The Magnetic Field of the Earth

(Concepts & Elements)

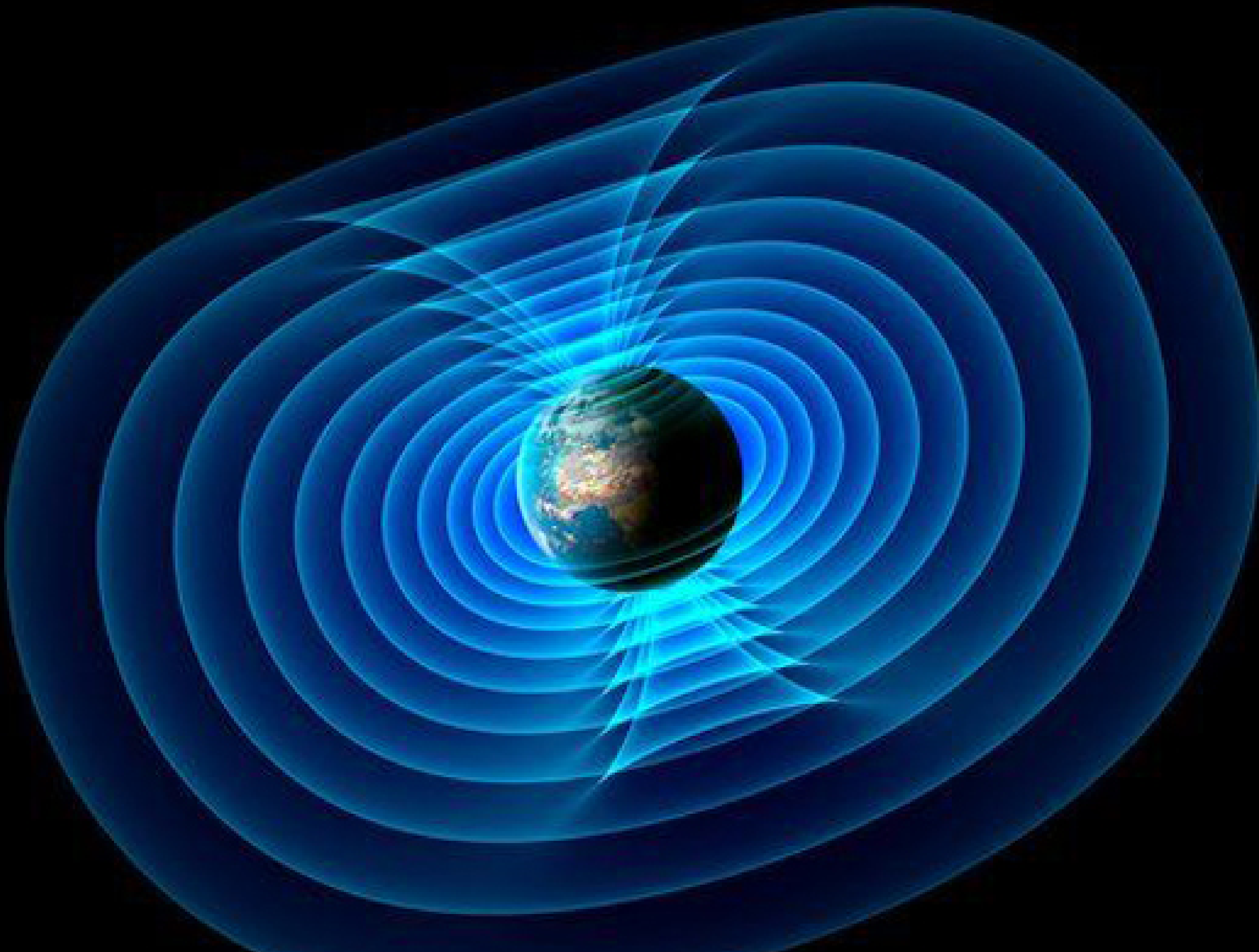

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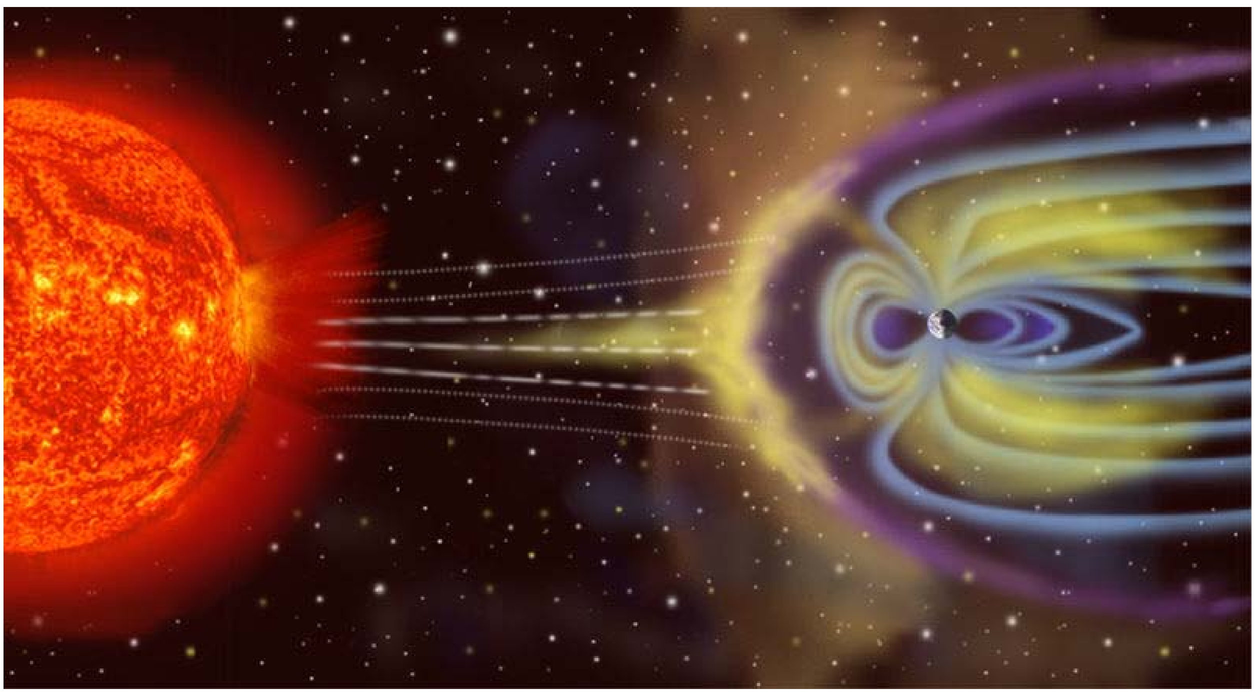
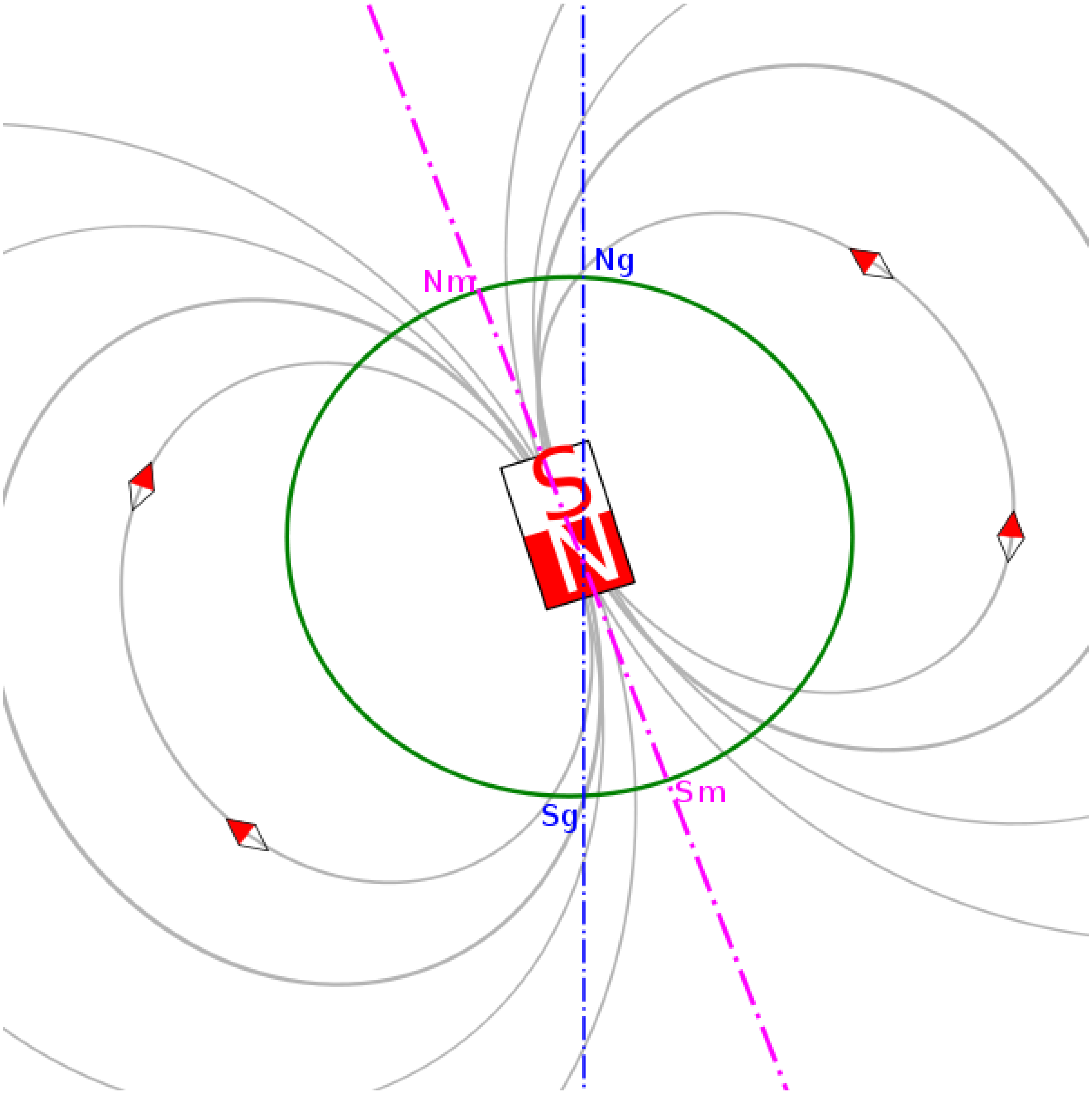
Table of Contents

Chapter- 1

Earth's Magnetic Field



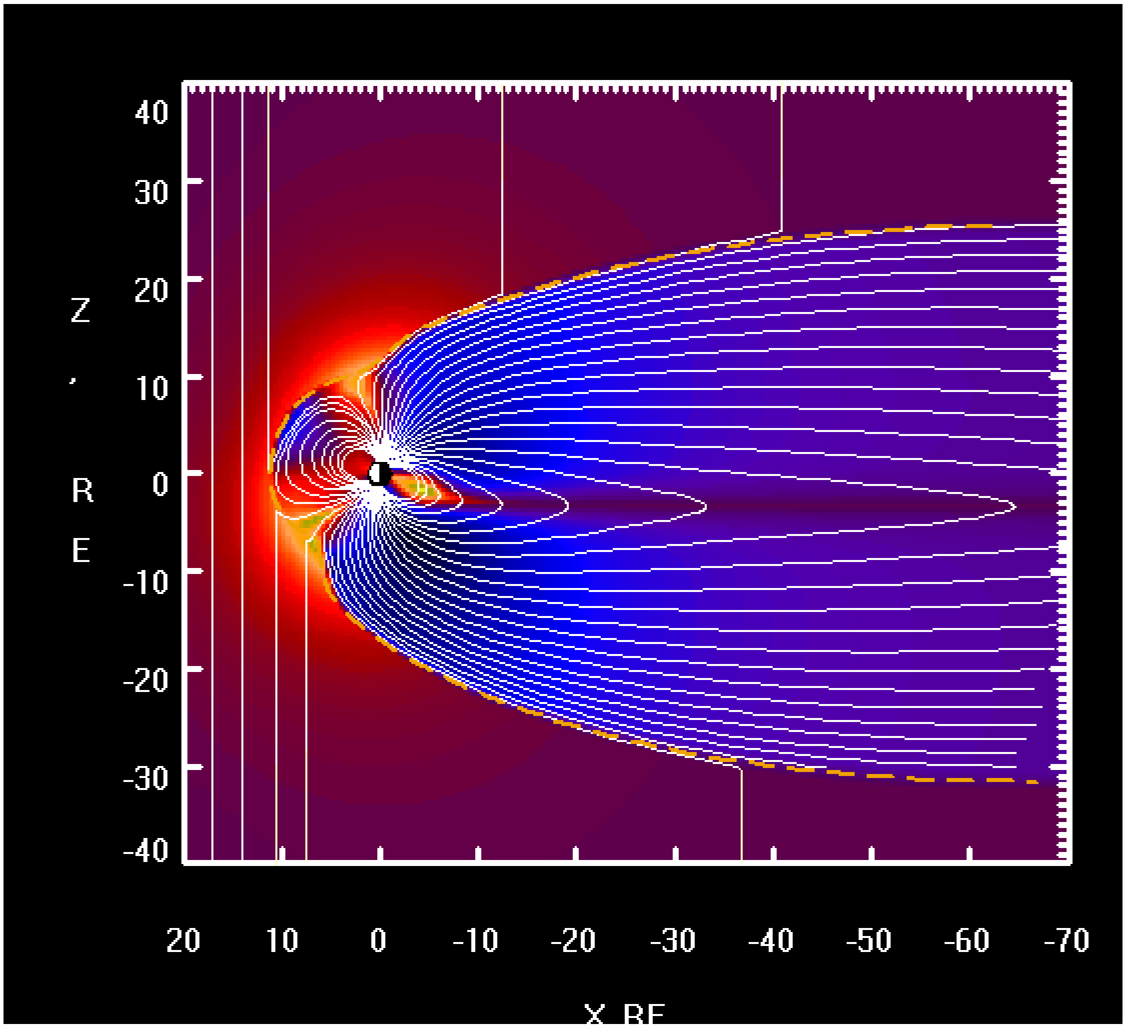
The magnetosphere shields the surface of the Earth from the charged particles of the solar wind and is generated by electric currents located in many different parts of the Earth. It is compressed on the day (Sun) side due to the force of the arriving particles, and extended on the night side. (Image not to scale.)



The variation between magnetic north and "true" north

Earth's magnetic field (and the **surface magnetic field**) is approximately a magnetic dipole, with the magnetic field South pole near the Earth's geographic north pole and the other magnetic field N pole near the Earth's geographic south pole. This makes the compass usable for navigation. The cause of the field can be explained by dynamo theory. A magnetic field extends infinitely, though it weakens with distance from its source. The Earth's magnetic field, also called the **geomagnetic field**, which effectively extends several tens of thousands of kilometres into space, forms the Earth's magnetosphere. A paleomagnetic study of Australian red dacite and pillow basalt has estimated the magnetic field to be at least 3.5 billion years old.

Importance

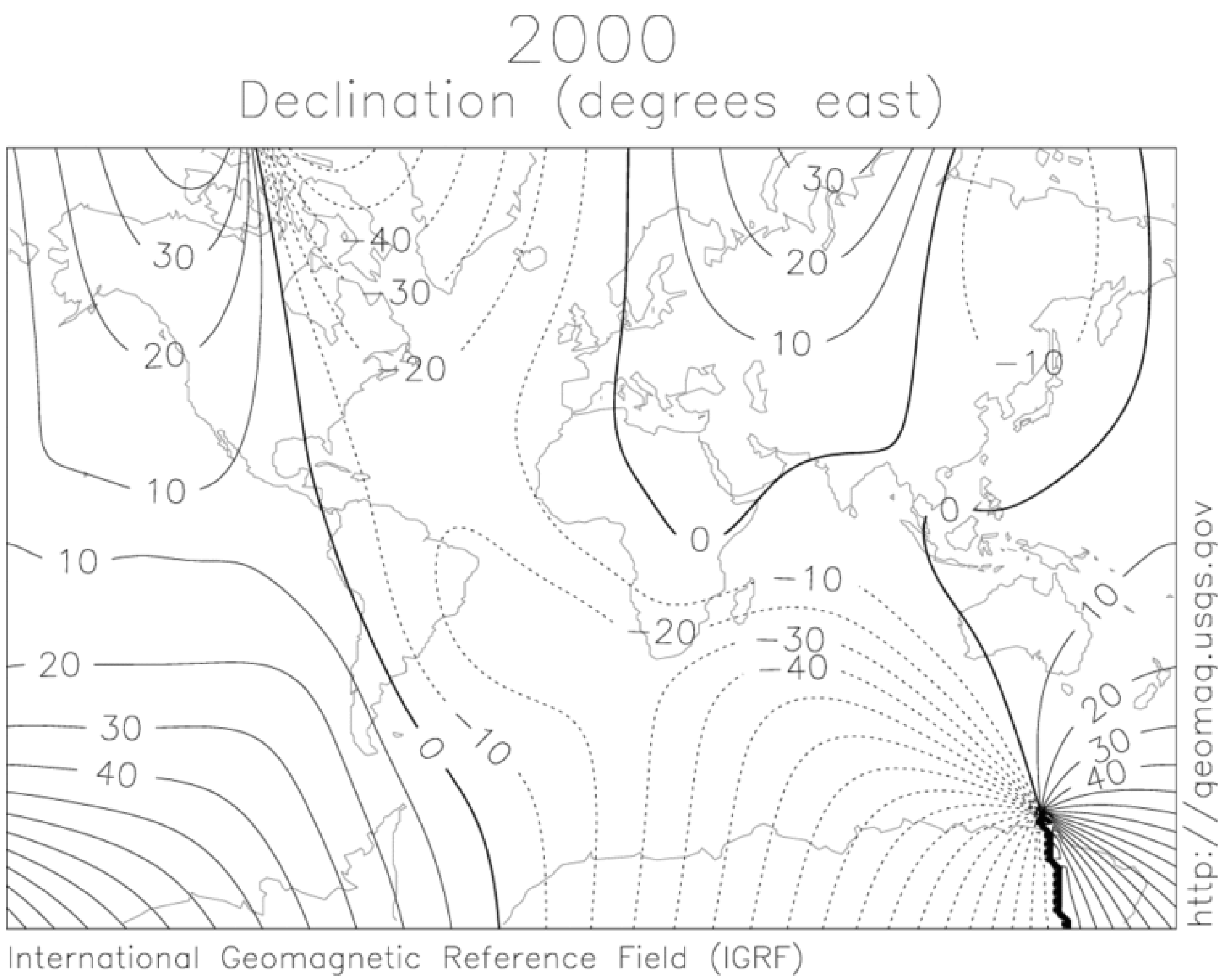


Simulation of the interaction between Earth's magnetic field and the interplanetary magnetic field

