Superconductor Origin of Earth's Magnetic Field

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Abstraction

Earth's magnetic field shields life on Earth from the harmful solar wind. However, its origin is not well understood. The dynamo theory is usually employed to explain the origin. However, it cannot account for the magnetic fields on other planets, especially those with cooled cores. In light of new understandings of superconductivity, a new hypothesis is proposed in this study to provide a general mechanism for the origin of planetary magnetic fields. The "unified theory of low and high-temperature superconductivity" suggests that superconductors are the ordinary state of matter and are common at high pressures. As pressure increases deep into Earth, superconducting substances likely exist under the mantle. Driven by the rotation of Earth, the floating superconductors on the outer core accumulate towards the equator and eventually assemble into a belt looping around the core under the equator, producing a resistance-free path for currents. Earth's magnetic field was created by a Mesnner-like effect in the Sun's magnetic field. The field compensates the Sun's field inside and superimposes it outside of Earth. Without electrical resistance in the superconductor belt, currents loop indefinitely under the equator, maintaining the geomagnetic field. Convections in the outer core disturb the loop and occasionally break its continuity, causing polar wandering and paleomagnetism discontinuity. As the loop resamples each time, the polarity of the new field may be created in a different direction depending on whether the north or south pole is tilted towards the Sun at different seasons, resulting in a magnetic reversal. Superconductors may also be responsible for the magnetic origin of other planets. As planets cooled down, the superconductors froze inside the planets. Some might survive various celestial events throughout the planet's history, even with significant orbital changes, which explains the large angle and offset between the magnetic dipole and rotation axis of both Uranus and Neptune.

Introduction

Earth's magnetic field extends from Earth's interior out several tens of thousands of kilometers into space above the ionosphere, known as the magnetosphere. The magnitude of Earth's magnetic field at the surface ranges from 0.25 to 0.65 G.[1] The intensity of the magnetic field changes over time. Over the last two centuries, the strength has decreased at a rate of 6.3% per century.

Without the magnetic field, the charged particles from solar wind and cosmic rays would reach the surface and kill the lift on Earth. Charged particles moving in the magnetic field are deflected by the Lorentz force, spiral along magnetic lines, and converge at the north or south pole. Radiation is released as positive and negative charges merge. Photons are also emitted when high-energy particles collide with air molecules. Polar lights are caused by the particles before reaching the surface of the Earth. This is why auroras are often seen in the sky at high latitudes.

The Earth's magnetic field may be represented by a magnetic dipole through the center of Earth currently tilted at an angle of about 11° with respect to the axis of Earth's rotation. While the north and south magnetic poles are usually located near the geographic poles, they move slowly and continuously over geological time scales, namely polar wandering.

Occasionally, Earth's magnetic poles may trade places, known as magnetic reversals. The magnetic field has alternated between periods of normal polarity, in which the predominant direction of the field is the same as the present, and reverse polarity, in which it is the opposite. Earth's magnetic reversal history has been well preserved on the seafloor as the ocean floor spreads from the mid-ocean ridge, Figure 1.[2] The direction of the magnetic field was frozen in the new ocean floor that had just formed in the mid-ocean ridge. Like a tape recorder, the ocean floors recorded the change history of the Earth's magnetic field. By studying paleomagnetism, scientists were able to reconstruct magnetic reversal history.[3] Reversal occurrences are statistically random, lasting as little as 200 years. The latest brief reversal happened 41,000 years ago and lasted only about 440 years. There have been 183 reversals over the last 83 million years.[4-6]

