6\,\mathbf{U}_\rho(z)\,\{\varphi_2[\omega(z)] - \varphi_1[\omega(z)]\sin^2\theta\}. \quad (5)$$

It is seen the upward $\nabla\rho$ advection in the deep layers at the equatorial plane. The two functions, which depend on the Coriolis number,

$$\varphi_1(\omega) = \frac{1}{4\omega^2}\left[\frac{\omega^2+3}{\omega}\,\mathrm{arctg}\,\omega - 3\right], \quad (6)$$

$$\varphi_2(\omega) = \frac{1}{8\omega^2}\left[1 + \frac{\omega^2-1}{\omega}\,\mathrm{arctg}\,\omega\right], \quad (7)$$

describe the rotational influence on turbulent convection [28]. Our calculations [40] have revealed differences in behavior of these functions depending on the depth in the SCZ (see Table). Evidently, depending on the sign of factor $\{\varphi_2[\omega(z)] - \varphi_1[\omega(z)]\sin^2\theta\}$, radial magnetic advection may be directed downward (when this sign is positive) and upward (when the sign is negative). This produces a complicated latitude and depth dependencies of the magnetic advection velocity $U_{\rho r}^{T}(z,\theta,\omega)$ in the SCZ.

According to the data of helioseismology experiments [55], the angular velocity field $\Omega(r,\theta)$ in the SCZ is naturally divided into fast and slow rotation domains with the opposite signs of the radial gradient of the angular velocity (Fig. 6). It should be noted that in the near-polar domain of fast rotation conditions are created for the preferable excitation of the dipole mode of the poloidal magnetic field, while in the near-equator domain of slow rotation conditions are more favorable for the excitation of the quadrupole mode [41].

In the near-equatorial (low latitudes, θ* < 45°) fast-rotation domain, the angular velocity mostly decreases with depth ($\partial\Omega/\partial r > 0$), while this velocity increases inward the Sun ($\partial\Omega/\partial r < 0$) in the near-polar (high latitudes, θ* > 45°) slow-rotation domain (θ* = 90° – θ is a heliolatitude preferred by observers). We used the data on the angular velocity distribution [23], when calculated the Coriolis number $\omega(z)$ and the functions $\varphi_1[\omega(z)]$ and $\varphi_2[\omega(z)]$ (see Table). Our calculations for the SCZ model by M.Stix [59] showed that, in the high-latitude domain (θ* > 45°), the toroidal field transport velocity $U_{\rho r}^{T}(z,\theta,\omega)$ is directed downward (as in the absence of rotation) over the entire radial stretch of the convective zone (Fig. 7).

Let's explain in more detail the results of our calculations. One should await a quite significant reconstructing of magnetic field due to the most essential modification of the $\nabla\rho$-effect in the near equatorial domain in the deep layers since here physical condition are appropriate to fast rotation approach, $\omega \approx 5 \div 20$, which should produce strong convection anisotropy. Our calculations showed that in the near-equatorial domain (θ* < 45°) the transport direction depends on the radius (depth). The magnetic $\nabla\rho$-pumping is directed downward in the upper part of the SCZ, however, it changes its direction to the opposite (from descending to ascending), in the deep layers (Fig. 7). This is due to the fact that at heliolatitude < 45° factor ($\varphi_2 - \varphi_1 \sin^2\theta$) changes its sign from positive to negative. The latitude boundary of zero velocity, $U_{\rho r}^{T}(z, \theta, \omega) = 0$, can be determined by equation $\theta_0(z) = \arcsin[\varphi_2(z)/\varphi_1(z)]^{1/2}$. We have calculated the boundary latitude values $\theta_0^* = 90° - \theta_0$ for different depths of the lower part of the equatorial domain (last right column in Table). It can be seen from Table and Fig.7 that the maximum heliolatitude, where the ∇ρ-pumping start to contribute lifting the field up, near the SCZ bottom corresponds to $\theta \approx 45°$, which coincides with latitude of polar boundary of the "royal zone". At the same time, the segment of upwardly directed magnetic pumping gradually expands as it shifts to low latitudes, reaching its maximum extent over depth at the equator.

