I. Introduction to Geomagnetism

The magnetosphere is one of the least familiar elements of Earth's environment in the typical physical science curriculum. Students may learn that it resembles a bar magnet, but what they seldom encounter is the "big picture." The magnetosphere, Earth's magnetic environment in space, is a vast collection of currents as well as multiple systems of matter and energy, spanning nearly a trillion cubic kilometers of space. The Sun affects these systems through its sporadic storm events, which can cause the magnetosphere to change drastically. These changes produce magnetic storms, and energized flows of particles that can cause aurora, satellite outages, and even electrical power blackouts. (http://image.gsfc.nasa.gov/poetry/tour/AAmag.html).

Other planets also have magnetospheres, such as Jupiter and Saturn. Venus does not have a magnetosphere. Mars has the remainder of a magnetosphere captured in its crust and left as crustal magnetic fields. There are times when comparing these magnetic fields to Earth's magnetosphere can be useful.

1.1 Earth's magnetic field in space

As you have probably read in other textbooks, magnetism is an ancient discovery. The earliest recorded description of magnetic forces occurred in China in 2637 B .C., when Emperor Hoang-ti's troops lost their way in heavy fog while in pursuit of Prince Tcheyeou. The Emperor constructed a chariot upon which stood a figure that always pointed south no matter how the chariot was pointed. Also, the Greek philosopher Thales of Miletus (640-546 BC) is credited with having conducted a careful study of lodestone and its magnetic properties, but this did not include knowledge of magnetic polarity or its directive properties within Earth's magnetic field —the basis for a true compass.

At the time of Columbus, magnetic compasses for navigation had been standard technology for at least several centuries, but it was on Columbus's first voyage in 1492 that he discovered the needle didn't point to True North (Pole Star) in some locations. In fact, the deviation was as high as 10 degrees west of True North.

To avoid an impending mutiny, it is claimed that Columbus altered the compass card to match the direction of the needle. This was very risky, because a nautical rule on the book stated that the penalty for tampering with a compass was that *"the hand which is most used would be fastened to the mast by a dagger thrust through it."* (Fleming, pp. 2)

Figure 1 - A standard compass

Substantial work on magnetism, particularly terrestrial magnetism, was described in 1600 by Dr. William Gilbert. In an introduction to his book ***De Magnete***, Gilbert debunks many of the older ideas of the causes and properties of magnetism. He attacked alchemists for their obscure language, and put many of the legendary claims for lodestone to direct experimental tests. One of these claims was that the lodestone's power, dulled at night, could be restored by a bath in goat's blood! One of Gilbert's most famous discoveries is that Earth is, itself, a magnet, which is why mariners' compasses work. He was the first to distinguish between magnetic and electrical attraction, and is credited with coining the term **electricity**. Next, it was Descartes who ultimately made "intangible and invisible" magnetic forces visible to the naked eye by inventing the iron filing method. He presented this technique in his ***Principles of Philosophy*** published in 1644, explaining that, "*The filings will arrange themselves in lines which display to view the curved paths of the filaments around the magnet...".*

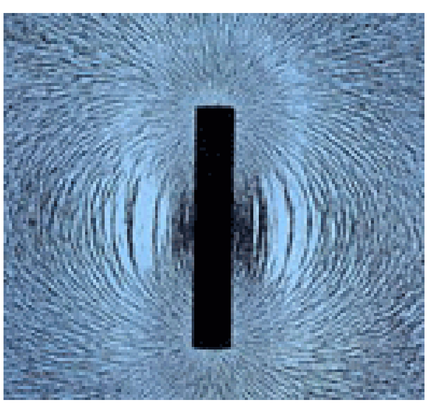

Figure 2 - Iron filings reveal the pattern of magnetic lines of force around a bar magnet.

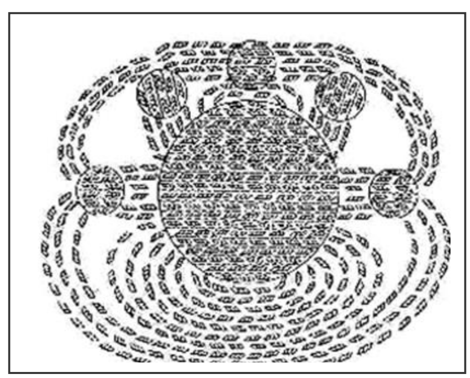

Figure 3 - Decarte's original sketch of the lines of magnetic force made in 1644.

The pattern revealed by the iron filings vividly illustrated that something extremely well organized existed beyond the surface of the magnet, and which was perhaps the origin of the magnetic force itself.

A compass works the way it does because Earth has a magnetic field that looks a lot like the one belonging to a simple magnet. The Earth's field is completely invisible, but it can be felt by a compass needle on Earth's surface, and it reaches thousands of kilometers out into space. If you were to study the Earth's invisible magnetic field from space by moving a compass around outside your spacecraft, you would discover that it doesn't really look like the field of a bar magnet at all, except in the inner magnetosphere — within about 50,000 kilometers of Earth.

The Sun has a wind of gas that pushes Earth's field from the left to the right, as in the picture below. Because of this external pressure, Earth's magnetic field gets stretched out into a comet-like shape with a tail of magnetism that stretches millions of kilometers behind the Earth, away from the Sun. Scientists have studied many different parts of Earth's magnetic field and have given them names.