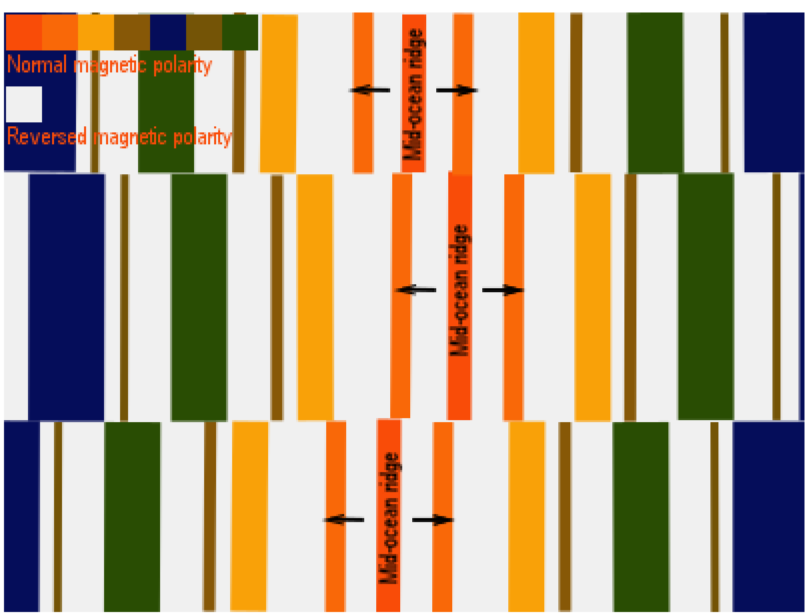

Figure 1: Paleo-magnetic reversal stripes recorded on the seafloor.

These are some of the observations about the magnetic field of Earth. Dipole-like magnetic fields are also detected on many other planets and even on some of their satellites. However, the origin of the magnetic fields is not well understood.

Geodynamo

The dynamo theory is borrowed to explain Earth's magnetic (or geomagnetic) field.[7-8] The theory was initially proposed by Joseph Larmor in 1919.[7] It has been modified and adapted lately according to magnetohydrodynamics equations. Magnetohydrodynamics was initiated by Hannes Alfvén[9] to explain the magnetic fields created by plasma, such as in the Sun, which is much more dynamic in terms of velocity and viscosity compared to the convection in the outer core of Earth.

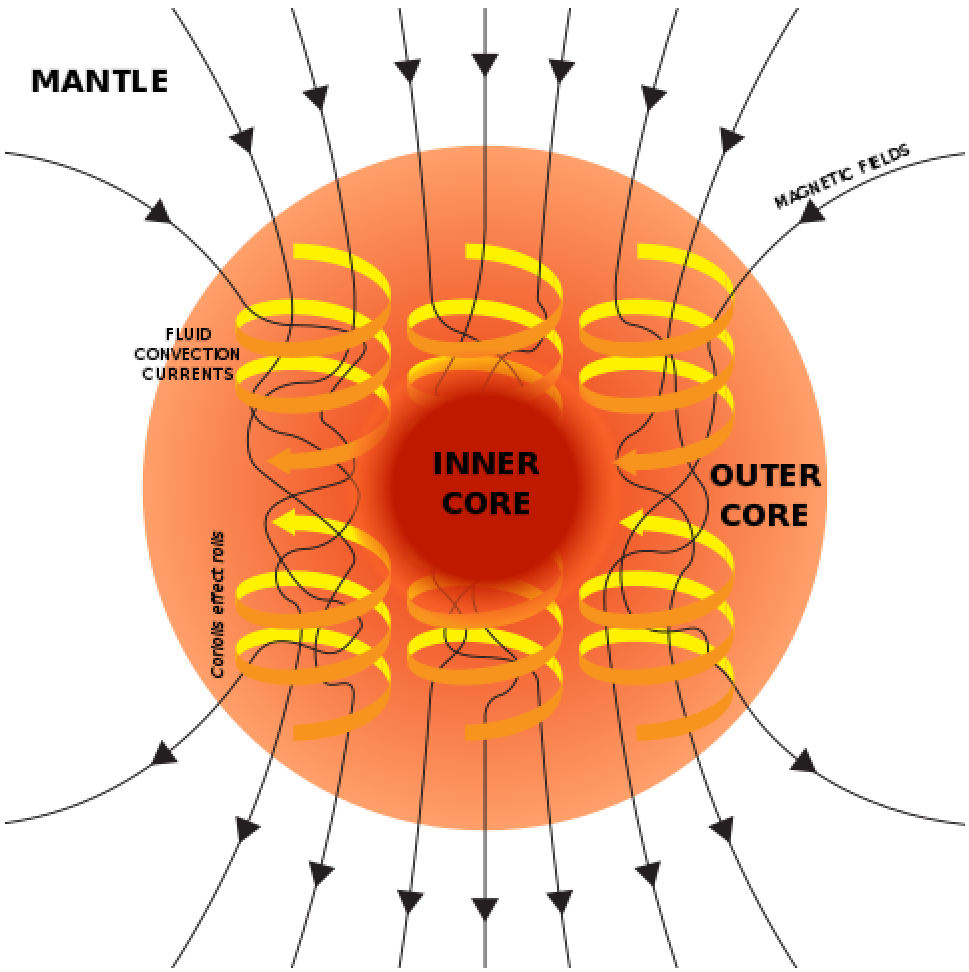

Figure 2: Dynamo theory for Earth's magnetic field.[10]

