

Superconductor Origin of Earth's Magnetic Field

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Abstraction

Earth's magnetic field shields life from harmful cosmic rays, but its origin remains poorly understood. The dynamo theory is commonly used to explain this origin, but it falls short in accounting for the magnetic fields of other planets, especially those with cooled cores. In light of new understandings of superconductivity, this study proposes an alternative hypothesis to provide a general mechanism for the origin of planetary magnetic fields. The "[unified theory of low and high-temperature superconductivity](#)" predicts that superconductors are an ordinary state of matter and are common at high pressures. Deep within the Earth, where pressure is immense, superconducting materials likely exist beneath the mantle. Driven by Earth's rotation, superconductors in the outer core accumulate toward the equator, eventually assembling into a belt looping around the core under the equator. This belt creates a resistance-free path for currents. Earth's magnetic field might be induced by a Meissner-like effect in the Sun's magnetic field. The currents around this loop generate a magnetic field resembling a magnetic dipole. Without electrical resistance in the superconductor belt, the currents circulate indefinitely, maintaining a stable magnetic field. Convection currents in the outer core may disturb this loop, causing polar wandering, occasionally breaking its continuity, and leading to disruptions in Earth's magnetic field. When the superconductor belt reassembles into a new loop later, the polarity of a new magnetic field may be recuperated in a different direction depending on whether the north or south pole tilts towards the Sun at different seasons, leading to a magnetic reversal. Superconductors may also be responsible for the magnetic fields of other planets. As planets cooled, superconductors became trapped within them. Some might have survived various celestial events throughout their histories, despite significant changes in their axis and orbits. This could explain the large angle and offset between the magnetic dipole and rotation axis observed in both Uranus and Neptune.

Introduction

Earth's magnetic, or geomagnetic, field extends from the planet's interior out several tens of thousands of kilometers into space above the ionosphere, forming the magnetosphere. The magnitude of the geomagnetic field at the surface ranges from 0.25 to 0.65 G.^[1] Despite some slow fluctuations over time, the intensity of the magnetic field remains relatively consistent. Over the last two centuries, the strength has decreased at a rate of 6.3% per century.

Without the geomagnetic field, charged particles from the solar wind and cosmic rays would reach the surface and threaten life on Earth. These high-energy particles could collide with the nuclei of atoms in their path, triggering nuclear reactions in the air or within human tissues, thereby altering genes. Charged particles moving through the magnetic field are deflected by the Lorentz force, causing them to spiral along magnetic lines and converge at the north or south pole, effectively shielding life on Earth. The high concentration of these particles in the polar atmosphere increases the likelihood of

interactions between positive and negative charges, as well as collisions with air molecules. One result of these interactions is the beautiful auroras observable near the polar regions.

The Earth's magnetic field can be represented by a magnetic dipole centered within the Earth, currently tilted at an angle of about 11° to the axis of the Earth's rotation. While the north and south magnetic poles are generally located near the geographic poles, they move slowly over geological time scales, a phenomenon known as polar wandering.

Occasionally, Earth's magnetic poles trade places in a process called magnetic reversal. The geomagnetic field alternates between periods of normal polarity, where the field direction is the same as it is now, and reverse polarity, where it is opposite. This history of Earth's magnetic reversals is well preserved on the seafloor over time, as shown in Figure 1.^[2] When the newly formed ocean floor moves away from the ridge, the direction of the magnetic field at that time becomes "frozen" in the cooled rock. Similar to a tape recorder, the ocean floors document the history of Earth's magnetic field changes. By studying paleomagnetism, scientists have reconstructed this history.^[3] Magnetic reversals occur at statistically random intervals and can last as little as 200 years. The most recent brief reversal occurred 41,000 years ago and lasted about 440 years. Over the last 83 million years, there have been 183 magnetic reversals.^[4-6]

