Numerical Simulations of Geodynamo and Liquid Metal Convection

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Geomagnetic field is generated and maintained by the convective motion of liquid iron in the outer core of the Earth. The geomagnetic field observed at the surface corresponds to the poloidal component, whereas the toroidal component is bound to the core. Constraining the strength and spatial distribution of toroidal component is important to understand the dynamics of the geodynamo and the electromagnetic core-mantle coupling. We tested a toroidal magnetic field imaging method using our dynamo simulation model, by introducing a thin electrically conductive layer at the bottom of the mantle. The imaged magnetic field successfully reproduced magnitude and pattern of the dynamo model field. On the other hand, we studied flow patterns in the presence of an imposed magnetic field as an important basic process for liquid metal convection. Viscosity of liquid metals is very low and their flow easily becomes turbulent, but when a magnetic field is applied on liquid metals, it makes anisotropic flow structure with suppression of turbulence depending on its direction and intensity. When the flow is moderately constrained by magnetic field, intermittent reversals of flow direction occur with random intervals. It is recognized by our numerical simulation that an emergence of large-scale global circulation in the horizontal plane induces flow reversal. It can provide important insight to the mechanism of geomagnetic field reversals.

Keywords: Geomagnetic field, Geodynamo, Core-mantle boundary, Stable stratification, Liquid metal convection

1. Introduction

The existence of geomagnetic field makes the Earth's surface environment suitable for life. The geomagnetic field is maintained by convective motions in the outer core. Core convection is thought to be driven by the buoyancy arising from thermal and chemical effects relating to the secular cooling of the Earth's interior. 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 most characteristic variation of the geomagnetic field is repetitions of magnetic polarity reversal with random interval. To better understand the geomagnetic field variation in many time scales, we performed numerical simulations of geodynamo with various effects and compared the results with the observed behavior of the geomagnetic field. Here we report two topics of dynamo simulations.

Besides full geodymamo simulations in a rotating spherical shell, we are conducting the study of convection under an imposed magnetic field in a simpler setting. The study on the nature of turbulence in liquid metals under a magnetic field is also important for the dynamics of Earth's core. In this type of simple setting, we can deal with the realistic values of Prandtl numbers those of liquid metal, which is difficult to deal in full dynamo simulations. Here we provide a detailed process of the reversal of flow field in turbulent Rayleigh–Bénard convection.

2. Toroidal field estimation using geodynamo simulations with the D" layer

The geomagnetic main field and its secular variation observed by satellites orbiting the Earth and at magnetic observatories correspond to those of the poloidal part, whereas the counterparts of the toroidal one, which are bound to the core due to large electrical resistivity of the mantle, cannot be measured above the core-mantle boundary (CMB). In spite of the fact mentioned above, the finite CMB toroidal field could exist, because the electrical conductivity of the lowermost mantle, that is, the D” layer, is much larger than that above [1]. Constraining the strength, the spatial distribution and secular variation of the toroidal constituents of the geomagnetic field is essentially important to understand the dynamics of the core and geodynamo.

A global distribution of the toroidal field at the CMB can be estimated by a method based on a core flow model inverted from the radial components of the geomagnetic field and its secular variation via frozen-flux hypothesis [2]. However, a fact must be kept in mind that the inverted core flows are in principle non-unique [3], and there is no way to know how well the toroidal field is retrieved properly from such a flow model. Here, we test the method to infer the toroidal magnetic field at the CMB using a numerical dynamo model. We could have benefit from utilizing numerical dynamo modeling, because numerical dynamos provide us with complete knowledge on the poloidal field, core flow and also the toroidal field.

A thin electrically conducting solid layer above the CMB are included in a numerical dynamo model to mimic the D” layer. The thickness and electrical conductivity of the layer can be specified arbitrarily. The thickness of the layer adopted here is fixed at 5% of the core radius, which corresponds to about 180 km for the Earth being comparable with D” layer thickness. It is assumed that the electrical conductivity is uniform within the layer, and that the conductivity of the layer is 1/2500 of the core conductivity, which is comparable with the electrical conductivity of the post-perovskite phase [1].

