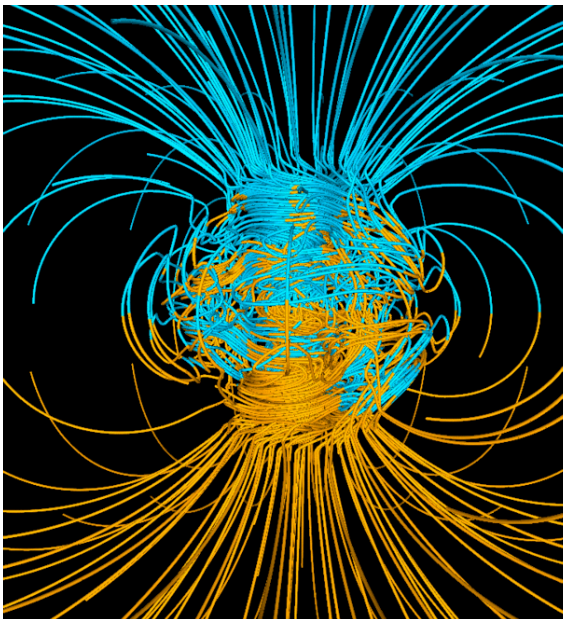
Contents

Chapter 1

Earth's magnetic field



Computer simulation of the Earth's field in a period of normal polarity between reversals.[1] The lines represent magnetic field lines, blue when the field points towards the center and yellow when away. The rotation axis of the Earth is centered and vertical. The dense clusters of lines are within the Earth's core.*[2]*

Earth's magnetic field, also known as the **geomagnetic field**, is the magnetic field that extends from the Earth's interior out into space, where it meets the solar wind, a stream of charged particles emanating from the Sun. Its magnitude at the Earth's surface ranges from 25 to 65 microteslas (0.25 to 0.65 gauss).*[3] Roughly speaking it is the field of a magnetic dipole currently tilted at an angle of about 10 degrees with respect to Earth's rotational axis, as if there were a bar magnet placed at that angle at the center of the Earth. The North geomagnetic pole, located near Greenland in the northern hemisphere, is actually the south pole of the Earth's magnetic field, and the South geomagnetic pole is the north pole. Unlike a bar magnet, Earth's magnetic field changes over time because it is generated by a geodynamo (in Earth's case, the motion of molten iron alloys in its outer core).

While the North and South magnetic poles are usually located near the geographic poles, they can wander widely over geological time scales, but sufficiently slowly for ordinary compasses to remain useful for navigation. However, at irregular intervals averaging several hundred thousand years, the Earth's field reverses and the North and South Magnetic Poles relatively abruptly switch places. These reversals of the geomagnetic poles leave a record in rocks that are of value to paleomagnetists in calculating geomagnetic fields in the past. Such information in turn is helpful in studying the motions of continents and ocean floors in the process of plate tectonics.

The magnetosphere is the region above the ionosphere that is defined by the extent of the Earth's magnetic field in space. It extends several tens of thousands of kilometers into space, protecting the Earth from the charged particles of the solar wind and cosmic rays that would otherwise strip away the upper atmosphere, including the ozone layer that protects the Earth from harmful ultraviolet radiation.

1.1 Importance

The Earth's magnetic field serves to deflect most of the solar wind, whose charged particles would otherwise strip away the ozone layer that protects the Earth from harmful ultraviolet radiation.*[4] One stripping mechanism is for gas to be caught in bubbles of magnetic field, which are ripped off by solar winds.*[5] Calculations of the loss of carbon dioxide from the atmosphere of Mars, resulting from scavenging of ions by the solar wind, indicate that the dissipation of the magnetic field of Mars caused a near total loss of its atmosphere.*[6]*[7]

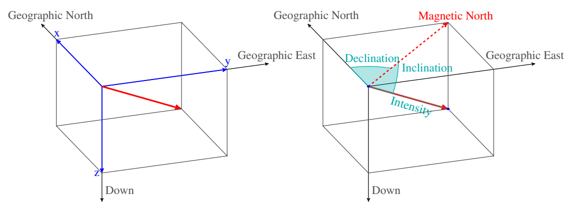
The study of past magnetic field of the Earth is known as paleomagnetism.*[8] The polarity of the Earth's magnetic field is recorded in igneous rocks, and reversals of the field are thus detectable as “stripes” centered on mid-ocean ridges where the sea floor is spreading, while the stability of the geomagnetic poles between reversals has allowed paleomagnetists to track the past motion of continents. Reversals also provide the basis for magnetostratigraphy, a way of dating rocks and sediments.*[9] The field also magnetizes the crust, and magnetic anomalies can be used to search for deposits of metal ores.*[10]

Humans have used compasses for direction finding since the 11th century A.D. and for navigation since the 12th century.*[11] Although the magnetic declination does shift with time, this wandering is slow enough that a simple compass remains useful for navigation. Using magnetoception various other organisms, ranging from some types of bacteria to pigeons, use the Earth's magnetic field for orientation and navigation.

1.2 Main characteristics

1.2.1 Description

At any location, the Earth's magnetic field can be represented by a three-dimensional vector. A typical procedure for measuring its direction is to use a compass to determine the direction of magnetic North. Its angle relative to true North is the *declination* (D) or *variation*. Facing magnetic North, the angle the field makes with the horizontal is the *inclination* (I) or *magnetic dip*. The *intensity* (F) of the field is proportional to the force it exerts on a magnet. Another common representation is in X (North), Y (East) and Z (Down) coordinates.*[12]



Common coordinate systems used for representing the Earth's magnetic field.

Intensity

The intensity of the field is often measured in gauss (G), but is generally reported in nanoteslas (nT), with 1 G = 100,000 nT. A nanotesla is also referred to as a gamma (γ).*[13] The tesla is the SI unit of the Magnetic field, **B**. The Earth's field ranges between approximately 25,000 and 65,000 nT (0.25–0.65 G). By comparison, a strong refrigerator magnet has a field of about 10,000,000 nanoteslas (100 G).*[14]

A map of intensity contours is called an *isodynamic chart*. As the World Magnetic Model shows, the intensity tends to decrease from the poles to the equator. A minimum intensity occurs in the South Atlantic Anomaly over South America while there are maxima over northern Canada, Siberia, and the coast of Antarctica south of Australia.*[15]

Inclination

Main article: Magnetic dip

The inclination is given by an angle that can assume values between −90° (up) to 90° (down). In the northern hemisphere, the field points downwards. It is straight down at the North Magnetic Pole and rotates upwards as the latitude decreases until it is horizontal (0°) at the magnetic equator. It continues to rotate upwards until it is straight up at the South Magnetic Pole. Inclination can be measured with a dip circle.

An *isoclinic chart* (map of inclination contours) for the Earth's magnetic field is shown below.

Declination

Main article: Magnetic declination

Declination is positive for an eastward deviation of the field relative to true north. It can be estimated by comparing the magnetic north/south heading on a compass with the direction of a celestial pole. Maps typically include information on the declination as an angle or a small diagram showing the relationship between magnetic north and true north. Information on declination for a region can be represented by a chart with isogonic lines (contour lines with each line representing a fixed declination).

1.2.2 Geographical variation

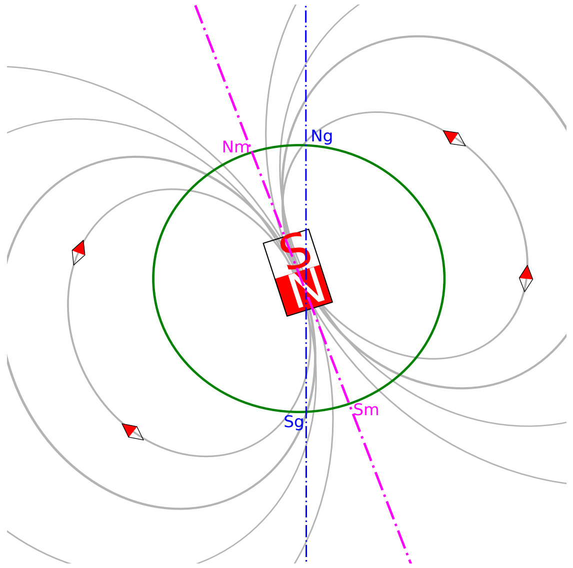
Components of the Earth's magnetic field at the surface from the World Magnetic Model for 2015.*[15]

- File:World Magnetic Field 2015.pdf
  Intensity
- File:World Magnetic Inclination 2015.pdf
  Inclination
- File:World Magnetic Declination 2015.pdf
  Declination

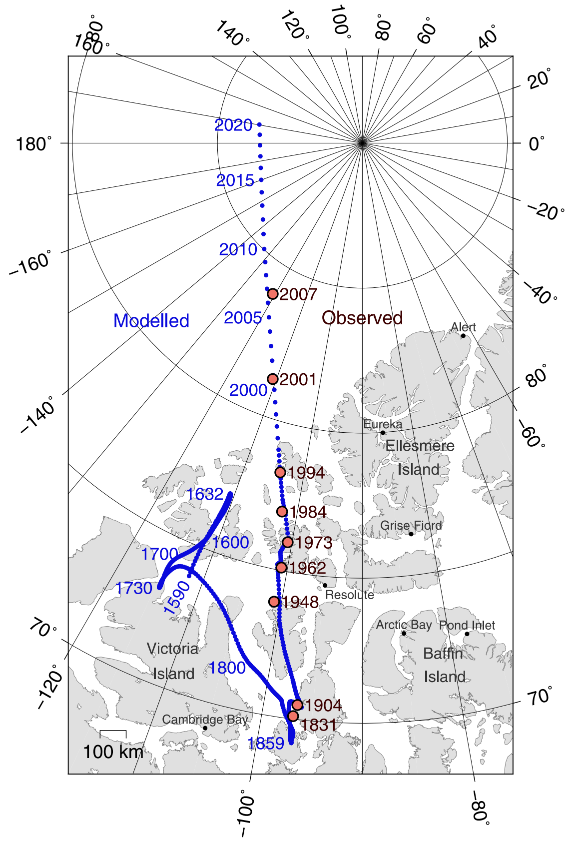
1.2.3 Dipolar approximation

See also: Dipole model of the Earth's magnetic field

Near the surface of the Earth, its magnetic field can be closely approximated by the field of a magnetic dipole positioned at the center of the Earth and tilted at an angle of about 11° with respect to the rotational axis of the Earth.*[13] The dipole is roughly equivalent to a powerful bar magnet, with its south pole pointing towards the geomagnetic North Pole.*[16] This may seem surprising, but the north pole of a magnet is so defined because, if allowed to rotate freely, it points roughly northward (in



The variation between magnetic north (N_m) and "true" north (N_g).



The movement of Earth's North Magnetic Pole across the Canadian arctic.

the geographic sense). Since the north pole of a magnet attracts the south poles of other magnets and repels the north poles, it must be attracted to the south pole of Earth's magnet. The dipolar field accounts for 80–90% of the field in most locations.*[12]

1.2.4 Magnetic poles

The positions of the magnetic poles can be defined in at least two ways: locally or globally.*[17]

One way to define a pole is as a point where the magnetic field is vertical.*[18] This can be determined by measuring the inclination, as described above. The inclination of the Earth's field is 90° (downwards) at the North Magnetic Pole and −90° (upwards) at the South Magnetic Pole. The two poles wander independently of each other and are not directly opposite each other on the globe. They can migrate rapidly: movements of up to 40 kilometres (25 mi) per year have been observed for the North Magnetic Pole. Over the last 180 years, the North Magnetic Pole has been migrating northwestward, from Cape Adelaide in the Boothia Peninsula in 1831 to 600 kilometres (370 mi) from Resolute Bay in 2001.*[19] The *magnetic equator* is the line where the inclination is zero (the magnetic field is horizontal).

The global definition of the Earth's field is based on a mathematical model. If a line is drawn through the center of the Earth, parallel to the moment of the best-fitting magnetic dipole, the two positions where it intersects the Earth's surface are called the North and South geomagnetic poles. If the Earth's magnetic field were perfectly dipolar, the geomagnetic poles and magnetic dip poles would coincide and compasses would point towards them. However, the Earth's field has a significant non-dipolar contribution, so the poles do not coincide and compasses do not generally point at either.

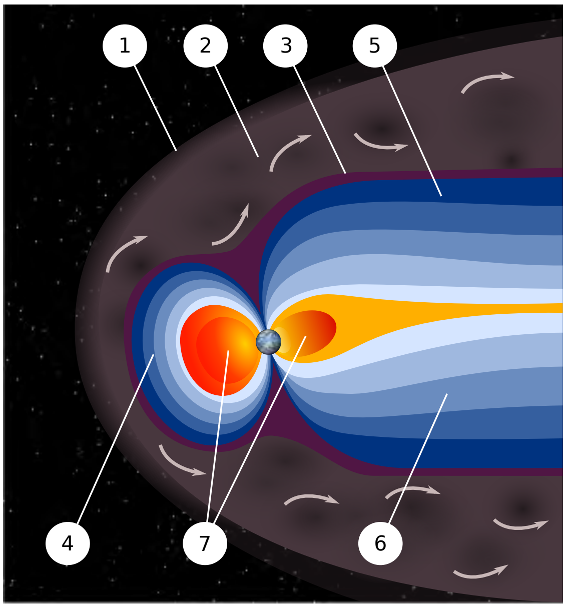
1.3 Magnetosphere

Main article: Magnetosphere

Earth's magnetic field, predominantly dipolar at its surface, is distorted further out by the solar wind. This is a stream of charged particles leaving the Sun's corona and accelerating to a speed of 200 to 1000 kilometres per second. They carry with them a magnetic field, the interplanetary magnetic field (IMF).*[20]

The solar wind exerts a pressure, and if it could reach Earth's atmosphere it would erode it. However, it is kept away by the pressure of the Earth's magnetic field. The magnetopause, the area where the pressures balance, is the boundary of the magnetosphere. Despite its name, the magnetosphere is asymmetric, with the sunward side being about 10 Earth radii out but the other side stretching out in a magnetotail that extends beyond 200 Earth radii.*[21] Sunward of the magnetopause is the bow shock, the area where the solar wind slows abruptly.*[20]

Inside the magnetosphere is the plasmasphere, a donut-shaped region containing low-energy charged particles,



An artist's rendering of the structure of a magnetosphere. 1) Bow shock. 2) Magnetosheath. 3) Magnetopause. 4) Magnetosphere. 5) Northern tail lobe. 6) Southern tail lobe. 7) Plasmasphere.

or plasma. This region begins at a height of 60 km, extends up to 3 or 4 Earth radii, and includes the ionosphere. This region rotates with the Earth.*[21] There are also two concentric tire-shaped regions, called the Van Allen radiation belts, with high-energy ions (energies from 0.1 to 10 million electron volts (MeV)). The inner belt is 1–2 Earth radii out while the outer belt is at 4–7 Earth radii. The plasmasphere and Van Allen belts have partial overlap, with the extent of overlap varying greatly with solar activity.*[22]

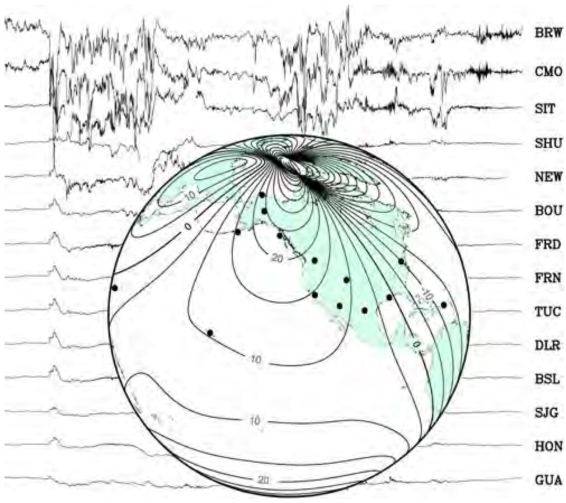
As well as deflecting the solar wind, the Earth's magnetic field deflects cosmic rays, high-energy charged particles that are mostly from outside the Solar system. (Many cosmic rays are kept out of the Solar system by the Sun's magnetosphere, or heliosphere.*[23]) By contrast, astronauts on the Moon risk exposure to radiation. Anyone who had been on the Moon's surface during a particularly violent solar eruption in 2005 would have received a lethal dose.*[20]

Some of the charged particles do get into the magnetosphere. These spiral around field lines, bouncing back and forth between the poles several times per second. In addition, positive ions slowly drift westward and negative ions drift eastward, giving rise to a ring current. This current reduces the magnetic field at the Earth's surface.*[20] Particles that penetrate the ionosphere and collide with the atoms there give rise to the lights of the aurorae and also emit X-rays.*[21]

The varying conditions in the magnetosphere, known as space weather, are largely driven by solar activity. If the solar wind is weak, the magnetosphere expands; while if it is strong, it compresses the magnetosphere and more of it gets in. Periods of particularly intense activity, called geomagnetic storms, can occur when a coronal mass ejection erupts above the Sun and sends a shock wave through the Solar System. Such a wave can take just two days to reach the Earth. Geomagnetic storms can cause a lot of disruption; the "Halloween" storm of 2003 damaged more than a third of NASA's satellites. The largest documented storm occurred in 1859. It induced currents strong enough to short out telegraph lines, and aurorae were reported as far south as Hawaii.*[20]*[24]

1.4 Time dependence

1.4.1 Short-term variations



***Background**: a set of traces from magnetic observatories showing a magnetic storm in 2000.*
***Globe**: map showing locations of observatories and contour lines giving horizontal magnetic intensity in μ T.*

The geomagnetic field changes on time scales from milliseconds to millions of years. Shorter time scales mostly arise from currents in the ionosphere (ionospheric dynamo region) and magnetosphere, and some changes can be traced to geomagnetic storms or daily variations in currents. Changes over time scales of a year or more mostly reflect changes in the Earth's interior, particularly the iron-rich core.*[12]

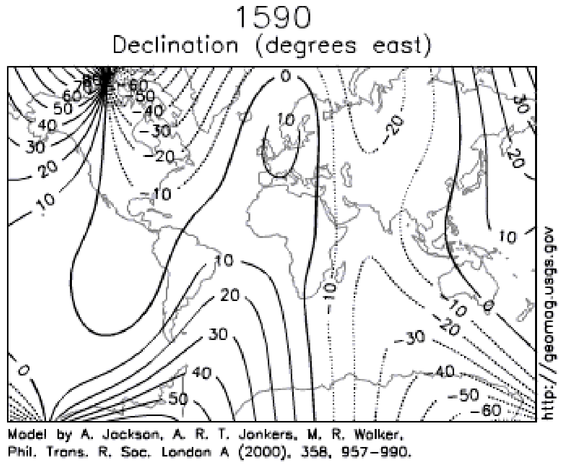
Frequently, the Earth's magnetosphere is hit by solar flares causing geomagnetic storms, provoking displays of aurorae. The short-term instability of the magnetic field is measured with the K-index.*[25]

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.*[26]

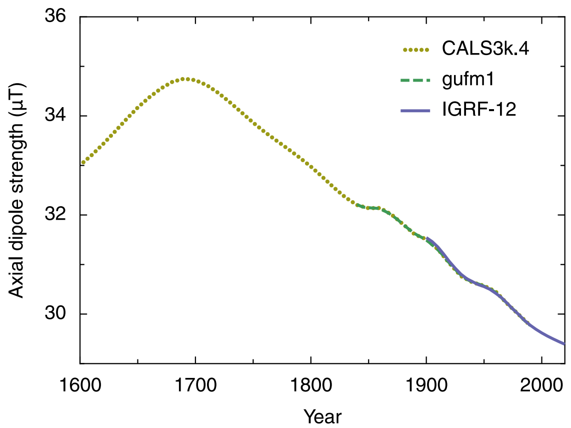
1.4.2 Secular variation

Main article: Geomagnetic secular variation

Changes in Earth's magnetic field on a time scale of a year



Estimated declination contours by year, 1590 to 1990 (click to see variation).



Strength of the axial dipole component of Earth's magnetic field from 1600 to 2020.

or more are referred to as *secular variation*. Over hundreds of years, magnetic declination is observed to vary over tens of degrees.*[12] A movie on the right shows how global declinations have changed over the last few centuries.*[27]

The direction and intensity of the dipole change over time. Over the last two centuries the dipole strength has been decreasing at a rate of about 6.3% per century.*[12] At this rate of decrease, the field would be negligible in about 1600 years.*[28] However, this strength is about average for the last 7 thousand years, and the current rate of change is not unusual.*[29]

A prominent feature in the non-dipolar part of the secular variation is a *westward drift* at a rate of about 0.2 degrees per year.*[28] This drift is not the same everywhere and has varied over time. The globally averaged drift has been westward since about 1400 AD but eastward between about 1000 AD and 1400 AD.*[30]

Changes that predate magnetic observatories are recorded in archaeological and geological materials. Such changes are referred to as *paleomagnetic secular variation* or *paleosecular variation (PSV)*. The records typically include long periods of small change with occasional large changes reflecting geomagnetic excursions and reversals.*[31]

1.4.3 Magnetic field reversals

Main article: Geomagnetic reversal

Although generally Earth's field is approximately dipolar, with an axis that is nearly aligned with the rotational axis, occasionally the North and South geomagnetic poles trade places. Evidence for these *geomagnetic reversals* can be found in basalts, sediment cores taken from the ocean floors, and seafloor magnetic anomalies.*[32] Reversals occur nearly randomly in time, with intervals between reversals ranging from less than 0.1 million years to as much as 50 million years. The most recent geomagnetic reversal, called the Brunhes–Matuyama reversal, occurred about 780,000 years ago.*[19]*[33] A related phenomenon, a geomagnetic excursion, amounts to an incomplete reversal, with no change in polarity.*[34]*[35] The Laschamp event is an example of an excursion, it having occurred during the last ice age (41,000 years ago).

