Earth's Magnetic Field and its Wandering Magnetic Poles*

Nandini Nagarajan

The Earth's magnetic field has been a constant source of curiosity and wonder, for its ubiquitous use in navigation, the properties of magnetic attraction and the influence and connection to celestial phenomena like aurora, sunspots, etc. Records of magnetic measurements exist going back 400 years. Modern measurements, with the addition of satellite-borne observations, provide accuracy and enables understanding of intriguing characteristics of the geomagnetic field. Some of these are: magnetic polarity reversals, wandering of the magnetic poles and the most fundamental one: the origin of the field in the Earth's interior and the mechanisms that have sustained it for over a billion years.

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Keywords
Magnetic field, polarity reversal, axial dipole, polar wander, dipole moment, dip pole.

Introduction

Surface observations of physical properties and potential fields of the Earth, provide different kinds of information about the Earth's interior, and even, about the fields themselves. We know the curvature, rotation speed and angular velocity, mass and angular momentum of the Earth from these observations. Very little is known about the structure and properties of the Earth's interior, through direct observation or measurements at the surface, and drilling only provide information up to depths ~10 km. Deeper information has been only been inferred from observations of earthquakes, gravity and magnetic measurements and laboratory simulations of conditions in the interior. Pressure and temperature inside the Earth increase with depth, leading to changes in the viscosity and composition of matter. It is challenging to simu-

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late these properties under laboratory conditions below a certain depth. Therefore, the understanding of processes in the Earth's deep interior, the core, progresses cautiously, with several caveats and disclaimers, by collating results from laboratory and computational simulations, repeated and more precise measurements, continuing into the 21st century.

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Defining the Earth's Magnetic Field

The primary definition of the Earth's magnetic field as approximated by a dipole, was found to have discrepancies. For example, even early navigation, and charts plotted from ship's measurements of declination showed that the location of the North Magnetic Pole was not coincident with the Earth's axial poles. The intensity of the field, estimated from moment experiments, and charts showing lines of equal intensity and declination show more irregularity as in *Figure* 1. To reproduce such observed fields, the concept of quadrupole arrangements was proposed. The simplest multipole magnet is the dipole, then quadrupole (four poles), octupole (eight poles), etc. Any magnetic field can be described as a dipole and its strength approximated by the dipole moment and

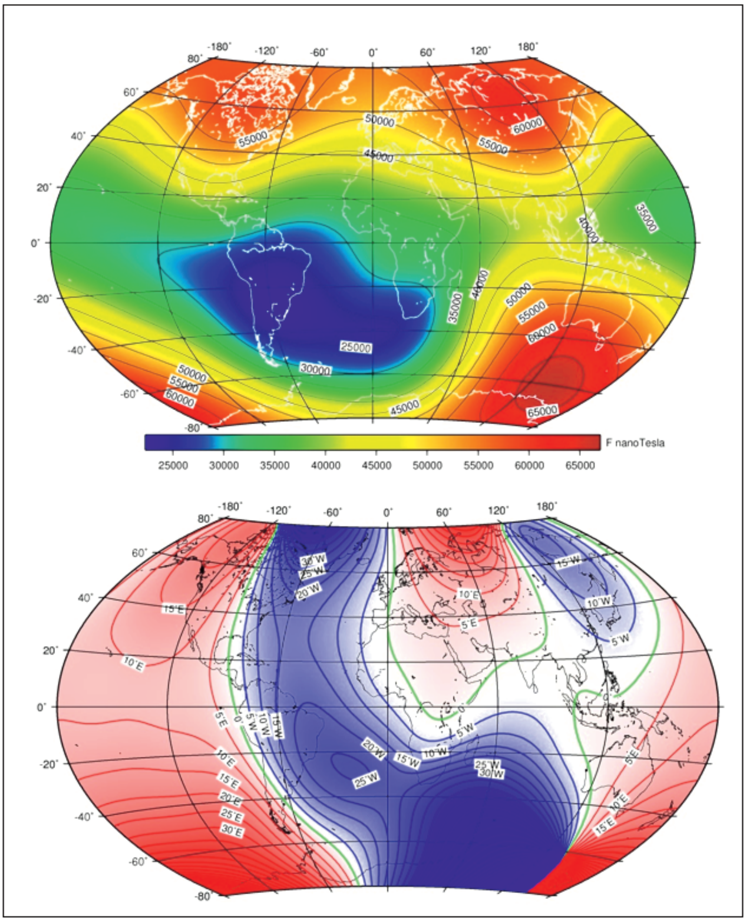

Figure 1. Contours of magnetic field intensity (top) and declination (below) where the blue contours are east and the red are west. (Image credit: http://www.geomag.bgs.ac.uk/research/modelling/IGRF.html)