The dynamo theory suggests that the geomagnetic field is induced and constantly maintained in the liquid iron outer core by the convections of the heat exchange feedback loops. The Coriolis effect due to the rotation of the Earth deforms the feedback loops into spiral coils aligned along the rotation axis, Figure 2.[10] The magnetic field is mainly generated by the electric currents in the outer core with molten iron. As conducting fluid flows across an existing magnetic field, electric currents are induced according to magnetohydrodynamics equations, creating another magnetic field.[9,11] When this magnetic field reinforces the original field, a dynamo is created and self-sustains.

However, the dynamo theory faces many challenges in explaining the origin of the geomagnetic field, let alone the magnetic fields on other planets. Firstly, the dynamo does not provide a mechanism for geomagnetic reversals observed throughout Earth’s history. Secondly, the theory fails to explain the tilt of the magnetic dipole from the Earth's rotation axis. The dynamo is developed in the internal convection driven by the Coriolis effect due to the rotation of the Earth. As a result, the magnetic dipole should closely align with the rotation axis. Thirdly, the dynamo cannot account for the magnetic fields of internally frozen planets, such as Mercury. Mercury's size is about 14% of Earth's.[12] Because of its small size, it is thought that Mercury’s core has cooled over the years. However, its magnetic field is still active. Finally, Mercury has a slow, 59-day-long rotation. Its Coriolis effect is negligible. It is too stretching to apply the dynamo theory without a significant Coriolis effect.

Data from NASA shows that the effective magnetic dipoles of Uranus and Neptune are tilted 59° and 47° from their respective rotational axes.[13] The dynamo theory cannot justify the large angles between the magnetic dipoles and the planet's rotation axes. In light of new understandings of superconductivity, an alternative hypothesis is proposed in this study to provide a general mechanism for the origin of planetary magnetic fields, including the geomagnetic field.

Superconductor Origin

Superconductors are proposed in this study to be responsible for the origin of planetary magnetic fields. The “Unified Theory of Low and High-Temperature Superconductivity”[14] not only offers a comprehensive explanation of all superconductivity properties and phenomena but also unifies the electrical resistance mechanism for both superconductors and conductors. The theory suggests that superconductors are common. The superconducting state of any matter can be obtained at high pressures. As shown in the state diagram, Figure 3, superconducting is just an ordinary state of matter and mostly exists at low temperatures or high pressures. Most of the superconductors observed in the early days were at low temperatures. More and more high-temperature superconductors have been discovered recently under high pressures.[15-16]

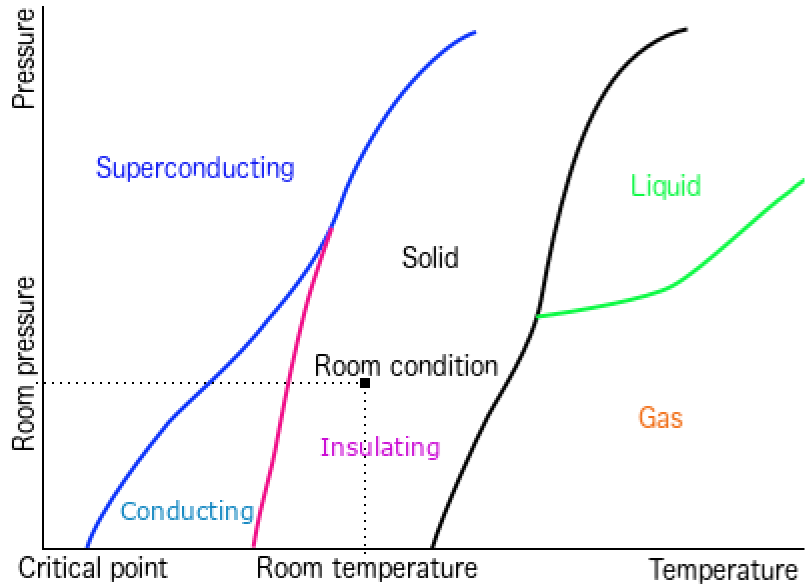

Figure 3, State diagram with superconductivity.[14]