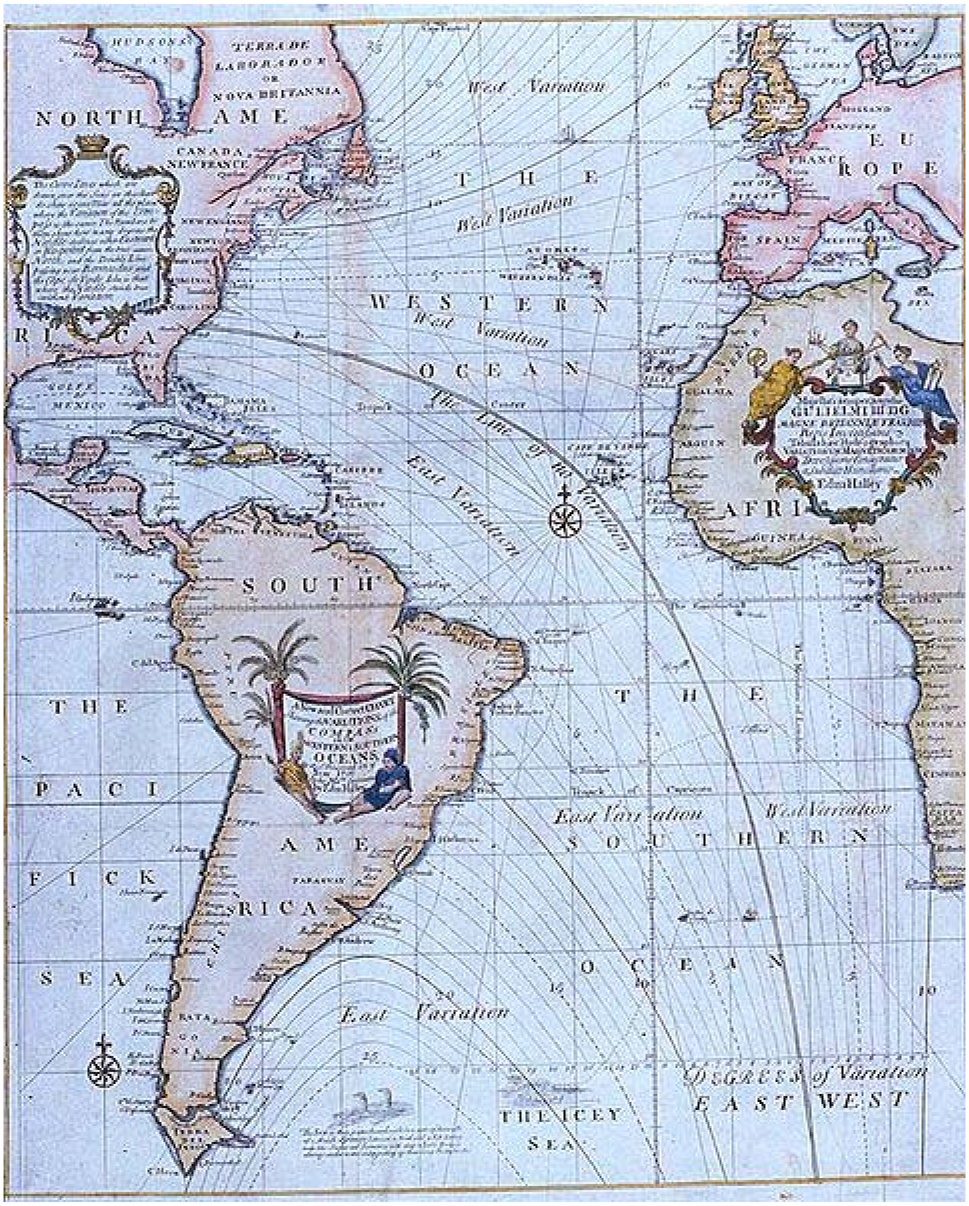
The Earth is largely protected from the solar wind, a stream of energetic charged particles emanating from the Sun, by its magnetic field, which deflects most of the charged particles. Some of the charged particles from the solar wind are *trapped* in the Van Allen radiation belt. A smaller number of particles from the solar wind manage to travel, as though on an electromagnetic energy transmission line, to the Earth's upper atmosphere and ionosphere in the auroral zones. The only time the solar wind is observable on the Earth is when it is strong enough to produce phenomena such as the aurora and geomagnetic storms. Bright auroras strongly heat the ionosphere, causing its plasma to expand into the magnetosphere, increasing the size of the plasma geosphere, and causing escape of atmospheric matter into the solar wind. Geomagnetic storms result when the pressure of plasmas contained inside the magnetosphere is sufficiently large to inflate and thereby distort the geomagnetic field.

The solar wind is responsible for the overall shape of Earth's magnetosphere, and fluctuations in its speed, density, direction, and entrained magnetic field strongly affect Earth's local space environment. For example, the levels of ionizing radiation and radio interference can vary by factors of hundreds to thousands; and the shape and location of the magnetopause and bow shock wave upstream of it can change by several Earth radii, exposing geosynchronous satellites to the direct solar wind. These phenomena are collectively called space weather. The mechanism of atmospheric stripping is caused by gas being caught in bubbles of magnetic field, which are ripped off by solar winds. Variations in the magnetic field strength have been correlated to rainfall variation within the tropics.

Magnetic poles and magnetic dipole



Magnetic declination from true north in 2000



Magnetic declination from true north in 1700

The positions of the magnetic poles can be defined in at least two ways.

Often, a magnetic (dip) pole is viewed as a point on the Earth's surface where the magnetic field is entirely vertical. Another way of saying this is that the inclination of the Earth's field is 90° at the North Magnetic Pole and -90° at the South Magnetic Pole. At a magnetic pole, a compass held in the horizontal plane points randomly, while otherwise it points nearly to the North Magnetic Pole or away from the South Magnetic Pole, though local deviations exist. The two poles wander independently of each other and are not at directly opposite positions on the globe. Magnetic dip pole can migrate rapidly: movements of up to 40 km per year have been observed for the North Magnetic Pole.

The Earth's magnetic field can be closely approximated by the field of a magnetic dipole positioned near the centre of the Earth. A dipole's orientation is defined by an axis. The two positions where the axis of the dipole that best fits the geomagnetic field intersect the Earth's surface are called the North and South geomagnetic poles. For best fit the dipole representing the geomagnetic field should be placed about 500 km off the center of the Earth. This causes the inner radiation belt to skim lower in Southern Atlantic ocean, where the surface field is the weakest, creating what is called the South Atlantic Anomaly.

If the Earth's magnetic field were perfectly dipolar, the geomagnetic and magnetic dip poles would coincide. However, significant non-dipolar terms in an accurate description of the geomagnetic field cause the position of the two pole types to be in different places.

Magnetic pole positions

North Magnetic Pole	(2001) 81°18′N 110°48′W / 81.3°N 110.8°W	(2004 est) 82°18′N 113°24′W / 82.3°N 113.4°W	(2005 est) 82°42′N 114°24′W / 82.7°N 114.4°W	(2010 est) 85°00′N 132°36′W / 85.0°N 132.6°W
South Magnetic Pole	(1998) 64°36′S 138°30′E / 64.6°S 138.5°E	(2004 est) 63°30′S 138°00′E / 63.5°S 138.0°E	(2005 est) 63°06′S 137°30′E / 63.1°S 137.5°E	(2010 est) 64°24′S 137°18′E / 64.4°S 137.3°E

Field characteristics

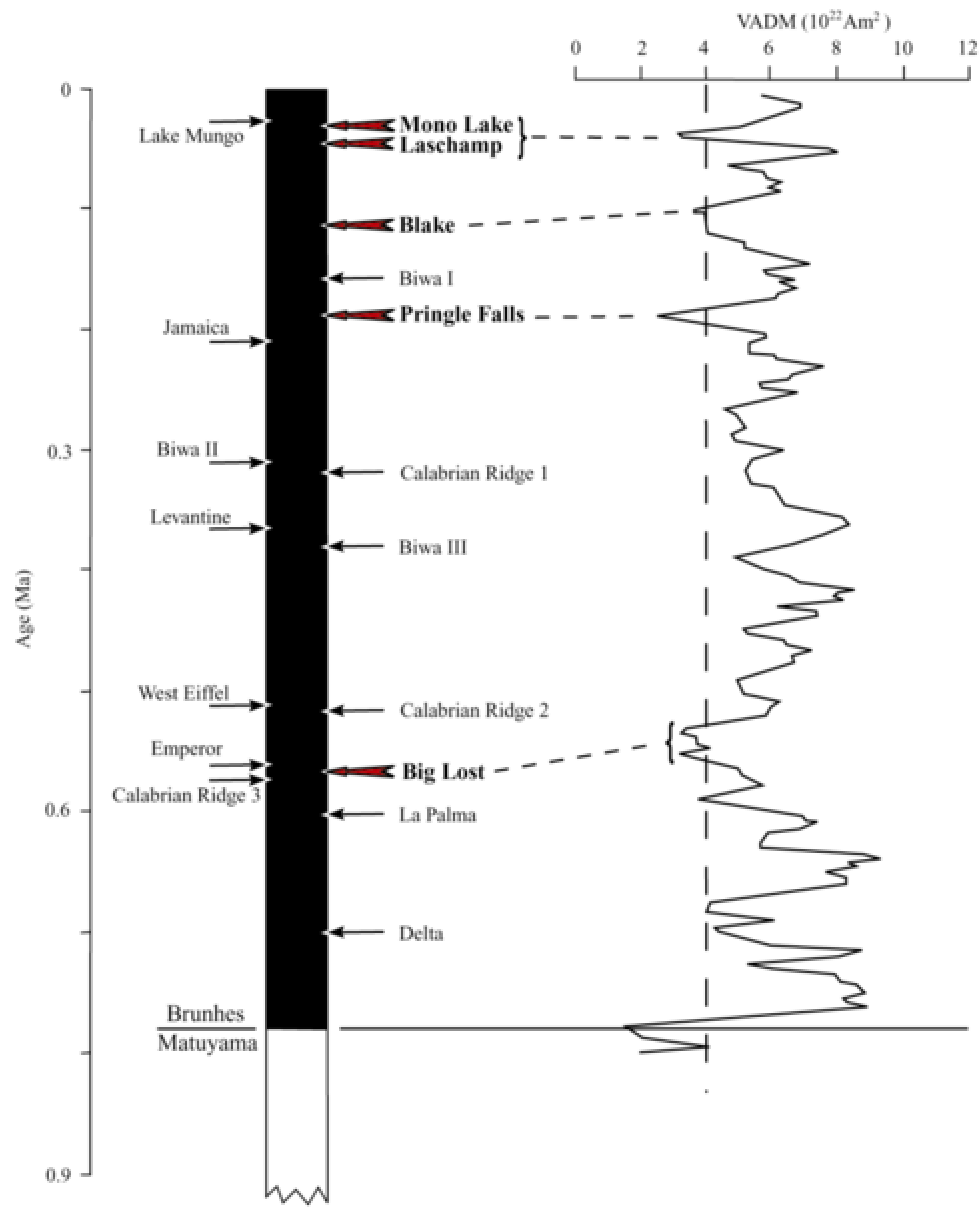
The strength of the flux density at the Earth's surface ranges from less than 30 microteslas (0.3 gauss) in an area including most of South America and South Africa to over 60 microteslas (0.6 gauss) around the magnetic poles in northern Canada and south of Australia, and in part of Siberia. The average flux density in the Earth's outer core was calculated to be 25 Gauss, 50 times stronger than the magnetic field at the surface.

The field is similar to that of a bar magnet. The Earth's magnetic field is mostly caused by electric currents in the liquid outer core. The Earth's core is hotter than 1043 K, the Curie point temperature, above which the orientations of spins within iron become randomized. Such randomization causes the substance to lose its magnetization.

Convection of molten iron within the outer liquid core, along with a Coriolis effect caused by the overall planetary rotation, tends to organize these "electric currents" in rolls aligned along the north-south polar axis. When conducting fluid flows across an existing magnetic field, electric currents are induced, which in turn creates another magnetic field. When this magnetic field reinforces the original magnetic field, a dynamo is created that sustains itself. This is called the Dynamo Theory and it explains how the Earth's magnetic field is sustained.

Another feature that distinguishes the Earth magnetically from a bar magnet is its magnetosphere. At large distances from the planet, this dominates the surface magnetic field. Electric currents induced in the ionosphere also generate magnetic fields. Such a field is always generated near where the atmosphere is closest to the Sun, causing daily alterations that can deflect surface magnetic fields by as much as one degree. Typical daily variations of field strength are about 25 nanoteslas (nT) (i.e. ~ 1:2,000), with variations over a few seconds of typically around 1 nT (i.e. ~ 1:50,000).

Magnetic field variations



Geomagnetic variations since last reversal

The currents in the core of the Earth that create its magnetic field started up at least 3,450 million years ago.

Magnetometers detect minute deviations in the Earth's magnetic field caused by iron artifacts, kilns, some types of stone structures, and even ditches and middens in archaeological geophysics. Using magnetic instruments adapted from airborne magnetic anomaly detectors developed during World War II to detect submarines, the magnetic variations across the ocean floor have been mapped. The basalt — the iron-rich, volcanic rock making up the ocean floor — contains a strongly magnetic mineral (magnetite) and can locally distort compass readings. The distortion was recognized by Icelandic mariners as early as the late 18th century. More important, because the presence of magnetite gives the basalt measurable magnetic properties, these magnetic variations have provided another means to study the deep ocean floor. When newly formed rock cools, such magnetic materials record the Earth's magnetic field.

Frequently, the Earth's magnetosphere is hit by solar flares causing geomagnetic storms, provoking displays of aurorae. The short-term instability of the magnetic field is measured with the K-index.

Data from THEMIS show that the magnetic field, which interacts with the solar wind, is reduced when the magnetic orientation is aligned between Sun and Earth - opposite to the previous hypothesis. During forthcoming solar storms, this could result in blackouts and disruptions in artificial satellites.

Magnetic field reversals

Based upon the study of lava flows of basalt throughout the world, it has been proposed that the Earth's magnetic field reverses at intervals, ranging from tens of thousands to many millions of years, with an average interval of approximately 200,000 to 300,000 years. However, the last such event, called the Brunhes–Matuyama reversal, is observed to have occurred some 780,000 years ago.

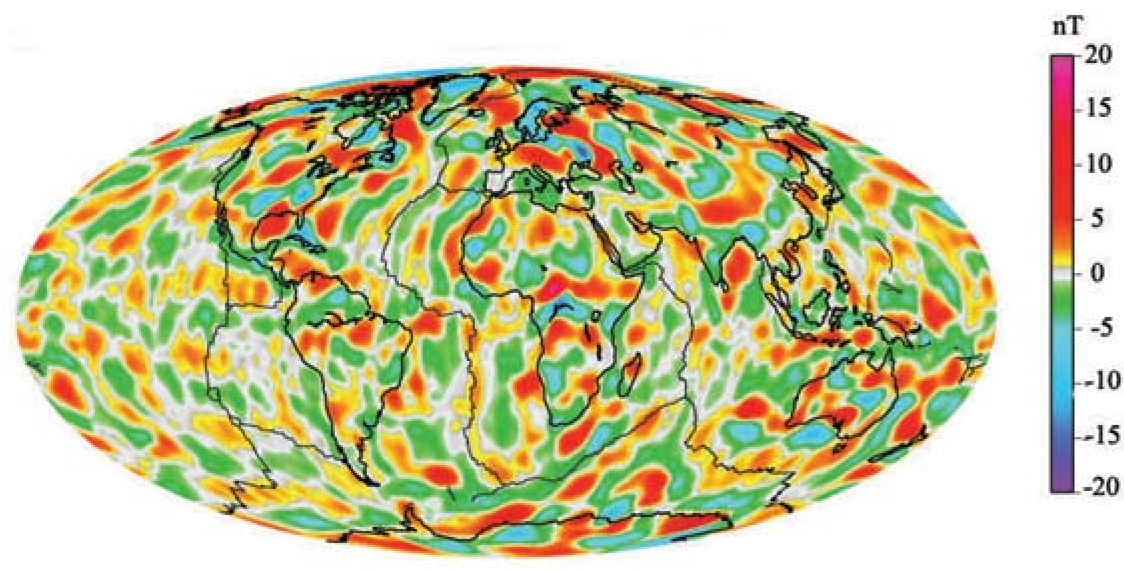
There is no clear theory as to how the geomagnetic reversals might have occurred. Some scientists have produced models for the core of the Earth wherein the magnetic field is only quasi-stable and the poles can spontaneously migrate from one orientation to the other over the course of a few hundred to a few thousand years. Other scientists propose that the geodynamo first turns itself off, either spontaneously or through some external action like a comet impact, and then restarts itself with the magnetic "North" pole pointing either North or South. External events are not likely to be routine causes of magnetic field reversals due to the lack of a correlation between the age of impact craters and the timing of reversals. Regardless of the cause, when the magnetic pole flips from one hemisphere to the other this is known as a reversal, whereas temporary dipole tilt variations that take the dipole axis across the equator and then back to the original polarity are known as excursions.

Studies of lava flows on Steens Mountain, Oregon, indicate that the magnetic field could have shifted at a rate of up to 6 degrees per day at some time in Earth's history, which significantly challenges the popular understanding of how the Earth's magnetic field works.

Paleomagnetic studies such as these typically consist of measurements of the remanent magnetization of igneous rock from volcanic events. Sediments laid on the ocean floor orient themselves with the local magnetic field, a signal that can be recorded as they solidify. Although deposits of igneous rock are mostly paramagnetic, they do contain traces of ferri- and antiferromagnetic materials in the form of ferrous oxides, thus giving them the ability to possess remnant magnetization. In fact, this characteristic is quite common in numerous other types of rocks and sediments found throughout the world. One of the most common of these oxides found in natural rock deposits is magnetite.

As an example of how this property of igneous rocks allows us to determine that the Earth's field has reversed in the past, consider measurements of magnetism across ocean ridges. Before magma exits the mantle through a fissure, it is at an extremely high temperature, above the Curie temperature of any ferrous oxide that it may contain. The lava begins to cool and solidify once it enters the ocean, allowing these ferrous oxides to eventually regain their magnetic properties, specifically, the ability to hold a remnant magnetization. Assuming that the only magnetic field present at these locations is that associated with the Earth itself, this solidified rock becomes magnetized in the direction of the geomagnetic field. Although the strength of the field is rather weak and the iron content of typical rock samples is small, the relatively small remnant magnetization of the samples is well within the resolution of modern magnetometers. The age and magnetization of solidified lava samples can then be measured to determine the orientation of the geomagnetic field during ancient eras.

Magnetic field detection



A model of the deviations in earth's magnetic field, measured by satellites with sensitive magnetometers

The Earth's magnetic field strength was measured by Carl Friedrich Gauss in 1835 and has been repeatedly measured since then, showing a relative decay of about 10% over the last 150 years.

The Magsat satellite and later satellites have used 3-axis vector magnetometers to probe the 3-D structure of the Earth's magnetic field. The later Ørsted satellite allowed a comparison indicating a dynamic geodynamo in action that appears to be giving rise to an alternate pole under the Atlantic Ocean west of S. Africa.

Governments sometimes operate units that specialise in measurement of the Earth's magnetic field. These are geomagnetic observatories, typically part of a national Geological Survey, for example the British Geological Survey's Eskdalemuir Observatory. Such observatories can measure and forecast magnetic conditions that sometimes affect communications, electric power, and other human activities.

The International Real-time Magnetic Observatory Network, with over 100 interlinked geomagnetic observatories around the world has been recording the earths magnetic field since 1991.

The military determines local geomagnetic field characteristics, in order to detect *anomalies* in the natural background that might be caused by a significant metallic object such as a submerged submarine. Typically, these magnetic anomaly detectors are flown in aircraft like the UK's Nimrod or towed as an instrument or an array of instruments from surface ships.

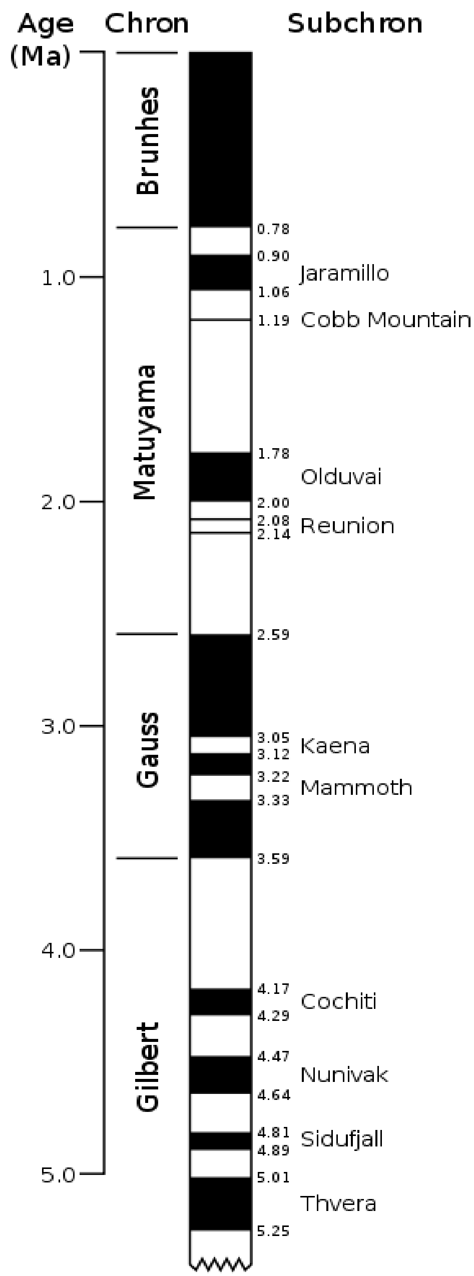
Commercially, geophysical prospecting companies also use magnetic detectors to identify naturally occurring anomalies from ore bodies, such as the Kursk Magnetic Anomaly.