The azimuthal component of the toroidal field is imaged at the CMB using the radial magnetic field and horizontal velocity field obtained from a dynamo model. The dynamo model toroidal field and the corresponding imaged toroidal field are compared in Fig. 1. As a whole, the toroidal field is appreciably well reproduced with respect to the amplitude and spatial pattern in both the fully resolved and truncated cases. However, an obvious discrepancy is found around the equator, where the amplitude of the field tends to be underestimated, and the direction is even reversed in several places. We consider that degradation in imaging quality at low latitude is ascribed to the fact that we have neglected effects of diffusion in retrieving the toroidal field [4].

3. Geodynamo simulations with a stably stratified layer

While seismic observations detect a stably stratified layer beneath the CMB [5], the origin of the stable layer is still uncertain. In order to constrain the origin of the stable layer below the CMB from a viewpoint of magnetic field, we have carried out numerical dynamo simulations driven by double diffusive convection. The Ekman number ranges from 3×10^{-5} to 3×10^{-4}, whereas the three Prandtl numbers are fixed at 0.1 for the ordinary thermal Prandtl number, 1 for the compositional one, and 3 for the magnetic one, respectively. Moreover, a thin stably stratified layer beneath the outer boundary is implemented to mimic a stably stratified layer. The layer is either thermally or compositionally stably stratified. The layer thickness is 10% of the core radius (~350 km).