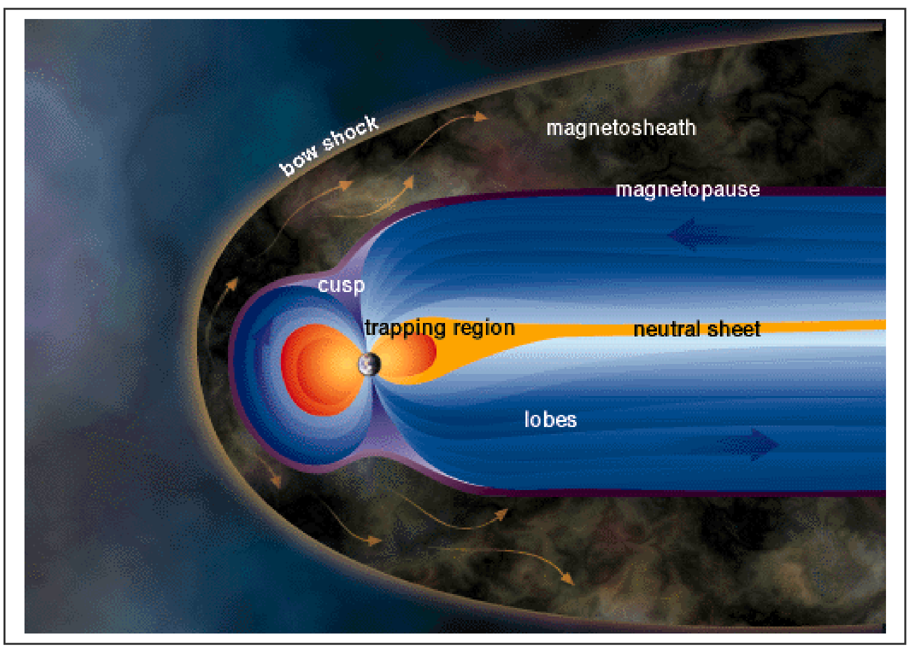

Figure 4 - Earth's magnetic field has a comet-like shape because the solar wind consists of electrified gases (blowing from the left to right) that interact with the 'magnetosphere' to give it its shape. This sketch shows the major regions identified by scientists.

The region around Earth where Earth's magnetic field influences the motions of charged particles is called the **magnetosphere**. Outside this region—what space scientists call the **Interplanetary Magnetic Field (IMF)**— the solar magnetic field is stronger than Earth's magnetosphere and the IMF dominates. The boundary between the magnetosphere and the IMF is called the **magnetopause**. The part of the magnetosphere that extends from Earth away from the Sun is called the **magnetotail**.

On the Sun side, the magnetosphere extends to a distance of about 10 Earth radii (10 **Re**) under normal solar conditions, but can be as little as 4 to 6 Re during severe solar storms. *(By the way, space scientists use this unit of measurement, the Re, much the same way astronomers use the light-year or parsec. It equals the radius of Earth: 6,378 kilometers.)* On the side away from the Sun, the magnetosphere is stretched by the solar wind so it extends a great distance. Its properties as a system can be measured to over 1000 Re. (For comparison, the moon orbits at a distance of about 60 Re .)

1.2 Origin of Earth's field

In your classroom, you can make a magnetic field by letting a current flow through a piece of wire wrapped around a nail. When you attach the battery, the nail becomes an **electromagnet** and you can use it to lift paper clips.

Figure 5 - Current flowing in a wire creates an electromagnet as shown in this cartoon sketch. The nail amplifies the magnetism enough for it to pick up a few metallic paperclips.

Geophysicists are convinced that the core of the Earth is also an electromagnet. If the main "dipole" field was "imprinted" on the Earth at its time of formation 4.5 billion years ago, it can be calculated that it would have dissipated into space within a few million years. Because

Earth is billions of years old and we still have a strong magnetic field, there must be something that regenerates this field from year–to-year and century-to-century, even over geologic ages. The best, and most likely, candidate is a magnetic dynamo process.

Although the crust is solid, seismic studies show that Earth's core is surrounded by a mixture of molten iron and nickel. The magnetic field of Earth is caused by currents of electricity that flow in the molten outer core. These currents carry trillions of amperes of electricity, are hundreds of kilometers wide, and flow at thousands of kilometers per hour as Earth rotates. Like currents flowing in a wire, they create the global magnetic field so long as these currents persist. They will continue to do so until the entire core of the Earth becomes solid in the far future, a billion or more years from now.

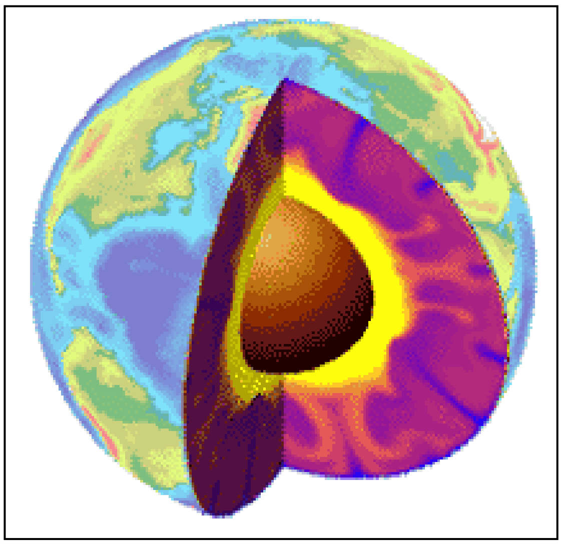

Figure 6 - A cut-away view of Earth's core showing the convecting mantle and core regions (Courtesy NASA)

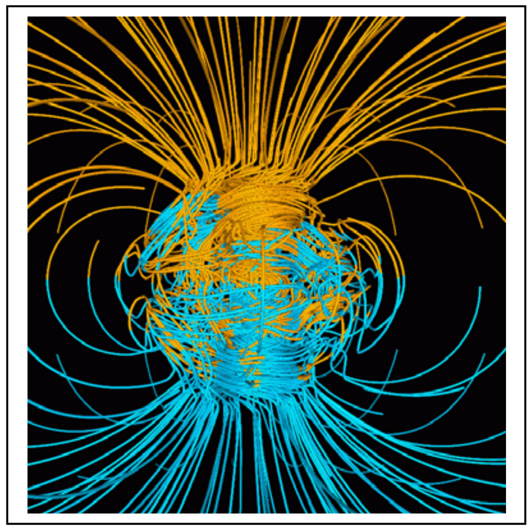

Figure 7 - Magnetic field generated by dynamo action (Courtesy *Gary A Glatzmaier - Los Alamos National Laboratory)*

The powerful magnetic field generated by this dynamo process passes out through Earth's core, through the crust that we stand upon with our compasses, and enters space. Figure 6 shows the solid inner core region (inner circle) surrounded by a molten outer core (in yellow). The currents flow in the outer core, and the lines of force (shown in Figure 7 in blue and gold) travel outwards through the rest of Earth's interior. If the electric currents in the outer core were stronger, Earth would have a stronger magnetic field.

By the time the field has reached the surface of Earth, it has weakened a lot, but it is still strong enough to keep your compass needles pointed towards one of its poles. As you recall from grade-school science classes, magnets have two POLES: a North Pole and a South Pole. Scientists call this a **dipolar field**.

