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Mantle cooling regulation and ancient geomagnetic field

M. Yu. Reshetnyak*[1,2]

[1] *Schmidt Institute of Physics of the Earth of the Russian Academy of Sciences, Moscow, Russia*
[2] *Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences, Moscow, Russia*

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The joined core and mantle thermal evolution model of the Earth for 6 Gy is considered. The model describes evolution of the heat fluxes, temperature distribution in the Earth, energy available for the magnetic field generation. Using Monte Carlo method we find parameters of the model which produce realistic inner core size, heat flux at the surface of the planet, viscosity and temperature of the mantle. The quite large heat flux at the core-mantle boundary and corresponding energy source for geodynamo after accretion help to explain existence of the ancient geomagnetic field before the inner core origin.

Keywords: liquid core, thermal and compositional convection, geodynamo.

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Introduction

The magnetic field of the Earth is produced by the motions of conducting medium in the core. It is supposed that the core appeared in 50–100 Ma after accretion. Since that time its radius supposed to be the same [*Drake*, 2000; *Solomatov*, 2007]. Due to the cooling of the planet, fluid motions in the core generate magnetic field, observed at the surface of the planet. The age of the oldest measurements of the field, dated to 3.6 Ga in the past, is comparable in order of magnitude to the age of the planet 4.6 Gy [*Tarduno et al.*, 2010]. Whether the present magnetic field behavior is possible to reproduce in the models, than the ancient magnetic field is still the subject of numerous discussions. To the moment it is not clear how this field can be generated at all [*Olson*, 2013]. The problem comes from the simple energy estimates of the thermal and compositional counterparts. It is believed that the thermal convection alone is insufficient for the magnetic field generation. So far compositional convection started with appearance of the inner core (IC), which is quite young 1–2 Ga, the so-called core's paradox takes place: the paleomagnetic observations contradict to the thermal evolution models of the Earth, which can not explain existence of the magnetic field before IC origin.

The main point of such a cooling models is the slow decrease of the prescribed heat flux Q_b at the core-mantle boundary (CMB). Its behavior determines slow cooling of the core and as a result the quite young IC [*Labrosse et al.*, 1997]. On the other hand it is well known that cooling of the mantle was very different: the corresponding heat flux Q_s at its surface decreased in order of magnitudes during the age of the planet [*Abe*, 1993; *Solomatov*, 2007]. The most dramatic changes of Q_s took place just after separation of the core and mantle after accretion, and continued not more than 1 Gy. It is this time interval, when IC was absent, and the thermal convection was the single energy source in geodynamo. Here we show how increase of the Earth's cooling in the past can help to explain existence of the geomagnetic field before IC origin.

Thermodynamics of the Earth

The core

Following [*Labrosse et al.*, 1997; *Labrosse*, 2003; *Reshetnyak*, 2019] we consider scenario of the Earth's evolution, where soon after the end of the accretion process, the Earth's core of radius r_b was fully convective. Then, it cooled due to the thermal flux Q_b at CMB, $r = r_b$, and as a result, depending on the amplitude of Q_b, the solid IC could appear. Its radius c started to grow with time t.

*Corresponding author: m.reshetnyak@gmail.com

Radial distributions of density $\rho(r)$, pressure $P(r)$ and gravity $g(r)$ satisfy to the hydrostatic balance equations:

$$\nabla P = -\rho g, \qquad g(r) = \frac{4\pi G}{r^2}\int_0^r \rho(u)u^2\,du, \quad (1)$$

with G the gravitational constant. The logarithmic equation of state

$$P = K_\circ \frac{\rho}{\rho_\circ}\ln\frac{\rho}{\rho_\circ}, \quad (2)$$

closes system of equations for (P, ρ, g), where $K_\circ$, $\rho_\circ$ are incompressibility and density at zero pressure, respectively. The jump of the density, observed at the surface of IC, and which effect on the evolution of the core is quite small, is introduced as follows:

$$\rho = \begin{cases} \rho + \delta\rho, & \text{if } r \le c \\ \rho, & \text{if } r > c. \end{cases} \quad (3)$$

