NEGATIVE MAGNETIC BUOYANCY AND FORMATION OF A SUNSPOT BELT

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Magnetic buoyancy constrains the magnitude of toroidal field excited by the Ω-effect near the bottom of the solar convection zone (SCZ). Therefore, we examined two negative magnetic buoyancy effects: i) macroscopic turbulent diamagnetism (the γ-effect) and ii) magnetic advection caused by vertical inhomogeneity of plasma density in the SCZ, which we called the $\nabla\rho$-effect. The Sun's rotation which yields the $\nabla\rho$-effect with new properties was taken into account. The reconstruction of toroidal field was calculated as a result of the balance of mean-field magnetic buoyancy, turbulent diamagnetism and the rotationally modified $\nabla\rho$-effect. It is shown that at high latitudes negative buoyancy effects block the magnetic fields in the deep layers of the SCZ, and this may be the most plausible reason why a deep-seated field here could not become as apparent at the solar surface as sunspots. However, in the region located near equator the $\nabla\rho$-effect causes the upward magnetic advection. So, it can facilitate penetration of strong magnetic fields (about 3000–4000 G) to solar surface where they then arise in the "royal zone" as the sunspots.

INTRODUCTION

For the excitation of toroidal magnetic field, $\vec{B}_{\rm T}$, by the Sun's differential rotation stretching a weak poloidal field (the Ω-process) to be effective, the magnetic flux tubes are to be kept in the generation region in the solar convection zone (SCZ) for a long time. However, due to fast buoyant rise of magnetic fields it is generally difficult to ensure their significant amplification and storage during time comparable to the solar cycle period. The magnetic buoyancy effect can be written as a loss term $\nabla\times\left(\vec{V}_B\times\vec{B}_{\rm T}\right)$, where $\vec{V}_B$ is the buoyant velocity, in the equation of toroidal field's generation. Therefore, it constrains the magnitude of the toroidal field excited by Ω-effect [12]. Thus, some "magnetic antibuoyancy" (negative buoyancy) effects are required to compensate the losses of magnetic flux in generation zone. Several advection (transport) mechanisms of this kind have been proposed in the past (see reviews by Schüssler [14] and Parker [13]). The well-known and the best studied transport mechanisms include the macroscopic turbulent diamagnetism, or the γ-effect [17, 18], and the magnetic pumping caused by the vertical fluid inhomogeneity in the turbulent fluid [1, 16]. Here we intend to examine whether these advection effects really suppress the magnetic buoyancy and attempt to clarify whether they may promote penetration of the magnetic field to the solar surface at the sunspot belt ("royal zone").

MAGNETIC PUMPING IN THE SOLAR CONVECTION ZONE

The macroscopic turbulent diamagnetism forces the large-scale magnetic field $\vec{B}$ to transfer along the gradient of turbulent viscosity $\nu_{\rm T}\approx(1/3)vl\approx(1/3)\tau v^2$ with the effective velocity $\vec{V}_\mu=-\nabla\nu_{\rm T}/2$ [17] (here v, l, and τ are the rms velocity, mixing length, and characteristic time of the turbulence, respectively). In the deep layers of the SCZ the turbulent diamagnetism acts against magnetic buoyancy, displacing the horizontal fields downwards [7]. The non-linear downdraft velocity [6],

$$V_{\rm D}(\beta)=6V_\mu\Psi_{\rm D}(\beta), \tag{1}$$

is sufficient ($V_{\rm D}\approx 3\cdot 10^2$ cm/s [10]) to resist the magnetic buoyant velocity,

$$V_{\rm B}(\beta)\approx\left(\frac{l}{H_P}\right)\left(\frac{v}{\gamma}\right)\frac{\beta^2}{15}, \tag{2}$$

calculated by Kitchatinov & Pipin [5] within the framework of the mean-field magnetohydrodynamics. Here $\Psi_{\rm D}(\beta)$ is the quenching (decreasing) function, $\beta=B/B_{\rm eq}$ is the field strength normalized to the energy equipar-

