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博士論文の要旨

The magnetic fields of planetary and astrophysical bodies, such as the Sun and the Earth, are believed to be generated by a dynamo action in a moving electrically conducting fluid. The mathematical problem describing the generation of magnetic fields by self-inductive action in an electrically conducting fluid is called the dynamo problem. The dynamo process converts the mechanical energy of electrically conducting fluid into the magnetic energy and dissipates it in the form of ohmic heat.

On the surface of the Earth and above, the dipole component of the Earth's magnetic field is dominant, and its dipole axis is ever changing. The Earth's magnetic field has existed on average at roughly its present strength in its history and is constantly changing. Its polarity has reversed many hundreds of times at irregular intervals during the Earth's history.

Recent accelerated development in supercomputer technology makes it possible to achieve three-dimensional MHD dynamo simulations which self-consistently solve for fluid flow and magnetic field in three dimensions. Significant progress in recent years is the development of numerical simulation of convection-driven dynamo in rotating spherical shells that achieve self-sustaining dynamo actions. Some models have realized dominant dipole fields outside the shells. Several numerical models of convective dynamos even successfully have thus far reproduced some of the basic properties of the Earth's magnetic field.

Reversal of the magnetic field is one interesting and challenging problem in MHD theory. Some authors have already succeeded in demonstration of magnetic field reversal by three dimensional dynamo simulations. In particular, Glatzmaier and Roberts presented the first numerical simulation of a complete field reversal. The first numerical simulation of dynamical flip-flop type transition of the magnetic energy level and its association with the reversals of the dipole and octupole field polarity
were obtained by Kageyama and Sato. Later, Glatzmaier et al. showed that more frequent reversals occur in their simulation by changing the core-mantle boundary condition. Coe et al. described the evolution of the morphology and/or spectral energy of simulated magnetic fields during reversals. However, physical understanding of the mechanism of magnetic polarity reversals is yet veiled.

The mechanism of the magnetic field reversal still remains one of the challenging phenomena in MHD dynamo theory. To understand the mechanism by which the polarity of the magnetic field is reversed in MHD dynamo, a very long time numerical simulation is carried out by using Kageyama-Sato MHD dynamo model in this thesis. The simulation results show that the generated magnetic field is dipole dominated in most simulation time and reverses its polarity. The reversals of magnetic field occur repeatedly and irregularly. The magnetic field reversal appears to occur without any regular rule. It does reverse suddenly and the reversal does continue endlessly. As a whole, it is unlikely that the existence of one polarity predominates over the other.

The thermal convection in the rapidly rotating spherical shell is caused by gravity and the temperature difference between inner and outer cores, which takes the form of columnar cells which are parallel to the rotation axis. The magnetic field is generated and amplified through the fluid convection motion which stretches and twists the magnetic field lines. The magnetic field structure inside the spherical shell is very complicated. Generally, the magnetic field lines spiral around the convection columns. Interestingly, in the whole evolution, the total magnetic and kinetic energies exhibit a flip-flop alternation between a high energy state and a low energy state. The different energy states correspond to different magnetic field configurations and convection patterns. In low energy states, the convection columns drift westwards and keep almost unchanged structures. The convection motion in high energy states exhibits the basic columnar structure, but nevertheless it is time-dependent.

The magnetic field reversal is studied in details. From the analysis of the time evolution of magnetic field, we obtain the necessary conditions for the occurrence of a dipole reversal: (1) the system is in a high energy state, (2) the high energy state lasts for a certain period, (3) the quadrupole mode is on the average in a growing phase, and (4) the magnitude of the quadrupole mode exceeds that of the dipole mode on the outer boundary.

The magnetic field is generated by the convection motion of the electrically conducting fluid in the sphere shell. So the magnetic field pattern is strongly correlated with the fluid flow. In low energy states, the axial component of fluid velocity in the equatorial plane (i.e., trans-equatorial flow) is very weak. The convection motion is symmetric around the equatorial plane. While in high energy states, the trans-equatorial component of fluid velocity in the equatorial plane is very strong. The north-south symmetry around the equatorial plane is broken. The existence of the trans-equatorial flows in high energy states suggest that there is a strong interaction of fluid motion between the northern hemisphere and the southern hemispheres. This strong interaction of fluid flow is likely to initiate a reversal of magnetic field.