The past magnetic field is recorded mostly by strongly magnetic minerals, particularly iron oxides such as magnetite, that can carry a permanent magnetic moment. This remanent magnetization, or *remanence*, can be acquired in more than one way. In lava flows, the direction of the field is "frozen" in small minerals as they cool, giving rise to a thermoremanent magnetization. In sediments, the orientation of magnetic particles acquires a slight bias towards the magnetic field as they are deposited on an ocean floor or lake bottom. This is called *detrital remanent magnetization*.*[8]

Thermoremanent magnetization is the main source of the magnetic anomalies around ocean ridges. As the seafloor spreads, magma wells up from the mantle, cools to form new basaltic crust on both sides of the ridge, and is carried away from it by seafloor spreading. As it cools, it records the direction of the Earth's field. When the Earth's field reverses, new basalt records the reversed direction. The result is a series of stripes that are symmetric about the ridge. A ship towing a magnetometer on the surface of the ocean can detect these stripes and infer the age of the ocean floor below. This provides information on the rate at which seafloor has spread in the past.*[8]

Radiometric dating of lava flows has been used to establish a *geomagnetic polarity time scale*, part of which is shown in the image. This forms the basis of magnetostratigraphy, a geophysical correlation technique that can be used to date both sedimentary and volcanic sequences as well as the seafloor magnetic anomalies.*[8]

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.*[36] This finding was later attributed to unusual rock magnetic properties of the lava flow under study, not rapid field change, by one of the original authors of the 1995 study.*[37]

Temporary dipole tilt variations that take the dipole axis across the equator and then back to the original polarity are known as *excursions*.*[35]

1.4.4 Earliest appearance

Paleomagnetic studies of Paleoarchean lava in Australia and conglomerate in South Africa have concluded that the magnetic field has been present since at least about 3,450 million years ago.*[38]*[39]*[40]

1.4.5 Future

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; 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.

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, are not sufficient to extrapolate an overall trend in the field strength. It has gone up and down in the past for unknown reasons. 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 kilometres (6.2 mi) per year at the beginning of the 20th century, up to 40 kilometres (25 mi) per year in 2003,*[19] and since then has only accelerated.*[41]

1.5 Physical origin

Main article: Dynamo theory

The Earth's magnetic field is believed to be generated by electric currents in the conductive material of its core, created by convection currents due to heat escaping from the core. However the process is complex, and computer models that reproduce some of its features have only been developed in the last few decades.

1.5.1 Earth's core and the geodynamo

The Earth and most of the planets in the Solar System, as well as the Sun and other stars, all generate magnetic fields through the motion of electrically conducting fluids.*[43] The Earth's field originates in its core. This is a region of iron alloys extending to about 3400 km (the radius of the Earth is 6370 km). It is divided into a solid inner core, with a radius of 1220 km, and a liquid outer core.*[44] The motion of the liquid in the outer core is driven by heat flow from the inner core, which is about 6,000 K (5,730 °C; 10,340 °F), to the core-mantle boundary, which is about 3,800 K (3,530 °C; 6,380 °F).*[45] The pattern of flow is organized by the rotation of the Earth and the presence of the solid inner core.*[46]

The mechanism by which the Earth generates a magnetic field is known as a dynamo.*[43] The magnetic field is generated by a feedback loop: current loops generate magnetic fields (Ampère's circuital law); a changing magnetic field generates an electric field (Faraday's law); and the electric and magnetic fields exert a force on the charges that are flowing in currents (the Lorentz force).*[47] These effects can be combined in a partial differential equation for the magnetic field called the *magnetic induction equation*:

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

...where **u** is the velocity of the fluid; **B** is the magnetic B-field; and $\eta=1/\sigma\mu$ is the magnetic diffusivity, which is inversely proportional to the product of the electrical conductivity σ and the permeability μ .*[48] The term $\partial\mathbf{B}/\partial t$ is the time derivative of the field; ∇^2 is the Laplace operator and $\nabla\times$ is the curl operator.

The first term on the right hand side of the induction equation is a diffusion term. In a stationary fluid, the magnetic field declines and any concentrations of field spread out. If the Earth's dynamo shut off, the dipole part would disappear in a few tens of thousands of years.*[48]

In a perfect conductor ($\sigma = \infty$), there would be no diffusion. By Lenz's law, any change in the magnetic field would be immediately opposed by currents, so the flux through a given volume of fluid could not change.

As the fluid moved, the magnetic field would go with it. The theorem describing this effect is called the *frozen-in-field theorem*. Even in a fluid with a finite conductivity, new field is generated by stretching field lines as the fluid moves in ways that deform it. This process could go on generating new field indefinitely, were it not that as the magnetic field increases in strength, it resists fluid motion.*[48]

The motion of the fluid is sustained by convection, motion driven by buoyancy. The temperature increases towards the center of the Earth, and the higher temperature of the fluid lower down makes it buoyant. This buoyancy is enhanced by chemical separation: As the core cools, some of the molten iron solidifies and is plated to the inner core. In the process, lighter elements are left behind in the fluid, making it lighter. This is called *compositional convection*. A Coriolis effect, caused by the overall planetary rotation, tends to organize the flow into rolls aligned along the north-south polar axis.*[46]*[48]

A dynamo can amplify a magnetic field, but it needs a "seed" field to get it started.*[48] For the Earth, this could have been an external magnetic field. Early in its history the Sun went through a T-Tauri phase in which the solar wind would have had a magnetic field orders of magnitude larger than the present solar wind.*[49] However, much of the field may have been screened out by the Earth's mantle. An alternative source is currents in the core-mantle boundary driven by chemical reactions or variations in thermal or electric conductivity. Such effects may still provide a small bias that are part of the boundary conditions for the geodynamo.*[50]

The average magnetic field in the Earth's outer core was calculated to be 25 gauss, 50 times stronger than the field at the surface.*[51]

Numerical models

Simulating the geodynamo requires numerically solving a set of nonlinear partial differential equations for the magnetohydrodynamics (MHD) of the Earth's interior. Simulation of the MHD equations is performed on a 3D grid of points and the fineness of the grid, which in part determines the realism of the solutions, is limited mainly by computer power. For decades, theorists were confined to creating *kinematic dynamo* computer models in which the fluid motion is chosen in advance and the effect on the magnetic field calculated. Kinematic dynamo theory was mainly a matter of trying different flow geometries and testing whether such geometries could sustain a dynamo.*[52]

The first *self-consistent* dynamo models, ones that determine both the fluid motions and the magnetic field, were developed by two groups in 1995, one in Japan*[53] and one in the United States.*[1]*[54] The latter received attention because it successfully reproduced some of the characteristics of the Earth's field, including geomagnetic reversals.*[52]

1.5.2 Currents in the ionosphere and magnetosphere

Electric currents induced in the ionosphere generate magnetic fields (ionospheric dynamo region). 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) (one part in 2000), with variations over a few seconds of typically around 1 nT (one part in 50,000).*[55]

1.6 Measurement and analysis

1.6.1 Detection

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.*[56] 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.*[57]

Governments sometimes operate units that specialize 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 such as magnetic storms 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.

1.6.2 Crustal magnetic anomalies

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. 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.

1.6.3 Statistical models

Each measurement of the magnetic field is at a particular place and time. If an accurate estimate of the field at some other place and time is needed, the measurements must be converted to a model and the model used to make predictions.

Spherical harmonics

See also: Multipole expansion

The most common way of analyzing the global variations in the Earth's magnetic field is to fit the measurements to a set of spherical harmonics. This was first done by Carl Friedrich Gauss.*[59] Spherical harmonics are functions that oscillate over the surface of a sphere. They are the product of two functions, one that depends on latitude and one on longitude. The function of longitude is zero along zero or more great circles passing through the North and South Poles; the number of such *nodal lines* is the absolute value of the *order* m. The function of latitude is zero along zero or more latitude circles; this plus the order is equal to the *degree* ℓ. Each harmonic is equivalent to a particular arrangement of magnetic charges at the center of the Earth. A *monopole* is an isolated magnetic charge, which has never been observed. A *dipole* is equivalent to two opposing charges brought close together and a *quadrupole* to two dipoles brought together. A quadrupole field is shown in the lower figure on the right.*[12]

Spherical harmonics can represent any scalar field (function of position) that satisfies certain properties. A magnetic field is a vector field, but if it is expressed in Cartesian components X, Y, Z, each component is the derivative of the same scalar function called the *magnetic potential*. Analyses of the Earth's magnetic field use a modified version of the usual spherical harmonics that differ by a multiplicative factor. A least-squares fit to the magnetic field measurements gives the Earth's field as the sum of spherical harmonics, each multiplied by the best-fitting *Gauss coefficient* $g_m{}^*\ell$ or $h_m{}^*\ell$.*[12]

The lowest-degree Gauss coefficient, $g_0{}^0$, gives the contribution of an isolated magnetic charge, so it is zero. The next three coefficients – $g_1{}^0$, $g_1{}^1$, and $h_1{}^1$ – determine the direction and magnitude of the dipole contribution. The best fitting dipole is tilted at an angle of about 10° with respect to the rotational axis, as described earlier.*[12]

Radial dependence Spherical harmonic analysis can be used to distinguish internal from external sources if measurements are available at more than one height (for example, ground observatories and satellites). In that case, each term with coefficient $g_m{}^*\ell$ or $h_m{}^*\ell$ can be split into two terms: one that decreases with radius as $1/r^*\ell$+1 and one that *increases* with radius as $r^*\ell$. The increasing terms fit the external sources (currents in the ionosphere and magnetosphere). However, averaged over a few years the external contributions average to zero.*[12]

The remaining terms predict that the potential of a dipole source (ℓ=1) drops off as $1/r^2$. The magnetic field, being a derivative of the potential, drops off as $1/r^3$. Quadrupole terms drop off as $1/r^4$, and higher order terms drop off increasingly rapidly with the radius. The radius of the outer core is about half of the radius of the Earth. If the field at the core-mantle boundary is fit to spherical harmonics, the dipole part is smaller by a factor of about 8 at the surface, the quadrupole part by a factor of 16, and so on. Thus, only the components with large wavelengths can be noticeable at the surface. From a variety of arguments, it is usually assumed that only terms up to degree 14 or less have their origin in the core. These have wavelengths of about 2,000 kilometres (1,200 mi) or less. Smaller features are attributed to crustal anomalies.*[12]

Global models

The International Association of Geomagnetism and Aeronomy maintains a standard global field model called the International Geomagnetic Reference Field. It is updated every 5 years. The 11th-generation model, IGRF11, was developed using data from satellites (Ørsted, CHAMP and SAC-C) and a world network of geomagnetic observatories.*[60] The spherical harmonic expansion was truncated at degree 10, with 120 coefficients, until 2000. Subsequent models are truncated at degree 13 (195 coefficients).*[61]

Another global field model, called World Magnetic Model, is produced jointly by the United States National Centers for Environmental Information (formerly the National Geophysical Data Center) and the British Geological Survey. This model truncates at degree 12 (168 coefficients) with an approximate spatial resolution of 3,000 kilometers. It is the model used by the United States Department of Defense, the Ministry of Defence (United Kingdom), the United States Federal Aviation Administration (FAA), the North Atlantic Treaty Organization, and the International Hydrographic Office as well as in many civilian navigation systems.*[62]

A third model, produced by the Goddard Space Flight Center (NASA and GSFC) and the Danish Space Research Institute, uses a "comprehensive modeling" approach that attempts to reconcile data with greatly varying temporal and spatial resolution from ground and satellite sources.*[63]

For users with higher accuracy needs, the United States National Centers for Environmental Information developed the Enhanced Magnetic Model (EMM), which extends to degree and order 720 and resolves magnetic anomalies down to a wavelength of 56 kilometers. It was compiled from satellite, marine, aeromagnetic and ground magnetic surveys. The latest version, EMM2015, includes data from The European Space Agency's Swarm satellite mission.*[64]

1.7 Biomagnetism

Main article: Magnetoception

Animals including birds and turtles can detect the Earth's magnetic field, and use the field to navigate during migration.*[65] 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.*[66]*[67] In 2011, researchers reported their failed attempt to replicate the finding using different Google Earth images.*[68]

Researchers found out that very weak electromagnetic fields disrupt the magnetic compass used by European robins and other songbirds to navigate using the Earth's magnetic field. Neither power lines nor cellphone signals are to blame for the electromagnetic field effect on the birds, according to the new study published in the 8 May 2014 edition of the journal Nature. Instead, the culprits consist of frequencies between 2 kHz and 5 MHz, such as AM radio signals and ordinary electronic equipment that might be found in businesses or private homes.*[69]

1.8 See also

- Thermal History of the Earth
- Geomagnetic jerk
- Geomagnetic latitude
- History of geomagnetism
- Magnetic field of the Moon
- Magnetosphere of Jupiter
- Magnetotellurics
- Carnegie (ship)
- Galilee (ship)

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1.11 External links

- *Geomagnetism & Paleomagnetism background material*. American Geophysical Union Geomagnetism and Paleomagnetism Section.
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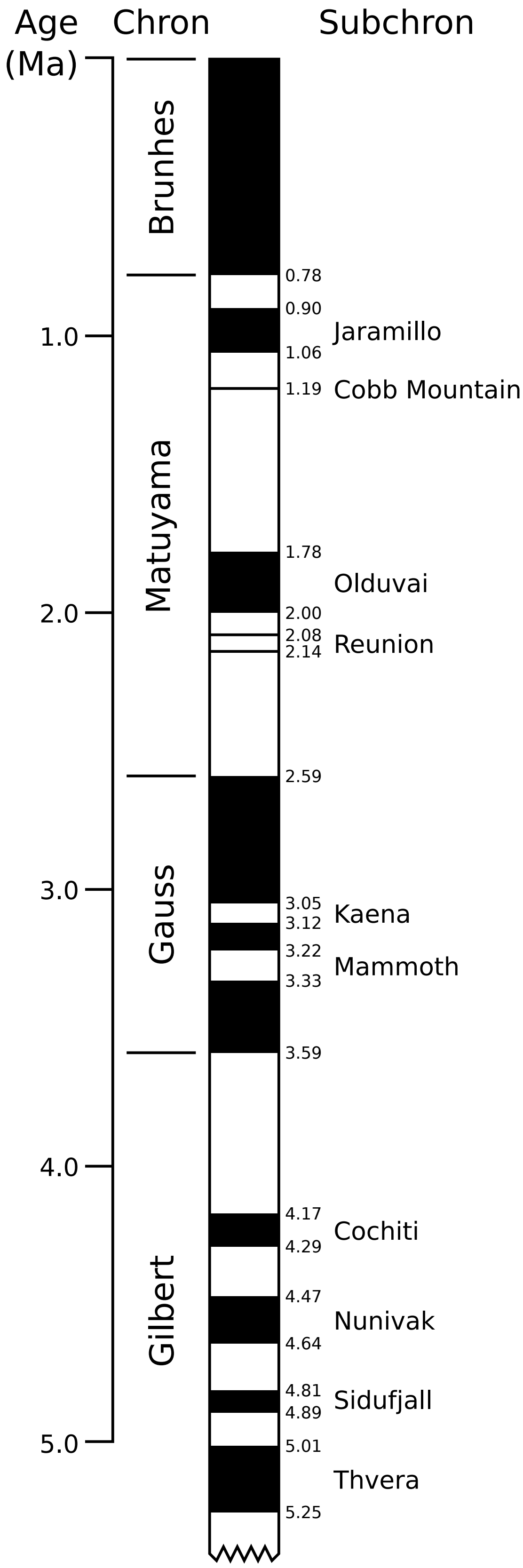
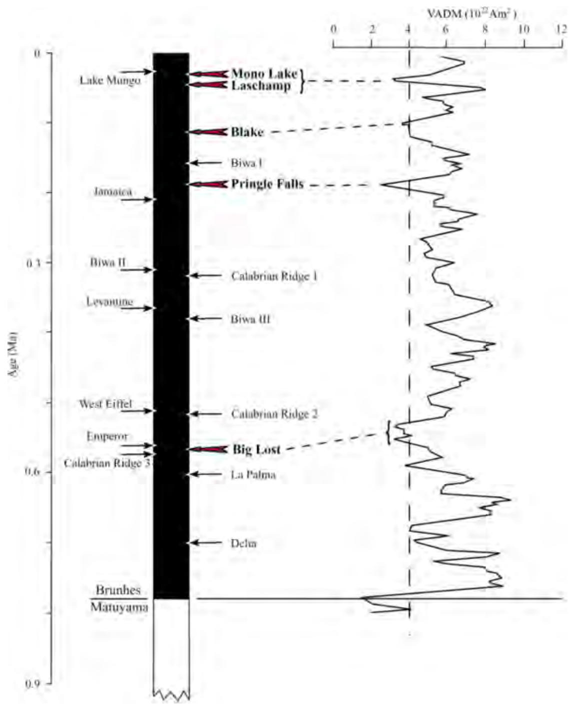
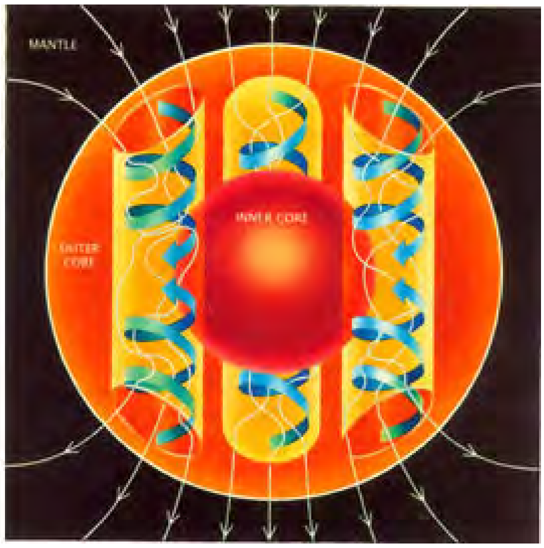
- *Dr. Dan Lathrop: The study of the Earth's magnetic field*. Interview with Dr. Dan Lathrop, Geophysicist at the University of Maryland, about his experiments with the Earth's core and magnetic field. 7 - 3 - 2008
- International Geomagnetic Reference Field 2011
- Global evolution/anomaly of the Earth's magnetic field Sweeps are in 10 degree steps at 10 years intervals. Based on data from: The Institute of Geophysics, ETH Zurich



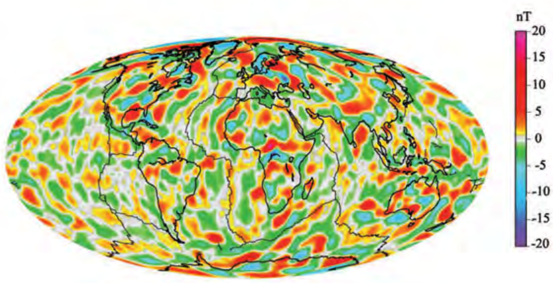
Geomagnetic polarity during the late Cenozoic Era. Dark areas denote periods where the polarity matches today's polarity, light areas denote periods where that polarity is reversed.



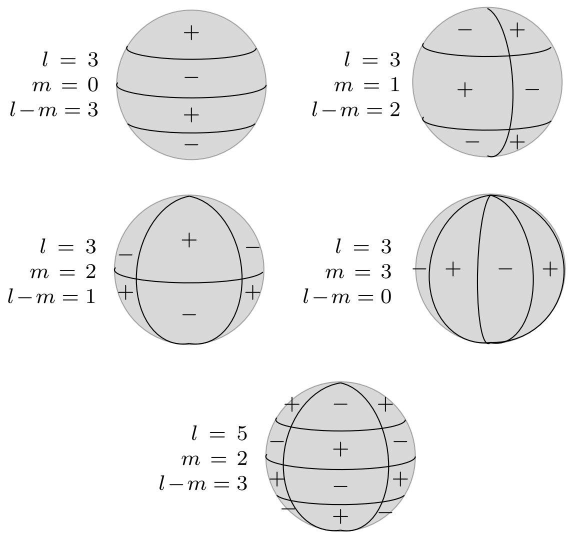
Variations in virtual axial dipole moment since the last reversal.



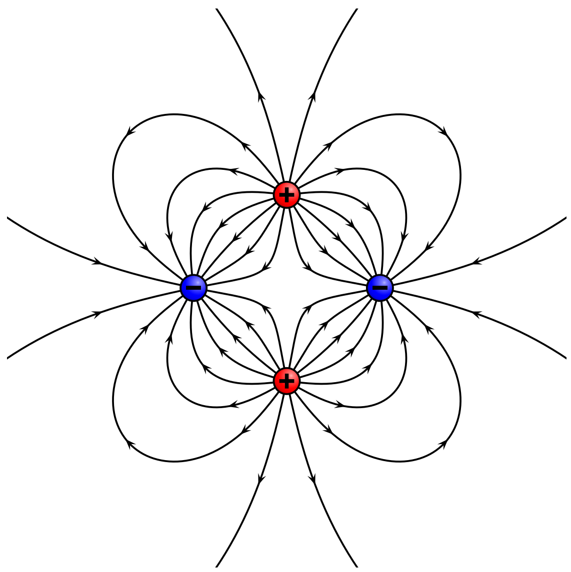
A schematic illustrating the relationship between motion of conducting fluid, organized into rolls by the Coriolis force, and the magnetic field the motion generates. [42]*



A model of short-wavelength features of Earth's magnetic field, attributed to lithospheric anomalies. [58]*



Schematic representation of spherical harmonics on a sphere and their nodal lines. $P_{\ell m}$ is equal to 0 along m great circles passing through the poles, and along ℓ-m circles of equal latitude. The function changes sign each ℓtime it crosses one of these lines.



