HONORS UNIVERSITY PHYSICS II

# The Origin of Earth's Magnetic Field and Theories on Polarity Reversal

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**11/29/2010**

The Encyclopedia Britannica defines a magnetic pole as “the region at each end of a magnet where the external magnetic field is strongest.”(Encyclopedia Britannica 2010) Every bar magnet has two poles: a north and a south. Much like a simple bar magnet, the Earth’s magnetic field is essentially a magnetic dipole. (Wikipedia 2010) In general, magnetic objects in or on Earth will orient themselves according to this dipole field – north to north and south to south. However, discoveries have been made since the early twentieth century of igneous rock within the Earth that has just about opposite orientation. These discoveries spurred the theory of geomagnetic reversal – a flipping of the Earth’s magnetic poles. (Jacobs 1994, 1) This paper will attempt to convey theories about the origin of the Earth’s magnetic field and information on the effects of geomagnetic reversals.

Over the years there have been dozens of attempts by renowned scientists to discover the origin of Earth’s magnetic field. In 1905, Albert Einstein stated that the problem regarding the origin of Earth’s magnetic field was one of the five most important problems in the subject physics that has yet to be solved. One of the first suggestions as to the origin of the magnetic field of the Earth came from William Gilbert. In *De Magnete* Gilbert proposed that the origin of the magnetic field of Earth is within the Earth itself. He suggested that there was a lodestone (presently called magnetite, a highly magnetic form of iron oxide) (Encyclopedia Britannica 2010) in the center of the Earth that produced a magnetic field. (Merrill 1983, 12-13)

Shortly after this theory came Renee Descartes’ explanation. Descartes suggested that the Earth’s magnetism was in relation to a number of what he called “threaded parts.” Descartes said that there were two types of threaded parts, those that entered the North Pole and exited the South Pole and vice versa. Also, some parts travelled through air while others travelled through the Earth. Those through the air would connect with those through the Earth at the Poles. Apparently, if these parts were to come across a lodestone, they would shift their paths and go through the lodestone. This was a very complex explanation, indeed. (Merrill 1983, 12-13)

In the 1940's and 50's a physicist named Patrick Blackett, Baron Blackett produced a theory that revolved around the idea that the angular momentum of astronomical bodies would create a dipole moment. Blackett tested his theory by attempting to measure a weak magnetic field generated of a pure gold sphere as it rotated. He used a super-sensitive magnetometer that was designed specifically for the experiments. His tests returned negative results, however, and his hypothesis, he said, was erroneous. A possible justification for Blackett's hypothesis lies in the fact that a rotating body that contained change separation would produce an external magnetic field. However, this possibility was debunked by D. R. Inglis in 1955 because of the temperature and pressure gradients of the Earth. (Merrill 1983, 13)

The dynamo theory is one of the most accepted theories as to how the Earth's magnetic field came about to date. This theory suggests that molten metal (mostly iron) within the Earth's outer core creates a self-sustaining dynamo. This dynamo moves the liquid metal across a weak magnetic field within the Earth, which creates an electric current. This rotating electric current produces a stronger magnetic field. This magnetic field also interacts with the fluid motion, helping to sustain it, and creates another magnetic field. These fields combined are stronger than the original magnetic field and are directed almost directly through the Earth's axis of rotation. (brit) This branch of physics is called magnetohydrodynamics or MHD. (Merrill 1983, 13)

