Numerical Simulations of Present and Ancient Dynamos in the Earth

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The core-mantle boundary (CMB) region is important to understand the generation mechanisms of the geomagnetic field and its secular variations, whereas convective motions in the Earth's outer core at present are driven by the buoyancy arising from thermal and chemical effects at the inner core boundary. To better understand the thermo-chemical buoyancy of the Earth's core, we performed numerical simulations of the geodynamo powered by double diffusive convection. We find three sorts of dynamos, that is, dipolar, non-dipolar and hemispherical dynamos. Flow dynamics in these dynamos can be characterized by the zonal flow and relative axial helicity. Then, dynamo simulations with a thin stably stratified layer imposed below the core-mantle boundary were run. It is found that dynamos can strongly be affected even with the slightly thin stable layer. While the present geodynamo is predominantly driven by inner core solidification, the ancient geodynamo probably operated without an inner core. It was thus exclusively driven by secular cooling and radiogenic heating. We also explore lateral CMB heat flux variations on dynamos with and without an inner core, by comparing dynamos driven by homogeneous internal sources and by bottom buoyancy sources. Our results indicate that the field intensity and morphology of the ancient geodynamo was more variable and more sensitive to the thermal CMB structure than that after onset of inner core growth.

Keywords: Geodynamo, Geomagnetic field, Core convection, Magnetohydrodynamics

1. Introduction

Internal activities of the Earth are the consequence of convective motions of the mantle and core. The convection of mantle and core also control Earth's surface environment through material circulations, volcanism, continental drift, geomagnetic field, and so on. The mantle convection, driven by both cooling of the Earth and internal radiogenic heating, takes the form of rigid-plate motions at the surface. As the mantle cools by the subducting plates, the underlying liquid metallic core becomes thermally unstable and the resulting convective motion causes generation of the geomagnetic field and its time variations. As a result of cooling of the liquid core containing some lighter elements, a solid denser inner core grows from below, causing compositional instability in the liquid outer core. Seismic studies have illuminated detailed structures inside of the Earth, such as subducting plate in the mantle and strong heterogeneity at the core-mantle boundary (CMB), and stratified layer in the outer core. The geomagnetic field has been monitored at the surface or from satellites. It contains information on both the core convection and the electrical conductivity of the mantle. Paleomagnetic records provide information on the long-term variation and the evolution of geomagnetic filed. The purpose of our group is to construct a comprehensive view on the structure and dynamics of the Earth's deep interior, by including the results of latest observations. We report here several topics on geodynamo.

2. Geodynamo simulations with double diffusive convection and stable stratification

The most likely source of the geomagnetic field generation and its secular variation is a dynamo action due to convective motions in the Earth's outer core. Convective motions in the Earth's core are driven by buoyancy force originating from thermal and compositional effects. Thermal convection is driven by the super-adiabatic temperature difference across the core, release of latent heat upon inner core growth at the inner core boundary, and core secular cooling. Compositional convection is fueled by light element ejection into the outer core at the inner core boundary.

According to the molecular diffusivity, the thermal Prandtl number Pr^T is about 0.1, while the corresponding compositional Prandtl number Pr^C is of the order of 10^2. In spite of such a huge gap in the Prandtl numbers, an optimistic assumption of turbulent diffusivity due to turbulence in the core somehow allows us to adopt the same values of thermal and compositional Prandtl numbers. Then, temperature and composition can be treated simultaneously by using a new variable, codensity [1]. However, the codensity treatment is not fully verified because of our limited knowledge on turbulence in the core. Instead of introducing the codensity, we employ a double diffusive convection (DDC) model to investigate the effects of co-existence of two buoyancy sources with different diffusivity coefficients on the core convection and the geodynamo.