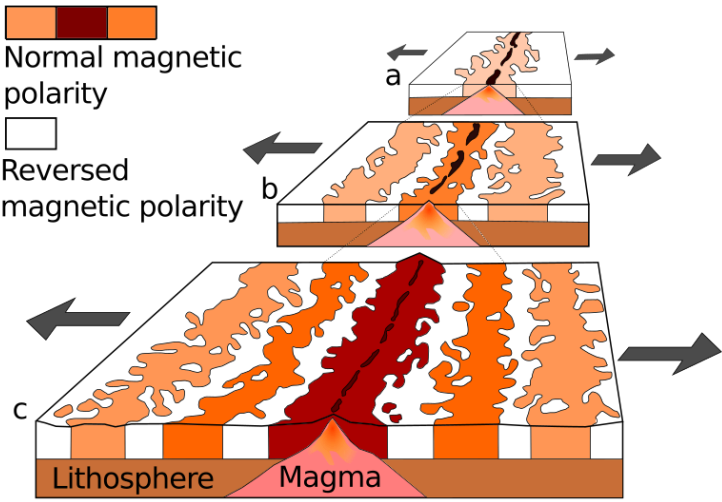


Figure 1: Paleo-magnetic reversal stripes recorded on the spreading seafloor from mid-ocean ridges. Different time snapshots of the seafloor are illustrated by (a), (b), and (c) from old to present. The figure is from Wikipedia.

Dipole-like magnetic fields have also been detected on many other planets and some of their satellites. However, the origins of these magnetic fields are not well understood.

Challenges to the Geodynamo Theory

The dynamo theory is a widely accepted explanation for the geomagnetic field.^[7-8] Initially proposed by Joseph Larmor in 1919 to explain sunspots, the theory has since been modified and adapted to incorporate magnetohydrodynamics (MHD) equations. Magnetohydrodynamics, initiated by Hannes Alfvén,^[9] explains magnetic fields created by plasma, such as in the Sun, which is far more dynamic in terms of velocity and viscosity compared to the convection in Earth's outer core.

The dynamo theory suggests that the Earth's magnetic field is induced and constantly maintained in the liquid iron outer core by convection-driven heat exchange feedback loops. The Coriolis effect, resulting from Earth's rotation, deforms these feedback loops into spiral coils aligned along the rotation axis, as shown in Figure 2.^[10] The magnetic field is primarily generated by electric currents in the outer core, which consists of molten iron. As this conducting fluid flows across an existing magnetic field, electric currents are induced according to magnetohydrodynamic equations, creating an additional magnetic field.^[9,11] When this new magnetic field reinforces the original one, a self-sustaining dynamo is created.