additional complexity is simulated by an arrangement of dipoles, that would produce quadrupole/multipole fields. This was an attempt to seek a physical model that would replicate the patterns of field intensity observed on the Earth's surface. The features noted could be represented as a superposition of multiple dipoles oriented in the Earth's core, in addition to the main axial dipole. This is the physical representation of the Earth's magnetic field.

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Box 1. Superposition of Dipoles and Multipoles

It is seen, from the older and even the latest contours of surface field intensity that there are large scale irregularities in the field that could not be modelled by a dipole. A physical representation of the magnetic fields that are not typical dipole fields, is created by superposing additional pairs of dipoles, of varying intensity and orientation. A configuration of such dipoles, oriented at certain angles to each other, is defined as a quadrupole or multipole, The ensuing configuration of field lines and potential surfaces could then describe a more complex field.

The significant contributions of the non-dipole, or higher-order terms of spherical harmonic terms, required an equally complex mechanism or model of the Earth magnetic field, within the core. In the absence of an observable mechanism, while theories for the origin of the field were still debated, the physical complexity of the field could be described with a configuration of quadrupoles at certain locations within the Earth. Again, these are representations which help us understand the complexity but do not define the mechanism.

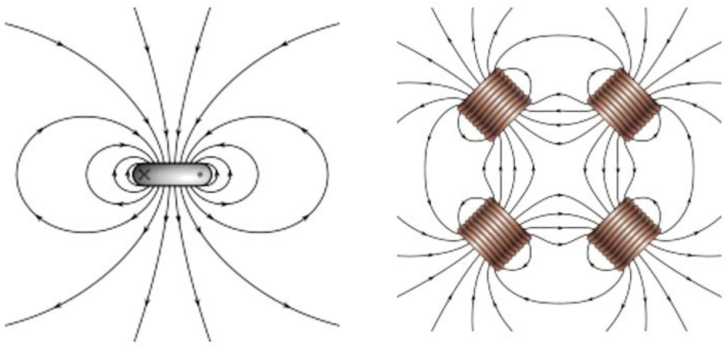

Figure A. Field line configurations of a dipole (left) and a multipole (right).

magnetic field has to be of internal origin (90%) and could be expressed mathematically, in terms of spherical harmonics, where the coefficients of the sine and cosine terms had physical significance. This was a mathematical expression of the magnetic field that was validated by fitting it to actual observations. Gauss used spherical harmonics to express the magnetic potential and obtained coefficients in the form of a series – Legendre polynomials – by fitting the surface harmonics to the available magnetic data at that time (obtained from limited magnetic observatories and surveys). There are two solutions to the potential expression separating that due to internal and external sources:

– potential V_{i} due to sources internal to the Earth (r< RE)

– potential V_e due to sources external to the Earth (r> RE), such that $V = V_i + V_e$.

The solutions are given as multipoles or spherical harmonic expansions where V_e varies as r^n and V_{i} varies as r^{-n}. From this, it was deduced that the contributions of the external fields are considerably smaller and most of the field intensity is from internal sources. The potential from internal sources is defined as:

$$V(r,\theta,\phi,t) = a \sum_{n=1}^{N} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+1} \left[g_n^m(t)\, \cos(m\phi) + h_n^m(t)\, \sin(m\phi)\right] P_n^m(\cos\theta),$$

Where

- φ = longitude
- θ = colatitude
- r = radial distance
- a = radius of the Earth
- n is the degree of the term
- m is the order of the term
- V is the scalar potential
- g_n^m, h_n^m are the Gauss coefficients
- $P_n^m \cos\theta$ are Legendre polynomials

He then demonstrated that these coefficients were close to the coefficients for a field due to a magnetized sphere or a dipole. These Gauss coefficients also delineated the physical form of the field, viz.; the first-order coefficients represent an axial, symmetric dipole. Higher-order coefficients represent the deviations from