Example of a quadrupole field. This can also be constructed by moving two dipoles together.

Chapter 2

History of geomagnetism

A reconstruction of an early Chinese compass. A spoon made of lodestone, its handle pointing south, was mounted on a brass plate with astrological symbols.[*][1]

The **history of geomagnetism** is concerned with the history of the study of Earth's magnetic field. It encompasses the history of navigation using compasses, studies of the prehistoric magnetic field (archeomagnetism and paleomagnetism), and applications to plate tectonics.

Magnetism has been known since prehistory, but knowledge of the Earth's field developed slowly. The horizontal direction of the Earth's field was first measured in the fourth century BC but the vertical direction was not measured until 1544 AD and the intensity was first measured in 1791. At first, compasses were thought to point towards locations in the heavens, then towards magnetic mountains. A modern experimental approach to understanding the Earth's field began with *de Magnete*, a book published by William Gilbert in 1600. His experiments with a magnetic model of the Earth convinced him that the Earth itself is a large magnet.

2.1 Early ideas on magnetism

Knowledge of the existence of magnetism probably dates back to the prehistoric development of iron smelting. Iron can be obtained on the Earth's surface from meteorites; the mineral lodestone is rich in the magnetic mineral magnetite and can be magnetized by a lightning strike. In his *Natural History*, Pliny the Elder recounts a legend about a Magnes the shepherd on the island of Crete whose iron-studded boots kept sticking to the path. The earliest ideas on the nature of magnetism are attributed to Thales (c. 624 BC – c. 546 BC).[*][1][*][2]

In classical antiquity, little was known about the nature of magnetism. No sources mention the two poles of a magnet or its tendency to point northward. There were two main theories about the origins of magnetism. One, proposed by Empedocles of Acragas and taken up by Plato and Plutarch, invoked an invisible *effluvium* seeping through the pores of materials; Democritus of Abdera replaced this effluvium by atoms, but the mechanism was essentially the same. The other theory evoked the metaphysical principle of *sympathy* between similar objects. This was mediated by a purposeful life force that strove toward perfection. This theory can be found in the writings of Pliny the Elder and Aristotle, who claimed that Thales attributed a soul to the magnet.[*][2] In China, a similar life force, or *qi*, was believed to animate magnets, so the Chinese used early compasses for feng shui.[*][3]

Little changed in the view of magnetism during the Middle Ages, and some classical ideas lingered until well after the first scientific experiments on magnetism. One belief, dating back to Pliny, was that fumes from eating garlic and onions could destroy the magnetism in a compass, rendering it useless. Even after William Gilbert disproved this in 1600, there were reports of helmsmen on British ships being flogged for eating garlic.[*][4] However, this belief was far from universal. In 1558 Giambattista della Porta reported "When I enquired of mariners whether it were so that they were forbid to eat onyones and garlick for that reason, they said they were old wives fables and things ridiculous, and that sea-men would sooner lose their lives then abstain from eating onyons and garlick." [*][5]

2.2 Measurement of the field

See also: Earth's magnetic field § Description

At a given location, a full representation of the Earth's magnetic field requires a vector with three coordinates (see figure). These can be Cartesian (North, East and

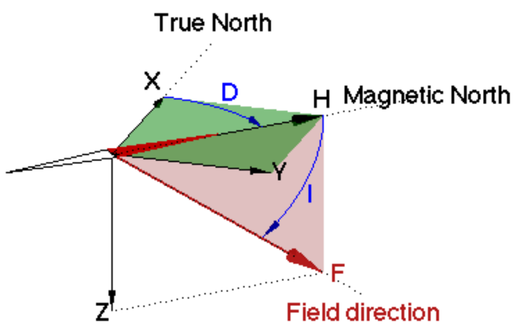


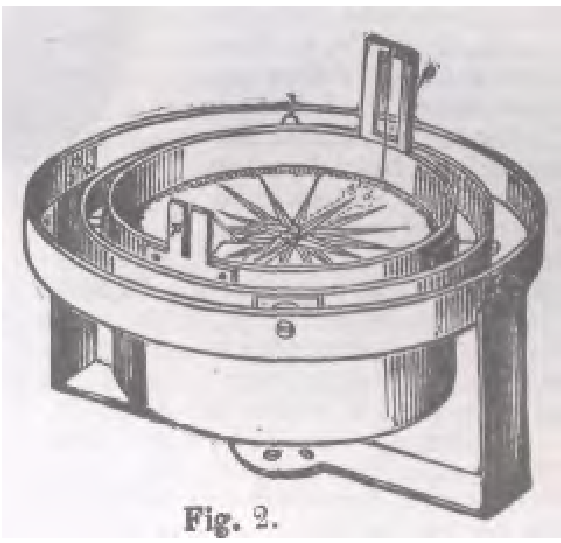
Illustration of the coordinate systems used for representing the Earth's magnetic field. The coordinates X,Y,Z correspond to North, East and down; D is the declination and I is the inclination.

Down) or spherical (declination, inclination and intensity). In the latter system, the declination (the deviation from true north, a horizontal angle) must be measured first to establish the direction of magnetic North; then the dip (a vertical angle) can be measured relative to magnetic North.*[6] In China, the horizontal direction was measured as early as the fourth century BC, and the existence of declination first recognized in 1088. In Europe, this was not widely accepted until the middle of the fifteenth century AD. Inclination (also known as *magnetic dip*) was first measured in 1544 AD. The intensity was not measured until 1791, after advances in the understanding of electromagnetism.

2.2.1 Declination

Main article: Compass § History

The magnetic compass existed in China back as far as the fourth century BC. It was used as much for feng shui as for navigation on land. It was not until good steel needles could be forged that compasses were used for navigation at sea; before that, they could not retain their magnetism for long. The existence of magnetic declination, the difference between magnetic north and true north, was first recognized by Shen Kuo in 1088.*[3]



An azimuth compass has visors of unequal height, allowing the sighting of objects above the horizon.

The first mention of a compass in Europe was in 1190 AD by Alexander Neckam. He described it as a common navigational aid for sailors, so the compass must have been introduced to Europe some time earlier. Whether the knowledge came from China to Europe, or was invented separately, is not clear. If the knowledge was transmitted, the most likely intermediary was Arab merchants, but Arabic literature does not mention the compass until after Neckam. There is also a difference in convention: Chinese compasses point south while European compasses point north.*[1]

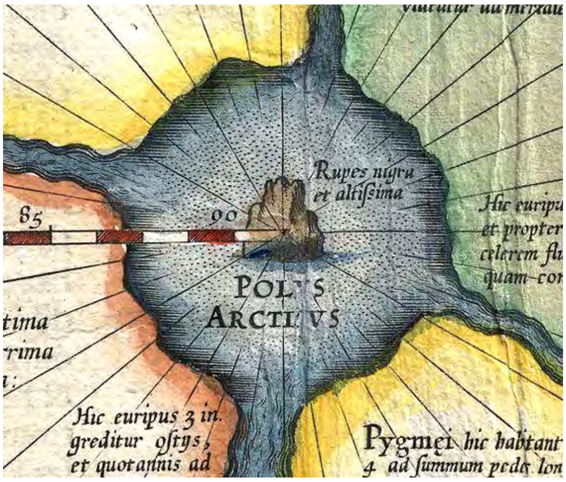
In 1269, Pierre de Maricourt (commonly referred to as *Petrus Peregrinus*) wrote a letter to a friend in which he described two kinds of compass, one in which an oval lodestone floated in a bowl of water, and the first dry compass with the needle mounted on a pivot. He also was the first to write about experiments with magnetism and describe the laws of attraction. An example is the experiment where a magnet is broken into two pieces and the two pieces can attract and repel each other (in modern terms, they both have north and south poles).*[7] This letter, generally referred to as *Epistola de Magnete*, was a landmark in the history of science.*[1]*[2]

Petrus Peregrinus assumed that compasses point towards true north. While his contemporary Roger Bacon is reputed to observe that compasses deviated from true north, the idea of magnetic declination was only gradually accepted. At first it was thought that the declination must be the result of systematic error. However, by the middle of the fifteenth century, sundials in Germany were oriented using corrections for declination.*[8]

2.2.2 Inclination

A compass must be balanced to counter the tendency of the needle to dip in the direction of the Earth's field. Otherwise, it will not spin freely. Often, compasses that are balanced for one latitude do not work as well at a different latitude. This problem was first reported by Georg Hartmann, a vicar in Nuremberg, in 1544. Robert Norman was the first to recognize that this occurs because the Earth's field itself is tilted from the vertical. In his book *The Newe Attractive*,*[9] Norman called inclination "a newe discouered secret and subtil propertie concernyng the Declinyng of the Needle." He created a compass in which the needle was floated in a goblet of water, attached to a cork to make it neutrally buoyant. The needle could orient itself in any direction, so it dipped to align itself with the Earth's field. Norman also created a dip circle, a compass needle pivoted about a horizontal axis, to measure the effect.*[4]*[8]

2.3 Early ideas about the source



Detail of a map by Mercator showing the "very high black rock" at the North Pole

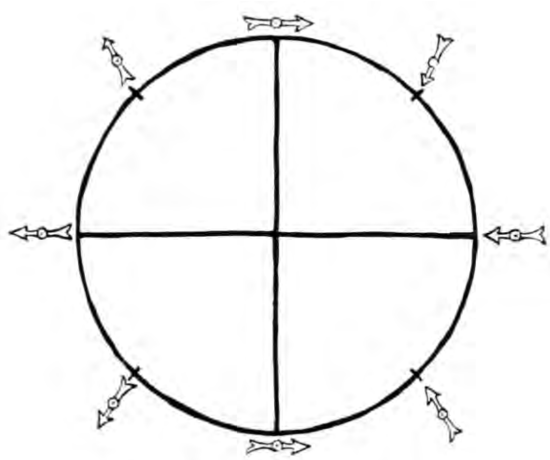
In early attempts to understand the Earth's magnetic field, measuring it was only part of the challenge. Understanding the measurements was also difficult because the mathematical and physical concepts had not yet been developed – in particular, the concept of a vector field that associates a vector with each point in space. The Earth's field is generally represented by field lines that run from pole to pole; the field at any point is parallel to a field line but does not have to point at either pole. As late as the eighteenth century, however, a natural philosopher would believe that a magnet had to be pointing directly at something. Thus, the Earth's magnetic field had to be explained by localized sources, and as more was learned about the Earth's field, these sources became increasingly complex.*[2]

At first, in both China and Europe, the source was assumed to be in the heavens – either the celestial poles or the Pole star. These theories required that magnets point at (or very close to) true north, so they ran into difficulty when the existence of declination was accepted. Then natural philosophers began to propose earthly sources such as a rock or mountain.*[2]

Legends about magnetic mountains go back to the classical era. Ptolemy recounted a legend about magnetic islands (now thought to be near Borneo) that exerted such a strong attraction on ships with nails that the ships were held in place and could not move. Even more dramatic was the Arab legend (recounted in *One Thousand and One Nights*) that a magnetic mountain could pull all the nails out of a ship, causing the ship to fall apart and founder. The story passed to Europe and became part of several epic tales.*[1]*[2]

Europeans started to place magnetic mountains on their maps in the sixteenth century. A notable example is Gerardus Mercator, whose famous maps included a magnetic mountain or two near the North Pole. At first, he just placed a mountain in an arbitrary location; but later he attempted to measure its location based on declinations from different locations in Europe. When subsequent measurements resulted in two contradictory estimates for the mountain, he simply placed two mountains on the map.*[2]*[8]

2.4 Beginnings of modern science



An illustration of compass directions at various latitudes on the Earth from de Magnete. *North is to the right.*

2.4.1 William Gilbert

> Magnus magnes ipse est globus terrestris.
> (The Earth itself is a great magnet.)
> —William Gilbert, *De Magnete*

1600 was a notable year for William Gilbert. He became president of the Royal College of Physicians of London, was appointed personal physician for Queen Elizabeth I, and wrote *De Magnete*, one of the books that mark the beginning of modern science. *De Magnete* is most famous for introducing (or at least popularizing) an experimental approach to science and deducing that the Earth is a great magnet.*[10]

Gilbert's book is divided into six chapters. The first is an introduction in which he discusses the importance of experiment and various facts about the Earth, including the insignificance of surface topography compared to the radius of the Earth. He also announces his deduction that the Earth is a great magnet. In book 2, Gilbert deals with "coition", or the laws of attraction. Gilbert distinguishes between magnetism and static electricity (the latter being induced by rubbing amber) and reports many experiments with both (some dating back to Peregrinus). One involves breaking a magnet in two and showing that both parts have a north and south pole.*[7] He also dismisses the idea of perpetual motion. The third book has a general description of magnetic directions along with details on how to magnetize a needle. He also introduces his *terella*, or "little Earth" . This is a magnetized sphere that he uses to model the magnetic properties of the Earth. In chapters 4 and 5 he goes into more detail about the two components of the direction, declination and inclination.*[11]*[12]

In the late 1590s Henry Briggs, a professor of geometry at Gresham College in London, had published a table of magnetic inclination with latitude for the earth. It agreed well with the inclinations that Gilbert measured around the circumference of his terella. Gilbert deduced that the Earth's magnetic field is equivalent to that of a uniformly magnetized sphere, magnetized parallel to the axis of rotation (in modern terms, a *geocentric axial dipole*). However, he was aware that declinations were not consistent with this model. Based on the declinations that were known at the time, he proposed that the continents, because of their raised topography, formed centers of attraction that made compass needles deviate. He even demonstrated this effect by gouging out some topography on his terella and measuring the effect on declinations. A Jesuit monk, Niccolò Cabeo, later took a leaf from Gilbert's book and showed that, if the topography was on the correct scale for the Earth, the differences between the highs and lows would only be about one tenth of a millimeter. Therefore, the continents could not noticeably affect the declination.*[11]*[12]

The sixth book of *de Magnete* was devoted to cosmology. He dismissed the prevailing Ptolemaic model of the universe, in which the planets and stars are organized in a series of concentric shells rotating about the Earth, on the grounds that the speeds involved would be absurdly large ("there cannot be diurnal motion of infinity").*[12] Instead, the Earth was rotating about its own axis. In place of the concentric shells, he proposed that the heavenly bodies interacted with each other and Earth through magnetic forces. Magnetism maintained the Earths position and made it rotate, while the magnetic attraction of the Moon drove the tides. Some obscure reasoning led to the peculiar conclusion that a terella, if freely suspended, would orient itself in the same direction as the Earth and rotate daily. Both Kepler and Galileo would adopt Gilbert's idea of magnetic attraction between heavenly bodies, but Newton's law of universal gravitation would render it obsolete.*[11]

2.4.2 Guillaume le Nautonier

In about 1603, the Frenchman Guillaume le Nautonier (William the Navigator),*[13] Sieur de Castelfranc, published a rival theory of the Earth's field in his book *Mecometrie de l'eymant (Measurement of longitude with a magnet)*. Le Nautonier was a mathematician, astronomer and Royal Geographer in the court of Henry IV. He disagreed with Gilbert's assumption that the Earth had to be magnetized parallel to the rotational axis, and instead produced a model in which the magnetic moment was tilted by 22.5° – in effect, the first tilted dipole model. The last 196 pages of his book were taken up with tables of latitudes and longitudes with declination and inclination for use by mariners. If his model had been accurate, it could have been used to determine both latitude and longitude using a combination of magnetic declination and astronomical observations.*[2]*[7]*[12]

Le Nautonier tried to sell his model to Henry IV, and his son to the English leader Oliver Cromwell, both without success. It was widely criticized, with Didier Dounot concluding that the work was based on "unfounded assumptions, errors in calculation and data manipulation" . However, the geophysicist Jean-Paul Poirier examined the works of both le Nautonier and Dounot, and found that the error was in Dounot's reasoning.*[7]

2.4.3 Temporal variation

Portrait of Edmond Halley holding an image of his concentric spheres theory.

One of Gilbert's conclusions was that the Earth's field could not vary in time. This was soon to be proved false by a series of measurements in London. In 1580, William

Borough measured the declination and found it to be $11\ {}^{1}\!/_{4}^{\circ}$ NE. In 1622, Edmund Gunter found it to be 5° 56' NE. He noted the difference from Borough's result but concluded that Borough must have made a measurement error. In 1633, Henry Gellibrand measured the declination in the same location and found it to be 4° 05' NE. Because of the care with which Gunther had made his measurements, Gellibrand was confident that the changes were real. In 1635 he published *A Discourse Mathematical on the Variation of the Magneticall Needle* stating that the declination had changed by more than 7° in 54 years. The reality of geomagnetic secular variation was rapidly accepted in England, where Gellibrand had a high reputation, but in other countries it was met with skepticism until it was confirmed by further measurements.*[2]*[14]

The observations of Gellibrand inspired extensive efforts to determine the nature of variation - global or local, predictable or erratic. It also inspired new models for the origin of the field. Henry Bond Senior gained notoriety by successfully predicting in 1639 that the declination would be zero in London in 1657. His model, which involved a precessing dipole, was strongly criticized by a royal commission, but it continued to be published in navigational instruction manuals for decades. Dynamic models involving multiple poles were also proposed by Peter Perkins (1680) and Edmond Halley (1683, 1692), among others. In Halley's model, the Earth consisted of concentric spheres. Two magnetic poles were on a fixed outer sphere and two more were on an inner sphere that rotated westwards, giving rise to a “westward drift”. Halley was so proud of this theory that a portrait of him at the age of eighty included a diagram of it.*[15]

2.5 Magnetic navigation

Detail of a world map published by Guillaume Brouscon in 1543, showing rhumb lines for navigation

Early mariners used portolan charts for navigation. These charts showed coastline with rhumb lines connecting ports. A mariner could navigate by aligning the chart with a compass and following the compass heading. Early charts had distorted coastlines because the cartographers did not know about declination, but the charts still worked because mariners were sailing in straight lines.*[8]

While boats mainly plied seas the size of the Mediterranean, rhumb lines were sufficient for navigation. However, when they ventured into the Atlantic and Pacific oceans, it was no longer sufficient to plot a straight-line course from one destination to another.*[16] Mariners needed to determine their latitude and longitude.

In the Age of Sail, dating from the sixteenth to the mid-nineteenth century, international trade was dominated by sailing ships. More than one European government offered a generous prize to the first person who could accurately determine longitude. The British prize, the longitude prize, led to the development of the marine chronometer by John Harrison, a clockmaker from Yorkshire.*[8]

2.6 See also

- History of geophysics
- Timeline of electromagnetic theory
- Rhumbline network

2.7 Notes and references

[1] Turner 2010, Chapter 1

[2] Jonkers 2003, Chapter 2

[3] Temple 2006, pp. 162–166

[4] Stern 2003, Section 2

[5] Jonkers 2003, Chapter 6

[6] Merrill, McElhinny & McFadden 1996, Chapter 2

[7] Courtillot & Le Mouël 2007

[8] Turner 2010, Chapter 2

[9] Norman, Robert (1974) [First published in 1581]. *The newe attractive*. Amsterdam: Theatrum Orbis Terrarum. ISBN 978-90-221-0616-7.

[10] Merrill, McElhinny & McFadden 1996

[11] Jonkers 2003, Chapter 3

[12] Turner 2010, Chapter3

[13] Some reputable sources (including Turner 2010, Chapter 3 and Jonkers 2003, Chapter 2) refer to him as Guillaume de Nautonier, which would translate as “William of Navigator”. Others, including Courtillot & Le Mouël 2007, refer to him as “le Nautonier” (“the navigator”).

[14] Turner 2010, Chapter 4

[15] Merrill 2010, Chapter 1

[16] An exception is Christopher Columbus, who used dead reckoning and a fixed compass direction (Pickering 2008).

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Chapter 3

Compass

This article is about the direction finding instrument used in navigation. For other uses, see Compass (disambiguation).

A **compass** is an instrument used for navigation and ori-

A simple dry magnetic portable compass

entation that shows direction relative to the geographic "cardinal directions", or "points". Usually, a diagram called a compass rose shows the directions north, south, east, and west on the compass face as abbreviated initials. When the compass is used, the rose can be aligned with the corresponding geographic directions, so, for example, the "N" mark on the rose really points to the north. Frequently, in addition to the rose or sometimes instead of it, angle markings in degrees are shown on the compass. North corresponds to zero degrees, and the angles increase clockwise, so east is 90 degrees, south is 180, and west is 270. These numbers allow the compass to show azimuths or bearings, which are commonly stated in this notation.

