POLARITY REVERSALS AND TILT OF THE EARTH's MAGNETIC DIPOLE

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There is evidence that the terrestrial magnetic field is connected with the Earth's mantle: (1) There are magnetic anomalies that do not take part in the westward drift of the main field, but are fixed with respect to the mantle [1, 2], (2) The geomagnetic pole position flips in particular way by preferred meridional paths during a reversal [3], (3) Magnetic polarity reversals are correlated with the activations of geological processes [4]. These facts may be explaned if we take into account that a significant horizontal temperature gradient can exist in the top levels of the liquid core because of the different thermoconductivity of the different areas of the core-mantle boundary. This temperature inhomogeneities can penetrate in the core because fluxes along the core boundary (the thermal wind) can be strongly suppressed by a small redistribution of the chemical composition in the top of the core (see Dolginov this volume). The nonparallel gradients of the temperature, density, and composition on the top of the core create a curled electric field that produces a current and a magnetic field. This seed - field can be amplified by motions in the core. The resulting field does not forget the seed - field distribution and in this way the field on the Earth surface (that can be created only in regions with high conductivity, i.e. in the core) is connected with the core-mantle boundary.

Contrary to the usual approach to the dynamo problem we will take into account that the seed field of thermoelectric origin is acting not only at some initial moment of time but permanently.

The equation that governs the magnetic field amplified from the seed field by differential rotation and convection in the core has the form

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\alpha \mathbf{B} + \mathbf{v} \times \mathbf{B}) - D_m \nabla^2 \mathbf{B} = Q_\varphi \tag{1}$$

where $\alpha\mathbf{B} + \mathbf{v} \times \mathbf{B}$ is the electromotive force created by convection and differential rotation ($\alpha\omega$ dynamo). $Q_\varphi = -c\nabla \times [\eta \nabla T]_{curl}$, η is the termopower. If the conductivity is of the metallic type then $\eta = \pi^2 (k_B/e)(k_B T/\zeta)$, where T is the temperature and ζ is the chemical potential. The trace element doping might well change the conductivity by a large factor. This doping in most cases increases the conductivity of substances which are insulator in a pure state (e.g. silicon), and does not decrease substantially the conductivity of good conductors (e.g. molten iron). Thus the doping might work in favor of the field generation mechanism. The brakets $[..]_{curl}$ denote the vortex part of the expression. As an example we take the temperature distribution in the form $T(\mathbf{r}) = T_a(r) + T_1(r)\cos\theta$, where $T_1 = T_1^0 \exp[-(R-r)/L]$ and $L << R$. We assume that horizontal gradients of themperature are maximum near the core-mantle boundary (r = R). The similar expressions are taken for the thermopower and electric conductivity distributions. In this case only the φ component of the seed field is non zero. We use the simplest model of the $\alpha\omega$ dynamo that allows us to show the dependence of the resulting field from the permanent existing seed field and allows us to estimate characteristic time of the field evolution. Consider the case when the velocity field is a much sharper function of space coordinates than the magnetic field and disregard the term $(\mathbf{v}\nabla)\mathbf{B}$ as compared with $(\mathbf{B}\nabla)\mathbf{v}$. Estimate the term $D_m \nabla^2 \mathbf{B}$ as $\mathbf{B}/\tau$, where $\tau = L^2/D_m$ and L is the characteristic space scale of the $\mathbf{B}$. We will use the representation employed by many authors $\alpha = \alpha_0(r)\cos\theta$ for α effect and $\mathbf{v} = \omega(r) \times \mathbf{r}$. In this approximation equation (1) has the following solution

$$B_\varphi = \frac{Q_\varphi \tau}{4 + \lambda^2 \tau^2} \{ \frac{2}{\lambda\tau} [\sinh \frac{\lambda t}{2} + \frac{\lambda\tau}{2} \cosh(\frac{\lambda t}{2})] \exp(-\frac{t}{\tau}) - 1 \} \tag{2}$$

$$\lambda^2(r,\theta) = -4\frac{\alpha_0}{r^2}(\alpha_0 + r\frac{\partial}{\partial r}(r\omega))\sin\theta - 4(\frac{\partial \alpha_0}{\partial r} + \omega)\cos\theta > 0 \tag{3}$$

In the case $\lambda = 0$ and $t \to \infty$ we obtain from (2) the stationary solution for the seed field

$$(B_{tor})_\varphi = Q_\varphi \frac{\tau}{4} = \frac{4\pi}{c} \sqrt{\frac{1}{3}} \frac{r}{R} (1 - \frac{r^3}{R^3}) \eta_a \sigma_a T_1^0 \sin\theta \tag{4}$$