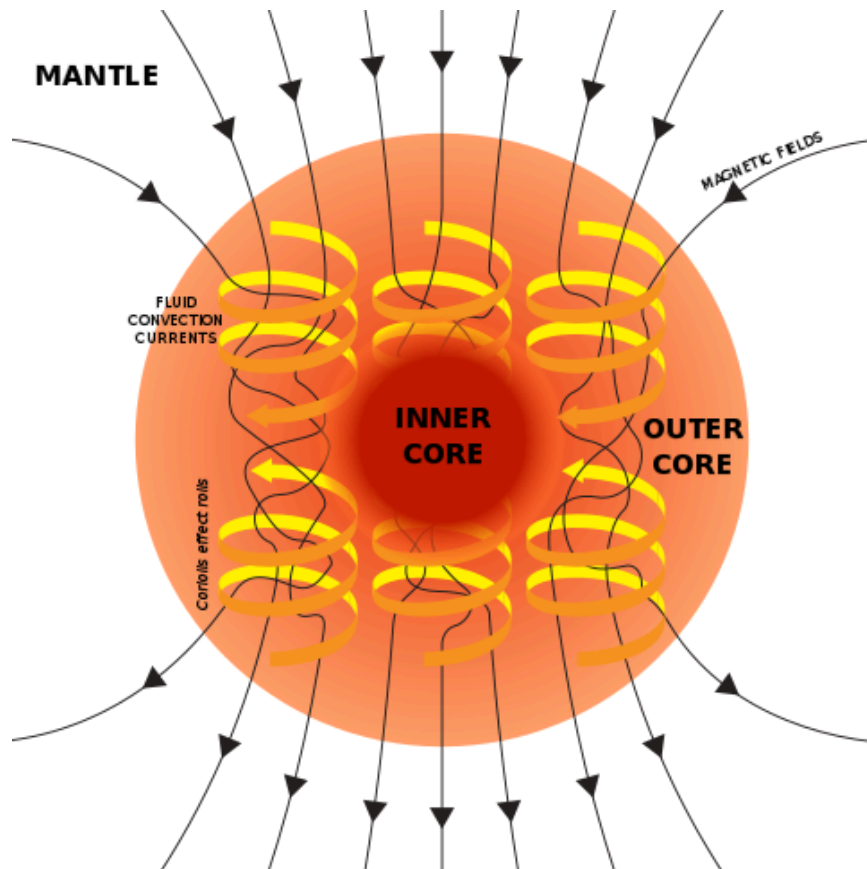


Figure 2: Geodynamo theory: the Earth's magnetic field is induced in the coils of the outer core flows as a result of the Coriolis effect.^[10] The [figure](#) is from [Wikipedia](#).

However, the dynamo theory encounters several challenges in accounting for the origin of planetary magnetic fields. One major issue is that it does not explain the mechanism behind geomagnetic reversals observed throughout Earth's history, as depicted in Figure 1.

Secondly, the dynamo theory cannot explain the magnetic fields of planets with solid, frozen interiors, such as Mercury. Mercury, which is about 14% the size of Earth,^[12] is believed to have a cooled core due to its small size. Since the dynamo theory relies on a flowing liquid core, it is inapplicable to Mercury. Additionally, Mercury's slow rotation, taking 59 days to complete, results in a negligible Coriolis effect, further undermining the dynamo's applicability. Despite these factors, Mercury still maintains an active magnetic field.

Finally, the dynamo theory fails to account for the magnetic fields of planets with a significant tilt between their magnetic dipoles and rotational poles. Data from NASA indicates that the magnetic dipoles of Uranus and Neptune are tilted 59° and 47° from their respective rotational axes, as shown in Figure 3.^[13] Since the Coriolis effect, which influences the dynamo process, is generated by planetary rotation and should align closely with the rotation axis, the theory cannot explain these substantial deviations.

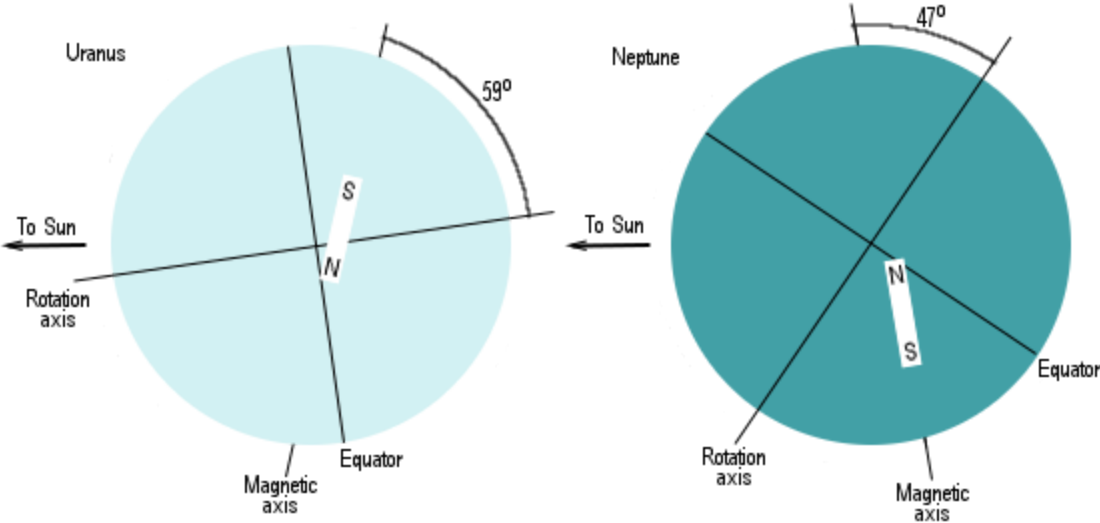


Figure 3: Magnetic field deviations of Uranus and Neptune measured by Voyager 2.^[13]

In light of recent advancements in our understanding of superconductivity, this study proposes an alternative hypothesis that provides a comprehensive mechanism for the origin of planetary magnetic fields, addressing the shortcomings of the current theory.