Using our numerical dynamo code [2-4], numerical simulations of DDC are performed at the Ekman number, $E = 3\times10^{-4}$, and 10^{-4}, whereas the two Prandtl numbers are fixed at $Pr^T = 0.1$, $Pr^C = 1$ and $Pm = 3$, where Pm is the magnetic Prandtl number. The Ekman number adopted here is not extremely low to allow us to perform a parameter survey. Varying the two Rayleigh numbers representing strength of thermal and compositional convection, we have obtained three types of dynamos: dipolar dynamo, non-dipolar dynamo and hemispherical dynamo [4]. In Fig. 1, the typical magnetic field morphology is exhibited. The non-dipolar and hemispherical dynamos tend to appear when thermal buoyancy prevails relative to compositional one. The opposite situation regarding the buoyancy force results in the dipolar dynamos.

Flow dynamics responsible for such distinct dynamos are then examined. Consequently, it is found that the dipolar dynamos and other non-dipolar and hemispherical dynamos are distinguished by strength of the zonal flows. The non-dipolar and hemispherical dynamos tend to have larger fractions of the zonal flow kinetic energy to the total kinetic energy than the dipolar ones. Figure 2a shows that the threshold value seems about 12%. Figure 2b represents the relative axial helicity, $|H^{rel}_z|$ defined by Soderlund et al. [5] with respect to the zonal flow. The relative axial helicity is defined by

$$\left|H_z^{rel}\right| = \frac{\left|\left\langle H_z\right\rangle_{\mathrm{h}}\right|}{\left(\left\langle u_z u_z\right\rangle_{\mathrm{h}} \left\langle \omega_z \omega_z\right\rangle_{\mathrm{h}}\right)^{1/2}} ,$$

where $H_z = u_z\, \omega_z$ is the axial helicity, the product of the axial velocity u_z and the axial vorticity ω_z, and $\langle\rangle_{\mathrm{h}}$ is the volumetric average taken in each hemisphere. It is evident that $|H^{rel}_z|$ is anti-correlated with the zonal flow, and the dipolar dynamos tend to have $|H^{rel}_z|$ larger than the non-dipolar dynamos as well as hemispherical dynamos. Such an anti-correlation suggests two possible mechanisms. One is that the columnar convection, which generates the axial helicity, is suppressed by the strong zonal flow, and the other is that the dipolar magnetic field forces the flow to enhance the helicity and to brake the zonal flow [6]. According to the results that fraction of the zonal flow kinetic energy is not so large that the columnar convection

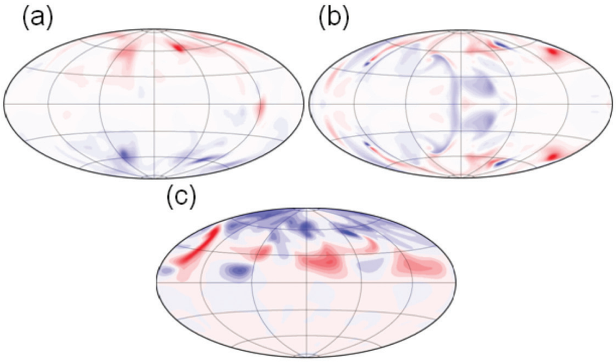

Fig. 1 Typical simulation results for (a) dipolar dynamo, (b) non-dipolar dynamo and (c) hemispherical dynamo. The radial magnetic field at the core surface is represented. Red regions denote the outward radial field and blue regions denote the inward field.