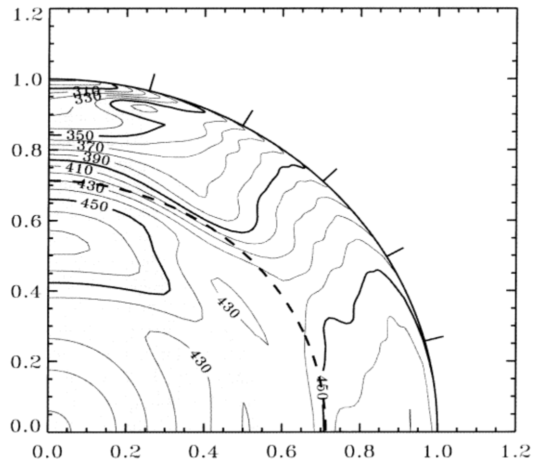

Fig. 6. A picture of the Sun's internal rotation based on helioseismic measurements from the Michelson Doppler Imager aboard the SOHO space station [55]. The numbers near the contours of the constant angular velocity (Ω = const) indicate the value of Ω in nanohertz. It is seen that the field of angular velocity in the SCZ is divided into the low-latitude domain of fast and high-latitude company domain of slow rotation with opposite signs of the radial gradient of the angular velocity $\partial\Omega/\partial r$. The dotted line corresponds to the lower base of the SCZ ($r \approx 0{,}71R$), deeper than which is the radiant tachocline

Therefore, there are three areas in each hemisphere of the Sun with different conditions of radial transport of the toroidal fields due to the rotary ∇ρ effect. The first area, where the fields are transported downward, covers near-polar domain. However, the near-equatorial domain, which coincides in heliolatitude with the royal zone of sunspots, is divided by radius (depth) into two layers (lower and upper) in which the fields are transported in different directions – upward and downward, respectively. In our opinion, it is fundamentally important that the upward magnetic ∇ρ pumping in the lower layer of the near-equatorial domain coincides with direction of magnetic buoyancy. As will be shown below, this considerably affects the magnetic field reconstructing pattern.

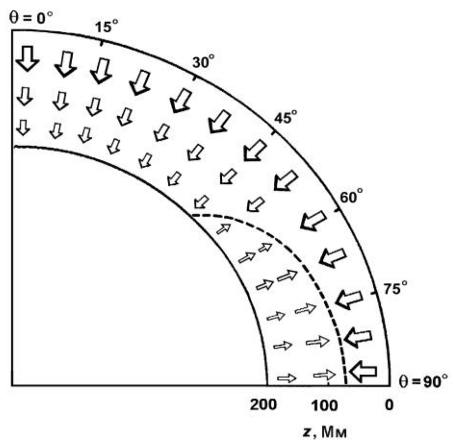

Fig. 7. Meridional cut of the SCZ, which shows the radial velocity distribution of the radial magnetic field advection of toroidal field $U_{\rho r}^{T}(z, \theta, \omega)$ by depth z and co-latitude θ (heliolatitude $\theta^* = 90° - \theta$). The arrows show the direction of the ∇ρ transport, the velocity of which varies from $\approx 7 \times 10^1$ cm/s near the SCZ bottom to $\approx 5 \times 10^3$ cm/s in the surface layers. The zero velocity isoline $U_{\rho r}^{T}(z,\theta,\omega) = 0$ (dotted curve), where the direction of the radial magnetic ∇ρ-flux changes, begins near the lower base of the SCZ at heliolatitude $\theta^* = 45°$, then it shifts upward and the region of lower latitudes, reaching the equator at a depth of $z \approx 60 \times 10^3$ km

Meridional circulation. The propagation of dynamo waves provides no enough adequate explanation for the observed migration of sunspots towards the equator. Therefore, it was proposed to explain this equatorial migration by deep meridional flows [6, 7, 10, 47, 63]. The deep circulation forces the toroidal field belts (which are responsible for the surface activity) to move equatorward. The existence of the meridional circulation was first inferred from the observation that there were unipolar patches of magnetic field in certain latitude belts [3] and that these patches shifted pole-ward with time [21, 62]. At the moment it is known that near the surface of the Sun, the uppermost 10 ÷ 20 Mm, there is a flow directed towards the poles of the order of 10 ÷ 20 m/s [35, 66]. Based on the law of conservation of matter, the researchers concluded that at the lower base of the SCZ there should be a meridional flow in the opposite direction from the poles to the equator. Under this condition, the substance at the poles should fall down to the tachocline, while at the equator it should rise from the depths to the surface, so as to ensure a closed cycle of the meridional (poloidal) circulation of the substance in the SCZ. It was shown by a numerical simulation based on helioseismological experiments that meridional circulation exists in all the SCZ layers and can even penetrate below the tachocline into the radiative zone [22, 24]. The calculated profile of the flows has a complex spatial structure of several cells distributed by depth and latitude (multi-cell circulation structure) [54, 67]. However, the profile of poloidal flows of substance in the solar interior (one, two, or more cells) is still unclear at present. Therefore, to simplify the calculations, we consider one global circulation cell. According to the calculations based on the data of local helioseismology [45, 53], the amplitude of the velocity of the reverse flow to the equator $U_M^{(deep)}$ in the lower part of the SCZ is in the range of 2 ÷ 5 m/s, which is consistent with the estimate obtained from the analysis of the migration speed of the sunspot band to the equator [20].