Superconductor Origin

This study proposes that superconductors play a crucial role in the origin of planetary magnetic fields. The "[Unified Theory of Low and High-Temperature Superconductivity](#)"^[14] provides a comprehensive explanation of superconductivity properties and integrates the mechanisms of electrical resistance in both superconductors and normal conductors into a unified framework. According to this theory, superconductors are an ordinary state of matter under high pressure. The state diagram in Figure 4 illustrates that superconductivity is typically found at high pressures and low temperatures. Early superconductors were mainly observed at low temperatures, but recent discoveries have identified more high-temperature superconductors under high-pressure conditions.^[15-16] The scarcity of superconductors on Earth is primarily due to the unfavorable conditions, specifically, low pressures and high temperatures, found on the planet's surface.

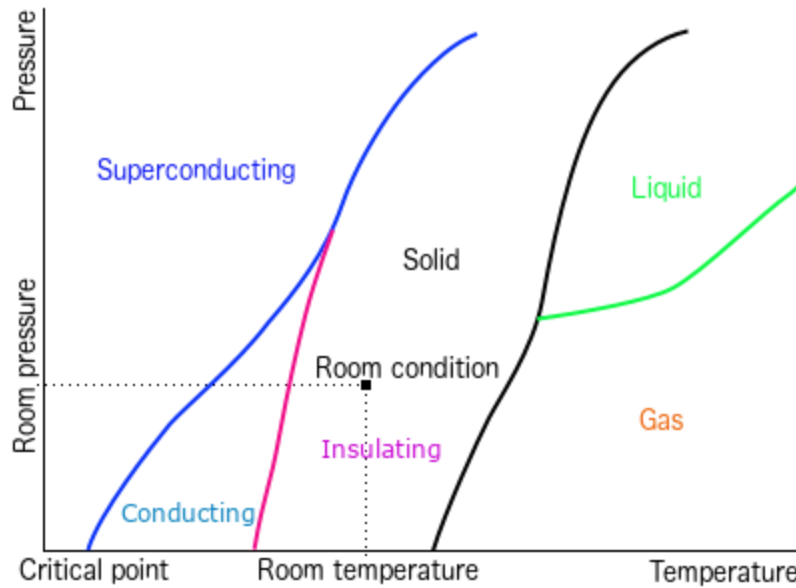


Figure 4: Electrical state diagram indicating superconductivity as an ordinary state of matter, and common at high pressures.^[14]