Equations (1)–(3) with given c can be solved numerically. Then, with known (P, ρ, g), adiabatic temperature profile can be derived:

$$T_{ad}(r) = T_c(c)\,e^{-\int\limits_c^r \frac{\alpha(u)g(u)}{C_p}\,du}, \quad (4)$$

where $T_c(c)$ is the temperature at $r = c$, thermal expansion coefficient

$$\alpha(r) = \frac{\gamma C_p \rho_\circ}{K_\circ\left(1 + \ln\dfrac{\rho}{\rho_\circ}\right)}, \quad (5)$$

with C_p specific heat, and γ for Grüneisen parameter.

If IC is still absent, $c = 0$, then $T_c(c) = T_\circ$, where the temperature in the center of the Earth $T_\circ$ can be found from the heat balance equation:

$$\begin{aligned} Q_b &= -4\pi\int_0^{r_b} \rho C_p \frac{\partial T_{ad}}{\partial t} r^2\,dr = -\frac{\partial T_\circ S}{\partial t}, \\ S &= 4\pi C_p \int_0^{r_b} e^{-\frac{1}{C_p}\int\limits_0^r \alpha(a)g(a)\,da} \rho r^2\,dr. \end{aligned} \quad (6)$$

The growth of IC starts, when temperature of the outer core (OC) is equal to the temperature of solidification:

$$T_s(r) = T_s^\circ \left(\frac{\rho(r)}{\rho(c)}\right)^{2(\gamma - \frac{1}{3})}, \quad (7)$$

where T_s° is the temperature of solidification in the center of the Earth. Solidification process starts in the core's center, i.e. $T_c = T_\circ = T_s^\circ$, $r = c = 0$. Then, for $c > 0$, T_s defines adiabatic temperature at the boundary c in (4): $T_c(c) = T_s(c)$.

Position of IC boundary c can be derived from the heat flux equation:

$$Q_b - Q_c = Q_L + Q_G + Q_C + Q_R \quad (8)$$

with Q_c heat flux at IC boundary, Q_L latent heat, Q_G release of gravitational energy, Q_C adiabatic cooling, and Q_R for radiogenic heating in the core.

Let introduce functions P_L, P_G, P_C such that:

$$Q_L = \dot{c}P_L, \qquad Q_G = \dot{c}P_G, \qquad Q_C = \dot{c}P_C. \quad (9)$$

The latent heat source is defined as

$$P_L(c) = 4\pi\rho(c)c^2\delta S\, T_s(c), \quad (10)$$

with δS entropy of crystallization.

The gravitational energy due to the growth of IC [*Loper*, 1984] and adiabatic cooling have the form:

$$\begin{aligned} P_G &= \frac{2\pi}{5} G M_\circ \delta\rho \frac{c^2}{r_b}\left(3 - 5\left(\frac{c}{r_b}\right)^2\right), \\ P_C &= -\pi C_p \int_c^{r_b} \rho \frac{\partial T_{ad}}{\partial c} r^2\,dr, \end{aligned} \quad (11)$$

with $M_\circ$ mass of the core. Equations (8)–(11) govern evolution of IC boundary c. They can be resolved with respect to $\dot{c}$ and integrated in time.

From condition of continuity of the temperature at the boundary c, follows that $T_s(c)$ is the boundary condition for the thermal-diffusion in IC, $0 < r < c$, with a moving boundary $c(t)$:

$$\frac{\partial T}{\partial t} = k\Delta T, \quad (12)$$

where k is the thermal diffusivity. The second boundary condition in the center $r = 0$ is $T' = 0$, where $'$ is a derivative on r. The joined system (1)–(12) defines evolution of the fields in the core with prescribed Q_b. Equations (1)–(12) were solved numerically, using iterative methods with under-relaxation method to provide numerical stability, see for parameters values Table 1.