The stationary value of the seed field created in the top of the core can be estimated from the formula (5). Taking the upper core conductivity as $\sigma = 3 \cdot 10^{15}\ s^{-1} \sim 3 \cdot 10^3\ ohm^{-1} cm^{-1}$, $\eta_a \approx 2 \cdot 10^{-5}\ volt/degree$, σ_1 is about 10 - 20 % of σ_a, and temperature inhomogeneities $T_1 \approx 10$ K, we obtain the seed toroidal field inside the core of the order of 0.1 - 1 G. Because the real parameters of the Earth's core are poor known larger values of T_m, σ_m and η, and, hence, the large field estimate are possible. It is important to emphasize that the obtained seed field values are of the same order of magnitude as the magnetic anomalies observed on the Earth surface. If $\lambda > 2$ the field increases exponentially with time. In the $\alpha\omega$ dynamo theory the strength of the ω and α effects are measured by magnetic Reynolds numbers $R_\omega = \omega\tau$ and $R_\alpha = \alpha\tau/L$. The dynamo works if $(R_\omega R_\alpha)^{1/2} > 1$. One can see from (3) that λ^2 is of the order of $4\alpha\omega/L$ and the condition $\lambda\tau > 2$ coincides with the dynamo criteria. The field amplification stops when the nonlinear effects begin to act.

We can see from (2) that the space structure of the resulting field does not coincide with that of the seed field because of the radial and angular dependence of α and ω but the dependence on the seed field structure remains. Expressions for B_r and B_θ can be easily obtained from (1) and (2)

$$B_r = \frac{Q_\varphi \tau^2}{4+\lambda^2\tau^2}\frac{\alpha_0}{r}\sin\theta\{1-[1+\frac{2}{\lambda\tau}\sinh\frac{\lambda t}{2}+\frac{4}{\lambda^2\tau^2}(\cosh\frac{\lambda t}{2}-1)]\exp(-\frac{t}{\tau})\} \quad (5)$$

B_r increases with time under the same conditions as B_φ. The expression of B_θ is similar to that of B_r. Solutions of (1) with $Q_\varphi = 0$ may be added to (2) and (5). These solutions are usually considered in the dynamo theory. We have not use these solutions assuming that the initial initial field is zero.

Some surface magnetic anomalies do not travel with the main field but remain fixed with respect to the mantle [1, 2]. It can be explained taking into account that the seed field are tight to the mantle and travel with it. The field amplified by the dynamo does not forget the seed field distribution that provides connection of some surface magnetic anomalies with the mantle.

It was demonstrated in [4] that periods of the Earth's field reversal coincide with the strong activation of geological processes. This result connects field reversals with mantle convection that exhibits itself in the surface tectonic activity. Magnetic field reversal frequency seems to correlate inversely to mantle plume activity, corresponding to convective intensity in Earth's outer core. Apparently a significant thermal flux is created in the core, as would be expected in the process of the inner core formation. The mantle acts as a thermal blanket. The hot matter is concentrated at the top of the outer core until the temperature on the mantle bottom reaches some critical value that radically changes the thermoconductivity and viscosity of the mantle lower levels and may change the mode of convection. It provide more effective heat transport and the core gets rid of the thermal excess. The change of thermoconductivity and viscosity distribution on the core-mantle boundary leads to the change of the seed field distribution, which depends on the temperature and density gradients. It may result in total magnetic field reversal.

The assumption that both the seed field distribution and convection patterns in the core are dependent on the inhomogeneous distribution of the temperature, composition and density near the mantle boundary suggests the natural explanation that the tilt of the magnetic axis reflects the deviation of this distribution from the axialsymmetric one. This statement may be generalized to the case of the giant planets. Some of them have a magnetic axis highly tilted to the axis of rotation. A magnetic field is commonly assumed to be generated in the highly conducting metallic core or in layers immediately above the core. The planet's interior above the core and possibly inside the core is in a high turbulent state. However, it does not prevent the existence of very long lived well organized structures there. Even on the surface we can observe long lived zonal flows and solitonlike spots (for example the Jovian red spot). The temperature and substance distributions in zonal fluxes and spots are not homogeneous. Thus we have grounds to expect that very long lived inhomogeneities exist in regions with high conductivity. These inhomogeneities may create a magnetic field as in the cases considered above. The field structure will reflect the distribution of the inhomogeneities. For example, Uranus' axis of rotation is strongly inclined to the orbital plane . It makes the tides inside Uranus, which are driven by its satellites, nonaxialsymmetric. It may lead to a slightly nonaxial symmetric distribution of temperature, composition, and velocities in the highly conducting interior of Uranus and, as a result, to the highly tilted magnetic axis.

References : [1] Bloxham J., Gibbins D., (1987) Nature, 325, 511 ; [2] Gibbins D., Bloxham J. (1987) Nature, 325, 500 ; [3] Constable C., Nature, 358, 230, (1992); [4] Larson R., Geology 19, 963 (1991)