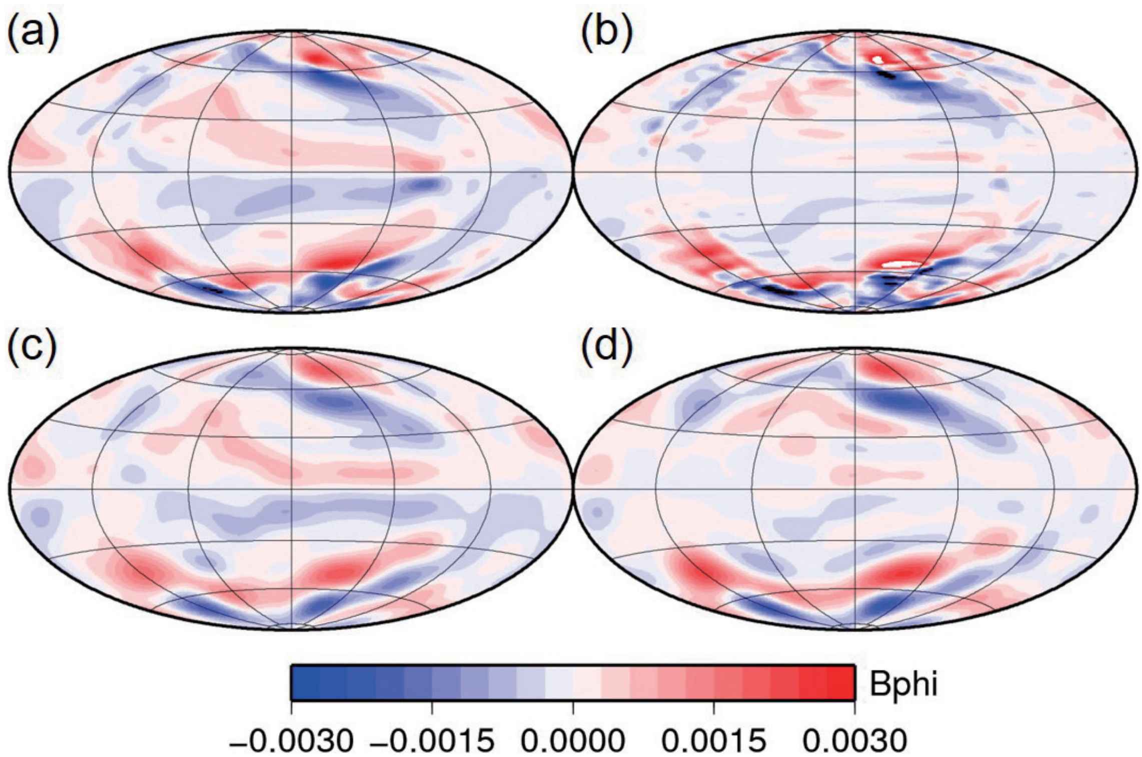

Fig. 1 The azimuthal component of the CMB toroidal magnetic field. (a, c) Dynamo model magnetic field and (b, d) the imaged magnetic field. (a) and (b) are in full resolution, while (c) and (d) are in truncated resolution with spherical harmonic degree 12.

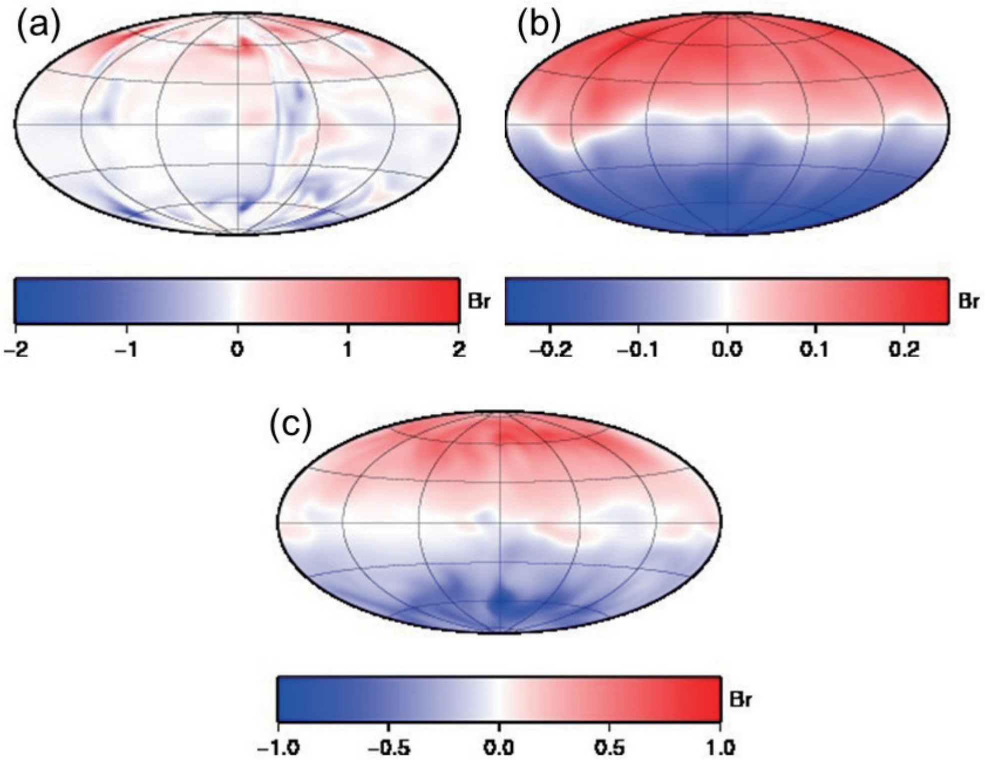

Fig. 2 The radial component of the magnetic field at the CMB for a dynamo model (a) without a stably stratified layer, (b) with a compositionally stably stratified layer, and (c) with a thermally stably stratified layer.

