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MACROSCOPIC TURBULENT DIAMAGNETISM OF SOLAR PLASMA

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ABSTRACT. Turbulent motions and convection in cosmic plasma play a key role in the processes of magnetic fields evolution in astrophysical conditions. Involvement of turbulent motions in the consideration, when studying the reconstruction of magnetic fields, ended with the creation of the theory of magnetohydrodynamics of mean turbulent magnetic fields, which in the literature was called macroscopic MHD. One of the important effects of macroscopic MHD is called turbulent diamagnetism. The physical essence of the effect of macroscopic turbulent diamagnetism consists in the displacement of global (mean) magnetic fields from areas of increased intensity of turbulent pulsations to places with less developed turbulence along the gradient of turbulent viscosity gradient ν_T with an effective macroscopic velocity $U_\mu = -\nabla\nu_T/2$ ($\nu_T \approx (1/3)\,ul$, u and l are the effective velocity and the characteristic pulsation scale of the velocity). We considered the role of macroscopic turbulent diamagnetism in the formation of the magnetic field layer in the lower part of the solar convection zone (SCZ). We calculated the radial distribution of the turbulent viscosity ν_T along the depth z for the SCZ model of Stix (2002). It was found that the radial distribution of this parameter has the form of a convex function $\nu_T(z)$ with a maximum approximately in the middle of the SCZ ($z \approx 140{,}000$ km). Noticeable positive radial gradient of the turbulent viscosity $\nabla\nu_T$, which is found in the lower part of the SCZ, causes a downward intense diamagnetic displacement of the toroidal magnetic field, the velocity of which reaches the value $U_\mu \approx 4\text{x}10^3$ cm/s near the lower base of the SCZ ($z \approx 180{,}000$ km). Therefore, macroscopic turbulent diamagnetism in deep layers plays the role of negative magnetic buoyancy. Macroscopic diamagnetism acts against magnetic buoyancy, the velocity of which is $U_B(B) = B/(4\pi\rho)^{1/2}$ (B is the magnetic induction, ρ is the density of plasma), and contributes to the formation of a magnetic layer of a steady state toroidal magnetic field with a strength of $B_S = (4\pi\rho)^{1/2}\,\nu_T/2 \approx 3000$–$4000$ G.

Keywords: magnetic fields, turbulence, magnetic buoyancy, macroscopic MHD, macroscopic turbulent diamagnetism.

АНОТАЦІЯ. Турбулентні рухи і конвекція в космічній плазмі відіграють ключову роль у процесах еволюції магнітних полів в астрофізичних умовах. Залучення до розгляду турбулентних рухів при вивченні реконструкції магнітних полів завершилося створенням теорії магнітогідродинаміки середніх турбулентних магнітних полів, яка в літературі отримала назву макроскопічної МГД. Один із важливих ефектів макроскопічної МГД називається турбулентним діамагнетизмом. Фізична суть ефекту макроскопічного турбулентного діамагнетизму полягає у зміщенні глобальних (середніх) магнітних полів із областей підвищеної інтенсивності турбулентних пульсацій у місця з менш розвиненою турбулентністю вздовж градієнту турбулентного градієнта в'язкості ν_T з ефективною макроскопічною швидкістю $U_\mu = -\nabla\nu_T/2$ ($\nu_T \approx (1/3)ul$, u та l – ефективна швидкість та характерний масштаб пульсацій). Розглянуто роль макроскопічного турбулентного діамагнетизму у формуванні магнітного шару в нижній частині сонячної конвективної зони (СКЗ). Ми розрахували радіальний розподіл турбулентної в'язкості ν_T по глибині z для моделі SCZ Стікса (2002). Встановлено, що радіальний розподіл цього параметра має вигляд опуклої функції $\nu_T(z)$ з максимумом приблизно по середині СКЗ ($z \approx 140\,000$ км). Помітний позитивний радіальний градієнт турбулентної в'язкості $\nabla\nu_T$, який знаходиться в нижній частині СКЗ, викликає низхідне інтенсивне діамагнітне зміщення тороїдального магнітного поля, швидкість якого досягає значення $U_\mu \approx 4\text{x}10^3$ см/с біля нижньої основи СКЗ ($z \approx 180\,000$ км). Тому макроскопічний турбулентний діамагнетизм у глибоких шарах відіграє роль *негативної магнітної плавучості.* Макроскопічний діамагнетизм протидіє магнітній плавучості, швидкість якої становить $U_B(B) = B/(4\pi\rho)^{1/2}$ (B – магнітна індукція, ρ – густина плазми), і сприяє утворенню магнітного шару усталеного тороїдального магнітного поля напруженістю $B_S = (4\pi\rho)^{1/2}\,\nu_T/2 \approx 3000 - 4000$ Гс.

