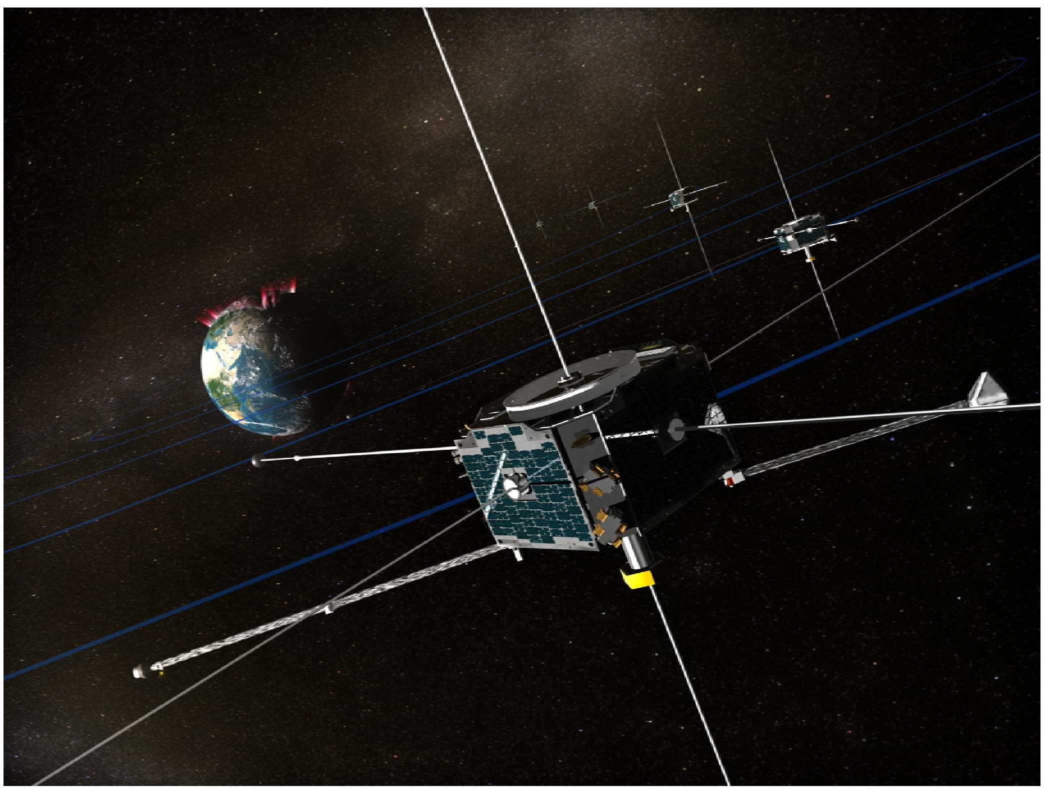
National Aeronautics and
Space Administration

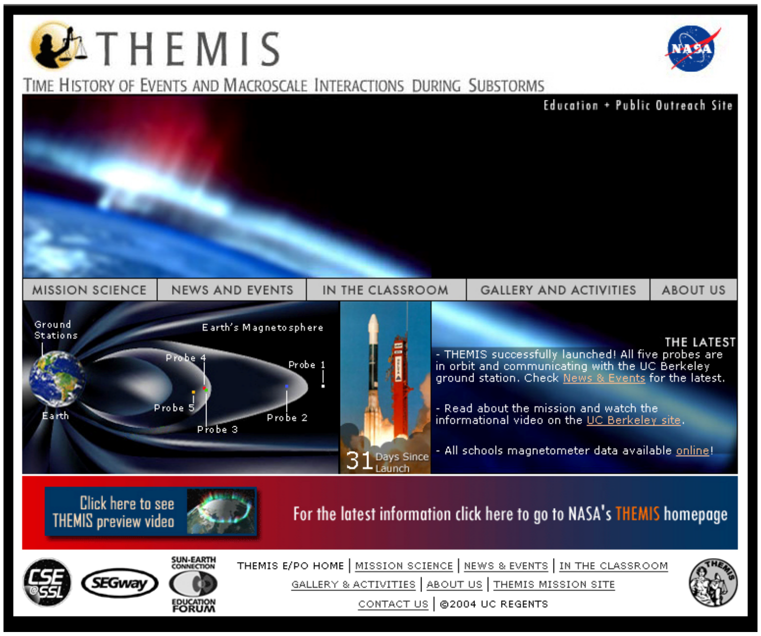
Teacher's Guide

Grades 9-14

THEMIS* GEONS**
Background Science and User's Guide



* (Time History of Events and Macroscale Interactions during Substorms)
** (Geomagnetic Event Observation Network by Students)



This teacher's guide is designed to support a multi-year investigation of Earth's magnetic field using the magnetometer network and resources of NASA's THEMIS (Time History of Events and Macroscale Interactions during Substorms) satellite mission education program. The education program's web site can be found at http://ds9.ssl.berkeley.edu/themis/. One particular THEMIS education program, the Geomagnetic Event Observation Network by Students (GEONS), aims to bring magnetometer data to high school classrooms. These guides support that effort.

The activities were designed in partnership with the IMAGE (Imager for Magnetopause-to-Aurora Global Exploration) satellite's education program (http://image.gsfc.nasa.gov/poetry) and the many activities developed for that mission in the exploration of the magnetosphere. The FAST (Fast Auroral Snapshot) education program also contributed to this effort (http://cse.ssl.berkeley.edu/fast_epo).

Authors:

Dr. Sten Odenwald - THEMIS E/PO (education and public outreach) Specialist at Astronomy Café

Dr. Laura Peticolas - Co-Director, THEMIS E/PO

Dr. Nahide Craig - Director, THEMIS E/PO

Victor Trautman - high school science teacher in Petersburg, AK

Teacher input and testing:

Laura Barber, Ray Benson, Cris DeWolf, Wendy Esch, Sean Estill, Wendell Gehman, Harriet Howe, Keith Little, Frank Martin, Terry Parent and Holly Wyllie

Scientist/Engineer input and testing:

Dr. Vassilis Angelopoulos - THEMIS Principal Investigator (PI)

Dr. Chris Russell - E/PO Science Advisor

Editorial/Layout assistance:

Karin Hauck

Introduction to the THEMIS Magnetism Series

This is one of four magnetism activity guides—plus a background guide for teachers—that provide students with the opportunity to build on science concepts related to Earth's magnetism and its changes. If your students engage in the activities in these four guides, they will have the skills, language and conceptual understandings of magnetism— one-half of the four fundamental forces of nature (the whole force is known as electromagnetism).

All of these guides have been:

- Classroom tested
- Checked for science accuracy by NASA and THEMIS scientists
- Designed to utilize math and writing

The goal of these guides is to give students an appreciation of the major role magnetism plays on Earth and in space, and ultimately enable them to use NASA data as "scientists" researching our magnetic connection to the Sun. We achieve this goal through sequential activities in the four teachers' guides, from basic explorations with magnets, compasses and galvanometers to scientific discoveries using data from instruments called magnetometers. These magnetometers are located in schools across the U.S, as part of the THEMIS education project.

The four activity guides have been used in different types of classes, from physical science and physics classes, to geology and astronomy classes. The excitement of actually participating in the THEMIS project helps motivate the students to learn challenging physical science concepts.

1. **Magnetism and Electromagnetism** is a review of basic magnetism, similar to what is encountered in most grade-level physical science texts. Students map field lines around bar magnets to visualize the magnetic dipole field, and create their own electromagnet using copper wire, battery and a pencil to learn that electric currents create magnetic fields. Two activities introduce generators and Lenz's law, in one case using Earth's magnetic field and a large conducting wire. These materials can be used by teachers presenting Earth and Physical Science courses in grades 6-9, and would fit well into a lab at the end of a high school physics class. These activities are a classroom-ready prerequisite to understanding magnetism on Earth and in space.

2. **Exploring Magnetism on Earth** is intended to help students explore Earth's magnetic field through a variety of math-based activities. This guide contains problems focusing on Earth's changing magnetic field in time and space. Students use compasses to discover how these changes can impact navigation on Earth's surface. They use basic math skills to interpret graphical information showing polar wander and magnetic changes, and answer questions about quantitative aspects of these changes. These lessons can be used in geology and astronomy classes.

3. **Magnetic Mysteries of the Aurora** is a prerequisite to using magnetometer data as students will in the next guide, **Earth's Magnetic Personality**. **Magnetic Mysteries of the Aurora** introduces students to Earth's magnetic field and Northern and Southern Lights (aurora) within the context of the Sun and space weather. Using worksheets, globes, and a single light source, students review time-keeping on Earth—time zones and Universal Time. Students then go through a series of activities to discover the causes of the aurora and their relation to Earth's magnetosphere and solar storms. Students classify images of aurora by shape and color, create a model of Earth's magnetosphere, forecast magnetic storms using geomagnetic indices, and engage in a presentation about space weather. These lessons have been used in physics and astronomy classes as well.

4. **Earth's Magnetic Personality** is the culmination of all the previous guides. It was developed with the goal that students can now work directly with the THEMIS magnetometer data. Students review vectors through calculations, learn to interpret x-y-z magnetometer plots, predict auroral activity using the x-y-z magnetometer data, calculate the total magnetic field strength and observe it over months, and discover that waves in Earth's magnetic field are excited by large magnetic storms by comparing spectrograms with magnetic indices.

5. The background guide for teachers, the **THEMIS GEONS Users Guide,** describes the important role that terrestrial magnetism plays in shaping a number of important Earth systems. It also explains the basic operating principles behind magnetometers—particularly the system you are now in the process of using to investigate magnetic storms at your school.

Table of Contents

Introduction.. 3
Chapter I : Introduction to Geomagnetism.. 6
1.1 Earth's magnetic field in space
1.2 Origin of Earth's magnetic field
1.3 The crustal magnetic field
1.4 The wandering dipole field
1.5 Paleomagnetism
1.6 Earth's magnetic field in the Universe
1.7 Some quantative considerations

Chapter II: Space Weather Effects.. 24
2.1 Magnetic storms and auroral activity
2.2 Solar storms
2.3 Magnetic storms and substorms

Chapter III: The THEMIS Mission... 31
3.1 Scientific objectives
3.2 Magnetic field coordinate systems

Chapter IV: Magnetism and Measurement Techniques.......................... 36
4.1 The soda-bottle magnetometer
4.2 The dip circle
4.3 The Bache magnetometer
4.4 The electromagnetic magnetometer
4.5 The Proton presession magnetometer

Chapter V: The Fluxgate Magnetometer.. 39
5.1 Operating principles
5.2 Applications in science, medicine and industry

Chapter VI: The THEMIS Magnetometer.. 41
6.1 Design and block diagram
6.2 Hardware Setup
6.3 Computer and Software Setup
6.4 Calibration and Data Collection

Chapter VII: Web Resources... 45

Bibliography.. 48

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...".*

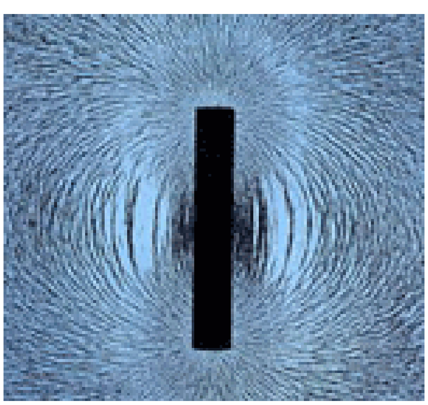


Figure 2 - Iron filings reveal the pattern of magnetic lines of force around a bar magnet.