The magnetic compass was first invented as a device for divination as early as the Chinese Han Dynasty (since about 206 BC),*[1]*[2] and later adopted for navigation by the Song Dynasty Chinese during the 11th century.*[3]*[4]*[5] The first usage of a compass recorded in Western Europe and the Islamic world occurred around the early 13th century.*[6]*[7]

A smartphone that can be used as a compass because of the magnetometer inside.

3.1 Magnetic compass

The magnetic compass is the most familiar compass type. It functions as a pointer to "magnetic north", the local magnetic meridian, because the magnetized needle at its heart aligns itself with the horizontal component of the Earth's magnetic field. The magnetic field exerts a torque on the needle, pulling the North end or *pole* of the needle approximately toward the Earth's North magnetic pole, and pulling the other toward the Earth's South magnetic pole.*[8] The needle is mounted on a low-friction pivot point, in better compasses a jewel bearing, so it can turn easily. When the compass is held level, the needle turns until, after a few seconds to allow oscillations to die out,

A military compass that was used during World War I

it settles into its equilibrium orientation.

In navigation, directions on maps are usually expressed with reference to geographical or true north, the direction toward the Geographical North Pole, the rotation axis of the Earth. Depending on where the compass is located on the surface of the Earth the angle between true north and magnetic north, called magnetic declination can vary widely with geographic location. The local magnetic declination is given on most maps, to allow the map to be oriented with a compass parallel to true north. The location of the Earth's magnetic poles slowly change with time, which is referred to as geomagnetic secular variation. The effect of this means a map with the latest declination information should be used.*[9] Some magnetic compasses include means to manually compensate for the magnetic declination, so that the compass shows true directions.

3.2 History

Main article: History of the compass

The first compasses in ancient Han dynasty China were made of lodestone, a naturally magnetized ore of iron.*[2] The compass was later used for navigation during the Song Dynasty of the 11th century.*[10] Later compasses were made of iron needles, magnetized by striking them with a lodestone. Dry compasses began to appear around 1300 in Medieval Europe and the Islamic world.*[11]*[7] This was supplanted in the early 20th century by the liquid-filled magnetic compass.*[12]

3.3 Modern compasses

A liquid-filled protractor or orienteering compass with lanyard

3.3.1 Magnetic compass

Modern compasses usually use a magnetized needle or dial inside a capsule completely filled with a liquid (lamp oil, mineral oil, white spirits, purified kerosene, or ethyl alcohol is common). While older designs commonly incorporated a flexible rubber diaphragm or airspace inside the capsule to allow for volume changes caused by temperature or altitude, some modern liquid compasses utilize smaller housings and/or flexible capsule materials to accomplish the same result.*[13] The liquid inside the capsule serves to damp the movement of the needle, reducing oscillation time and increasing stability. Key points on the compass, including the north end of the needle are often marked with phosphorescent, photoluminescent, or self-luminous materials*[14] to enable the compass to be read at night or in poor light. As the compass fill liquid is noncompressible under pressure, many ordinary liquid-filled compasses will operate accurately underwater to considerable depths.

Many modern compasses incorporate a baseplate and protractor tool, and are referred to variously as "orienteering", “baseplate”, “map compass” or “protractor” designs. This type of compass uses a separate magnetized needle inside a rotating capsule, an orienting “box” or gate for aligning the needle with magnetic north, a transparent base containing map orienting lines, and a bezel (outer dial) marked in degrees or other units of angular measurement.*[15] The capsule is mounted in a transparent baseplate containing a *direction-of-travel* (DOT) indicator for use in taking bearings directly from a map.*[15]

Cammenga air filled lensatic compass

Other features found on modern orienteering compasses are map and romer scales for measuring distances and plotting positions on maps, luminous markings on the face or bezels, various sighting mechanisms (mirror, prism, etc.) for taking bearings of distant objects with greater precision, “global” needles for use in differing hemispheres, adjustable declination for obtaining instant true bearings without resorting to arithmetic, and devices such as inclinometers for measuring gradients.*[16] The sport of orienteering has also resulted in the development of models with extremely fast-settling and stable needles for optimal use with a topographic map, a land navigation technique known as *terrain association*.*[17]

The military forces of a few nations, notably the United States Army, continue to issue field compasses with magnetized compass dials or cards instead of needles. A magnetic card compass is usually equipped with an optical, lensatic, or prismatic sight, which allows the user to read the bearing or azimuth off the compass card while simultaneously aligning the compass with the objective (see photo). Magnetic card compass designs normally require a separate protractor tool in order to take bearings directly from a map.*[18]*[19]

The U.S. M-1950 military lensatic compass does not use a liquid-filled capsule as a damping mechanism, but rather electromagnetic induction to control oscillation of it magnetized card. A “deep-well” design is used to allow the compass to be used globally with a card tilt of up to 8 degrees without impairing accuracy.*[20] As induction forces provide less damping than fluid-filled designs, a needle lock is fitted to the compass to reduce wear, operated by the folding action of the rear sight/lens holder. The use of air-filled induction compasses has declined over the years, as they may become inoperative or inaccurate in freezing temperatures or extremely humid environments due to condensation or water ingress.*[21]

Some military compasses, like the U.S. M-1950 (Cammenga 3H) military lensatic compass, the Silva 4b *Militaire*, and the Suunto M-5N(T) contain the radioactive material tritium ($_1H^3$) and a combination of phosphors.*[22] The U.S. M-1950 equipped with self-luminous lighting contains 120 mCi (millicuries) of tritium. The purpose of the tritium and phosphors is to provide illumination for the compass, via radioluminescent tritium illumination, which does not require the compass to be “recharged” by sunlight or artificial light.*[23] However, tritium has a half-life of only about 12 years,*[24] so a compass that contains 120 mCi of tritium when new will contain only 60 when it is 12 years old, 30 when it is 24 years old, and so on. Consequently, the illumination of the display will fade.

Mariner's compasses can have two or more magnets permanently attached to a compass card, which moves freely on a pivot. A *lubber line*, which can be a marking on the compass bowl or a small fixed needle, indicates the ship's heading on the compass card. Traditionally the card is divided into thirty-two points (known as *rhumbs*), although modern compasses are marked in degrees rather than cardinal points. The glass-covered box (or bowl) contains a suspended gimbal within a binnacle. This preserves the horizontal position.

Thumb compass

Main article: Thumb compass

A **thumb compass** is a type of compass commonly used

Thumb compass on left

in orienteering, a sport in which map reading and terrain association are paramount. Consequently, most thumb compasses have minimal or no degree markings at all, and are normally used only to orient the map to magnetic north. Thumb compasses are also often transparent so that an orienteer can hold a map in the hand with the compass and see the map through the compass.

3.3.2 Gyrocompass

Main article: Gyrocompass

A *gyrocompass* is similar to a gyroscope. It is a non-magnetic compass that finds true north by using an (electrically powered) fast-spinning wheel and friction forces in order to exploit the rotation of the Earth. Gyrocompasses are widely used on ships. They have two main advantages over magnetic compasses:

- they find *true north*, i.e., the direction of Earth's rotational axis, as opposed to magnetic north,
- they are not affected by ferromagnetic metal (including iron, steel, cobalt, nickel, and various alloys) in a ship's hull. (No compass is affected by nonferromagnetic metal, although a magnetic compass will be affected by any kind of wires with electric current passing through them.)

Large ships typically rely on a gyrocompass, using the magnetic compass only as a backup. Increasingly, electronic fluxgate compasses are used on smaller vessels. However, magnetic compasses are still widely in use as they can be small, use simple reliable technology, are comparatively cheap, are often easier to use than GPS, require no energy supply, and unlike GPS, are not affected by objects, e.g. trees, that can block the reception of electronic signals.

3.3.3 Solid state compasses

Main article: Magnetometer

Small compasses found in clocks, mobile phones, and other electronic devices are solid-state compasses, usually built out of two or three magnetic field sensors that provide data for a microprocessor. The correct heading relative to the compass is calculated using trigonometry.

Often, the device is a discrete component which outputs either a digital or analog signal proportional to its orientation. This signal is interpreted by a controller or microprocessor and either used internally, or sent to a display unit. The sensor uses highly calibrated internal electronics to measure the response of the device to the Earth's magnetic field.

3.3.4 GPS receivers used as compasses

GPS receivers using two or more antennae mounted separately and blending the data with an inertial motion unit (IMU) can now achieve 0.02° in heading accuracy and have startup times in seconds rather than hours for gyrocompass systems. The devices accurately determine the positions (latitudes, longitudes and altitude) of the antennae on the Earth, from which the cardinal directions can be calculated. Manufactured primarily for maritime and aviation applications, they can also detect pitch and roll of ships. Small, portable GPS receivers with only a single antenna can also determine directions if they are being moved, even if only at walking pace. By accurately determining its position on the Earth at times a few seconds apart, the device can calculate its speed and the true bearing (relative to *true north*) of its direction of motion. Frequently, it is preferable to measure the direction in which a vehicle is actually moving, rather than its heading, i.e. the direction in which its nose is pointing. These directions may be different if there is a crosswind or tidal current.

GPS compasses share the main advantages of gyrocompasses. They determine true North, as opposed to magnetic North, and they are unaffected by perturbations of the Earth's magnetic field. Additionally, compared with gyrocompasses, they are much cheaper, they work better in polar regions, they are less prone to be affected by mechanical vibration, and they can be initialized far more quickly. However, they depend on the functioning of, and communication with, the GPS satellites, which might be disrupted by an electronic attack or by the effects of a severe solar storm. Gyrocompasses remain in use for military purposes (especially in submarines, where magnetic and GPS compasses are useless), but have been largely superseded by GPS compasses, with magnetic backups, in civilian contexts.

3.3.5 Specialty compasses

A standard Brunton Geo, used commonly by geologists

Apart from navigational compasses, other specialty compasses have also been designed to accommodate specific uses. These include:

- Qibla compass, which is used by Muslims to show the direction to Mecca for prayers.
- Optical or prismatic hand-bearing compass, most often used by surveyors, but also by cave explorers, foresters, and geologists. These compasses generally use a liquid-damped capsule*[25] and magnetized floating compass dial with an integral optical sight, often fitted with built-in photoluminescent or battery-powered illumination.*[26] Using the optical sight, such compasses can be read with extreme accuracy when taking bearings to an object, often to fractions of a degree. Most of these compasses are designed for heavy-duty use, with high-quality needles and jeweled bearings, and many are fitted for tripod mounting for additional accuracy.*[26]
- Trough compasses, mounted in a rectangular box whose length was often several times its width, date back several centuries. They were used for land surveying, particularly with plane tables.

3.3.6 Limitations of the magnetic compass

The magnetic compass is very reliable at moderate latitudes, but in geographic regions near the Earth's magnetic poles it becomes unusable. As the compass is moved closer to one of the magnetic poles, the magnetic declination, the difference between the direction to geographical north and magnetic north, becomes greater and greater. At some point close to the magnetic pole the compass will not indicate any particular direction but will begin to drift. Also, the needle starts to point up or down when getting closer to the poles, because of the so-called magnetic inclination. Cheap compasses with bad bearings may get stuck because of this and therefore indicate a wrong direction.

Magnetic compasses are influenced by any fields other than Earth's. Local environments may contain magnetic mineral deposits and artificial sources such as MRIs, large iron or steel bodies, electrical engines or strong permanent magnets. Any electrically conductive body produces its own magnetic field when it is carrying an electric current. Magnetic compasses are prone to errors in the neighborhood of such bodies. Some compasses include magnets which can be adjusted to compensate for external magnetic fields, making the compass more reliable and accurate.

A compass is also subject to errors when the compass is accelerated or decelerated in an airplane or automobile. Depending on which of the Earth's hemispheres the compass is located and if the force is acceleration or deceleration the compass will increase or decrease the indicated heading. Compasses that include compensating magnets are especially prone to these errors, since accelerations tilt the needle, bringing it closer or further from the magnets.

Another error of the mechanical compass is turning error. When one turns from a heading of east or west the compass will lag behind the turn or lead ahead of the turn. Magnetometers, and substitutes such as gyrocompasses, are more stable in such situations.

3.4 Construction of a magnetic compass

3.4.1 Magnetic needle

A magnetic rod is required when constructing a compass. This can be created by aligning an iron or steel rod with Earth's magnetic field and then tempering or striking it. However, this method produces only a weak magnet so other methods are preferred. For example, a magnetised rod can be created by repeatedly rubbing an iron rod with a magnetic lodestone. This magnetised rod (or magnetic needle) is then placed on a low friction surface to allow it to freely pivot to align itself with the magnetic field. It is then labeled so the user can distinguish the north-pointing from the south-pointing end; in modern convention the north end is typically marked in some way.

3.4.2 Needle-and-bowl device

If a needle is rubbed on a lodestone or other magnet, the needle becomes magnetized. When it is inserted in a cork or piece of wood, and placed in a bowl of water it becomes a compass. Such devices were universally used as compass until the invention of the box-like compass with a 'dry' pivoting needle sometime around 1300.

3.4.3 Points of the compass

Main article: Points of the compass

Originally, many compasses were marked only as to the direction of magnetic north, or to the four cardinal points (north, south, east, west). Later, these were divided, in China into 24, and in Europe into 32 equally spaced points around the compass card. For a table of the thirty-two points, see compass points.

In the modern era, the 360-degree system took hold. This system is still in use today for civilian navigators. The degree system spaces 360 equidistant points located clockwise around the compass dial. In the 19th century some European nations adopted the "grad" (also called grade or gon) system instead, where a right angle is 100 grads to give a circle of 400 grads. Dividing grads into tenths to give a circle of 4000 decigrades has also been used in armies.

Wrist compass of the Soviet Army with counterclockwise double graduation: 60° (like a watch) and 360°

Most military forces have adopted the French "millieme" system. This is an approximation of a milli-radian (6283 per circle), in which the compass dial is spaced into 6400 units or “mils” for additional precision when measuring angles, laying artillery, etc. The value to the military is that one angular mil subtends approximately one metre at a distance of one kilometer. Imperial Russia used a system derived by dividing the circumference of a circle into chords of the same length as the radius. Each of these was divided into 100 spaces, giving a circle of 600. The Soviet Union divided these into tenths to give a circle of 6000 units, usually translated as “mils” . This system was adopted by the former Warsaw Pact countries (e.g. Soviet Union, East Germany), often counterclockwise (see picture of wrist compass). This is still in use in Russia.

3.4.4 Compass balancing (magnetic dip)

Because the Earth's magnetic field's inclination and intensity vary at different latitudes, compasses are often balanced during manufacture so that the dial or needle will be level, eliminating needle drag which can give inaccurate readings. Most manufacturers balance their compass needles for one of five zones, ranging from zone 1, covering most of the Northern Hemisphere, to zone 5 covering Australia and the southern oceans. This individual zone balancing prevents excessive dipping of one end of the needle which can cause the compass card to stick and give false readings.*[27]

Some compasses feature a special needle balancing system that will accurately indicate magnetic north regardless of the particular magnetic zone. Other magnetic compasses have a small sliding counterweight installed on the needle itself. This sliding counterweight, called a 'rider', can be used for counterbalancing the needle against the dip caused by inclination if the compass is taken to a zone with a higher or lower dip.*[27]

3.4.5 Compass correction

Main article: Magnetic deviation

Like any magnetic device, compasses are affected by

A binnacle containing a ship's standard compass, with the two iron balls which correct the effects of ferromagnetic materials. This unit is on display in a museum.

nearby ferrous materials, as well as by strong local electromagnetic forces. Compasses used for wilderness land navigation should not be used in proximity to ferrous metal objects or electromagnetic fields (car electrical systems, automobile engines, steel pitons, etc.) as that can affect their accuracy.*[28] Compasses are particularly difficult to use accurately in or near trucks, cars or other mechanized vehicles even when corrected for deviation by the use of built-in magnets or other devices. Large amounts of ferrous metal combined with the on-and-off electrical fields caused by the vehicle's ignition and charging systems generally result in significant compass errors.

At sea, a ship's compass must also be corrected for errors, called deviation, caused by iron and steel in its structure and equipment. The ship is *swung*, that is rotated about a fixed point while its heading is noted by alignment with fixed points on the shore. A compass deviation card is prepared so that the navigator can convert between compass and magnetic headings. The compass can be corrected in three ways. First the lubber line can be adjusted so that it is aligned with the direction in which the ship travels, then the effects of permanent magnets can be corrected for by small magnets fitted within the case of the compass. The effect of ferromagnetic materials in the compass's environment can be corrected by two iron balls mounted on either side of the compass binnacle. The coefficient a_0 representing the error in the lubber line, while a_1, b_1 the ferromagnetic effects and a_2, b_2 the non-ferromagnetic component.*[29]

A similar process is used to calibrate the compass in light general aviation aircraft, with the compass deviation card often mounted permanently just above or below the magnetic compass on the instrument panel. Fluxgate electronic compasses can be calibrated automatically, and can also be programmed with the correct local compass variation so as to indicate the true heading.

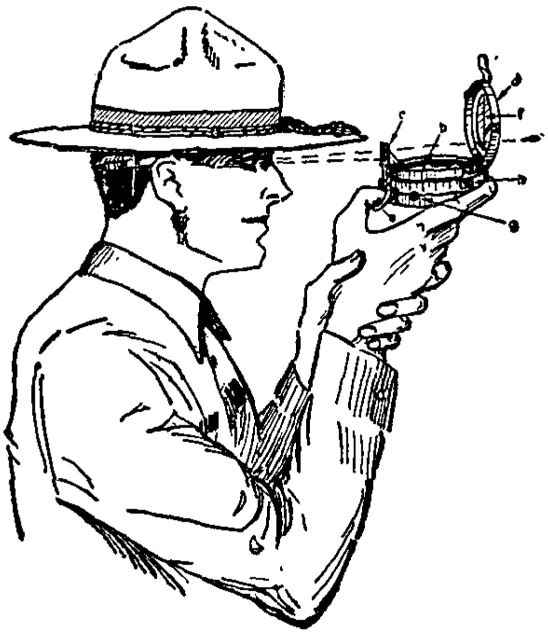
3.5 Using a magnetic compass

Turning the compass scale on the map (D – the local magnetic declination)

When the needle is aligned with and superimposed over the outlined orienting arrow on the bottom of the capsule, the degree figure on the compass ring at the direction-of-travel (DOT) indicator gives the magnetic bearing to the target (mountain).

A magnetic compass points to magnetic north pole, which is approximately 1,000 miles from the true geographic North Pole. A magnetic compass's user can determine true North by finding the magnetic north and then correcting for variation and deviation. Variation is defined as the angle between the direction of true (geographic) north and the direction of the meridian between the magnetic poles. Variation values for most of the oceans had been calculated and published by 1914.*[30] Deviation refers to the response of the compass to local magnetic fields caused by the presence of iron and electric currents; one can partly compensate for these by careful location of the compass and the placement of compensating magnets under the compass itself. Mariners have long known that these measures do not completely cancel deviation; hence, they performed an additional step by measuring the compass bearing of a landmark with a known magnetic bearing. They then pointed their ship to the next compass point and measured again, graphing their results. In this way, correction tables could be created, which would be consulted when compasses were used when traveling in those locations.

Mariners are concerned about very accurate measurements; however, casual users need not be concerned with differences between magnetic and true North. Except in areas of extreme magnetic declination variance (20 degrees or more), this is enough to protect from walking in a substantially different direction than expected over short distances, provided the terrain is fairly flat and visibility is not impaired. By carefully recording distances (time or paces) and magnetic bearings traveled, one can plot a course and return to one's starting point using the compass alone.*[31]



Soldier using a prismatic compass to get an azimuth

Compass navigation in conjunction with a map (*terrain association*) requires a different method. To take a map bearing or *true bearing* (a bearing taken in reference to true, not magnetic north) to a destination with a protractor compass, the edge of the compass is placed on the map so that it connects the current location with the desired destination (some sources recommend physically drawing a line). The orienting lines in the base of the compass dial are then rotated to align with actual or true north by aligning them with a marked line of longitude (or the vertical margin of the map), ignoring the compass needle entirely.*[32] The resulting *true bearing* or map bearing may then be read at the degree indicator or direction-of-travel (DOT) line, which may be followed as an *azimuth* (course) to the destination. If a *magnetic* north bearing or *compass bearing* is desired, the compass must be adjusted by the amount of magnetic declination before using the bearing so that both map and compass are in agreement.*[32] In the given example, the large mountain in the second photo was selected as the target destination on the map. Some compasses allow the scale to be adjusted to compensate for the local magnetic declination; if adjusted correctly, the compass will give the true bearing instead of the magnetic bearing.

The modern hand-held protractor compass always has an additional direction-of-travel (DOT) arrow or indicator inscribed on the baseplate. To check one's progress along a course or azimuth, or to ensure that the object in view is indeed the destination, a new compass reading may be taken to the target if visible (here, the large mountain). After pointing the DOT arrow on the baseplate at the target, the compass is oriented so that the needle is superimposed over the orienting arrow in the capsule. The resulting bearing indicated is the magnetic bearing to the target. Again, if one is using "true" or map bearings, and the compass does not have preset, pre-adjusted declination, one must additionally add or subtract magnetic declination to convert the *magnetic bearing* into a *true bearing*. The exact value of the magnetic declination is place-dependent and varies over time, though declination is frequently given on the map itself or obtainable on-line from various sites. If the hiker has been following the correct path, the compass' corrected (true) indicated bearing should closely correspond to the true bearing previously obtained from the map.

