University Physics II Honors Project:

Investigating Earth’s Magnetic Field

By: Hannah Perkins

Dr. John Stewart

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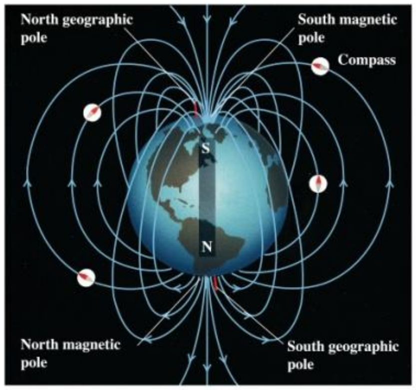
Introduction:

Earth's magnetic field, more commonly known as the geomagnetic field, is still yet a big mystery to many scientists and physicists; however, with the help of paleomagnetic records indicate the field has been around for approximately three billion years (7). In the course of time, different variations of Earth's magnetic field has happened including variations from a "timescale of seconds to secular variations on a timescale of hundreds of years and on an even longer timescale to complete reversals of polarity"(9). Even with all the variations Earth still produces a steady and sustainable magnetic field. By examining the characteristics, parts, and variations of Earth's steady magnetic field, one may see the importance of Earth's magnetic field.

Characteristics of Earth's Magnetic Field:

To really understand all the different aspects of Earth's magnetic field, first, compare the magnetic field of Earth to a bar magnet with a North and South pole that is titled about eleven degrees from Earth's spinning axis. The eleven degrees is angle between the North Pole pointing toward North America at 71 degrees West longitude of Greenwich. The magnetic field lines will point outward from the north pole and enter the south pole.(11) This is why a compass works and the direction North can be determined because the North arrow is pointed the geographic North pole that is in reality the magnetic south pole(11). See figure below.



Reference 2

Magnetic field lines generated by the earth or any other object are not real entities. In reality Earth's magnetic field is a continuous function. Even though one compares the earth's magnetic field to a bar magnet, the bar magnet really doesn't drive Earth's magnetic field. The magnetic field of the earth is a dipole field generated by electric currents from Earth's liquid core, which is the Dynamo Theory discussed later in the paper. Earth's magnetic field is comparable a dipole field because the shape is the similar to that of two charges of an opposite sign of an electric field. The dipole moment (μ) of the Earth in SI units is $7.95 \times 10^{22} \frac{A}{m^2}$(Amperes per square meter). If one knows the area (radius of the loop of the liquid core is $3.48 \times 10^6 m$), and dipole moment of the earth, one can solve use $\mu = I * A$ $(I = current, A = area)$ to find an equivalent current to be $2 \times 10^9\ A$. (11) Furthermore, Carl Gauss, German mathematician and astronomer of the early nineteenth century, studied and found that the main dipole component is within the Earth and a spherical harmonic method for the analysis of Earth's geomagnetic field. The spherical harmonic method simply proves: the dipole component is from Earth's interior, may divide the different contributions of Earth's magnetic field into distinctive parts even including the non-dipole components of the field, and allows a geomagnetic coordinate system that helps measure collect, organize, and explain Earth's magnetic field. (4)

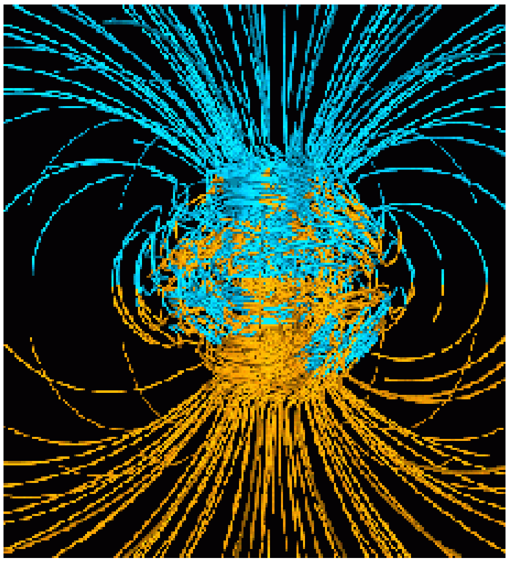
Earth's electromagnetic field can be described by Maxwell's equations. Maxwell's equations differentiates the direction of the two sources that is the colatitude, θ, and the longitude,$\emptyset$, are dependence upon distance, r. Gauss as mentioned above represents a solution to Maxwell's equations to represent spherical harmonics into two parts including external and internal currents. (4)