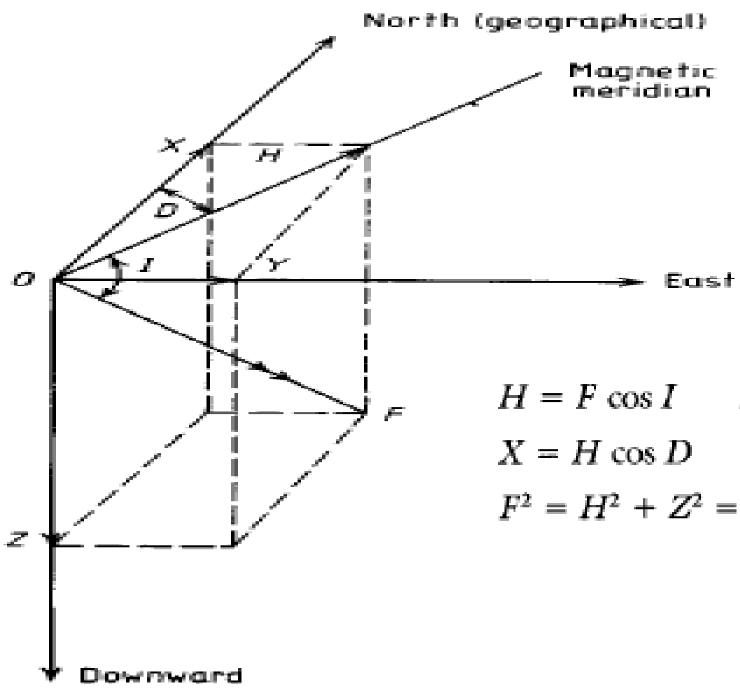
The first physicist to suggest a theory that a self-sustaining dynamo system could be the origin of the magnetic fields of celestial bodies was Sir Joseph Larmor in 1919. But, in the 1930's a British astronomer named Thomas Cowling "found" that it would be impossible for a magnetic field to be maintained if it is symmetric about a single axis. More anti-dynamo theoretical thinking surfaced until around 1970 when the work of G. O. Roberts and Stephen Childress disproved the existence of any general anti-dynamo theory. But before then great contributions were made to the dynamo theory by Walter Elsasser and Edward Bullard. In the mid to late 40's they became the first to propose the modern dynamo theory and actually put some math behind it. They were able to create models for a self-sustaining dynamo using magnetohydrodynamic theory. (McFadden 1996, 18)

Hannes Alfven was a Swedish physicist brought the magnetohydrodynamic theory a step further by applying Kelvin-Helmholtz theorems to perfectly conducting MHD fluid. In his 1942 paper he gave what is today known as Alfven's theorem: "Suppose that we have a homogeneous magnetic field in a perfectly conducting fluid. . . . In view of the infinite conductivity, every motion (perpendicular to the field) of the liquid in relation to the lines of force is forbidden because it would give infinite eddy currents. Thus the matter of the liquid is "fastened" to the lines of force…"(Gubbins 2007, 7) He also suggests that the magnetic flux for any surface moving through the field would be constant and that the conducting fluid would move in a sort of wave motion. Today, these are called Alfven waves. (McFadden 1996, 18)

One of the biggest controversies regarding the dynamo theory is figuring out how the geodynamo would be driven. More specifically what powers the geodynamo? If the liquid iron is flowing to create a magnetic field, then where is the energy coming from that is lost in creating the flow? There have been a few suggestions on how this energy may be transmitted. One theory is that the rotation of the Earth itself provides some of the energy for the dynamo to flow. However, this is unlikely because if it were true then the Earth would lose some rotational energy resulting in slower rotation and therefore longer days. One of the more plausible ideas is that of thermal convection within the Earth's core. This process would derive energy from the cooling of the Earth. As the dynamo uses energy the Earth loses it in the form of heat. This coincides with the idea that geomagnetic polarity reversals occur in relation to ice ages. If the Earth's temperature is too low, the dynamo would not be able to run and therefore could become irregular enough to change poles. Thermal convection could also occur in the presence of radioactive material within the core of the Earth. With radioactive decay, the materials would emit energy that could be obtained by the geodynamo system. Another form of convection that has been proposed is called compositional convection. This suggests a process of cooling and warming the iron core of the Earth. The inner core of the Earth is solid while the outer core is liquid. There is essentially a fluctuation of iron in which molten iron from the outer core is cooled and adds to the inner core. This process produces energy which could go into the geodynamo. (Gubbins 2007, 288-289)

Though the origin of the Earth's magnetic field is not definitively known, it definitely exists. Though the Earth's field may seem that it would be large because of the greatness of the Earth, it is relatively small. In fact, magnets such as the ones used in university physics labs produce a field that is hundreds of times stronger than that of the Earth. With that in mind it is easy to see how geomagnetism is delicate and precise business. This accuracy is exemplified in modern compasses. Any metal or magnetic field close to a compass can easily skew the readings. It is also imperative that a compass is held parallel to the ground. This is because compasses are made to rotate on a horizontal plane. However, there is some error that will always occur.