A compass should be laid down on a level surface so that the needle only rests or hangs on the bearing fused to the compass casing – if used at a tilt, the needle might touch the casing on the compass and not move freely, hence not pointing to the magnetic north accurately, giving a faulty reading. To see if the needle is well leveled, look closely at the needle, and tilt it slightly to see if the needle is swaying side to side freely and the needle is not contacting the casing of the compass. If the needle tilts to one direction, tilt the compass slightly and gently to the opposing direction until the compass needle is horizontal, lengthwise. Items to avoid around compasses are magnets of any kind and any electronics. Magnetic fields from electronics can easily disrupt the needle, preventing it from aligning with the Earth's magnetic fields, causing inaccurate readings. The Earth's natural magnetic forces are considerably weak, measuring at 0.5 Gauss and magnetic fields from household electronics can easily exceed it, overpowering the compass needle. Exposure to strong magnets, or magnetic interference can sometimes cause the magnetic poles of the compass needle to differ or even reverse. Avoid iron rich deposits when using a compass, for example, certain rocks which contain magnetic minerals, like Magnetite. This is often indicated by a rock with a surface which is dark and has a metallic luster, not all magnetic mineral bearing rocks have this indication. To see if a rock or an area is causing interference on a compass, get out of the area, and see if the needle on the compass moves. If it does, it means that the area or rock the compass was previously at is causing interference and should be avoided.

3.6 See also

- Absolute bearing
- Aircraft compass turns
- Astrocompass
- Beam compass
- Binnacle
- Boxing the compass
- Brunton compass
- Coordinates
- Earth inductor compass
- Fibre optic gyrocompass
- Fluxgate compass
- Geological compass
- Gyrocompass
- Hand compass
- Inertial navigation system
- Magnetic declination
- Magnetic deviation
- Magnetic dip
- Marching line
- Pelorus (instrument)
- Radio compass
- Radio direction finder
- Relative bearing
- Solar compass
- Wrist compass

3.7 Notes

[1] Li Shu-hua, p. 176

[2] Lowrie, William (2007). *Fundamentals of Geophysics*. London: Cambridge University Press. p. 281. ISBN 978-0-521-67596-3. Early in the Han Dynasty, between 300-200 BC, the Chinese fashioned a rudimentary compass out of lodestone... the compass may have been used in the search for gems and the selection of sites for houses... their directive power led to the use of compasses for navigation

[3] Kreutz, p. 367

[4] Needham, p. 252

[5] Li Shu-hua, p. 182f.

[6] Kreutz, p. 370

[7] Schmidl, Petra G. (2014-05-08). "Compass". In Ibrahim Kalin. *The Oxford Encyclopedia of Philosophy, Science, and Technology in Islam*. Oxford University Press. pp. 144–6. ISBN 978-0-19-981257-8.

[8] The magnetic lines of force in the Earth's field do not accurately follow great circles around the planet, passing exactly over the magnetic poles. Therefore the needle of a compass only approximately points to the magnetic poles.

[9] "Declination Adjustment on a Compass – REI Expert Advice". *Rei.com*. Retrieved 2015-06-06.

[10] Merrill, Ronald T.; McElhinny, Michael W. (1983). *The Earth's magnetic field: Its history, origin and planetary perspective* (2nd printing ed.). San Francisco: Academic press. p. 1. ISBN 0-12-491242-7.

[11] Lane, p. 615

[12] W. H. Creak: "The History of the Liquid Compass", *The Geographical Journal*, Vol. 56, No. 3 (1920), pp. 238-239

[13] *Gear Review: Kasper & Richter Alpin Compass*, Ocean-MountainSky.Com

[14] Nemoto & Co. Ltd., Article: In addition to ordinary phosphorescent luminous paint (zinc sulfide), brighter photoluminescent coatings which include radioactive isotopes such as Strontium-90, usually in the form of strontium aluminate, or tritium, which is a radioactive isotope of hydrogen are now being used on modern compasses. Tritium has the advantage that its radiation has such low energy that it cannot penetrate a compass housing.

[15] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. p. 110. ISBN 0-07-139303-X.

[16] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. pp. 110–111. ISBN 0-07-139303-X.

[17] Kjernsmo, Kjetil, '[www.learn-orienteering.org/old/buying.html How to use a Compass]*, retrieved 8 April 2012*

[18] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. p. 112. ISBN 0-07-139303-X.

[19] U.S. Army, *Map Reading and Land Navigation*, FM 21-26, Headquarters, Dept. of the Army, Washington, D.C. (7 May 1993), ch. 11, pp. 1-3: Any 'floating card' type compass with a straightedge or centerline axis can be used to read a map bearing by orienting the map to magnetic north using a drawn magnetic azimuth, but the process is far simpler with a protractor compass.

[20] 'Article MIL-PRF-10436N*, rev. 31 October 2003, Washington, D.C.: U.S. Dept. of Defense*

[21] Kearny, Cresson H., *Jungle Snafus...And Remedies*, Oregon Institute Press (1996), ISBN 1-884067-10-7, pp. 164-170: In 1989, one U.S. Army jungle infantry instructor reported that about 20% of the issue lensatic compasses in his company used in a single jungle exercise in Panama were ruined within three weeks by rain and humidity.

[22] Ministry of Defence, *Manual of Map Reading and Land Navigation*, HMSO Army Code 70947 (1988), ISBN 0-11-772611-7, ISBN 978-0-11-772611-6, ch. 8, sec. 26, pp. 6-7; ch. 12, sec. 39, p. 4

[23] "Military Compass". Orau.org. Retrieved 2009-06-30.

[24] CRC Handbook of Chemistry and Physics. page B247

[25] Kramer, Melvin G., U.S. Patent No. 4175333, *Magnetic Compass*, Riverton, Wyoming: The Brunton Company, pub. 27 November 1979: The *Brunton Pocket Transit*, which uses magnetic induction damping, is an exception.

[26] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. pp. 113–114. ISBN 0-07-139303-X.

[27] Global compasses, MapWorld.

[28] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. p. 122. ISBN 0-07-139303-X.

[29] Lushnikov, E. (December 2015). "Magnetic Compass in Modern Maritime Navigation". *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation*. Gdynia, Poland: Faculty of Navigation, Gdynia Maritime University. **9** (4): 539–543. doi:10.12716/1001.09.04.10. ISSN 2083-6481. Retrieved 11 February 2016.

[30] Wright, Monte, Most Probable Position, University Press of Kansas, Lawrence, 1972, p.7

[31] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. p. 149. ISBN 0-07-139303-X.

[32] Johnson, G. Mark (2003-03-26). *The Ultimate Desert Handbook*. McGraw-Hill Professional. pp. 134–135. ISBN 0-07-139303-X.

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3.9 External links

- Handbook of Magnetic Compass Adjustment
- How to Make a Compass Demonstration from the National High Magnetic Field Laboratory
- Compass in a Magnetic Field: Interactive Tutorial National High Magnetic Field Laboratory
- Paul J. Gans, The Medieval Technology Pages: Compass
- Evening Lecture To The British Association At The Southampton Meeting on Friday, August 25, 1882. Refers to compass correction by Fourier series.

Chapter 4

Magnetic dip

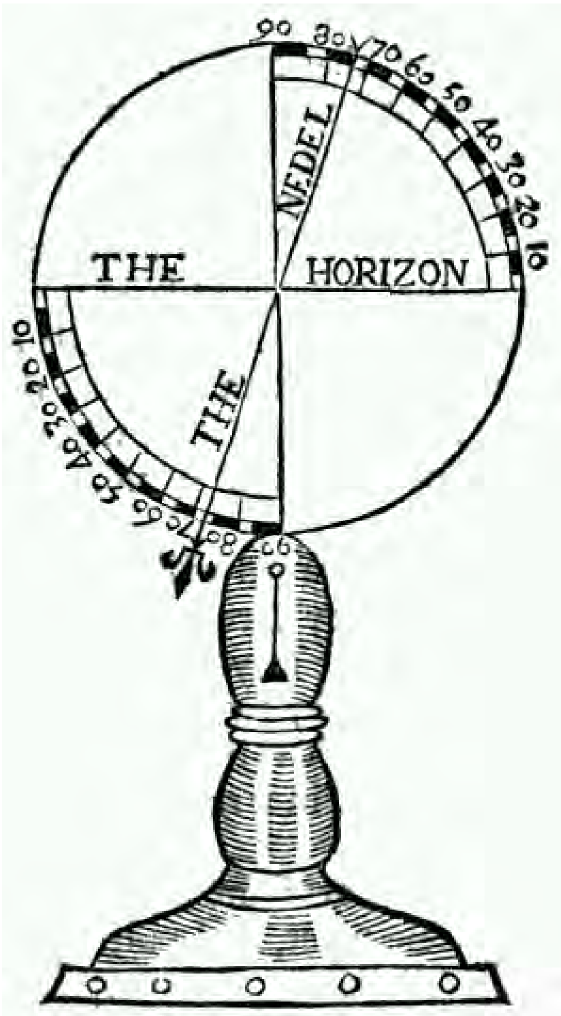
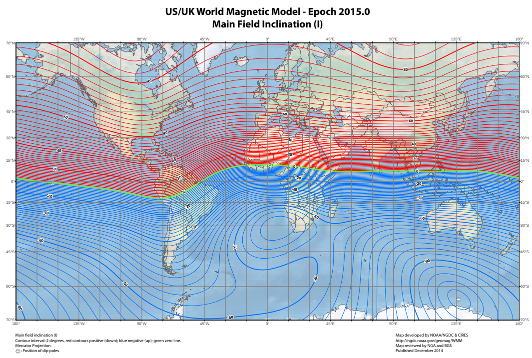


Illustration of magnetic dip from Norman's book, The Newe Attractive

Magnetic dip, **dip angle,** or **magnetic inclination** is the angle made with the horizontal by the Earth's magnetic field lines. This angle varies at different points on the Earth's surface. Positive values of inclination indicate that the magnetic field of the Earth is pointing downward, into the Earth, at the point of measurement, and negative values indicate that it is pointing upward. The dip angle is in principle the angle made by the needle of a vertically held compass, though in practice ordinary compass needles may be weighted against dip or may be unable to move freely in the correct plane. The value can be measured more reliably with a special instrument typically known as a dip circle.

Dip angle was discovered by the engineer Georg Hartmann in 1544.*[1] A method of measuring it with a dip circle was described by Robert Norman in England in 1581.*[2]

4.1 Explanation



Isoclinic lines for the year 2015.

Magnetic dip results from the tendency of a magnet to align itself with lines of force. As the Earth's magnetic lines of force are not parallel to the surface, the north end of a compass needle will point downward in the northern hemisphere (positive dip) or upward in the southern hemisphere (negative dip). The range of dip is from −90 degrees (at the South Magnetic Pole) to +90 degrees (at the North Magnetic Pole). Contour lines along which the dip measured at the Earth's surface is equal are referred to as isoclinic lines. The locus of the points having zero dip is called the *magnetic equator* or aclinic line.*[3]

4.2 Practical importance

The phenomenon is especially important in aviation, as it causes the airplane's compass to give erroneous readings during banked turns and airspeed changes. The latter errors occur because the compass card tilts on its mount when under acceleration.*[4]

Compass needles are often weighted during manufacture to compensate for magnetic dip, so that they will balance roughly horizontally. This balancing is latitude-dependent; see Compass balancing (magnetic dip).

4.3 See also

Geomagnetism – Wikipedia book

- Aircraft compass turns
- South Atlantic Anomaly
- Magnetic declination

4.4 References

[1] Charles Murray (2003). *Human Accomplishment* (First ed.). p. 176.

[2] Norman, Robert (1581). *The newe attractive: shewing the nature, propertie, and manifold vertues of the loadstone: with the declination of the needle, touched therewith under the plaine of the horizon*.

[3] James Wood, ed. (1907) [1900]. "Aclinic Line". *The Nuttall Encyclopædia*.

[4] *Instrument Flying Handbook: FAA-H-8083-15B*. Federal Aviation Administration, US Department of Transportation. 2014. pp. 5–13,5–14.

4.5 External links

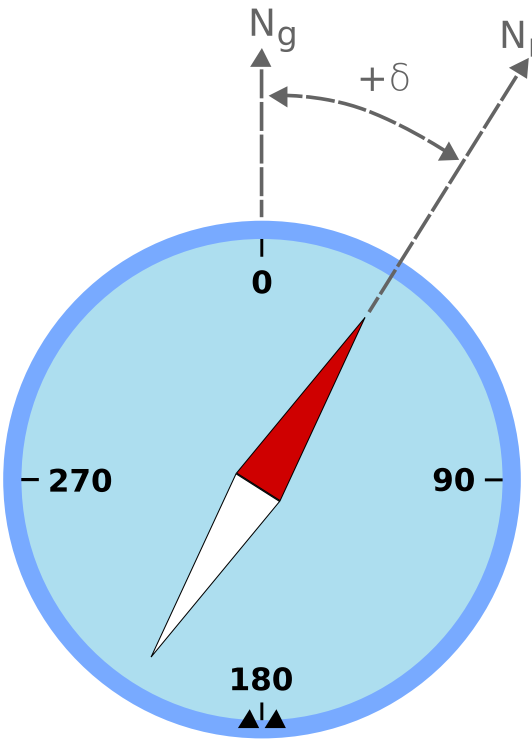
- Compass errors
- Look up magnetic dip values

Chapter 5

Magnetic declination

“Magnetic North” redirects here. For other uses, see Magnetic North (disambiguation).

Magnetic declination or **variation** is the angle on the horizontal plane between magnetic north (the direction the north end of a compass needle points, corresponding to the direction of the Earth's magnetic field lines) and true north (the direction along a meridian towards the geographic North Pole). This angle varies depending on position on the Earth's surface, and changes over time.



Example of magnetic declination showing a compass needle with a “positive” (or “easterly”) variation from geographic north. N_g is geographic or true north, N_m is magnetic north, and δ is magnetic declination

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.” *[1]

By convention, declination is positive when magnetic north is east of true north, and negative when it is to the west. *Isogonic lines* are lines on the Earth's surface along which the declination has the same constant value, and lines along which the declination is zero are called *agonic lines*. The lowercase Greek letter δ (delta) is frequently used as the symbol for magnetic declination.

The term **magnetic deviation** is sometimes used loosely to mean the same as magnetic declination, but more correctly it refers to the error in a compass reading induced by nearby metallic objects, such as iron on board a ship or aircraft.

Magnetic declination should not be confused with **magnetic inclination**, also known as magnetic dip, which is the angle that the Earth's magnetic field lines make with the downward side of the horizontal plane.

5.1 Declination change over time and location

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 16 degrees west in Maine, to 6 in Florida, to 0 degrees in Louisiana, to 4 degrees east (in Texas). The declination at London, UK is one degree 7 minutes west (2014), and as the country is quite small that figure is fairly good for the whole of the country. It is reducing, and scientists predict that in about 2050 it will be zero.*[2]

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.

As an example of how variation changes over time, see the two charts of the same area (western end of Long Island Sound), below, surveyed 124 years apart. The 1884 chart shows a variation of 8 degrees, 20 minutes West. The 2008 chart shows 13 degrees, 15 minutes West.

5.2 Determining declination

5.2.1 Direct measurement

The magnetic declination at any particular place can be measured directly by reference to the celestial poles—the points in the heavens around which the stars appear to revolve, which mark the direction of true north and true south. The instrument used to perform this measurement is known as a *declinometer*.

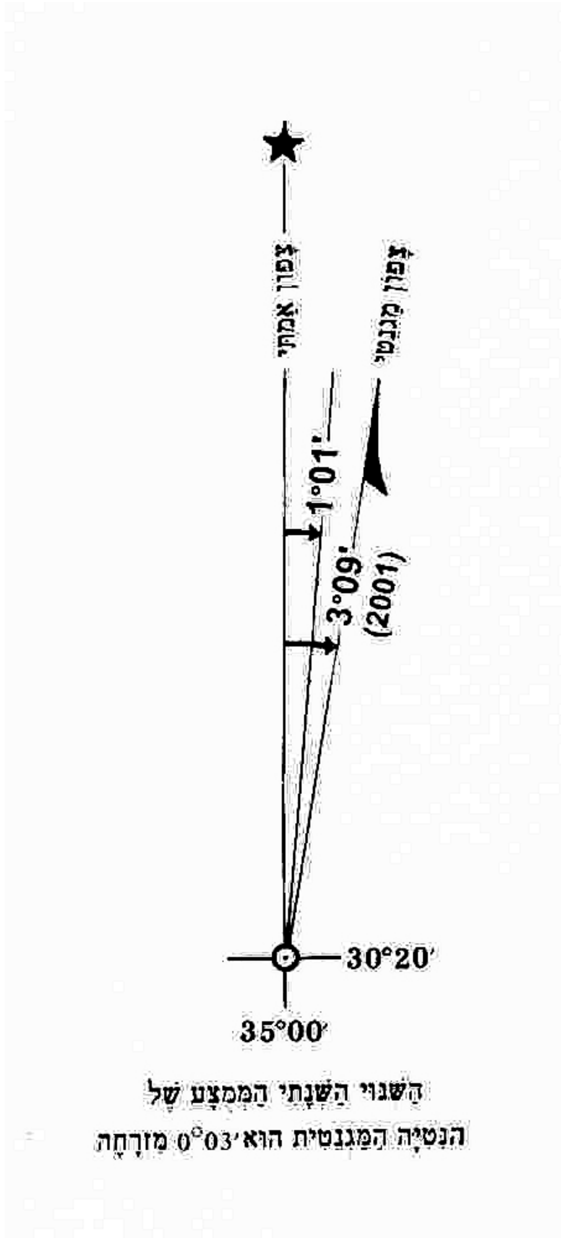
The approximate position of the north celestial pole is indicated by Polaris (the North Star). In the northern hemisphere, declination can therefore be approximately determined as the difference between the magnetic bearing and a visual bearing on Polaris. Polaris currently traces a circle 0.75° in radius 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.*[3]

5.2.2 Determination from maps and models

A rough estimate of the local declination (within a few degrees) can be determined from a general isogonic chart of the world or a continent, such as those illustrated above. Isogonic lines are also shown on aeronautical and nautical charts.

Larger-scale local maps may indicate current local declination, often with the aid of a schematic diagram. Unless the area depicted is very small, declination may vary measurably over the extent of the map, so the data may be referred to a specific location on the map. The current rate and direction of change may also be shown, for example in arcminutes per year. The same diagram may show the angle of grid north (the direction of the map's north-south grid lines), which may differ from true north.

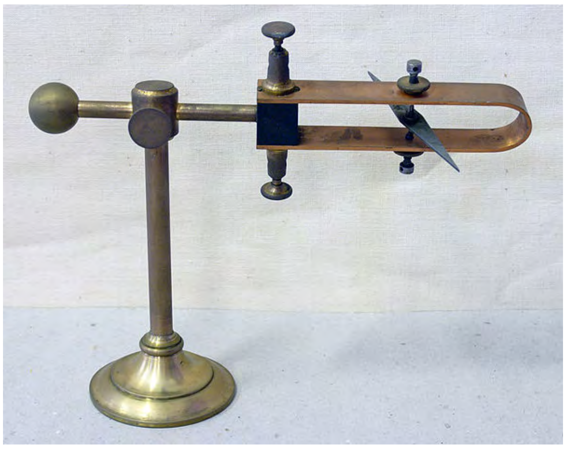
On the topographic maps of the U.S. Geological Survey (USGS), for example, a diagram shows the relationship between magnetic north in the area concerned (with an arrow marked "MN") and true north (a vertical line with a five-pointed star at its top), with a label near the



Magnetic declination indicated on an Israeli map. The arrows show true north, grid north and magnetic north, and the caption explains that the average yearly change in the magnetic declination is 0°03′ eastward.

angle between the MN arrow and the vertical line, stating the size of the declination and of that angle, in degrees, mils, or both.

A prediction of the current magnetic declination for a given location (based on a worldwide empirical model of the deep flows described above) can be obtained online from a web page operated by the National Geophysical Data Center, a division of the National Oceanic and Atmospheric Administration of the United States.*[4] This model is built with all the information available to the map-makers at the start of the five-year period it is prepared for. It reflects a highly predictable rate of change, and is usually more accurate than a map—which is likely



Antique declinometer

months or years out of date—and almost never less accurate.

5.2.3 Software

The National Geospatial-Intelligence Agency (NGA) provides source code written in C that is based on the World Magnetic Model (WMM). The source code is free to download and includes a data file updated every five years to account for movement of the magnetic north pole.

5.3 Using the declination

5.3.1 Adjustable compasses

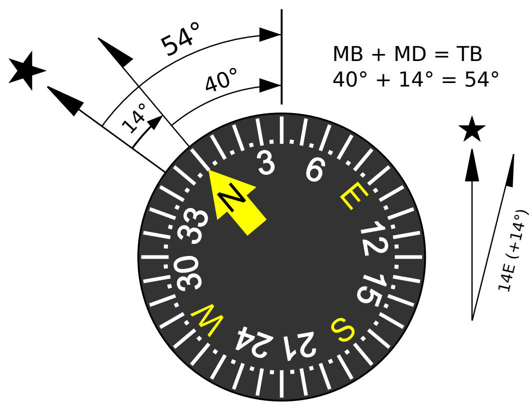
A magnetic compass points to magnetic north, not geographic north. Compasses of the style commonly used for hiking usually include a “baseplate” marked with a bezel that includes a graduated scale of degrees along with the four cardinal directions. Most advanced or costlier compasses include a declination adjustment. Such an adjustment moves the red “orienting arrow” (found on the base of the liquid filled cylinder that contains the needle) relative to the bezel and the baseplate. Either the cylinder has a mark to read against the scale of degrees on the baseplate, or a separate scale displays the current adjustment in degrees (i.e., the angle by which it has turned).