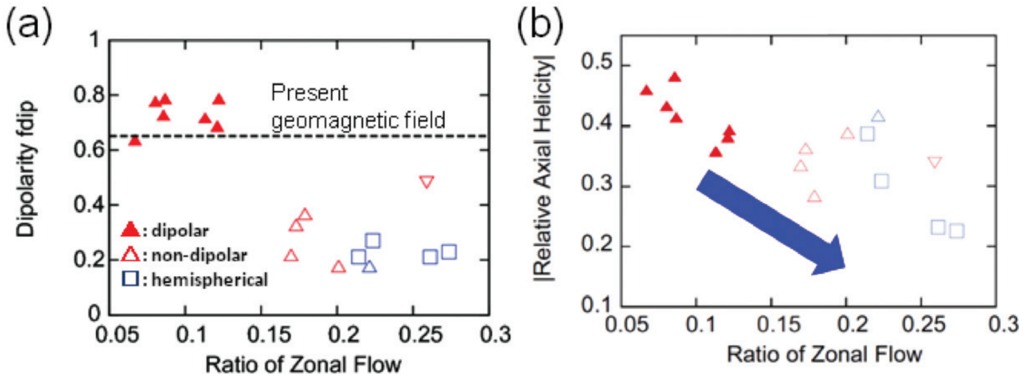

Fig. 2 (a) Dipolarity and (b) relative axial helicity as functions of the ratio of the zonal flow kinetic energy to the total kinetic energy. Results at Ekman number = 3 × 10^{-4} (10^{-4}) are drawn in red (blue). Axial dipolar (non-dipolar) dynamos are represented by filled (open) triangles. Equatorial dipolar dynamos are represented by down-pointing triangles. Hemispherical dynamos are denoted by squares. This figure was modified from [4].

is significantly affected, and that the enhanced anti-cyclones appear in dipolar dynamos, the latter case is more likely.

Then, we have also performed dynamo simulations with an imposed thin stably stratified layer beneath the outer boundary, which is implemented to mimic a stably stratified layer detected by seismic observations [7]. The Ekman number of 3×10^{-5} is adopted and layer thickness is 10% of the core radius (~350 km). It is apparent that magnetic field strength is much varied between the cases with and without the stable layer, although the dipolar morphology remains unchanged (Fig. 3a, c). Difference in spatial scale in the low-latitude region is also notable. The stable layer filters out the small-scale, short-period components through the skin effects. Comparing the results, the flow structure is substantially altered. The well-known thermal wind balance is found in the case without the stable layer (Fig. 3b), whereas the zonal flow structure in the corresponding case with the stable layer is almost invariant along the rotation axis (Fig. 3d). It is suggested that the flow is primarily controlled by the stable layer just below the outer boundary via the Taylor Proudman theorem.

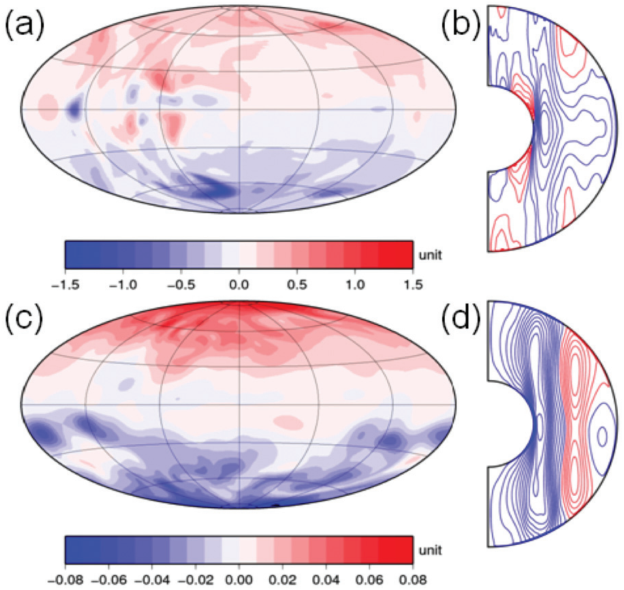

Fig. 3 (a, c) The radial component of the magnetic field at the outer boundary. (b, d) The zonal flow in the meridional plane. A case without stable layer is drawn in the top (a and b), while a case with stably stratified layer is displayed in the bottom (c and d). Positive (negative) values are represented by red (blue).

3. Ancient dynamos of Earth and Mars, without inner core growth

Paleomagnetic studies have been updating evidences for the geomagnetic field in ancient period, since approximately 3.5 Ga. Although the data seemingly show large variations, for instance, in virtual dipole moment and angular standard deviation, impacts of inner core growth on the field and paleomagnetic records has been extensively discussed. A recent convection-driven dynamo model, which was coupled with a thermal evolution model but included no lateral heterogeneity induced by mantle convection, proposed a rather minor impact of the inner core growth [8].