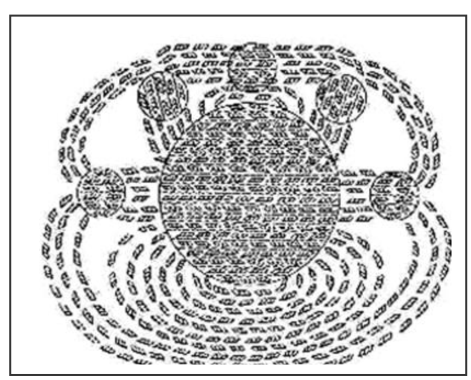


Figure 3 - Decarte's original sketch of the lines of magnetic force made in 1644.

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.

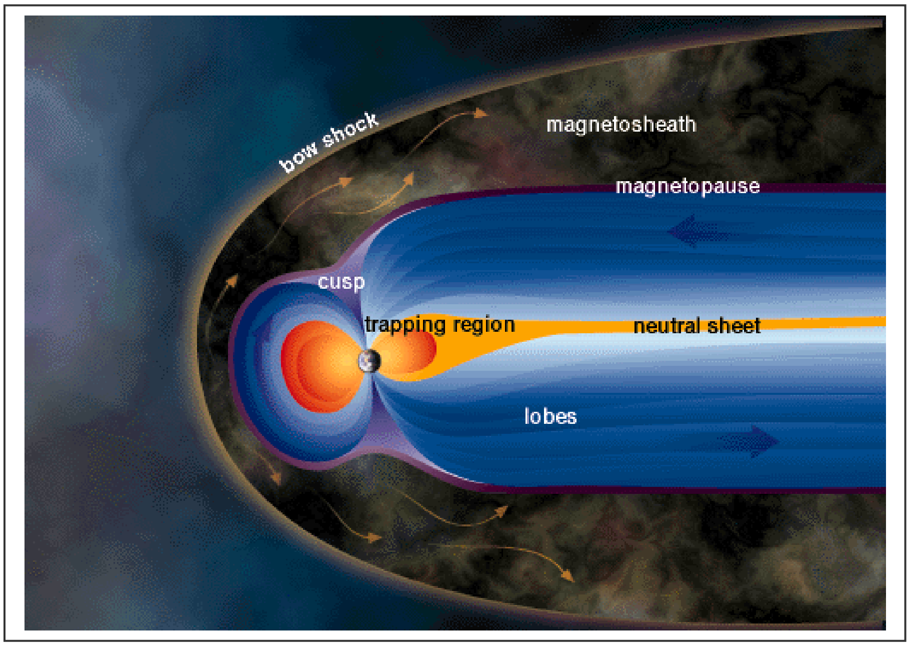


Figure 4 - Earth's magnetic field has a comet-like shape because the solar wind consists of electrified gases (blowing from the left to right) that interact with the 'magnetosphere' to give it its shape. This sketch shows the major regions identified by scientists.

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.

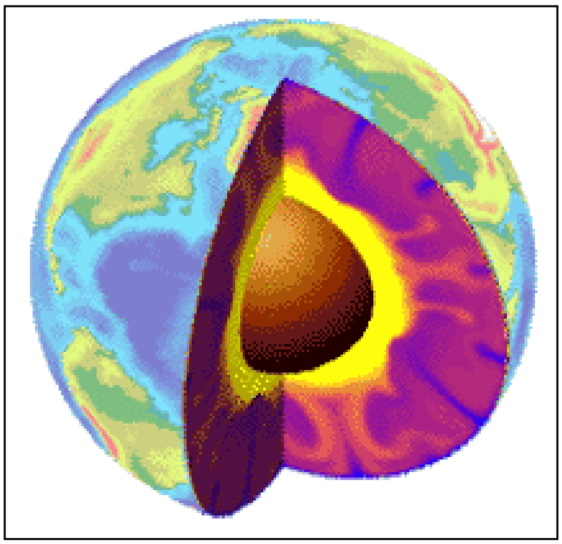


Figure 6 - A cut-away view of Earth's core showing the convecting mantle and core regions (Courtesy NASA)

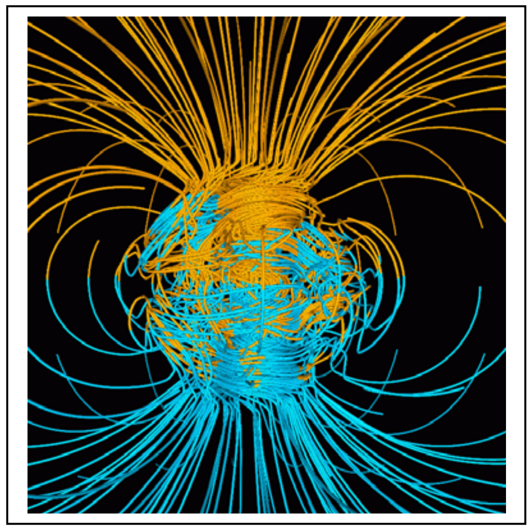


Figure 7 - Magnetic field generated by dynamo action (Courtesy *Gary A Glatzmaier - Los Alamos National Laboratory)*

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.

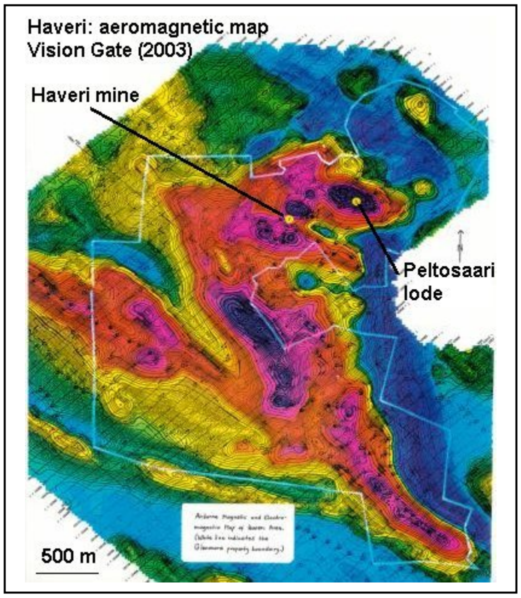


Figure 8 - Map of magnetic field changes over Finland. Red indicates regions with stronger fields due to iron deposits. (Courtesy Geological Survey of Finland)

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:

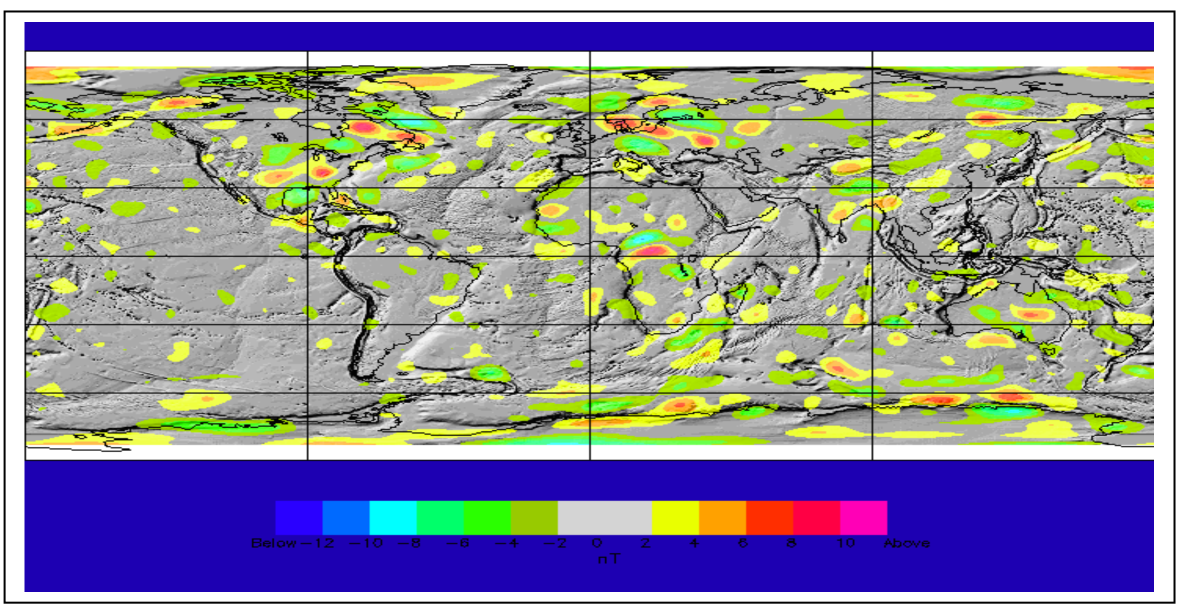


Figure 9 - Variations in Earth's global magnetic field measured by Magsat from an orbit of 400 km. (Courtesy NASA)

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.

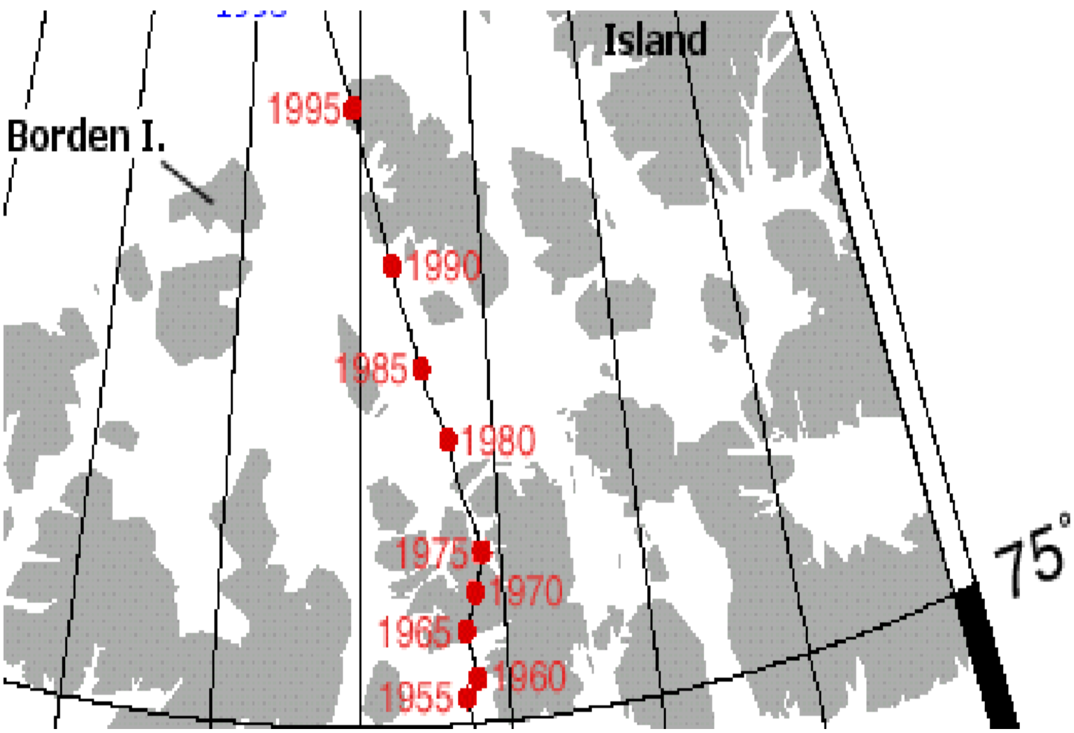


Figure 10 - A map of the track of Earth's magnetic pole in the Northern Hemisphere in Canada. The scale in this picture is 1 cm =133 cm. (Data Courtesy of the United States Geological Survey)

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).