Animals including birds and turtles can detect the Earth's magnetic field, and use the field to navigate during migration. Cows and wild deer tend to align their bodies north-south while relaxing, but not when the animals are under high voltage power lines, leading researchers to believe magnetism is responsible.

Seismo-electromagnetics is an area of research aimed at earthquake prediction.

Chapter- 2

Geomagnetic Reversal



Geomagnetic polarity during the late Cenozoic Era. Dark areas denote periods where the polarity matches today's polarity, light areas denote periods where that polarity is reversed.

A **geomagnetic reversal** is a change in the Earth's magnetic field such that the positions of magnetic north and magnetic south are interchanged. The Earth's field has alternated between periods of **normal** polarity, in which the direction of the field was the same as the present direction, and **reverse** polarity, in which the field was in the opposite direction. These periods are called **chrons**. The time spans of chrons are randomly distributed with most being between 0.1 and 1 million years. Most reversals are estimated to take between 1,000 and 10,000 years. The latest one, the Brunhes–Matuyama reversal, occurred 780,000 years ago. Brief disruptions that do not result in reversal are called geomagnetic excursions.

History

In the early 20th century geologists first noticed that some volcanic rocks were magnetized opposite to the direction of the local Earth's field. The first estimate of the timing of magnetic reversals was made in the 1920s by Motonori Matuyama, who observed that the magnetic fields of some rocks in Japan were reversed and that these rocks were all of early Pleistocene age or older. At the time, the Earth's polarity was poorly understood and the possibility of reversal aroused little interest.

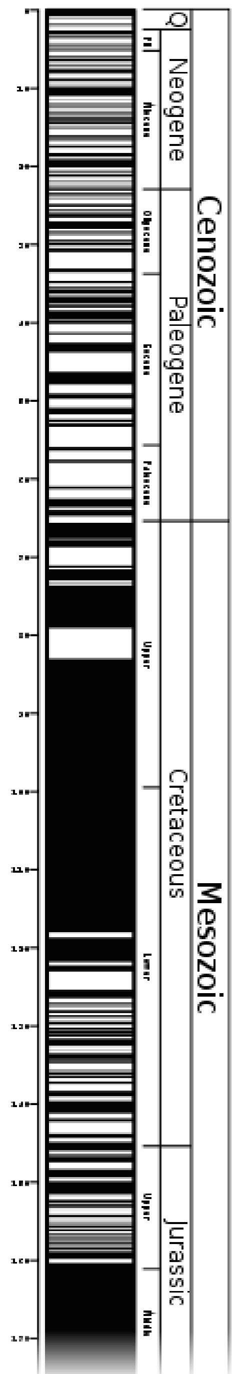
Three decades later, when Earth's magnetic field was better understood, theories were advanced suggesting that the Earth's field might have reversed in the remote past. Most paleomagnetic research in the late 1950s included an examination of the wandering of the poles and continental drift. Although it was discovered that some rocks would reverse their magnetic field while cooling, it became apparent that most magnetized volcanic rocks preserved traces of the Earth's magnetic field at the time the rocks had cooled. At first it was thought that reversals occurred approximately every million years, but by the 1960s it had become apparent that the timing of magnetic reversals was erratic.

During the 1950s and 1960s information about variations in the Earth's magnetic field was gathered largely by means of research vessels. But the complex routes of ocean cruises rendered the association of navigational data with magnetometer readings difficult. Only when data was plotted on a map, did it become apparent that remarkably regular and continuous magnetic stripes appeared on the ocean floors.

In 1963 Frederick Vine and Drummond Matthews provided a simple explanation by combining the seafloor spreading theory of Harry Hess with the known time scale of reversals: if new sea floor is magnetized in the direction of the field, then it will change its polarity when the field reverses. Thus, sea floor spreading from a central ridge will produce magnetic stripes parallel to the ridge. Canadian L. W. Morley independently proposed a similar explanation in January 1963, but his work was rejected by the scientific journals *Nature* and *Journal of Geophysical Research*, and remained unpublished until 1967, when it appeared in the literary magazine *Saturday Review*. The Morley–Vine–Matthews hypothesis was the first key scientific test of the seafloor spreading theory of continental drift.

Beginning in 1966, Lamont–Doherty Geological Observatory scientists found that the magnetic profiles across the Pacific-Antarctic Ridge were symmetrical and matched the pattern in the north Atlantic's Reykjanes ridges. The same magnetic anomalies were found over most of the world's oceans, which permitted estimates for when most of the oceanic crust had developed.

Observing past fields



Geomagnetic polarity since the middle Jurassic. Dark areas denote periods where the polarity matches today's polarity, light areas denote periods where that polarity is reversed.

Past field reversals can be and have been recorded in the "frozen" ferromagnetic (or more accurately, ferrimagnetic) minerals of consolidated sedimentary deposits or cooled volcanic flows on land.

Originally, however, the past record of geomagnetic reversals was first noticed by observing the magnetic stripe "anomalies" on the ocean floor. Lawrence W. Morley, Frederick John Vine and Drummond Hoyle Matthews made the connection to seafloor spreading in the Morley-Vine-Matthews hypothesis which soon led to the development of the theory of plate tectonics. Given that the sea floor spreads at a relatively constant rate, this results in broadly evident substrate "stripes" from which the past magnetic field polarity can be inferred by looking at the data gathered from towing a magnetometer along the sea floor.

However, because no existing unsubducted sea floor (or sea floor thrust onto continental plates, such as in the case of ophiolites) is much older than about 180 million years (Ma) in age, other methods are necessary for detecting older reversals. Most sedimentary rocks incorporate tiny amounts of iron rich minerals, whose orientation is influenced by the ambient magnetic field at the time at which they formed. Under favorable conditions, it is thus possible to extract information of the variations in magnetic field from many kinds of sedimentary rocks. However, subsequent diagenetic processes after burial may erase evidence of the original field.

Because the magnetic field is present globally, finding similar patterns of magnetic variations at different sites is one method used to correlate age across different locations. In the past four decades great amounts of paleomagnetic data about seafloor ages (up to ~250 Ma) have been collected and have become an important and convenient tool to estimate the age of geologic sections. It is not an independent dating method, but is dependent on "absolute" age dating methods like radioisotopic systems to derive numeric ages. It has become especially useful to metamorphic and igneous geologists where the use of index fossils to estimate ages is seldom available.

Geomagnetic polarity time scale

Through analysis of seafloor magnetic anomalies and dating of reversal sequences on land, paleomagnetists have been developing a *Geomagnetic Polarity Time Scale* (GPTS). The current time scale contains 184 polarity intervals in the last 83 million years.

Changing frequency of geomagnetic reversals over time

The rate of reversals in the Earth's magnetic field has varied widely over time. 72 million years ago (Ma), the field reversed 5 times in a million years. In a 4-million-year period centered on 54 Ma, there were 10 reversals; at around 42 Ma, 17 reversals took place in the span of 3 million years. In a period of 3 million years centering on 24 Ma, 13 reversals occurred. No fewer than 51 reversals occurred in a 12-million-year period, centering on 15 million years ago. Two reversals occurred during a span of 50,000 years. These eras of frequent reversals have been counterbalanced by a few "superchrons" – long periods when no reversals took place.

Statistical properties of reversals

Several studies have analyzed the statistical properties of reversals in the hope of learning something about their underlying mechanism. The discriminating power of statistical tests is limited by the small number of polarity intervals. Nevertheless, some general features are well established. In particular, the pattern of reversals is random. There is no correlation between the lengths of polarity intervals. There is no preference for either normal or reversed polarity, and no statistical difference between the distributions of these polarities. This lack of bias is also a robust prediction of dynamo theory. Finally, as mentioned above, the rate of reversals changes over time.

The randomness of the reversals is inconsistent with periodicity, but several authors have claimed to find periodicity. However, these results are probably artifacts of an analysis using sliding windows to determine reversal rates.

Most statistical models of reversals have analyzed them in terms of a Poisson process or other kinds of renewal process. A Poisson process would have, on average, a constant reversal rate, so it is common to use a non-stationary Poisson process. However, compared to a Poisson process, there is a reduced probability of reversal for some tens of thousands after a reversal. This could be due to some inhibition in the underlying mechanism, or it could just mean that some shorter polarity intervals have been missed. A random reversal pattern with inhibition can be represented by a gamma process. In 2006, a team of physicists at the University of Calabria found that the reversals also conform to a Lévy distribution, which describes stochastic processes with long-ranging correlations between events in time. The data are also consistent with a deterministic, but chaotic, process.

Superchrons

A *superchron* is a polarity interval lasting at least 10 million years. There are two well-established superchrons, the Cretaceous Normal and the Kiaman. A third candidate, the Moyero, is more controversial. The Jurassic Quiet Zone in ocean magnetic anomalies was once thought to represent a superchron, but is now attributed to other causes.

Cretaceous Normal Superchron

The Cretaceous Normal (also called the Cretaceous Superchron or C34) lasted for almost 40 million years, from about 120 to 83 million years ago, including stages of the Cretaceous period from the Aptian through the Santonian. The frequency of magnetic reversals steadily decreased prior to the period, reaching its low point (no reversals) during the period. Between the Cretaceous Normal and the present, the frequency has generally increased slowly.

Kiaman Reverse Superchron

The Kiaman Reverse Superchron lasted from approximately the late Carboniferous to the late Permian, or for more than 50 million years, from around 312 to 262 million years ago. The magnetic field had reversed polarity. The name "Kiaman" derives from the Australian village of Kiama, where some of the first geological evidence of the superchron was found in 1925.

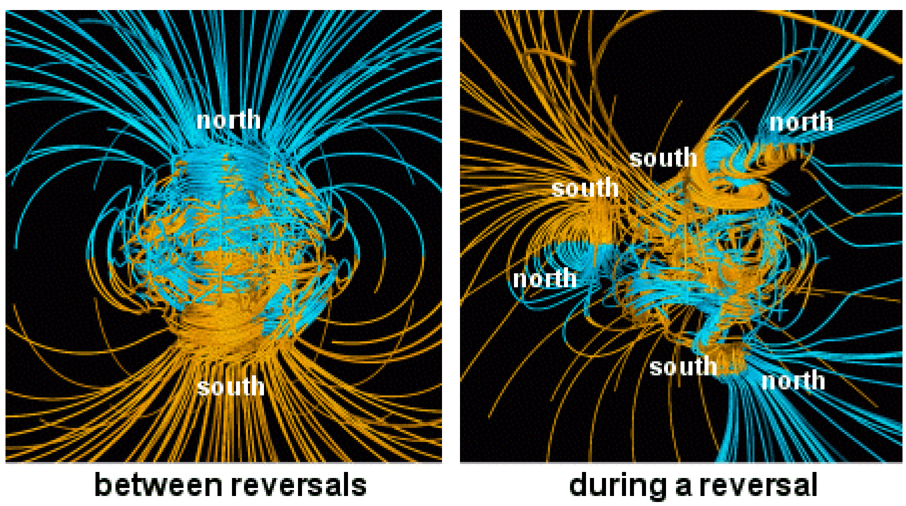
Moyero Reverse Superchron

This period in the Ordovician of more than 20 million years (485 to 463 million years ago) is suspected to host another superchron. But until now this possible superchron has only been found in the Moyero river section north of the polar circle in Siberia. Moreover, the best data from elsewhere in the world do not show evidence for this superchron.

Jurassic Quiet Zone

Certain regions of ocean floor, older than 160 Ma, have low-amplitude magnetic anomalies that are hard to interpret. They are found off the east coast of North America, the northwest coast of Africa, and the western Pacific. They were once thought to represent a superchron, but magnetic anomalies are found on land during this period. The geomagnetic field is known to have low intensity between about 130 Ma and 170 Ma, and these sections of ocean floor are especially deep, so the signal is attenuated between the floor and the surface.

Character of transitions



NASA computer simulation

Duration

Most estimates for the duration of a polarity transition are between 1,000 and 10,000 years. However, geologist Scott Bogue of Occidental College and Jonathan Glen of the US Geological Survey, sampling lava flows in Battle Mountain, Nevada, found evidence for a reversal that took only four years. The reversal was dated to approximately 15 million years ago. The latest reversal, the Brunhes–Matuyama reversal, occurred approximately 780,000 years ago.

Causes

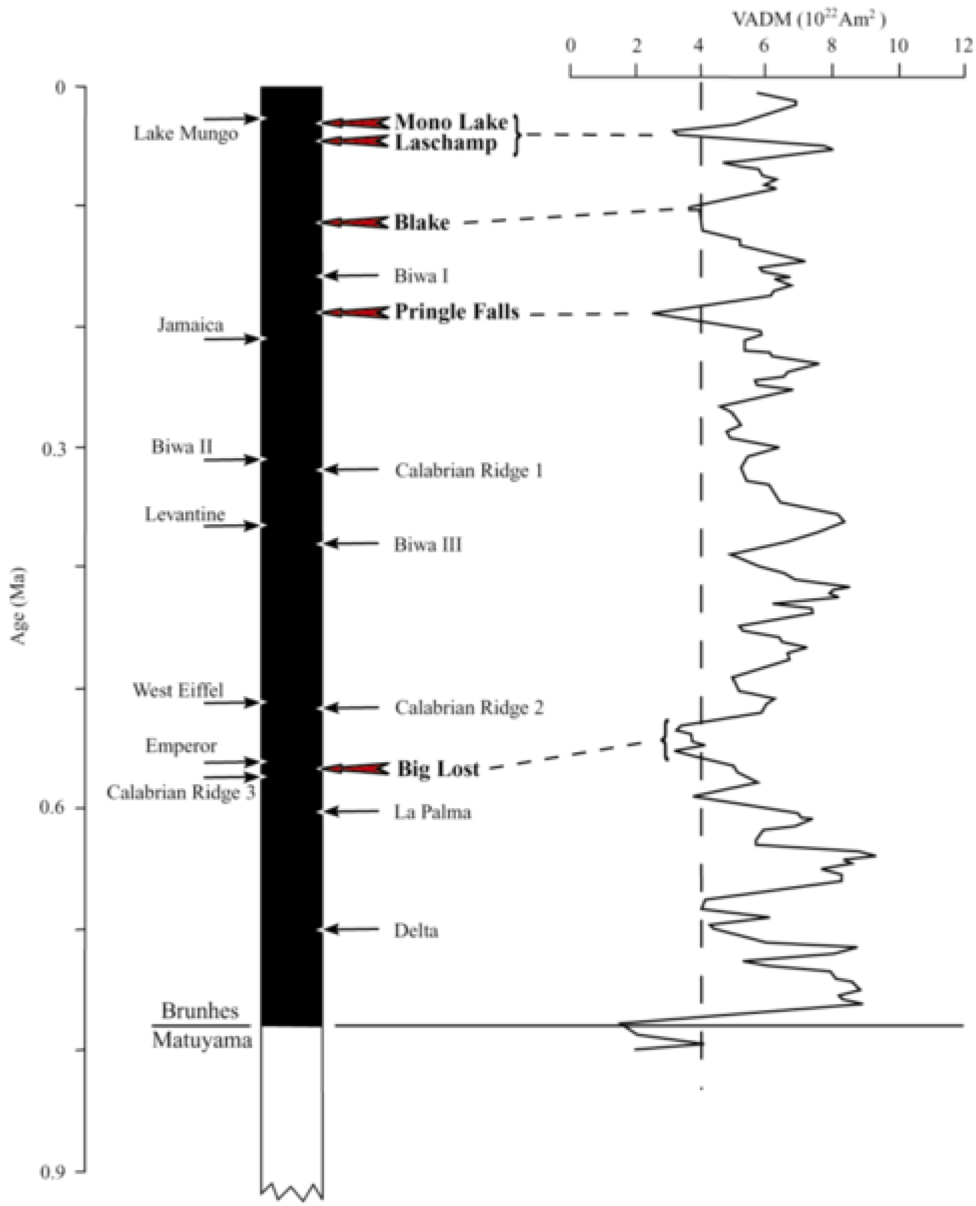
The magnetic field of the Earth, and those planets that have magnetic fields are generated by dynamo action in which convection of molten iron in the planetary core generates electric currents which in turn give rise to magnetic fields. Most scientists believe that reversals are an inherent aspect of this process. In simulations, it is observed that magnetic field lines can sometimes become tangled and disorganized through the chaotic motions of liquid metal in the Earth's core. For example, Gary Glatzmaier and collaborator Paul Roberts of UCLA have made a numerical model of the electromagnetic, fluid dynamical processes of Earth's interior. Their simulation reproduced key features of the magnetic field over more than 40,000 years of simulated time. Additionally, the computer-generated field reversed itself. During these periods, the direction and magnitude of the magnetic field observed at any point on the surface fluctuate, and net field strength is reduced by dipole-dipole interactions.

In some simulations, this leads to an instability in which the magnetic field spontaneously flips over into the opposite orientation. This scenario is supported by observations of the solar magnetic field, which undergoes spontaneous reversals every 9–12 years. However, with the sun it is observed that the solar magnetic intensity greatly increases during a reversal, whereas reversals on Earth seem to occur during periods of low field strength.

External triggers

Some scientists, such as Richard A. Muller, believe that geomagnetic reversals are not spontaneous processes but rather are triggered by external events that directly disrupt the flow in the Earth's core. Proposals include impact events or internal events such as the arrival of continental slabs carried down into the mantle by the action of plate tectonics at subduction zones or the initiation of new mantle plumes from the core-mantle boundary. Supporters of this theory hold that any of these events could lead to a large scale disruption of the dynamo, effectively turning off the geomagnetic field. Because the magnetic field is stable in either the present North-South orientation or a reversed orientation, they propose that when the field recovers from such a disruption it spontaneously chooses one state or the other, such that a recovery is seen as a reversal in about half of all cases.

Future of the geomagnetic field



Variations in virtual axial dipole moment since the last reversal

At present, the overall geomagnetic field is becoming weaker; the present strong deterioration corresponds to a 10–15% decline over the last 150 years and has accelerated in the past several years; however, geomagnetic intensity has declined almost continuously from a maximum 35% above the modern value achieved approximately 2,000 years ago. The rate of decrease and the current strength are within the normal range of variation, as shown by the record of past magnetic fields recorded in rocks (figure on right).

The nature of Earth's magnetic field is one of heteroscedastic fluctuation. An instantaneous measurement of it, or several measurements of it across the span of decades or centuries, is not sufficient to extrapolate an overall trend in the field strength. It has gone up and down in the past with no apparent reason. Also, noting the local intensity of the dipole field (or its fluctuation) is insufficient to characterize Earth's magnetic field as a whole, as it is not strictly a dipole field. The dipole component of Earth's field can diminish even while the total magnetic field remains the same or increases.

The Earth's magnetic north pole is drifting from northern Canada towards Siberia with a presently accelerating rate — 10 km per year at the beginning of the 20th century, up to 40 km per year in 2003, and since then has only accelerated. In the last decade magnetic north was shifting roughly one degree every five years.