We found that, with lateral heterogeneity at the CMB, the impact could become sizable through the different sensitivity to the CMB between core convection with and without inner core growth [9]. When an inner core is growing, core convection and dynamos are driven by buoyancy sources associated with the inner core growth, such as latent heat and light element releasing from the inner core boundary (ICB), yielding the onset of the convection very close to the ICB. Without inner core growth, convection and dynamos should be driven predominantly by secular cooling and sinks from the CMB induce the convection, which occurs at a mid depth of a sphere/spherical shell. Secularly cooled dynamos thus respond more sensitively to CMB thermal conditions than dynamos driven by inner core growth-related sources (Fig. 4). The result implies that inner core age might be detectable through variability of the paleomagnetic data.

This also involves implications for the ancient dynamo of Mars. Mars has no active dynamo action at present but likely had one in the past, from the time of core formation to the late heavy bombardment, 4 Ga. Thermal evolution models suggest that the early Martian dynamo probably operated without an inner core being present and was exclusively driven by secular cooling. The situation can thus reinstate the early geodynamo before an inner core started to grow.

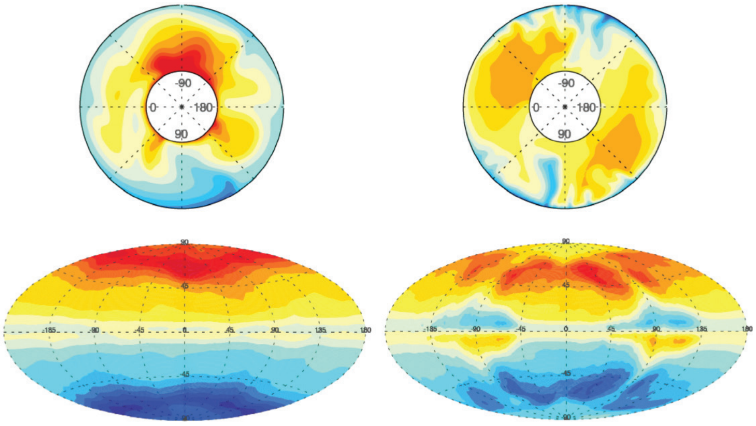

Fig. 4 Responses of convection and dynamos to a CMB thermal forcing with azimuthal wavenumber two (left) with and (right) without inner core growth. At $E=10^{-4}$, $Pm=3$ and $Pr=1$. (Top) temperature in the equatorial plane in snapshots and (bottom) time-averaged radial magnetic field at CMB. Red (blue) contours represent high (low) temperature and outward (inward) radial field. Larger impacts are found in the case without inner core growth (after [9]).

A challenging question is why and how the Martian dynamo ceased. Several scenarios have been proposed: for example, a result of natural cooling of the core, changes of the style of mantle convection, and subcritical dynamo action. While the subcriticality cannot explain the cessation of the Martian dynamo by itself, it can help to understand why the dynamo did not recover after some temporary effects stopped it operating. This possibility is expected through rotating magnetoconvection studies, but fully nonlinear dynamo simulations in spherical shells have reported rather narrow subcritical regimes [6,10], indicating that it may not play an important role for the cessation. By adopting a more appropriate model for the early dynamo driven by secular cooling, we found that the subcritical regime could become much wider than previously reported [11]. This supports that subcriticality may have played a role in the shutdown of the early Martian dynamo and that it would have been difficult to restart the dynamo once the magnetic field has decayed.

