EVOLUTION OF LARGE-SCALE MAGNETIC FIELDS IN THE SUN

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A scenario of evolution of the large-scale magnetic fields in the Sun is proposed. The analysed models of the Sun allow one to accept the shearing of the poloidal field by differential rotation, helical turbulence and also the advective transport of the magnetic flux by meridional circulation as the main processes of the solar activity. We found that toroidal magnetic field (TMF) was more effectively generated in the strong radial shear layer (tachocline). It has a small value of diffusion and is carried out by meridional circulation toward the equator, where diffusion of the fields with different signs takes place. Casual force takes away the partial TMF in the solar convective zone and magnetic buoyancy sends the field to the surface. Using the Babcock–Leighton idea, we give confirmation of the generation of the poloidal magnetic field only near the surface and poles. The approximate decisions enable one to build the model of the solar dynamo in accordance with the observations.

INTRODUCTION

The basic models of the solar dynamo established that the solar cycle involves a recycling of two main components of the Sun's large-scale magnetic field [10]. The toroidal component of the magnetic field is generated by the shearing of the poloidal field in a region of strong radial gradient in the rotation known as the tachocline, located at the base of the solar convection zone (SCZ), from where it erupts to the surface due to magnetic buoyancy and gives rise to bipolar sunspot pairs. It was believed that propagation of this toroidal field wave at the base of the SCZ manifested itself on the surface as the migration of the sunspot activity belt toward the equator. But some problems exist in description of this process.

Firstly, the polar weak magnetic field of the Sun is of order 10 G, whereas the toroidal magnetic field at the bottom of the convection zone has been estimated to be 10^5 G. Simple order-of-magnitude estimates show that the shear in the tachocline is not sufficient to stretch a radial field into a high mean TMF [4]. Stretching by shear in the tachocline is then expected to produce a highly intermittent magnetic configuration at the bottom of the convection zone. The meridional flow at the bottom of the convection zone should be able to carry this intermittent magnetic field equatorward [9]. In avoidance of buoyancy, the analysis and calculations confirmed the possibility of the TMF generation in the SCZ and pushing down the field into the stable radiative layers. There the TMF is formed completely and is transported by the meridional circulation equatorward through this stable region. The TMF produced at high latitudes cannot erupt there if it is pushed down into the stable layers. But when the meridional flow rises at low latitudes, the toroidal field can come out through the base of the SCZ and be subjected to magnetic buoyancy, erupting outward to form sunspots. Possibly, the toroidal field emerging is related to the radial gradient of angular speed, which at the negative value does not give the magnetic tubes to approach the SCZ bottom, while at the negative value such possibility is more credible. This scenario is explicitly shown through the results of the dynamo simulations and it is remarkably successful in giving a consistent description of the observations of sunspots at low latitudes in light of recent developments [2, 5, 6, 9, 13].

When a flux tube from the bottom of the convection zone rises to a region of pre-existing poloidal field at the surface, we point out that it picks up a twist in accordance with the observations of current helicities at the solar surface.

The poloidal component of the magnetic field (identified with the weak diffuse field observed outside sunspots) is regenerated from the toroidal field by a process known as the α-effect, in which the toroidal field is lifted and twisted into the meridional plane. Contrasting mechanisms have been proposed to explain the origin of this α-effect, for example helical convection [10]; decay of tilted bipolar sunspot pairs [1]; buoyancy instability coupled with rotation [3]; hydrodynamic instability of the differential rotation [5]. First two models explain the mechanism of transformation of the poloidal fields, last two give a substitution to a source of alpha-effect. Although these various mechanisms differ in their nature and location, one common feature is that all of them predict positive α-effect in the northern hemisphere of the Sun and negative α-effect in the southern hemisphere. The author supports the Babcock–Leighton idea, which was developed by Nandy and Choudhuri [8], that the poloidal field is generated at the surface of the Sun from the decay of active regions.

PRELIMINARY NOTES

So, the large-scale magnetic field is in a nonconvective environment of the overshoot layer. This means that TMF can exist there for the time long enough, but certain force compels magnetic tubes to appear in the SCZ. The authors of [8] believe that the dynamo generated magnetic fields are of limited value. They found that critical fields for eruption should be more than 10^5 G limiting the magnitude and distribution of the magnetic field generated within the overshoot layer. Another part of the TMF continues motion along the meridional direction. In this study it was not examined. We were interested in expression of α-effect in the SCZ. We will notice that a convective environment has the asymmetrical field with small-scale casual speeds and convective elements carry out radial motions, which are collinear with the direction of emerging. On identical depths these motions have characteristic speeds and length scales:

$$l = \left(\frac{\alpha_{MLT}}{\gamma}\right) H_\rho, \tag{1}$$

where α_{MLT} is characteristic value of the model (it is 5/3 for the Stix model SCZ), γ is the adiabatic index (it is approximately 7/5), $H_\rho = \left|\frac{\rho \partial r}{\partial \rho}\right|$ is a density height scale. The presence of TMF in the SCZ cannot be fixed because the force tube emerges, though there can be nonlinear effects which compel it to remain long time at the bottom of SCZ [7]. Speed of emerging is characterized by constant Alfen speed [10] and $B_\varphi/\sqrt{\rho} = const$, where B_φ is TMF intensity. At a motionless force magnetic tube the curvature occurs due to movements, which have turbulent character and are described by parameter turbulent helicity (α-parameter). This parameter has been offered by Rädhler and Krause, and then specified by Rüdiger and Kichatinov. But the analysis of contribution of the relative velocity to α-parameter is not essential and we can neglect it. Using some suppositions, we get:

$$\alpha = -\frac{2}{3}\Omega\, l^2 \left(\frac{\partial \rho}{\rho \partial r} + \frac{\partial V}{V \partial r}\right)\cos\theta = \frac{2}{3}\Omega\, l^2 \left|\frac{\partial B_\varphi^2}{B_\varphi^2 \partial r}\right| \cos\theta, \tag{2}$$

where Ω is the angular velocity of the SCZ rotation, $\frac{\partial \rho}{\rho \partial r} + \frac{\partial V}{V \partial r}$ is the sum of gradient rates of a natural logarithm of a density and the relative velocity of turbulent oscillations. This means that the sign of α-parameter is positive in the northern hemisphere and negative in the southern hemisphere, as suggested by Rüdiger *et al.* [11].

BASIC EQUATIONS

The large-scale magnetic fields in the spherical coordinates (r, θ, ϕ) have the form:

$$\begin{aligned} &\left\{\frac{\partial}{\partial t} - \eta\left(\nabla^2 - \frac{1}{r^2 \sin^2\theta}\right)\right\} B_\varphi + \frac{1}{r}\left[\frac{\partial}{\partial r}(r v_r B_\varphi) + \frac{\partial}{\partial \theta}(v_\theta B_\varphi)\right] \\ &\qquad = r\sin\theta\left(B_r \frac{\partial \Omega}{\partial r} + B_\theta \frac{1}{r}\frac{\partial \Omega}{\partial \theta}\right), \end{aligned} \tag{3}$$

$$\begin{aligned} &\left\{\frac{\partial}{\partial t} - \eta \Delta\right\} B_{r,\theta} + \frac{1}{r}\left[\frac{\partial}{\partial r}(r v_r B_\theta) + \frac{1}{\sin\theta}\frac{\partial}{\partial \theta}(v_\theta B_r \sin\theta)\right] \\ &\qquad = \alpha \operatorname{rot} B_\varphi + \operatorname{grad}\alpha \cdot B_\varphi, \end{aligned} \tag{4}$$

where B_r, B_θ, B_ϕ are the components of the magnetic induction, η is coefficient of turbulent magnetic diffusivity, v_r and v_θ are the components of meridional velocity, including the radial magnetic buoyancy. Thus, we have non-homogeneous equations (3) and (4) with the zero initials and boundary conditions for the northern hemisphere, where the lowest bounder TMF-penetrating equals 0.6 of the solar radius.

RESULTS

The straight order of the equation (3) and (4) with initials and boundary conditions was used. We obtained:

$$B_\varphi(r,\theta,t) = \sum_{n,m=1}^{\infty}\left[\int_0^t e^{-\eta^2\pi^2\left[\frac{4n^2}{\pi^2 r_0^2}+\frac{m^2}{(0.3R)^2}\right](t-\tau)} f_{mn}(\tau)d\tau\right] \times \sin\left(2n\theta + \frac{2nv_\theta t}{0.7R\pi}\right)\sin\left(\frac{r-0.7R+v_r t}{0.7R}\right), \quad (5)$$

where $m, n \in N$; R is the solar radius.

We believe that poloidal field is created near the surface from the decay of titled active regions. It should be noted that α-coefficient in the Babcock–Leighton dynamo is not given by the mean helicity of turbulence as in conventional mean-field MHD. It was confirmed by Vainstein *et al.* [12] that TMF spread in the SCZ without dissipation right up to the top of SCZ. In this approach the α-effect generating the poloidal field results phenomenologically; we consider it to be essential for the formulation of the Babcock–Leighton dynamo for the mean field. The angular factor $\cos\theta$ arises from the angular dependence of the Coriolis force, which causes the tilts of active regions. Our results confirm the idea of Babcock–Leighton on maximal transformation of TMF to weak meridional magnetic fields near the Sun's surface. This hypothesis also takes place in the theory of the turbulent dynamo, suggested on the basis of many models of the SCZ.

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