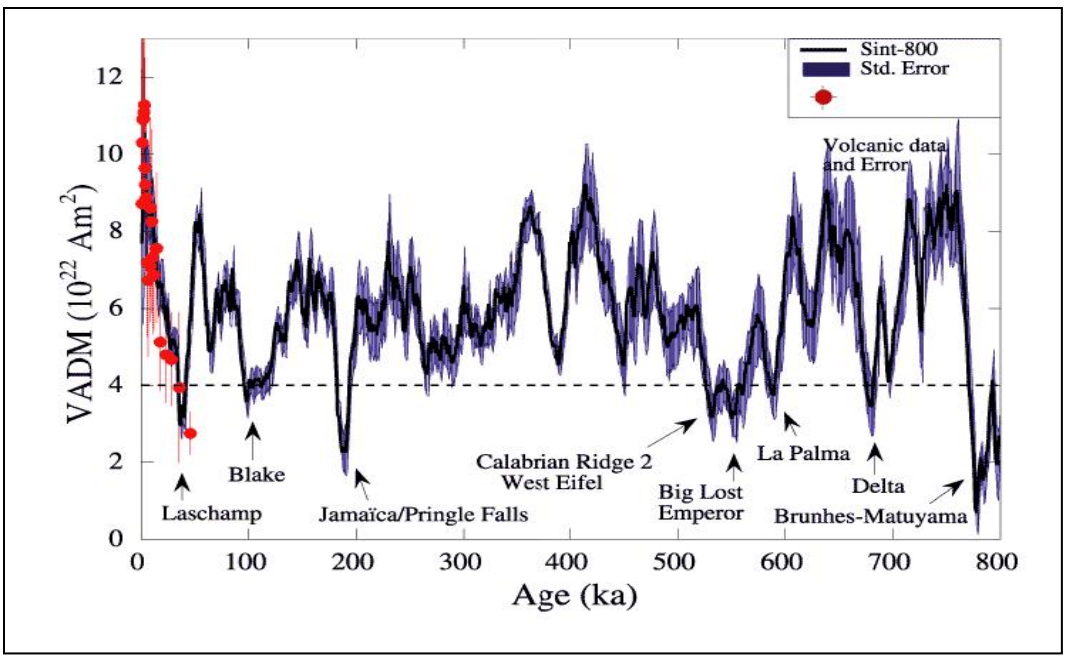


Figure 11 - The changes in Earth's dipole magnetic field strength and orientation during the last 800,000 years. 'VADM' refers to the magnitude of the virtual axial dipole moment of Earth.

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.

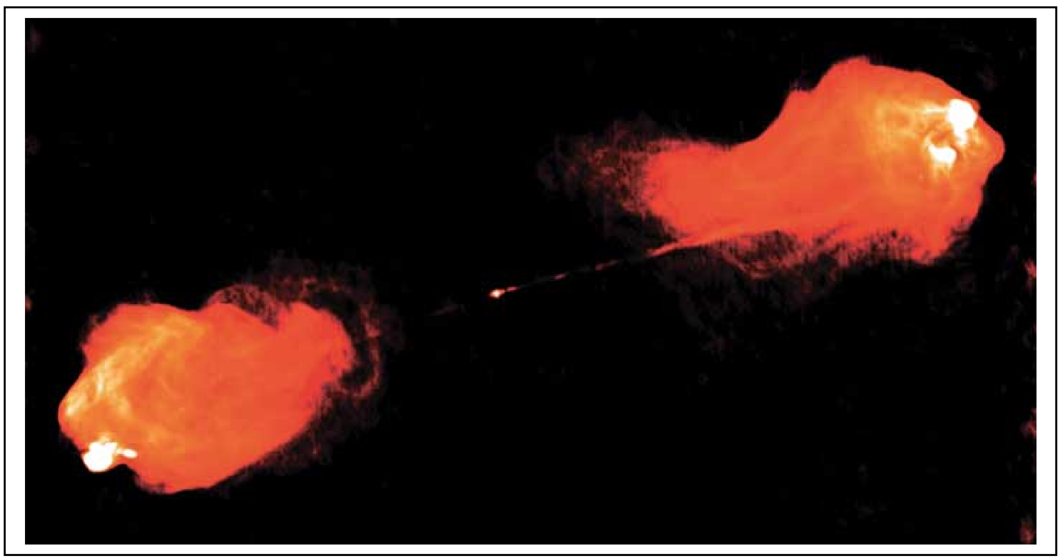


Figure 13 - The radio galaxy Cygnus-A (Courtesy NRAO)

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.

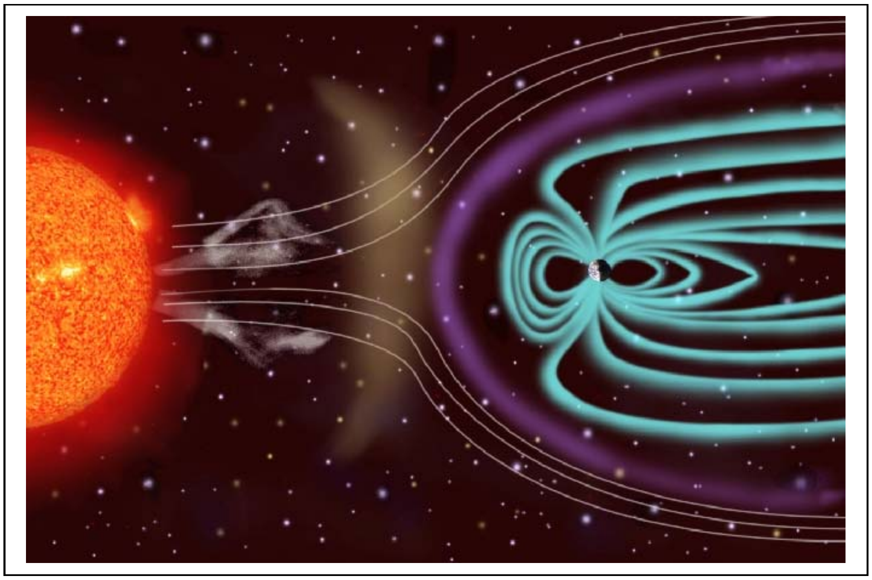


Figure 14 - A cartoon sketch of the Sun's interaction with Earth's magnetic field. Note, none of the elements are drawn to scale!

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.

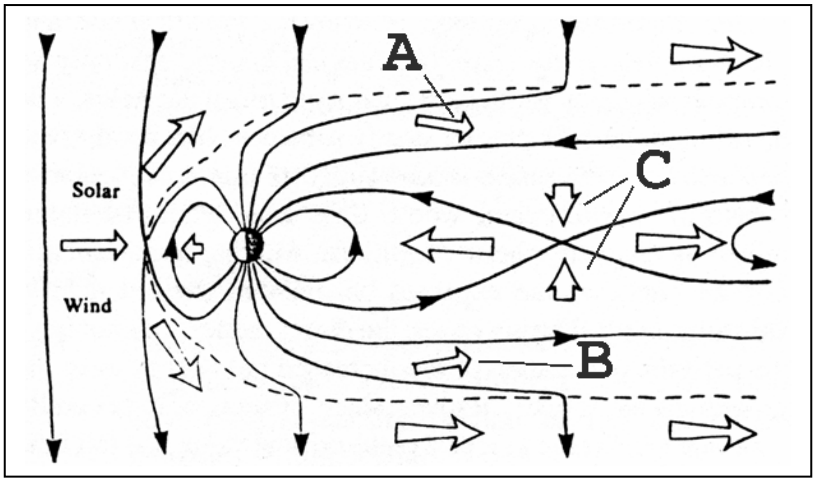


Figure 15 - A drawing of magnetic field lines in the magnetosphere. The solar and terrestrial fields can reconnect, causing plasma and magnetic motions shown by the arrows.

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.

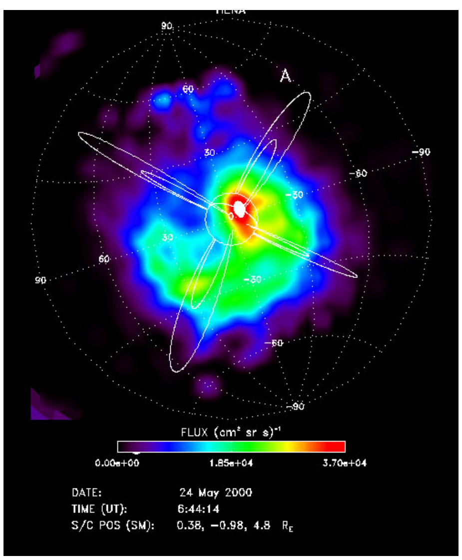


Figure 16 - An image of particles in the ring current after a strong magnetic storm. Earth is outlined as a sphere, with some representative magnetic field lines drawn-in. (Courtesy -IMAGE)

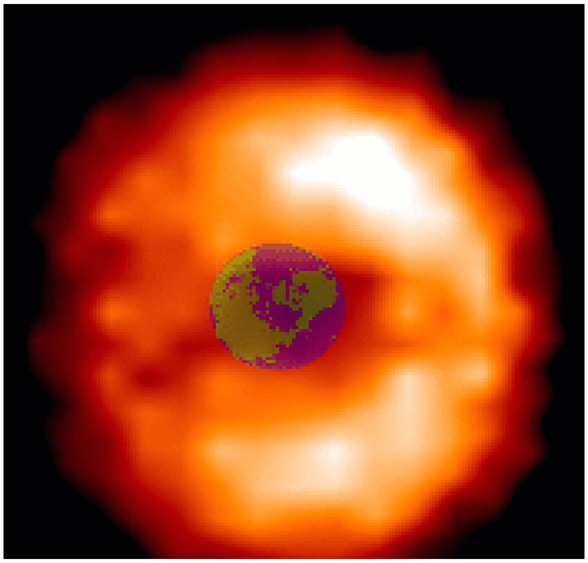


Figure 17 - An image of particles in the ring current during quiet times between storms. (Courtesy IMAGE)

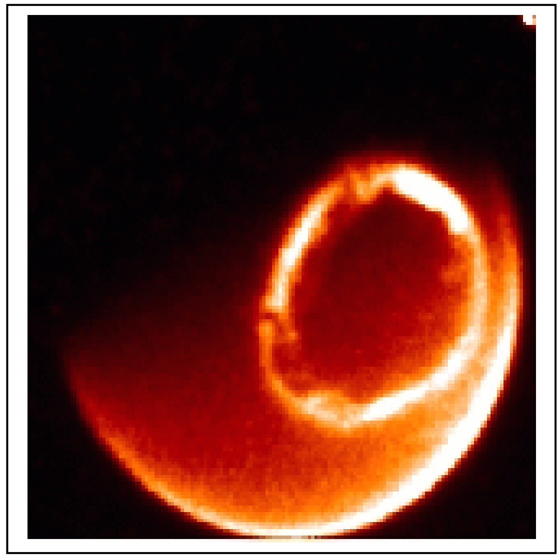


Figure 18 - The auroral oval images from space is a nearly perfect circle. (Courtesy IMAGE)

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.