Reconstructing of toroidal field of the Sun. We now analyze the pattern of reconstructing of the toroidal field (excited by the Ω-effect at the SCZ bottom) due to the combined action of magnetic buoyancy, macroscopic turbulent diamagnetism, the turbulent ∇ρ-pumping and meridional circulation. Let us consider the situation separately for the near-polar (high-latitude) and near-equatorial domains.

The possible reason why sunspots are never observed at the near-polar zones. In the lower part of the near-polar domain, turbulent diamagnetism and ∇ρ-pumping push horizontal toroidal magnetic field into the deep layers. Counteracting magnetic buoyancy, they largely neutralize the rise of the fields. The condition of three magnetic fluxes velocities balance in deep layers,

$$\uparrow \mathbf{U}_B + \downarrow \mathbf{U}_D + \downarrow \mathbf{U}_{\rho r}^T \approx 0 \qquad (8)$$

(where the upward and downward field transports are indicated by the vertical arrows, ↑ and ↓, respectively) yields the following parameter of the normalized steady near-polar field blocked near the SCZ bottom:

$$\beta_S^P \approx \left\{ \frac{5\left[U_\mu + 6\left(\varphi_2 - \sin^2\Theta\varphi_1\right)U_\rho\right]}{6U_\mu + (1/3)(l/H_P)(u/\gamma)} \right\}^{1/2} \qquad (9)$$

From the physical conditions at a depth of $z \approx 184\times10^3$ km [$u \approx 4{,}9\times10^3$ cm/s, $\rho \approx 1{,}95\times10^{-1}$ g/cm^3 (see Table); $B_{eq} \approx 7650$ G; $\downarrow U_\mu \approx 1{,}6\times10^3$ cm/s; $\downarrow U_\rho \approx 2\times10^3$ cm/s (see Fig. 5)] for $\theta = 25^\circ$ (where $\varphi_1 \approx 0{,}0161$; $\varphi_1 \approx 0{,}0090$; see Table) we obtained due to calculating the following estimates: $\beta_S^p \approx 0{,}85$; $\uparrow U_B(\beta_S^p) \approx 2{,}84\times10^2$ cm/s; $\downarrow U_D(\beta_S^p) \approx 2{,}1\times10^2$ cm/s; $\downarrow U_{\rho r}^T \approx 7{,}4\times10^1$ cm/s; $B_S^p \approx 6500$ G

Thus, in the deep layers of the high-latitude domains the two antibuoyancy effects can neutralize floating of intensive fields. As a result, the magnetic layer of a strong toroidal field ≈ 6500 G must form near the tachocline. Obviously, it is these two antibuoyancy effects that prevent the strong near-polar toroidal fields, rooted in this layer, from rising to the surface. Perhaps, these two antibuoyancy effects might be the possible reason why sunspots at the near-polar zones are never observed. In other words, strong deep-seated fields at high latitudes may well be there, but they not produce sunspots (Fig. 8).

