Exploring the Nature of the Earth's Magnetic Field

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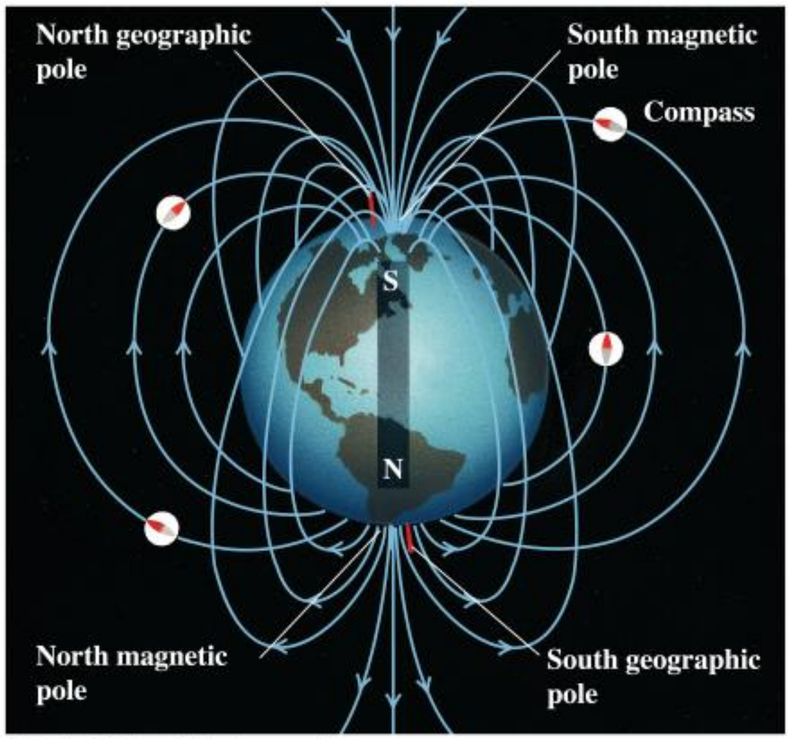
Section H1

The origin of the Earth's magnetic field has been a mystery to scientists and physicists alike for centuries. Though an exact mechanism for the existence of the magnetic field is not known, it is largely agreed upon in the scientific community that the prevailing theory is that of the Dynamo Effect. The purpose of this paper will be to explore exactly why the Earth emits the magnetic field that it does and why the field behaves certain ways under certain conditions. The paper will focus on the Dynamo Effect to attempt to answer the question, "How does the Earth get its magnetic field?" The Dynamo Effect will also be used to touch on the subject of the sustainability of the Earth's magnetic field. Furthermore, the paper will attempt to explore and describe the nature of the Earth's magnetic field, also commonly known as the magnetosphere. Finally, the benefits of the presence of the Earth's magnetic field will be examined.

The Earth's magnetic field is actually very similar to a bar magnet. A bar magnet is any material or object that produces a magnetic field. A bar magnet has a north pole and a south pole. These poles can be distinguished by the magnetic field that surrounds the magnet. The field lines of the magnetic field will flow outward from the north pole to the south pole. A compass is actually a magnet itself and will line up with the magnetic field of the Earth, thus pointing the arrow designated for "north" to the geographic North Pole which is, in all actuality, a magnetic south pole. (8) In geomagnetism, extremely small magnetic fields are being measured. The Earth's magnetic field is strongest near the poles. In all actuality, the magnetic field of the Earth is several hundred times weaker than the magnetic field between the two ends of a horseshoe magnet. (10)