Declination is the difference on a compass reading between the magnetic north that the compass reads and the geographical north. In the northern hemisphere, the northern point of the compass will also dip slightly downward. This is called inclination. The declination, D, inclination, I, and total intensity, F, are used to identify the magnetic field at any point on Earth and are as related in Figure 1 and shown in Figure 2, where H and Z are the horizontal and vertical components of F, respectively. (Jacobs 1994, 1)




$$H = F \cos I \qquad Z = F \sin I \qquad \tan I = Z/H$$
$$X = H \cos D \qquad Y = H \sin D \qquad \tan D = Y/X$$
$$F^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2$$

**Figure 1**

**Figure 2**

As can be seen with the magnetic meridian, the geomagnetic poles of Earth are not exactly where the geographical poles are. The geomagnetic poles of Earth are located approximately at 79º N, 70º W and 79º S, 110º E. This makes the geomagnetic axis of the Earth about 11º off the geographical axis. (Jacobs 1994, 7)

Possibly the most peculiar part of the Earth's magnetic field is that the poles actually shift positions every few hundred thousand years (or so). Generally, the poles make just about a full 180º turn during a geomagnetic polarity reversal. Probably the first scientist to have hypothesized about geomagnetic reversals was Bernard Bruhnes around the beginning of the twentieth century. He found that at one period during the Miocene Epoch the magnetic South Pole had to have been the closest pole to France. Then, in 1929, a Japanese physicist named Matayuma observed a reversal of the magnetic poles of the flow of lava between Japan and Manchuria. However, it was not until right around the 1960's when substantial research was conducted on such lava flows. With the invention of K-Ar dating came a reliable way to find the age of certain samples of rock or lava. With such testing came the first Geomagnetic Polarity Timescales and magnetostratigraphic timescales. Figure 3(Jacobs 1994, 63) is an example of an early Geomagnetic Polarity Timescale or GTPS. The best way we have found to measure the occurrence of geomagnetic polarity reversals is by analyzing the outer crust of the earth near oceanic rifts caused by the shifting of tectonic plates. Knowing the rate at which the crust expands from the rift lets observers know the time period over which to project data. Essentially, as the crust slowly moves out of the rift the magma within it cools and is magnetized by the Earth's magnetic field. Recording and analyzing the magnetization of the cooled lava shows whether the Earth's field was normal or reversed when the crust first comes out from within the Earth. This is illustrated in Figure 4. (McFadden 1996, 175)

It is still a mystery as to why these shifts occur, and many say solving this mystery is essential to figuring out how the Earth's magnetic field exists in the first place. But while it is not known why they occur, physicists over the years have created their own unique models as to what may cause the shifts. (Gubbins 2007, 320-324)