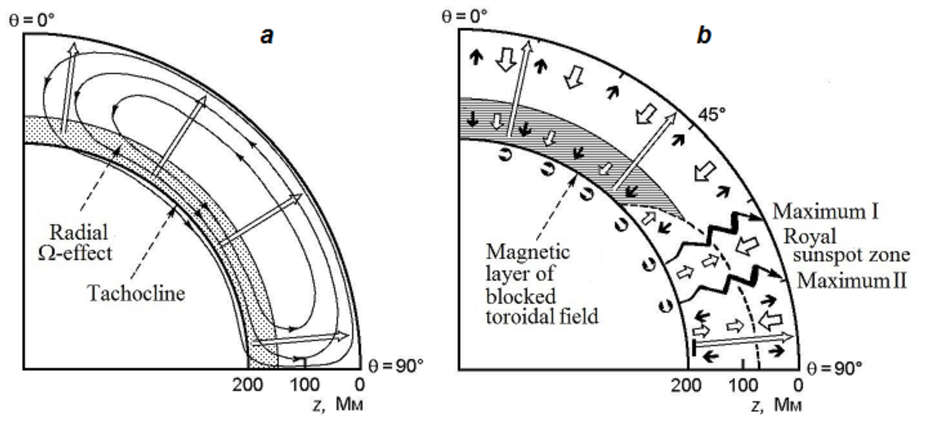

Fig. 8. Scheme of the turbulent reconstructing of the toroidal magnetic field in the SCZ: (a) meridional circulation (closed lines with arrows); magnetic buoyancy (long open arrows); and the layers associated with the radial Ω-effect (dashed area) near the SCZ bottom; (b) meridional transport (the ➲ signs) of the deep toroidal field (dashed area), blocked near the tachocline, from high latitudes to the near-equatorial domain, due to the deep meridional circulation; two surface-ward advection surges of the toroidal field (broken arrows) attributed to the combined action of magnetic buoyancy (long open arrows), macroscopic turbulent diamagnetism (short solid arrows); and the ∇ρ advection of the magnetic field (short open arrows), which cause the first and second maximums of sunspots to appear in the royal zone, shifted in time by 1÷2 years. The dotted curve corresponds to the zero velocity line $U_{\rho r}^T(z, \theta, \omega) = 0$, where there is a change in the direction of the radial ∇ρ transport

It is interesting to see what the condition of balance between the effects of turbulent pumping and magnetic buoyancy gives for the case of discrete flux tubes. To do this, let us turn to the mechanisms of magnetic buoyancy by M. Schüssler [56], and V. Kuznetsov and S. Syrovatskij [43], in which it was assumed that in the subphotospheric layers, most of the magnetic fields consist of separate intensive flux tubes. These mechanisms take into account the inhomogeneity of turbulent viscosity and the stratification of matter in the SCZ, as a result of which, when floating, the magnitude of the magnetic induction decreases and the transverse dimensions of the flux tubes increase. It turns out that under such conditions more powerful (about 10^5 G) steady-state fields can be retained in deep layers [39].

"Royal zone" of sunspots. As noted above, a change in the sign ($\varphi_2 - \varphi_1 \sin^2\theta$) leads to a change in the direction of pumping $U_{\rho r}^{\mathbf{T}}$ (see (5)). Therefore the pattern of transport of the toroidal field in the near-equatorial domain ($\theta^* = 0 \div 45°$) is completely different. As is seen in Figs. 5 and 7, here the magnetic ∇ρ-pumping in the deep layers (velocity $U_{\rho r}^{\mathbf{T}}$ with taking into account rotation), as well as magnetic buoyancy, are directed upward. Therefore the condition for balance of the velocities has a new form, which differs from condition Eq. (8) by term $\uparrow\mathbf{U}_{\rho r}^{T}$ instead $\downarrow\mathbf{U}_{\rho r}^{T}$:

$$\uparrow\mathbf{U}_B + \downarrow\mathbf{U}_D + \uparrow\mathbf{U}_{\rho r}^{T} \approx 0. \quad (10)$$

In this case, parameter of the normalized steady near-equatorial field blocked near the SCZ bottom, β_S^e, is similar to the expression (9), only the positive sign of factor ($\varphi_2 - \varphi_1 \sin^2\theta$) changes to negative one in new expression. As noted above, a change in the sign ($\varphi_2 - \varphi_1 \sin^2\theta$) leads to a change in the direction of pumping $U_{\rho r}^{\mathbf{T}}$ (see (5)) Calculations for $\theta = 75°$ ($\theta^* = 15°$) gave the following estimates for depth of $z \approx 184\times10^3$km ($u \approx 4{,}9 \times 10^3$ cm/s, $\rho \approx 1{,}95 \times 10^{-1}$ g/cm^3; $B_{eq} \approx 7650$ G; $\downarrow U_\mu \approx 1{,}6 \times 10^3$ cm/s; $\downarrow U_\rho \approx 2 \times 10^3$ cm/s): $\beta_S^e \approx 0{,}81$; $\uparrow U_B(\beta_S^e) \approx 2{,}59\times10^2$ cm/s; $\downarrow U_D(\beta_S^e) \approx 3{,}33 \times 10^2$ cm/s; $\uparrow U_{\rho r}^{T} \approx 7{,}40 \times 10^1$ cm/s; $B_S^e = \beta_S^e B_{eq} \approx 6200$ G.

Thus, it is this upward magnetic ∇ρ pumping ($\uparrow U_{\rho r}^{T} \approx 7{,}40 \times 10^2$ cm/s for the heliolatitude $\theta^* \approx 15°$) that helps magnetic buoyancy ($\uparrow U_B \approx 2{,}59\times 10^2$ cm/s) to neutralize turbulent diamagnetism ($\downarrow U_D \approx 3{,}33 \times 10^2$ cm/s) (Fig. 8). The value of the steady-state toroidal magnetic field $B_S^e \approx 6200$ G blocked near the SCZ in the near-equatorial domain is smaller than $B_S^p \approx 6500$ G in the near-polar domain. Therefore, strong toroidal fields above 6200 G must move upward. The upward ∇ρ transport acts, in fact, as a possible trigger for rising of strong deep fields to the surface at latitudes $\theta^* \le 45$. Thus, rotational ∇ρ-effect in the lower part of the equatorial domain plus magnetic buoyancy together ensure upward transfer of fragments of strong fields to the surface in the sunspots "royal zone" (see Fig. 8).