In either case, the underlying concept is that for a declination of 10° W, the red orienting arrow on the cylinder must lie 10° W of 0°/N on the bezel. (Basically, in this case, you are permanently subtracting 10° from your future bearings to compensate for the −10° declination. If your declination was 10°E you would rotate the baseplate's red orienting arrow 10° E 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

Adjustable compass set to a declination of 0° and a bearing of 307°

within an area on the same isogonic line).

5.3.2 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.

To work with both true and magnetic bearings, the user of a non-adjustable compass needs to make simple calculations that take into account the local magnetic declination. The example on the left shows how you would convert a magnetic bearing (one taken in the field using a non-adjustable compass) to a true bearing (one that you could plot on a map) by *adding* the magnetic declination. The declination in the example is 14°E (+14°). If, instead, the declination was 14°W ($-14°$), you would still "add" it to the magnetic bearing to obtain the true bearing: 40°+ ($-14°$) = 26°.

The opposite procedure is used in converting a true bearing to a magnetic bearing. With a local declination of 14°E, a true bearing (perhaps taken from a map) of 54° is converted to a magnetic bearing (for use in the field) by *subtracting* the declination: 54° - 14° = 40°. If, instead, the declination was 14°W ($-14°$), you would still "subtract" it from the true bearing to obtain the magnetic bearing: 26°- ($-14°$) = 40°.

5.4 Navigation

On aircraft or vessels there are three types of bearing: true, magnetic, and compass bearing. Compass error is divided into two parts, namely magnetic variation and magnetic deviation, the latter originating from magnetic properties of the vessel or aircraft. Variation and deviation are signed quantities. As discussed above, positive (easterly) variation indicates that magnetic north is east of geographic north.

Compass, magnetic and true bearings are related by:

$T = M + V$

$M = C + D$

The general equation relating compass and true bearings is

$T = C + V + D$

Where

C is Compass bearing

M is Magnetic bearing

T is True bearing

V is Variation

D is compass Deviation

$V < 0, D < 0$ for Westerly Variation and Deviation

$V > 0, D > 0$ for Easterly Variation and Deviation

To calculate true bearing from compass bearing (and known deviation and variation):

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

To calculate compass bearing from true bearing (and known deviation and variation):

- True bearing – variation = Magnetic bearing
- Magnetic bearing – deviation = Compass bearing.

These rules are often combined with the mnemonic "West is Best, East is least"; that is to say, add W declinations when going True headings to Magnetic Compass, and subtract E ones.

Another simple way to remember which way to apply the correction for Continental USA is:

- 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.

Common abbreviations are:

- TC = true course;
- V = variation (of the Earth's magnetic field);
- MC = 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;
- CC = compass course.

5.4.1 Deviation

Magnetic deviation is the angle from a given magnetic bearing to the related bearing mark of the compass. Deviation is positive if a compass bearing mark (e.g., compass north) is right of the related magnetic bearing (e.g., magnetic north) and vice versa. For example, if the boat is aligned to magnetic north and the compass' north mark points 3° more east, deviation is +3°. Deviation varies for every compass in the same location and depends on such factors as the magnetic field of the vessel, wristwatches, etc. The value also varies depending on the orientation of the boat. Magnets and/or iron masses can correct for deviation, so that a particular compass accurately displays magnetic bearings. More commonly, however, a correction card lists errors for the compass, which can then be compensated for arithmetically. Deviation must be added to compass bearing to obtain magnetic bearing.

5.4.2 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 twice each year to reflect the current magnetic variation correction from true north.

For example, as of March 2010, near San Francisco, magnetic north is about 14.3 degrees east of true north, with the difference decreasing by about 6 minutes of arc per year.*[5]

When plotting a course, most small aircraft pilots plot a trip using true north on a sectional (map), then convert the true north bearings to magnetic north for in-plane navigation using the magnetic compass. During flight, the pilot derives the correct compass course by adding or subtracting the local variation displayed on a sectional.

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.

Runways are designated by a number between 01 and 36, which is generally one tenth of the magnetic azimuth of the runway's heading: a runway numbered 09 points east (90°), runway 18 is south (180°), runway 27 points west (270°) and runway 36 points to the north (360° rather than 0°).*[6] However, due to magnetic declination, changes in runway names have to occur at times to keep their name in line with the runway's magnetic heading. An exception is made for runways within the Northern Domestic Airspace of Canada; these are numbered relative to true north because proximity to the magnetic North Pole makes the magnetic declination large.

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; the unit can then 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.

5.5 See also

-  Nautical portal
- *Geomagnetism* – Wikipedia book
- Compass survey
- Geomagnetism
- L-shell
- Magnetic inclination
- Pole star
- Shen Kuo
- Voyages of Christopher Columbus

5.6 References

[1] Bowditch, Nathaniel (2002). *American Practical Navigator*. Paradise Cay Publications. p. 849. ISBN 9780939837540.

[2] "Find the magnetic declination at your location" . Magnetic-Declination.com. Retrieved 6 December 2013.

[3] *Magnetic declination, what it is , how to compensate.*

[4] "Estimated Value of Magnetic Declination" . *Geomagnetism*. NOAA National Geophysical Data Center. Retrieved 6 December 2013.

[5] According to NOAA Geophysical Data Center on-line model

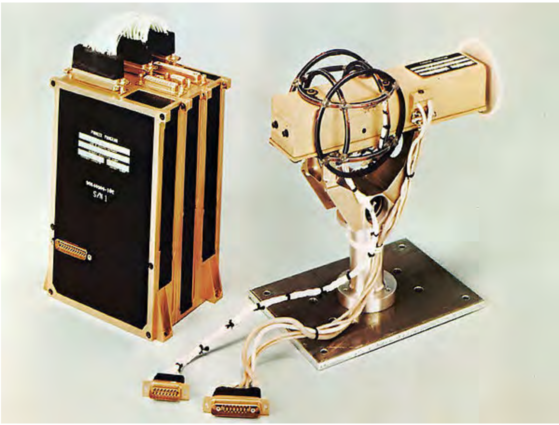
[6] Federal Aviation Administration Aeronautical Information Manual, Chapter 2, Section 3 Airport Marking Aids and Signs part 3b

5.7 External links

- USGS Geomagnetism Program
- Looks up your IP address location and tells you your declination.
- Online declination calculator at the National Geophysical Data Center (NGDC)
- Online declination and field strength calculator at the NGDC
- Mobile web-app for magnetic declination at the NGDC
- Historical magnetic declination viewer at the NGDC
- Magnetic declination calculator at Natural Resources Canada
- A Google spreadsheet application to bulk calculate magnetic declination
- World Magnetic Model source code download site

Chapter 6

Magnetometer



Helium Vector Magnetometer (HVM) of the Pioneer 10 and 11 spacecraft

A **magnetometer** is an instrument that measures magnetism—either magnetization of magnetic material like a ferromagnet, or the direction, strength, or the relative change of a magnetic field at a particular location. A compass is a simple example of a magnetometer, one that measures the direction of an ambient magnetic field.

The first magnetometer capable of measuring the absolute magnetic intensity was invented by Carl Friedrich Gauss in 1833 and notable developments in the 19th century included the Hall Effect, which is still widely used.

Magnetometers are widely used for measuring the Earth's magnetic field and in geophysical surveys to detect magnetic anomalies of various types. They are also used in the military to detect submarines. Consequently, some countries, such as the United States, Canada and Australia, classify the more sensitive magnetometers as military technology, and control their distribution.

Magnetometers can be used as metal detectors: they can detect only magnetic (ferrous) metals, but can detect such metals at a much larger depth than conventional metal detectors; they are capable of detecting large objects, such as cars, at tens of metres, while a metal detector's range is rarely more than 2 metres.

In recent years, magnetometers have been miniaturized to the extent that they can be incorporated in integrated circuits at very low cost and are finding increasing use as compasses in consumer devices such as mobile phones and tablet computers.

6.1 Introduction

6.1.1 Magnetic fields

Magnetic fields are vector quantities characterized by both strength and direction. The strength of a magnetic field is measured in units of tesla in the SI units, and in gauss in the cgs system of units. 10,000 gauss are equal to one tesla.*[1] Measurements of the Earth's magnetic field are often quoted in units of nanotesla (nT), also called a gamma.*[2] The Earth's magnetic field can vary from 20,000 to 80,000 nT depending on location, fluctuations in the Earth's magnetic field are on the order of 100 nT, and magnetic field variations due to magnetic anomalies can be in the picotesla (pT) range.*[3] *Gaussmeters* and *teslameters* are magnetometers that measure in units of gauss or tesla, respectively. In some contexts, magnetometer is the term used for an instrument that measures fields of less than 1 millitesla (mT) and gaussmeter is used for those measuring greater than 1 mT.*[1]

6.1.2 Types of magnetometer

There are two basic types of magnetometer measurement. *Vector magnetometers* measure the vector components of a magnetic field. *Total field magnetometers* or *scalar magnetometers* measure the magnitude of the vector magnetic field.*[4] Magnetometers used to study the Earth's magnetic field may express the vector components of the field in terms of *declination* (the angle between the horizontal component of the field vector and magnetic north) and the *inclination* (the angle between the field vector and the horizontal surface).*[5]

Absolute magnetometers measure the absolute magnitude or vector magnetic field, using an internal calibration or known physical constants of the magnetic sensor.*[6] *Relative magnetometers* measure magnitude or vector magnetic field relative to a fixed but uncalibrated baseline. Also called *variometers*, relative magnetometers are used

The Magnetometer experiment for the Juno orbiter for Juno can be seen here on the end of a boom. The spacecraft uses two fluxgate magnetometers. (see also Magnetometer (Juno))

to measure variations in magnetic field.

Magnetometers may also be classified by their situation or intended use. *Stationary magnetometers* are installed to a fixed position and measurements are taken while the magnetometer is stationary.*[4] *Portable* or *mobile magnetometers* are meant to be used while in motion and may be manually carried or transported in a moving vehicle. *Laboratory magnetometers* are used to measure the magnetic field of materials placed within them and are typically stationary. *Survey magnetometers* are used to measure magnetic fields in geomagnetic surveys; they may be fixed base stations, as in the INTERMAGNET network, or mobile magnetometers used to scan a geographic region.

6.1.3 Performance and capabilities

The performance and capabilities of magnetometers are described through their technical specifications. Major specifications include*[1]*[3]

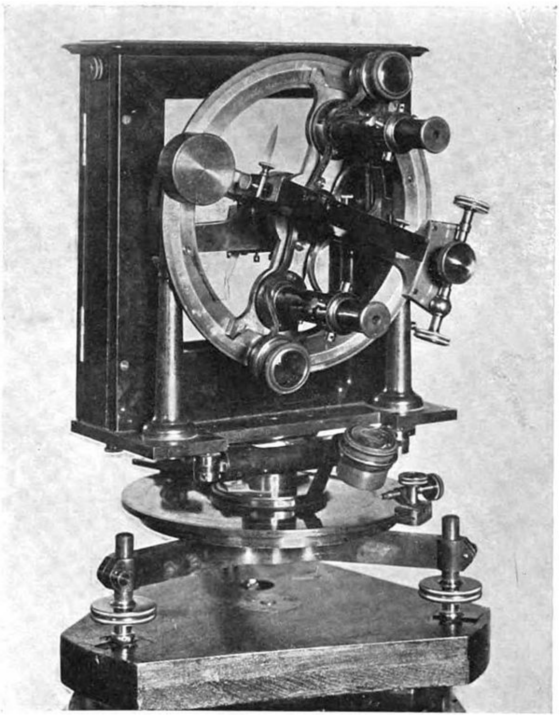
- *Sample rate* is the amount of readings given per second. The inverse is the *cycle time* in seconds per reading. Sample rate is important in mobile magnetometers; the sample rate and the vehicle speed determine the distance between measurements.
- *Bandwidth* or *bandpass* characterizes how well a magnetometer tracks rapid changes in magnetic field. For magnetometers with no onboard signal processing, bandwidth is determined by the Nyquist limit set by sample rate. Modern magnetometers may perform smoothing or averaging over sequential samples. achieving a lower noise in exchange for lower bandwidth.
- *Resolution* is the smallest change in a magnetic field the magnetometer can resolve. A magnetometer should have a resolution a good deal smaller than the smallest change one wishes to observe.
- Quantization error is caused by recording roundoff and truncation of digital expressions of the data.
- *Absolute error* is the difference between the readings of a magnetometer true magnetic field.
- *Drift* is the change in absolute error over time.
- *Thermal stability* is the dependence of the measurement on temperature. It is given as a temperature coefficient in units of nT per degree Celsius.
- *Noise* is the random fluctuations generated by the magnetometer sensor or electronics. Noise is given in units of $nT/\sqrt{Hz}$, where frequency component refers to the bandwidth.
- *Sensitivity* is the larger of the noise or the resolution.
- *Heading error* is the change in the measurement due to a change in orientation of the instrument in a constant magnetic field.
- The *dead zone* is the angular region of magnetometer orientation in which the instrument produces poor or no measurements. All optically pumped, proton-free precession, and Overhauser magnetometers experience some dead zone effects.
- *Gradient tolerance* is the ability of a magnetometer to obtain a reliable measurement in the presence of a magnetic field gradient. In surveys of unexploded ordnance or landfills, gradients can be large.

6.1.4 Early magnetometers

The compass, consisting of a magnetized needle whose orientation changes in response to the ambient magnetic field, is a simple type of magnetometer, one that measures the direction of the field. The oscillation frequency of a magnetized needle is proportional to the square-root of the strength of the ambient magnetic field; so, for example, the oscillation frequency of the needle of a horizontally situated compass is proportional to the square-root of the horizontal intensity of the ambient field.

In 1833, Carl Friedrich Gauss, head of the Geomagnetic Observatory in Göttingen, published a paper on measurement of the Earth's magnetic field.*[7] It described a new

The compass is a simple type of magnetometer.



Coast and Geodetic Survey Magnetometer No. 18.

instrument that consisted of a permanent bar magnet suspended horizontally from a gold fibre. The difference in the oscillations when the bar was magnetised and when it was demagnetised allowed Gauss to calculate an absolute value for the strength of the Earth's magnetic field.*[8]

The gauss, the CGS unit of magnetic flux density was named in his honour, defined as one maxwell per square centimeter; it equals 1×10*−4 tesla (the SI unit).*[9]

Francis Ronalds and Charles Brooke independently invented magnetographs in 1846 that continuously recorded the magnet's movements using photography, thus easing the load on observers.*[10] They were quickly utilised by Edward Sabine and others in a global magnetic survey and updated machines were in use well into the 20th century.*[11]*[12]

6.2 Laboratory magnetometers

Laboratory magnetometers measure the magnetization, also known as the magnetic moment of a sample material. Unlike survey magnetometers, laboratory magnetometers require the sample to be placed inside the magnetometer, and often the temperature, magnetic field, and other parameters of the sample can be controlled. A sample's magnetization, is primarily dependent on the ordering of unpaired electrons within its atoms, with smaller contributions from nuclear magnetic moments, Larmor diamagnetism, among others. Ordering of magnetic moments are primarily classified as diamagnetic, paramagnetic, ferromagnetic, or antiferromagnetic (although the zoology of magnetic ordering also includes ferrimagnetic, helimagnetic, toroidal, spin glasses, etc.). Measuring the magnetization as a function of temperature and magnetic field can give clues as to the type of magnetic ordering, as well as any phase transitions between different types of magnetic orders that occur at critical temperatures or magnetic fields. This type of magnetometry measurement is very important to understand the magnetic properties of materials in physics, chemistry, geophysics and geology, as well as sometimes biology.

6.2.1 SQUID (Superconducting quantum interference device)

Main article: SQUID

SQUIDs are a type of magnetometer used both as survey and as laboratory magnetometers. SQUID magnetometry is an extremely sensitive absolute magnetometry technique. However SQUIDs are noise sensitive, making them impractical as laboratory magnetometers in high DC magnetic fields, and in pulsed magnets. Commercial SQUID magnetometers are available for temperatures between 300 mK and 400 kelvins, and magnetic fields up to 7 tesla.

6.2.2 Inductive Pickup Coils

Main article: Inductive sensor

Inductive pickup coils (also referred as inductive sensor) measure the magnetization by detecting the current induced in a coil due to the changing magnetic moment of the sample. The sample's magnetization can be changed by applying a small ac magnetic field (or a rapidly changing dc field), as occurs in capacitor-driven pulsed magnets. These measurements require differentiating between the magnetic field produced by the sample and that from the external applied field. Often a special arrangement of cancellation coils is used. For example, half of the pickup coil is wound in one direction, and the other half in the other direction, and the sample is placed in only one half. The external uniform magnetic field is detected by both halves of the coil, and since they are counter-wound, the external magnetic field produces no net signal.

6.2.3 VSM (Vibrating Sample Magnetometer)

VSM (vibrating sample magnetometers) detect the magnetization of a sample by mechanically vibrating the sample inside of an inductive pickup coil or inside of a SQUID coil. Induced current or changing flux in the coil is measured. The vibration is typically created by a motor or a piezoelectric actuator. Typically the VSM technique is about an order of magnitude less sensitive than SQUID magnetometry. VSMs can be combined with SQUIDs to create a system that is more sensitive than either one alone. Heat due to the sample vibration can limit the base temperature of a VSM, typically to 2 Kelvin. VSM is also impractical for measuring a fragile sample that is sensitive to rapid acceleration.

6.2.4 Pulsed Field Extraction Magnetometry

Pulsed Field Extraction Magnetometry is another method making use of pickup coils to measure magnetization. Unlike VSMs where the sample is physically vibrated, in Pulsed Field Extraction Magnetometry, the sample is secured and the external magnetic field is changed rapidly, for example in a capacitor-driven magnet. One of multiple techniques must then be used to cancel out the external field from the field produced by the sample. These include counterwound coils that cancel the external uniform field, and background measurements with the sample removed from the coil.

6.2.5 Torque Magnetometry

Magnetic torque magnetometry can be even more sensitive than SQUID magnetometry. However, magnetic torque magnetometry doesn’t measure magnetism directly as all the previously mentioned methods do. Magnetic torque magnetometry instead measures the torque τ acting on a sample’s magnetic moment μ as a result of a uniform magnetic field B, $\tau=\mu\times B$. A torque is thus a measure of the sample's magnetic or shape anisotropy. In some cases the sample's magnetization can be extracted from the measured torque. In other cases, the magnetic torque measurement is used to detect magnetic phase transitions or quantum oscillations. The most common way to measure magnetic torque is to mount the sample on a cantilever and measure the displacement via capacitance measurement between the cantilever and nearby fixed object, or by measuring the piezoelectricity of the cantilever, or by optical interferometry off the surface of the cantilever.

6.2.6 Faraday Force Magnetometry

Faraday force magnetometry uses the fact that a spatial magnetic field gradient produces force that acts on a magnetized object, $F=(M\cdot\nabla)B$. In Faraday Force Magnetometry the force on the sample can be measured by a scale (hanging the sample from a sensitive balance), or by detecting the displacement against a spring. Commonly a capacitive load cell or cantilever is used because of its sensitivity, size, and lack of mechanical parts. Faraday Force Magnetometry is approximately one order of magnitude less sensitive than a SQUID. The biggest drawback to Faraday Force Magnetometry is that it requires some means of not only producing a magnetic field, but also producing a magnetic field gradient. While this can be accomplished by using a set of special pole faces, a much better result can be achieved by using set of gradient coils. A major advantage to Faraday Force Magnetometry is that it is small and reasonably tolerant to noise, and thus can be implemented in a wide range of environments, including a dilution refrigerator. Faraday Force Magnetometry can also be complicated by the presence of torque (see previous technique). This can be circumvented by varying the gradient field independently of the applied DC field so the torque and the Faraday Force contribution can be separated, and/or by designing a Faraday Force Magnetometer that prevents the sample from being rotated.

6.2.7 Optical Magnetometry

Optical magnetometry makes use of various optical techniques to measure magnetization. One such technique, Kerr Magnetometry makes use of the magneto-optic Kerr effect, or MOKE. In this technique, incident light is directed at the sample’s surface. Light interacts with a magnetized surface nonlinearly so the reflected light has an elliptical polarization, which is then measured by a detector. Another method of optical magnetometry is Faraday Rotation Magnetometry. Faraday Rotation Magnetometry utilizes nonlinear magneto-optical rotation to measure a sample’s magnetization. In this method a Faraday Modulating thin film is applied to the sample to be measured and a series of images are taken with a camera that senses the polarization of the reflected light. To reduce noise, multiple pictures are then averaged together. One advantage to this method is that it allows mapping of the magnetic characteristics over the surface of a sample. This can be especially useful when studying such things as the Meissner Effect on superconductors.

6.3 Survey magnetometers

Survey magnetometers can be divided into two basic types:

- *Scalar magnetometers* measure the total strength of the magnetic field to which they are subjected, but not its direction
- *Vector magnetometers* have the capability to measure the component of the magnetic field in a particular direction, relative to the spatial orientation of the device.