There is another thing we know about magnets and magnetism: when you put like poles together (South facing South or North facing North) they repel each other. You can feel this force of repulsion yourself! When you put unlike poles together (South facing North) you can feel magnetic attraction.

In the Northern Hemisphere, your compass needle points North, but if you think about it for a moment, you will discover that the magnetic pole in the Earth's Northern Hemisphere has to be of a South polarity. This is so, because the North-type magnetism of the compass needle has to be attracted by a South-type magnetism in the Earth in order to 'seek out' the North Pole. In the GEONS lessons, we try to keep this from being too confusing by not using "North Magnetic Pole" and instead saying "the magnetic pole in the Northern Hemisphere."

1.3 The Crustal field

The Earth's crustal magnetic field is more complicated than a simple bar magnet dipole field, and much less intense than the main dipole field by nearly a factor of 100. Whenever molten lava solidifies on Earth's surface, some of the ferro-magnetic elements in the lava (e.g. iron, nickel etc.) align themselves with the local dipole field. Once the lava cools below the Curie Point (about 800 F), the ferro-magnetic atoms can no longer move freely, and so their magnetic orientation is frozen in.

The process is not 100% effective, so the magnetization of this crustal magma is very weak, but it can be easily detectable with suitable equipment. In fact, prospectors for various commercially important ores and minerals use sensitive magnetometers to scan the surface for magnetic enhancements over the much stronger dipole field.

Although the dipole field (~ 50,000 nanoTeslas at the surface) changes from day to day, and century to century, the weak crustal field (~ 800 nanoTeslas) is only affected by new volcanic activity, continental drift and orogenic processes. The entire land surface of the United States has been magnetically surveyed over the last century. Figure 8 is a map of the magnetic variations in Finland. There are rich deposits of iron ore in the region that stand out as the deep red blotches in the field map.

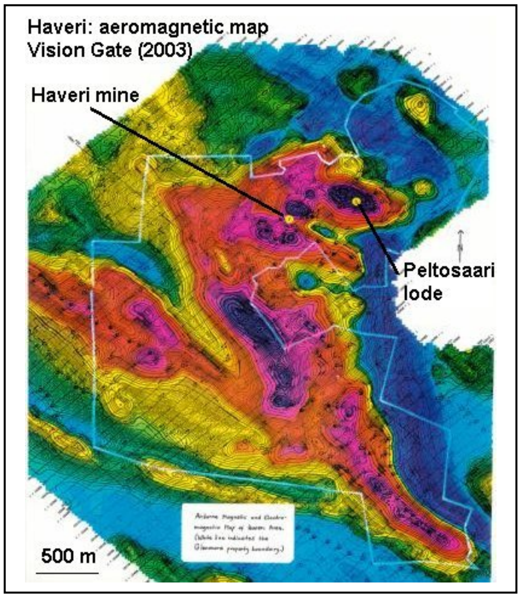

Figure 8 - Map of magnetic field changes over Finland. Red indicates regions with stronger fields due to iron deposits. (Courtesy Geological Survey of Finland)

Although geologists prospecting for minerals and fossil fuels have surveyed the local conditions of this non-dipole crustal field for years, only recently have scientists accurately surveyed by satellite the global dimensions of this crustal field. Satellite mapping of magnetic anomalies has been conducted, for example, by Magsat between 1979-1985. The data revealed many variations in the magnetic field that can be traced to major geologic and crustal features. Figure 9 displays the variations in this field:

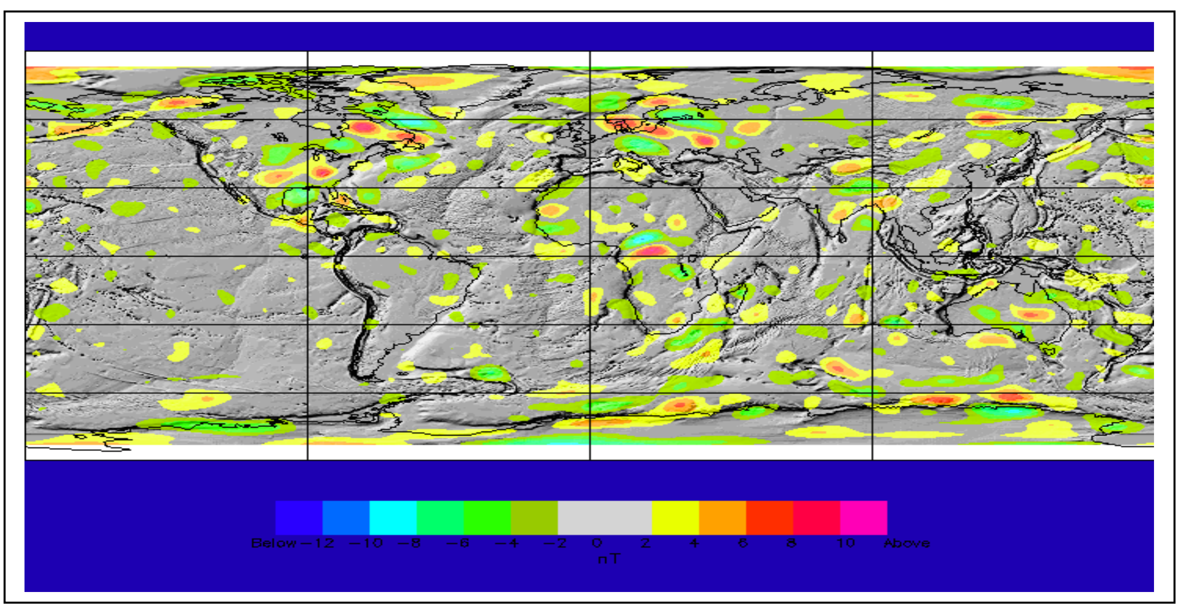

Figure 9 - Variations in Earth's global magnetic field measured by Magsat from an orbit of 400 km. (Courtesy NASA)

What you can see in the map above is that the blotchiness of the surface field doesn't seem to follow the concentrations of the land masses. They also don't follow the Pacific Rim where lava flows are common. Instead, they trace a deeper level of the Earth within the mantle and outer core.