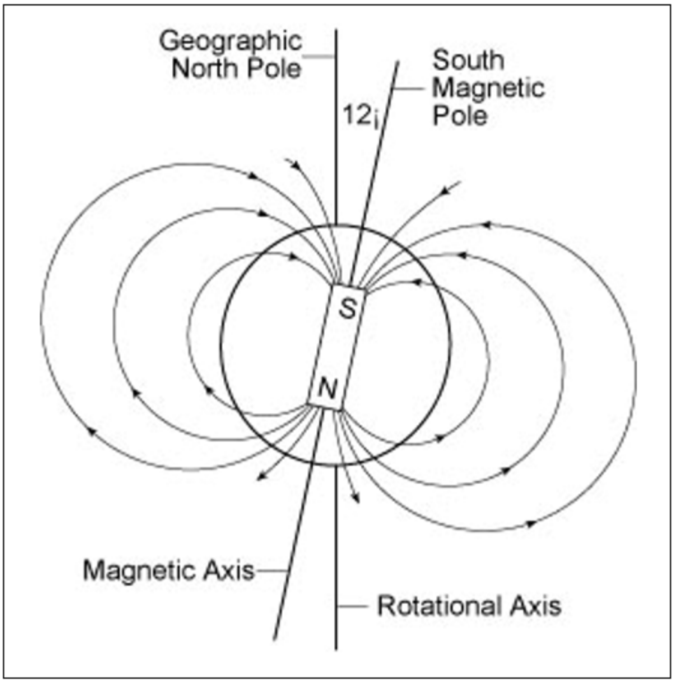

Figure 2. Representation of the Earth's magnetic field as a axial, tilted, eccentric dipole. (Image source: www.ase.tufts.edu)

this, which could also be represented by a configuration of multipoles, in the form of tilt of the axis, eccentricity, and displacement from the centre of the Earth. This further established an equivalence between the patterns of multipole configurations and the coefficient terms. Further, using spectral analysis, Gauss showed that the best fit to the observed field was obtained if the dipole was not purely axial but made an angle of about 11^{o} with the Earth's rotation axis. The Earth's magnetic field is thus defined as a 'tilted eccentric dipole', (*Figure* 2) with a nearly spherical equipotential surface, tilted and offset from the axis of rotation.

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These spherical harmonic coefficients were determined periodically, providing estimates of the changes in the Earth's magnetic field over a century (1850–1950). These models with limited accuracy needed revision, with more surface measurements, as the need arose for more precise base values for more detailed mapping of magnetic variations for magnetic surveys, resource ex-

Box 2. Properties of Spherical Harmonic Terms

The expansion of cosine terms describes features of the internal field. Variation of these terms with order m and degree n, determine the number of oscillations with colatitude, θ, and longitude, φ, which then define the configuration of multipoles needed to fit the irregularities in the field. These angular characteristics are also defined in terms of the wavelength (fraction of the earth's circumference), which imparts a physical dimension to the irregular features observed in magnetic field intensity, declination and inclination, observed on the Earth's surface, that we seek to describe. IGRF can be considered to consist of two parts:

– mathematical functions that describe how each multipole field changes as a function of latitude, longitude, and radius ('geometry of the multipole field')

– coefficients ($2n + 1$ for each $n \geq 1$) associated with each multipole ('strength of the multipole field'). The large wavelengths (approximately up to $n < 14$) are associated with the main field: where terms of $n = 1$ represent the dipole component, $2 \leq n < 14$: non-dipole or anomalous components of the main field, generated in the Earth's core.

ploration, and modern navigation. Studies of natural phenomena: sunspots, magnetic storms, auroral displays, and daily variability of the ionosphere[1], also required more accurate estimates of the Earth's magnetic field. Collaboration between groups of scientists and observers evolved into a global co-operative movement: the International Geophysical Year (IGY, 1957–58). Protocols to reduce all magnetic measurements made by different agencies, with different instruments, were evolved and global measurements, at irregular spacing on each continent were collated to arrive at a representation of the geomagnetic field. However, improvements in the accuracy of the field models needed far better spatial coverage. This was first provided by a series of Polar Orbiting Geophysical Observatory (POGO) satellites, measuring total field values. With this improved coverage, the Earth's magnetic field was estimated with coefficients up to order 10. This expression of the dipole field, eccentricity and tilt, and additional irregularities, was defined as the International Geomagnetic Reference Field (IGRF), first published in 1970. The IGRF is the product of a collaborative effort between magnetic field modellers and the institutes involved in collecting and disseminating

[1] An ionized layer of the atmosphere 100–1000 km above the Earth's surface that enables and disrupts radio communication.