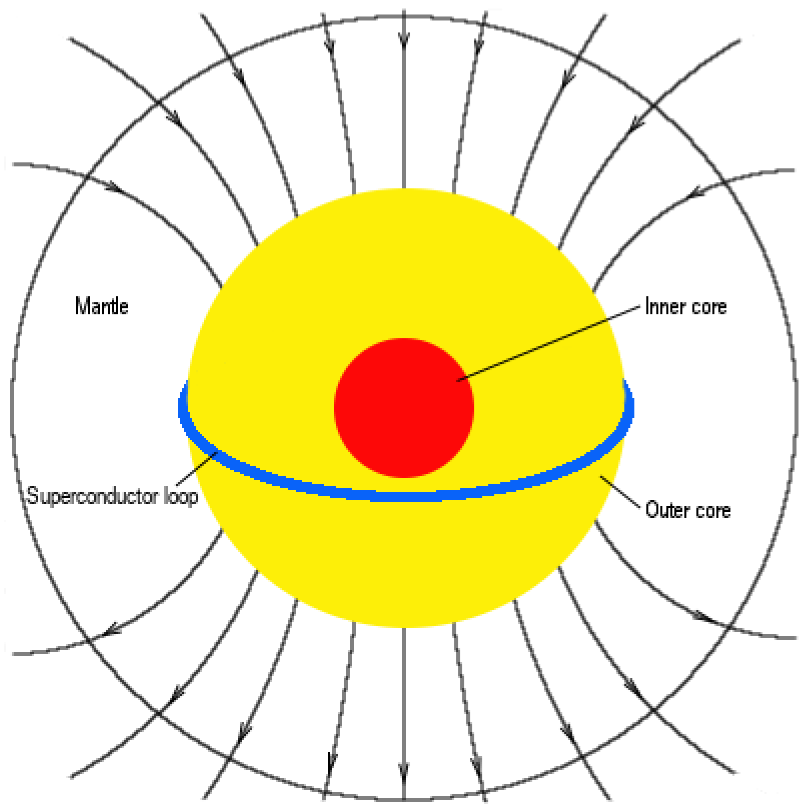

Figure 4, Superconductor origin of Earth's magnetic field.

The pressures between the lower mantle and outer core range from 136 to 360 gigapascals.[17-19] With such high pressures, superconductors likely exist under the mantle according to the unified theory. Superconducting materials may float on the outer core surface.

The rotation of the Earth causes the superconductors to accumulate towards the equator under the mantle. Enough superconductors will eventually assemble into a loop in the vicinity around the equator, named the **superconductor loop**, Figure 4. Without electrical resistance in the conductors, currents may flow along the loop indefinitely. The geomagnetic field is maintained by the loop currents.

Creation of Magnetic Field

We believe that the planetary magnetic fields are created by a Meissner-like effect of superconductors in the Sun's magnetic field. The Meissner effect is a phenomenon where an external magnetic field is expelled from superconductors after the transition to superconductivity.[20] Note, that a magnetic field created by induction requires a change in magnetic flux according to Faraday's law of induction.[21] The Meissner effect occurs during the transition to the superconducting state in an existing magnetic field when there is no change in magnetic flux.

The mechanism of the Meissner effect has been explained in the unified theory of superconductivity.[14] According to the theory, electrodrifts in superconductors create random currents naturally. Normally, these currents would not produce observable magnetic fields because the random fields cancel each other locally. In an external magnetic field, the flow of currents is deflected by the Lorentz force.[22-24] Looking in the direction of the magnetic field, a moving electron is deflected to circulate clockwise. Deflected by the Lorentz force, the currents in a superconductor reorient in circular motions creating a magnetic field that compensates the original magnetic field inside of the superconductor and superimposes the field outside of the superconductor. The net result appears as if the original field is expelled from the superconductor. In other words, the Meissner effect is not because of induction. Rather, it is a result of natural currents in superconductors deflected by the Lorentz force.

Before the superconductors on the outer core assemble into a loop in the vicinity of the equator, the Sun's field is expulsed out of the superconductors in the normal Meissner effect. When the superconductors connect into a loop, a strong magnetic field is enclosed in the loop resulting from the Sun's field superimposed by the field due to the Meissner effect. Effectively, there is a magnet bar in the superconductor loop. Driven by the Lorentz force, currents circulate along the loop path in the direction to compensate for the enclosed field. The currents are created in a Meissner-like effect but not induction because there is no flux change in the loop. Without electrical resistance in the superconductors, the currents circulate in the loop indefinitely maintaining the geomagnetic field as illustrated in Figures 4 and 5.