1.4 The wandering dipole field

The magnetic poles of Earth are not fixed on the surface, but wander quite a bit, as the map in Figure 10 shows. The black line with red dots and years shows that the magnetic pole in the Northern Hemisphere is moving northwards in geographic latitude. The scale in this figure is 1cm = 133 km. Figure 10 shows how the average speed the magnetic pole moved an average speed of 10 km/year from 1955-1975 and then 20 km/year from 1975 to 1995.

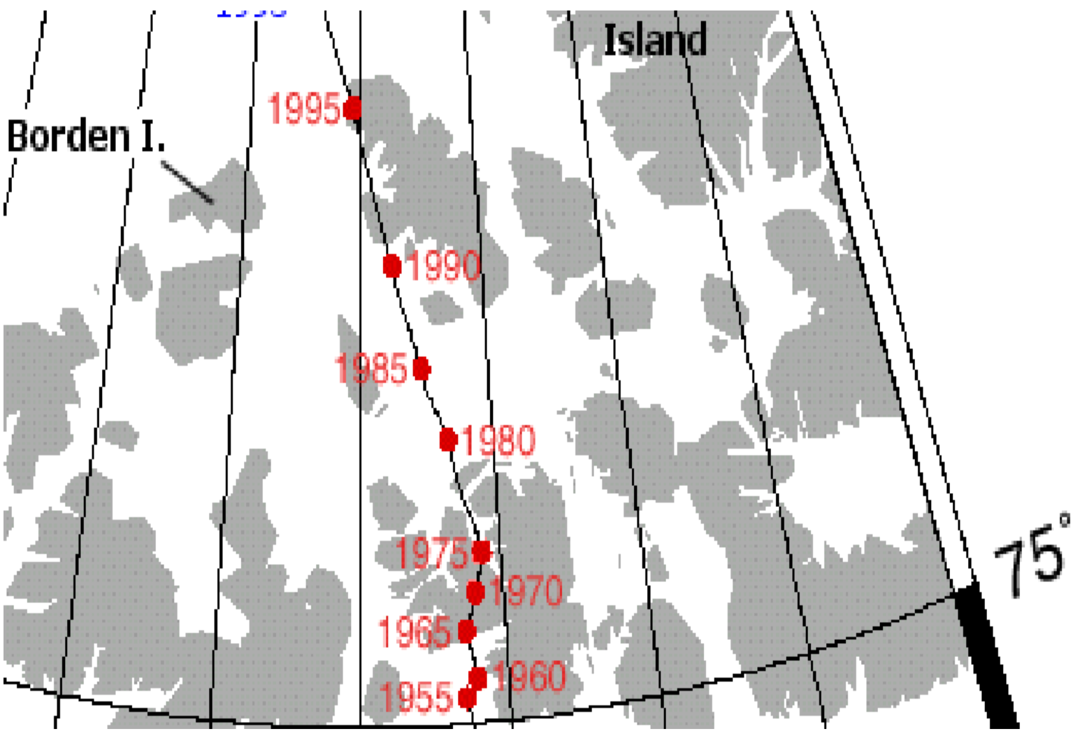

Figure 10 - A map of the track of Earth's magnetic pole in the Northern Hemisphere in Canada. The scale in this picture is 1 cm =133 cm. (Data Courtesy of the United States Geological Survey)

On any given day, the magnetic pole moves erratically by many tens of meters because of changes in the currents inside Earth's core, as well as the influence of electrical currents in the ionosphere, and the changing space environment due to solar storms and winds.

1.5 Paleomagnetism

Studies of the Mid-Atlantic Ridge in the Atlantic Ocean, halfway between North America and Europe, have shown that as the fresh rock cools, it records the polarity of Earth’s field. By dating the rocks on either side of the ridge, geologists discovered that the polarity changes over the course of thousands of years. This was an exciting discovery that not only verified the theory of Continental Drift, but demonstrated that Earth's magnetism isn't constant over millions of years. The magnetic field of Earth actually changes its polarity over time. They are called **Polarity Reversals**, but should not be confused with the rotation of Earth actually changing.

Figure 11 shows a plot of the changes in the dipole field strength and orientation during the last 800,000 years as collected by Yohan Guyodo and Jean-Pierre Valet at the Institute de Physique in Paris and published in the journal *Nature* on May 20, 1999 (page 249-252).

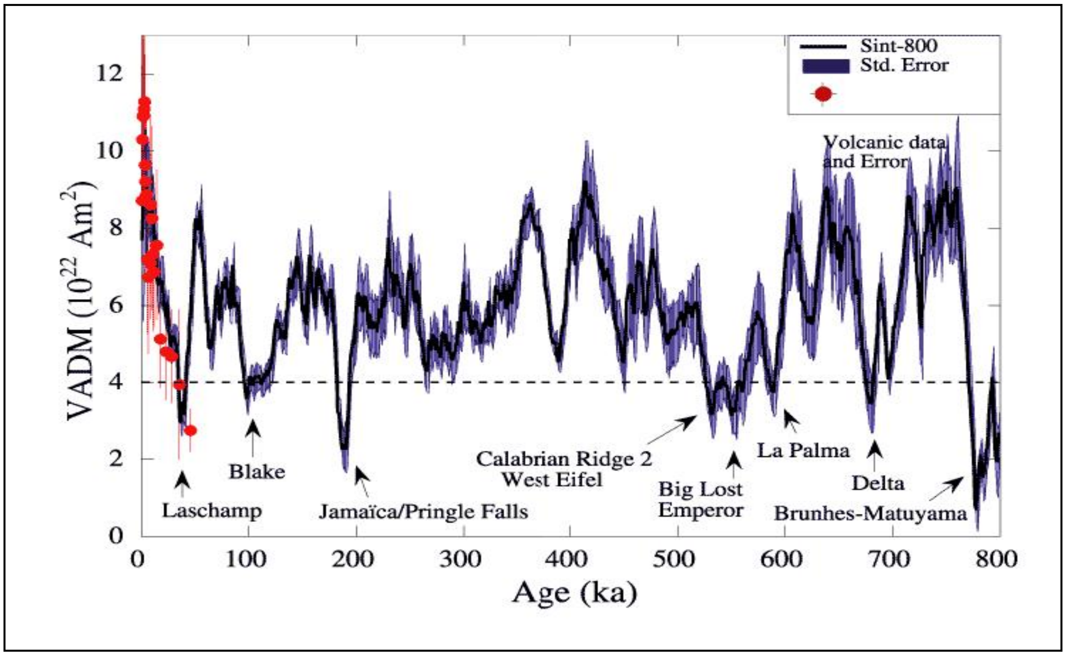

Figure 11 - The changes in Earth's dipole magnetic field strength and orientation during the last 800,000 years. 'VADM' refers to the magnitude of the virtual axial dipole moment of Earth.