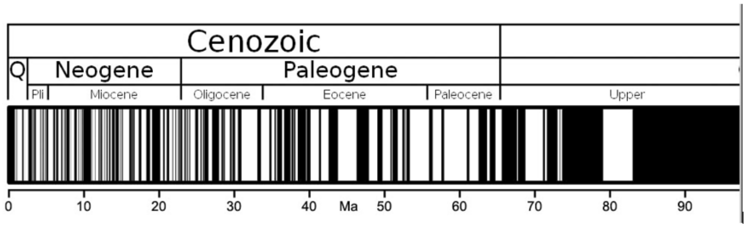

Figure 3. Time scale of the magnetic polarity reversals recorded in geologically recent time (~100 million years, Myr). (Image source: ttps://wileyearthpages.wordpress.com/2015/11/16/the-cores-influence-on-geology-how-does-it-do-it/magnetic-reversals/)

ments of magnetic field found in rocks of different ages. This study of remnant magnetic fields – palaeomagnetism – established the persistence of the dipole field. The most significant finding is that the polarity of the field was found to be reversed in measurements from rocks of certain ages. The polarity has reversed several times, wherein, the magnetic North and South Pole positions are reversed. The polarity that is the same as the present time, is termed normal and that which is opposite is termed reversed. Magnetic polarity reversals have occurred often, on a scale of ~1 million years, from the palaeomagnetic record, obtained by sampling rocks of different environments and ages. The series of polarity reversals extends back about 1.2 billion years, with diminishing clarity and accuracy. A stunning signature of these polarity reversals, extending back about 160 Ma, has been retrieved from magnetic anomalies of the ocean floor, which consists of lava flows from sea-floor spreading ridges in the Atlantic and the Pacific Ocean. The reversal patterns recorded in the rocks are termed sea-floor magnetic lineaments. Corresponding lineaments have also been found in other oceans. A sequence of such reversals has been constructed from palaeomagnetic measurements and validated using radiometric dating of the rocks to estimate geologic ages of the rocks. Lava flows along the oceanic spreading ridges commonly preserve this pattern of polarity reversals as they cool, and this pattern is also used to determine the rate of ocean ridge spreading. A section of this reversal sequence is shown in *Figure* 3.

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The Earth's field has alternated between periods of normal polarity, in which the predominant direction of the field was the same as the present direction, and reverse polarity, in which it was the opposite. Reversal occurrences are statistically random. There have been 183 reversals over the last 83 million years. The latest, the Brunhes–Matuyama reversal, occurred 780,000 years ago. From the sampling of rocks deposited during a polarity reversal, the evolution and duration of the reversal process are estimated. Although variable, the duration of a full reversal is typically between 2000 and 12000 years, which is one to two orders of magnitude less than the duration of a polarity interval (magnetic chron). It is the discovery of magnetic reversals, their frequency and duration that provide the most compelling evidence and arguments in favour of the dynamo theory for the generation of Earth's magnetic field. Further, the phenomenon of reversal also puts constraints on physical properties of the Earth's core that are indirectly estimated from seismology.

Origin of the Earth's Magnetic Field

Observations and mathematical expressions have established the form, shape, strength and persistence of the Earth's magnetic field over billion years (Gyr). The temperature inside the Earth increases with depth and is above the Curie point, 570°C, at a depth of 50 km and, therefore, the rocks below that depth do not retain their ferromagnetism and the mantle which is composed of metallic silicate rocks is not conducting enough to generate induced magnetism. Seismology reveals that the outer core is liquid and metallic, with a temperature of $\sim$ 3000°K. This is the region which could generate induced magnetization or a dynamo action. Of the several theories that were proposed, historically, the only one that fits all observable properties of the Earth and fulfils the requirement of producing a persistent, nearly dipole field that also displays polarity reversal is the geodynamo. This theory has grown out of mathematical advances in constraining complex magneto-hydrodynamic equations and the combined observations from seismology, gravity and geomagnetism. The theory of 'magneto-hydro- dynamics' that deals with magnetic fields in