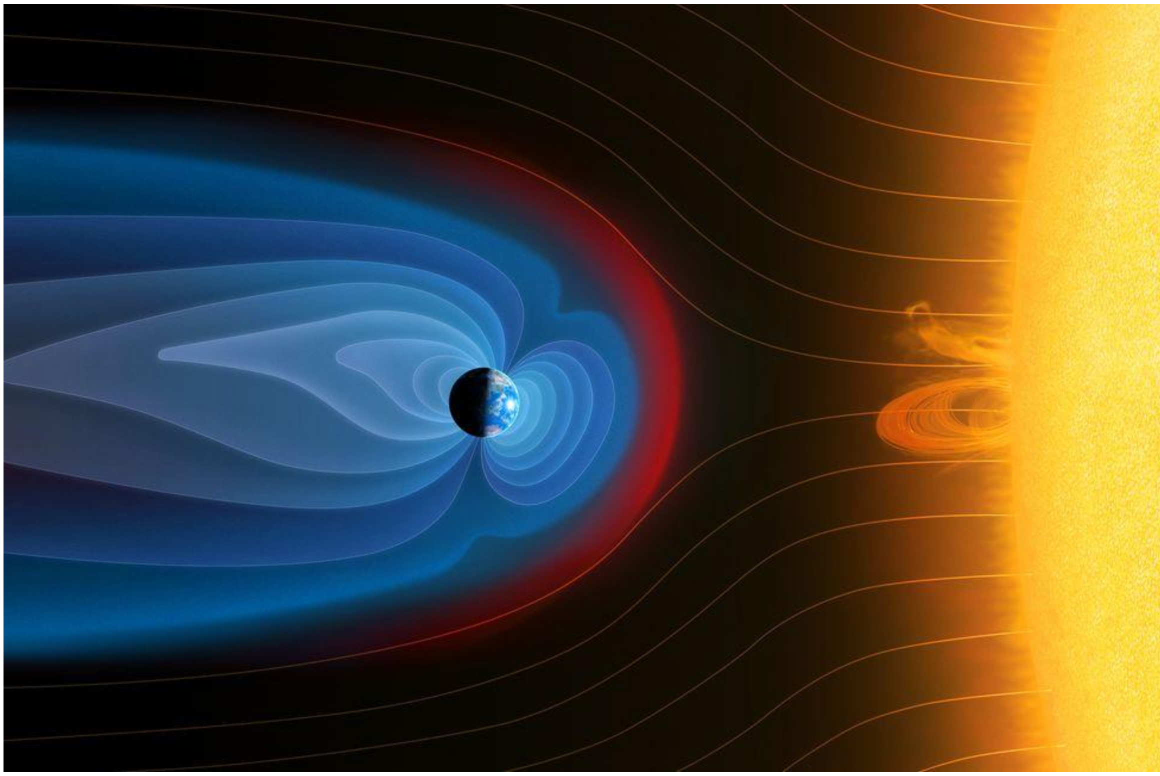

Figure 5, Geomagnetic field resulted in a Meissner-like effect. This image is from Popular Mechanics.

The superconductor loop is not a perfect ring and does not align exactly with the equator either but in the vicinity of the equator. The effective magnetic dipole resulting from the loop is expected to be close to the rotation axis of the Earth. Convections in the outer core disturb the loop and constantly change the direction of the effective dipole, causing polar wandering and the deviation of the dipole from Earth's rotation axis.

Occasionally the connectivity of the loop is broken by strong convections in the outer core. The loop currents are cut off temporarily. The currents in the loop have to shortcut through the non-superconducting materials and are reduced quickly by the resistance between the broken ends. If the loop cannot reconnect quickly, the loop currents will eventually disappear completely, and so will the geomagnetic field, resulting in a magnetic inactive/quiet period or paleomagnetic discontinuity.

The rotation of the Earth would eventually reassemble and reconnect the superconductor loop and the geomagnetic field will reestablish too. However, the polarity of the new field may be created in a different direction. The rotation axis of the Earth tilts with respect to the orbital plane. The North Pole may tilt towards or away from the Sun at different seasons. The direction of the Sun's field varies at different seasons with respect to the superconductor loop. As a result, the new geomagnetic field may be created in a different polarity from the previous one, resulting in a magnetic reversal.