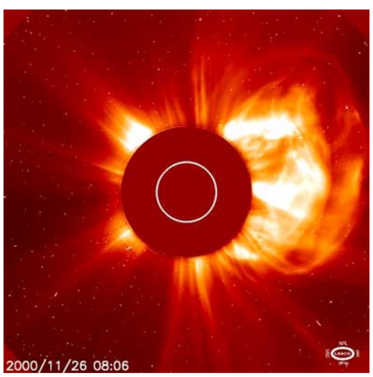


Figure 19a -Coronal Mass Ejection (CME) ejection (SOHO)

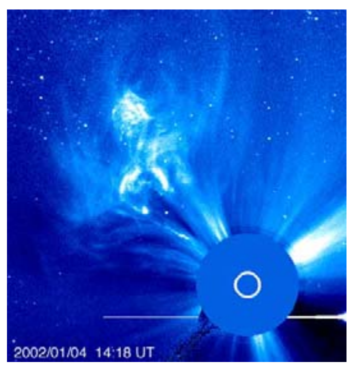


Figure 19b - CME ejection (SOHO)

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.

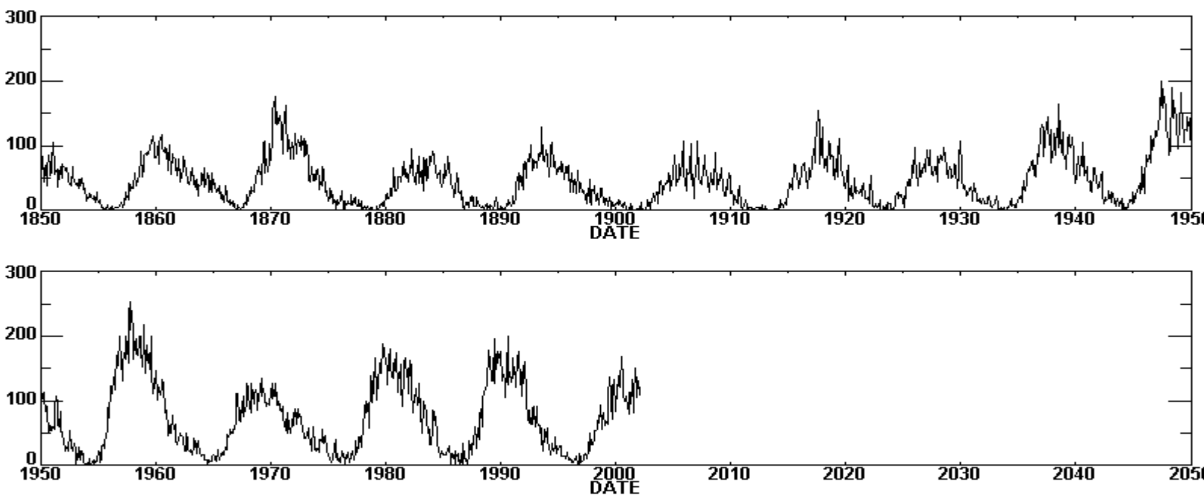


Figure 20 - The number of sunspots over a 150 year interval. The Sun is more active when more sunspots are seen near the peak of each cycle.

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.

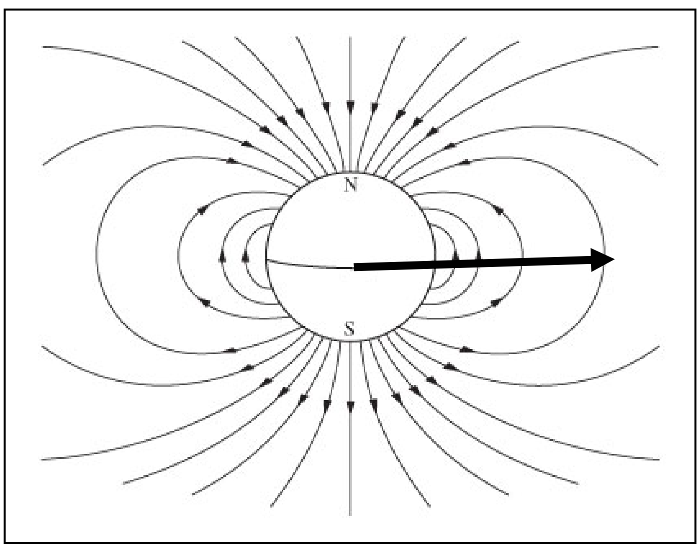


Figure 21 - Lines of magnetic force based on equations 1-5, showing the 'dipole' shape. The straight black arrow represents **L** in polar coordinates.

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).

The most spectacular manifestation of the connection between the Sun and Earth are the aurora. For millennia, people have watched them and worried about what ill portents they were heralding. It wasn't until the mid-1800s that scientific studies began to uncover many of their mysteries.

Scientists learned that auroras often accompanied magnetic changes. They came and went with the sunspot cycle, and their colors were the product of excited oxygen and nitrogen atoms hundreds of kilometers above the surface of the Earth.

By the turn of the 20th century, scientists actually created artificial aurora in their laboratories. Once television and the fluorescent lamp were invented, it was pretty clear just how aurora worked. What scientists still didn't understand was what was triggering them. Some thought it was from direct currents of particles from the Sun itself. Others felt it was more complicated than that.

Thanks to intensive study by research satellites during the Space Age, auroras have been substantially de-mystified, even as their ethereal beauty has remained to dazzle us and inspire awe. When the magnetism of the solar wind is the same as the south-type polarity in the daytime side of the Earth, an invisible valve opens in the magnetotail region, allowing particles and energy to penetrate deep into the magnetosphere (see Figure 16). In the delicately balanced magnetic tail of the Earth, magnetic fields can become crossed just as in solar flares. The energy stored in the magnetic field can be liberated as currents of charged particles.

Auroras are formed in the atmosphere at elevations from 100 to 300 kilometers where the density of the air is very low - in fact almost a perfect vacuum. Enormous amounts of electrical energy are produced during an aurora when millions of amperes of electric currents pass through the atmosphere and generate nearly 900 billion watts of energy - mostly in heat but about a few percent in light. Unfortunately, this power is spread out over millions of kilometers of atmospheric area, so that the total auroral energy (1 microwatt per square meter) is far less than solar energy (164 watts per square meter).

One of the biggest mysteries to science during the 18th and 19th centuries was the reason behind why Earth has aurora at all. It wasn't until scientists began to measure auroral properties and to describe them in detail by cataloging their forms, that progress was eventually made to understand them.

The other planets that have magnetospheres also have auroras in part because of the interaction with the solar wind and the planet's magnetosphere. Jupiter is a spectacular example of such another planet, with auroras covering its polar cap region.

In the 1740's, George Graham (1674-1751) in London, and Anders Celsius (1701-1744) in Uppsala, Sweden began taking detailed hourly measurements of changes in the Earth's magnetic declination. The fact that this quantity varied at all was known as early as 1634 by Gellibrand's observation of the 'variation of the (magnetic) variation' (Fleming, 1939). It didn't take very long before Celsius and his assistant Olof Hiorter uncovered in the 6638 hourly readings, a correlation between these disturbances and local auroral activity. Moreover, comparing the records between Uppsala and London, it became quite apparent that the magnetic disturbances occurred at the same times at both locations. By 1805, the independently wealthy, scientific traveler, Baron von Humbolt (1769-1859), had also noted these magnetic disturbances and called them magnetic storms' since they caused the same gyrations of his compass needles as local lightning storms would do. Just as Celsius and Hiorter nearly 100 years earlier, during a 13 month period, Humbolt and his assistant also made thousands of half-hourly readings of a compass needle.

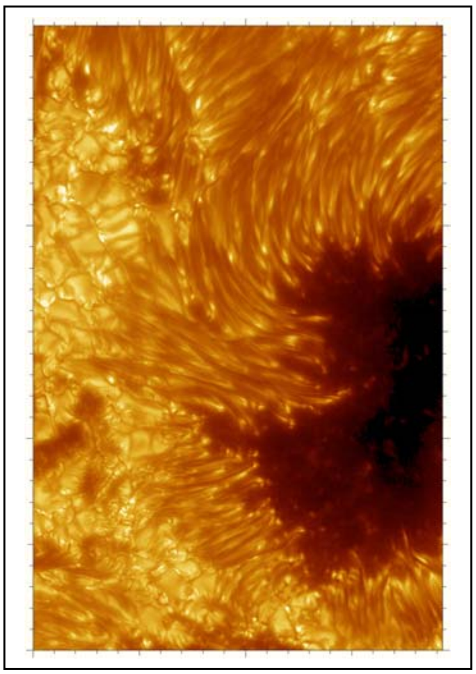
Using his considerable influence and popularity, following a two-decade hiatus caused by European wars, von Humbolt acquired the resources needed to set up a number of magnetic 'observatories' in Paris, Freiburg, and later across Russia in the 1830's. The first magnetometers were quite crude affairs. A human 'reader' would peer into a microscope at a needle on a graduated scale, little more than an ordinary compass. At half-hourly intervals, day and night, the position of the needle would be noted. By the 1850's, networks of observatories amassed millions of these observations.