Effects on biosphere and human society

Because the magnetic field has never been observed to reverse by humans with instrumentation, and the mechanism of field generation is not well understood, it is difficult to say what the characteristics of the magnetic field might be leading up to such a reversal.

Some speculate that a greatly diminished magnetic field during a reversal period will expose the surface of the Earth to a substantial and potentially damaging increase in cosmic radiation. However, *Homo erectus* and their ancestors certainly survived many previous reversals, though they did not depend on computer systems that could be damaged by large coronal mass ejections.

There is no uncontested evidence that a magnetic field reversal has ever caused any biological extinctions. A possible explanation is that the solar wind may induce a sufficient magnetic field in the Earth's ionosphere to shield the surface from energetic particles even in the absence of the Earth's normal magnetic field.

Another possible explanation is that magnetic field actually does not vanish completely, with many poles forming chaotically in different places during reversal, until it stabilizes again.

Chapter- 3

North Magnetic Pole and South Magnetic Pole

North magnetic pole

Part of the Carta Marina of 1539 by Olaus Magnus, depicting the location of magnetic north vaguely conceived as "Insula Magnetu[m]" (Latin for "Island of Magnets") off modern day Murmansk. The man holding the rune staffs is the Norse hero Starkad.

The Earth's **North Magnetic Pole** is the point on the surface of the Northern Hemisphere at which the Earth's magnetic field points vertically downwards (i.e., the "dip" is 90°). Though geographically in the north, it is, by the direction of the magnetic field lines, physically the *south* pole of the Earth's magnetic field.

The North Magnetic Pole moves slowly over time due to magnetic changes in the Earth's core. In 2001, it was determined by the Geological Survey of Canada to lie near Ellesmere Island in northern Canada at 81°18′N 110°48′W / 81.3°N 110.8°W. It was estimated to be at

82°42′N 114°24′W / 82.7°N 114.4°W in 2005. In 2009, it was moving toward Russia at between 34 and 37 mi (55-60 km) per year.

Its southern hemisphere counterpart is the South Magnetic Pole. Because the Earth's magnetic field is not exactly symmetrical, the North and South Magnetic Poles are not antipodal: a line drawn from one to the other does not pass through the centre of the Earth; it actually misses by about 530 km (330 mi).

The Earth's North and South Magnetic Poles are also known as **Magnetic Dip Poles**, with reference to the vertical "dip" of the magnetic field lines at those points.

Polarity

In physics, all magnets have two poles that are distinguished by the direction of the magnetic flux. In principle these poles could be named in any way; for example, as "+" and "−", or "A" and "B". However, based on the early use of magnets in compasses they were named the "north pole" (or more explicitly "north-seeking pole"), "N", and the "south pole" (or "south-seeking pole"), "S", with the north pole being the pole that pointed north (i.e. the one attracted to the Earth's North Magnetic Pole). Because opposite poles attract, the Earth's North Magnetic Pole is therefore, by this definition, physically a magnetic field *south* pole. Conversely, the Earth's South Magnetic Pole is physically a magnetic field *north* pole.

History

In early times European navigators believed that compass needles were attracted either to a "magnetic mountain" or "magnetic island" somewhere in the far north, or to the Pole Star. The idea that the Earth itself acts as a giant magnet was first proposed in 1600 by the English physician and natural philosopher William Gilbert. He was also the first to define the North Magnetic Pole as the point where the Earth's magnetic field points vertically downwards. This is the definition used nowadays, though it would be several hundred years before the nature of the Earth's magnetic field was understood properly.

Expeditions and measurements

The first expedition to reach the North Magnetic Pole was led by James Clark Ross, who found it at Cape Adelaide on the Boothia Peninsula on June 1, 1831. Roald Amundsen found the North Magnetic Pole in a slightly different location in 1903. The third observation was by Canadian government scientists Paul Serson and Jack Clark, of the Dominion Astrophysical Observatory, who found the pole at Allen Lake on Prince of Wales Island in 1947.

The Canadian government has made several measurements since, which show that the North Magnetic Pole is moving continually northwestward. In 1996 an expedition certified its location by magnetometer and theodolite at 78°35.7′N 104°11.9′W / 78.595°N 104.1983°W. Its estimated 2005 position was 82°42′N 114°24′W / 82.7°N 114.4°W, to the west of Ellesmere Island in Canada. During the 20th century it moved 1100 km, and since 1970 its rate of motion has accelerated from 9 km/year to approximately 41 km/year, or 1.3 mm/sec (2001–2003 average. If it maintained its present speed and direction it would reach Siberia in about 50 years, but it is expected to veer from its present course and slow its rate of motion.

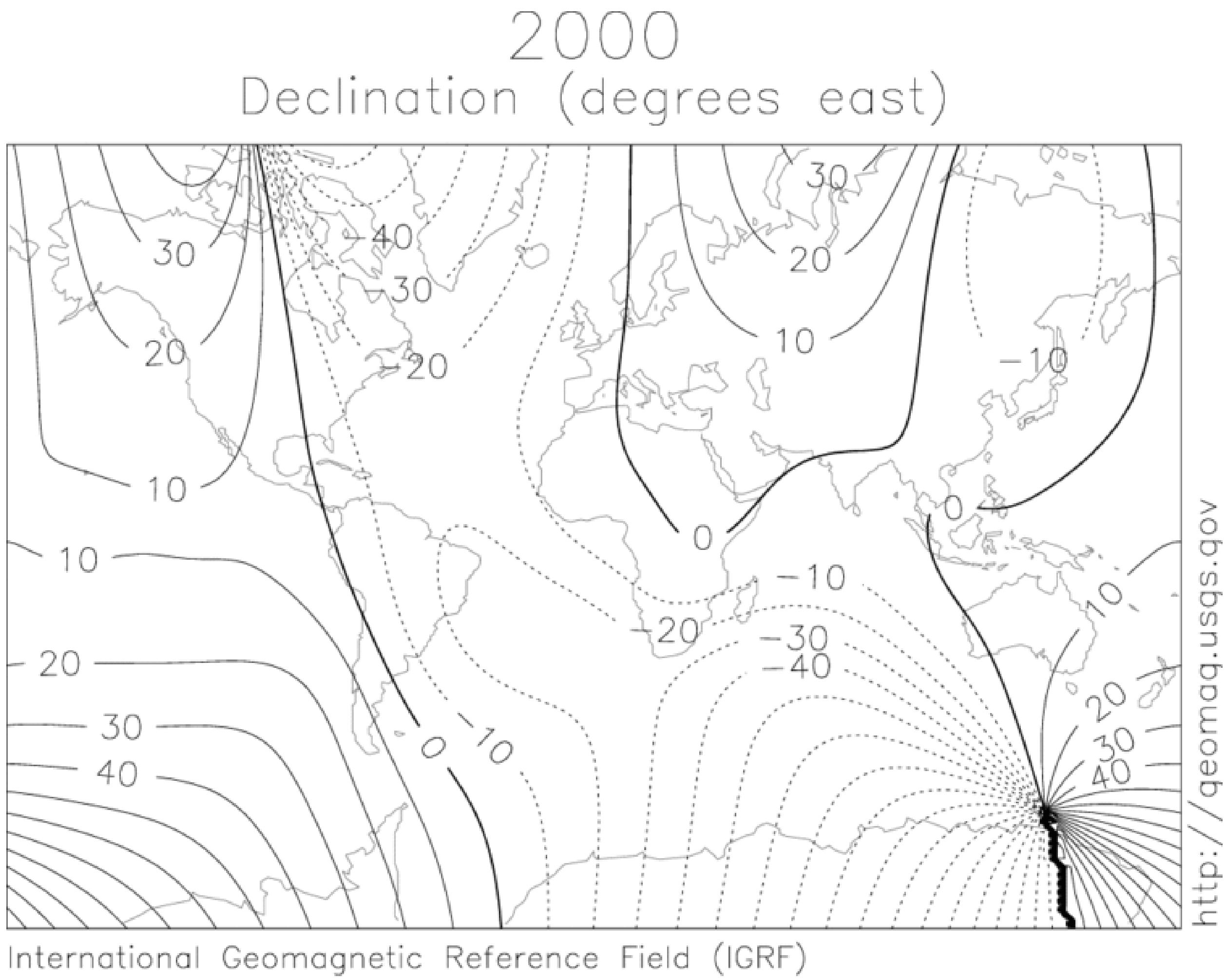
This general movement is in addition to a daily or *diurnal* variation in which the North Magnetic Pole describes a rough ellipse, with a maximum deviation of 80 km from its mean position. This effect is due to disturbances of the geomagnetic field by charged particles from the Sun.

North Magnetic Pole	(2001) 81°18′N 110°48′W / 81.3°N 110.8°W	(2004 est) 82°18′N 113°24′W / 82.3°N 113.4°W	(2005 est) 82°42′N 114°24′W / 82.7°N 114.4°W
South Magnetic Pole	(1998) 64°36′S 138°30′E / 64.6°S 138.5°E.	(2004 est) 63°30′S 138°00′E / 63.5°S 138.0°E	

The first team of novices to reach the Magnetic North Pole did so in 1996, led by David Hempleman-Adams. It included the first British woman and first Swedish woman to reach the Pole. The team also successfully tracked the location of the Magnetic North Pole on behalf of the University of Ottawa.

The biennial Polar Race takes place between Resolute Bay in northern Canada and the 1996-certified location of the North Magnetic Pole at 78°35.7′N 104°11.9′W / 78.595°N 104.1983°W. On 25 July 2007, the *Top Gear Polar Challenge Special* was broadcast on BBC Two in the United Kingdom, in which Jeremy Clarkson and James May became the first people in history to reach this location in a car.

Magnetic north and magnetic declination



Magnetic declination from true north in 2000

The direction in which a compass needle points is known as magnetic north. In general, this is not exactly the direction of the North Magnetic Pole (or of any other consistent location). Instead, the compass aligns itself to the local geomagnetic field, which varies in a complex manner over the Earth's surface, as well as over time. The angular difference between magnetic north and true north (defined in reference to the Geographic North Pole), at any particular location on the Earth's surface, is called the magnetic declination. Most map coordinate systems are based on true north, and magnetic declination is often shown on map legends so that the direction of true north can be determined from north as indicated by a compass.

Magnetic declination has been measured in many countries, including the U.S. The line of zero declination (the **agonic line**) in the U.S. runs from the North Magnetic Pole through Lake Superior and southward into the Gulf of Mexico. Along this line, true north is the same as magnetic north. West of the line of zero declination, a compass will give a reading that is east of true north. Conversely, east of the line of zero declination, a compass reading will be west of true north.

Magnetic declination is still very important for certain types of navigation that have traditionally made much use of magnetic compasses.

North Geomagnetic Pole

As a first-order approximation, the Earth's magnetic field can be modelled as a simple dipole (like a bar magnet), tilted about 11° with respect to the Earth's rotation axis (which defines the Geographic North and Geographic South Poles) and centred at the Earth's centre. The North and South Geomagnetic Poles are the antipodal points where the axis of this theoretical dipole intersects the Earth's surface. If the Earth's magnetic field were a perfect dipole then the field lines would be vertical at the Geomagnetic Poles, and they would coincide with the Magnetic Poles. However, the approximation is imperfect, and so the Magnetic and Geomagnetic Poles lie some distance apart.

Like the North Magnetic Pole, the North Geomagnetic Pole attracts the north pole of a bar magnet and so is in a physical sense actually a *south* magnetic pole. It is the centre of the region of the magnetosphere in which the Aurora Borealis can be seen. As of 2005 it was located at approximately 79°44′N 71°47′W / 79.74°N 71.78°W, off the northwest coast of Greenland, but it is now drifting away from North America and toward Siberia.

Geomagnetic reversal

Over the life of the Earth, the orientation of Earth's magnetic field has reversed several times, with magnetic north becoming magnetic south and vice versa – an event known as a geomagnetic reversal. Evidence of geomagnetic reversals can be seen at mid-ocean ridges where tectonic plates move apart and the seabed is filled in with magma. As the magma seeps out of the mantle the magnetic particles contained within it are oriented in the direction of the magnetic field at the time the magma cools and solidifies.

South Magnetic Pole

The Earth's **South Magnetic Pole** is the wandering point on the Earth's surface where the geomagnetic field lines are directed vertically upwards. It should not be confused with the lesser known **South Geomagnetic Pole** described later.

For historical reasons, the "end" of a magnet that points (roughly) north is itself called the "north pole" of the magnet, and the other end, pointing south, is called magnet's "south pole". Because opposite poles attract, the Earth's South Magnetic Pole is physically actually a magnetic *north* pole.

The South Magnetic Pole is constantly shifting due to changes in the Earth's magnetic field. As of 2005 it was calculated to lie at 64°31′48″S 137°51′36″E / 64.53°S 137.86°E, just off the coast of Adelie Land, French Antarctica. That point lies outside the Antarctic Circle. Due to polar drift, the pole is moving north west by about 10 to 15 kilometers per year.

North Magnetic Pole	(2001) 81°18′N 110°48′W / 81.3°N 110.8°W	(2004 est) 82°18′N 113°24′W / 82.3°N 113.4°W	(2005 est) 82°42′N 114°24′W / 82.7°N 114.4°W
South Magnetic Pole	(1998) 64°36′S 138°30′E / 64.6°S 138.5°E	(2004 est) 63°30′S 138°00′E / 63.5°S 138.0°E	(2008 est) 65°S 138°E / 65°S 138°E

Expeditions

Early unsuccessful attempts to reach the South Magnetic Pole included those of French explorer Dumont d'Urville (1840), American Charles Wilkes (expedition of 1838–42) and Briton James Clark Ross (expedition of 1839–43).

On January 16, 1909 three men (Douglas Mawson, Edgeworth David, and Alistair Mackay) from Sir Ernest Shackleton's Nimrod Expedition claimed to have found the South Magnetic Pole, which was at that time located on land. However, there is now some doubt as to whether their location was correct.

The approximate position of the pole on 16 January 1909 was 72° 25'S 155° 16'E.

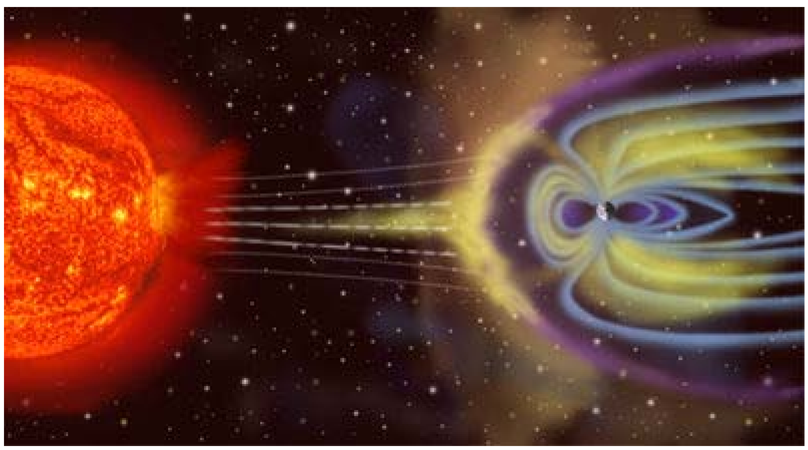
South Geomagnetic Pole

The Earth's geomagnetic field can be approximated by a tilted dipole (like a bar magnet) placed at the center of the Earth. The South Geomagnetic Pole is the point where the axis of this best-fitting tilted dipole intersects the Earth's surface in the southern hemisphere. As of 2005 it was calculated to be located at 79°44′S 108°13′E / 79.74°S 108.22°E, near the Vostok Station. Because the field is not an exact dipole, the South Geomagnetic Pole does not coincide with the

South Magnetic Pole. Furthermore, the South Geomagnetic Pole is wandering for the same reason its northern magnetic counterpart wanders.

Chapter- 4

Geomagnetic Storm



Solar particles interact with Earth's magnetosphere

A **geomagnetic storm** is a temporary disturbance of the Earth's magnetosphere caused by a disturbance in the interplanetary medium. A geomagnetic storm is a major component of space weather and provides the input for many other components of space weather. A geomagnetic storm is caused by a solar wind shock wave and/or cloud of magnetic field which interacts with the Earth's magnetic field. The increase in the solar wind pressure initially compresses the magnetosphere and the solar wind magnetic field will interact with the Earth's magnetic field and transfer an increased amount of energy into the magnetosphere. Both interactions cause an increase in movement of plasma through the magnetosphere (driven by increased electric fields inside the magnetosphere) and an increase in electric current in the magnetosphere and ionosphere. During the main phase of a geomagnetic storm, electric current in the magnetosphere create magnetic force which pushes out the boundary between the magnetosphere and the solar wind. The disturbance in the interplanetary medium which drives the geomagnetic storm may be due to a solar coronal mass ejection (CME) or a high speed stream (co-rotating interaction region or CIR) of the solar wind originating from a region of weak magnetic field on the Sun's surface. The frequency of geomagnetic storms increases and decreases with the Sunspot cycle. CME driven storms are more common during the maximum of the solar cycle and CIR driven storms are more common during the minimum of the solar cycle. In 1989, a geomagnetic storm energized ground induced currents which disrupted electric power distribution throughout most of Quebec province and caused aurorae as far south as Texas.

Definition of a geomagnetic storm

A geomagnetic storm is defined by changes in the Dst (disturbance – storm time) index. The Dst index estimates the globally averaged change of the horizontal component of the Earth's magnetic field at the magnetic equator based on measurements from a few magnetometer stations. Dst is computed once per hour and reported in near-real-time. During quiet times, Dst is between +20 and -20 nano-Tesla (nT).

A geomagnetic storm has three phases: an initial phase, a main phase and a recovery phase. The initial phase is characterized by Dst (or its one-minute component SYM-H) increasing by 20 to 50 nT in tens of minutes. The initial phase is also referred to as a storm sudden commencement (SSC). However, not all geomagnetic storms have an initial phase and not all sudden increases in Dst or SYM-H are followed by a geomagnetic storm. The main phase of a geomagnetic storm is defined by Dst decreasing to less than -50 nT. The selection of -50 nT to define a storm is somewhat arbitrary. The minimum value during a storm will be between -50 and approximately -600 nT. The duration of the main phase is typically between 2 and 8 hours. The recovery phase is the period when Dst changes from its minimum value to its quiet time value. The period of the recovery phase may be as short as 8 hours or as long as 7 days.

The size of a geomagnetic storm is classified as moderate (-50 nT >minimum of Dst > -100 nT), intense (-100 nT > minimum Dst > -250 nT) or super-storm (minimum of Dst < -250 nT).

Historical occurrences

On September 1 – 2, 1859, the largest recorded geomagnetic storm occurred. From August 28 until September 2, 1859, numerous sunspots and solar flares were observed on the Sun, the largest flare occurring on September 1. This is referred to as the 1859 solar superstorm or the the Carrington Event. It can be assumed that a massive Coronal mass ejection (CME), associated with the flare, was launched from the Sun and reached the Earth within eighteen hours — a trip that normally takes three to four days. The horizontal intensity of geomagnetic field was reduced by 1600 nT as recorded by the Colaba observatory near Bombay, India. It is estimated that Dst would have been approximately -1750 nT. Telegraph wires in both the United States and Europe experienced induced emf, in some cases even shocking telegraph operators and causing fires. Auroras were seen as far south as Hawaii, Mexico, Cuba, and Italy — phenomena that are usually only seen near the poles.

On March 13, 1989 a severe geomagnetic storm caused the collapse of the Hydro-Québec power grid in a matter of seconds as equipment protection relays tripped in a cascading sequence of events. Six million people were left without power for nine hours, with significant economic loss. The storm even caused auroras as far south as Texas. The geomagnetic storm causing this event was itself the result of a coronal mass ejection, ejected from the Sun on March 9, 1989.

Ice cores show evidence that events of similar intensity recur at an average rate of approximately once per 500 years. Since 1859, less severe storms have occurred in 1921 and 1960, when widespread radio disruption was reported.

In August 1989, another storm affected microchips, leading to a halt of all trading on Toronto's stock market.