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Box 4. Structure and State of the Earth's Interior

Structure of the Earth is a layered planet of radius 6370 km, with a thin light outermost layer (~50km), the crust, made up of silicate rocks. The next layer, the mantle, 2800 km thick, comprised of metallic silicate rock is stratified into the elastic lithosphere, upper and lower mantle. The outer core, 2000 km thick, is much denser, consists of very metallic material (Fe, Ni, Co). The solid inner core, radius 1200 km, is denser and has a more complex structure, that is not found in metals under laboratory-simulated temperatures and pressures. The properties of this deepest region of the earth, are being inferred from highly sensitive seismological studies was well as more realistic simulations of the magnetic field produced in the outer core.

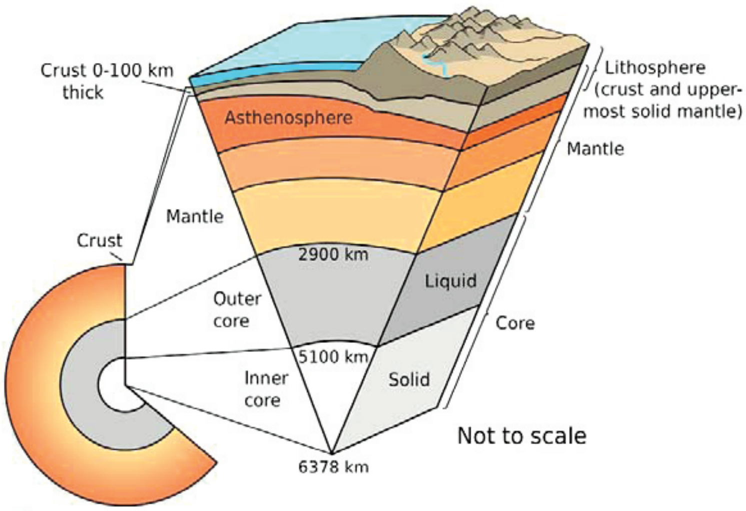

Figure B. Structure and state of the Earth's interior. (Image credit: pubs.usgs.gov)

moving liquids is complex, and several simplifications were made to obtain solutions. However, these solutions did not provide a mechanism for sustaining the dynamo action. Therefore, solutions to the complete equation were sought using numerical and computational methods. With increasing computational power, it is possible to test simulations with different combinations of physical constants representing thermal, viscous and electromagnetic properties of the Earth's core. The simulations also demonstrate the type of convection cells that form in the core. These are complex structures, without which, the axial dynamo cannot be sustained. The errors of estimates of the physical properties of the outer core are usually large, and are then constrained by the bounds placed by the constants in the dynamo equation. Geodynamo models seek to replicate the simplest axial dipole. About 90% of the magnetic field energy at the surface of the Earth is due to its dipole moment, and the axial dipole component (g_0^1, the first-order Gauss coefficient) is responsible for most of that. The dominance of the 'axial dipole' throughout geological time is perhaps the most fundamental property of the geomagnetic field. Palaeomagnetic data are consistent with the hypotheses that the geomagnetic field has been dipolar, with an axis very close to the rotational axis for over ~ billion years (Gyr).

At present, computer simulations of the geodynamo have achieved considerable complexity and could replicate the most important features of geomagnetic measurements, viz.; the axial dipole, defined by the first-order harmonic, reversals and persistence of dipole strength. These simulated magnetic field generators are compared against observational models of secular variation and palaeomagnetic representation of past magnetic fields. Simulations have been increasingly successful in matching processes and timescales evident in observations within limited time frames. Computational power and the time taken to simulate a time-varying geodynamo could only simulate secular variation to the scale of ~100 years, and is yet to resolve the origin and persistence of features observed in modern measurements. The most significant features of the geodynamo, simulated on ~million year scales are a replication of the strength and stability of the axial dipole and obtaining a reversal sequence resembling the statistical properties of the observed sequence. This simulation has only only extended up to 5 Myr. The number of reversals within this period is not an adequate statistical sample and showed some skewness when compared to the record of reversals. The inferences, therefore, are qualified by the shortfall in computational speed required to produce time sequences of longer intervals of simulations (~100 Myr) of the geodynamo. Despite these seeming drawbacks, some constraints from simulated models refine the range of possible values of physical constants, modes of convection and state of the outer core.