The mantle

Cooling of the mantle occurs due to the heat flux into the near-earth space. It is usually assumed that the temperature at the Earth's surface T_s is fixed. An important difference between the mantle and the core is presence of the pronounced thermal boundary layers in the mantle, corresponding to the D'' layer and the lithosphere, associated with the large Rayleigh numbers in the mantle and a strong dependence of viscosity on temperature in the mantle [*Schubert et al.*, 2001]. In order to describe temperature jumps in the boundary layers,

Table 1: Parameters of the core

Parameter	Deno-tation	Value
gravitational constant	G	$6.69\times 10^{-11}\, m^3/(kg\, s^2)$
thermal diffusivity	k	$7\times 10^{-6}\, m^2/s$
kinematic viscosity	ν	$10^{-6}\, m^2/s$
light element diffusivity	λ	$10^{-9}\, m^2/s$
coefficient of chemical expansion	β	1
Grüneisen parameter	γ	1.5
core radius	r_b	$3480\, km$
entropy of crystallization	δS	$118\, J/(kg\, K)$
density at zero pressure	$\rho_\circ$	$7500\, kg/m^3$
density jump at ICB	$\delta\rho$	$500\, kg/m^3$
incompressibility of the core	$K_\circ$	$4.76\times 10^{11}\, Pa$
modern IC radius	$\hat{c}$	1.22×10^6 m
specific heat	C_p	$860\, J/(kg\, K)$

Table 2: Parameters of the mantle

Parameter	Deno-tation	Value
Earths' radius	r_s	6.371×10^6 m
density	ρ	3.4×10^3 kg/m^3
critical Rayleigh number	$\mathrm{R}a^{crit}$	1200
specific heat	C_p	$1230\, J/(kg\, K)$
gravity	g	10 m/s^2
coefficient of thermal expansion	α	3×10^{-5} K^{-1}
thermal diffusivity	κ	10^{-6} m^2/s
scaling constant	β	0.3
modern heat flux at Earth's surface	$\hat{Q}_s$	44 TW
temperature at Earth's surface	T_s	0 K

the following elegant approach is used [Stevenson et al., 1983; Schubert et al., 2001]. The cooling equation for the average temperature T_m of the mantle of mass M_m with heat capacity C_p^m has the form:

$$C_p M_m \frac{\partial T_m}{\partial t} = Q_b - Q_s + H(t), \tag{13}$$

where Q_s is a heat-flux at the surface of the Earth, H is a specific radiogenic heat production rate decays with time according to an exponential decay law $H = H_\circ e^{-\frac{t}{\tau}}$, τ is a decay time. The mean temperature of the mantle T_m is average over the bulk of the mantle between boundary layers of the thickness δ_1 and δ_2. The jumps of the temperature in the layers satisfy relations: $\delta T_1 = T_m - T_b$, $\delta T_2 = T_s - T_m$, $\delta T_1 + \delta T_2 = \delta T$, $\delta T = T_s - T_b$.

There are two unknown heat fluxes in rhs of (13), which should be derived as a functions of T_m. The flux Q_s and layer's thickness δ_2 depend on δT as $Q_s = S_s k \dfrac{\delta T}{r_s - r_b}\mathrm{N}u$, and $\delta_2 = \mathrm{N}u^{-1}(r_s - r_b)$, where $\mathrm{N}u = \left(\dfrac{\mathrm{R}a}{\mathrm{R}a^{cr}}\right)^\beta$ is the Nusseldt number, $k = \kappa\rho C_p$ thermal diffusivity, β scaling constant, $S_s = 4\pi r_s^2$ – surface of the Earth. The Rayleigh number $\mathrm{R}a = \dfrac{g\alpha\delta T\,(r_s - r_b)^3}{\kappa\nu}$, with