There have been about 170 of these reversals during the last 76 million years, according to geological evidence. The mean time between reversals seems to be growing longer, and is currently about 300,000 years or so. The last one of these happened about 770,000 years ago (770 on the above graph). We are currently living during a period that has been called the **Brunhes Magnetic Chron,** when the South Magnetic Pole is in the Northern Hemisphere. During the previous Matumaya Magnetic Chron, the North Magnetic Pole was in the Northern Hemisphere!

These reversals can happen very quickly in terms of geologic time scales, also, in some cases much less than 10,000 years. Presently, Earth's magnetic field is weakening in strength by 5% every 100 years. It may be near zero in another few thousand years at this rate! Science fiction movies such as ***The Core*** not withstanding, the likely impact of a field reversal on the biosphere is negligible based on the fossil records for past reversal episodes.

Earth is not the only planet that has recorded the planet's history of its magnetic field. Mars also has regions which have recorded a strong global magnetic field. On Earth, this global magnetic field is constantly regenerated by the dynamo process. On Mars ,this mechanism is no longer operating and only the fossil traces of it where ancient, molted crust solidified and took on the magnetic field. These regions are known as crustal magnetic fields. It is thought that perhaps Mars had a thick atmosphere but that the loss of the global magnetic field has taken away the shield protecting it from the solar wind. The idea is that this would lead to a loss of Mars' atmosphere.

1.6 Magnetic Fields in the Universe

For thousands of years, mariners have used the Earth's magnetic field as a compass to find their way to safe harbor. The Earth's field looks similar to the magnetic field of a common bar magnet. Every square foot of the Earth is pierced by a line of magnetic force, which loops from deep inside the Earth, and far into space, only to return back in a great closed circuit thousands of kilometers away. The axis of the field is tilted by about 11.5 degrees to the axis of rotation of Earth. It is a mystery why this is so.

No one knows why, but these kinds of offsets between the magnetic and rotational axis are found among the magnetic fields of some of the other planets shown in Table 1. It doesn't have much to do with any other obvious planetary property that we know of.

Table 1: Magnetic Data for the Planets

Planet	Offset (degrees)	Strength (Teslas / m^3)	Fluid
Mercury	~14	6×10^{12}	Fe-Ni
Earth	11.5	8×10^{15}	Fe-Ni
Jupiter	10	1.66×10^{20}	Metallic H
Saturn	0	4.6×10^{18}	Metallic H
Uranus	59	3.9×10^{17}	Unknown
Neptune	47	2.16×10^{17}	Unknown

The Sun and planets in our solar system are not the only bodies known to have magnetic fields. Astronomers have been able to determine that some dark, interstellar clouds several light years across—similar to the one shown below—may be partially supported against gravitational collapse by internal magnetic fields or gas turbulence.

Figure 12 - A typical dark interstellar cloud illuminated by a star behind it. (Courtesy NASA-Hubble Space Telescope)

These fields are a thousand times weaker than Earth's magnetic field, but fill up a volume of space many cubic light years in size. Table 2 summarizes some of these field strengths in typical young, star-forming objects.

Table 2 - Properties of Interstellar Clouds

Cloud Name	Field Strength
CB 26	74 microGauss
S-106	1000 microGauss
TMC-1	40 microGauss
M17-SW	300 microGauss

Astronomers have also detected magnetic fields within clouds of plasma ejected by massive black holes in the cores of some galaxies. Figure 13 spans 1 million light years from edge-to-edge and shows a pair of gas clouds supplied by magnetically-focused beams of plasma from the core of the galaxy, seen only as a spot of light at the center of the image.

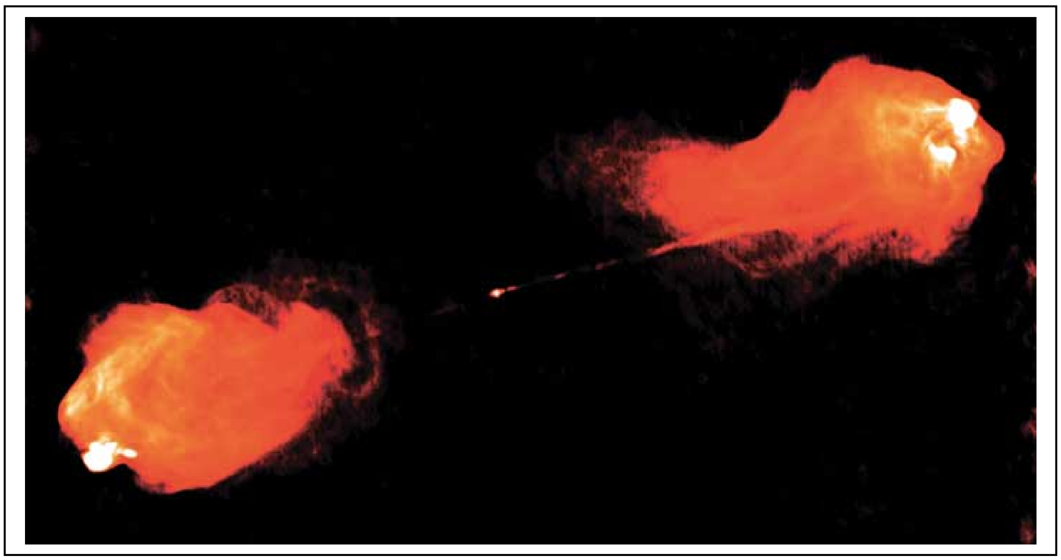

Figure 13 - The radio galaxy Cygnus-A (Courtesy NRAO)

If there were no Sun or solar wind, Earth's magnetic field would extend far beyond the orbit of the moon, and millions of kilometers into interplanetary space, in the same shape as a bar magnet field outlined by iron filings. In reality, the action of the solar wind changes this picture rather dramatically. As figure 14 shows, on the daytime side (left), the field shown with the turquoise lines, is pushed-in by the solar wind pressure, and on the nighttime side (right), it is invisibly stretched out like a comet's tail.