Since 1989, power companies in North America, the UK, Northern Europe and elsewhere evaluated the risks of geomagnetically induced currents (GIC) and developed mitigation strategies.

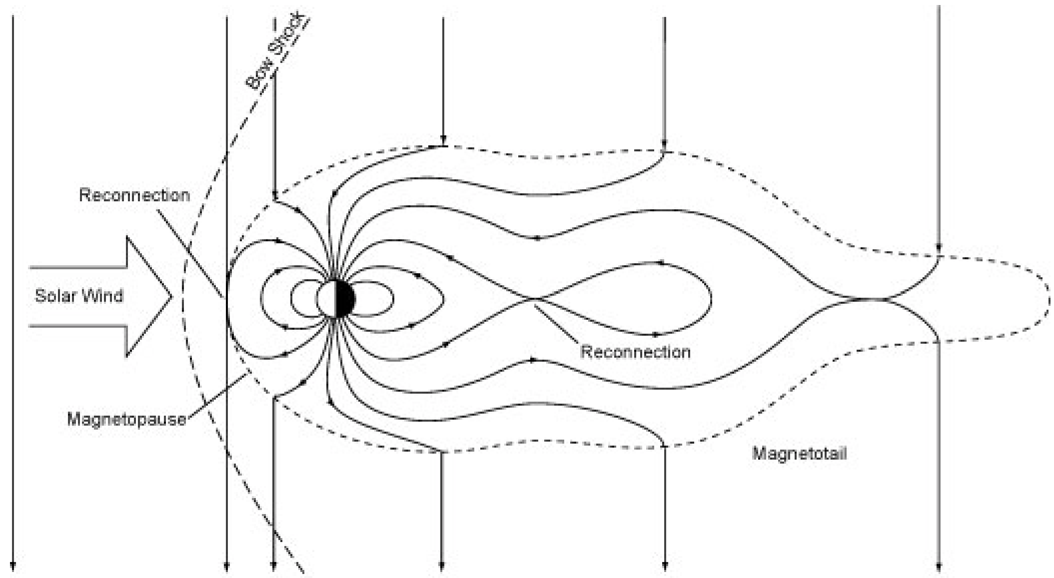
Since 1995, geomagnetic storms and solar flares have been monitored from the Solar and Heliospheric Observatory (SOHO) joint-NASA-European Space Agency satellite.

On February 26, 2008 the magnetic fields erupted inside the magnetotail, releasing about 10^{15} Joules of energy. The blast launched two gigantic clouds of protons and electrons, one toward Earth and one away from Earth. The Earth-directed cloud crashed into the planet below, sparking vivid auroras in Canada and Alaska.

Interactions with planetary processes

The solar wind also carries with it the magnetic field of the Sun. This field will have either a North or South orientation. If the solar wind has energetic bursts, contracting and expanding the magnetosphere, or if the solar wind takes a southward polarization, geomagnetic storms can be expected. The southward field causes magnetic reconnection of the dayside magnetopause, rapidly injecting magnetic and particle energy into the Earth's magnetosphere.

During a geomagnetic storm, the ionosphere's F_2 layer will become unstable, fragment, and may even disappear. In the northern and southern pole regions of the Earth, auroras will be observable in the sky.



Magnetosphere in the near-Earth space environment

Geomagnetic storm effects

Radiation hazards to humans

Intense solar flares release very-high-energy particles that can cause radiation poisoning to humans (and mammals in general) in the same way as low-energy radiation from nuclear blasts.

Earth's atmosphere and magnetosphere allow adequate protection at ground level, but astronauts in space are subject to potentially lethal doses of radiation. The penetration of high-energy particles into living cells can cause chromosome damage, cancer, and a host of other health problems. Large doses can be fatal immediately.

Solar protons with energies greater than 30 MeV are particularly hazardous. In October 1989, the Sun produced enough energetic particles that, if an astronaut were to have been standing on the Moon at the time, wearing only a space suit and caught out in the brunt of the storm, he would probably have died; the expected dose would be about 7000 rem. Note that astronauts who had time to gain safety in a shelter beneath moon soil would have absorbed only slight amounts of radiation.

The cosmonauts on the Mir station were subjected to daily doses of about twice the yearly dose on the ground, and during the solar storm at the end of 1989 they absorbed their full-year radiation dose limit in just a few hours.

Solar proton events can also produce elevated radiation aboard aircraft flying at high altitudes. Although these risks are small, monitoring of solar proton events by satellite instrumentation allows the occasional exposure to be monitored and evaluated, and eventually the flight paths and altitudes adjusted in order to lower the absorbed dose of the flight crews.

Biology

There is a growing body of evidence that changes in the geomagnetic field affect biological systems. Studies indicate that physically stressed human biological systems may respond to fluctuations in the geomagnetic field. Interest and concern in this subject have led the International Union of Radio Science to create a new commission entitled *Commission **K** — Electromagnetics in Biology and Medicine*, current chair Dr. Frank Prato.

Possibly the most closely studied of the variable Sun's biological effects has been the degradation of homing pigeons' navigational abilities during geomagnetic storms. Pigeons and other migratory animals, such as dolphins and whales, have internal biological compasses composed of the mineral magnetite wrapped in bundles of nerve cells. This gives them the sense known as magnetoception. While this probably is not their primary method of navigation, there have been many pigeon race smashes, a term used when only a small percentage of birds return home from a release site. Because these losses have occurred during geomagnetic storms, pigeon handlers have learned to ask for geomagnetic alerts and warnings as an aid to scheduling races.

Disrupted systems

Communications

Many communication systems use the ionosphere to reflect radio signals over long distances. Ionospheric storms can affect radio communication at all latitudes. Some radio frequencies are absorbed and others are reflected, leading to rapidly fluctuating signals and unexpected propagation paths. TV and commercial radio stations are little affected by solar activity, but ground-to-air, ship-to-shore, shortwave broadcast, and amateur radio (mostly the bands below 30 MHz) are frequently disrupted. Radio operators using HF bands rely upon solar and geomagnetic alerts to keep their communication circuits up and running.

Some military detection or early warning systems are also affected by solar activity. The *over-the-horizon radar* bounces signals off the ionosphere to monitor the launch of aircraft and missiles from long distances. During geomagnetic storms, this system can be severely hampered by radio clutter. Some submarine detection systems use the magnetic signatures of submarines as one input to their locating schemes. Geomagnetic storms can mask and distort these signals.

The Federal Aviation Administration routinely receives alerts of solar radio bursts so that they can recognize communication problems and avoid unnecessary maintenance. When an aircraft and a ground station are aligned with the Sun, jamming of air-control radio frequencies can occur. This can also happen when an Earth station, a satellite, and the Sun are in alignment.

The telegraph lines in the past were affected by geomagnetic storms as well. The telegraphs used a long wire for the data line, stretching for many miles, using ground as the return wire and being fed with DC power from a battery; this made them (together with the power lines mentioned below) susceptible to being influenced by the fluctuations caused by the ring current. The voltage/current induced by the geomagnetic storm could have led to diminishing of the signal, when subtracted from the battery polarity, or to overly strong and spurious signals when added to it; some operators in such cases even learned to disconnect the battery and rely on the induced current as their power source. In extreme cases the induced current was so high the coils at the receiving side burst in flames, or the operators received electric shocks. Geomagnetic storms affect also long-haul telephone lines, including undersea cables unless they are fiber optic.

Damage to communications satellites can disrupt non-terrestrial telephone, television, radio, and Internet links. The National Academy of Sciences reported in 2008 on possible scenarios of widespread disruption in the 2012–2013 solar peak.

Navigation systems

Systems such as GPS, LORAN, and the now-defunct OMEGA are adversely affected when solar activity disrupts their signal propagation. The OMEGA system consisted of eight transmitters located throughout the world. Airplanes and ships used the very low frequency signals from these transmitters to determine their positions. During solar events and geomagnetic storms, the system gave navigators information that is inaccurate by as much as several miles. If navigators had been alerted that a proton event or geomagnetic storm was in progress, they could have switched to a backup system.

GPS signals are affected when solar activity causes sudden variations in the density of the ionosphere, causing the GPS signals to scintillate (like a twinkling star). The scintillation of satellite signals during ionospheric disturbances is studied at HAARP during ionospheric modification experiments. It has also been studied at the Jicamarca Radio Observatory.

One technology used to allow GPS receivers to continue to operate in the presence of some confusing signals is Receiver Autonomous Integrity Monitoring (RAIM). However, RAIM is predicated on the assumption that a majority of the GPS constellation is operating properly, and so it is much less useful when the entire constellation is perturbed by global influences such as geomagnetic storms. Even if RAIM detects a loss of integrity in these cases, it may not be able to provide a useful, reliable signal.

Satellite hardware damage

Geomagnetic storms and increased solar ultraviolet emission heat Earth's upper atmosphere, causing it to expand. The heated air rises, and the density at the orbit of satellites up to about 1,000 km (621 mi) increases significantly. This results in increased drag on satellites in space, causing them to slow and change orbit slightly. Unless Low Earth Orbit satellites are routinely boosted to higher orbits, they slowly fall, and eventually burn up in Earth's atmosphere.

Skylab is an example of a spacecraft reentering Earth's atmosphere prematurely in 1979 as a result of higher-than-expected solar activity. During the great geomagnetic storm of March 1989, four of the Navy's navigational satellites had to be taken out of service for up to a week, the U.S. Space Command had to post new orbital elements for over 1000 objects affected, and the Solar Maximum Mission satellite fell out of orbit in December the same year.

The vulnerability of the satellites depends on their position as well. The South Atlantic Anomaly is a perilous place for a satellite to pass through.

As technology has allowed spacecraft components to become smaller, their miniaturized systems have become increasingly vulnerable to the more energetic solar particles. These particles can cause physical damage to microchips and can change software commands in satellite-borne computers.

Another problem for satellite operators is **differential charging**. During geomagnetic storms, the number and energy of electrons and ions increase. When a satellite travels through this energized environment, the charged particles striking the spacecraft cause different portions of the spacecraft to be differentially charged. Eventually, electrical discharges can arc across spacecraft components, harming and possibly disabling them.

Bulk charging (also called **deep charging**) occurs when energetic particles, primarily electrons, penetrate the outer covering of a satellite and deposit their charge in its internal parts. If sufficient charge accumulates in any one component, it may attempt to neutralize by discharging to other components. This discharge is potentially hazardous to the satellite's electronic systems.

Geologic exploration

Earth's magnetic field is used by geologists to determine subterranean rock structures. For the most part, these geodetic surveyors are searching for oil, gas, or mineral deposits. They can accomplish this only when Earth's field is quiet, so that true magnetic signatures can be detected. Other geophysicists prefer to work during geomagnetic storms, when strong variations in the Earth's normal subsurface electric currents allow them to sense subsurface oil or mineral structures. This technique is called magnetotellurics. For these reasons, many surveyors use geomagnetic alerts and predictions to schedule their mapping activities.

Electric grid

When magnetic fields move about in the vicinity of a conductor such as a wire, a geomagnetically induced current is produced in the conductor. This happens on a grand scale during geomagnetic storms (the same mechanism also influences telephone and telegraph lines, see above) on all long transmission lines. Power companies which operate long transmission lines (many kilometers in length) are thus subject to damage by this effect. Notably, this chiefly includes operators in China, North America, and Australia; the European grid consists mainly of shorter transmission cables, which are less vulnerable to damage.

The (nearly direct) currents induced in these lines from geomagnetic storms are harmful to electrical transmission equipment, especially generators and transformers — induces core saturation, constraining their performance (as well as tripping various safety devices), and causes coils and cores to heat up. This heat can disable or destroy them, even inducing a chain reaction that can overload and blow transformers throughout a system. This is precisely what happened on March 13, 1989: in Québec, as well as across parts of the northeastern U.S., the electrical supply was cut off to over 6 million people for 9 hours due to a huge geomagnetic storm. Some areas of Sweden were similarly affected.

According to a study by Metatech corporation, a storm with a strength comparative to that of 1921, 130 million people would be left without power and 350 transformers would be broken, with a cost totaling 2 trillion dollars.

By receiving geomagnetic storm alerts and warnings (e.g. by the Space Weather prediction Center; via Space Weather satellites as SOHO or ACE), power companies can (and often do) minimize damage to power transmission equipment, by momentarily disconnecting transformers or by inducing temporary blackouts. Preventative measures also exist, including digging transmission cables into the soil, placing lightning rods on transmission wires, reducing the operating voltages of transformers, and using cables that are shorter than 10 km.

Pipelines

Rapidly fluctuating geomagnetic fields can produce geomagnetically induced currents in pipelines. This can cause multiple problems for pipeline engineers. Flow meters in the pipeline can transmit erroneous flow information, and the corrosion rate of the pipeline is dramatically increased. If engineers incorrectly attempt to balance the current during a geomagnetic storm, corrosion rates may increase even more. Once again, pipeline managers thus receive space weather alerts and warnings to allow them to implement defensive measures.

Instruments

A wide range of ground-based magnetospheric observatories exist. Magnetometers monitor the auroral zone as well as the equatorial region. Two types of radar — coherent scatter and incoherent scatter — are used to probe the auroral ionosphere. By bouncing signals off ionospheric irregularities (which convect with their field lines) one can trace their motion and infer magnetospheric convection.

Spacecraft instruments include:

- Magnetometers, usually of the flux gate type. Usually these are at the end of booms, to keep them away from magnetic interference by the spacecraft and its electric circuits.

- Electric sensors at the ends of opposing booms are used to measure potential differences between separated points, to derive electric field associated with convection. The method works best at high plasma densities in low Earth orbit; far from Earth long booms are needed, to avoid shielding-out of electric forces.

- Radio sounders from the ground can bounce radio waves of varying frequency off the ionosphere, and by timing their return get the profile of electron density in the ionosphere — up to its peak, past which radio waves no longer return. Radio sounders in low Earth orbit aboard the Canadian Alouette 1 (1962) and Alouette 2 (1965), beamed radio waves earthward and observed the electron density profile of the "topside ionosphere." Other radio sounding methods were also tried in the ionosphere (e.g. on IMAGE).

- A great variety of "particle detectors" have operated in orbit. The original observations of the Van Allen radiation belt used a Geiger counter, a crude detector unable to tell particle charge or energy. Later scintillator detectors were used, and still later "channeltron" electron multipliers have found particularly wide use. To derive charge and mass composition, as well as energies, a variety of mass spectrograph designs were used. For energies up to about 50 keV (which constitute most of the magnetospheric plasma) time-of-flight spectrometers (e.g. "top-hat" design) are widely used.

Computers have made it possible to bring together decades of isolated magnetic observations and extract average patterns of electrical currents and average responses to interplanetary variations. They also run simulations of the global magnetosphere and its responses, by solving the equations of magnetohydrodynamics (MHD) on a numerical grid. Appropriate extensions must be added to cover the inner magnetosphere, where magnetic drifts and ionospheric conduction also need to be taken into account. So far the results are difficult to interpret, and certain assumptions are still needed to cover small-scale phenomena.

Chapter- 5

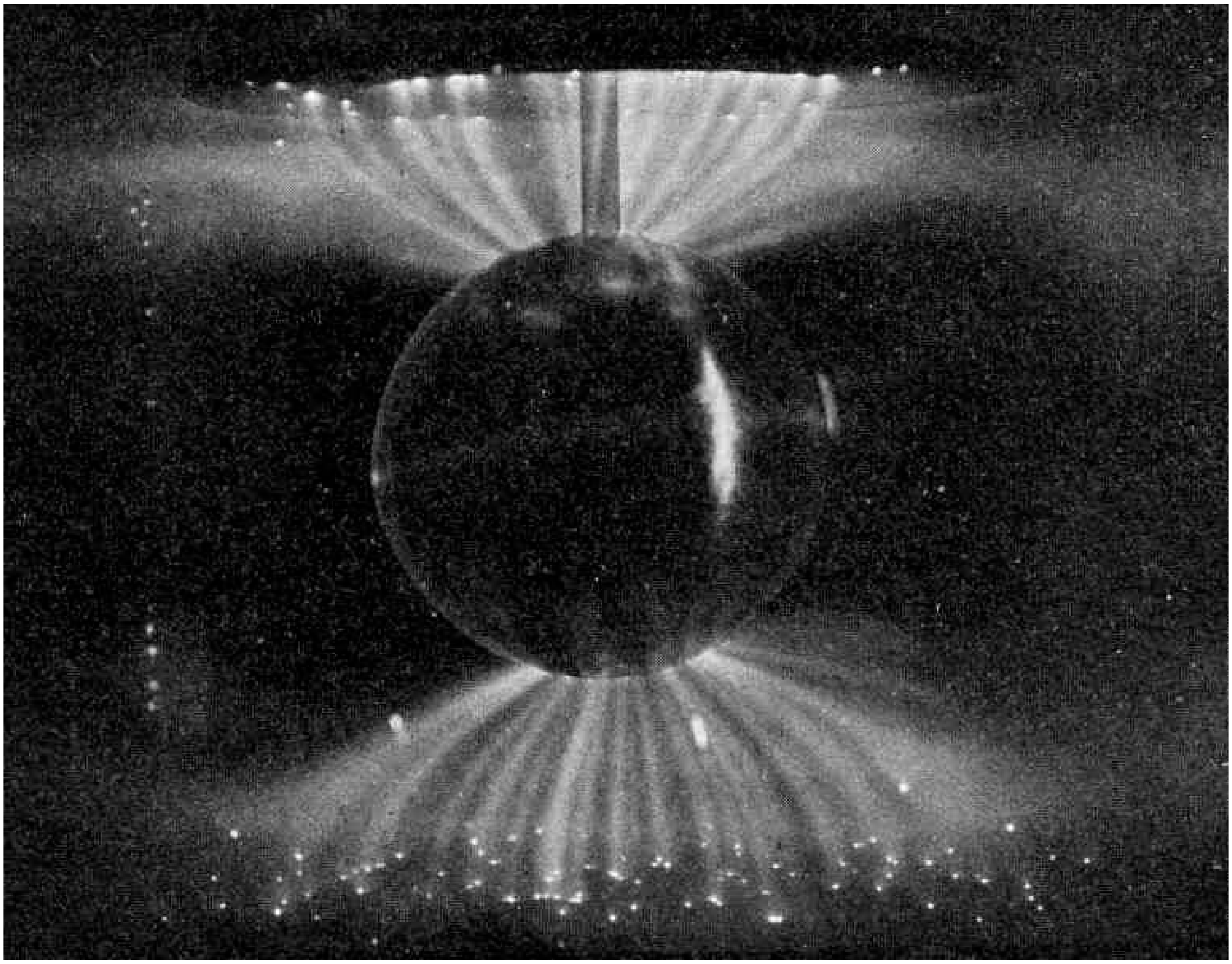
Solar Wind

The **solar wind** is a stream of charged particles ejected from the upper atmosphere of the Sun. It mostly consists of electrons and protons with energies usually between 10 and 100 keV. The stream of particles varies in temperature and speed over time. These particles can escape the Sun's gravity because of their high kinetic energy and the high temperature of the corona.

The solar wind creates the heliosphere, a vast bubble in the interstellar medium that surrounds the solar system. Other phenomena include geomagnetic storms that can knock out power grids on Earth, the aurorae (northern and southern lights), and the plasma tails of comets that always point away from the Sun.

History

The continuous stream of particles flowing outward from the Sun was first suggested by British astronomer Richard C. Carrington. In 1859, Carrington and Richard Hodgson independently made the first observation of what would later be called a solar flare. This is a sudden outburst of energy from the Sun's atmosphere. On the following day, a geomagnetic storm was observed, and Carrington suspected that there may be a connection. George Fitzgerald later suggested that matter was being regularly accelerated away from the Sun and was reaching the Earth after several days.



Laboratory simulation of the magnetosphere's influence on the Solar Wind; these auroral-like Birkeland currents were created in a terrella, a magnetised anode globe in an evacuated chamber.