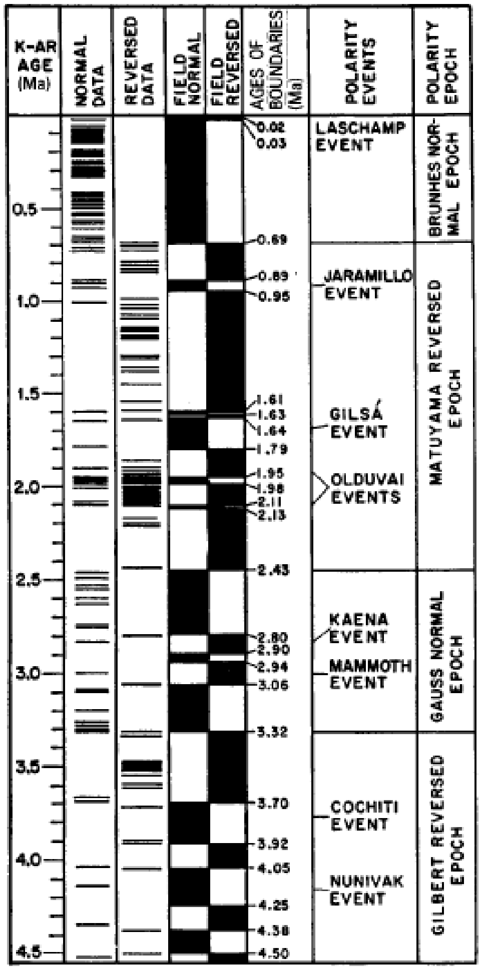



**Figure 3**

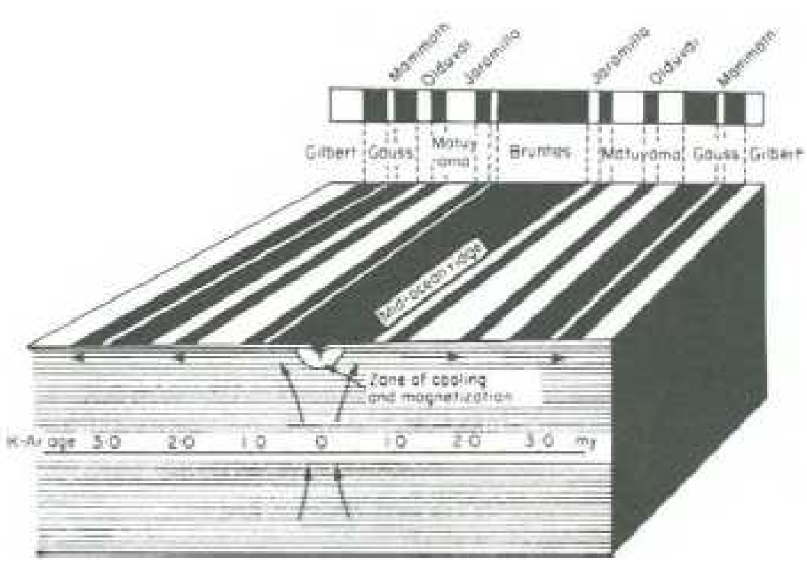



**Figure 4**

There are essentially two classes of theories as to why polar reversals occur. The first of these classes of theories suggests that the magnetic polarity reversal is a result of magnetic hydrodynamic instabilities that are caused by perturbations to the seemingly stable dynamo. Generally, these perturbations are thought to originate within the Earth, such as an irregularity in the patterns of convective flow of the liquid iron within the Earth's crust. Though external causes have been suggested, they seem very unlikely. The second class of theories on polar reversals suggests that the irregularity comes from the dynamo itself. It is suggested that because the Earth's magnetic axis is not exactly linear it does not need any perturbation to excite a reversal. Because it is non-linear, the dynamo that supposedly creates the Earth's magnetic field is by nature inclined to oscillate and therefore should have a pattern of reversals over time. The second set of theories also accounts for why geomagnetic polarity shifts are sporadic. Because the oscillation of the Earth's dynamo is irregular there would not be a standard time period between reversals. (Jacobs 1994, 124)

Reasonably accurate data has been collected regarding the geomagnetic reversals over the past 160 million years(Ma). It is apparent that the normal and reverse states of Earth's magnetic field have the same magnitude but opposite signs. It can also be concluded that the reversals occur in a small time frame relative to the time between them. It is suggested that reversals generally occur over a time period between seven and ten thousand years. From data that has been collected, it is apparent that from 160 Ma to around 118 Ma the frequency of reversals slowly lowered. At about 118 Ma the reversal process ceased which resulted in a very long paleomagnetic era called a superchron. During this time the polarity was normal (as opposed to reversed) but there wasn't really anything special about it; it just happened to last a long time. Right before 83 Ma the dynamo process shifted again resulting in a geomagnetic reversal at 83

Ma. Since then the reversal rate has been increasing steadily. It has peaked at approximately 12 Ma. This is just about all that can be concluded about the history of geomagnetic polarity reversals. Because the dynamo system is so sporadic there is almost no way of predicting a reversal. (McFadden 1996, 204)