As Earth rotates, and as the solar wind and solar storms buffet it from the outside, the magnetosphere trembles and can become unstable. When these rapid, though subtle, changes take place, compass bearings can become unreliable by up to several degrees at Earth's surface. In space, even more dramatic changes can happen.

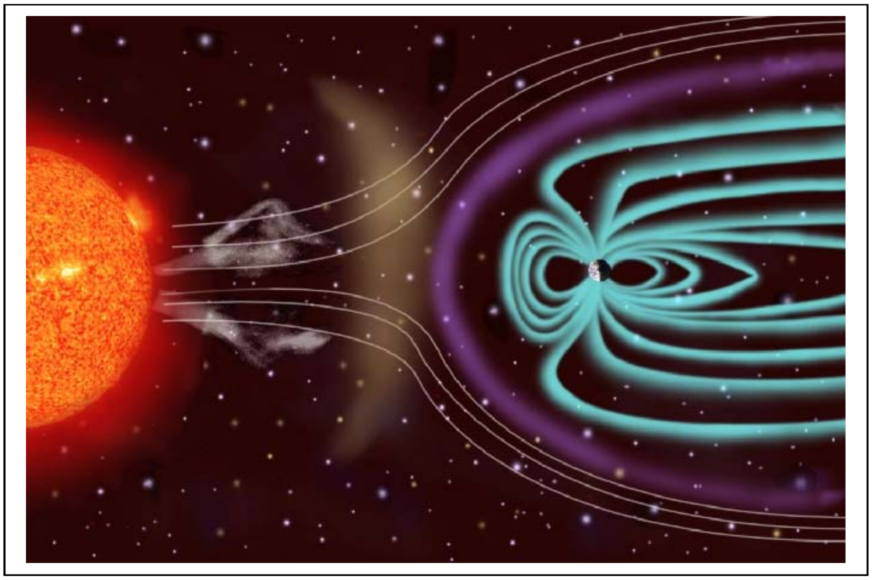

Figure 14 - A cartoon sketch of the Sun's interaction with Earth's magnetic field. Note, none of the elements are drawn to scale!

When the solar wind and the magnetosphere are taken together as a system, they operate like a set of powerful, but invisible, valves that open and close depending on their polarity. When the solar wind's magnetic field is of the south-type polarity, it meets up with Earth's magnetic field at the daytime side of the magnetosphere. Here, Earth's field points north as shown in Figure 16. These fields are opposite in direction and reconnect, causing a transfer of particles and magnetic energy into Earth's magnetosphere from the solar wind. **Severe magnetic storms** are triggered, and these can be easily seen even at ground level with sensitive magnetic field detectors called **magnetometers**.

Changes in the solar wind and in the magnetosphere can also cause the magnetotail region to change in complex ways. As we mentioned in Section 1.1, the magnetotail resembles a comet's tail and is stretched by the solar wind into a vast cylinder of magnetism over one million kilometers long. Magnetic fields in the magnetotail can snap like rubber bands and reconnect themselves (See Region C in the figure below). Magnetic energy is liberated during the reconnection process, and causes charged particles and plasma to be boosted in energy. The particles flow down these field lines and plunge deep into the interior of the magnetosphere cavity (see left-directed arrow near Region C) and are detected as "Bursty Bulk Flows." Other particles flow outwards (right-directed arrow near Region C) and are ejected from Earth as plasmoid clouds which travel into interplanetary space.

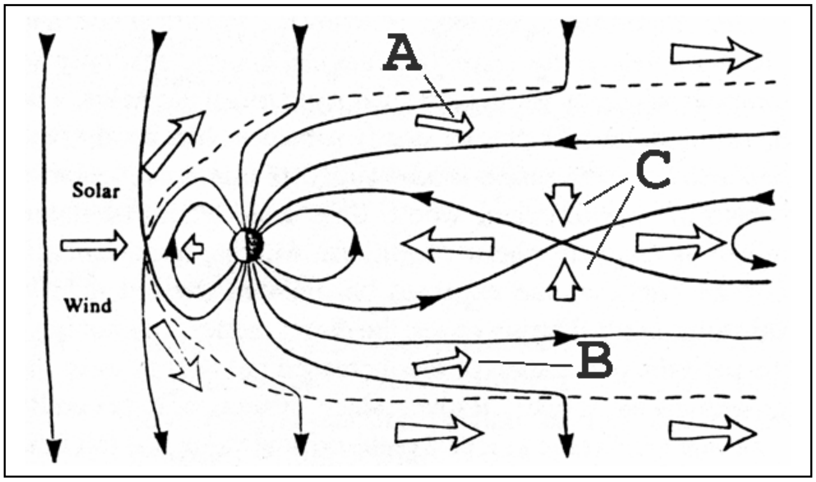

Figure 15 - A drawing of magnetic field lines in the magnetosphere. The solar and terrestrial fields can reconnect, causing plasma and magnetic motions shown by the arrows.

Some of the particles moving toward Earth enter the Current Disruption Region and take up temporary residence in an equatorial zone called the ring current shown in Figures 16 and 17. In this vast, invisible river circling Earth, nearly 40,000 kilometers wide, positively-charged particles flow westwards and negatively-charged particles flow eastwards like two trains on the same track. Unlike the eminent collision between the trains, however, the flows are so dilute they actually occupy the same volumes of space with little interaction.

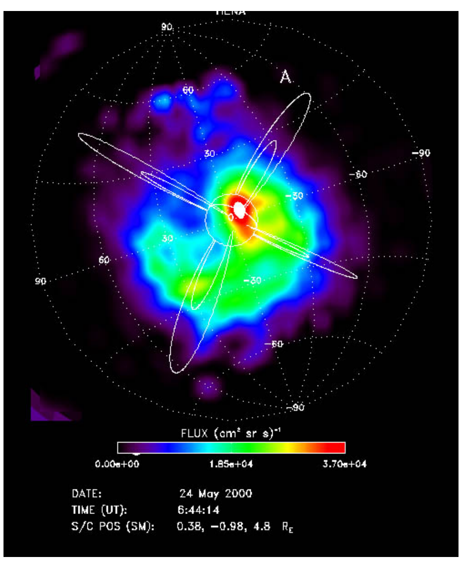

Figure 16 - An image of particles in the ring current after a strong magnetic storm. Earth is outlined as a sphere, with some representative magnetic field lines drawn-in. (Courtesy -IMAGE)

