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# A role of magnetic advection mechanisms in the formation of a sunspot belt

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**Abstract.** We examined two "magnetic antibuoyancy" effects: i) turbulent diamagnetism and ii) magnetic advection caused by vertical inhomogeneity of plasma density in the SCZ (the $\nabla\rho$ effect). The Sun's rotation which yields the $\nabla\rho$ effect with new properties was taken into account. It is shown that at high latitudes antibuoyancy effects block the magnetic fields in the deep layers of the SCZ. However, in the region located near-equator the $\nabla\rho$ effect, modified by rotation, causes the upward magnetic advection. So it can facilitate penetration of strong magnetic fields to solar surface where they then arise in the "royal zone" as the sunspots.

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In order to compensate the buoyant loses of magnetic flux in generation zone we involve two "magnetic antibuoyancy" (negative buoyancy) effects: i) macroscopic turbulent diamagnetism and ii) magnetic pumping caused by the vertical plasma inhomogeneity in the solar convection zone (SCZ). The turbulent diamagnetism forces the large-scale magnetic field $\vec{B}$ to transfer along the gradient of turbulent viscosity $\nu_{\rm T}\approx\left(\frac{1}{3}\right)vl\approx\left(\frac{1}{3}\right)\tau v^2$ ($v, l$ and $\tau$ are the r.m.s. velocity, mixing length and characteristic time of the turbulence, respectively) with the effective velocity $\vec{V}_\mu = -\nabla\nu_{\rm T}/2$ (Vainshtein, Zel'dovich & Ruzmaikin 1980). In the deep layers of the SCZ the turbulent diamagnetism acts against magnetic buoyancy, displacing the horizontal fields downwards (Krivodubskij 1984). The non-linear downdraft velocity, $V_{\rm D}(\beta) = 6V_\mu\Psi_{\rm D}(\beta)$ (Kitchatinov & Rüdiger 1992), is sufficient ($V_{\rm D}\approx 3\cdot 10^2$ cm/s, Kryvodubskyj, Rüdiger & Kitchatinov 1994) to resist the magnetic buoyant velocity, $V_{\rm B}(\beta)\approx\left(\frac{l}{H_P}\right)\left(\frac{v}{\gamma}\right)\frac{\beta^2}{15}$, calculated by Kitchatinov & Pipin (1993) within the framework of the mean-field magnetohydrodynamics. Here $\Psi_{\rm D}(\beta)$ is the quenching function, $\beta = B/B_{\rm eq}$ is the field strength normalized to the energy equipartition value $B_{\rm eq}\approx(4\pi\rho)^{1/2}v$, $\rho$ is the plasma density, $H_P$ is the pressure scale and $\gamma = 5/3$ is the adiabaticity index. Another magnetic transfer effect in turbulent plasma may be caused by inhomogenity of density $\rho$ (Drobyshevskij 1977; Vainshtein 1983). The net distribution of the global magnetic field in the non-linear regime is equivalent to field transfer with the effective velocity, $\vec{V}_\rho\approx\left(\frac{1}{6}\right)\tau v^2\left(\frac{\nabla\rho}{\rho}\right)$ (Kitchatinov 1982). Since the plasma density $\rho$ 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 (Krivodubskij 1987). We refer this process as the $\nabla\rho$ effect. 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 (Kitchatinov 1991). The radial magnetic advection of the azimuthal (toroidal) field $\vec{B}_{\rm T}$ is of main interests because this field is involved in the origin of sunspot on the solar surface. The corresponding transport velocity, which depends on depth $z$ and colatitude $\theta$, can be determined by the following equation, $\vec{V}^{\rm T}_{\rho r}(z,\theta)\approx 6\{\varphi_2[\omega(z)] - \sin^2\theta\ \varphi_1[\omega(z)]\}\vec{V}_\rho(z)$ (Kitchatinov 1991). 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 ($\Omega$ is the angular

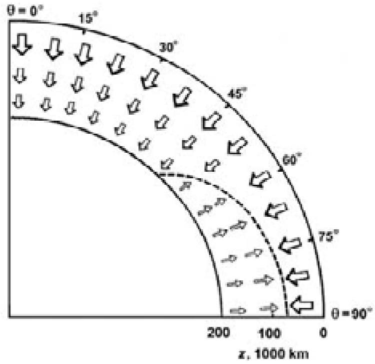


**Figure 1.** A meridional cross section of the SCZ which shows the distribution of the radial velocity of toroidal magnetic field advection, $V_{\rho\mathrm{r}}^{\mathrm{T}}(z,\theta)$, along radius (depth $z$) and colatitude $\theta$. The arrows denote the direction of advection, which amplitude varies from $\approx 10^2$ cm/s near zone bottom to $\approx 10^4$ cm/s at the surface layers. 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 upwards advection which, on the contrary, forwards the magnetic buoyancy.

velocity). Evidently, depending on the sign of $(\varphi_2[\omega(z)] - \sin^2\theta\ \varphi_1[\omega(z)])$, 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 (Figure 1).

Our calculations for the SCZ model (Stix 1989) shown that in the high latitudes domain two downward transfer effects, diamagnetism and $\nabla\rho$ advection, may counteract magnetic buoyancy and block the strong fields, of about 3000 – 4000 G, in the deep layers (Krivodubskij 1992). Thus, the negative buoyancy effects may be the most plausible reason for why a deep-seated field could not become apparent at the solar surface as sunspots at high latitudes. However, in the deep-layer region located near-equator the $\nabla\rho$ effect causes the upwards advection which forwards the magnetic buoyancy. Then two combined magnetic updrafts ensure the penetration of strong fields to the solar surface. As a result the sunspot belt is formed on the photospheric level during solar cycle.

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