As to the upper layers of the near-equatorial domain, the situation here is very sophisticated. On the one hand, due to a significant decrease in the density of matter, the efficiency of magnetic buoyancy increases here. However, on the other hand, a sharp density radial gradient results in the velocity of downward ∇ρ pumping strongly increases near the surface. At the same time, in the upper part of the SCZ, the radial turbulent diamagnetic pumping changes its direction, so that here it already becomes directed upward. In addition, the Babcock-Leighton alpha effect plays an important role in the reconstructing of magnetism in the surface layers. Therefore, the author postpones the study of the near-surface effects of magnetic reconstructing to the future.

Calculation of two maxima of the sunspot cycle.

The most favourable place for the generation of a toroidal field due to the Ω-effect is the deep layers near the SCZ bottom. The large plasma density provides here the minimum magnetic buoyant velocity in the SCZ. This contributes to the conservation of magnetic fields here until the Ω-effect creates a sufficiently strong field and the buoyancy becomes more effective.

The nature of the subsequent transport of the generated deep field to the surface depends on the heliolatitude (Fig. 8). As shown above, *deep* fields of about 6500 G in high-latitude domains are blocked near the SCZ bottom by the two antibuoyancy effects (turbulent diamagnetism and magnetic ∇ρ pumping).

At the same time, in the *deep layers* of the near-equatorial domain, the value of the blocked field here, B_S^e, turns out to be smaller and is about 6200 G. In the case of a stronger magnetic field, the two upward magnetic fluxes (magnetic buoyancy and the ∇ρ advection) prevail over downward diamagnetic pumping. This ensures a transfer of deep strong fields to the surface.

Let us illustrate it by calculations for the strong magnetic field with a value ≈ 6500 G that corresponds to the value of the blocked field near bottom of the near-polar domain. The magnetic buoyancy velocity near the SCZ bottom for this field is $\uparrow U_B(6500\text{ G}) \approx 2{,}84 \times 10^2$ cm/s, while the velocities of the other two magnetic fluxes are $\downarrow U_D(6500\text{ G}) \approx 2{,}10 \times 10^2$ cm/s and $\uparrow U_{\rho r}^{T} \approx 7{,}4 \times 10^1$ cm/s ($\theta = 75°$). Under these conditions, the time τ of the upward radial transfer for this magnetic field from the SCZ bottom ($z_0 \approx 184\times10^3$ km) to a layer at a depth of $z_1 \approx 60\times10^3$km (where the magnetic ∇ρ advection changes its direction) in the radial plane $\theta^* \approx 15°$ is $\tau \approx (z_0 - z_1)/(U_B + U_{\rho r}^{T} - U_D) \approx 8{,}38 \times 10^7$ s $\approx 2{,}5$ years.

Thus, during the rising phase of the cycle the deep toroidal fields, exited by Ω-effect, in the near-equatorial domain are transported to the surface due to the combined action of magnetic buoyancy and the two turbulent pumping effects. Surfaced the fragments of this field are observed as sunspots in the latitudinal band ($\Delta\theta^* \approx 45\div10°$) of the royal zone. This first upward advection surge of the toroidal field is responsible for the first maximum of sunspots.

In the near-polar domains, two downward magnetic transport effects (turbulent diamagnetism and the ∇ρ pumping), acting against magnetic buoyancy, lead to the formation of a strong magnetic field layer near the SCZ bottom. The strong toroidal fields blocked in this layer, are transported due to a deep equator-ward meridional current from the polar latitudes to the middle and then the low latitudes. If we take the value $U_M^{(deep)} \approx 2\div5$ m/s (Hathaway *et al.*, 2003; Rajaguru and Antia, 2015; Mandal *et al.*, 2018) for the velocity of the deep meridional current near the SCZ bottom ($r \approx 5 \times 10^{10}$ cm), the characteristic time of the field migration from the latitude $\theta_1^* = 70°$ to the latitude $\theta_2^* = 15°$ is $\tau_M \approx r(\Delta\theta^*/360°)/U_M^{(deep)} \approx 1 \div 2$ years. In low-latitude areas, where are favourable conditions for rising of field, these belated fields are transported upward to surface, that leads to the second upward magnetic advection surge. As a result, the intensity of sunspot activity, which by that time had decreased (since most of the fragments of the first surge of the strong toroidal field had already reached the surface at higher latitudes), again increases, because now is the time when belated fields rise to the surface. In our view, it is this second batch of deep toroidal fields, which arrives in the near-equatorial domain from polar areas due to meridional circulation, and then with a delay is brought to the surface at low latitudes, can invoke the second maximum of sunspots activity.