A vector is a mathematical entity with both magnitude and direction. The Earth's magnetic field at a given point is a vector. A magnetic compass is designed to give a horizontal bearing direction, whereas a *vector magnetometer* measures both the magnitude and direction of the total magnetic field. Three orthogonal sensors are required to measure the components of the magnetic field in all three dimensions.

They are also rated as "absolute" if the strength of the field can be calibrated from their own known internal constants or "relative" if they need to be calibrated by reference to a known field.

A *magnetograph* is a magnetometer that continuously records data.

Magnetometers can also be classified as "AC" if they measure fields that vary relatively rapidly in time (>100 Hz), and "DC" if they measure fields that vary only slowly (quasi-static) or are static. AC magnetometers find use in electromagnetic systems (such as magnetotellurics), and DC magnetometers are used for detecting mineralisation and corresponding geological structures.

6.3.1 Scalar magnetometers

Proton precession magnetometer

Main article: Proton magnetometer

*Proton precession magnetometer*s, also known as *proton magnetometers*, PPMs or simply mags, measure the resonance frequency of protons (hydrogen nuclei) in the magnetic field to be measured, due to nuclear magnetic resonance (NMR). Because the precession frequency depends only on atomic constants and the strength of the ambient magnetic field, the accuracy of this type of magnetometer can reach 1 ppm.*[13]

A direct current flowing in a solenoid creates a strong magnetic field around a hydrogen-rich fluid (kerosene and decane are popular, and even water can be used), causing some of the protons to align themselves with that field. The current is then interrupted, and as protons realign themselves with the ambient magnetic field, they precess at a frequency that is directly proportional to the magnetic field. This produces a weak rotating magnetic field that is picked up by a (sometimes separate) inductor, amplified electronically, and fed to a digital frequency counter whose output is typically scaled and displayed directly as field strength or output as digital data.

For hand/backpack carried units, PPM sample rates are typically limited to less than one sample per second. Measurements are typically taken with the sensor held at fixed locations at approximately 10 metre increments.

Portable instruments are also limited by sensor volume (weight) and power consumption. PPMs work in field gradients up to 3,000 nT/m, which is adequate for most mineral exploration work. For higher gradient tolerance, such as mapping banded iron formations and detecting large ferrous objects, Overhauser magnetometers can handle 10,000 nT/m, and caesium magnetometers can handle 30,000 nT/m.

They are relatively inexpensive (< 8,000 USD) and were once widely used in mineral exploration. Three manufacturers dominate the market: GEM Systems, Geometrics and Scintrex. Popular models include G-856, Smartmag and GSM-18 and GSM-19T.

For mineral exploration, they have been superseded by Overhauser, Caesium and Potassium instruments, all of which are fast-cycling, and do not require the operator to pause between readings.

Overhauser effect magnetometer

The *Overhauser effect magnetometer* or *Overhauser magnetometer* uses the same fundamental effect as the *proton precession magnetometer* to take measurements. By adding free radicals to the measurement fluid, the nuclear Overhauser effect can be exploited to significantly improve upon the proton precession magnetometer. Rather than aligning the protons using a solenoid, a low power radio-frequency field is used to align (polarise) the electron spin of the free radicals, which then couples to the protons via the Overhauser effect. This has two main advantages: driving the RF field takes a fraction of the energy (allowing lighter-weight batteries for portable units), and faster sampling as the electron-proton coupling can happen even as measurements are being taken. An Overhauser magnetometer produces readings with a 0.01 nT to 0.02 nT standard deviation while sampling once per second.

Caesium vapour magnetometer

The *optically pumped caesium vapour magnetometer* is a highly sensitive (300 fT/Hz*0.5) and accurate device used in a wide range of applications. It is one of a number of alkali vapours (including rubidium and potassium) that are used in this way, as well as helium.*[14]

The device broadly consists of a photon emitter containing a caesium light emitter or lamp, an absorption chamber containing caesium vapour, a "buffer gas" through which the emitted photons pass and a photon detector, arranged in that order.

The basic principle that allows the device to operate is the fact that a caesium atom can exist in any of nine energy levels, which can be informally thought of as the placement of electron atomic orbitals around the atomic nucleus. When a caesium atom within the chamber encounters a photon from the lamp, it is excited to a higher energy state, emits a photon and falls to an indeterminate lower energy state. The caesium atom is "sensitive" to the photons from the lamp in three of its nine energy states, and therefore, assuming a closed system, all the atoms eventually fall into a state in which all the photons from the lamp pass through unhindered and are measured by the photon detector. At this point, the sample (or population) is said to be polarized and ready for measurement to take place. This process is done continuously during operation. This theoretically perfect magnetometer is now functional and so can begin to make measurements.

In the most common type of caesium magnetometer, a very small AC magnetic field is applied to the cell. Since the difference in the energy levels of the electrons is determined by the external magnetic field, there is a frequency at which this small AC field makes the electrons change states. In this new state, the electron once again can absorb a photon of light. This causes a signal on a photo detector that measures the light passing through the cell. The associated electronics use this fact to create a signal exactly at the frequency that corresponds to the external field.

Another type of caesium magnetometer modulates the light applied to the cell. This is referred to as a Bell-Bloom magnetometer, after the two scientists who first investigated the effect. If the light is turned on and off at the frequency corresponding to the Earth's field, there is a change in the signal seen at the photo detector. Again, the associated electronics use this to create a signal exactly at the frequency that corresponds to the external field. Both methods lead to high performance magnetometers.

Potassium vapour magnetometer

Potassium is the only optically pumped magnetometer that operates on a single, narrow electron spin resonance (ESR) line in contrast to other alkali vapour magnetometers that use irregular, composite and wide spectral lines and Helium with the inherently wide spectral line.*[15]

Applications

The caesium and potassium magnetometers are typically used where a higher performance magnetometer than the proton magnetometer is needed. In archaeology and geophysics, where the sensor sweeps through an area and many accurate magnetic field measurements are often needed, caesium and potassium magnetometers have advantages over the proton magnetometer.

The caesium and potassium magnetometer's faster measurement rate allows the sensor to be moved through the area more quickly for a given number of data points. Caesium and potassium magnetometers are insensitive to rotation of the sensor while the measurement is being made.

The lower noise of caesium and potassium magnetometers allow those measurements to more accurately show the variations in the field with position.

6.3.2 Vector magnetometers

Vector magnetometers measure one or more components of the magnetic field electronically. Using three orthogonal magnetometers, both azimuth and dip (inclination) can be measured. By taking the square root of the sum of the squares of the components the total magnetic field strength (also called total magnetic intensity, TMI) can be calculated by Pythagoras's theorem.

Vector magnetometers are subject to temperature drift and the dimensional instability of the ferrite cores. They also require levelling to obtain component information, unlike total field (scalar) instruments. For these reasons they are no longer used for mineral exploration.

Rotating coil magnetometer

The magnetic field induces a sine wave in a rotating coil. The amplitude of the signal is proportional to the strength of the field, provided it is uniform, and to the sine of the angle between the rotation axis of the coil and the field lines. This type of magnetometer is obsolete.

Hall effect magnetometer

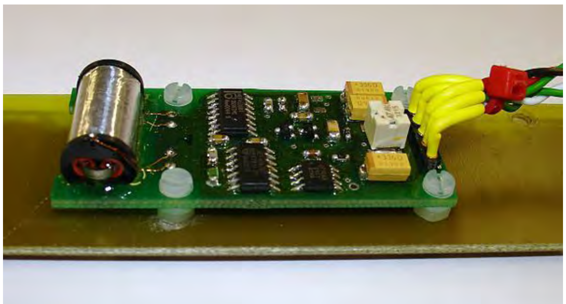
Main article: Hall effect sensor

The most common magnetic sensing devices are solid-state Hall effect sensors. These sensors produce a voltage proportional to the applied magnetic field and also sense polarity. They are used in applications where the magnetic field strength is relatively large, such as in anti-lock braking systems in cars, which sense wheel rotation speed via slots in the wheel disks.

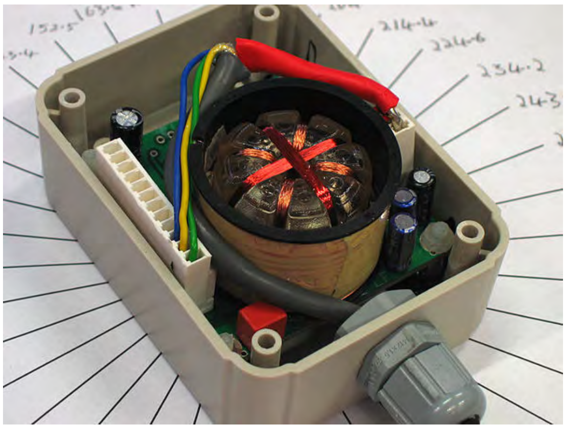
Magnetoresistive devices

These are made of thin strips of permalloy (NiFe magnetic film) whose electrical resistance varies with a change in magnetic field. They have a well-defined axis of sensitivity, can be produced in 3-D versions and can be mass-produced as an integrated circuit. They have a response time of less than 1 microsecond and can be sampled in moving vehicles up to 1,000 times/second. They can be used in compasses that read within 1°, for which the underlying sensor must reliably resolve 0.1°.*[16]

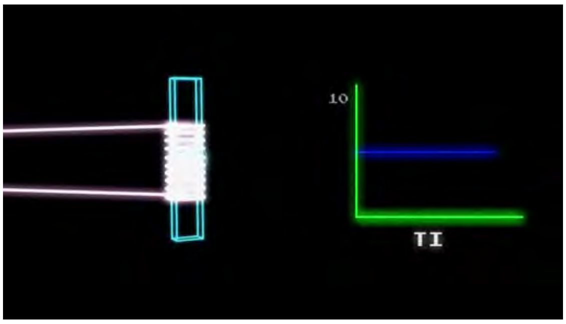
Fluxgate magnetometer



A uniaxial fluxgate magnetometer.



A fluxgate compass/inclinometer.



Basic principles of a fluxgate magnetometer.

The fluxgate magnetometer was invented by H. Aschenbrenner and G. Goubau in 1936.*[17]*[18]*:4 A team at Gulf Research Laboratories led by Victor Vacquier developed airborne fluxgate magnetometers to detect submarines during World War II, and after the war confirmed the theory of plate tectonics by using them to measure shifts in the magnetic patterns on the sea floor.*[19]

A fluxgate magnetometer consists of a small, magnetically susceptible core wrapped by two coils of wire. An alternating electric current is passed through one coil, driving the core through an alternating cycle of magnetic saturation; i.e., magnetised, unmagnetised, inversely magnetised, unmagnetised, magnetised, and so forth. This constantly changing field induces an electric current in the second coil, and this output current is measured by a detector. In a magnetically neutral background, the input and output currents match. However, when the core is exposed to a background field, it is more easily saturated in alignment with that field and less easily saturated in opposition to it. Hence the alternating magnetic field, and the induced output current, are out of step with the input current. The extent to which this is the case depends on the strength of the background magnetic field. Often, the current in the output coil is integrated, yielding an output analog voltage, proportional to the magnetic field.

A wide variety of sensors are currently available and used to measure magnetic fields. Fluxgate compasses and gradiometers measure the direction and magnitude of magnetic fields. Fluxgates are affordable, rugged and compact with miniaturization recently advancing to the point of complete sensor solutions in the form of IC chips, including examples from both academia *[20] and industry.*[21] This, plus their typically low power consumption makes them ideal for a variety of sensing applications. Gradiometers are commonly used for archaeological prospecting and unexploded ordnance (UXO) detection such as the German military's popular *Foerster*.*[22]

The typical fluxgate magnetometer consists of a "sense" (secondary) coil surrounding an inner "drive" (primary) coil that is closely wound around a highly permeable core material, such as mu-metal. An alternating current is applied to the drive winding, which drives the core in a continuous repeating cycle of saturation and unsaturation. To an external field, the core is alternately weakly permeable and highly permeable. The core is often a toroidally-wrapped ring or a pair of linear elements whose drive windings are each wound in opposing directions. Such closed flux paths minimise coupling between the drive and sense windings. In the presence of an external magnetic field, with the core in a highly permeable state, such a field is locally attracted or gated (hence the name fluxgate) through the sense winding. When the core is weakly permeable, the external field is less attracted. This continuous gating of the external field in and out of the sense winding induces a signal in the sense winding, whose principal frequency is twice that of the drive frequency, and whose strength and phase orientation vary directly with the external field magnitude and polarity.

There are additional factors that affect the size of the resultant signal. These factors include the number of turns in the sense winding, magnetic permeability of the core, sensor geometry, and the gated flux rate of change with respect to time.

Phase synchronous detection is used to extract these harmonic signals from the sense winding and convert them into a DC voltage proportional to the external magnetic field. Active current feedback may also be employed, such that the sense winding is driven to counteract the external field. In such cases, the feedback current varies linearly with the external magnetic field and is used as the basis for measurement. This helps to counter inherent non-linearity between the applied external field strength and the flux gated through the sense winding.

SQUID magnetometer

Main article: SQUID

SQUIDs, or superconducting quantum interference devices, measure extremely small changes in magnetic fields. They are very sensitive vector magnetometers, with noise levels as low as 3 fT Hz*−½ in commercial instruments and 0.4 fT Hz*−½ in experimental devices. Many liquid-helium-cooled commercial SQUIDs achieve a flat noise spectrum from near DC (less than 1 Hz) to tens of kilohertz, making such devices ideal for time-domain biomagnetic signal measurements. SERF atomic magnetometers demonstrated in laboratories so far reach competitive noise floor but in relatively small frequency ranges.

SQUID magnetometers require cooling with liquid helium (4.2 K) or liquid nitrogen (77 K) to operate, hence the packaging requirements to use them are rather stringent both from a thermal-mechanical as well as magnetic standpoint. SQUID magnetometers are most commonly used to measure the magnetic fields produced by laboratory samples, also for brain or heart activity (magnetoencephalography and magnetocardiography, respectively). Geophysical surveys use SQUIDs from time to time, but the logistics of cooling the SQUID are much more complicated than other magnetometers that operate at room temperature.

Spin-exchange relaxation-free (SERF) atomic magnetometers

Main article: SERF

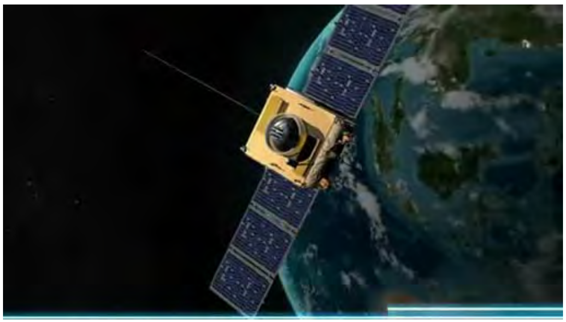
At sufficiently high atomic density, extremely high sensitivity can be achieved. Spin-exchange-relaxation-free (SERF) atomic magnetometers containing potassium, caesium or rubidium vapor operate similarly to the caesium magnetometers described above, yet can reach sensitivities lower than 1 fT Hz*−½. The SERF magnetometers only operate in small magnetic fields. The Earth's field is about 50 µT; SERF magnetometers operate in fields less than 0.5 µT.

Large volume detectors have achieved a sensitivity of 200 aT Hz*−½.*[23] This technology has greater sensitivity per unit volume than SQUID detectors.*[24] The technology can also produce very small magnetometers that may in the future replace coils for detecting changing magnetic fields. This technology may produce a magnetic sensor that has all of its input and output signals in the form of light on fiber-optic cables.*[25] This lets the magnetic measurement be made near high electrical voltages.

6.4 Calibration of magnetometers

The calibration of magnetometers is usually performed by means of coils which are supplied by an electrical current to create a magnetic field. It allows to characterize the sensitivity of the magnetometer (in terms of V/T). In many applications the homogeneity of the calibration coil is an important feature. For this reason, coils like Helmholtz coils is commonly used either in a single axis or a three axis configuration. For demanding applications high homogeneity magnetic field is mandatory, in such cases magnetic field calibration can be performed using Maxwell coil, cosine coils *[26] or calibration in the highly homogenous Earth's magnetic field.

6.5 Uses



Magnetometers can measure the magnetic fields of planets.

Magnetometers have a very diverse range of applications, including locating objects such as submarines, sunken ships, hazards for tunnel boring machines, hazards in coal mines, unexploded ordnance, toxic waste drums, as well as a wide range of mineral deposits and geological structures. They also have applications in heart beat monitors, weapon systems positioning, sensors in anti-locking brakes, weather prediction (via solar cycles), steel pylons, drill guidance systems, archaeology, plate tectonics and radio wave propagation and planetary exploration.

Depending on the application, magnetometers can be deployed in spacecraft, aeroplanes (*fixed wing* magnetometers), helicopters (*stinger* and *bird*), on the ground (*backpack*), towed at a distance behind quad bikes (*sled* or *trailer*), lowered into boreholes (*tool*, *probe* or *sonde*) and towed behind boats (*tow fish*).

6.5.1 Archaeology

Main article: Magnetic survey (archaeology)

Magnetometers are also used to detect archaeological sites, shipwrecks and other buried or submerged objects. Fluxgate gradiometers are popular due to their compact configuration and relatively low cost. Gradiometers enhance shallow features and negate the need for a base station. Caesium and Overhauser magnetometers are also very effective when used as gradiometers or as single-sensor systems with base stations.

The TV program *Time Team* popularised 'geophys', including magnetic techniques used in archaeological work to detect fire hearths, walls of baked bricks and magnetic stones such as basalt and granite. Walking tracks and roadways can sometimes be mapped with differential compaction in magnetic soils or with disturbances in clays, such as on the Great Hungarian Plain. Ploughed fields behave as sources of magnetic noise in such surveys.

6.5.2 Auroras

Magnetometers can give an indication of auroral activity before the light from the aurora becomes visible. A grid of magnetometers around the world constantly measures the effect of the solar wind on the Earth's magnetic field, which is then published on the K-index.*[27]

6.5.3 Coal exploration

Whilst magnetometers can be used to help map basin shape at a regional scale, they are more commonly used to map hazards to coal mining, such as basaltic intrusions (dykes, sills and volcanic plugs) that destroy resources and are dangerous to longwall mining equipment. Magnetometers can also locate zones ignited by lightning and map siderite (an impurity in coal).

The best survey results are achieved on the ground in high-resolution surveys (with approximately 10 m line spacing and 0.5 m station spacing). Bore-hole magnetometers using a Ferret can also assist when coal seams are deep, by using multiple sills or looking beneath surface basalt flows.

Modern surveys generally use magnetometers with GPS technology to automatically record the magnetic field and their location. The data set is then corrected with data from a second magnetometer (the base station) that is left stationary and records the change in the Earth's magnetic field during the survey.*[28]

6.5.4 Directional drilling

Magnetometers are used in directional drilling for oil or gas to detect the azimuth of the drilling tools near the drill. They are most often paired with accelerometers in drilling tools so that both the inclination and azimuth of the drill can be found.

6.5.5 Military

For defensive purposes, navies use arrays of magnetometers laid across sea floors in strategic locations (i.e. around ports) to monitor submarine activity. The Russian 'Goldfish' (titanium submarines) were designed and built at great expense to thwart such systems (as pure titanium is non-magnetic).*[29]

Military submarines are degaussed—by passing through large underwater loops at regular intervals —to help them escape detection by sea-floor monitoring systems, magnetic anomaly detectors, and magnetically-triggered mines. However, submarines are never completely demagnetised. It is possible to tell the depth at which a submarine has been by measuring its magnetic field, which is distorted as the pressure distorts the hull and hence the field. Heating can also change the magnetization of steel.

Submarines tow long sonar arrays to detect ships, and can even recognise different propeller noises. The sonar arrays need to be accurately positioned so they can triangulate direction to targets (e.g. ships). The arrays do not tow in a straight line, so fluxgate magnetometers are used to orient each sonar node in the array.

Fluxgates can also be used in weapons navigation systems, but have been largely superseded by GPS and ring laser gyroscopes.

Magnetometers such as the German Foerster are used to locate ferrous ordnance. Caesium and Overhauser magnetometers are used to locate and help clean up old bombing/test ranges.

UAV payloads also include magnetometers for a range of defensive and offensive tasks.

6.5.6 Mineral exploration

Main article: Exploration geophysics

Magnetometric surveys can be useful in defining magnetic anomalies which represent ore (direct detection), or in some cases gangue minerals associated with ore deposits (indirect or inferential detection). This includes iron ore, magnetite, hematite and often pyrrhotite.

Developed countries such as Australia, Canada and USA invest heavily in systematic airborne magnetic surveys of their respective continents and surrounding oceans, to assist with map geology and in the discovery of mineral deposits. Such aeromag surveys are typically undertaken

A Diamond DA42 light aircraft, modified for aerial survey with a nose-mounted boom containing a magnetometer at its tip

with 400 m line spacing at 100 m elevation, with readings every 10 meters or more. To overcome the asymmetry in the data density, data is interpolated between lines (usually 5 times) and data along the line is then averaged. Such data is gridded to an 80 m × 80 m pixel size and image processed using a program like ERMapper. At an exploration lease scale, the survey may be followed by a more detailed helimag or crop duster style fixed wing at 50 m line spacing and 50 m elevation (terrain permitting). Such an image is gridded on a 10 x 10 m pixel, offering 64 times the resolution.