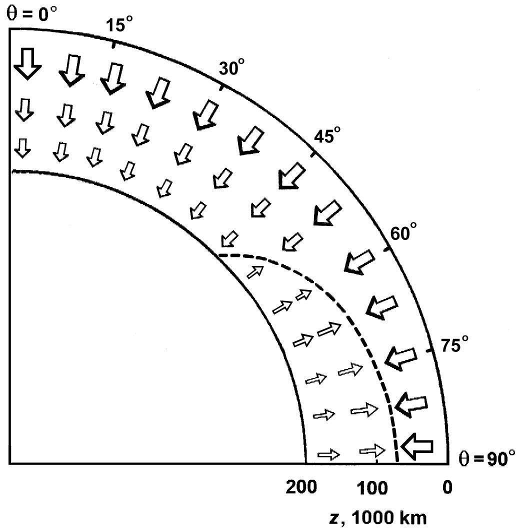

Figure 1. A meridional cross section of the SCZ which shows the distribution of the radial velocity of toroidal magnetic field advection, $V^{\mathrm{T}}_{\rho \mathrm{r}}(z,\theta)$, along the radius (depth z) and colatitude θ. The arrows denote the direction of advection. The velocity amplitudes vary from $\approx 10^2$ cm/s near the bottom of the SCZ to $\approx 10^4$ cm/s at the surface. The dashed curve indicates the level of zero velocity, $V^{\mathrm{T}}_{\rho \mathrm{r}}(z,\theta)=0$, which is determined by the equation $\theta^*(z) = \arcsin\sqrt{\varphi_2(z)/\varphi_1(z)}$. The zero velocity level begins at the heliolatitude of $\theta^* \approx 45°$ near bottom of the SCZ, then it is displaced to the solar surface at mid to low latitudes, reaching the equator at a depth of about 70 000 km. In the bulk of the SCZ the $\nabla\rho$-effect causes the magnetic downdraft which opposes the magnetic buoyancy. However, in the deep layers at the near-equator region the $\nabla\rho$-effect provokes the upward advection which, on the contrary, forwards the magnetic buoyancy, and so it can facilitate penetration of the strong fields to a surface where they appear as sunspots of the "royal zone"

tition value $B_{\mathrm{eq}} \approx (4\pi\rho)^{1/2} v$, ρ is the plasma density, H_P is the pressure scale, and $\gamma = 5/3$ is the adiabaticity index.

Besides the turbulent diamagnetism, another macroscopic transport effect caused by inhomogeneity of the material density may arise in turbulent plasma under certain conditions. Drobyshevskij [1] and Vainshtein [16] had found that in inhomogeneous turbulent fluid the mean magnetic field $\vec{B}$ can transfer along the gradient of the material density ρ. This magnetic transport effect can be interpreted as follows. The amplitude of the magnetic fluctuations, $\vec{b}$, produced by turbulent pulsations, $\vec{v}$, is increasing in the direction of the gradient of the fluid density, $b^2 \approx 4\pi\rho v^2$. At the same time, the random electric currents, $\vec{j} = (c/4\pi)\,\mathrm{curl}\,\vec{b}$, are also increasing in this direction. These modified currents change the initial distribution of the large-scale field $\vec{B}$. In the non-linear regime, the net distribution of the global magnetic field is equivalent to its transport with the effective velocity [2],

$$\vec{V}_\rho \approx \left(\frac{1}{6}\right) \tau v^2 \left(\frac{\nabla\rho}{\rho}\right). \tag{3}$$

We call it the "$\nabla\rho$-effect". Since the plasma density ρ varies by five or six orders of magnitude over a vertical extent of the SCZ, a very strong downward magnetic pumping should exist here, $V_\rho \approx 10^2$–10^4 cm/s [8].

The rotation imparts new properties to the $\nabla\rho$-advection. Under the Sun's rotation the $\nabla\rho$-effect realizes the "fields selection", which results in an independent transfer of the azimuthal and meridional field components [3]. The radial magnetic advection of the azimuthal (toroidal) field $\vec{B}_{\mathrm{T}}$ is of main interest because this field is involved in the origin of sunspot on the solar surface. The corresponding transport velocity, which depends on the depth z and colatitude θ, can be determined by the following equation [3]

$$\vec{V}^{\mathrm{T}}_{\rho r}(z,\theta) \approx 6\{\varphi_2[\omega(z)] - \sin^2\theta\ \varphi_1[\omega(z)]\}\vec{V}_\rho(z). \tag{4}$$

Two functions, $\varphi_1(\omega)$ and $\varphi_2(\omega)$, depending on the Coriolis number $\omega = 2\tau\Omega$, describe the rotation effect on turbulent convection, Ω is the angular velocity.