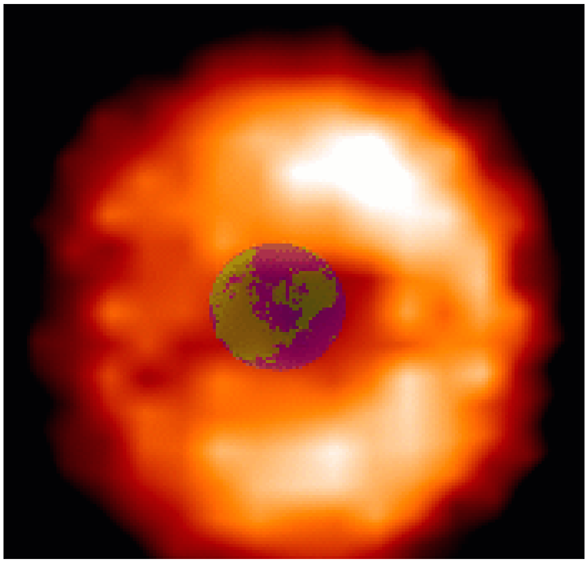

Figure 17 - An image of particles in the ring current during quiet times between storms. (Courtesy IMAGE)

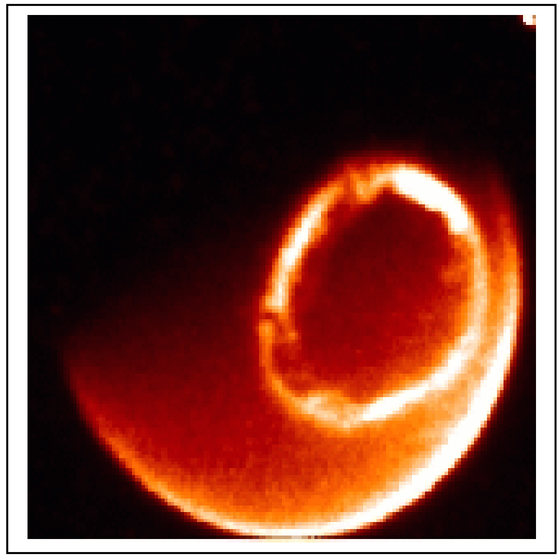

Figure 18 - The auroral oval images from space is a nearly perfect circle. (Courtesy IMAGE)

Other particles from the magnetotail ride the field lines deep into the Earth's atmosphere and create beautiful aurora. These are called Field Aligned Currents (or FACs). From space, Earth's Polar Regions are encircled by two halos of light called the Auroral Oval as shown in Figure 18.

It is a common fallacy found in many textbooks, that aurora are caused by flows of particles directly from the Sun. This is not the case for most aurora. The most spectacular and familiar ones are created by particles within Earth's magnetosphere, and specifically from the magnetotail region above the night-time hemisphere.

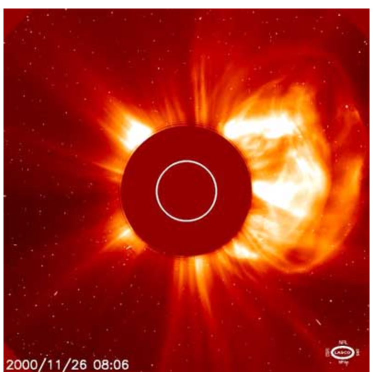

Figure 19a -Coronal Mass Ejection (CME) ejection (SOHO)

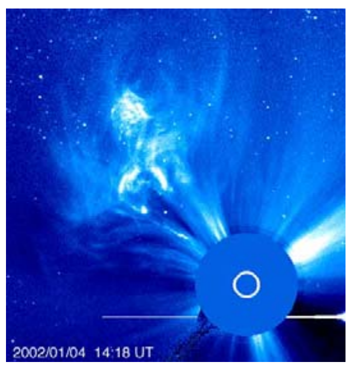

Figure 19b - CME ejection (SOHO)

As the solar wind flows outward from the Sun and encounters Earth's magnetic field, it compresses Earth's field on the side toward the Sun and stretches it out on the side away from the Sun. Severe solar storms, called **Coronal Mass Ejections** (CME) can produce major disturbances in Earth's magnetic field that last for many days at a time and cause Aurora, as well as occasionally triggering satellite outages, and electrical blackouts on Earth.

The images in Figure 19, taken with the Solar Heliospheric Observatory (SOHO) satellite show two spectacular CME events. These images were obtained by the satellite, which created an artificial 'total eclipse' with a circular plate placed over the bright solar disk. Conditions on the Sun, and the related solar wind, are not constant over time. When the Sun is at the active stage of the approximately 11-year solar cycle, solar flares and Coronal Mass Ejections are more common. There have been 22 of these sunspot cycles since the mid-1700's, when these cycles were first discovered. The diagram in Figure 20 shows some of the more recent solar cycles. The end of Cycle-23 occurred in 2006. We are now in sunspot cycle 24.

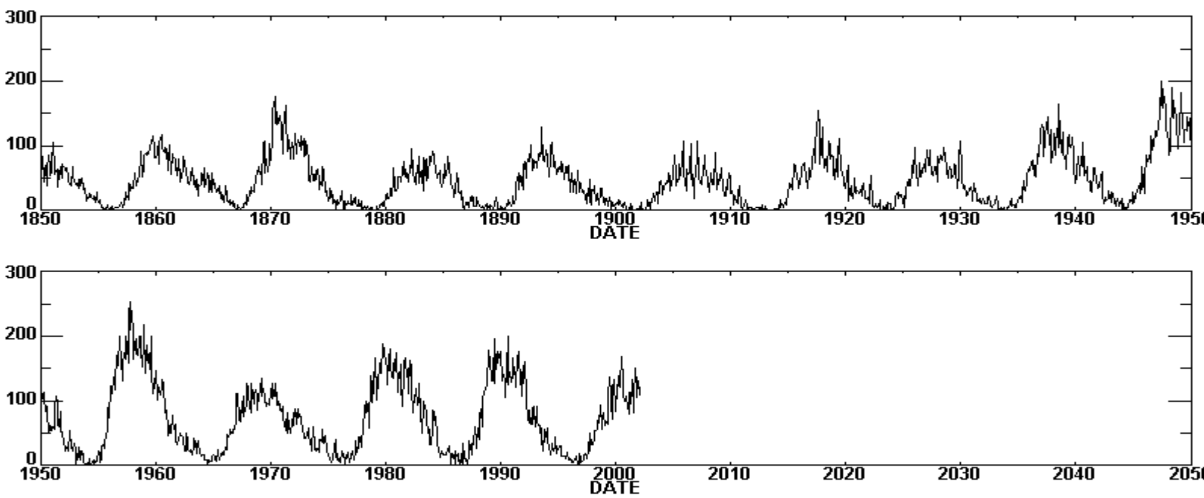

Figure 20 - The number of sunspots over a 150 year interval. The Sun is more active when more sunspots are seen near the peak of each cycle.