Although ninety percent of the geomagnetic field comes from Earth's interior, each of the part of Earth's magnetic field plays an important role in the earth's magnetic field. The majority, or the ninety percent of the geomagnetic field, comes from dipolar field specifically the core. Earth's core is unique by having a solid iron ball or the "inner core" that its' temperature is the same as the sun and seventy percent the size of Earth's moon (10). The solid inner core and outer liquid core interactions cause convention that carries heat through the earth's core when at rest. The liquid part of the core produces a magnetic field by being electrically conducting, some sort of magnetic field must already be present, and a force adds to the liquid such that the initial magnetic field is distorted by a Coriolis force. Founded by Gaspard-Gustave Coriolis a Coriolis force is simply "creates cyclonic storms in the Earth's atmosphere, and in the Northern Hemisphere it causes a fluid rising radial to rotate counter clockwise(6)." In addition to the ninety percent of geomagnetic dynamo which causes Earth's magnetic field, layers above Earth's interior including the ionospheric dynamo, magnetopause current, magnetotail current, and the field-aligned currents, help maintain a stable magnetic field 1. Each of the layers above Earth is dependent on the main geomagnetic dynamo. (6)

Another important point about the geomagnetic field is that since its produced by a electric current different aspects of the magnetic field are measureable. For instance B or the magnetic induction is like the electric field, E, which is proportional to force. The force is defined by the Lorentz-force equation. The force is the charge of q times the cross product of velocity, v, cross magnetic induction, B, or $F = q(v \times B)$. Since the magnetic field depends on the direction of the current or the direction of positive charges. The right-hand rule must be used to determine B.(4) The components of F have both vertical and horizontal components or more commonly known as X and Y components whereas the X component points northward and the Y component points eastward(9). The magnetic field is measured in the International System of Units (SI) in tesla (T) or volts per meter. Although within geomagnetism, Earth produces a small magnetic field that is measured in nanotesla units or a gamma. Such that $1\gamma = 1nT = 10^{-9}T$. The geomagnetic field can be defined at any point with the magnetic field by total intensity, declination, and inclination. The declination, D, is when the needle on a compass in a horizontal plane is has deviation from geographical North to magnetic North vertically. On the other hand, inclination (I) is when the needle of a compass makes an angle with the horizontal lines or a magnetic dip. (6)

The Dynamo Theory

Even though there are some variations about the origin of Earth's magnetic field, the Dynamo Theory is the only one considered in the present time. What the Dynamo Theory is when the Earth's core is thought to provide a source of energy and a product of this is the self-sustaining magnetic field. Instead of Earth's magnetic field being drawn from a giant bar magnet, the Earth is driven by a geomagnetic dynamo. The Dynamo theory basic idea is an electric motor or generator symbolizes what powers Earth's magnetic field. For instance, when an electric current goes through a metal wire, a magnetic field is created around the wire and this magnetic field will create an electric field. (13) The Earth is just like an electric motor or an electric generator due to the Earth's core. As previous described the outer layer of the core is liquid metal. This liquid ocean of the core is in constant motion and an electrically conducting fluid that causes an electric current. When this happens the electric current creates a secondary-stronger magnetic field. As the current increases, the magnetic field increases. The loop created is self-sustaining and part of the geomagnetic dynamo. (12) Earth's rotation creating the Coriolis forces plays an important role in the sustainability and origin of Earth's magnetic field. (11) The liquid core of the Earth along with the all the other components produce a greater magnetic field in comparison to that of just the liquid core.