2.2 Solar Storms

Believe it or not, although you cannot hold in your hand a piece of the Sun, you can explore a model of the forces that control most of its active surface. The Sun has a magnetic personality. For over 100 years, astronomers have known from direct observations that the Sun's surface has an average magnetic field that is about twice as strong as the Earth's, but spread out over 10,000 times the area. We don't exactly know where it comes from. It may have been left over from the interstellar cloud that created the Sun over 4.5 billion years ago. Astronomers think it is actually generated by the Sun itself. Over all, the Sun's field looks a lot like a bar magnet. It has a north and south polarity as all magnets do. Much of its shape can be seen during a total solar eclipse as it leaves an imprint on the Sun's outer gases, just like iron filings outline the field of a bar magnet. But there is more to the Sun's magnetism than what you might find by just looking at a bar magnet.

In the mid-1800s astronomers discovered from thousands of sunspot sightings that, when they tabulated and graphed them, their numbers increased and decreased over time in a repeatable cycle. These extremes represent the amplitude of the cycle. We now call this the solar activity cycle or the sunspot cycle, which you can see in Figure 20. During the last 200 years, the period of the cycle has been about 11 years, but sunspot cycles can be as short as 9 (Cycles 1, 3 and 8) or as long as 13 years (Cycle 4). During sunspot minimum conditions, such as the year 1996, astronomers counted fewer than 5 sunspots on the surface of the Sun at any one time. During sunspot maximum conditions, as many as 250 could be seen. On September 20, 2000 one very large sunspot group could be seen with the naked eye with the proper safety precautions.

(You should never look directly at the Sun without proper shielding to avoid eye damage!).



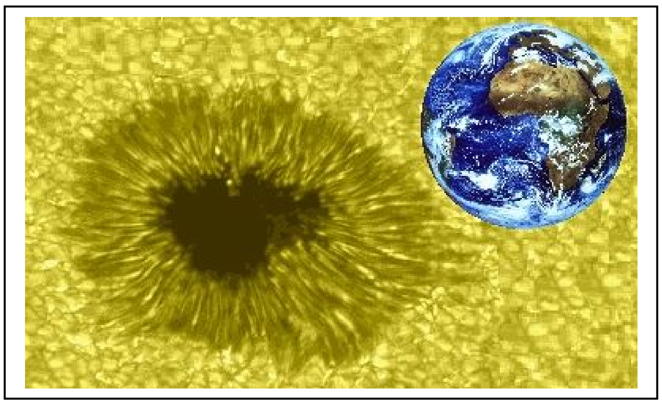


Figure 23 - Two views of sunspots showing solar surface and magnetic details. Note the Earth disk size in relation to a small sunspot!

Sunspots contain a dark, central region called the umbra, surrounded by a lighter region called the penumbra. Magnetic fields from below the solar surface become buoyant, like helium balloons released in the air, and float up to the surface. They erupt as a loop of magnetism with two 'foot points' forming a pair of sunspots. The magnetic field near the center can be over 5,000 gauss in strength—or nearly 1000 times stronger than the average solar field. This causes the normal convection of energy below the surface to be reduced, causing a cooling of the surface by up to 2,000 K in the umbral region of a sunspot. Sunspots appear dark only because the gases emit about 1/10 the light of the rest of the solar surface!

Scientists can learn a great deal about how the currents and magnetism on the Sun work as a system by studying models of the Sun's surface in their laboratories or in detailed computer calculations. Even though the difference in radius between the Sun (6.9 x 10^8 meters) and a lap top computer (0.3 meters) is enormous (about 2x 10^{11} times), many physical laws can be scaled up or down in size so that even enormous solar flares can be investigated in human-sized models. Sometimes one group of sunspots collides with another, like ships floating on the Sun's plasma ocean. Sometimes a brand new sunspot can appear inside one that was

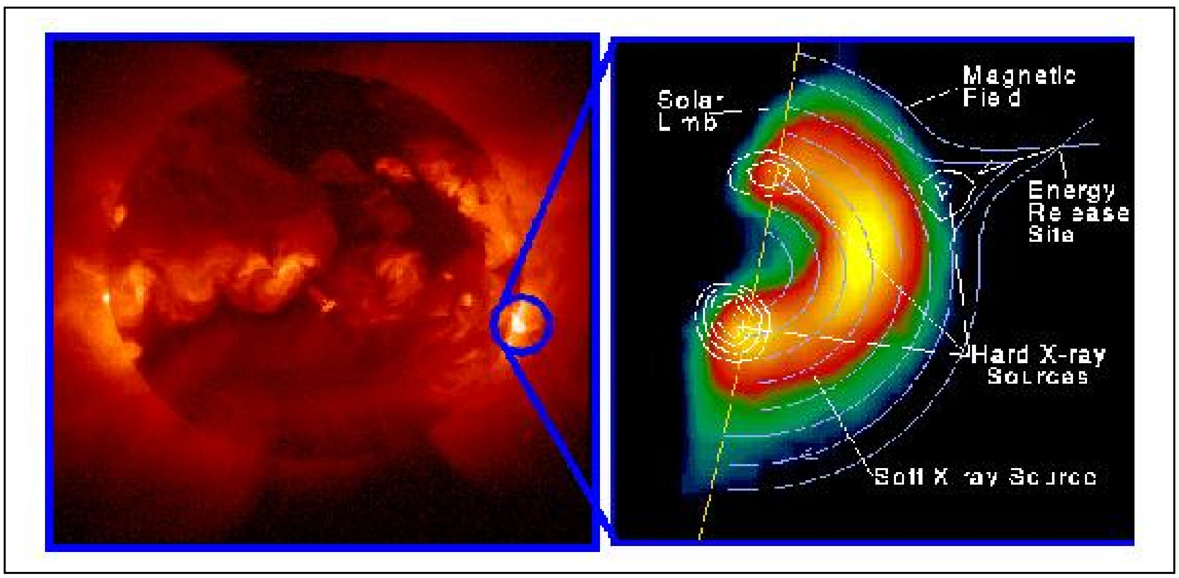


Figure 24 - An X-ray image of the Sun reveals the patterns of magnetic energy being released (left), and a zoom-in of one of these regions shows the many distinct physical regions that make-up a solar flare.

already there. These conditions lead to the build up of magnetic energy and inevitably the release of this energy in powerful solar flares.

Because sunspots and the gases around them can flow at thousands of kilometers a minute, it only takes a few seconds before magnetic conditions can escalate from a minor solar squall to a major explosion of energy. The billions of amperes of current moving through the solar atmosphere release over 10^{15} (1000 trillion) Joules of energy; more energy than in a thousand hydrogen bombs. Within five minutes, the magnetic field reconnects into a smoother shape to release the energy. Meanwhile, gas has been heated to millions of degrees and a blast of x-rays and other energetic particles leaves the scene of the event. In a little over 8 minutes, the x-rays traveling at the speed of light (300,000 kilometers/second) arrive at the Earth, located 149 million kilometers (93 million miles) from the Sun, and cause short-wave radio blackouts across the entire daytime face of the planet. An hour or so later, a burst of slower-moving but enormously energetic particles flows by the Earth. Any astronauts in space, or sensitive satellites, will be bombarded by these particles and may suffer lethal doses of radiation. These solar flare events, though spectacular, have no effect upon Earth's magnetic field. To find the culprits behind magnetic storms we have to look at another type of solar storm, which often accompanies solar flares.

For days, a heated cloud of plasma can be suspended by magnetic pressure just above the photosphere in a region called the *chromosphere*. Then, for reasons not fully understood, this billion-ton cloud can become unhinged and be propelled away from the Sun. The cloud may only have started off as a gentle puff of plasma. As it enters the lower reaches of the solar corona, the Sun's outer atmosphere, the cloud expands and accelerates enormously to speeds of millions of kilometers per hour. Within a few days, the cloud has reached the orbit of Earth, while parts of the cloud itself still envelop the orbits of Venus and Mercury.

In time, these coronal mass ejections cause interplanetary space to be filled with a changing patina of cloud fragments and magnetic field blobs, millions of kilometers across, and flowing in a great pinwheeling pattern, out beyond the orbit of Pluto.

No two CMEs are exactly the same, so astronomers describe these explosions by average properties, just as we often say that the average adult human being is about 2-meters (six feet) tall. CMEs are actually not very dense by the time they reach the Earth's orbit. As they expand through space, their density falls from millions of particles per cubic centimeter near the Sun, to barely a dozen particles per cubic centimeter near Earth. Most of them travel at nearly one million kilometers per hour and take two to three days to reach Earth's orbit. The fastest ones can travel at nearly three times this speed and get to Earth within 18 to 24 hours. Many CMEs are actually quite hollow and resemble enormous soap bubbles blown into space by the Sun.

The outer surface still contains some of the Sun's original magnetic field, though weakened by over a million times as it is stretched across the orbits of Mercury and Venus. The field arriving at Earth is still magnetically connected to the surface of the Sun, making this one of the largest natural structures in the solar system!

As spectacular as these solar storms can be, there is little cause for concern that the Earth's atmosphere will be 'blown away' by them. A CME blast wave is actually a better vacuum than what you would find in a television picture tube, but this doesn't mean that they are completely without any consequence.

Many systems in our solar system, and even in the Milky Way galaxy, are like pencils balanced on their points. The subtle pressure changes that CMEs bring with them into the depths of the solar system can affect the delicate balances in other physical systems elsewhere in space.

2.3 Magnetic storms and substorms

Since Kristian Birkeland (1867-1917) first coined the term "magnetic" storm in the early 1800's, magnetic disturbances have been further categorized as either magnetic storms, or substorms. The former are typically very large events during which time the local magnetic field conditions change abruptly during the so-called Storm Sudden Commencement (SSC) phase. Within a matter of minutes, measurements of the field may change from quiescent conditions to very disturbed conditions, and the new level of activity can persist for hours or days. Auroral displays may be seen in many localities across the globe, especially the Great Aurora which can be seen as far south as the Mediterranean or Japan.

Magnetic storms are apparently spawned by major Coronal Mass Ejections (CMEs). If the Earth happens to be in the wrong place in its orbit, within a few days, these million kilometer/hour plasma clouds reach the Earth and impact its magnetic field. The momentary compression of the field causes an increase in the field strength at the Earth's surface causing the SSC. Many physical processes are then precipitated as the CME particles and magnetic fields invade geospace (the space around Earth enclosed by Earth's magnetosphere), especially the amplification of the equatorial Ring Current. This current induces its own magnetic field which interacts with the Earth's field to cause fluctuations in the geomagnetic field near ground level and a net decrease in the field strength. Magnetometers then notice complex field changes which last until the CME plasma passes the Earth and geospace conditions return to normal.

Major magnetic storm events also lead to spectacular auroral displays even at low geographic latitudes.

Substorms were first documented in 1964 by Syun-Ichi Akasofu of the University of Alaska using a network of all-sky cameras. They are generally less dramatic than magnetic storms, and may come and go within a few hours or so, always with accompanying auroral displays seen in the upper latitudes in Canada, Scandinavia and Alaska. Although there is considerable variation on a central theme, the evolution of substorm aurora (also called auroral substorms) follows a non-random basic script. Beginning with quiet auroral curtains, they brighten and pick up streaks or rays. Then a series of sweeping folds or spirals appear near the eastern horizon and surge westward as the 'expansion phase' begins. The sky brightens again and dissolves into myriad rapidly moving forms, followed by a 'recovery phase' where conditions return to a vague diffuse cloudiness, with patches of diffuse glow pulsating on and off with a period of a few seconds.