It is found that magnetic field strength substantially varies between the cases with and without the stable layer irrespective of the origin of stratification. In general, the stable layer filters out the small-scale, short-period components through the skin effects. Consequently, the resultant magnetic field at the CMB is much weaker than the case without the stable layer (Fig. 2a, b), which may not support the presence of the stably stratified layer beneath the Earth's CMB. However, in case that compositional buoyancy dominates thermal one like the Earth's core, and the layer is thermally stably stratified, we have found that the dynamo-generated magnetic field is, on average, stronger than the case without the stable layer. In that case, strength of the magnetic field at the CMB is comparable without the stable layer in spite of the skin effect (Fig. 2c). Based on these results, it is suggested to be compatible with the geomagnetic field that the stably stratified layer below the CMB detected from seismic wave observations are thermal origin due to high core heat flux across the CMB [6].

4. Reversal process of flow field in liquid-metal convection in the presence of a magnetic field

Coherent flow structures in the outer core are controlled by the magnetic field and rotation of the Earth. It is important to know the basic behavior of flow in relation to the magnetic field, for understanding the flow patterns observed in the real Earth and core dynamo simulations. On the other hand, the occurrence of flow reversals in Rayleigh–Bénard convection is exhibited by many laboratory experiments and numerical simulations, in which reversals are related to large-scale circulations in turbulent convections (recent review in [7]). The mechanism of reversal may provide important insights to the geomagnetic field reversals.

We performed numerical simulations of Rayleigh–Bénard convection of an electrically conductive low-Prandtl-number fluid under a uniform horizontal magnetic field. We reproduced flow reversals in a square vessel with an imposed horizontal magnetic field, that is consistent with observed behaviors in laboratory experiments previously reported in [8]. Here we present a three-dimensional process of a flow reversal in Fig. 3. The Q_{3D} criterion [9] is used to illuminate the roll structures and their transition. At the time t=40.1 in the figure, the pattern shows 5-roll structure with its axis parallel to the magnetic field; the direction of circulation is clockwise for the rolls located close to the right and left sidewalls and at the center. These roll structures bend horizontally at t=40.8, with the rolls at frontal half are moving toward right, and the roll at the right sidewall is shrinking. Bended 4-roll structure is observed at t=41.3, and the flow velocity is much smaller than that of 5-roll structure. Then, reconnection of the rolls between front and back occurs, and aligned 4-roll structure emerges for a short period. A new roll is growing along the left sidewall at t=42.0, and 5-roll structure is reproducing. In this process, the key mechanism is the emergence of a global circulation in the horizontal plane. The horizontal circulation is related to the skewed-varicose instability of two-dimensional roll structure aligned in the direction of the magnetic field. An increase of global circulation induces bend and reconnection of convection rolls. It establishes a reversed flow state through roll number transitions. This is a newly identified mechanism of flow reversal that works in large-scale three-dimensional geometry.