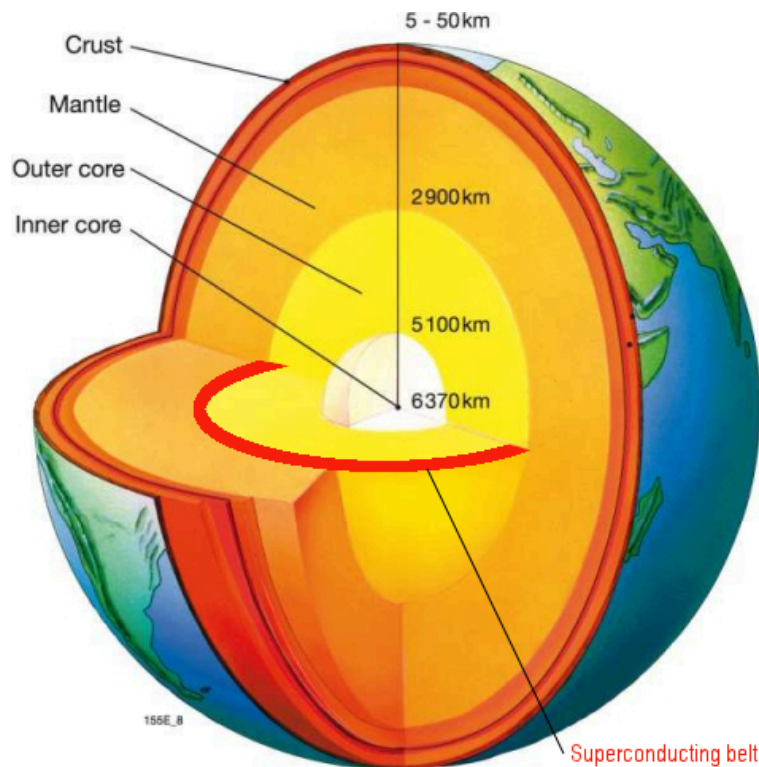


Figure 5: Superconducting belt assembled along the equator of the outer core due to the rotation of the Earth. This figure is adapted from the [source](#) in [Weebly Geology](#).

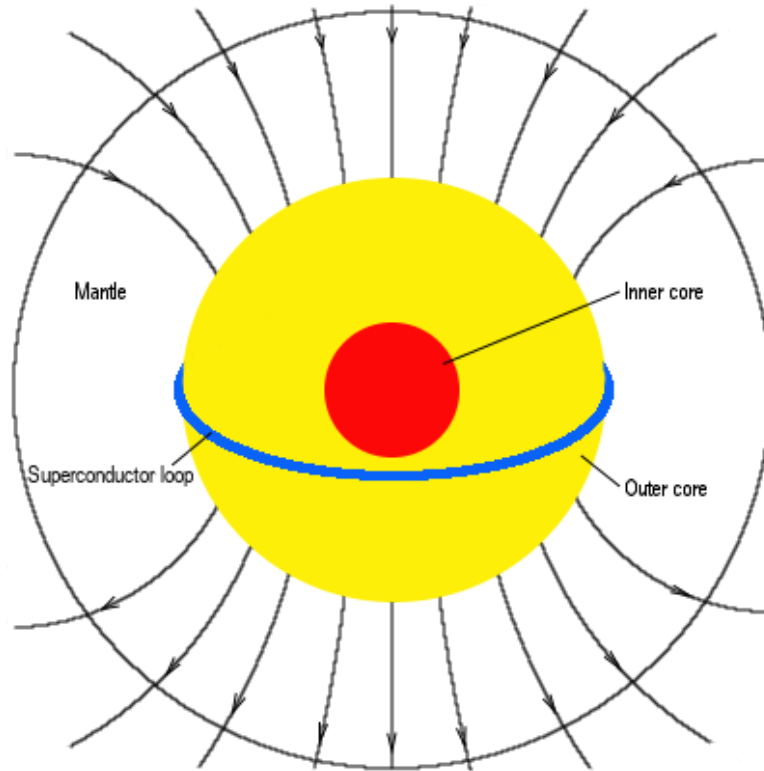


Figure 6: Geomagnetic field, maintained by electrical currents looping around a superconducting belt along the equator on the outer core.

The pressures between the lower mantle and the outer core range from 136 to 360 gigapascals.^[17-19] According to the unified theory, superconductors likely exist beneath the mantle under such high pressures. These superconducting materials may float on the outer core surface. The Earth's rotation causes these superconductors to accumulate towards the equator under the mantle. Eventually, sufficient superconductors gather to form a belt looping around the equator, known as the superconductor loop, as illustrated in Figures 5 and 6. Without electrical resistance, currents can flow around the loop indefinitely, thereby maintaining the stability of the geomagnetic field.

Induction of Magnetic Field

We propose that planetary magnetic fields are induced by a Meissner-like effect of superconductors within the Sun's magnetic field. The Meissner effect is a phenomenon where an external magnetic field is expelled from superconductors upon transitioning to the superconducting state.^[20] It is important to note that a magnetic field created by induction requires a change in magnetic flux, as stated by Faraday's law of induction.^[21] However, the Meissner effect occurs during the transition to the superconducting state in the presence of an existing magnetic field, without any change in magnetic flux.