Planetary Magnetic Fields

Dipole-like magnetic fields are detected not only on Earth but also on many other planets and even on some of their satellites. The dynamo model fails to explain the magnetic fields observed on Uranous and Neptune. The effective dipole centers of Uranus and Neptune are offset by 33% and 55% of their respective radii, Figure 6.[13,25] The magnetic dipole of Uranus is shifted from the center towards the south rotational pole by as much as one-third of the planetary radius, while this shifting is even more in Neptune. The effective magnetic dipole of Uranus and Neptune are tilted 59° and 47° from their respective rotational axes.[13]

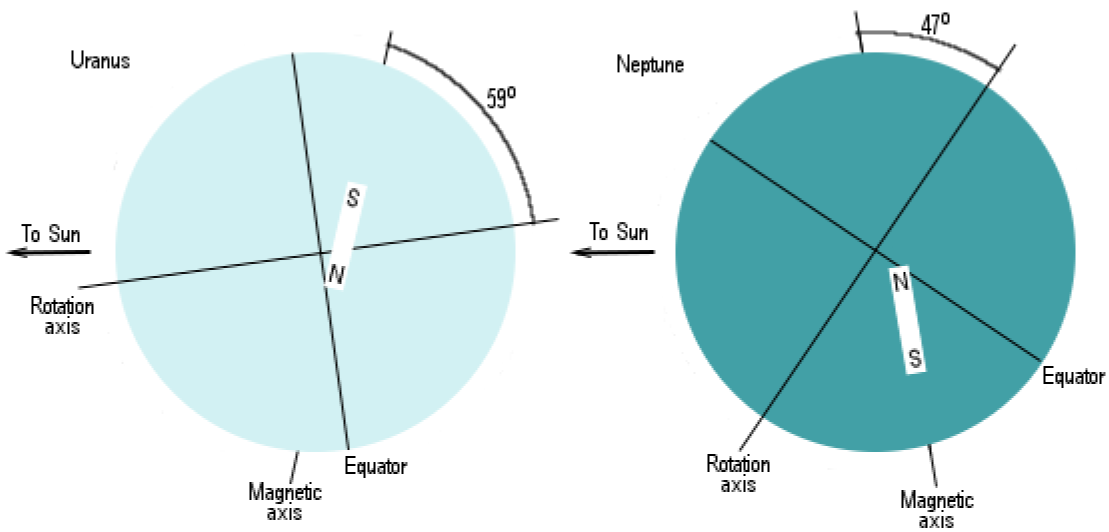

Figure 6: Magnetic fields of Uranus and Neptune measured by Voyager 2.[13]

Both Uranus and Neptune have concentric interior structures.[26-29] If their magnetic fields are created by the convection coils, the magnetic dipoles should be aligned closely with the rotational axes. The large offset and tilted magnetic dipoles make it hard for physicists to fit a working model for these planets in the dynamo theory. On the other hand, this can be easily explained in the proposed theory. Their magnetic fields might have formed early with magnetic dipoles and rotation axes aligned like that on Earth. As planets cooled down, their superconductors were frozen inside of the planets. Without protection from large planets like Jupiter and Saturn, these outer planets are more prone to impacts from asteroids or comets. The rotations, orbits, and bodies of the planets were eventually altered by the impacts, causing their magnetic dipoles to deviate from rotation axes. These may be the reason for the tilts and offsets of Uranus and Neptune's magnetic fields from their geographical axes.

Conclusions

The dynamo model fails to explain the origin of the magnetic fields of Uranus, Neptune, and Mercury, besides the challenges of modeling the Earth's magnetic fields. The superconducting hypothesis provides simple explanations for observed planetary magnetic fields. Based on the unified theory, superconductors are common at high pressures and likely exist inside many planets. A superconductor loop floating on the surface of the outer core near the equator may account for the origin of the geomagnetic field, which better explains the polar wandering and magnetic reversals. The existence of superconductors inside other planets may also be responsible for the origin of their magnetic fields.

Revision History

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- 08/20/2022: "Superconductive Origin of Planetary Magnetic Fields".
- 01/30/2023: "Superconductors Cause Planetary Magnetic Fields".
- 02/08/2023: "Superconductor Origin of Earth's Magnetic Field".

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