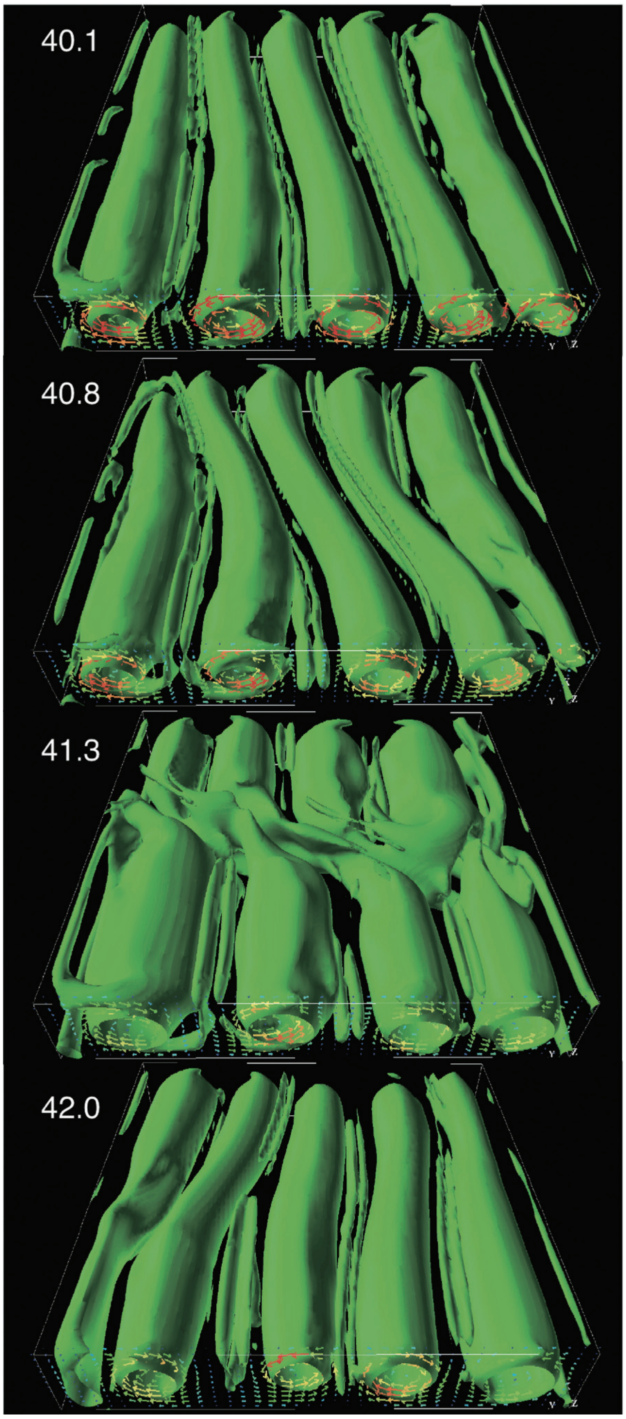

Fig. 3 A process of flow reversal reproduced by a numerical simulation. The isosurface of Q_{3D}=0 is shown, with the flow near the x=0 wall is displayed by arrows. Homogeneous magnetic field is imposed in the x-direction.

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地球ダイナモと液体金属の対流に関する数値シミュレーション

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地球に磁場が存在することは地表環境を生命に適したものに保つ上での重要な要素である。地磁気の変動の様子は地表で常に観測されているとともに、古地磁気学の研究から過去の磁場変動についても復元が進んでいる。外核での溶融鉄の対流運動により地球磁場は生成維持されると考えられている。このような地球ダイナモ作用について我々は数値的にモデリングする研究をおこなっており、様々な時間スケールでの磁場変動のメカニズムの解明を目指してきた。

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。この境界の上に D” 層を模した固体電気伝導層を与えたダイナモシミュレーションを実施して、地磁気観測に基づく外核－マントル境界でのトロイダル磁場の推定可能性を検討した。得られた観測磁場モデルと外核の対流モデルを用いて、磁場凍結近似に基づく理論的手法によって外核－マントル境界でのグローバルなトロイダル磁場分布を推定した。推定結果とシミュレーションによるトロイダル磁場を比較したところ、低緯度の磁気拡散効果が比較的大きな領域を除いて、概ねトロイダル磁場の振幅及びパターンを再現できることが明らかになった。

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。そこでこの対流を二重拡散対流として取り扱い、さらに、外核最上部に熱的あるいは組成的安定成層を置いた際のダイナモの振舞を、エクマン数を 3×10^{-5} まで下げて調査した。その結果、組成対流が卓越する場合、地球コア最上部の安定成層の起源は熱的なものである可能性が示唆された。

これらのダイナモシミュレーションに加えて、我々は、ダイナモ計算の際には扱うことの困難な、現実の小さいプラントル数を用いた乱流の研究も進めてきた。磁場や回転の効果で乱流中に方向性の強い構造が実現する過程を、液体金属の物性を用いた対流シミュレーションで再現し、広いパラメータ範囲にわたって室内実験と良く一致する結果を得ている。ある条件下では流れ場の自発的な反転が起こる。そのプロセスにおいて水平面内で大規模な循環が間欠的に生じることを示した。これは地磁気反転のメカニズムを考察する際にも重要である。

キーワード: 地磁気, 地球ダイナモ, コア - マントル境界, 密度成層, 液体金属対流