The mechanism of the Meissner effect is clarified in the unified theory of superconductivity.^[14] According to this theory, the natural flow of electrons in superconductors generates currents. Typically, these currents do not produce observable magnetic fields, as the random fields they generate cancel each other out locally. However, in the presence of an external magnetic field, the Lorentz force acts on the flow of electrons.^[22-24] When observed in the direction of the magnetic field, a

moving electron is deflected to circulate clockwise. The currents in a superconductor generate a magnetic field that cancels the applied magnetic field inside the superconductor, while the field outside the superconductor is enhanced. The net effect is that the original magnetic field appears to be expelled from the superconductor.

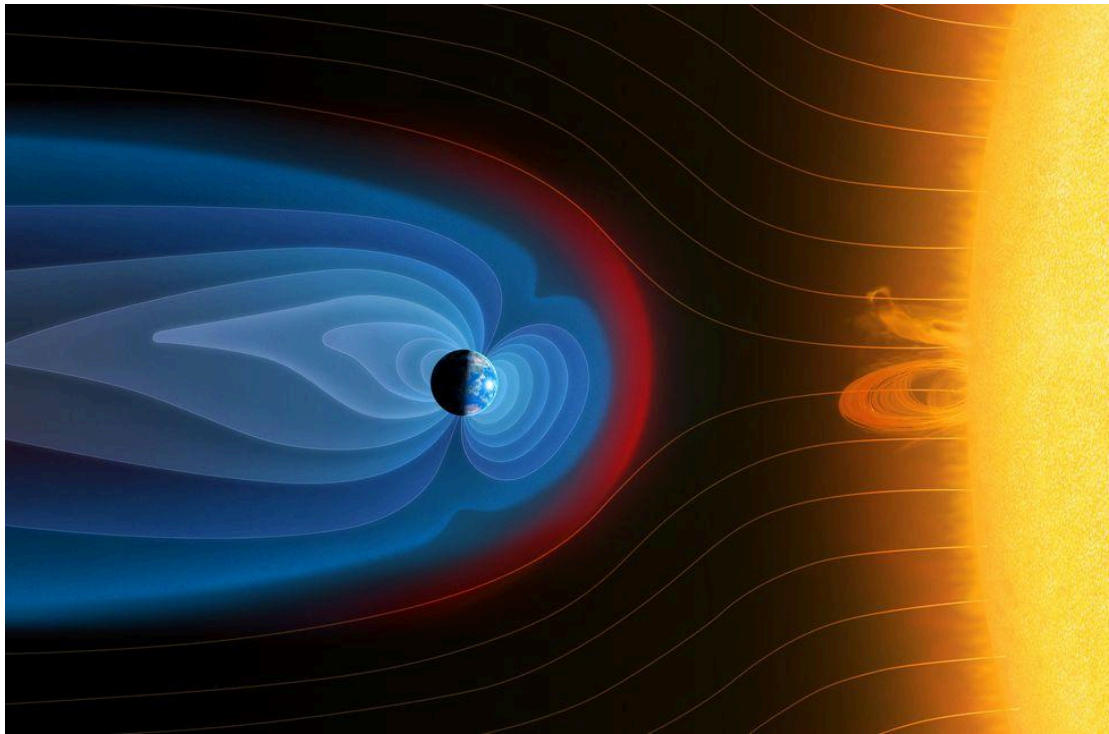


Figure 7: Geomagnetic field induced within the Sun's magnetic field and further sustained by currents in the superconductor belt. The [figure](#) is from [Popular Mechanics](#).

Before the superconductors in the outer core assemble into a loop near the equator, each superconducting segment expels the Sun's magnetic field locally through the Meissner effect. This process strengthens the Sun's magnetic field near the superconductors, resulting in a stronger overall magnetic field in terms of flux density within the Earth than the Sun's initial field. However, this field is unstable and susceptible to changes in Earth's orbit and the Sun's magnetic field. Once the superconductors form a loop, the magnetic field enclosed within the loop becomes a magnetic dipole. Any changes in the dipole field induce currents in the superconductor loop, counteracting further changes. Essentially, the dipole field is stabilized at the strength it had when the superconductor belt connected to the loop. Since then, the currents in the superconductor loop have effectively safeguarded the field against alterations, regardless of changes in Earth's orbit or the Sun's magnetic field, thereby maintaining the stability of the geomagnetic field, as illustrated in Figures 6 and 7.