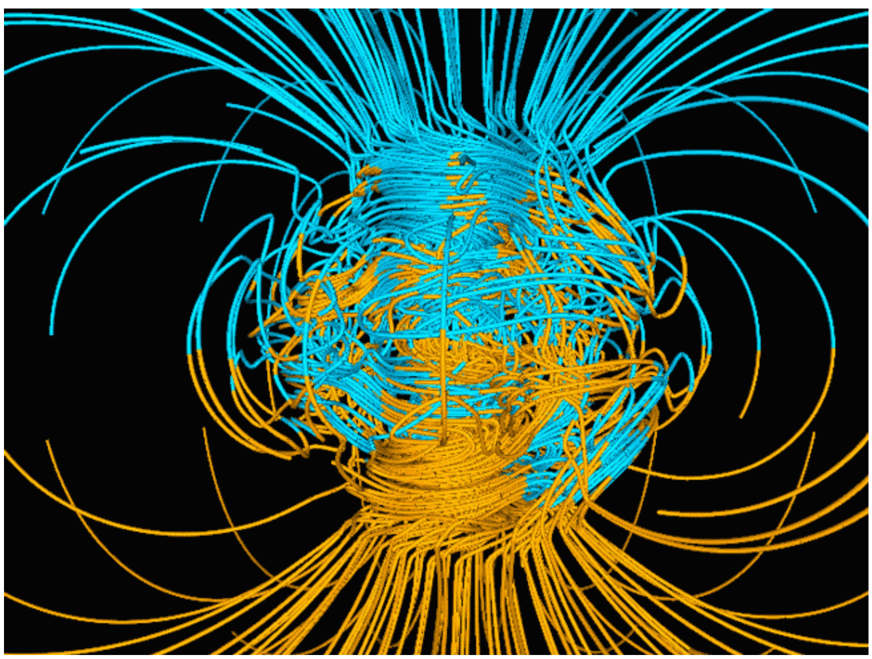
Reference: (2)

The above diagram shows in detail what has just been discussed. The geographic North and South Poles are actually magnetic north and south poles respectively. A compass will thus align with the field lines shown and will point towards the geographic North Pole or, as is clearly shown, the magnetic south pole.

The magnetic field lines mentioned above are not real entities. The magnetic field of the Earth, as with all other magnetic fields, is a continuous function. It exists at every point in space. When drawn with field lines, the magnetic field's direction and magnitude can be more properly visualized, but the field lines do not really exist; there is only the nature of the magnetic field itself. Since the magnetic field of the Earth is comparable to a bar magnet, it has the same shape as the electric field produced by two slightly separated charges of opposite sign; these opposite charges are the north and south magnetic poles of the Earth, mentioned above. Even though the dipolar field of the Earth is similar to a bar magnet, this does not mean that there is a giant bar magnet inside of the Earth. Its field is actually produced by electric currents within the Earth's liquid core; an explanation of this phenomenon has been attempted with the Dynamo Theory which will be discussed later in this paper. In SI units the dipole moment, μ, for the Earth is 7.95×10^{22} A/m2. Since μ = IA, a loop the size of the liquid core of the Earth with a radius that is approximately 3.48×10^{6} m would require a current of approximately 2×10^{9} A. (8)

The Dynamo Theory is the geophysical theory that explains the origin of the Earth's magnetic field. The theory was originally proposed by physicist Walter M. Elsasser and geophysicist Edward Bullard during the mid-1900s. (6) There have been other attempts to introduce supposed mechanisms for generating the Earth's magnetic field, but the Dynamo Theory is the only one seriously considered at the present time.

The exact details of the theory are not fully known or understood. In the general mechanism, the motion of fluid in the Earth's outer core moves conducting material across a magnetic field that already exists but is weak, and this motion generates an electric current. The conducting material in question is liquid iron. (6) In order for the field to be maintained, the outer core must constantly undergo convection. It is thought that heat from radioactive decay in the core is responsible for supplying the necessary convective motion. The electric current produced by the motion of fluid then produces a magnetic field. This field proceeds to interact with the same fluid, thus creating a secondary magnetic field. The rotation of the Earth plays a great role in the origin and sustainability of the Earth's magnetic field. The Dynamo Effect is based off of the model of the rotation of a fluid metal and a rotating conductor. The liquid iron in the outer core is simply not enough to create the magnetic field on its own. (9)



Reference: (7)

The above picture shows a computer simulation of the Dynamo Effect and the resulting magnetic field lines. Based on the Dynamo Theory, as presented above, portions of the outer core are constantly cooling and falling inward while parts of the liquid iron-rich inner core rise outward. This forces the currents into a helical motion when the spin of the Earth is introduced into the system. This computer simulation shows the resulting magnetic field lines; the blue lines are directed inward and the yellow lines are directed outward. (7)

As proof that the liquid iron in the outer core is simply not enough to create the magnetic field on its own, studies have been done on the composition of Venus's outer core. The planet Venus has a liquid iron outer core content that is very similar to that of the Earth. However, the rotation of Venus is approximately 243 Earth days. Because the planet Venus is spinning so slowly, there is simply not enough rotation to produce a measurable magnetic field. (11) Since two objects together produce a greater field than a single object alone, this clearly causes the strength of the resulting field to be greater than the original.