Ключові слова: магнітні поля, турбулентність, магнітна плавучість, макроскопічна МГД, макроскопічний турбулентний діамагнетизм.

1. The necessity to find "anti-buoyancy" effects

According to modern ideas, the global magnetic field of the Sun contains two components. The first component is a weak poloidal (meridional) magnetic field, the lines of force of which cross the solar surface at high heliolatitudes and are therefore clearly observed in the polar regions of the Sun. The second component is a strong toroidal (azimuthal) magnetic field hidden in the deep layers, fragments of which, when floating on the solar surface in some places, cause the appearance of sunspots. Both magnetic components change cyclically in time in magnitude and polarity in antiphase with a period of about 22 years, called the Hale magnetic cycle. When explaining the magnetic cycle of the Sun, the so-called $\alpha\Omega$ dynamo model, which is based on the joint action of helical turbulence (α effect) and differential rotation (Ω effect) in the solar convective zone (SCZ), became the most popular among researchers.

For effective excitation of the toroidal field of the Sun as a result of the effect of differential rotation on the poloidal field (Ω effect), it is necessary that the magnetic power tubes stay in the generation area for a long time. However, due to the magnetic buoyancy of Parker (1979), it is difficult to ensure significant amplification and storage of strong fields in the entire volume of the SCZ for a long time. The rate of magnetic emergence of the B field according to Parker is determined by the expression

$$U_B(B,\rho) \approx B/(4\pi\rho)^{1/2}, \qquad (1)$$

is determined by the expression from which it can be seen that the value of magnetic buoyancy velocity is inversely proportional to the plasma density ρ, which leads to a limitation on the amplitude of the excited toroidal field. In view of this, the most favorable conditions for maintaining strong magnetic fields in the solar depths exist near the bottom of the SCZ, where the plasma density is the highest. And therefore, this is where the velocity of magnetic buoyancy will be the lowest.

But even near the bottom of the SCZ, it is difficult to ensure the strengthening and maintenance of fields with a magnitude of more than 100 G for a time comparable to the period of the solar cycle (due to the rapid evacuation of strong magnetic fields from the generation zone) (Parker, 1979). Therefore, the problem of compensating the magnetic buoyancy of strong fields and maintaining them for a long time in the dynamo area comes to the fore with special need. Considering this, there is an urgent need to search for mechanisms of magnetic "anti-buoyancy" ("negative magnetic buoyancy"). As it turned out, the macroscopic turbulent plasma diamagnetism can play the role of such a mechanism in SCZ.

2. Macroscopic turbulent diamagnetism of solar plasma - against magnetic buoyancy

The effect was discovered by Zeldovich (1956) for the case of two-dimensional turbulence and later named macroscopic turbulent diamagnetism by Rädler (1968). The physical meaning of the latter consists in the displacement of the initially uniform magnetic field from areas with increased intensity of turbulent motions to places with less developed turbulence (along the turbulent viscosity gradient $\nabla\nu_T$) with an effective velocity U_μ

$$U_\mu = -\nabla\nu_T/2. \qquad (2)$$

In the work (Krivodubskij, 2024) we calculated the radial profile of turbulent viscosity $\nu_T(z) \approx (1/3)\,ul$ (u and l are the effective velocity and characteristic size of the turbulent convective motions, respectively). It was found that the parameter $\nu_T(z)$ has the form of a convex function with a maximum $\nu_T \approx 10^{13}$ cm/s approximately in the middle of the SCZ of z = 120000 – 140000 km (Fig. 1).