Conclusions. The cyclic regeneration of the Sun's large-scale magnetic field is at the root of all phenomena collectively known as "solar activity". The sunspot cycle is arguably the best known manifestation of the solar magnetic cycle. We outlined here the scenario of reconstructing of toroidal magnetic field in the SCZ, which, on our opinion, may help to understand why magnetic fields rise to the solar surface only in the sunspot "royal zone" and what is reason of the phenomenon of double maximum of sunspots cycle. The effect of turbulent magnetic pumping (advection) caused by radial inhomogeneity of matter with taking into account Sun's rotation [28], in conjunction with deep meridional circulation, play a key role in proposed scenario. Magnetic buoyancy constrains the magnitude of toroidal field produced by the Ω effect near the bottom of the SCZ. Therefore, we examined two "antibuoyancy" effects: macroscopic turbulent diamagnetism and magnetic advection caused by radial inhomogeneity of fluid density in the SCZ, which we call the $\nabla\rho$ effect. The Sun's rotation substantially modifies the $\nabla\rho$ effect. The reconstructing of the toroidal field was examined assuming the balance between mean-field magnetic buoyancy, turbulent diamagnetism and the rotationally modified $\nabla\rho$ effect. We found that the reconstructing of large-scale magnetism develops differently in the near-polar and equatorial domains of the SCZ. At the beginning of a cycle, the deep radial differential rotation generates a toroidal field near the SCZ bottom by affecting the poloidal field of the previous cycle. In the near-polar domain, two downward pumping effects (macroscopic diamagnetism and rotational pumping) act against magnetic buoyancy and, as a result, they neutralize magnetic buoyancy and block the toroidal field near the tachocline. Therefore, these two antibuoyancy effects might be the possible reason why sunspots at the near-polar zones are never observed. In other words, strong deep-seated fields at high latitudes may well be there, but they not produce sunspots.

At the same time, in the deep layers of the equatorial domain, the rotational turbulent pumping due to the latitudinal convection anisotropy changes its direction to the opposite one (from downward to upward), thereby facilitating the migration of the field to the surface. We call this transport as first (upward) magnetic advection surge. The fragments of floating up field can be observed after a while as sunspots at latitudes of the "royal zone".

Meanwhile, a deep equator-ward meridional flow ensures transporting of deep-seated toroidal field, which is blocked near pole in tachocline, from high latitudes to low ones where are favourable conditions for the floating up of the strong field. Here this strong belated field is transported upward to solar surface (the second upward magnetic advection surge). Therefore, as shown our calculation, in the equatorial domain in reality may be developing two upward advection surges which are shifted in time by 1÷2 years. Ultimately, these two time-delayed upward magnetic surges may cause on the surface in the "royal zone" the first and second maxima of sunspots cycle.

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ПРО "КОРОЛІВСЬКУ ЗОНУ" СОНЯЧНИХ ПЛЯМ І ПОДВІЙНИЙ МАКСИМУМ СОНЯЧНОГО ЦИКЛУ

Циклічна регенерація крупномасштабного магнітного поля Сонця лежить в основі всіх явищ, відомих під загальною назвою "сонячна активність". Цикл сонячних плям, можливо, є найвідомішим проявом сонячного магнітного циклу. Ми окреслили сценарій перебудови тороїдального магнітного поля в сонячній конвективній зоні (СКЗ), який, на наш погляд, може допомогти зрозуміти, чому магнітні поля піднімаються до поверхні Сонця лише в "королівській зоні" сонячних плям і що є причиною явища подвійного максимуму циклу сонячних плям. Ефект турбулентного магнітного накачування (адвекції), викликаний радіальною неоднорідністю речовини з урахуванням обертання Сонця [28], у поєднанні з глибокою меридіональною циркуляцією, відіграє ключову роль у запропонованому сценарії. Магнітна плавучість обмежує величину тороїдального поля, що генерується Ω-ефектом біля дна СКЗ. Тому ми розглянули два ефекти "антиплавучості": макроскопічний турбулентний діамагнетизм і турбулентну магнітну адвекцію, спричинену радіальною неоднорідністю густини плазми в СКЗ, яку ми називаємо ∇ρ-ефектом. Обертання Сонця істотно модифікує ∇ρ-ефект. Було досліджено перебудову тороїдального поля з урахуванням балансу між магнітною плавучістю середнього поля, турбулентним діамагнетизмом і ∇ρ-ефектом, який був модифікований обертанням. Ми виявили, що перебудова великомасштабного магнетизму по-різному розвивається у приполярному та екваторіальному доменах СКЗ. У приполярному домені два ефекти накачування вниз (макроскопічний діамагнетизм і ротаційна накачка) діють проти магнітної плавучості; і, як результат, нейтралізують магнітну плавучість і блокують тороїдальне поле (яке породжується Ω-ефектом) поблизу тахокліну. Тому ці два ефекти антиплавучості можуть бути причиною того, чому сонячні плями у приполярних зонах ніколи не спостерігаються. Іншими словами, глибоко вкорінені сильні поля у високих широтах цілком можуть бути там, але вони не породжують сонячні плями.