Polar Wandering and Magnetic Reversal

The superconductor loop is not a perfect ring and does not align exactly with the equator, but rather lies in its vicinity. The effective magnetic dipole maintained by the loop is expected to deviate slightly from the Earth's rotation axis, accounting for the imperfect alignment between the geomagnetic dipole and the Earth's rotation axis. Convections in the outer core disturb the loop and continually alter the direction of the effective dipole, leading to polar wandering.

Occasionally, strong convections in the outer core disrupt the connectivity of the loop, temporarily cutting off the loop currents. To maintain the existing dipole magnetic field, the currents in the loop may shortcut the broken ends of the superconductor belt through normal conductors in the iron core, but they quickly dissipate due to electrical resistance. If the belt cannot reconnect into a loop promptly, the loop currents will eventually cease, leading to the disappearance of the global magnetic field. This results in a period of inconsistent magnetic fields, known as a paleomagnetic discontinuity.

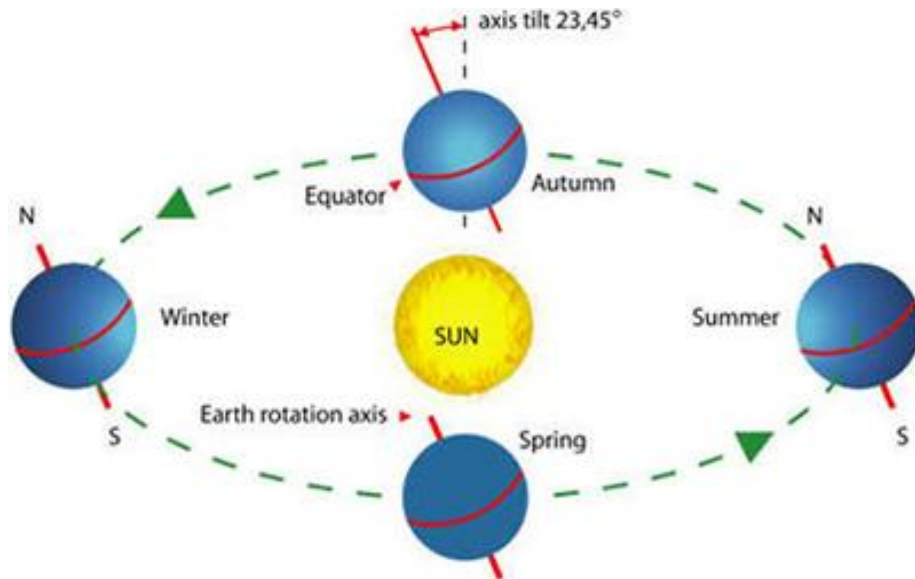


Figure 8, Geomagnetic field reversal related to the seasonal variation of Earth's orbital inclination at initialization. The [figure](#) is from the [Utah Education Network](#).

Eventually, the Earth's rotation would realign the superconductors and reconnect them into a new loop, while the geomagnetic field would also recover. However, the strength and polarity of this new field may differ from the previous one. Since the Earth's rotation axis is not perpendicular to its orbital plane, the North Pole tilts toward or away from the Sun at different times of the year, as illustrated in Figure 8. Consequently, the direction of the Sun's magnetic field relative to the superconductor loop varies with the seasons. This variation can lead to a new geomagnetic field with a different strength and polarity, potentially causing a magnetic reversal.