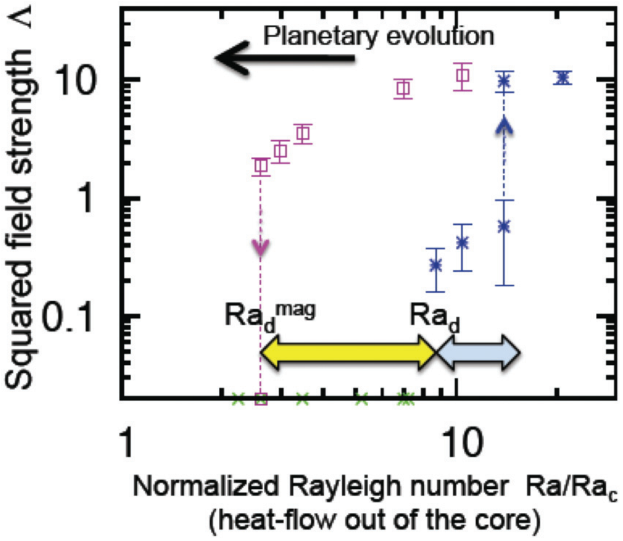

Fig. 5 Squared field strength Λ versus the Rayleigh number, *Ra/Ra*$_c$, normalized by the critical Rayleigh number *Ra*$_c$ for the onset of the nonmagnetic convection. At $E=10^{-4}$, $Pm=3$ and $Pr=1$. Stars and squares represent dynamo runs started from a seed field and from a strong dipolar field, respectively. Failed dynamo runs are also represented by the symbols located at the base of the diagram. Possible thresholds for seed field growth and for strong field maintenance are indicated by Ra_d and Ra_d^{mag}, respectively, and the region between the two values presents the window for subcritical dynamos (after [11]).

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現在および過去の地球ダイナモに関する数値シミュレーション

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マントルとコアでの対流は、地球に生起する諸々の自然現象の原因をつかさどる根本的な物理プロセスであり、また両者の対流は様々な関係で結合している。コアの対流により地磁気が生成・維持されることで、表層環境が穏やかに保たれてきた一方、このコアの冷却を支配するのは周囲のマントルである。マントルとコアの結合の理解に重要なマントル最下層の構造が、地震学により詳細に明らかになってきた。さらには外核に安定な成層の存在も示唆されている。そして地球史をさかのぼった地磁気の変遷についての情報も蓄積されてきた。我々はこれまで、マントルとコアという2つの対流系を、より観測事実に則した条件のもとで、また一方では地球進化を想定して、数値的にモデリングする研究をおこなってきた。ここでは特にコアの対流に焦点を絞って、コア対流の駆動源、外核での成層構造、内核成長の役割、等のダイナモ作用への影響を報告する。また、それに基づき現在と古代の地球ダイナモの差異や、火星でのダイナモ作用の消失過程について議論する。

現在の外核の対流は、内核成長に伴い放出される潜熱や軽元素の放出によって駆動されている。加えて外核とマントルの境界は、地球磁場の生成や永年変化のメカニズムに重要な役割を果たす。これらをふまえて我々は、昨年度に続き熱対流と組成対流を二重拡散対流として同時に取り扱い、エクマン数を 3×10^{-4}、1×10^{-4}、熱プラントル数0.1、組成プラントル数1.0、磁気プラントル数3.0として、ダイナモシミュレーションを実施した。その結果、双極子的、非双極子的、半球的の3つの磁場形態が見出された。これら磁場の形態と帯状流の強さ、ヘリシティの大きさの間には相関があり、組成対流の寄与が30-40%程度あれば地球型の双極子磁場が維持されることを示した。さらに、外核の最上部に熱的な安定成層を置き、二重拡散対流ダイナモにおける効果を、エクマン数を 3×10^{-5} まで下げて調査した。この安定成層の有無は、生成される磁場の強度とパターンに大きな影響を与えることが確認された。

一方で地球史をさかのぼると、古代地球コアにおけるダイナモ作用は現在のものとは異なっていたかもしれない。内核成長が開始する前の古代ダイナモでは、地球形成時から続く永年冷却が主な駆動源であっただろうと考えられる。永年冷却により駆動される対流とそのダイナモの数値シミュレーションを行った結果、内核成長に伴う場合に比べて、コア－マントル境界における熱的境界条件に対し敏感に応答することがわかった。本結果は、古地磁気学的データのばらつきにより内核成長の開始時期が制約できる可能性を示唆する。また、同モデルは古代火星ダイナモへ拡張することも可能である。火星では約40億年前までコアダイナモが駆動されていたと示唆されており、そこでは内核成長が開始していなかったと見積もられている。上述の古代ダイナモモデルにおいて詳細なパラメータサーベイを行った結果、解の亜臨界的分岐が顕著となることがわかった。これは、古代火星ダイナモが急速に消失していった理由を説明し得ることを示すものである。

キーワード: 地球ダイナモ, 地磁気, コア対流, 磁気流体力学