The most important and crucial discovery of this thesis is the generation of trans-equatorial flows in a spherical system that make the convection pattern vulnerable and the whole system marginally stable, the reversal of the dipole magnetic field thereby being triggered occasionally and unexpectedly.

The effects of electrical resistivity and the temperature difference between the inner and outer boundaries to the magnetic field reversals are also analyzed. We find that the electrical resistivity is one of important physical parameters to the generation and reversal of the magnetic field.

To sum up, in our numerical simulations of MHD dynamo, we have observed repeated and sudden magnetic field reversals, and obtained the conditions for magnetic field reversal. Furthermore, we have studied the physical mechanism of the magnetic field reversals and come to the conclusion that the break of the north-south symmetry around the equatorial plane of convection motion must be the primary cause of the magnetic field reversal.

論文の審査結果の要旨

地球など種々の天体に観られる双極子磁場構造の生成・維持がどのようなメカニズムで説明されるかは長年の謎であった。近年、回転球殻における磁気ダイナモ作用に関する大規模な計算機シミュレーションの実行によって、磁気流体の流れと磁場が絡み合った無撞着な動的過程の結果として整った双極子磁場構造が確かに形成されることや、その機構の理解が飛躍的に深まってきた。本論文はこのような磁気ダイナモ計算機シミュレーション研究をさらに発展させたものである。特に、地球磁場でよく知られている観測事実である双極子磁場極性の間欠的反転という顕著な現象に着目し、現象の計算機上での再現とその特性解明の課題に取り組んだものである。

本論文においては、回転球殻ダイナモ作用に関する計算機シミュレーションにおいて先進的な成果を挙げてきた、いわゆる Kageyama-Sato モデルに基づくシミュレーション研究を発展させている。これまでの研究によって、回転する球殻において境界条件として与えられる内側、外側の球殻の温度差によって熱対流が誘起されること、サイクロン・アンチサイクロンと呼ばれる互いに逆向きの回転をする渦柱のペアが経度方向に数組並んだような整った熱対流構造が形成されること、このような流れ構造の中に種となる微小磁場を加えることによって磁場の増幅作用が発現し、やがて双極子磁場構造が形成され、その全磁場エネルギー量は対流の全運動エネルギー量をはるかに凌駕するまでに成長して定常的な状態に到達することが見出されてきた。このような過程を支配する物理パラメータは、粘性、電気抵抗、熱伝導率、球殻の回転速度、内外球殻の温度差など多岐にわたり、広大なパラメータ空間を構成している。本研究のシミュレーション計算は最大級のスーパーコンピュータを用いても数百時間のターンアラウンド時間を要する大規模なものであり、一見定常に落ち着いたかに見える双極子磁場構造がいつ突発的な反転の性質を現すか予測することは困難な課題であった。申請者は極めて長時間のシミュレーション計算を実現することに成功し、先進的可視化表現法を駆使して計算結果の注意深い解析を繰り返すことによって、磁場極性の急激な反転が繰り返し不定期間隔で発生する過程の発見に到達した。そして、そのような現象が顕著に表れる領域をパラメータ空間の中で絞り込んだ。

その結果、回転球殻ダイナモ作用における磁場極性の反転に係わる磁気流体の性質として、次のようないくつかの重要な特性を発見した。①定常状態においては、双極子磁場成分が他の多重極成分と比べて卓越した磁場成分である。双極子成分は極性の向きに関して２つの安定状態を持つ。②運動・磁場の全エネルギーは高低２つの準安定エネルギー状態を間欠的に遷移する。低エネルギー状態においては熱対流渦柱のモード数は安定であるが、高エネルギー状態ではモード数が時折変化する。③双極子磁場極性反転は高エネルギー状態がしばらく継続する時にのみ発生する。④極性反転直前に四重極磁場成分が一時的に双極子磁場成分よりも卓越し、双極子という奇関数磁場構造が四重極という偶関数構造を経由して反対極性の双極子構造に到達するという性質を呈する。⑤反転に際して対流パターンの赤道面に関する対称性に破れが生じ、整った渦柱構造の破壊から反転構造への遷移へと発展するきっかけとなる。⑥物理パラメータの中で電気抵抗値がその特性に深く係わっている。これらの特性は本研究において初めて見出されたものであり、回転球殻ダイナモ作用に関するシミュレーション研究にさらに豊かな物理的内容を付加し、動的過程の理解

に重要な貢献をするものである。

　以上の内容は学位論文にふさわしい学術的価値を有すると判断する。