Our calculations [4, 9] for the SCZ model [15] have revealed differences in behaviour of these functions depending on the depth. The profile of $\varphi_1[\omega(z)]$ is a convex curve that approaches to ≈ 0.0005 in the upper SCZ and ≈ 0.003 near the bottom of the SCZ, and it has a maximal value of about 0.057 at the depth z $\approx$ 50 000 km. At the same time, the function $\varphi_2[\omega(z)]$ varies smoothly in the range from ≈ 0.17 near the surface to ≈ 0.0015 in deep layers. Evidently, depending on the sign of factor $(\varphi_2[\omega(z)] - \sin^2\theta\ \varphi_1[\omega(z)])$, magnetic advection may be directed downward (when this sign is positive) and upward (when the sign is negative). This property produces a complicated distribution of the magnetic advection velocity $\vec{V}_{\rho\mathrm{r}}^{\mathrm{T}}$ over the SCZ (Fig. 1).

RECONSTRUCTION OF AZIMUTHAL MAGNETIC FIELD

Now we attempt to draw a reconstruction chart for the azimuthal field. One can expect a rather simple picture to appear in the high latitudes domains, where the relation $\varphi_2[\omega(z)] > \sin^2\theta\ \varphi_1[\omega(z)]$ is valid over the entire vertical extent of the SCZ. Assuming the balance between the buoyancy and two downward magnetic transports,

$$\uparrow \vec{V}_{\mathrm{B}}(\beta_{\mathrm{S}}^{\mathrm{p}}) + \downarrow \vec{V}_{\mathrm{D}}(\beta_{\mathrm{S}}^{\mathrm{p}}) + \downarrow \vec{V}_{\rho\mathrm{r}}^{\mathrm{T}} = 0, \tag{5}$$

one can determine the value of the steady near-polar magnetic field $B_{\mathrm{S}}^{\mathrm{p}} = \beta_{\mathrm{S}}^{\mathrm{p}} B_{\mathrm{eq}}$, for which the buoyant rise is compensated for by two negative buoyancy effects. Here the upward and downward field transports are indicated by the vertical arrows, $\uparrow$ and $\downarrow$, respectively. By using the equations for the velocities of the mean-field buoyancy (2), diamagnetic (1), and $\nabla\rho$-advection (4), we find the parameter of the normalized steady near-polar field

$$\beta_{\mathrm{S}}^{\mathrm{p}} \approx \left\{ \frac{5[V_\mu + 6(\varphi_2 - \sin^2\theta\ \varphi_1)V_\rho]}{6V_\mu - (lv/3\gamma H_{\mathrm{P}})} \right\}^{1/2}, \tag{6}$$

where both V_μ and V_ρ have negative sign. Calculations show that two downward fluxes, $\downarrow V_{\mathrm{D}} \approx 3\cdot 10^2$ cm/s and $\downarrow V_{\rho\mathrm{r}}^{\mathrm{T}} \approx 10^2$ cm/s, lock the relatively strong fields, close to the bottom of the SCZ: $\beta_{\mathrm{S}}^{\mathrm{p}} \approx$0.5–0.6, $B_{\mathrm{S}}^{\mathrm{p}} \approx$3000–4000 G. As a result, the subsurface intense azimuthal field is stored in *deep-rooted magnetic layer.* Thus, *the magnetic antibuoyancy effects may be the most plausible reason why a deep-rooted field could not become apparent at the surface as sunspots at high latitudes.*

However, in the deep layers region located near equator the $\nabla\rho$-effect causes the upward advection which forwards the magnetic buoyancy and thus *it can facilitate penetration of strong fields to the surface.* Here the balance condition can be rewritten as follows:

$$\uparrow \vec{V}_{\mathrm{B}}(\beta_{\mathrm{S}}^{\mathrm{ed}}) + \downarrow \vec{V}_{\mathrm{D}}(\beta_{\mathrm{S}}^{\mathrm{ed}}) + \uparrow \vec{V}_{\rho\mathrm{r}}^{\mathrm{T}} = 0. \tag{7}$$