Substorms are thought to be produced by minor changes in the orientation of the solar wind magnetic field as it collides with the geomagnetic field. If magnetic 'kinks' in the solar wind field meet up with the geomagnetic field, rapid polarity changes can lead to reconnection and current disruption events in the magnetopause and magnetotail regions. These events can cause particles to be accelerated to high energy and flow into the atmosphere to produce aurora. Substorms cannot be anticipated in advance because the interplanetary magnetic field is a complex phenomenon that is largely invisible. Major magnetic storms, however, are known to follow the Sun spot cycle; a fact uncovered by Edward Sabine in 1839, but not formally recognized by the scientific community until the turn of the 20th century. The best time to observe magnetic storms is when the solar surface is active, or has large sunspot groups transiting its surface.

III. The THEMIS mission

3.1 Scientific Objectives

The Time History of Events and Macroscale Interactions during Substorms (**THEMIS**) program consists of a five-satellite constellation with the job of determining the causes of the global reconfigurations of the Earth's magnetosphere observed during the abrupt beginning of 'onset' of an auroral substorm. Each satellite carries identical electric, magnetic, and particle detectors that will be put in carefully coordinated orbits. Every four days, the satellites will line up like pearls on a string along the Earth's magnetic tail, allowing them to track disturbances from this distant region, all the way to Earth's outer atmosphere. The satellite data will be combined with observations of the aurora from a network of observatories across Canada and Alaska, as well as additional magnetic observatories located in schools in the northern U.S. states.

"Basically, we hope to solve the mystery surrounding the transport and explosive release of solar wind energy within Earth's space environment," said Michael J. Cully, Director of Civil and Commercial Programs for Swales Aeospace. "In addition, we believe THEMIS will also be able to answers some critical questions about radiation belt physics as that science relates to solar winds." The launch of the THEMIS mission aboard a Delta II rocket happened successfully on February 17, 2007. (Updates at http://ds9.ssl.berkeley.edu/themis/news.html)

The data collected by THEMIS will allow scientists to determine which magnetotail process is responsible for the start of a magnetic substorm. Is it caused by a local disruption of the currents flowing in the plasma sheet, a bed of hot electrons and ions located in the magnetotail? Or is a magnetic substorm the result of the rapid influx of plasma from magnetic reconnection events occurring deep within the magnetotail at a distance of ~25Re?

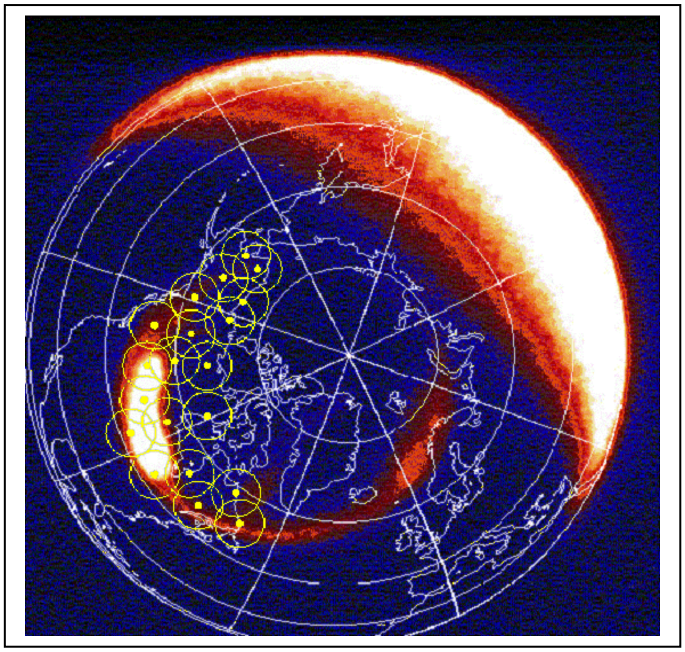


Figure 25 - The Earth imaged in ultraviolet light with a map overlaid to show where the bright emissions are located. The upper right white is from the upper atmosphere glowing with the Sun's daytime light. The white 'peanut' shape is an aurora during substorm onset.

Three inner probes at ~10Re will monitor current disruption onset, while two outer probes, at 20 and 30Re respectively, will remotely monitor plasma acceleration due to reconnection events. In addition to addressing its primary objective, THEMIS answers critical questions in radiation belt physics and solar wind-magnetosphere energy transfer.

The image in Figure 25 of an auroral oval shows an intense substorm event occurring over Canada. The circles show the locations of Canadian magnetometer stations.

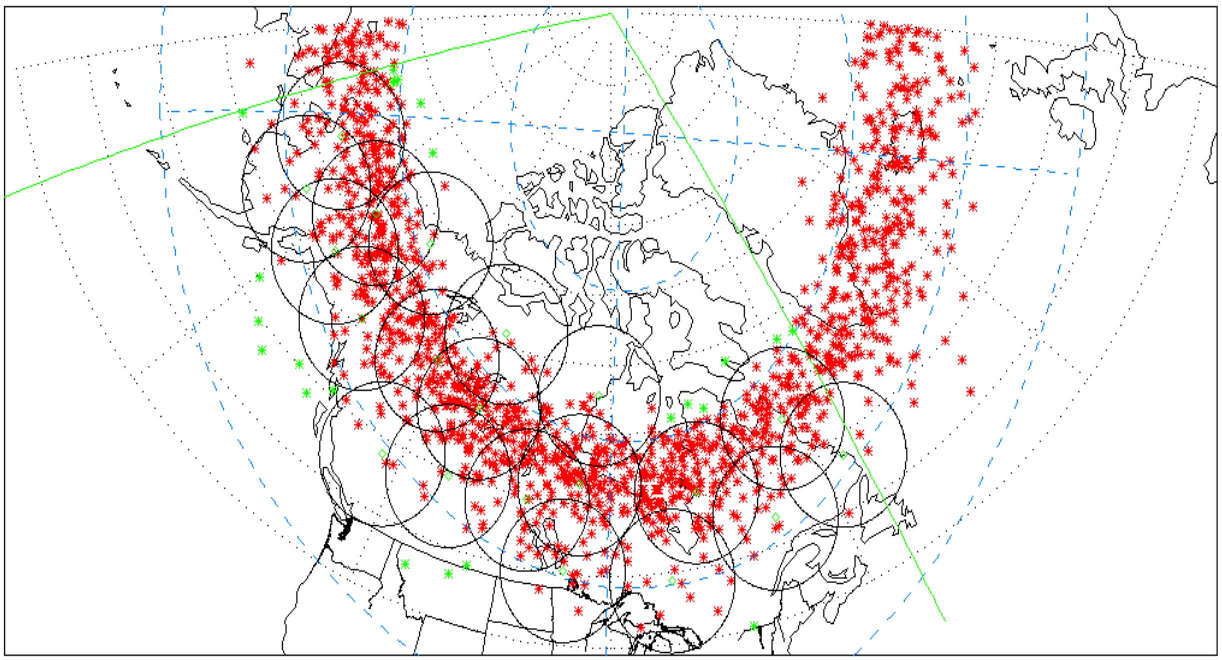


Figure 26 - Field-of-view of THEMIS all-sky imagers are shown as circles, with the stars indicating where substorm events have been seen during the IMAGE satellite mission between 2000-2005.

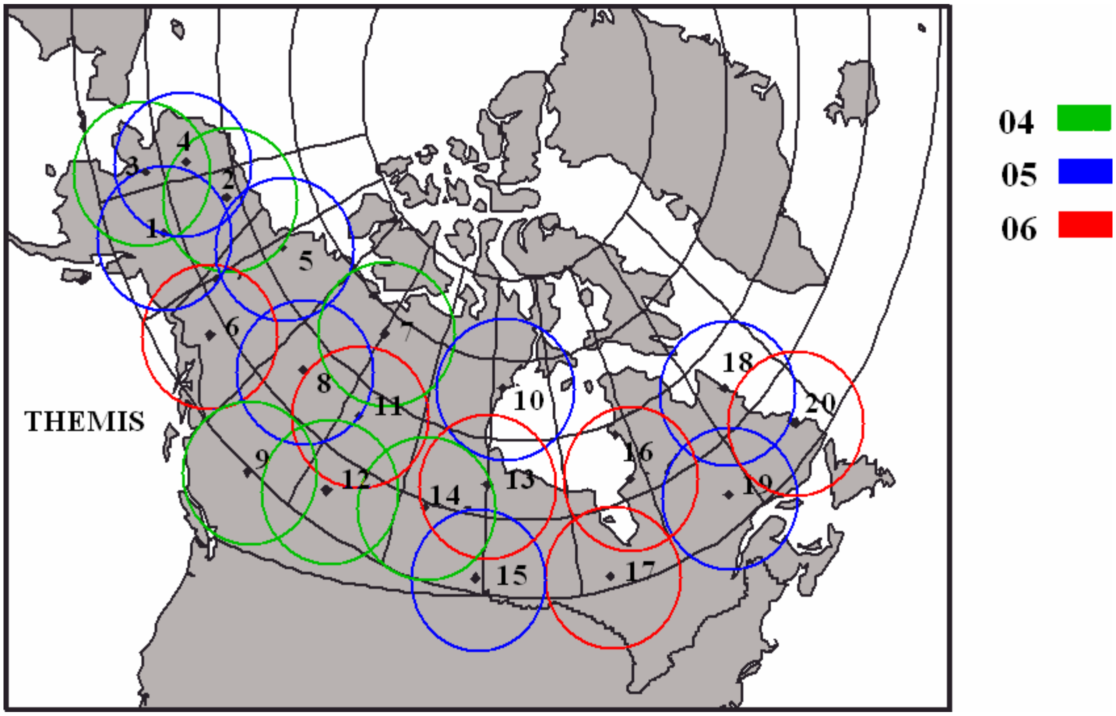


Figure 27 - Field-of-view of the 20 THEMIS all-sky imagers and the year in which they were installed indicated by color.