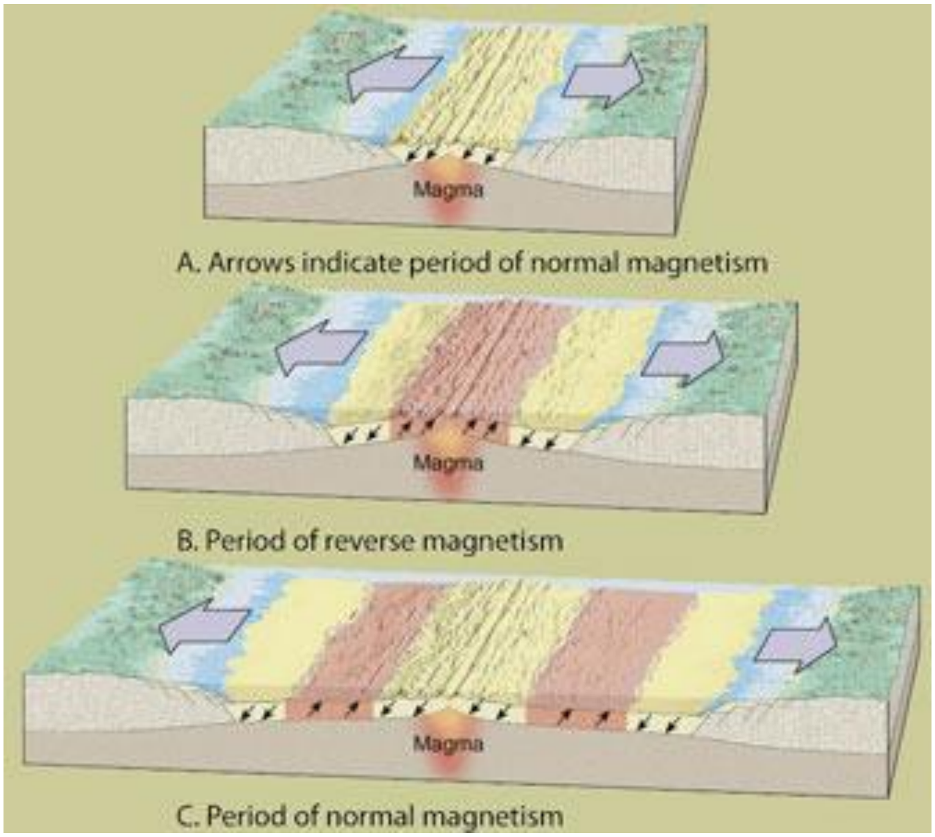
In the case of the Earth, the magnetic field is induced by the convection of liquid iron in the outer core, as stated previously. This convection is also the means by which sustainability of the Earth's magnetic field is achieved. Convection is the movement of molecules within liquids, and the presence of the liquid iron in the outer core allows for a continuous means of convection, thus successfully maintaining the Earth's magnetic field.

The work of Selkin *et al* in Stillwater, Montana, showed data of more than 100 measurements from a large reservoir in the area. From these measurements, they were successfully able to determine that the strength of the Earth's field 2.7 billion years ago was maintained to the present day. This is due to the sustainability of the Earth's magnetic field – even over a course of 2.7 billion years, there is no indication that the field’s strength either increased or decreased notably. (4) Even though the strength of the magnetic field was and is even now maintained, this does not mean that variations in the magnetic field do not ever occur. The field does indeed undergo slight variations, known as secular variations, and these secular variations often point to the approaching reversal of the magnetic field.