This increased solar activity can result in frequent large-scale disturbances of the magnetosphere called **magnetic storms**. The most common effect of a magnetic storm is an increase in the intensity of the **Aurora Borealis**, or Northern Lights. In the Southern Hemisphere, they are called the **Aurora Australis** or the "Southern Lights." During severe solar storms, both Polar Regions sport haloes of light in a phenomenon called auroral conjugacy.

1.7 Mathematical Model of the Dipole Field

Because the magnetic field of Earth is a key player in the transport and transformation of energy from solar storms into the upper atmosphere, a tremendous effort has been expended in understanding the details of terrestrial magnetism. The magnetic field of Earth can be described as a three-dimensional vector at each point in space,

Equation 1 $B = Bx\,\mathbf{X} + By\mathbf{Y} + Bz\mathbf{Z}$

Where, **X, Y** and **Z** are the coordinate unit vectors, and the magnitude of the field in each direction is described by the equations:

Equation 2 $Bx = 3xz\ M\ /\ r^5$

Equation 3 $By = 3yz\ M\ /\ r^5$

Equation 4 $Bz = (3\,z^2 - r^2)\ M\ /\ r^5$

Equation 5 $r^2 = x^2 + y^2 + z^2$

where M is the Earth's magnetic moment along the Z axis and is given by $M = 30{,}000\ Re^3$, and the x, y and z coordinates (with an origin at the center of Earth) are expressed in units of Re.

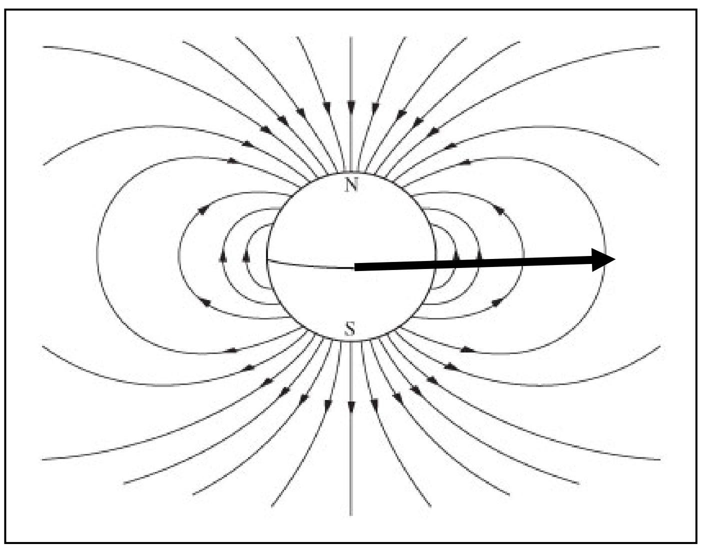

Figure 21 - Lines of magnetic force based on equations 1-5, showing the 'dipole' shape. The straight black arrow represents **L** in polar coordinates.

Exercise 1. A space physicist wants to design a satellite magnetometer to measure the strength of the geomagnetic field at a location given by the xyz coordinates (discussed above) in units of Re as (1.5, 3.1, 10.4). What will be the predicted strength of the field at this location in space?

Answer: Near the surface of Earth, scientists define the X, Y and Z coordinate unit vectors, **V**, in such a way that Y follows the lines of longitude, X follows the latitude great circles and Z is in the vertical direction towards the local zenith. The Bx and By components lie in the local horizontal plane and the angle between them is the so-called magnetic declination angle D measured positively eastward. This angle is familiar to anyone that has had to use a magnetic compass to navigate with a map. One can also define the magnitude of the horizontal component of the magnetic field as

Equation 7 $$H = (Bx^2 + By^2)^{1/2}$$

The remaining component along the Z-axis, measured to be positive downwards and negative towards the local zenith, gives the Dip Angle, I, according to

Equation 8 $$\tan(I) = \left(\frac{Bz}{H} \right)$$

The total magnitude of the magnetic field vector is about 0.5 Gauss units or equivalently 50,000 nanoTeslas (nT).

Exercise 2. Using polar coordinate paper, plot Equation 5 for field lines at L = 1.5, 2.5, 3.5 and 6.0.

Answer: The equation of a single field line in polar coordinates takes a simple form

Equation 6 $$R = L \cos^2 (\Lambda)$$

where L is the length of the arrow in Figure 22 in units of Earth radii (Re) and Λ is the magnetic latitude angle where the field line enters Earth's surface. The shape is symmetric about the magnetic equator.

Exercise 3. Find the magnetic latitudes for field lines that cross the equatorial plane at L = 3.0, L=10.0, L=20.0 and L = 30.0. If magnetic storms are produced by magnetic reconnection events between L=15 and L = 35, at what magnetic latitudes will ground stations observe significant changes?

Answer: In the above equation, a dipole field line that extends to L = 4Re, reaches the surface of the Earth (r = 1.0) at a magnetic latitude of 60^{o}.

II. Space Weather Effects

2.1 Magnetic Storms and Auroral Activity

Near the poles of Earth, observers have often seen glowing clouds shaped like curtains, tapestries, snakes, or even spectacular radiating beams. Northern Hemisphere observers call them the Northern Lights or Aurora Borealis. Southern Hemisphere observers call them the Southern Lights or Aurora Australis. Because most people, and land masses, are found north of the equator, we have a longer record of observing them in northern regions such as Alaska, Canada, Scandinavia, but sometimes as far south as the Mediterranean Sea or Mexico!

Figure 22 - A photograph of an aurora borealis taken in Alaska. (Courtesy Dick Hutchenson).