The ideas of Fitzgerald and others were further developed by the Norwegian physicist Kristian Birkeland. His geomagnetic surveys showed that auroral activity was nearly uninterrupted. As these displays and other geomagnetic activity were being produced by particles from the Sun, he concluded that the Earth was being continually bombarded by "rays of electric corpuscles emitted by the Sun". In 1916, Birkeland was probably the first person to successfully predict that, "From a physical point of view it is most probable that solar rays are neither exclusively negative nor positive rays, but of both kinds". In other words, the solar wind consists of both negative electrons and positive ions. Three years later in 1919, Frederick Lindemann also suggested that particles of both polarities, protons as well as electrons, come from the Sun.

Around the 1930s, scientists had determined that the temperature of the solar corona must be a million degrees Celsius because of the way it stood out into space (as seen during total eclipses). Later spectroscopic work confirmed this extraordinary temperature. In the mid-1950s the British mathematician Sydney Chapman calculated the properties of a gas at such a temperature and determined it was such a superb conductor of heat that it must extend way out into space, beyond the orbit of Earth. Also in the 1950s, a German scientist named Ludwig Biermann became interested in the fact that no matter whether a comet is headed towards or away from the Sun, its tail always points away from the Sun. Biermann postulated that this happens because the Sun emits a steady stream of particles that pushes the comet's tail away. Wilfried Schröder claims in his book, *Who First Discovered the Solar Wind?*, that the German astronomer Paul Ahnert was the first to relate solar wind to comet tail direction based on observations of the comet Whipple-Fedke (1942g).

Eugene Parker realised that the heat flowing from the Sun in Chapman's model and the comet tail blowing away from the Sun in Biermann's hypothesis had to be the result of the same phenomenon, which he termed the "solar wind". Parker showed that even though the Sun's corona is strongly attracted by solar gravity, it is such a good conductor of heat that it is still very hot at large distances. Since gravity weakens as distance from the Sun increases, the outer coronal atmosphere escapes supersonically into interstellar space. Furthermore, Parker was the first person to notice that the weakening effect of the gravity has the same effect on hydrodynamic flow as a de Laval nozzle: it incites a transition from subsonic to supersonic flow.

Opposition to Parker's hypothesis on the solar wind was strong. The paper he submitted to the Astrophysical Journal in 1958 was rejected by two reviewers. It was saved by the editor Subrahmanyan Chandrasekhar (who later received the 1983 Nobel Prize in physics).

In January 1959, the Soviet satellite Luna 1 first directly observed the solar wind and measured its strength. They were detected by hemispherical ion traps. The discovery, made by Konstantin Gringauz, was verified by Luna 2, Luna 3 and by the more distant measurements of Venera 1. Three years later its measurement was performed by Americans (Neugebauer and collaborators) using the Mariner 2 spacecraft.

However, the acceleration of the fast wind is still not understood and cannot be fully explained by Parker's theory. The first numerical simulation of the solar wind in the solar corona including closed and open field lines was performed by Pneuman and Knopp in 1971. The magnetohydrodynamics equations in steady state were solved iteratively starting with an initial dipolar configuration.

In the late 1990s the Ultraviolet Coronal Spectrometer (UVCS) instrument on board the SOHO spacecraft observed the acceleration region of the fast solar wind emanating from the poles of the Sun, and found that the wind accelerates much faster than can be accounted for by thermodynamic expansion alone. Parker's model predicted that the wind should make the transition to supersonic flow at an altitude of about 4 solar radii from the photosphere; but the transition (or "sonic point") now appears to be much lower, perhaps only 1 solar radius above the photosphere, suggesting that some additional mechanism accelerates the solar wind away from the Sun.

In 1990, the Ulysses probe was launched to study the solar wind from high solar latitudes. All prior observations had been made at or near the solar system's ecliptic plane.

Emission

While early models of the solar wind used primarily thermal energy to accelerate the material, by the 1960s it was clear that thermal acceleration alone cannot account for the high speed of solar wind. An additional unknown acceleration mechanism is required, and likely relates to magnetic fields in the solar atmosphere.

The Sun's corona, or extended outer layer, is a region of plasma that is heated to over a million degrees Celsius. As a result of thermal collisions, the particles within the inner corona have a range and distribution of speeds described by a Maxwellian distribution. The mean velocity of these particles is about 145 km/s, which is well below the solar escape velocity of 618 km/s. However, a few of the particles achieve energies sufficient to reach the terminal velocity of 400 km/s, which allows them to feed the solar wind. At the same temperature, electrons, due to their much smaller mass, reach escape velocity and build up an electric field that further accelerates ions - charged atoms - away from the Sun.

The total number of particles carried away from the Sun by the solar wind is about 1.3×10^{36} per second. Thus, the total mass loss each year is about $(2–3) \times 10^{-14}$ solar masses, or 6.7 billion tons per hour. This is equivalent to losing a mass equal to the Earth every 150 million years. However, only about 0.01% of the Sun's total mass has been lost through the solar wind. Other stars have much stronger stellar winds that result in significantly higher mass loss rates.

Components

The solar wind is divided into two components, respectively termed the slow solar wind and the fast solar wind. The slow solar wind has a velocity of about 400 km/s, a temperature of $1.4–1.6 \times 10^6$ K and a composition that is a close match to the corona. By contrast, the fast solar wind has a typical velocity of 750 km/s, a temperature of 8×10^5 K and it nearly matches the composition of the Sun's photosphere. The slow solar wind is twice as dense and more variable in intensity than the fast solar wind. The slow wind also has a more complex structure, with turbulent regions and large-scale structures.

The slow solar wind appears to originate from a region around the Sun's equatorial belt that is known as the "streamer belt". Coronal streamers extend outward from this region, carrying plasma from the interior along closed magnetic loops. Observations of the Sun between 1996 and 2001 showed that emission of the slow solar wind occurred between latitudes of 30–35° around the equator during the solar minimum (the period of lowest solar activity), then expanded toward the poles as the minimum waned. By the time of the solar maximum, the poles were also emitting a slow solar wind.

The fast solar wind is thought to originate from coronal holes, which are funnel-like regions of open field lines in the Sun's magnetic field. Such open lines are particularly prevalent around the Sun's magnetic poles. The plasma source is small magnetic fields created by convection cells in the solar atmosphere. These fields confine the plasma and transport it into the narrow necks of the coronal funnels, which are located only 20,000 kilometers above the photosphere. The plasma is released into the funnel when these magnetic field lines reconnect.

Coronal mass ejection

Both the fast and slow solar wind can be interrupted by large, fast-moving bursts of plasma called interplanetary coronal mass ejections, or ICMEs. ICMEs are the interplanetary manifestation of solar coronal mass ejections, which are caused by release of magnetic energy at the Sun. CMEs are often called "solar storms" or "space storms" in the popular media. They are sometimes, but not always, associated with solar flares, which are another manifestation of magnetic energy release at the Sun. ICMEs cause shock waves in the thin plasma of the heliosphere, launching electromagnetic waves and accelerating particles (mostly protons and electrons) to form showers of ionizing radiation that precede the CME.

When an CME impacts the Earth's magnetosphere, it temporarily deforms the Earth's magnetic field, changing the direction of compass needles and inducing large electrical ground currents in Earth itself; this is called a geomagnetic storm and it is a global phenomenon. CME impacts can induce magnetic reconnection in Earth's magnetotail (the midnight side of the magnetosphere); this launches protons and electrons downward toward Earth's atmosphere, where they form the aurora.

ICMEs are not the only cause of space weather. Different patches on the Sun are known to give rise to slightly different speeds and densities of wind depending on local conditions. In isolation, each of these different wind streams would form a spiral with a slightly different angle, with fast-moving streams moving out more directly and slow-moving streams wrapping more around the Sun. Faster-moving streams tend to overtake slower streams that originate westward of them on the sun, forming turbulent co-rotating interaction regions that give rise to wave motions and accelerated particles, and that affect Earth's magnetosphere in the same way as, but more gently than, CMEs.

Effect on the Solar System

Over the lifetime of the Sun, the surface rotation rate has decreased significantly. This loss of rotation is thought to have been caused by interaction of the Sun's surface layers with the escaping solar wind. The wind is considered responsible for the tails of comets, along with the Sun's radiation. The solar wind contributes to fluctuations in celestial radio waves observed on the Earth, through an effect called interplanetary scintillation.

Magnetospheres

As the solar wind approaches a planet that has a well-developed magnetic field (such as Earth, Jupiter and Saturn), the particles are deflected by the Lorentz force. This region, known as the magnetosphere, causes the particles to travel around the planet rather than bombarding the atmosphere or surface. The magnetosphere is roughly shaped like a hemisphere on the side facing the Sun, then is drawn out in a long wake on the opposite side. The boundary of this region is called the magnetopause, and some of the particles are able to penetrate the magnetosphere through this region by partial reconnection of the magnetic field lines.

Earth itself is largely protected from the solar wind by its magnetic field, which deflects most of the charged particles, however some of the charged particles are *trapped* in the Van Allen radiation belt. A smaller number of particles from the solar wind manage to travel, as though on an electromagnetic energy transmission line, to the Earth's upper atmosphere and ionosphere in the auroral zones. The only time the solar wind is observable on the Earth is when it is strong enough to produce phenomena such as the aurora and geomagnetic storms. Bright auroras strongly heat the ionosphere, causing its plasma to expand into the magnetosphere, increasing the size of the plasma geosphere, and causing escape of atmospheric matter into the solar wind. Geomagnetic storms result when the pressure of plasmas contained inside the magnetosphere is sufficiently large to inflate and thereby distort the geomagnetic field.

The solar wind is responsible for the overall shape of Earth's magnetosphere, and fluctuations in its speed, density, direction, and entrained magnetic field strongly affect Earth's local space environment. For example, the levels of ionizing radiation and radio interference can vary by factors of hundreds to thousands; and the shape and location of the magnetopause and bow shock wave upstream of it can change by several Earth radii, exposing geosynchronous satellites to the direct solar wind. These phenomena are collectively called space weather.

Atmospheres

The solar wind affects the other incoming cosmic rays interacting with the atmosphere of planets. Moreover, planets with a weak or non-existent magnetosphere are subject to atmospheric stripping by the solar wind.

Venus, the nearest and most similar planet to Earth in our solar system, has an atmosphere 100 times denser than our own. Modern space probes have discovered a comet-like tail that extends to the orbit of the Earth.

Mars is larger than Mercury and four times farther from the Sun, and yet even here it is thought that the solar wind has stripped away up to a third of its original atmosphere, leaving a layer 1/100th as dense as the Earth's. It is believed the mechanism for this atmospheric stripping is gas being caught in bubbles of magnetic field, which are ripped off by solar winds.

Planetary surfaces

Mercury, the nearest planet to the Sun, bears the full brunt of the solar wind, and its atmosphere is vestigial and transient, its surface bathed in radiation.

Mercury has an intrinsic magnetic field, for normal solar wind conditions, the solar wind cannot penetrate the magnetosphere created around Mercury, but particles only reach the surface in the cusp regions. During coronal mass ejections however, the magnetopause may get pressed into the surface of the planet, and thus in these conditions, the solar wind may interact freely with the planetary surface.

The Earth's Moon has no atmosphere or intrinsic magnetic field, and consequently its surface is bombarded with the full solar wind. The Project Apollo missions deployed passive aluminum collectors in an attempt to sample the solar wind, and lunar soil returned for study confirmed that the lunar regolith is enriched in atomic nuclei deposited from the solar wind. There has been speculation that these elements may prove to be useful resources for future lunar colonies.

Outer limits

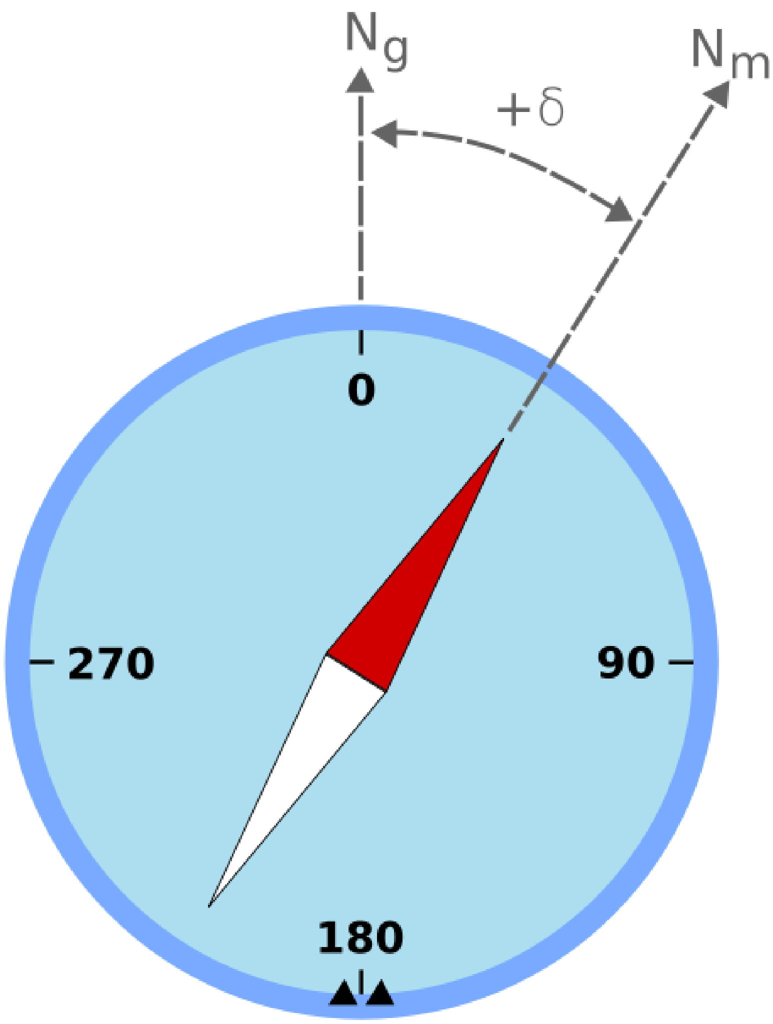
The solar wind "blows a bubble" in the interstellar medium (the rarefied hydrogen and helium gas that permeates the galaxy). The point where the solar wind's strength is no longer great enough to push back the interstellar medium is known as the heliopause, and is often considered to be the outer "border" of the solar system. The distance to the heliopause is not precisely known, and probably varies widely depending on the current velocity of the solar wind and the local density of the interstellar medium, but it is known to lie far outside the orbit of Pluto. Scientists hope to gain more perspective on the heliopause from data acquired through the Interstellar Boundary Explorer (IBEX) mission, launched in October 2008.

Notable Events

- From May 10, 1999 to May 12, NASA's Advanced Composition Explorer (ACE) and WIND (spacecraft) spacecraft observed a 98% decrease of solar wind density. This allowed energetic electrons from the Sun to flow to Earth in narrow beams known as "strahl", which caused a highly unusual "polar rain" event, in which a visible aurora appeared over the North Pole. In addition, Earth's magnetosphere increased to between 5 and 6 times its normal size.
- December 13, 2010, Voyager 1 determined that the velocity of the solar wind, at its location 10.8 billion miles from Earth has now slowed to zero. "We have gotten to the point where the wind from the Sun, which until now has always had an outward motion, is no longer moving outward; it is only moving sideways so that it can end up going down the tail of the heliosphere, which is a comet-shaped-like object," said Dr. Edward Stone, the Voyager project scientist.

Chapter- 6

Magnetic Declination



Example of magnetic declination showing a compass needle with a "positive" (or "easterly") variation from geographic north.

Magnetic declination is the angle between magnetic north (the direction the north end of a compass needle points) and true north. The declination is positive when the magnetic north is east of true north. The term **magnetic variation** is a synonym, and is more often used in navigation. **Isogonic** lines are where the declination has the same value, and the lines where the declination is zero are called **agonic lines**.

Somewhat more formally, Bowditch defines variation as "the angle between the magnetic and geographic meridians at any place, expressed in degrees and minutes east or west to indicate the direction of magnetic north from true north. The angle between magnetic and grid meridians is called grid magnetic angle, grid variation, or grivation. Called magnetic variation when a distinction is needed to prevent possible ambiguity. Also called magnetic declination."

Change of declination in time and space

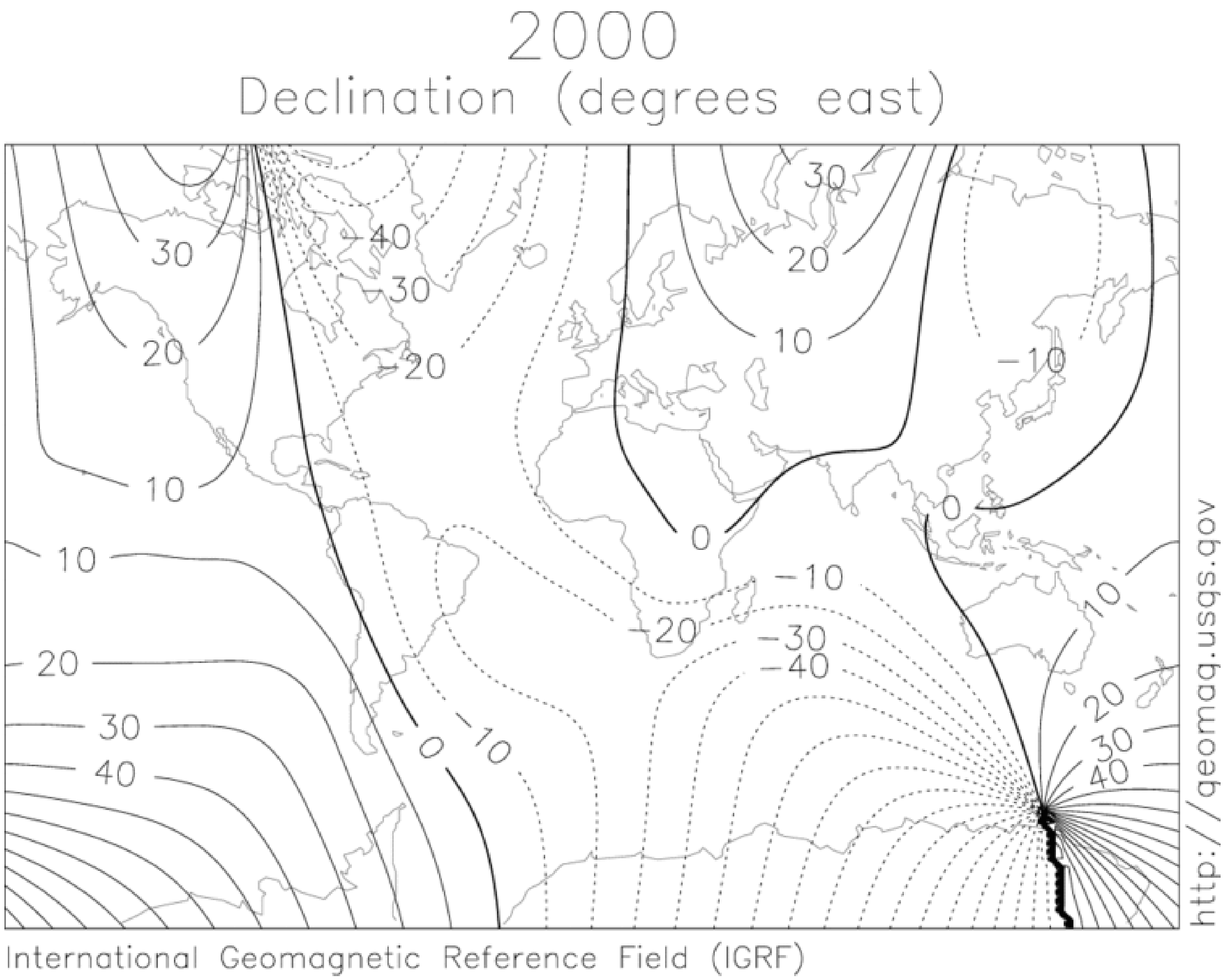
Magnetic declination varies both from place to place, and with the passage of time. As a traveller cruises the east coast of the United States, for example, the declination varies from 20 degrees west (in Maine) to zero (in Florida), to 10 degrees east (in Texas), meaning a compass adjusted at the beginning of the journey would have a true north error of over 30 degrees if not adjusted for the changing declination. In the UK it is degree 34 minutes west (London) and as the country is quite small that figure is fairly good for the whole of the country It is declining and about 2050 will be zero.