The reversal of the Earth’s magnetic field is a large-scale variation. It is not, however, the only variation that takes place in the magnetic field. At the surface of Earth, changes are continuously observed over time. These changes are known as secular variation. Indeed, these are the actual variations that are observed and are used to determine that the magnetic field will be undergoing a reversal relatively soon. (12)

There is evidence that 171 reversals of the Earth’s magnetic field have occurred over the past 71 million years. On average, the dipole moment of Earth reverses every 300,000 to 1,000,000 years. The switch occurs at a relatively quick pace – it only takes about 5,000 years. However, this time can vary greatly. Studies have not shown a particular pattern or periodicity in the reversals. (13) For example, a very long interval of N-S polarity may be followed by a significantly shorter interval of S-N polarity.

There is indisputable evidence that Earth’s magnetic field truly does reverse. The seafloor itself acts as something of a “magnetic tape” which captures the alternating field orientations. This is made possible by molten basalt flowing out of spreading centers on the seafloor. The basalt is an iron-rich, volcanic rock. It contains a strongly magnetic mineral known as magnetite. Its spread occurs in a symmetric pattern. Due to the magnetic characteristics of the basalt, it cools in such a way that the magnetic field's orientation is captured and spread along the seafloor. One such location is the Mid-Atlantic Ridge. (13) Study of locations such as these allows the determination of the field orientation at various points in time throughout the geological history of the Earth to be determined. An illustrative example of this is shown in the figure below.



Reference: (1)

Further evidence that the field does undergo reversal can be found in rocks. Rocks found near the magnetic equator show evidence of a horizontal orientation. As the latitude increases or decreases from the magnetic equator, the rocks will contain a field pointing up or down accordingly. (13) Older rocks can actually show the wandering of the field over time.

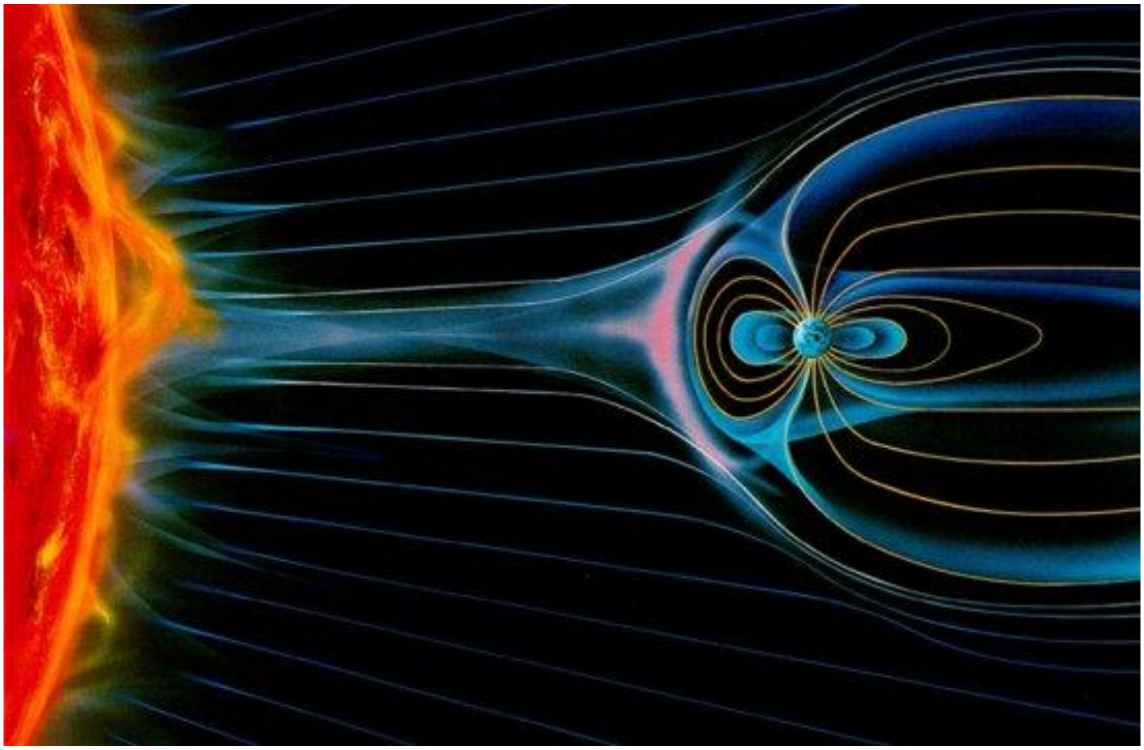
The magnetic field reversals happen so rapidly that they cannot possibly be explained only by geological processes. This means that the reversals must be caused by the dynamo effect, the mechanism that causes the magnetic field in the first place. The reversal itself is simply the shrinking of the dipole component to zero, keeping its orientation, then growing back to its former strength with an opposite orientation. However, this is not quite explanation enough. The minor changes in the magnetic field configuration have to be amplified by thermal convection – this allows the observed rapid growth of the field in the opposite configuration. (13)