Водночас у глибоких шарах екваторіального домену ротаційна турбулентна накачка завдяки широтній анізотропії конвекції змінює свій напрямок на протилежний (знизу догори), полегшуючи тим самим міграцію поля на поверхню. Ми називаємо це перенесення першим (висхідним) сплеском магнітної адвекції. Фрагменти спливаючого поля можна спостерігати через деякий час як сонячні плями на широтах "королівської зони".

Спрямований до екватора глибинний меридіональний потік забезпечує перенесення глибоко вкоріненого тороїдального поля, яке заблоковане біля полюса в тахокліні, з високих широт у низькі, де існують сприятливі умови для спливання сильного поля. Тут це запізніле сильне поле переноситься вгору на сонячну поверхню (другий сплеск магнітної адвекції вгору). У підсумку два спрямовані догори магнітні сплески, що виявилися затриманими в часі, можуть спричинити на поверхні в "королівській зоні" перший і другий максимуми циклу сонячних плям.

Ключові слова: сонячні плями, "королівська зона", сонячний цикл, магнітні поля, турбулентна конвекція, магнітна плавучість, турбулентна магнітна накачка, меридіональна циркуляція.

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О "КОРОЛЕВСКОЙ ЗОНЕ" СОЛНЕЧНЫХ ПЯТЕН И ДВОЙНОМ МАКСИМУМЕ СОЛНЕЧНОГО ЦИКЛА

Циклическая регенерация крупномасштабного магнитного поля Солнца лежит в основе всех явлений, известных под общим названием "солнечная активность". Цикл солнечных пятен, возможно, является самым известным проявлением солнечного магнитного цикла. Мы изложили здесь сценарий перестройки тороидального магнитного поля в солнечной конвективной зоне (СКЗ), который, на наш взгляд, может помочь понять, почему магнитные поля поднимаются к поверхности Солнца только в "королевской зоне" солнечных пятен и что является причиной явления двойного максимума цикла солнечных пятен. Эффект турбулентной магнитной накачки (адвекции), вызванный радиальной неоднородностью вещества с учетом вращения Солнца [28], в сочетании с глубокой меридиональной циркуляцией, играет ключевую роль в предлагаемом сценарии. Магнитная плавучесть ограничивает величину тороидального поля, создаваемого Ω-эффектом у дна СКЗ. Поэтому мы рассмотрели два эффекта "антиплавучести": макроскопический турбулентный диамагнетизм и турбулентную магнитную адвекцию, вызванную радиальной неоднородностью плотности плазмы в СКЗ, которую мы называем ∇ρ-эффектом. Вращение Солнца существенно модифицирует ∇ρ-эффект. Было исследовано перестройку тороидального поля в предположении баланса между магнитной плавучестью среднего поля, турбулентным диамагнетизмом и ∇ρ-эффектом, модифицированным вращением. Мы обнаружили, что перестройка крупномасштабного магнетизма по-разному развивается в околополярном и экваториальном доменах СКЗ. В приполярном домене два эффекта накачки вниз (макроскопический диамагнетизм и ротационная накачка) действуют против магнитной плавучести; и, как результат, нейтрализуют магнитную плавучесть и блокируют тороидальное поле (генерируемое Ω-эффектом) вблизи тахоклина. Поэтому эти два эффекта антиплавучести могут быть причиной того, почему солнечные пятна в приполярных зонах никогда не наблюдаются. Другими словами, глубоко расположенные сильные поля в высоких широтах вполне могут быть там, но они не порождают солнечных пятен.

В то же время в глубоких слоях экваториальной области вращательная турбулентная накачка из-за широтной анизотропии конвекции меняет свое направление на противоположное (с нисходящего на восходящее), что способствует миграции поля к поверхности. Мы называем этот перенос первым (восходящим) всплеском магнитной адвекции. Фрагменты всплывающего поля через некоторое время можно будет наблюдать как солнечные пятна на широтах "королевской зоны".