Present-day simulations of the geodynamo through computational models, involve the magneto-hydrodynamic equation and several constraints, bounds and quasi-linearization and use physical constants approximating viscosity, conductivity and temperature conditions in the outer core. These constants sometimes differ from inferred estimates by several orders of magnitude. Nonetheless, it is an achievement of interdisciplinary collaboration, between mathematics, computational methods, laboratory physics and geophysics that geodynamo models are capable of producing much details of the observed magnetic field, as well as a close approximation of the estimates of secular variation. The field configurations obtained surpass the complexity of models with superposed quadrupoles, but do simulate similar conditions, thereby validating the superposed multipole models as well. These time-varying models, are specifically tailored to replicate or simulate changes observed in the palaeomagnetic record (~Myr) viz.; reversals, over scales of millions of years on one hand and on the other, different models have been created to simulate changes of the order of decades in attempts to match secular variation observed over the past 300 years. Scientists, trying to understand the origin of the geomagnetic field, do so to resolve one of the fundamental questions about the Earth, to expand the boundaries of understanding of matter at temperatures and pressures not achieved in the laboratory. These models are of academic interest to understand these processes and do not serve as predictors of either secular variation or polarity reversal.

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Wandering Magnetic Poles

Historic (~100 yr) and palaeomagnetic records (~1 Myr) clearly show that, in addition to polarity reversals, the magnetic poles have moved over time scales of decades to millions of years. This is called the 'polar wander'. The North and South magnetic poles

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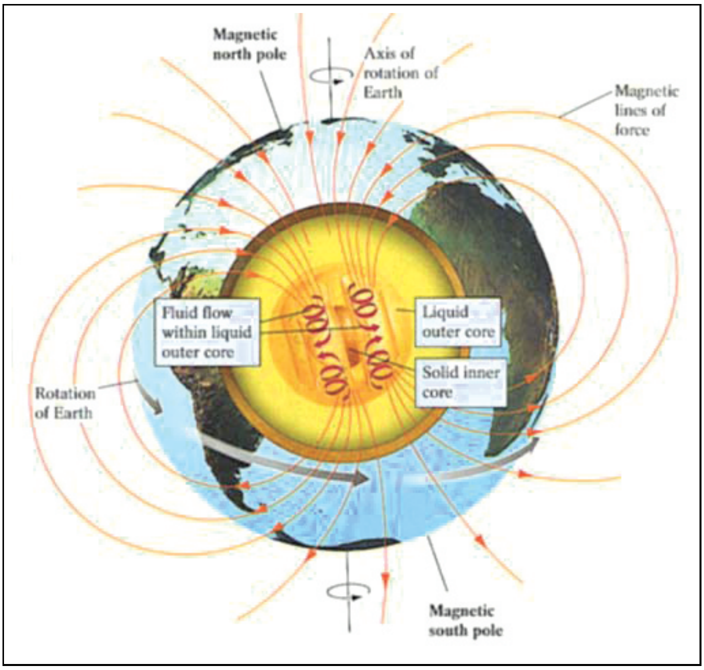

Figure 4. A sketch showing how the geodynamo could generate magnetic fields within the conducting liquid outer core, and the expression of the dipole field outside the conducting space. (Image source: https://quizlet.com/153411924/the-geodynamo-flash-cards/)

are usually located near the geographic poles. Slow and continuous movement, of the poles, is evident from the records of navigation over three centuries, which was sufficiently slow for the purpose of navigation. Since the continental landmass and population are much greater in the Northern Hemisphere, more ships logs with magnetic measurements are available, producing a long record of polar wander of the North Pole. It is also observed that the movement of the South Pole is not synchronous with the North Pole. For modern navigation, communication and surveys, it is essential to track this movement with greater accuracy, even on scales of a year. This has been achieved for both poles, with greater accuracy, using successive satellite measurements with improved instrumentation. The present accuracy of magnetic data, spatial coverage and advances in modelling are such that it is possible to model the field each year and check whether the predicted secular variation, of the IGRF, is accurate. In a recent instance, when the IGRF 2015 generated models for succeeding years, using the 2015 secular variation coefficients, were

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compared with actual satellite data, the discrepancy was greater than acceptable limits. The IGRF model had to be recalculated. It was this recalculation that delineated the rapid movement of the North Magnetic Pole, since 2015. The effects of this drift, of the magnetic poles, severely compromise the precision of direction-finding of airport runways in the Northern Hemisphere, as well as navigation at high latitudes, precision surveys and drilling. This was the reason that estimation of polar wander received much publicity in 2018–2019 in articles such as – 'Earth's Magnetic North Pole Keeps Moving Towards Siberia at a Mysteriously Fast Pace'. An animation created by scientists at Colorado University can be accessed at: https://www.ncei.noaa.gov/news/tracking-changes-earth-magnetic-poles.