Reference 7

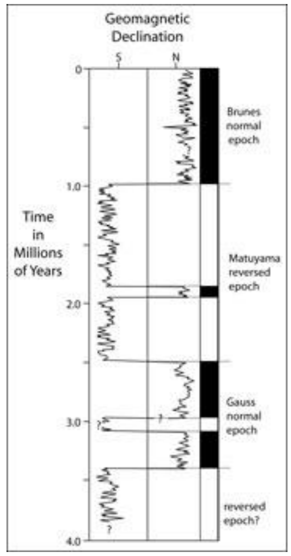
In the figure above this represents an example of the Dynamo theory with a computer aid design. The blues are where the field is directed inward and the yellow lines are where they are directed outward. As seen the lines come out from the earth and create a sustainable and potential field outside the earth's core. (7)

Variations of Earth's Magnetic Field

Earth's main field has sustained its strength throughout time as seen by paleomagnetic measurements. (9) Although the strength of the magnetic field is maintained, variations in the main field changes within the main field will occur. For example, secular variations, when a field may undergo just slight variations, my lead to a reversal in the magnetic field. The reversal of Earth's magnetic field, a larger scale variation, may lead to a secular variation. Secular variation is when geologic and physical processes changes. The actual variations are observed and can then be used to see if the main magnetic field will may reverse. (6)

As studies reveal, reversals in Earth's magnetic field does not occur in any sort of pattern. Over the past 71 million years there is only evidence for 171 reversals of Earth's main magnetic field. Earth's dipole moment reverses approximately 300,000 to 1,000,000 years taking about 5,000 years on the geologic timescale. (9)

Without a doubt Earth's magnetic field actually reverses by geographic evidence. A group of scientists Allan Cox, Brent Dairymple, and Richard Doell studied Earth's magnetic field's orientation. They did this by looking at volcanic rocks that had just acquired magnets after the volcano erupted. Volcanic rock is also known as basalt that is iron-rich. Then they used radioactive isotopes to figure out the dates of the reversals.



Reference 1

The figure above represents different times at which reversals of Earth's magnetic field could have occurred by geophysical evidence. (1)

The time scale from the variations in the magnetic field made figuring out the patterns of different magnetic differences on the sea easier to interpret if any changes occurred.

For instance, now the seafloor can be observed to see if the magnetic field does in reality flip. The seafloor is made molten basalt coming from the centers on the seafloor. Basalt contains magnetite, which is a strong magnetic mineral. After a volcano has erupted, due to being magnetic basalt cools such that the magnetic field's orientation is observed and spread symmetrically on the seafloor. (6). Thus the magnetic field orientation can be determined throughout geological history.

In addition to the seafloor being able to tell about reversal in the field, rocks give information on the dipole moment. For example, if a rock is formed at the magnetic equator it will contain a horizontal magnetization. Likewise, if a rock is formed at high or low magnetic latitude the field points up or down accordingly. (6)

Nevertheless, geological processes can give insight to a magnetic field reversing, but a reversal occurs very rapidly in which a geological process cannot explain the reversal. Thus Earth's magnetic field switching and the dynamo effect play hand in hand. This holds true due to the fact that the dipole moment is shrinking down to zero, keeping its direction, then it grows back to the strength as before with an opposite direction. Thermal convection, with the liquid core, has to amplify small changes in Earth's magnetic field to observe a growth of the magnetic field in the opposite orientation. (6)

Importance of Earth's magnetic field

Earth's magnetic field cannot be seen physically; yet, with some geographical evidence traces of it can be. Even if the magnetic field of the Earth is constantly changing, it provides benefits to all living/non-living organisms on this Earth.