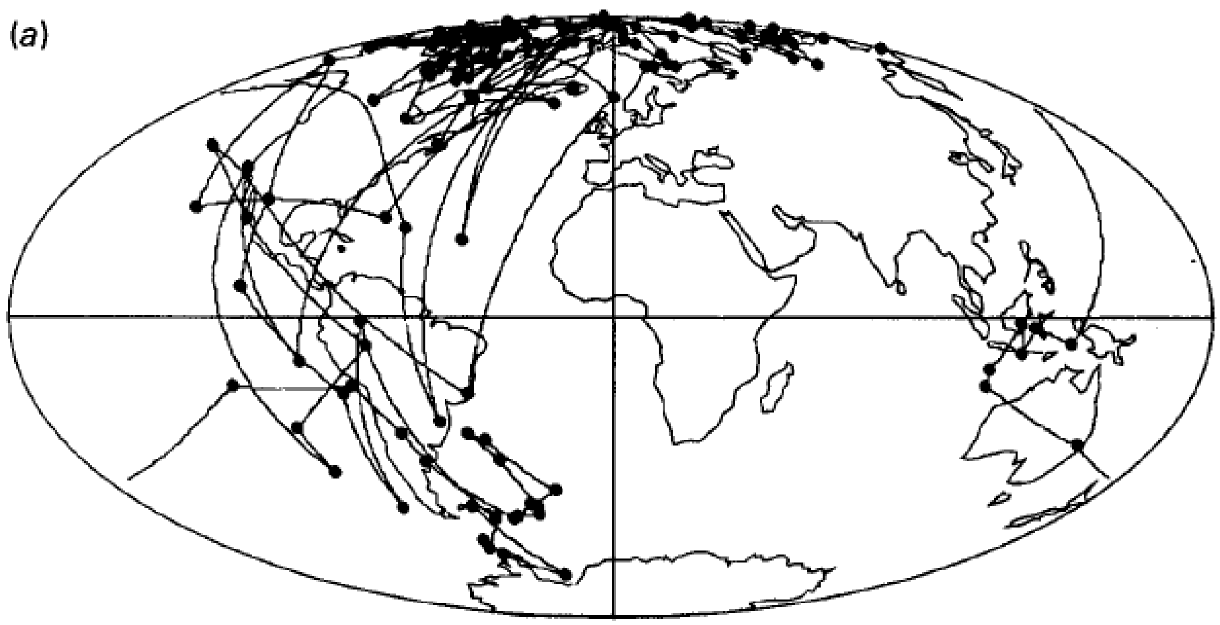



**Figure 5**

Figure 5 shows an example of the VGP (Virtual Geomagnetic Pole) trajectories of a reversal that has been named the "Blake Event." This occurred around 105 and 114 ka: a relatively recent event. The sedimentation rates suggest a duration of about five to seven thousand years. (Jacobs 1994, 107-109)

While there are probably hundreds of different models for a geomagnetic polarity reversal, most of them can be classified as one of two types: the 'standing field' model and the 'flooding' model. The standing field model suggests that the main dipole field and part of a nondipole field will decay to zero and then redevelop with an opposite polarity. This theory seems to be consistent with observations done to test for the path of the poles during a polar shift. The flooding model on the other hand proposes that geomagnetic reversal tends to begin in specific zones. According to the flood theory these zones have opposite flux of what they should have and grow until they eventually flood through the Earth's core and reverse the flux of the entire magnetic field of Earth. (Jacobs 1994, 124-125)

Similar phenomena occur much more often than polarity reversals. These are called magnetic excursions. Magnetic excursions happen when the geomagnetic axis moves rapidly askew from the normal (or reversed) geomagnetic poles but does not fully flip over itself. The consistency of these events agrees with the idea that the Earth's magnetic field is constantly fluctuating. It also agrees with the dynamo theory in that there could be times where the dynamo is not working as efficiently as normal or does not have a steady source of energy and allows a dip in magnetic field intensity. The phenomena also lend to a theory that there is some kind of threshold of irregularity that must be broken in order for a geomagnetic reversal to occur. Some physicists see magnetic excursions at "failed reversals." This mindset suggests that the magnetic field may purposefully need to shift every so often for one reason or another and that more often than not the attempt at reversal in unsuccessful. Either way, it is pretty accepted that the Earth's magnetic field and whatever creates is in a constant state of fluctuation. (Gubbins 2007, 294)

In conclusion, it can be said that there is a lot of information to learn about the origins and reversals of the magnetic field of the Earth. The subject, however, is relatively new, just about a hundred years old and actual tests on the subject on the subject started even more recently. As technological advances produce better ways to test and observe, more and more information will appear and hopefully a few of the questions about Earth will be answered while many more will probably be raised. It’s pretty reasonable to say, however, that the magnetic field won’t leave Earth any time soon.

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