$$\nu = \nu_\circ e^{\frac{A_\circ}{T_m}} \tag{14}$$

for a kinematic viscosity of the mantle, and $\nu_\circ$, $A_\circ$ are the constants. It is supposed that $\mathrm{R}a \gg \mathrm{R}a^{crit}$, where $\mathrm{R}a^{crit}$ is a critical value, corresponding to the threshold of the thermal convection. Whether Q_b is prescribed, then (13) and (14) can be integrated in time. In spite of the fact that due to smallness of Q_b, $Q_b \ll Q_s$, Q_b is usually omitted in the mantle simulations, it is in the core simulations Q_b is extremely important and should be taken into account.

Numerical experiments reveal that to find δ_1 it is convenient to use the following empirical technique, based on the estimate of the critical Rayleigh number for a boundary layer with variable viscosity [Stevenson et al., 1983]:

$$\mathrm{R}a_{crb} = \frac{g\alpha\delta T_1 \delta_1^3}{\kappa\nu_1} \approx 2\times 10^3. \tag{15}$$

Then

$$\begin{aligned} l\delta_1 &= \left(\frac{\mathrm{R}a_{crb}\,\kappa\nu_1}{g\alpha\delta T_1}\right)^{1/3}, \\ \delta T_1 &= \delta T - \delta T_2, \\ Q_b &= S_b k \frac{\delta T_1}{\delta_1}, \end{aligned} \tag{16}$$

where $S_b = 4\pi r_b^2$ is a surface of OC. System of (13)–(16) for the given δT was solved with respect to T_m for the values specified in the Table 2.

To find solution of the joint core and mantle cooling problem the following algorithm was used.

At constant T_s jump δT depends only on the temperature T_b, which changes as the core is cooling. The condition for matching the cooling of the core and mantle follows from the continuity of the temperature at r_b. Let the flux Q_b is known at the current iteration. This (together with the initial conditions) is enough to solve (1)–(12) for the core and find adiabatic temperature $T_{ad}(r_b)$ at the outer boundary of the core. Then, with known δT, (13)–(16) are solved with respect to T_m and Q_b. The iterative process, including calculation of the physical fields for the core and mantle at the current time step, stops when the certain accuracy criterion is met.

Geodynamo

To the moment nothing was mentioned on capability of the core convection to generate magnetic field **B**. Geodynamo process transforms kinetic energy, produced by heating and IC growth, into the energy of the magnetic field E_m. After some time E_m, due to the ohmic dissipation, transforms again to the heat Q_J. So far E_m is the intermediate kind of energy, it is absent in (8). To estimate $E_m \sim Q_J$ in OC one needs additional equation for the entropy balance in OC [*Backus*, 1975; *Braginsky and Roberts*, 1995; *Labrosse*, 2003]:

$$\frac{Q_b}{T_b} = \frac{Q_C}{\overline{T}} + \Sigma + \frac{Q_J}{T_D} + \frac{1}{T_c}\left(Q_L + Q_c\right), \qquad (17)$$

with the mean temperature $\overline{T} = V^{-1}\int T_{ad}\, dV$, elementary volume dV, entropy production by adiabatic cooling $\Sigma = C_P^{-2}\int \kappa\,(\alpha g)^2\, dV$. Note, that before IC origin $Q_L = Q_G = Q_c = 0$. The estimate of the temperature, corresponding to the entropy production by ohmic dissipation, is $T_D = \dfrac{\overline{T} + T_b}{2}$. Deriving Q_J from (8),(17) leads to the estimate of the energy available to geodynamo:

$$\begin{aligned} Q_J = T_D\Big[Q_b\left(\frac{1}{T_b} - \frac{1}{\overline{T}}\right) - \Sigma + \\ (Q_L + Q_c)\left(\frac{1}{\overline{T}} - \frac{1}{T_c}\right) + \frac{Q_G}{\overline{T}}\Big], \end{aligned} \qquad (18)$$

with already known rhs. Note, that Carnot-like expression (18) is more complex compared to the scaling law prediction $B \sim Q_b^{1/3}$ [*Christensen and Aubert*, 2006].