Planetary Magnetic Fields

Dipole-like magnetic fields are observed not only on Earth but also on many other planets and some of their moons. However, the dynamo model cannot explain the magnetic fields observed on Uranus and Neptune. The effective dipole centers of Uranus and Neptune are offset by 33% and 55% of their respective radii, as illustrated in Figure 3.^[13,25] The magnetic dipole of Uranus is shifted from the center towards the south rotational pole by up to one-third of the planetary radius, with an even more pronounced shift in Neptune. Additionally, the effective magnetic dipole of Uranus and Neptune is tilted 59° and 47° from their respective rotational axes.^[13]

Both Uranus and Neptune are sufficiently large to have concentric interior structures.^[26-29] If their magnetic fields were generated by convection currents, their magnetic dipoles would be expected to align closely with their rotational axes. However, the significant offsets and tilts of their magnetic dipoles pose challenges for physicists attempting to reconcile these observations with the dynamo theory.

The proposed theory provides a straightforward explanation for these observations. It suggests that the magnetic fields of Uranus and Neptune may have initially formed with their magnetic dipoles and rotation axes aligned. As the planets cooled from the outside, their superconductors solidified within them. Being farther from protective large planets like Jupiter and Saturn, Uranus and Neptune are more vulnerable to impacts from asteroids or comets. These impacts could have altered the planets' rotations, orbits, and structures, causing their magnetic dipoles to deviate from their original orientations. This may explain the tilts and offsets observed in the magnetic fields of Uranus and Neptune relative to their rotational axes.

A similar explanation may apply to Mercury. Its magnetic field might have originated like that of other planets. As Mercury cooled, its superconductor loop solidified and was preserved within its interior. Being an inner planet, it is more protected by the outer planets and less susceptible to impacts from celestial bodies.

Summary

Magnetic fields are common phenomena on many planets, yet the conventional dynamo theory faces significant challenges in explaining their origins. The superconducting hypothesis provides a new perspective on planetary magnetic fields and offers more convincing explanations for the observed phenomena. Continued research and exploration are crucial to validate and refine this hypothesis, enhancing our understanding of planetary magnetism.

Revision History

- [06/28/2019: Initial Post on Stanford Site](#)
- [11/02/2025: Published on Zenodo](#)
- [12/17/2025: Adding Links to Summaries of Related Articles](#)

Links to Summaries of Related Articles

- <https://cs.stanford.edu/people/zjl/abstract.html>, [PDF](#)
- <https://sites.google.com/view/zjl/abstracts>, [PDF](#)
- <https://xenon.stanford.edu/~zjl/abstract.html>, [PDF](#)
- <https://doi.org/10.5281/zenodo.17967154>, [PDF](#)

Further Literature

- [Misconceptions in Thermodynamics \(PDF: DOI\) \(中文: DOI\)](#)

- [The Mechanism Driving Crookes Radiometers \(PDF: DOI\) \(中文: DOI\)](#)
- [The Cause of Brownian Motion \(PDF: DOI\) \(中文: DOI\)](#)
- [Can Temperature Represent Average Kinetic Energy? \(PDF: DOI\) \(中文: DOI\)](#)
- [The Nature of Absolute Zero Temperature \(PDF: DOI\) \(中文: DOI\)](#)
- [The Triangle of Energy Transformation \(PDF: DOI\) \(中文: DOI\)](#)
- [Is Thermal Expansion Due to Particle Vibration? \(PDF: DOI\) \(中文: DOI\)](#)
- [Superfluids Are Not Fluids \(PDF: DOI\) \(中文: DOI\)](#)
- [Why a Phase Transition Temperature Remains Constant \(PDF: DOI\) \(中文: DOI\)](#)
- [What Causes Friction to Produce Heat? \(PDF: DOI\) \(中文: DOI\)](#)
- [The Easiest Way to Grasp Entropy \(PDF: DOI\) \(中文: DOI\)](#)
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- [The Restoration Principle \(PDF: DOI\) \(中文: DOI\)](#)
- [Is There a Sea of Free Electrons in Metals? \(PDF: DOI\) \(中文: DOI\)](#)
- [Electron Tunnel \(PDF: DOI\) \(中文: DOI\)](#)
- [Unified Theory of Low and High-Temperature Superconductivity \(PDF: DOI\) \(中文: DOI\)](#)
- [LK-99 Limitations and Significances \(PDF: DOI\) \(中文: DOI\)](#)
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