Is a Polarity Reversal Approaching?

Another reason for publicity was the speculation that this rapid movement is a precursor to a polarity reversal! There has been speculation in both research and public forums, for the past two decades, that a magnetic reversal is in the offing, in time frames of a decade or a century. Magnetic reversals, as characterized in the geologic record as well as in simulations have distinct imprints. These characteristics can be evaluated by collating all available observations of the Earth's magnetic field and evaluating the parameters, as outlined here:

As estimated from both – the historical and geologic records, there has been a steady and relatively rapid decrease of the dipole moment over the last four centuries. This constitutes the original and primary motive for considering the possibility of an approaching reversal.

Decay of the Dipole Moment

The 'dipole moment' is defined using the first terms of the spherical harmonic expansion. This is estimated from both – the historical and geologic records. There has been a steady and relatively rapid decrease in the dipole moment over the last four centuries. This constitutes the original and primary motive for considering the possibility of an approaching reversal.

In the span of human observation, this appears to be strong evidence of an approaching reversal. However, 400 years is a very short duration in the record of polarity reversals. An evaluation

Table 1. Dipole moment as provided by the International Geomagnetic Reference Field in 2005 and 2000 and the averaged value during the last 800 kyr and the 0.8–1.2 Ma interval. (Dormy 2006).

Date/Period	Dipole Moment	Source
2005	7.776×10^{22} A m^2	IGRF
2000	$7.779 \times {}^{22}$ A m^2	IGRF
800 Kyr	$7.5 \pm 1.7 \times 10^{22}$ A m^2	Valet et al, 2005, *Nature*, 435, 802–805
0.8–1.2 Ma	$5.3 \pm 1.5\times 10^{22}$ A m^2	Valet et al, 2005, *Nature*, 435, 802–805

of the dipole moment over the geologic record indicates that the present dipole moment is not decreasing compared to that of the past.

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Palaeomagnetism reveals that the geomagnetic field amplitude is a fluctuating quantity and the present decrease could just be part of such fluctuations. Further the present dipole moment is still significantly higher than its averaged value, over the last polarity interval (80,000 yr). 400 years of observation pales in comparison to that!

This also implies that the axial component of the dipole is actually growing and the contribution of the non-dipole components, that should significantly increase in strength (~ 50%), is has not happened over the past 80,000 yr.

Magnetic Dip Poles

Apart from the global spherical harmonic expression of the field, assessing dipole and non-dipole contributions, a distinct measurable quantity is the locally defined magnetic dip poles. These are two points on the Earth's surface where the magnetic field is vertical. It is difficult to survey such regions, but within the limits of error, these locations and their variation with time have been recorded. These poles are not exactly antipodal (as they would be for a bar magnet or an axial dipole). These are asymmetries in the Earth's magnetic field that result in this intriguing configuration. Thus, their movements are also independent of each other; the movement of the North Pole has been tracked more accurately over centuries.

The present sudden increase in the northern magnetic dip pole velocity, ~50 km/yr (2015–2019) is thought to be an indication of significant changes in the Earth's magnetic field, possibly heralding a reversal, invoking discussion of social and economic consequences. A surprising observation is that in contrast, the southern magnetic pole velocity has been decreasing over the last few years and is well below 10 km/year. Besides, it is also observed that both axial dipole (first-order spherical harmonic), as well as the north magnetic dip pole, are moving toward the geographic pole and not away from it! Put simply, the magnetic field is increasingly axial and dipolar. These observations indicate that the Earth's magnetic field is undergoing some oscillatory changes, but the axial dipole moment is strong, and there is no significant increase in the non-dipole contribution that would herald a polarity reversal. So are we approaching a magnetic reversal? Studies to date indicate, probably not. And we certainly will not know, since the reversal process could be ~1000 years!

Suggested Reading

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