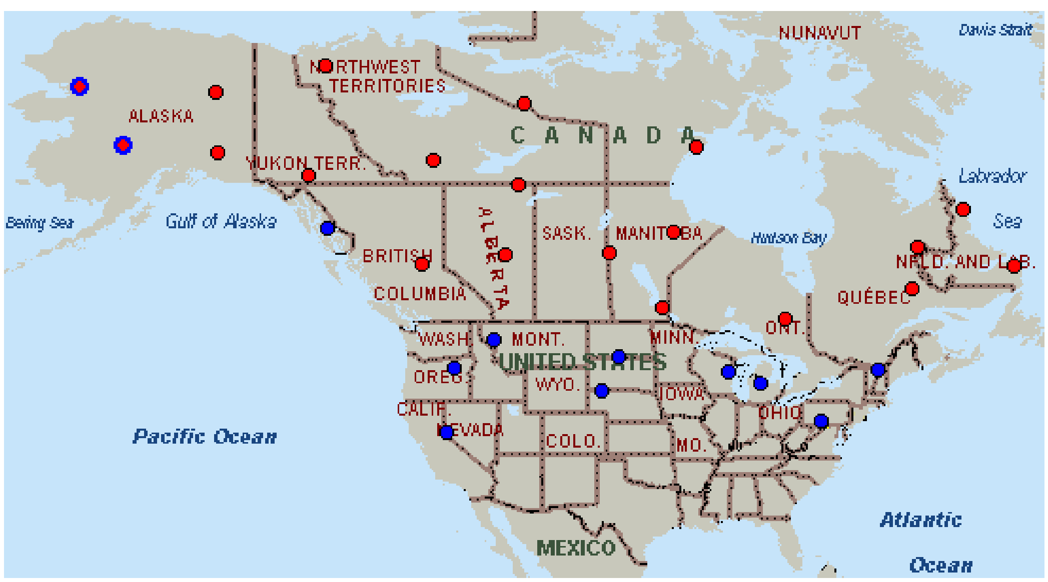


Figure 28 - A map with the locations of the THEMIS observatories .The blue dots indicate schools with magnetometers. The red dots indicate the ground-based observatories used by scientific researchers.

Table 2: Participating Schools:

School	Location	Teacher
Petersburg City Schools	Petersburg, AK	Victor Trautman
McGrath School	McGrath, AK	Ray Benson
Chippewa Hills HS	Remus, MI	Chris DeWolf
Hot Springs HS	Hot Springs, MT	Sean Estill
Western Nevada CC	Carson City, NV	Terry Parent, Jim Bean
Fort Yates Public School	Fort Yates, ND	Frank Martin, Harriet Howe
Ukiah School	Ukiah, OR	Laura Orr
Northern Bedford County HS	Loysburg ,PN	Keith Little
Red Cloud HS	Pine Ridge ,SD	Wendell Gehman
Shawano Community HS	Shawano ,WI	Wendy Esch
North County Union JHS	Derby ,VT	Holly Wiley, Manju Prakash *(located in ME, using VT mag.)*

3.2 The magnetic field coordinates

The typical THEMIS ground-based magnetometer (GMAG) is a three-channel flux-gate magnetometer that measures the strength (magnitude) of Earth's local field along three perpendicular axes. To find the average components of the magnetic field where you live, visit the International Geomagnetic Reference Field Model

http://nssdc.gsfc.nasa.gov/space/model/models/igrf.html

and enter the date, your geographic latitude, longitude and elevation. You can find the geographic coordinates for a specific location at

http://geonames.usgs.gov/pls/gnis/web_query.gnis_web_query_form.
Select 'Civil' for a town name.

Table 3 - Magnetic components of some familiar cities

City	Longitude	Latitude	Bx	By	Bz	Total B
Chicago	87 54 55	41 50 05	26454	1271	48893	55605
Boston	71 05 00	42 18 00	25251	2234	46676	53116
Miami	80 32 00	25 37 00	36274	0.0	28396	46067
Anchorage	149 15 02	61 10 00	16320	-3553	53774	56308

Table 3 shows the components for 2004 at sea level for different geographic coordinates. The vector components whose magnitudes are the numbers Bx, By and Bz are defined in units of nano-teslas (nT), B is the total field strength also in units of nT. You can use this information to calculate D, the declination angle between geographic and magnetic north, and I, the inclination or Dip Angle, in degrees below the local horizontal plane from Equations 7 and 8 in Section 1.7. The Declination angle, D, is the angle you will find on a geographic map that gives the compass correction to True North.

For example, in Chicago the components of the field are 26,454 nT, 1271 nT and 55,605 nT. The total magnitude of the field at the surface is then 55,605 nT or since there are 10,000 Gauss units per tesla, this equals 0.556 Gauss. The angle between geographic north and magnetic north at this location is 2.8 degrees, so that your compass will point 2.8 degrees west of true north. The needle of the compass will dip 61.6 degrees from the horizontal plane. You can actually see this if you have a compass with a needle suspended at its middle point.

IV. Magnetism Measurement Techniques

4.1 The Soda Bottle Magnetometer

Compasses are great for measuring the direction of a magnetic field locally, but don't provide enough detailed information to make these measurements precise enough for scientific study. They also don't tell us the actual strength of the magnetic field. To gather this data, we have to develop sensitive instruments. One simple instrument that is the next step up from a compass is the Soda Bottle or 'Jam Jar' magnetometer. It provides a greatly amplified measurement of the compass needle motion, and the direction changes of the ground-level magnetic field.

This instrument is nothing more than a magnet suspended by a thread in a compass-like manner, which merely indicates the local direction of the horizontal component of the magnetic field. Details for constructing and using this instrument may be found at the IMAGE education web site:

http://image.gsfc.nasa.gov/poetry

Here is a photo of a typical set up created by a middle-school student:

Figure 29 - A soda bottle magnetometer and its setup. The lamp illuminates a mirror on the suspended magnet, and creates a spot on the wall, whose displacement is measured by the ruler. For more accurate measurements, a laser pointer can be used, attached securely to a stand (test tube holder) so that the pointer-soda bottle system does not move during the course of the measurement program. This can be built with simple woodworking skills.

4.2 The Dip Circle

A bit more mechanically complex than the soda bottle magnetometer is the Dip Circle. Magnetic dip in the vertical direction went unrecognized until 1576, when Robert Norman stumbled upon the effect while carefully watching a compass needle mounted in such a way that it was free to move in the vertical plane. He constructed a simple instrument to measure this movement in 1576. It must have been an exhilarating moment when Norman first saw this effect, because it was a new aspect of magnetism that no one had thought to look for before. The compass, soda bottle, and Dip Circle all measure the direction of the local magnetic field, but not its strength. Instruments with this ability require much more care, and a deeper understanding of electromagnetism.

4.3 The Bache Magnetometer, circa 1844

A simple pendulum acted upon by gravity alone, and made from a non-magnetic material, will have a well-defined period of oscillation given by:

Equation 9 $2 \pi T = (L / g)^{1/2}$

where L is the length of the pendulum in centimeters and G is the acceleration of gravity, 980 cm per second per second. The addition of another force, such as magnetism, will change the oscillation period in a way that the period change can be used to measure the strength of the applied force. A pendulum with a non-magnetic weight of the same mass as a ferro-magnetic weight will oscillate at the gravity-induced frequency, but a ferro-magnetic weight will be influenced by the local magnetic field and have a different period of oscillation. The change on the period of the pendulum can be used to measure the strength of the magnetic field in which it is swinging, a principle first applied by Bache in 1844.

4.4 Electromagnetic Magnetometer

Beginning with the 1831 researches by Michael Faraday and Wilhelm Weber, several instruments were designed, based on a radically different principle. Instead of measuring the period of a magnetized pendulum, the new instruments measured the current generated by a rotating copper plate. As the plate is spun perpendicular to the plane of the magnetic field, a weak current is produced. Weber replaced the copper plate with a coil of wire that could be rotated, and a deflection caused by the current appeared on a galvanometer dial. This type of magnetometer allowed scientists to measure a changing strength and direction of a magnetic field, and is still used.

4.5 Proton Precession magnetometer

This magnetometer design can only measure the total magnetic field strength, but is often used for underwater location of metallic objects such as submarines. The operating principle here is that protons in a liquid (like ordinary water!) have a precession frequency of about 2000 Hertz in a 50 microTesla field. The precession frequency depends on the applied field strength. To sense the precession frequency, a non-ferromagnetic container with hydrogen-rich liquid such as alcohol is surrounded by a coil of wire. A current is passed through the wire to magnetize the liquid, then the field is turned off, and the current produced by the low-frequency radio signal from the gyrating protons is measured.

Although this device sounds complicated, in fact it is well within the skill of an amateur scientist/hobbyist to produce. There are several designs for this kind of instrument on the Web.

V. The fluxgate magnetometer

Although it was mainly built to detect submarines during World War II, the fluxgate magnetometer provides information about both the intensity and orientation of a magnetic field. It has become, by far, the most widely used instrument both for prospecting on Earth and for space-based research applications. This is the type of magnetometer used in the THEMIS ground-based and satellite observatories, including the education stations.

5.1 Operating principles

Consider an electromagnet with wires wrapped around a nail and attached to a battery. When the circuit is completed and the electricity flows, the coils produce a magnetic field. The iron nail is not necessary for an electromagnet, but it is used to enhance the magnetic field. A fluxgate magnetometer uses some of these same concepts, plus more.

A fluxgate magnetometer measures an external magnetic field in any direction by determining the amount of electric current needed to reduce the magnetic field strength in the core to zero along that direction. The core is in the center of the fluxgate sensor (like the iron nail in the electromagnet) and usually consists of a nickel ring wrapped with magnetic material, as shown in Figure 30. If there is an external magnetic field, a magnetic field in the core will exist before the fluxgate magnetometer is turned on. If there is no external magnetic field, there will be no magnetic field in the core before the fluxgate magnetometer is turned on. Around the core is a primary coil of wire (like the wire around the nail in the electromagnet) that magnetizes the core, in addition to any external magnetic field magnetization. A secondary coil is wrapped around the core to detect signals coming from it.

To magnetize the core, a fluxgate magnetometer applies an oscillating magnetic field (one that changes quickly and periodically in time) around the core that alternately produces a magnetic field parallel and antiparallel to the “sense” axis. An example of a sense axis is the x-axis on the THEMIS magnetometers. This oscillating magnetic field reverses the core’s polarity (its orientation of the North and South magnetic poles). If the average magnetic field is zero in the core, the secondary coil shown in Figure 31 picks up a symmetric signal. This signal arises when the current in the primary coil drives the magnetic material to saturation on each reversal of the core’s polarity. Saturation is the maximum magnetic field the magnetic material can hold. If there is some steady magnetic field in the core from an external magnetic field, the saturation produced by the primary coil will be asymmetric and a signal will be produced in the secondary coil at double the frequency of the signal in the primary coil.

To determine the amount of electric current needed to reduce the magnetic field strength in the core to zero, the current is increased until the asymmetric signal becomes symmetric again, signifying a zero field in the center of the sensor. The strength of this current is a measure of the magnetic field being studied.

