The Toroidal Magnetic Field inside the Sun

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Analysis of the fine structure of the solar oscillations has enabled us to determine the internal rotation of the Sun and to estimate the magnitude of the large-scale magnetic field inside the Sun. According to the data of Duvall *et al.* (1984), the core of the Sun rotates about twice as fast as the solar surface. Recently Dziembowski *et al.* (1989) have showed that there is a sharp radial gradient in the Sun's rotation at the base of the convection zone, near the boundary with the radiative interior. It seems to us that the sharp radial gradients of the angular velocity near the core of the Sun and at the base of the convection zone, acting on the relict poloidal magnetic field B_r, must excite an intense toroidal field B_ϕ, that can compensate for the loss of the magnetic field due to magnetic buoyancy.

Magnetic buoyancy plays the main role in constraining the amplitude of the magnetic induction of the toroidal field generated at the present stage of solar evolution (Dudorov *et al.*, 1989; Krivodubskij, 1990). There, from the condition of stationarity, $\partial B_\phi/\partial t = 0$, neglecting ohmic dissipation, we obtained the following expression for the maximum value of the established stationary toroidal field (Dudorov *et al.*, 1989; Krivodubskij, 1990):

$$\max|B_\phi| \equiv B_\phi^0 \simeq \left[r\frac{\Delta\omega}{\Delta r} B_r \frac{8\pi P_e L}{u_T} (\frac{a}{\lambda})^2 \right]^{1/3} . \tag{1}$$

Here $\Delta\omega$ is the increament in the angular velocity over the step Δr along the solar radius; P_e is the electron pressure; u_T is the mean velocity of upward transport of thermal energy; L is the space scale of the magnetic field; a is the transverse radius of the magnetic flux tube; λ is the temperature scale height; r is the distance from the centre of the Sun.

Krivodubskij (1990) performed an analysis of the energetic aspects of the problem. The total magnetic energy of the excited toroidal field, $E_H^* = E_H V_H$ ($E_H = B_\phi^2/8\pi$ is the magnetic energy density), cannot exceed the total kinetic energy of the rapidly rotating core, E_ω^*. To make $E_H^* \leq E_\omega^*$, toroidal field with

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intensity B_ϕ must be concentrated in the volume $V_H \leq E_\omega^*/E_H = 8\pi E_\omega^*/B_\phi^2$. In the generation mechanism considered the toroidal magnetic flux tubes are localized in the region of the radial jump of the angular velocity and are oriented along the parallels of solar latitude, with opposite signs on either side of the equatorial plane. Then $V_H = 2V_t = 2(2\pi r_0 S_t)$ where $S_t = d_t^2/4$ is the cross-sectional area of the torus with radius r_0 and volume V_t. The cross-sectional diameter $d_t = (4S_t/\pi)^{1/2}$ of the toroidal magnetic flux tube must not exceed the value $(8/\pi E_\omega^*/r_0 B_\phi^2)^{1/2}$.

The expression (1) together with the helioseismological data of Duvall *et al.* (1984), yields a maximum estimate of the toroidal field near the core of the Sun in the range $1 \times 10^7 - 2 \times 10^8$ G. Energetic constraints suggest that this toroidal field is concentrated in relatively thin magnetic flux tubes with diameters $d_t \leq 16\,000 - 800$ km, respectively (Krivodubskij, 1990).

Dziembowski *et al.* (1989) used the oscillation data of Libbrecht (1989), and found that there is a sharp radial jump of the angular velocity, $\Delta\omega \simeq 18$ nHz $\simeq 1.1 \times 10^{-7}$ rad/s at the transition from the convection zone to the radiative zone ($r = 0.7 R_\odot, \Delta\omega/\Delta r \simeq 1.6 \times 10^{-17}$ rad/s cm). If for the radial field B_r we take a value of about 1 G, which to order of magnitude is in agreement with the observed poloidal field on the surface of the Sun, then from the expression (1) we obtain an estimate of the maximum magnetic induction of the resulting stationary toroidal field of about 2×10^6 G near the bottom of the convection zone ($d_t \leq 50\,000$ km).

Dziembowski and Goode (1989) determined the value of the toroidal magnetic field inside the Sun directly from the analysis of the helioseismological data of Libbrecht (1989), using for this an asymptotic formulation of the inverse problem analogous to that from which the internal rotation of the Sun was determined (Dziembowski *et al.*, 1989). They investigated the effect of a magnetic field on the 5-min oscillations and found evidence for an axisymmetric quadrupole toroidal field of about $(2 \pm 1) \times 10^6$ G, centred near the base of the convection zone. This value clearly agrees with our estimate of the toroidal magnetic field.

As we pointed out, the origin of the strong toroidal field in deep layers of the Sun is the action of the differential rotation on the relict poloidal field. This has been noted also by Dicke (1979) (the excitation of the toroidal field near the boundary of the fast rotating core) as well as by Dziembowski and Goode (1989) (the toroidal field excitation of the boundary of the convection zone and the radiative zone). However, they neglected the effect of magnetic buoyancy on the magnetic field regeneration processes. In our investigation the effect of the magnetic buoyancy is taken into account and as a result it is shown that it is the magnetic buoyancy that is the factor which limits the maximum intensity of the toroidal field to about $(1-2) \times 10^6$ G near the base of the convection zone, and to about $10^7 - 2 \times 10^8$ G near the solar core.

The magnetic field intensities obtained by us are sufficient to induce the observed splitting effect in the 5-min oscillation frequencies. Therefore, to interpret the fine structure of the solar oscillations, the effect of the magnetic field and the effect of rotation must be taken equally into account. Considering the spatial structure of the excited toroidal field it should be remembered that the contribution of the magnetic field to the splitting of oscillations will depend on its distribution both with depth and latitude.

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