Направленный к экватору глубинный меридиональный поток обеспечивает перенос глубинного тороидального поля, заблокированного около полюса в тахоклине, из высоких широт в низкие, где есть благоприятные условия для всплытия поля. Здесь это запоздалое сильное поле переносится вверх на солнечную поверхность (второй всплеск магнитной адвекции вверх). В конечном итоге два направленных вверх магнитных всплеска, отсроченные по времени, могут вызвать на поверхности в "королевской зоне" первый и второй максимумы цикла солнечных пятен.

Ключевые слова: солнечные пятна; "королевская зона"; солнечный цикл; магнитные поля; турбулентная конвекция; магнитная плавучесть; турбулентная магнитная накачка; меридиональная циркуляция.

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АСТРОНОМІЧНА ОБСЕРВАТОРІЯ КИЇВСЬКОГО НАЦІОНАЛЬНОГО УНІВЕРСИТЕТУ ІМЕНІ ТАРАСА ШЕВЧЕНКА У 2020 РОЦІ

2020 р. в Астрономічній обсерваторії працювали 58 працівників, з яких 48 штатних і 10 сумісників, науковців – 34 (6 докторів наук і 17 кандидатів наук). Упродовж року виконувалися 4 бюджетні і 3 договірні теми.

Основні наукові результати. Показано, що спостережуване гамма-випромінювання ТеВ-ного діапазону з околу магнетара SGR 1900+14 – нейтронної зорі з надпотужним магнітним полем – може генеруватися двома пов'язаними з ним джерелами: ще не виявленим залишком Гіпернової, яка породила SGR 1900+14, та/або магнетарно-вітровою туманністю, породженою цим магнетаром. У межах виконання спільних міжнародних наукових проєктів проведено спостереження на 6-метровому БТА (САО РАН), 2-метровому HCT (Індія), 2,6-метровому ЗТШ (КрАО), 2-метровому (Терскол), 1,3-метровому (Словаччина) та інших телескопах 15 комет, 6 астероїдів, 8 супутників Юпітера і Сатурна та одного Кентавра, в результаті яких отримано великий масив фотометричних, поляриметричних і спектральних даних.

За результатами досліджень опубліковано 2 монографії, 76 наукових статей, зроблено 72 доповіді на наукових конференціях.

Ключові слова: відділ астрофізики, сектор астрометрії і малих тіл Сонячної системи, національне надбання, міжнародна наукова конференція.

Інформацію про роботу Астрономічної обсерваторії за 2019 р. було подано у Віснику Київського національного університету імені Тараса Шевченка [1]. У цій статті висвітлено результати наукових досліджень і найважливіші події у житті обсерваторії за 2020 рік.

Структура і склад. На початок 2020 р. в Астрономічній обсерваторії працювало 48 штатних працівників і 10 сумісників, з них співробітників, які беруть участь у виконанні НДР – 34, зокрема доктори – 8, кандидати наук – 17; обслуговуючий персонал – 24; штат музею – 1. У науковій роботі брали участь викладачі, аспіранти та студенти кафедри астрономії та фізики космосу фізичного факультету університету.

Упродовж року змін у структурі обсерваторії не було: до її складу входили відділ астрофізики (зав. відділу д-р фіз.-мат. наук, проф. В. І. Жданов), сектор астрометрії та малих тіл Сонячної системи (зав. сектору канд. фіз.-мат. наук, ст. наук. співроб. І. В. Лук'яник), а також дві спостережні станції (с. Лісники Києво-Святошинського р-ну і с. Пилиповичі Бородянського р-ну Київської обл.).

2020 р. померли ветерани праці, колишні працівники Астрономічної обсерваторії наук. співроб., канд. фіз.-мат. наук Майя Анатоліївна Нуждіна (14 січня 2020 р.), ст. наук. співроб., канд. фіз.-мат. наук Олександра Яківна Грегуль (27 лютого 2020 р.), проф., д-р фіз.-мат. наук Віталій Григорович Кручиненко (23 грудня 2020 р.).

Обсяг бюджетного фінансування 2020 р. склав 5603,9 тис. грн, договірного – 491,0 тис. грн.

Співробітниками обсерваторії 2019 р. опубліковано 2 монографії, 2 навчальні посібники, 76 наукових статей, з них 31 у зарубіжних виданнях, проведено 2 міжнародні конференції ("Астрономія і фізика космосу в Київському університеті", 27–29 травня 2020; "САММАС-2020", 17–19 листопада 2020), підготовлено 72 наукові доповіді на конференціях.