Thus, the vertical inhomogeneity of the parameter ν_T that we discovered indicates the diamagnetic properties of the solar turbulent plasma. The qualitatively physical content of the phenomenon of macroscopic diamagnetism is as follows. Due to the radial inhomogeneity of the turbulence, the percolation (seepage) of the turbulent pulsations occurs from areas of high pulsation intensity in the directions of their lower intensity. As a result of the freezing of magnetic lines of force in the plasma, magnetic fields will be transferred in a similar way.

Therefore, the global azimuthal field must be pushed out of this area in the radial direction, namely: in the upper half of the SCZ, the magnetic field will be transferred upwards to the solar surface, while in the lower half of the SCZ the magnetic field transfers down to the bottom of the SCZ.

It is relevant that the noticeable positive radial gradient of the turbulent viscosity $\nabla\nu_T$, which is located in the lower part of the SCZ, should cause a downward intensive diamagnetic displacement of the toroidal magnetic field. Indeed, according to our calculations, the velocity of downward diamagnetic displacement of the horizontal field near the bottom of the SCZ reaches $U_\mu \approx 2{\cdot}10^3$ cm/s (Fig. 2).

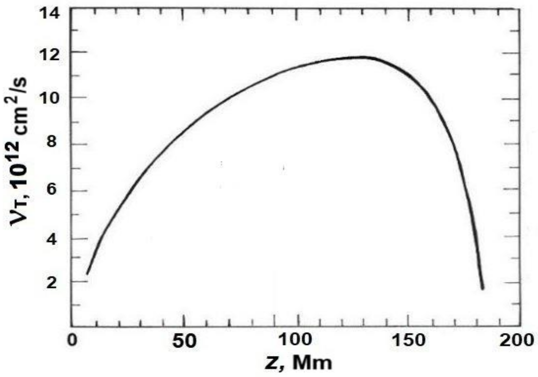


Figure 1: Radial distribution of the value of the turbulent viscosity coefficient $\nu_T(z) \approx (1/3)\,ul$ at the depth z, calculated for the physical parameters from the SCZ model by Stix (2002).

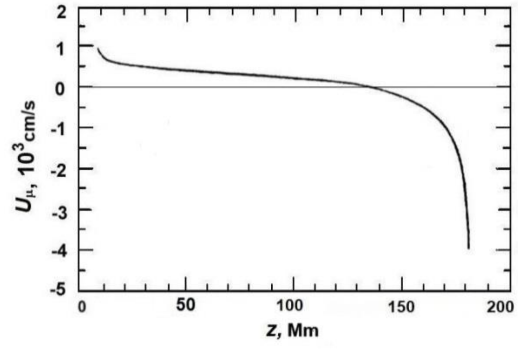


Figure 2: Radial distribution along the depth z of the velocity U_μ of the macroscopic diamagnetic transfer of the global toroidal magnetic field, calculated for the physical parameters from the SCZ model by Stix (2002).

Therefore, in the lower part of the SCZ, the macroscopic turbulent diamagnetism acts against magnetic buoyancy, i.e., here it performs the role of "negative magnetic buoyancy". Since the velocity of magnetic buoyancy depends on the magnitude of the field B, then from the condition of mutual compensation of the processes of buoyancy with velocity U_B (see expression (1)) and diamagnetic downward displacement with velocity U_μ (expression (2))

$$\uparrow U_B + \downarrow U_\mu = 0, \tag{3}$$

the value of the stationary toroidal field can be found

$$B_S \approx U_\mu (4\pi\rho)^{1/2}, \tag{4}$$

the buoyancy of which will be completely compensated by macroscopic turbulent diamagnetism (Fig. 3).