In most areas, the spatial variation reflects the irregularities of the flows deep in the earth; in some areas, deposits of iron ore or magnetite in the Earth's crust may contribute strongly to the declination. Similarly, secular changes to these flows result in slow changes to the field strength and direction at the same point on the Earth.

The magnetic declination in a given area may (most likely will) change slowly over time, possibly as little as 2–2.5 degrees every hundred years or so, depending upon how far from the magnetic poles it is. For a location closer to the pole like Ivujivik, the declination may change by 1 degree every three years. This may be insignificant to most travellers, but can be important if using magnetic bearings from old charts or metes (directions) in old deeds for locating places with any precision.

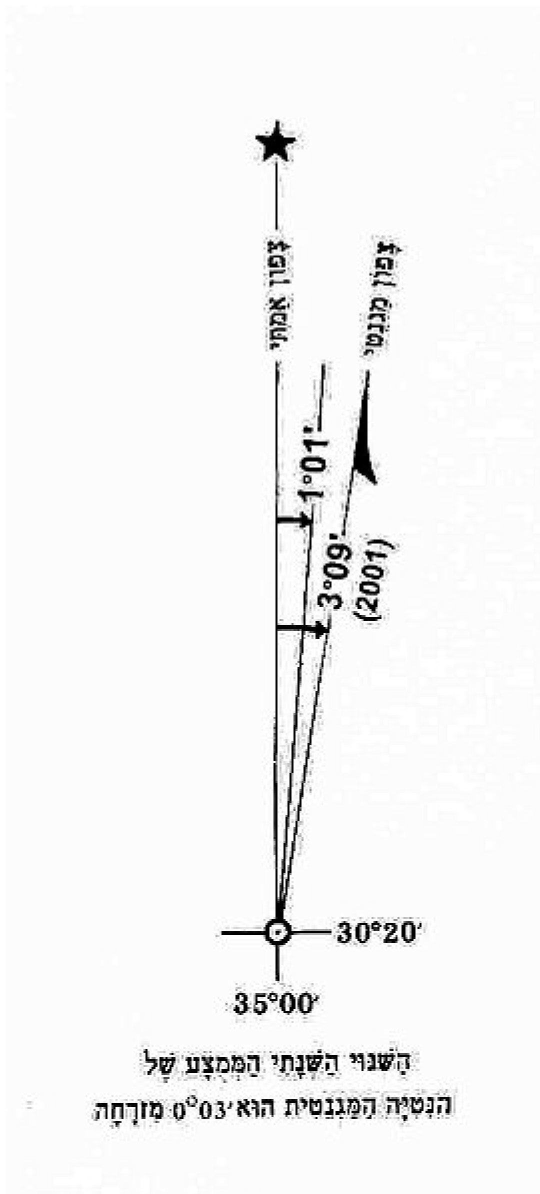
Simply speaking, true north is the direction in which the north pole is located along the Earth's rotational axis, while *magnetic north* is the direction toward which the compass needle points.

Stating the declination



Level curves drawn on a declination map to denote the magnetic declination, described by signed degrees. Each level curve is an isogonic line.

There are three main ways of stating the declination for a given location:



Change of magnetic declination in Israel map (Statement for 2010)

- In a diagram
    - On some maps intended for wilderness or navigational use, including the topographic maps of the U.S. Geological Survey (USGS), a diagram shows the relationship between magnetic north in the area concerned (with an arrow marked "MN") and true north (a vertical line with a five-pointed star at its top), with a label near the angle between the MN arrow and the vertical line, stating the size of the declination and of that angle, in degrees, mils, or both. (On USGS maps, the diagram is near the lower left hand corner, and the information labelled "GN" (grid north) in the same diagram is irrelevant to this discussion.)
- As the numeric size of the angle between magnetic and true north, and the direction from true north to magnetic north.

  - For instance, "10° W" would indicate that magnetic north lies 10 degrees counter-clockwise from true north.
  - Lines of equal declination (isogonic lines) are shown on aeronautical and nautical charts.
- As the signed number of degrees, where a positive angle indicates clockwise from true north and a negative counter-clockwise.
  - For instance, "-10°" would indicate the same as the "10° W" just discussed.

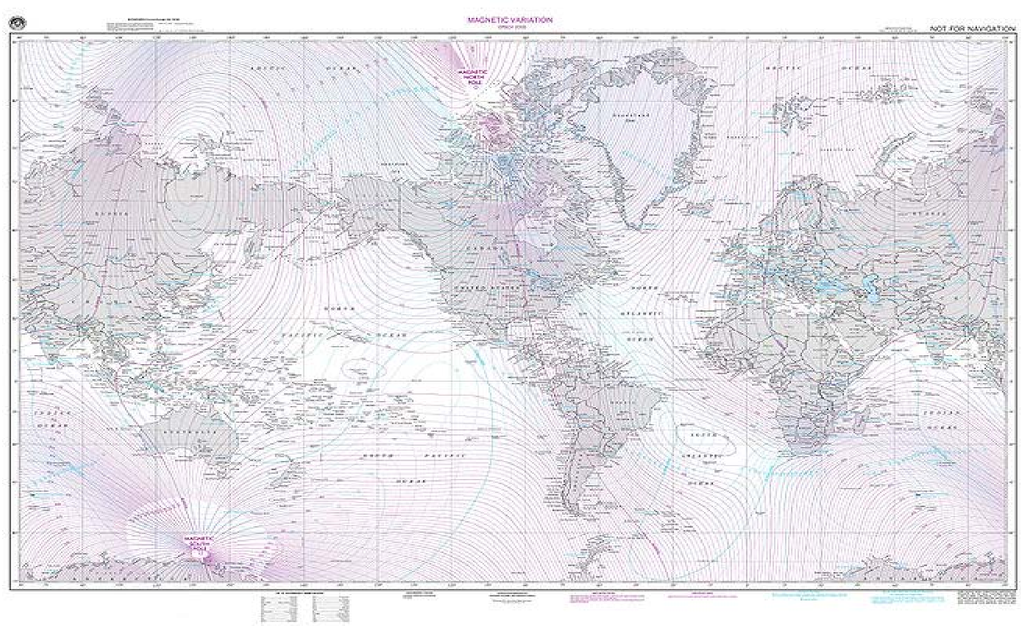
Declination converts between true and magnetic bearings: True Bearing equals Magnetic Bearing plus Magnetic Declination.

Discovering declination

An unknown declination can be discovered on location at that moment in time by reference to the celestial poles, the axis of circular motion of stars traversing the night sky.

In the northern hemisphere, if you can see Polaris (the North Star) the declination can be determined as the difference between the magnetic bearing and a visual bearing on the polestar. Polaris currently traces a circle 0.75° in radius around the north celestial pole, so this technique is accurate to within a degree. At high latitudes a plumb-bob is helpful to sight Polaris against a reference object close to the horizon, from which its bearing can be taken.

Learning the declination for an area



NIMA Magnetic Variation Map 2000

Most use of declination is in conjunction with a map; as stated, that map may state (or even illustrate) the local declination. If not,

- A general isogonic chart of the world or continent can be consulted for a rough estimate of the local declination (within a few degrees)
- A prediction of the current magnetic declination for a given location (based on a worldwide empirical model of the deep flows described above) can also be obtained on-line from a web page operated by the National Geophysical Data Center, a division of the National Oceanic and Atmospheric Administration of the United States.

One would of course rather have the *real* declination than a prediction. However, a map is sure to be months or years out of date, whereas the model is built with all the information available to the map makers at the start of the five-year period it is prepared for. The model reflects a highly predictable rate of change, and will usually be more accurate than a map, and almost never less accurate.

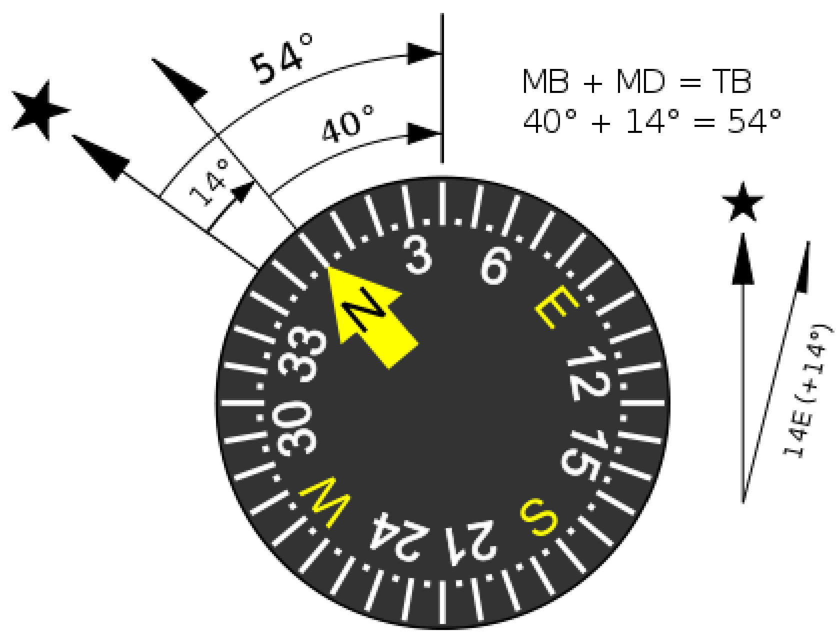
Using the declination

Adjustable compasses

Adjustable compass

A magnetic compass points to magnetic north, not geographic north. Compasses of style commonly used for hiking usually include a "baseplate" marked with a bezel that includes a graduated scale of degrees along with the four cardinal directions. Most advanced / costlier compasses include a declination adjustment. Such an adjustment moves the red "orienting arrow" (found on the base of the liquid filled cylinder), and measures the angle by which it has been turned. Either the cylinder will have a mark to be read against the scale of degrees on the baseplate, or a separate scale will display the current adjustment in degrees. In either case, the underlying concept is that for a declination of 10° W, the red arrow on the cylinder must lie 10° E of 0°/N on the bezel. (Basically, in this case, you are permanently adding 10° to your future bearings to compensate for the -10° declination. If your declination was 10°E you would rotate the baseplate's orienting arrow 10° W of 0°/N to compensate for the +10° declination). In this sense, it can be said that the compass has been adjusted to indicate true north instead of magnetic north (as long as the compass remains within an area on the same isogonic line).

Non-adjustable compasses



How to compensate for magnetic declination when reading a compass. In this example, the declination is 14°E (+14°), so the compass card points to a "north" 14 degrees to the East of true North. To obtain a true bearing, add 14 degrees to the bearing shown by the compass.

With a compass lacking an adjustable baseplate, a careful, well-practiced, compass user can analyse the combination of declination and task, and decide whether the declination is to be added or subtracted from the known direction to determine an unknown direction.

In a place where the declination needs to be *subtracted* from an angle measured on a map from true north to a destination, to learn the compass reading to follow (on an unadjusted compass) to walk that course, the declination needs to be *added* to the compass reading that a landmark lies along, to learn the direction on the map to seek the name to match the landmark with.

Navigation

In navigation the terminology of geomagnetism is used differently. In particular, magnetic declination is divided into two parts, namely magnetic variation and magnetic deviation. There are also three types of bearings—true, magnetic, and compass—which are related by the rules:

- Compass bearing +/- deviation = magnetic bearing
- Magnetic bearing +/- variation = true bearing.

This relationship (finding what the compass should show when the true course is known) is frequently taught as:

- T = true course;
- V = variation (of the Earth's magnetic field);
- M = magnetic course (what the course would be in the absence of local declination);
- D = deviation caused by magnetic material (mostly iron and steel) on the vessel;
- C = compass course.

It is often combined with "West is Best, East is least"; that is to say, add W declinations when going True to Magnetic to Compass, and subtract E ones.

If one knows the course shown by the compass and wishes to find the course relative to true north, the steps are inverted and the signs of deviation and variation inverted.

A simple way of remembering which way to apply the correction is as follows: (in the Continental USA) For locations east of the agonic line (zero declination), roughly east of the Mississippi: The magnetic bearing is **always** bigger. For locations west of the agonic line (zero declination), roughly west of the Mississippi: The magnetic bearing is **always** smaller.

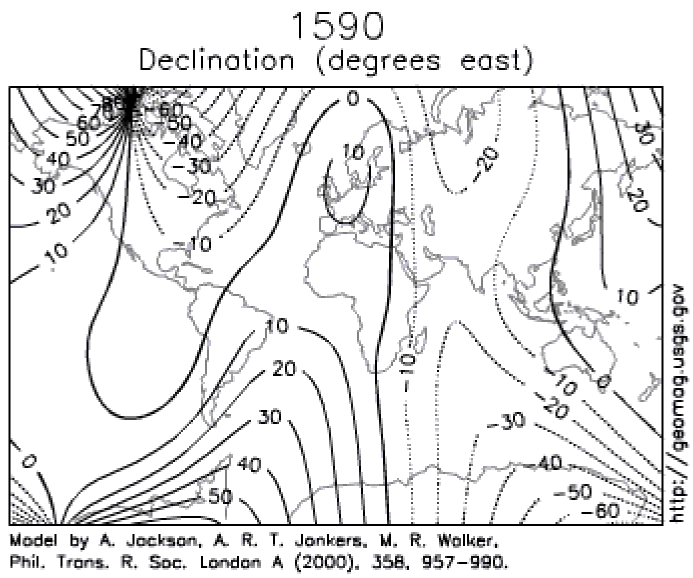
Variation

Magnetic variation is the difference between true bearings and magnetic bearings and is caused by the different locations of the Geographic North Pole and the Magnetic North Pole plus any local anomalies such as iron deposits. **Variation is the same for all compasses in the same location** and is usually stated on good quality maps and charts, along with the date it was measured.

Deviation

Magnetic deviation is the difference between magnetic bearings and compass bearings. **Deviation varies for every compass in the same location** and depends on such factors as the magnetic field of the boat, wristwatches, etc. The value will also vary depending on the orientation of the boat. Magnets and/or iron masses can be used to correct for deviation so that a particular compass will accurately give magnetic bearings. More commonly, however, a correction card will be drawn up listing errors for the compass which can then be compensated for arithmetically.

Air navigation



Magnetic declination has a very important influence on air navigation, since the most simple aircraft navigation instruments are designed to determine headings by locating magnetic north through the use of a compass or similar magnetic device.

Aviation sectionals (maps / charts) and databases used for air navigation are based on True north rather than magnetic north, and the constant and significant slight changes in the actual location of magnetic north and local irregularities in the planet's magnetic field require that charts and databases be updated at least 2 times per year to reflect the current magnetic variation correction from True north. For example, as of March 2010, near San Francisco the magnetic north is about 14.3 degrees east of True north, with the difference decreasing by about 6 minutes of arc per year.

When plotting a course, a pilot in most small planes will plot a trip using true north on a sectional (map), then, convert the true north bearings to magnetic north for in-plane navigation use (which rely on cockpit instruments that read magnetic north).

Radionavigation aids located on the ground, such as VORs, are also checked and updated to keep them aligned with magnetic north to allow pilots to use their magnetic compasses for accurate and reliable in-plane navigation.

The Earth’s magnetic north pole is slowly heading toward Russia, according to scientists, but one of the places being affected by this is Tampa International Airport (TIA) in Tampa, Florida. Airport officials closed its main runway in the second week of January 2011, to adjust the taxiway signs accounting for the magnetic pole shift, Tampa Bay Online reports. The runway designation change was called for by the Federal Aviation Administration (FAA) to reflect a previous National Geographic News report which indicated that the magnetic pole was heading in Russia's direction at almost 40 miles per year. TIA in Florida is closing some runways to make adjustments based on the shifting magnetic pole. Magnetic changes in Earth's core are causing this, possibly due to "a region of rapidly changing magnetism on the core's surface," according to National Geographic. Normally, magnetic fields do not require adjustments to be made at airports, a FAA spokesman said. Later this month, two other runways at the Tampa airport will also be closed to update the signs to their new designations. It is not known yet if similar changes will be needed at other airports in the United States.

GPS systems used for air navigation can use magnetic north or true north. In order to make them more compatible with systems that depend on magnetic north, magnetic north is often chosen, at the pilot's preference. The GPS receiver natively reads in true north, but can elegantly calculate magnetic north based on its true position and data tables calculate the current location and direction of the north magnetic pole and (potentially) any local variations, if the GPS is set to use magnetic compass readings.

Chapter- 7

Magnetotellurics

Magnetotellurics (MT) is an electromagnetic geophysical method of imaging the earth's subsurface by measuring natural variations of electrical and magnetic fields at the Earth's surface. Investigation depth ranges from 300m below ground by recording higher frequencies down to 10,000m or deeper with long-period soundings. Developed in Russia and France during the 1950s, MT is now an international academic discipline and is used in exploration surveys around the world. Commercial uses include hydrocarbon (oil and gas) exploration, geothermal exploration, mining exploration, as well as hydrocarbon and groundwater monitoring. Research applications include experimentation to further develop the MT technique, long-period deep crustal exploration, and earthquake precursor prediction research.

Commercial applications

Hydrocarbon exploration

For hydrocarbon exploration, MT is mainly used as a complement to the primary technique of Reflection seismology exploration. While seismic is able to image subsurface structure, it cannot detect the changes in resistivity associated with hydrocarbons and hydrocarbon-bearing formations. MT does detect resistivity variations in subsurface structures, which can differentiate between structures bearing hydrocarbons and those that do not.

At a basic level of interpretation, resistivity is correlated with different rock types. High-velocity layers are typically highly resistive, whereas sediments - porous and permeable - are typically much less resistive. While high-velocity layers are an acoustic barrier and make seismic ineffective, their electrical resistivity means the magnetic signal passes through almost unimpeded. This allows MT to see deep beneath these acoustic barrier layers, complimenting the seismic data and assisting interpretation. 3-D MT survey results in Uzbekistan (32 x 32 grid of soundings) have guided further seismic mapping of a large known gas-bearing formation with complex subsurface geology.

China National Petroleum Corporation (CNPC) uses onshore MT more than any other oil company in the world, conducting thousands of MT soundings for hydrocarbon exploration and mapping throughout all of China.

Mining exploration

MT is used for various base metals (nickel and precious metals exploration, as well as for Kimberlite) mapping.

INCO's 1991 proof-of-concept study in Sudbury, Ontario, Canada sensed a 1750 meter-deep nickel deposit. Falconbridge followed with a feasibility study in 1996 that accurately located two Ni-Cu mineralized zones at ~800 m and ~1350 m. Since then, both major and junior mining companies are increasingly using MT and AMT for both brownfields and greenfields exploration. Significant MT mapping work has been done on areas of the Canadian Shield.

Diamond exploration, by detecting Kimberlites, is also a proven application.

Geothermal exploration

MT Geothermal Exploration measurements allow detection of resistivity anomalies associated with productive geothermal structures, including faults and the presence of a cap rock, and allow for estimation of geothermal reservoir temperatures at various depths. Dozens of MT geothermal exploration surveys have been completed in Japan and the Philippines since the early 1980s, helping to identify several hundred megawatts of renewable power at places such as the Hatchobaru plant on Kyushu and the Togonang plant on Leyte. Geothermal exploration with MT has also been done in the United States, Iceland, Hungary, China, Ethiopia, Indonesia, Peru, and India.

Other commercial applications

MT is also used for groundwater exploration and mapping, hydrocarbon reservoir monitoring, deep investigation (100 km) of the electrical properties of the bedrock for High-Voltage Direct Current (HVDC) transmission systems, carbon dioxide sequestration, and other environmental engineering applications (e.g. nuclear blast site monitoring and nuclear waste disposal site monitoring).