Earth's cooling simulations

Equations (1)–(16) were integrated over 6 Gy from the moment when the core appeared at $t = 0$. Recall that the modern epoch corresponds to $t = 4.5$ Gy. So far accuracy of parameters in Table 1 and Table 2 is limited, the Monte-Carlo method was used to vary $T_\circ$, T_s°, responsible for the core's thermodynamics, and $\nu_\circ$, $A_\circ$, $H_\circ$ for the heat fluxes in the mantle. To find the optimal solution the following cost function was applied:

$$\begin{aligned} l\Psi &= 1 - e^{-\frac{R_1+R_2+R_3}{3}}, \\ R_1 &= \frac{|c-\hat{c}|}{\hat{c}},\ R_2 = \frac{|Q_s - \hat{Q}_s|}{\hat{Q}_s}. \end{aligned} \qquad (19)$$

The latter function R_3 in (19) is zero if the mean values of the ohmic dissipation $\overline{Q_J^a}$, $\overline{Q_J^b}$ over the time intervals before and after origin of IC at $t = t_c$, correspondingly, are larger than the given value $\hat{Q}_J$, otherwise $R_3 = 1$. Minimum of the cost function Ψ corresponds to the solution with the modern values of the core radius $c = \hat{c}$, the heat flux at the surface of the planet $Q_s = \hat{Q}_s$, as well as with $\overline{Q_J^a} > \hat{Q}_J$ and $\overline{Q_J^b} > \hat{Q}_J$, $\hat{Q}_J = 0.5$ TW.

The obtained optimal solution corresponds to $T_\circ = 6285$ K, $T_s^\circ = 5366$ K, $\nu_\circ = 1.502 \times 10^7$ m^2/s, $A_\circ = 6.937 \times 10^4$ K. The amplitude of the internal radiogenic sources C_m, decaying 4.5 times over 4.5 Gy. The Urey numbers at $t = 4.5$ Gy are $\mathrm{Ur}_1 = Q_R/Q_s = 0.2$, $\mathrm{Ur}_2 = Q_R/(Q_s - Q_b) = 0.25$.

As follows from Figure 1a, IC appears at $t_c = 1.87$ Gy and at $t = 4.5$ Gy its radius $c = 1350$ km is 10% larger than the modern one. The surface heat flux $Q_s = 54$ TW is 20% larger than the present flux.

Just after accretion Q_s was 500 times larger than the present value. During 1 Gy Q_s decreased to the modern level. Such a rapid stabilisation is due to the exponential dependence of the mantle kinematic viscosity on the temperature T_m (18): the larger is T_m, the smaller is viscosity ν, then the larger is the heat flux Q_s, and the faster is the mantle's cooling and decrease of T_m.

The thicknesses of the boundary layers $\delta_1 = 62$ km and $\delta_2 = 135$ km are compared to the thickness of D'' layer and lithosphere ~ 100 km. The temperature jumps in the layers $\delta T_1 = 100$ K, $\delta T_2 = 24{,}700$ K lead to $T_m = 2740$ K and $T_b = 3730$ K, comparable to expected in D'' layer and lithosphere [*Schubert et al.*, 2001]. Viscosity of the mantle is $\nu = 1.5 \times 10^{18}$ m^2/s and the Nusseldt number $\mathrm{N}u = 21$.

The heat flux Q_b at CMB, see Figure 1b, also has maximum at the early stage of evolution. However its magnitude is only 3 times larger than the present one. The rapid decrease of Q_b stopped at t_c, in the moment, when IC started to grow, supplying additional energy to the system. Since that time decrease of Q_b was of order 1 TW per Gy. The small Q_b at $t = 0$ is due to the initial homogeneous temperature distribution in the mantle, accepted in the model.