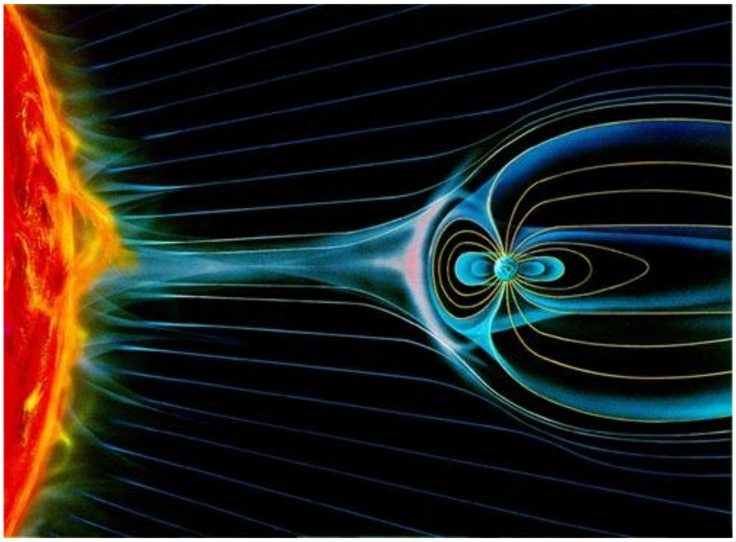
One of the main benefits of the magnetic field is that it is a compass. A compass works by a magnetized needle with a North and South ends balanced in a horizontal plane. The magnetized needle will point in the magnetic field vector. This tool has helped explorers find their way when they were discovering the New World. The magnetic field is a tool because the needle of a compass will always point to the magnetic South Pole or "north". Compass navigation was written about starting back in 250 B.C. and the Chinese were given credited for being the first to use the compass.

Reference 8

The picture above represents a Si Nan or a compass used for early navigation.

Another benefit of the magnetic field of the Earth it allows a magnetogram to be created. This is done by Earth's magnetic field being measured and recorded at numerous observatories. At these numerous locations there are reflecting mirrors with magnetized needles are "suspended by quartz fibers (6)". From the mirrors light beams are reflected and mounted on a photographic negative on a rotating drum. As previously stated, variations within the magnetic field may cause deflections. At such observatories the magnetic scale factors can vary from "2-10 nanoteslas per millimeter vertically and 20 millimeters per hour horizontally (6)". The magnetogram created has numerous applications of interactions between the Earth and the Sun, magnetic maps for surveying and navigation; and correction data from the oceans, air, and land for mineral and oil deposits. (1)

Instead of magnetic field of the Earth being just used for tool, it also provides protection from outside planet Earth. For example, Earth's magnetic field protects living things from harmful radiation from the sun. Furthermore, it creates a shield against solar winds from the sun. Solar winds made up of electrons and ions travels approximately 500 kilometers per second. Yet the solar winds are deflected since the magnetic field produces the self sustain loops and comet shape around planet Earth. As seen in the picture below. (3)



Reference 3

Conclusion

Earth's magnetic field provides the earth some of its' greatest features, even if there is still a lot about the magnetic field that remains a mystery. The origin of the earth is still unknown n; yet, the dynamo theory provides an insight of the existence of the magnetosphere. Earth's magnetic field came about due the interactions of the liquid core . This core has allowed a sustainable loop created to protect Earth's surface from harmful radiation and solar winds. Not only does the core provide protection, it also has allowed Earth's magnetic field to be uphold for thousands of years. The magnetic field is very sustainable; however, there are possibilities of a reversal. Such reversals where seen by volcanic rocks and rock layers within the ocean. Earth's magnetic field has provided many valuable resources when it comes down to navigation by driving a magnetic compass and drawing different field maps. Even when the magnetic field of the Earth is not fully known in detail, helped scientists and physicists alike learn a little bit more about the mysterious magnetic field. Many may not see the advantages of Earth’s magnetic field in everyday life; yet, it is still very remarkable benefits.

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