Research applications

Crustal research

MT has been used to investigate the distribution of silicate melts in the Earth's mantle and crust; large investigations have focused on the East Pacific Rise and the Tibetan Plateau. Other research work aims to better understand the plate-tectonic processes in the highly complex three-dimensional region formed by the collision of the African and European plates.

Earthquake precursor prediction research

Fluctuations in the MT signal may be able to predict the onset of seismic events. Stationary MT monitoring systems have been installed in Japan since April 1996, providing a continuous recording of MT signals at the Wakuya Station (previously at the Mizusawa Geodetic Observatory) and the Esashi Station of the Geographical Survey Institute of Japan. These stations measure fluctuations in the Earth's electromagnetic field that correspond with seismic activity. The raw geophysical time-series data from these monitoring stations is freely available to the scientific community, enabling further study of the interaction between EM events and earthquake activity.

Additional MT earthquake precursor monitoring stations in Japan are located in Kagoshima, in Sawauchi, and on Shikoku. Similar stations are also deployed in Taiwan on Penghu Island, as well as in the Fushan Reserve on the island of Taiwan proper.

POLARIS is a Canadian research program investigating the structure and dynamics of the Earth's lithosphere and the prediction of earthquake ground motion.

Theory and practice

Energy sources

Solar energy and lightning cause natural variations in the earth's magnetic field, inducing electric currents (known as telluric currents) under the Earth's surface. Simultaneous measurements of orthogonal components of the electric and magnetic fields are recorded, with the results calculated as the **impedance tensor.** A subsurface resistivity model is then created using this tensor.

Different rocks, sediments and geological structures have a wide range of different electrical conductivities. Measuring electrical resistivity allows different materials and structures to be distinguished from one another and can improve knowledge of tectonic processes and geologic structures.

The Earth's naturally varying electric and magnetic fields are measured over a wide range of magnetotelluric frequencies from 10,000 Hz to 0.0001 Hz (10,000s). These fields are due to electric currents flowing in the Earth and the magnetic fields that induce these currents. The magnetic fields are produced mainly by the interaction between the solar wind and the magnetosphere. In addition, worldwide thunderstorm activity causes magnetic fields at frequencies above 1 Hz. Combined, these natural phenomena create strong MT source signals over the entire frequency spectrum.

The ratio of the electric field to magnetic field provides simple information about subsurface conductivity. Because the skin effect phenomenon affects the electromagnetic fields, the ratio at higher frequency ranges gives information on the shallow Earth, whereas deeper information is provided by the low-frequency range. The ratio is usually represented as both apparent resistivity as a function of frequency and phase as a function of frequency.

Depth and resolution

MT measurements can investigate depths from about 300m down to tens of kilometres, though investigations in the range of 500m to 10,000m are typical. Greater depth requires measuring lower frequencies, which in turn requires longer recording times. Very deep, very long-period measurements (15km or more), may require recordings of several days to obtain satisfactory data quality.

Horizontal resolution of MT mainly depends on the distance between sounding locations- closer sounding locations increase the horizontal resolution. Continuous profiling (known as dipole-to-dipole) has been used, with only metres between the edges of each telluric dipole.

Vertical resolution of MT mainly depends on the frequency being measured, as lower frequencies have longer wavelengths. Accordingly, vertical resolution decreases as depth of investigation increases.

Signal strength and recording times

Magnetic fields in the frequency range of 1 Hz to approximately 20 kHz are part of the audio-magnetotelluric (AMT) range. These are parallel to the Earth surface and move towards the Earth's centre. This large frequency band allows for a range of depth penetration from several metres to several kilometres below the Earth's surface. Due to the nature of magnetotelluric source, the waves generally fluctuate in amplitude height. Long recording times are needed to ascertain usable reading due to the fluctuations and the low signal strength. Generally, the signal is weak between 1 to 5 kHz, which is a crucial range in detecting the top 100m of geology. The magnetotelluric method is also used in marine environments for hydrocarbon exploration and lithospheric studies. Due to the screening effect of the electrically conductive sea water, a usable upper limit of the spectrum is around 1 Hz.

2D and 3D Magnetotellurics

Two-dimensional surveys consist of a longitudinal profile of MT soundings over the area of interest, providing two-dimensional "slices" of subsurface resistivity.

Three-dimensional surveys consist of a loose grid pattern of MT soundings over the area of interest, providing a more sophisticated three-dimensional model of subsurface resistivity.

History

The magentotelluric technique was introduced by the French geophysicist Louis Cagniard and Russian geophysicist A. N. Tikhonov in the early 1950s. With advances in instrumentation, processing and modeling, MT has become one of the most important tools in deep Earth research.

Since the 1950s sensors, receivers and data processing techniques have followed the general trends in digital electronics, becoming less expensive and more capable with each generation.

Major advances in MT instrumentation and technique include the advent of remote referencing, GPS time-based synchronization, and 3D data acquisition and processing.

Variants

Audio-magnetotellurics (AMT)

AMT is a higher-frequency magnetotelluric technique for shallower investigations. While AMT has less depth penetration than MT, AMT measurements often take only about one hour to perform (but deep AMT measurements during low-signal strength periods may take up to 24 hours) and use smaller and lighter magnetic sensors. Transient AMT is an AMT variant that records only temporarily during periods of more intense natural signal (transient impulses), improving signal-to-noise-ratio at the expense of strong linear polarization.

Controlled source electromagnetics

CSEM Controlled source electro-magnetic is a deep-water offshore variant of controlled source audio magnetotellurics– CSEM is the named used in the offshore oil and gas industry.

Onshore CSEM / CSAMT may be effective where electromagnetic cultural noise (e.g. power lines, electric fences) present interference problems for natural-source geophysical methods. An extensive grounded wire (2 km or more) has currents at a range of frequencies (0.1 Hz to 100 kHz) passed through it. The electric field parallel to the source and the magnetic field which is at right angles are measured. The resistivity is then calculated, and the lower the resistivity, the more likely there is a conductive target (graphite, nickel ore or iron ore). CSAMT is also known in the oil and gas industry as Onshore controlled source electromagnetics (Onshore CSEM).

An offshore variant of MT, MMT uses instruments and sensors in pressure housings deployed by ship into shallow coastal areas where water is less than 300m deep. A derivative of MMT is offshore single-channel measurement of the vertical magnetic field only (the Hz, or "tipper"), which eliminates the need for telluric measurements and horizontal magnetic measurements. While the theory is sound, no commercial system is yet available. Furthermore, any such system would require a solution providing for the precise orientation and stabilization the magnetic sensor.

Exploration surveys

MT exploration surveys are done to acquire resistivity data which can be interpreted to create a model of the subsurface. Data is acquired at each sounding location for a period of time (overnight soundings are common), with physical spacing between soundings dependant on the target size and geometry, local terrain constraints and financial cost. Reconnaissance surveys can have spacings of several kilometres, while more detailed work can have 200m spacings, or even adjacent soundings (dipole-to-dipole). MT surveys are carried out year-round in the Americas, Europe, Asia, Africa and Oceania.

The HSE impact of MT exploration is relatively low because of light-weight equipment, natural signal sources, and reduced hazards compared to other types of exploration (e.g. no drills, no explosives, and no high currents).

Remote reference soundings

Remote Reference is an MT technique used to account for cultural electrical noise by acquiring simultaneous data at more than one MT station. This greatly improves data quality, and may allow acquisition in areas where the natural MT signal is difficult to detect because of man-made EM interference.

Survey equipment

A typical full suite of MT equipment (for a "five component" sounding) consists of a receiver instrument with five sensors: three magnetic sensors, and two telluric (electric) sensors. In many situations, only the telluric sensors will be used, and magnetic data borrowed from other nearby soundings to reduce acquisition costs.

A complete five-component set of MT equipment can be backpack-carried by a small field team (3 to 4 persons) or carried by a light helicopter (such as the MD Helicopters MD 500), allowing deployment in remote and rugged areas. Most MT equipment is capable of reliable operation over a wide range of environmental conditions, with ratings of typically -20C to +45C, from dry desert to high-humidity (condensing) and partial immersion.

Data processing and interpretation

Post-acquisition processing is required to transform raw time-series data into frequency-based inversions. The resulting output of the processing program is used as the input for subsequent interpretation. Processing may include the use of remote reference data or local data only.

Processed MT data is modelled using various techniques to create a subsurface resistivity map, with lower frequencies generally corresponding to greater depth below ground. Anomalies such as faults, hydrocarbons, and conductive mineralization appear as areas of higher or lower resistivity from surrounding structures.

Instrument and sensor manufacturers

Magnetotelluric station

MT instrumentation design and construction is a specialized international activity, with only a small number of companies and scientific organizations having the necessary expertise and technology. Three companies supply most of the commercial-use world market: one in the United States (Zonge Engineering and Research Organization, Inc.), one in Canada (Phoenix Geophysics, Ltd.) and one in Germany (Metronix Messgeraete und Elektronik GmbH). Other manufacturers include a limited number of government agencies and smaller companies producing MT instrumentation for internal use, including Vega Geophysics, Ltd. in Russia; the Russian Academy of Sciences (SPbF IZMIRAN); and the National Space Research Institute of Ukraine.

Chapter- 8

Earthquake Precursor

The nature and properties of a possible electric **earthquake precursor** (EEP) are inadequately understood. Although the electrification of rock prior to and during rupture is observed in laboratory experiments,

1. there is an incomplete understanding of how laboratory results may scale up to the enormous, heterogeneous rock volumes involved in the preparation zone of large earthquakes and
2. the *efficiency* of different electrification mechanisms is unspecified, as is any operative contribution per mechanism or interaction.

Warning signs

- Increased emission of radon;
- Increased helium emission;
- Increased methane gas emission, with possible formation of colored methane clouds - Earthquake clouds;
- Increased activity of mud volcanoes;
- Occurrence of microseismicity;
- Modification of ground electrical conductivity;
- Fluctuations in the Earth's magnetic field;
- Changes in the density of nearby rocks;
- Changes in well-water levels close to a fault;
- Anomalies in the behavior of animals, such as mass migration of amphibians;
- Increased emission of carbon dioxide in volcanic areas; volcanic paroxism;
- Occurrence of small sand volcanoes.

Earthquake

An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves. The seismicity or seismic activity of an area refers to the frequency, type and size of earthquakes experienced over a period of time. Earthquakes are measured with a seismometer; a device also known as a seismograph. The moment magnitude (or the related and mostly obsolete

Richter magnitude) of an earthquake is conventionally reported, with magnitude 3 or lower earthquakes being mostly imperceptible and magnitude 7 causing serious damage over large areas. Intensity of shaking is measured on the modified Mercalli scale.

At the Earth's surface, earthquakes manifest themselves by shaking and sometimes displacing the ground. When a large earthquake epicenter is located offshore, the seabed sometimes suffers sufficient displacement to cause a tsunami. The shaking in earthquakes can also trigger landslides and occasionally volcanic activity.

In its most generic sense, the word earthquake is used to describe any seismic event—whether a natural phenomenon or an event caused by humans—that generates seismic waves. Earthquakes are caused mostly by rupture of geological faults, but also by volcanic activity, landslides, mine blasts, and nuclear tests. An earthquake's point of initial rupture is called its focus or hypocenter. The term epicenter refers to the point at ground level directly above the hypocenter.

Precursor

A precursor in the context of an earthquake is an indicator of approaching events. A forerunner is a sign or warning of something to come.

Natural electric field of the Earth

Periodic variations in the Earth's electric field may serve as earthquake precursors.

Magnetotellurics

Magnetotellurics (MT) is an electromagnetic geophysical method of imaging the earth's subsurface by measuring natural variations of electrical and magnetic fields at the Earth's surface. Investigation depth ranges from 300 m by recording higher frequencies down to 10 km or more with long-period soundings. Developed in Russia and France during the 1950s, MT is now an international academic discipline and is used in exploration surveys around the world. Commercial uses include hydrocarbon (oil and gas) exploration, geothermal exploration, mining exploration, as well as hydrocarbon and groundwater monitoring. Research applications include experimentation to further develop the MT technique, long-period deep crustal exploration, and earthquake precursor prediction research.

Fluctuations in the MT signal may be able to predict the onset of seismic events.

Stationary MT monitoring systems have been installed in Japan since April 1996, providing a continuous recording of MT signals at the Wakuya Station (previously at the Mizusawa Geodetic Observatory) and the Esashi Station of the Geographical Survey Institute of Japan. These stations measure fluctuations in the Earth's electromagnetic field that correspond with seismic activity. Additional MT earthquake precursor monitoring stations in Japan are located in Kagoshima, in Sawauchi, and on Shikoku.

Similar stations are also deployed in Taiwan on Penghu Island, as well as in the Fushan Reserve on the island of Taiwan proper.

POLARIS is a Canadian research program investigating the structure and dynamics of the Earth's lithosphere and the prediction of earthquake ground motion.

Earthquake satellite

Satellites can be used to detect a variety of signals that may be forerunners of an earthquake.

Intercosmos 24

The Intercosmos 24 satellite detected ELF-VLF electromagnetic emissions associated with earthquakes. During 180 orbits from November 16, 1989, to December 31, 1989, twenty-eight rather strong earthquakes (Ms between 5.2 and 6.1) took place with

1. emissions in the two frequency bands with spectrum maxima at ULF-ELF (f less than 1000 Hz) and at VLF (f = 10-15 kHz), typically observed as bursts, in the region nearly above the earthquake epicenter,
2. ULF-ELF emission spectrum intensity decreasing with increasing frequency,
3. only VLF emissions are observed far from the epicenter but near the appropriate L shell, and
4. emission occurrence probability is a maximum at 12-24 h before the main shock.

NOAA advanced very-high-resolution radiometer satellite

Each of the advanced TIROS-N satellites has carried aboard an advanced very-high-resolution radiometer (AVHRR) which produces thermal images associated with large linear structures and fault systems of the Earth's crust. Some of these images have indicated the presence of positive thermal anomalies:

1. in China a thermal anomaly is located near Beijing, at the interface between the mountains and plain, about 700 km in length and 50 km in width, appearing about 6–24 d before and continuing about a week after an earthquake, and
2. in Japan a thermal anomaly appears 7-10 d before the earthquake shock, but has a small size with a temperature magnitude that runs up to 6°C, and the tectonic position is unclear.

QuakeSat

Quakesat is an Earth observation satellite, specifically a nanosatellite based on 3 CubeSats. It is designed to be a proof-of-concept system for collecting extremely low frequency (ELF) earthquake precursor signals from space. The students working on the project are hoping that the detection of magnetic signals may have value in showing the onset of an earthquake. The company that put the satellites together is from Palo Alto, California. They're gathering data on the extremely low magnetic field fluctuations that are associated with earthquakes to help better understand this area of study that has its skeptics. The primary instrument is a magnetometer housed in a 2 foot (0.6 m) telescoping boom.

The June 30, 2003, 14:15 UTC launch and deployment of Quakesat occurred on a Rokot from Russia's Plesetsk Cosmodrome. A mission duration of 24 months may have resulted in deorbiting by July 2005.

Demeter

Artist's impression of Demeter in orbit above active volcano

A French minisatellite (125 kg) for *d*etection of *e*lectro*m*agnetic *e*missions *t*ransmitted from *e*arthquake *r*egions (Demeter) is currently in orbit. It was launched on June 29, 2004, 07:45 UTC aboard a Dnepr launch vehicle from Tyuratam (Baikonur Cosmodrome), Kazakhstan. It carries probes for electric fields (0-3 MHz) the Instrument Champ Electrique (ICE) and magnetic fields (10 Hz-18 kHz) (IMSC), a plasma analyzer (IAP), a Langmuir probe (ISL), and a particle detector (IDP) which measures the fluxes of energetic electrons in the energy range 60 keV to 600 keV.

The IDP has objectives to

1. measure modifications to the trajectories and energies of particles due to interaction with waves, particularly close to seismic epicenters, and
2. understand the chain of physical processes leading to the observations before and after earthquakes.

After more than 6.5 yr, Demeter is to be stopped on December 9, 2010.

Rock strain

In order to determine the likelihood of future seismic activity, geologists and other scientists examine the rock of an area to determine if the rock appears to be "strained". Studying the faults of an area to study the buildup time it takes for the fault to build up stress sufficient for an earthquake also serves as an effective prediction technique. Measurements of the amount of accumulated strain energy on the fault each year, time passed since the last major temblor, and the energy and power of the last earthquake are made. Together the facts allow scientists to determine how much pressure it takes for the fault to generate an earthquake. Though this method is useful, it has only been implemented on California's San Andreas Fault.

Seismo-electromagnetics

Seismo-electromagnetics is the study of electromagnetic phenomena associated with seismic activity such as earthquakes and volcanos, and also the use of electromagnetic methods in seismology such as magnetotellurics. Links between the electromagnetic fields in the lithosphere and those in the atmosphere and ionosphere are also studied. Earthquake prediction is one of the aims of this area of research.

Motion of charge

For elastic rock deformation and non-elastic deformation, dislocations can move and pile up to form and propagate cracks.

Highly mobile positive O type charge carriers are generated in oxide/silicate minerals from electrically inactive peroxy defects deriving from OH^- dissolved in the mineral structure.

Charge production and current generation during crack opening is short-lived. If any long-lasting EEP is observed, it is generated by the superposition of the signals from all the simultaneously propagating cracks and evolves in time just like crack propagation.

Precursory electric signals in dry, resistive rock samples indicate that strong precursory fields due to solid state mechanisms are anticipated from resistive rock blocks.

For a large granite block with a load applied to the central portion, a positive surface potential appears which increases with increasing load. Positive ions can be emitted from the rock surface due to the high electric field associated with a positive surface charge layer. Such an emission of positive ions from the Earth's surface may be related to ground-hugging fog or haze occurring prior to earthquake activity or during a sequence of aftershocks.

The associated electric field can reach hundreds of thousands of volts per cm, enough to cause field ionization and dielectric breakdown of the air to produce coronal discharges.

Electrokinetic effect

Electrification due to the flow of water driven through permeable rock by crustal strain or gravity (electrokinetic effect, EKE) has been demonstrated by laboratory experiments. Conditions suitable for EKE are plausible at least in the near-surface part of a seismogenic zone and quite consistent with wet models of the earthquake preparation process. EKE may be a source of precursory electric fields. Near the fault zone in saturated sandstone the amplitude of electrokinetic precursory signals are as large as the co-seismic.

Geomagnetic field

Large scale microfracturing may result in current excitation due to the motion of conductive Earth material in the geomagnetic field by crack-emitting acoustic waves. At distances far enough from opening cracks where the acoustic wave front is approximately spherical, the electromagnetic purtabations appear as forerunners to the arrival of the acoustic wave. A ULF precursor may be observed even in the absence of microseismic activity.

Any possible precursory ELF-VLF signals propagating through the Earth-ionosphere cavity must be associated with a magnetic field observable at the Earth’s surface.

Thermal anomaly

Thermal anomalies have been identified associated with large linear structures and fault systems in the Earth's crust, on the basis of satellite infrared thermal images of the Earth's surface. Sometimes, 5-10 d before an earthquake, short-lived thermal anomalies develop in the area around the future epicenter with a positive deviation of 2-3°C, disappearing rapidly 1-2 d after the earthquakes.

A true temperature increase of the ground due to heat coming from below can be ruled out from data of

1. heat capacity, where the energy required to heat by 1°C such large rock volumes exceeds the total energy released during an M = 7 earthquake and
2. heat conductivity, where such large volumes of rock can never heat up by several degrees and cool down again within a few days.

Infrared emissions have been recorded from granite blocks during loading until failure. It is likely that positive-charge holes, specifically p-hole charge carriers, generated in the granite during deformation in the core region spread through the entire volume and upon reaching the surface recombine with the emission of infrared photons.

On January 20, 2001, there is a strong land surface temperature (LST) increase (with a maximum of +4°C) for the area close to the epicenter of the January 26, 2001, Gujarat earthquake that dissipates within a few d after the event.