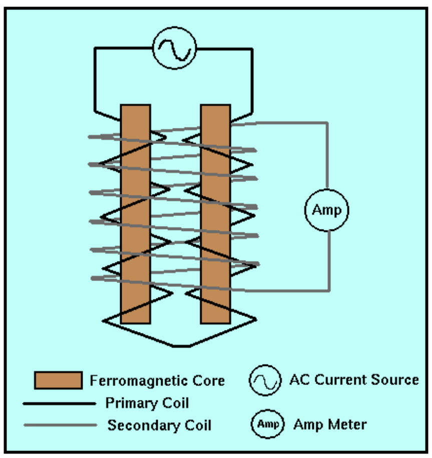


Figure 30 - A diagram showing one type of fluxgate magnetometer. A primary coil is wound around the iron bars and an alternating current is run through this wire. A secondary coil is wrapped around the iron bars to measure any changing magnetic fields due to magnetic saturation of the iron bars. An external magnetic field aligned parallel with the bars will influence the signal measured by the secondary coils. Some fluxgate magnetometers use rings of iron instead of bars.

5.2 Applications in science, medicine and industry

There are many applications of fluxgate magnetometry to science, medicine and industry. Here are some of the surprising ones!

Lung Research

Dr. David Cohen at the Massachusetts Institute of Technology (MIT) published a paper in 1979, concerning his findings on the human lungs. Air passages in the human body are lined with hair-like cilia, constantly waving back and forth and thus slowly sweeping out any dirt or debris deposited in them (Cohen called them "the moving carpet"). Cohen had a dozen volunteers inhale small amounts of iron oxide dust, which is harmless but can be magnetized. Over a year's time, each subject stood between a pair of coils, through which a large current was briefly passed. This magnetized the dust grains inside the lungs and aligned them with each other. The subjects then climbed into the shielded room, where the strength of the magnetization of their chest area was measured. During the year of observations the amount of dust declined steadily to about 10% of the original level. (For smokers, however, their lungs cleaned themselves much more slowly, and after one year, about 50% of the dust still remained.)

Cytology:

When Peter Valberg and later Jim Butler, both accomplished physicists, arrived at the Harvard School of Public Health, they invented Magnetic Twisting Cytometry to study the mechanical properties and movement of macrophages - organisms that eat viruses. They fed iron-rich food to a small number of macrophages, and by using a fluxgate magnetometer, they could study how these organisms behaved in lung tissues.

VI: The THEMIS Magnetometer

6.1 Design and block diagram

The THEMIS mission studies substorm signatures on the ground and in space with time resolutions less than 30 seconds. Existing and new ground-based magnetometers built by the University of California at Los Angeles (UCLA) determine the signatures of the ionospheric currents induced by substorm auroras with nominal resolution of 1 second.

The University of California at Berkeley (UCB) team is responsible for the deployment, maintenance and data retrieval from the Alaskan sites. Existing (non-THEMIS) sites already provide a capable magnetometer network, which THEMIS enhances to meet its spatial and temporal resolution goals. The THEMIS ground based magnetometers were developed after the heritage of dozens of such sensors already deployed by the same UCLA team which has installed similar units at various sites internationally.

There are 20 magnetometer stations installed at sub-auroral-latitudes in North America. The GMAGs form a network of detection sites, ancillary to existing US mid-latitude stations already in place. The magnetometer data from the schools goes to UCB, where it is plotted and made available via the World Wide Web.

6.2 Hardware Setup

The magnetometer consists of a sensor for detecting the geomagnetic field, an electronics box for operating the sensor—including calculating the magnetic field—and a computer that logs the data and transmits it to the central collection site at UCB. For more details about the setup and installation, see the THEMIS GEONS slideshow at

http://ds9.ssl.berkeley.edu/themis/schools/installations/carson_city01.html

The sensor is designed to be installed in a post hole about 1 meter (three feet) below ground surface to minimize temperature effects. Typically the post hole is 30-meters (~100 feet) away from the building where the PC is housed, to avoid magnetic noise from the operator/cars. It includes internal heaters, which can be used to further stabilize the temperature. A protected cable connects the PC to the sensor assembly.

The cable inside the hose is routed into the building where the computer has been set up. Because no in-line amplifiers are used on the cable, the maximum length of the cable to the sensor can be no more than 100 meters (300 feet) to the back of the PC being used.

The magnetometer uses a GPS link to determine the correct latitude and longitude of the GMAG station, but more importantly, it uses GPS time signals to obtain a universal time (UT) base for comparing the measurements by the entire network of stations in the GEONS program.

Installation and calibration takes 2-8 hours depending on soil conditions, after logistics (hole digging, power connection, cable access from building to site) have been dealt with. The entire operation takes 2-4 days, depending on availability of local support. In most instances, you will be assisted by a scientist from the THEMIS team who will travel to your location and help with the installation.

Figure 31 - Magnetometer sensor located in the black tube, with the sensor cable located inside a garden hose for protection against chewing little creatures.

Figure 32 - White GPS antenna being attached to a pipe at the Carson City, Nevada site. Usually it is better to have the GPS away from fences, but this one had a big enough field-of-view in the other direction to get data from the GPS satellites.
.

Figure 33 - Magnetometer electronics box (black box) sitting on a blue magnetic shield test can. Three wires come into this box: one is attached to the magnetometer sensor, one to the GPS, and the third is attached to the computer.

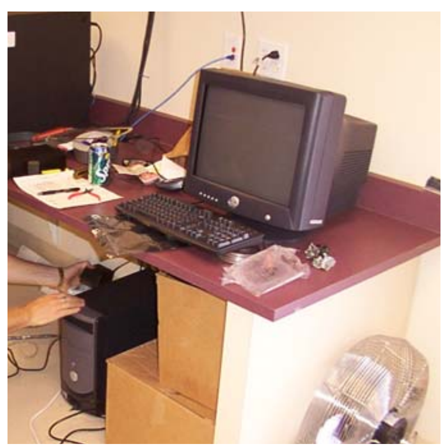


Figure 34 - The computer monitor and computer sitting in the classroom at the Western Nevada Community College in Carson City, Nevada. The electronics box is attached to the computer

6.3 Computer and Software Installation

The magnetometer board fits a standard desktop PC slot and has the following major sections:

1. GPS receiver
2. DC/DC converter, regulators
3. A single chip controller
4. ADC & low pass filters
5. Drive/sense circuits

6.4 Calibration and Data Collection

The calibration and qualification procedures entail sensor temperature drift, alignment and offset measurements. This is performed in a laboratory environment prior to shipping from UCB to the appropriate school.

GMAG data rate and volume:

- Digitization 16 bits
- Quantities 1+3 (time, Bx, By, Bz)
- Rep. rate 1 sample/sec
- Data rate 68 bits/s w/H/K & overhead
- Tx data per day 5.8 Mbits
- Tx Baud rate 30 kbps
- Tx time (only stream 1) 193 sec
- Data volume 0.265 Gbytes/year

Each site returns about 63 Gbytes of data per season via :

-
- Hard disk swapping
- Mail distribution
- Direct Internet FTP or upload

These amount to about 4 terrabytes for the lifetime of the mission, including full data retrieval from the two winters before the THEMIS launch. Most of this is imaging data. EPO magnetometer data can be analyzed with standard Windows software packages such as Excel, by simply importing the ASCII data generated in the Science Files. THEMIS ground data, accessible to the public and to schools that host the magnetometers, are equipped with ASCII conversion routines, and web-based download functions.

VII Related Web Resources

7.1 THEMIS-Related resources

The main THEMIS education and outreach web page supports this guide and the other teacher guides in this series. The data from the magnetometers in the classroom are available on the site, and also information on the schools and teachers involved in the program. Additional information about the THEMIS mission can be found there, as well as images from the building of the instruments and spacecraft, scientist and engineer interviews, launch videos, and information about the education team.

http://ds9.ssl.berkeley.edu/themis

7.2 THEMIS Satellite Information

- ✓ THEMIS Mission Science
  http://ds9.ssl.berkeley.edu/themis/mission_mystery.html

- ✓ News and Events
  http://ds9.ssl.berkeley.edu/themis/news.html

7.3 Magnetic observatories

Professional research observatories often have web pages displaying real-time magnetometer data similar to the type of data that you will be recording on your own station. Visit the NASA Student Observation Network web page for a complete introduction and links to sample sites.

http://son.gsfc.nasa.gov/magnetosphere/from_obs.html

7.4 ACE spacecraft data

The NASA ACE satellite is located 1.5 million kilometers (1 million miles) from Earth at what's known as the L1 point. It monitors the solar wind magnetic field on a minute-to-minute basis, and serves a critical role in modern space weather forecasting. Visit its web page and click on the SWEPAM instrument link. It can also be reached through the Student Observation Network portal:

http://son.gsfc.nasa.gov/magnetosphere/sat_ace.htm

7.5 Elementary geophysics

Here are some resources that will give you a quick introduction to basic geophysics and geomagnetism:

- ✓ USGS:

  http://geomag.usgs.gov

- ✓ NASA/GSFC – Exploring the Magnetosphere:

  http://www-istp.gsfc.nasa.gov/Education/Intro.html

- ✓ NASA/IMAGE:

  http://image.gsfc.nasa.gov/poetry/magnetism/magnetism.html

7.6 Paleomagnetism

There are many web pages that discuss this fascinating topic in detail.

- ✓ Education Resources:

  http://mahi.ucsd.edu/cathy/Gpmag/gphome.html

- ✓ Reversals and Wander

  http://www.geolab.nrcan.gc.ca/geomag/reversals_e.shtml

- ✓ More Reversal Info:

  http://www.geomag.bgs.ac.uk/reversals.html

7.7 Space Weather resources

- ✓ NASA/IMAGE: **http://image.gsfc.nasa.gov/poetry**
- ✓ NOAA/SEC: **http://www.sec.noaa.gov/SWN**
- ✓ Human Impacts **http://www.solarstorms.org**

7.8 Mathematical models of the IGRF Reference Field

Over 100 years of careful study have resulted in the design of a super-precise field model. Here is a page where you can access it:

- ✓ NASA/NSSDC International Geophysical Reference Field:
  http://nssdc.gsfc.nasa.gov/space/model/models/igrf.html

Bibliography

Birch, James, 2001, “The Fury of Space Storms,” *Scientific American*, April

Cohen, David et al., “Smoking Impairs Long-Term Dust Clearance from the Lung,” *Science*, 204, 514-7, 4 May 1979

Fleming, J. A. 1939, ***Physics of the Earth: Terrestrial Magnetism and Electricity***, Vol. VII. New York: McGraw-Hill Book Company. (QC815 N3 1939)).

Livesey, R., 1982, “A Jam-Jar Magnetometer, ” *Journal of the British Astronomical Society*, v. 93, p. 17.

Livesey, R. 1989, “A Jam-Jar magnetometer as an Aurora Detector,” *Sky and Telescope*, October, 1989, p. 426

Odenwald, S. 1998, “Solar Storms: Hidden Menace,” Sky and Telescope, March

Odenwald, S., ***The 23rd Cycle***, Columbia University Press, 2001

Pettitt, D. O., 1984, “A Fluxgate Magnetometer,” *Journal of the British Astronomical Society*, v. 94, p. 55.

Savage, C. 1994, ***Aurora: The Mysterious Northern Light***, (Sierra Club Books:SF), p. 59-67.