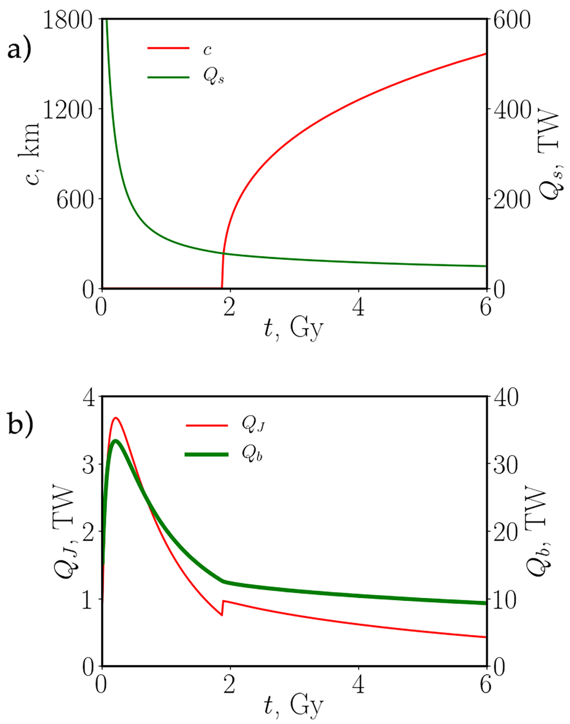

Figure 1: Evolution of IC radius c and surface heat flux Q_s (upper plane); ohmic heating Q_J and heat flux Q_b at CMB (lower plane).

Behavior of Q_J, associated with the energy of the magnetic field E_m, is very similar to Q_b. Its present value 0.6 TW is within the range of acceptable values [*Labrosse*, 2003]. Before IC origin Q_J was larger because of the larger flux at CMB Q_b, which forced convection in the core. As a result, convection in the core before IC origin could be more intensive than expected earlier [*Olson*, 2013]. This can explain existence of the magnetic field before IC origin.

The main difference of our model from the previous models, e.g., [*Labrosse et al.*, 1997; *Labrosse*, 2003], is intensive heat flux at CMB Q_b in the early past, while the other parameters and initial conditions are very similar. Due to increase of Q_b IC becomes older, its age is 2.9 Gy. To fit the present size of IC to observations one needs to increase the initial temperature of the center of the Earth after accretion $T_\circ$ up to 6280 K (5% percents larger of the value 6000 K adapted from [*Labrosse et al.*, 1997]). The older is IC the less is accuracy of paleomagnetic data, and it is more difficult to identify IC origin in the case of change of the magnetic field generation.

Conclusions

The main result of the work is taking into account the rapid change in the thermal evolution of the mantle just after accretion in the model of the evolution of the Earth's core. The large heat flux at the Earth's surface leads to the rapid freezing of the core and as a result to the old inner core. In its turn old inner core provides energy enough for the magnetic field generation 3Gy ago.

However, due to the strong cooling of the core by the mantle after accretion, change of geomagnetic field intensity because of IC origin is quite small in the model, making geomagnetic field intensity very pure characteristic for IC origin identification. The same conclusion follows from the paleomagnetic data which do not register apparent change of the field generation. It appears that the more subtle characteristics of the magnetic field than its intensity should be used to check IC origin.

Since the dipole magnetic field exists in the limited range of Rayleigh numbers [*Christensen and Aubert*, 2006], and can decay with a significant increase of convection, we can expect that at the early stage of Earth's evolution, when Q_s and Q_b were much larger than the present values, the geomagnetic field was multipolar. If we take this point of view, then the absence of observations of the dipole magnetic field during the first billion years is explained not only by the absence of geological rocks suitable for paleomagnetic measurements, but by the absence of the dipole magnetic field itself.

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