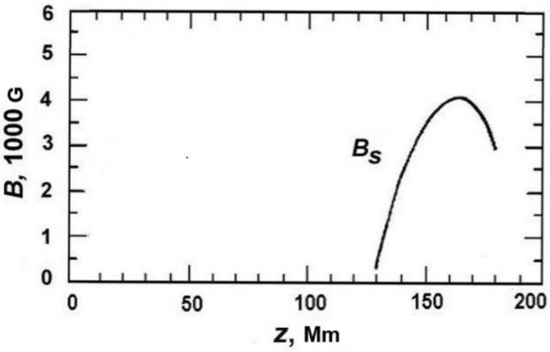
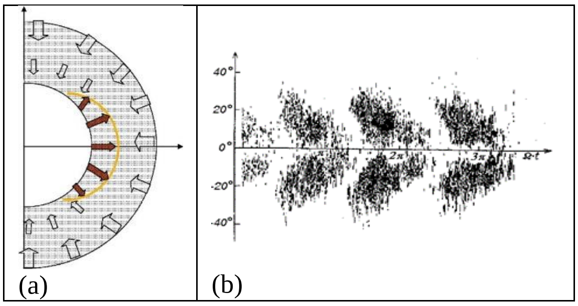


Figure 3: Distribution by depth z in the SCZ model by Stix (2002) of the steady horizontal field $B_S = (4\pi\rho)^{1/2}\, \nu_T/2$, the magnetic buoyancy of which is compensated by the macroscopic diamagnetic effect.



(a) (b)

Figure 4: (a) – A meridional cross-section of the SCZ, which demonstrates the direction of the radial transfer of the toroidal magnetic field according to our calculations. Arrows show the direction of field transfer. (b) – Maunder butterfly diagram ("royal sunspots zone"), according to observations from 1874 to 1913, showing areas of sunspot existence depending on heliographic latitude and phase of the solar cycle, Ωt. The area of upward transfer of the toroidal field is localized in the range of heliolatitudes (a), which coincides with the observed latitudinal "royal zone" of sunspots (b).

As a result of "negative magnetic buoyancy" caused by macroscopic diamagnetism, the concentration of a powerful toroidal magnetic field $B_S \approx 3000$–4000 G occurs near the bottom of the SCZ. At the same time, thanks to the continuous action of the Ω effect, further strengthening of the toroidal field continues. Therefore, over time, fragments of the toroidal field, where $B > 4000$ G, will rise to the surface in the "royal latitude zone" and thereby generate sunspots here (Fig. 4).

3. Conclusion

Thus, the noticeable positive radial gradient of the turbulent velocity $\nabla\nu_T$ near the bottom of the SCZ, revealed as a result of our calculations, causes an intense downward macroscopic diamagnetic displacement of the toroidal magnetic field with the velocity $U_\mu = \nabla\nu_T/2$. Acting against the magnetic buoyancy, the macroscopic turbulent diamagnetism in the SCZ performs the role of "negative magnetic buoyancy" and thereby contributes to the long-term maintenance of strong fields ($B_S \approx 3000 - 4000$ G) in the generation zone near the bottom of the SCZ.

Due to the continuous action of the Ω effect, in the future, fragments of the enhanced toroidal field, where $B > 4000$ G, will rise to the surface in the "royal latitude zone" and thereby generate sunspots here. At the same time, in the polar domain, such fields remain blocked near the bottom of the solar convective zone (there is another effect of "negative magnetic buoyancy" (Krivodubskij, 2005). And that is why deeply rooted strong toroidal fields in the polar domains cannot break through to the surface to be observed at high latitudes in the form of sunspots (Krivodubskij, 2021).

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