The parameter of the normalized steady near-equatorial (deep) field $\beta_{\mathrm{S}}^{\mathrm{ed}}$ is similar to the expression (6), only the positive sign of factor $(\varphi_2 - \sin^2\theta\ \varphi_1)$ changes to negative one in new expression. Then, at lower half of the SCZ, where $B_{\mathrm{S}}^{\mathrm{ed}} = \beta_{\mathrm{S}}^{\mathrm{ed}} B_{\mathrm{eq}} \approx$ 2900–3800 G, two upward fluxes, buoyancy, $\uparrow V_{\mathrm{B}}(B_{\mathrm{S}}^{\mathrm{ed}}) \approx 3\cdot 10^2$ cm/s, and the $\nabla\rho$ advection, $\uparrow V_{\rho\mathrm{r}}^{\mathrm{T}} \approx 10^2$ cm/s, together are able to neutralize and even overcome the diamagnetic downward field transport, $\downarrow V_{\mathrm{D}}(B_{\mathrm{S}}^{\mathrm{ed}}) \approx 3\cdot 10^2$ cm/s. As a result, the azimuthal field, slightly stronger than $B_{\mathrm{S}}^{\mathrm{ed}}$, propagates upward.

The upper layers. In the middle of the SCZ the $\nabla\rho$-effect reverses its sign. Then, this downward magnetic advection has to counteract both buoyancy and diamagnetism (directed upward here). Therefore, a new balance condition,

$$\uparrow \vec{V}_{\mathrm{B}}(\beta_{\mathrm{S}}^{\mathrm{eu}}) + \uparrow \vec{V}_{\mathrm{D}}(\beta_{\mathrm{S}}^{\mathrm{eu}}) + \downarrow \vec{V}_{\rho\mathrm{r}}^{\mathrm{T}} = 0, \tag{8}$$

can ensure storing of moderate fields only. The expression for the parameter of the normalized steady near-equatorial (upper) field, $\beta_{\mathrm{S}}^{\mathrm{eu}}$, again is similar to (6) but now value V_μ changes its sign from negative to positive. It is also necessary to remember that near the surface the magnetic buoyancy velocity grows due to decrease of the plasma density. So, it is very difficult to keep strong fields in the upper layers. For example, at depths of $z \approx$ 40 000–50 000 km, where $\uparrow V_\mu \approx 3\cdot 10^2$ cm/s and $\downarrow V_{\rho\mathrm{r}}^{\mathrm{T}} \approx 4\cdot 10^2$ cm/s ($\theta = 70°$), the normalized steady near-equatorial (upper) field parameter $\beta_{\mathrm{S}}^{\mathrm{eu}} \approx 0.5$ corresponds to the steady field of about $B_{\mathrm{S}}^{\mathrm{eu}} = \beta_{\mathrm{S}}^{\mathrm{eu}} B_{\mathrm{eq}} \approx$ 1500–2000 G. *The stronger fields will be transported to the surface where they emerge as sunspot patterns in the "royal zone".*

Recently, Nandy & Choudhury (2002) in the framework of the circulation-dominated dynamo model proposed a new attractive scenario of active regions formation on the solar surface. The strong negative radial shear in the rotation within the tachocline produces an intermittent toroidal field of about 10^5 G. The principal innovation is that a deep equatorward flow penetrates slightly below the SCZ to a depth greater than usually believed. This flow would take the excited field to the stable radiative layers beneath the SCZ, and thus it would not allow this field to emerge on the surface at high latitudes. Then, the toroidal field is transported toward the equator at low latitudes by the meridional circulation through the stable layers and simultaneously it comes within the SCZ; so that the strong toroidal field becomes buoyant only at low heliolatitudes where the meridional flow already rises too, thereby ensuring that the flux eruption takes place at the sunspot regions.

In our opinion, the crucial role in the establishing of the sunspot "royal zone" is played namely by the $\nabla\rho$-advection. Firstly, the downward magnetic advection blocks the toroidal field in the deep layers and so does not permit them to rise in a wide latitudinal range above 45°, whereas the meridional circulation descends only close to the solar poles. Secondly, the main argument in favour of the $\nabla\rho$-effect is the region of the upward magnetic $\nabla\rho$-transport (extending from 45° to the equator) coinciding with the sunspot belt latitudes, while the meridional flow becomes ascending only at near-equator narrow band where sunspots very rarely have been observed.

Nevertheless, the deep equatorward flow undoubtedly is involved in the origin of the sunspot activity. It is very likely that namely meridional circulation is responsible for observed occasionally *double* ("two-picks") sunspot cycles. We assume that the deep-seated strong toroidal fields are transported by equatorward flow from high to mid, and then to low, latitudes, where the upward $\nabla\rho$-advection (together with magnetic buoyancy) causes these "delayed" migrating fields to rise and produce *the second maximum* (shifted in time by one to two years later on the main maximum) of the sunspot cycle.

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