A geomagnetic excursion is very much like a geomagnetic reversal. It is another significant change in the Earth's magnetic field. Unlike reversals, an excursion does not change the large scale orientation of the field. Instead, it represents a very dramatic yet relatively short-lived decrease in field intensity. This intensity can range from 0 – 20% of the normal field strength. It can last anywhere from a few thousand years to tens of thousands of years. (14)

The magnetic field of the Earth does not simply exist, and it is not just another component of the planet on which we live to be taken for granted. The Earth's magnetic field is beneficial to all of humankind. Not only was the magnetic field instrumental in the discovery of much of the New World, it is also key to the survival of all life on Earth on a daily basis as a mode of protection against the solar wind.

Now matter the geological position on Earth, a compass will point to the magnetic south pole. Long before high tech navigational aids, compasses were used as an easy and efficient means of determining the direction of "north" and effectively orienting one's self. The way a compass works has been previously outlined in this paper with reference to the magnetic field and its direction, flowing from the magnetic north pole to the magnetic south pole. The first person recorded to have used the compass as a navigational aid was Zheng He (1371-1435), from the Yunnan province in China. He made seven ocean voyages between 1405 and 1433. The magnetic compass is the oldest known instrument for navigation. (5) It has been a vital tool for navigators at sea for centuries. The classic magnetic compass would be of no use to navigators if not for the magnetic field of the Earth and its consistent orientation.

Another benefit of the Earth's magnetic field is the shielding effect is has against the solar wind. The solar wind is a stream of ionized gases that blows outward from the Sun at about 400 km/second. It can vary in intensity with the amount of surface activity on the Sun. The solar wind will approach a planet, and if the planet has a well-developed magnetic field, the particles will be deflected. This is clearly shown in the picture below. The Earth's magnetic field is capable of shielding the planet from much of the solar wind. As the solar wind encounters the Earth's magnetic field, it is deflected. An appropriate analogy would be that of water being deflected around the bow of a ship. For this reason, the imaginary surface at which the solar wind is first deflected is known as the bow shock. The corresponding space behind this region and completely surrounding the Earth is called the magnetosphere. This region of space is dominated by the Earth's magnetic field and largely prevents the solar wind from entering. (3)



Reference: (3)

For thousands of years, man has been aware of the presence of Earth's magnetic field. He has even used it to his advantage in navigation. Despite its existence and constant presence, the Earth's magnetic field mostly remains a mystery today. The Dynamo Effect, the major theory that is widely accepted in the present day, attempts to explain the phenomenon that is the existence of the magnetosphere. Due to constant convection and the presence of liquid-iron in the Earth's inner core, the field not only came into creation, it has been sustained for billions of years without a great fluctuation in magnitude. Though little change in field strength occurs, the direction of the N-S polarity does tend to switch on occasion, and evidence of this can be seen in rocks all over the world as well as on the basalt beds of the ocean floor. Even though the magnitude of the Earth's magnetic field is relatively small and goes unnoticed in day to day life, its benefits are notable. If not for the Earth's well-developed and highly stable magnetosphere, the surface of the planet would be bombarded by the solar wind coming from the surface of the Sun. The Earth's magnetic field remains a great mystery, but one which scientists and physicists are constantly striving to explain.

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