Where targets are shallow (<200 m), aeromag anomalies may be followed up with ground magnetic surveys on 10 m to 50 m line spacing with 1 m station spacing to provide the best detail (2 to 10 m pixel grid) (or 25 times the resolution prior to drilling).

Magnetic fields from magnetic bodies of ore fall off with the inverse distance cubed (dipole target), or at best inverse distance squared (magnetic monopole target). One analogy to the resolution-with-distance is a car driving at night with lights on. At a distance of 400 m one sees one glowing haze, but as it approaches, two headlights, and then the left blinker, are visible.

There are many challenges interpreting magnetic data for mineral exploration. Multiple targets mix together like multiple heat sources and, unlike light, there is no magnetic telescope to focus fields. The combination of multiple sources is measured at the surface. The geometry, depth or magnetisation direction (remanence) of the targets are also generally not known, and so multiple models can explain the data.

Potent by Geophysical Software Solutions is a leading magnetic (and gravity) interpretation package used extensively in the Australian exploration industry.

Magnetometers assist mineral explorers both directly (i.e., gold mineralisation associated with magnetite, diamonds in kimberlite pipes) and, more commonly, indirectly, such as by mapping geological structures conducive to mineralisation (i.e., shear zones and alteration haloes around granites).

Airborne Magnetometers detect the change in the Earth's magnetic field using sensors attached to the aircraft in the form of a "stinger" or by towing a magnetometer on the end of a cable. The magnetometer on a cable is often referred to as a "bomb" because of its shape. Others call it a "bird".

Because hills and valleys under the aircraft make the magnetic readings rise and fall, a radar altimeter keeps track of the transducer's deviation from the nominal altitude above ground. There may also be a camera that takes photos of the ground. The location of the measurement is determined by also recording a GPS.

6.5.7 Mobile telephones

Many smartphones contain magnetometers; apps exist that serve as compasses. The iPhone 3GS has a magnetometer, a magnetoresistive permalloy sensor, the AN-203 produced by Honeywell.*[30] In 2009, the price of three-axis magnetometers dipped below US $1 per device and dropped rapidly. The use of a three-axis device means that it is not sensitive to the way it is held in orientation or elevation. Hall effect devices are also popular.*[31]

Researchers at Deutsche Telekom have used magnetometers embedded in mobile devices to permit touchless 3D interaction. Their interaction framework, called MagiTact, tracks changes to the magnetic field around a cellphone to identify different gestures made by a hand holding or wearing a magnet.*[32]

6.5.8 Oil exploration

Seismic methods are preferred to magnetometers as the primary survey method for oil exploration although magnetic methods can give additional information about the underlying geology and in some environments evidence of leakage from traps.*[33] Magnetometers are also used in oil exploration to show locations of geologic features that make drilling impractical, and other features that give geophysicists a more complete picture of stratigraphy.

6.5.9 Spacecraft

Main article: Spacecraft magnetometer

A three-axis fluxgate magnetometer was part of the Mariner 2 and Mariner 10 missions.*[34] A dual technique magnetometer is part of the Cassini–Huygens mission to explore Saturn.*[35] This system is composed of a vector helium and fluxgate magnetometers.*[36] Magnetometers were also a component instrument on the Mercury MESSENGER mission. A magnetometer can also be used by satellites like GOES to measure both the magnitude and direction of the magnetic field of a planet or moon.

6.5.10 Magnetic surveys

Ground surveying in Surprise Valley, Cedarville, California

Systematic surveys can be used to in searching for mineral deposits or locating lost objects. Such surveys are divided into:

- Aeromagnetic survey
- Borehole
- Ground
- Marine

Aeromag datasets for Australia can be downloaded from the GADDS database.

Data can be divided in point located and image data, the latter of which is in ERMapper format.

Magnetovision

On the base of space measured distribution of magnetic field parameters (e.g. amplitude or direction), the magnetovision images may be generated. Such presentation of magnetic data is very useful for further analyse and data fusion.

Gradiometer

Magnetic gradiometers are pairs of magnetometers with their sensors separated, usually horizontally,by a fixed distance. The readings are subtracted to measure the difference between the sensed magnetic fields, which gives the field gradients caused by magnetic anomalies. This is one way of compensating both for the variability in time of the Earth's magnetic field and for other sources of electromagnetic interference, thus allowing for more sensitive detection of anomalies. Because nearly equal values are being subtracted, the noise performance requirements for the magnetometers is more extreme.

Gradiometers enhance shallow magnetic anomalies and are thus good for archaeological and site investigation work. They are also good for real-time work such as unexploded ordnance location. It is twice as efficient to run a base station and use two (or more) mobile sensors to read parallel lines simultaneously (assuming data is stored and post-processed). In this manner, both along-line and cross-line gradients can be calculated.

Position control of magnetic surveys

In traditional mineral exploration and archaeological work, grid pegs placed by theodolite and tape measure were used to define the survey area. Some UXO surveys used ropes to define the lanes. Airborne surveys used radio triangulation beacons, such as Siledus.

Non-magnetic electronic hipchain triggers were developed to trigger magnetometers. They used rotary shaft encoders to measure distance along disposable cotton reels.

Modern explorers use a range of low-magnetic signature GPS units, including Real-Time Kinematic GPS.

Heading errors in magnetic surveys

Magnetic surveys can suffer from noise coming from a range of sources. Different magnetometer technologies suffer different kinds of noise problems.

Heading errors are one group of noise. They can come from three sources:

- Sensor
- Console
- Operator

Some total field sensors give different readings depending on their orientation. Magnetic materials in the sensor itself are the primary cause of this error. In some magnetometers, such as the vapor magnetometers (caesium, potassium, etc.), there are sources of heading error in the physics that contribute small amounts to the total heading error.

Console noise comes from magnetic components on or within the console. These include ferrite in cores in inductors and transformers, steel frames around LCD's, legs on IC chips and steel cases in disposable batteries. Some popular MIL spec connectors also have steel springs.

Operators must take care to be magnetically clean and should check the 'magnetic hygiene' of all apparel and items carried during a survey. Akubra hats are very popular in Australia, but their steel rims must be removed before use on magnetic surveys. Steel rings on notepads, steel capped boots and steel springs in overall eyelets can all cause unnecessary noise in surveys. Pens, mobile phones and stainless steel implants can also be problematic.

The magnetic response (noise) from ferrous object on the operator and console can change with heading direction because of induction and remanence. Aeromagnetic survey aircraft and quad bike systems can use special compensators to correct for heading error noise.

Heading errors look like herringbone patterns in survey images. Alternate lines can also be corrugated.

Image processing of magnetic data

Recording data and image processing is superior to real-time work because subtle anomalies often missed by the operator (especially in magnetically noisy areas) can be correlated between lines, shapes and clusters better defined. A range of sophisticated enhancement techniques can also be used. There is also a hard copy and need for systematic coverage.

6.6 See also

- Aeromagnetic survey
- Earth's field NMR (EFNMR)
- EMF measurement
- Intermagnet (a global network of observatories, monitoring the Earth's magnetic field)
- Magnetic immunoassay
- Magnetization
- Magnetogram (often displayed as images on the web, but usually the digital data are also available)
- MEMS magnetic field sensors (part of many hand-held devices such as smartphones)
- SQUID
- Vibrating sample magnetometer
- Zero field NMR

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6.8 Further reading

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6.9 External links

- Earthquake forecasting techniques and more research on the study of electromagnetic fields
- USGS Geomagnetism Program
- Earth's Field NMR (EFNMR)
- Space-based magnetometers
- Practical guidelines for building a magnetometer by hobbyists – Part 1 Introduction
- Practical guidelines for building a magnetometer by hobbyists – Part 2 Building

Chapter 7

Geomagnetic pole

For a broader coverage related to this topic, see Earth's magnetic poles.

The **geomagnetic poles** are antipodal points where the axis of a best-fitting dipole intersects the Earth's surface. This dipole is equivalent to a powerful bar magnet at the center of the Earth, and it is this theoretical dipole that comes closer than any other to accounting for the magnetic field observed at the Earth's surface. In contrast, the actual Earth's magnetic poles are not antipodal—that is, they do not lie on a line passing through the center of the Earth.

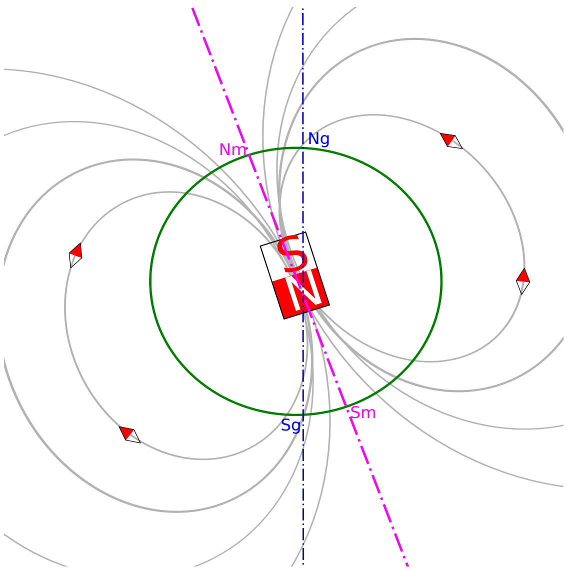

Illustration of the difference between geomagnetic poles (N_m and S_m) and geographical poles (N_g and S_g)

Owing to motion of fluid in the Earth's outer core, the actual magnetic poles are constantly moving. However, over thousands of years their direction averages to the Earth's rotation axis. On the order of once every half a million years, the poles *reverse* (north changes place with south).

7.1 Definition

As a first-order approximation, the Earth's magnetic field can be modelled as a simple dipole (like a bar magnet), tilted about 9.6° with respect to the Earth's rotation axis (which defines the Geographic North and Geographic South Poles) and centered at the Earth's center.*[1] The North and South Geomagnetic Poles are the antipodal points where the axis of this theoretical dipole intersects the Earth's surface, thus unlike the magnetic poles they always have an equal degree of latitude and supplementary degrees of longitude respectively (2017: Lat. 80.5°N, 80.5°S; Long. 72.8°W, 107.2°E).*[2] 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 North and South magnetic poles. However, the approximation is imperfect, and so the Magnetic and Geomagnetic Poles lie some distance apart.*[3]

7.2 Location

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 magnetic *south* pole. It is the center of the 'open' magnetic field lines which connect to the interplanetary magnetic field and provide a direct route for the solar wind to reach the ionosphere. As of 2015 it was located at approximately 80°22′N 72°37′W / 80.37°N 72.62°W, on Ellesmere Island, Nunavut, Canada.*[1]

The locations of geomagnetic poles are predicted by the International Geomagnetic Reference Field, a statistical fit to measurements of the Earth's field by satellites and in geomagnetic observatories.*[4] If the Earth's field were exactly dipolar, the north pole of a magnetic compass needle would point directly at the North Geomagnetic Pole. In practice it does not because the geomagnetic field that originates in the core has a more complex non-dipolar part, and magnetic anomalies in the Earth's crust also contribute to the local field.*[1]

7.3 Movement

The geomagnetic poles move over time because the geomagnetic field is produced by motion of the molten iron alloys in the Earth's outer core (see geodynamo). Over the past 150 years the poles have moved westward at a rate of 0.05° to 0.1° per year, with little net north or south motion.*[3]

Over several thousand years, the average location of the geomagnetic poles coincides with the geographical poles. Paleomagnetists have long relied on the *Geocentric axial dipole (GAD) hypothesis*, which states that, aside from during geomagnetic reversals, the time-averaged position of the geomagnetic poles has always coincided with the geographic poles. There is considerable paleomagnetic evidence supporting this hypothesis.*[5]

7.4 Geomagnetic reversal

Main article: Geomagnetic reversal

Over the life of the Earth, the orientation of Earth's magnetic field has reversed many times, with geomagnetic north becoming geomagnetic 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. As magma seeps out of the mantle and solidifies to become new ocean floor, the magnetic minerals in it are magnetized in the direction of the magnetic field. Thus, starting at the most recently formed ocean floor, one can read out the direction of the magnetic field in previous times as one moves further away to older ocean floor.

7.5 See also

- Dipole model of the Earth's magnetic field

7.6 Notes

[1] “Geomagnetism Frequently Asked Questions”. National Geophysical Data Center. Retrieved 1 June 2016.

[2] http://wdc.kugi.kyoto-u.ac.jp/poles/polesexp.html

[3] Merrill, McElhinny & McFadden 1996, Chapter 2

[4] IAGA Division V Working Group V-MOD. “International Geomagnetic Reference Field”. Retrieved 20 December 2016.

[5] Merrill, McElhinny & McFadden 1996, Chapter 6

7.7 References

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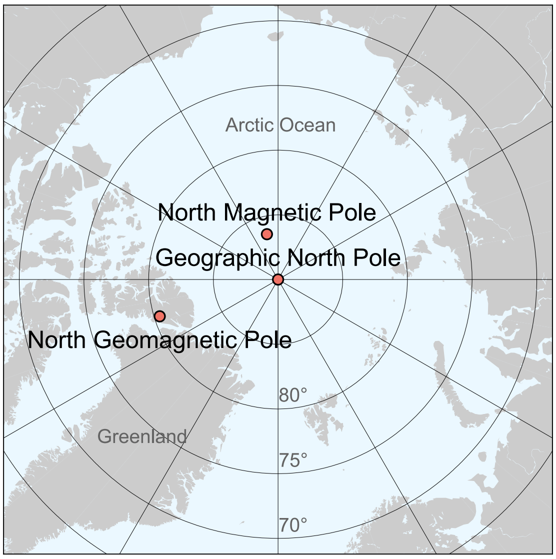
- Merrill, Ronald T. (2010). *Our Magnetic Earth: The Science of Geomagnetism*. University of Chicago Press. ISBN 0-226-52050-1.
- Merrill, Ronald T.; McElhinny, Michael W.; McFadden, Phillip L. (1996). *The magnetic field of the earth: Paleomagnetism, the core, and the deep mantle*. Academic Press. ISBN 978-0-12-491246-5.

7.8 External links

- NOAA—Geomagnetic-related web resources

Chapter 8

North Magnetic Pole



Location of the North Magnetic Pole and the North Geomagnetic Pole in 2016.

The **North Magnetic Pole** is the point on the surface of Earth's Northern Hemisphere at which the planet's magnetic field points vertically downwards (in other words, if a magnetic compass needle is allowed to rotate about a horizontal axis, it will point straight down). There is only one location where this occurs, near (but distinct from) the Geographic North Pole and the Geomagnetic North Pole.

The North Magnetic Pole moves over time due to magnetic changes in the Earth's core.*[1] 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 situated at 83°06′N 117°48′W / 83.1°N 117.8°W in 2005. In 2009, while still situated within the Canadian Arctic territorial claim at 84°54′N 131°00′W / 84.9°N 131.0°W,*[2] it was moving toward Russia at between 55 and 60 kilometres (34 and 37 mi) per year.*[3] As of 2016, the pole is projected to have moved beyond the Canadian Arctic territorial claim to 86°24′N 166°18′W / 86.4°N 166.3°W.*[2]

Its southern hemisphere counterpart is the South Magnetic Pole. Since the Earth's magnetic field is not exactly symmetrical, the North and South Magnetic Poles are not antipodal, meaning that a straight line drawn from one to the other does not pass through the geometric centre of the Earth.

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.*[4]

8.1 Polarity

See also: Magnet § Pole naming conventions

All magnets have two poles, where the lines of magnetic flux enter and emerge. By analogy with the Earth's magnetic field, these are called the magnet's "north" and "south" poles. The convention in early compasses was to call the end of the needle pointing to the Earth's North Magnetic Pole the "north pole" (or "north-seeking pole") and the other end the "south pole" (the names are often abbreviated to "N" and "S"). Because opposite poles attract, this definition means that the Earth's North Magnetic Pole is actually a magnetic *south* pole and the Earth's South Magnetic Pole is a magnetic *north* pole.*[5]*[6]

The direction of magnetic field lines is defined such that the lines emerge from the magnet's north pole and enter into the magnet's south pole.

8.2 History

Early European navigators believed that compass needles were attracted to a "magnetic island" somewhere in the far north (see Rupes Nigra), or to the Pole Star.*[7] 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 a few hundred years before the nature of the Earth's magnetic field was understood properly.*[7]

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.

8.3 Expeditions and measurements

See also: Arctic exploration, Farthest North, and List of Arctic expeditions

8.3.1 Early

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.[8]

8.3.2 Project Polaris

At the start of the Cold War, the United States Department of War recognized a need for a comprehensive survey of the North American Arctic and asked the United States Army to undertake the task. An assignment was made in 1946 for the newly formed Army's Air Corps Strategic Air Command to explore the entire Arctic Ocean area. The exploration was conducted by the 46th (later re-designated the 72nd) Photo Reconnaissance Squadron and reported on as a classified *Top Secret* mission named Project Nanook. This project in turn was divided into many separate, but identically classified, projects, one of which was Project Polaris, which was a radar, photographic (trimetrogon, or three-angle, cameras) and visual study of the entire Canadian Archipelago. A Canadian officer observer was assigned to accompany each flight.

Directing Project Polaris was its navigation leader, 1st Lieutenant Frank O. Klein, a World War II combat veteran. Incidental to the project and taken up at his own initiative was a study of northern terrestrial magnetism. The study was prompted by the surprise that the fluxgate compass did not behave erratically as expected. It oscillated no more than 1 to 2 degrees over much of the region.[9][10] With the cooperation of many of his squadron teammates in obtaining many hundreds of statistical readings, startling results were revealed:

The centre of the north magnetic dip pole was on Prince of Wales Island some 400 kilometres (250 mi) NNW of the positions determined by Amundsen and Ross, and the dip pole occupied a larger elliptical area, with foci about 400 km (250 mi) apart on Boothia Peninsula and Bathurst Island.

Klein called the two foci local poles, for their importance to navigation in emergencies when using a "homing" procedure. About 3 months after Klein's findings were officially reported, a Canadian ground expedition was sent into the Archipelago to locate the position of the magnetic pole. R. Glenn Madill, Chief of Terrestrial Magnetism, Department of Mines and Resources, Canada, wrote to Lt. Klein on 21 July 1948:

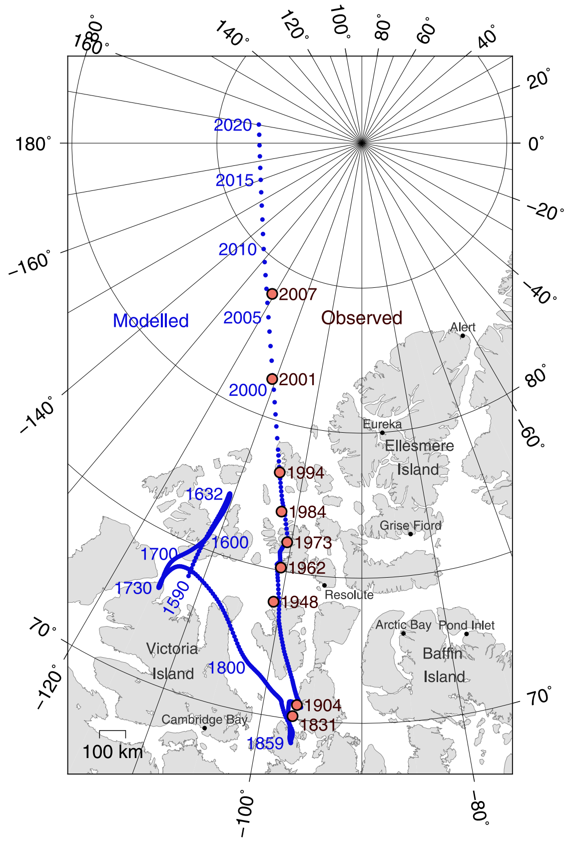
> …we agree on one point and that is the presence of what we can call the main magnetic pole on northwestern Prince of Wales Island. I have accepted as a purely preliminary value the position latitude 73°N and longitude 100°W. Your value of 73°15'N and 99°45' W is in excellent agreement, and I suggest that you use your value by all means.
> —R. Glenn Madill[9]

(The positions were less than 30 km (20 mi) apart.)

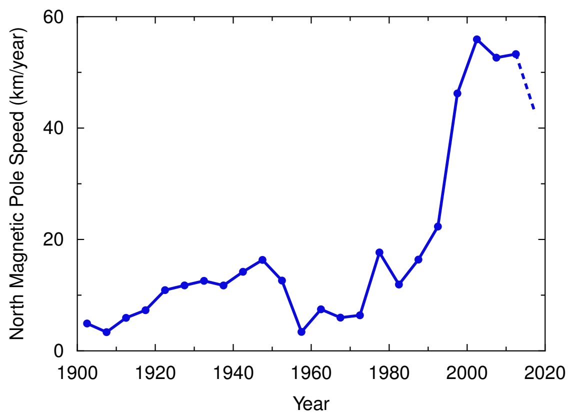
8.3.3 Modern (post-1996)

The Canadian government has made several measurements since, which show that the North Magnetic Pole is moving continually northwestward. In 2001, an expedition located the pole at 81°18′N 110°48′W / 81.3°N 110.8°W. In 2007, the latest survey found the pole at 83°57′N 120°43′W / 83.95°N 120.72°W.[11] During the 20th century it moved 1100 km, and since 1970 its rate of motion has accelerated from 9 km/year to approximately 52 km/year (2001–2007 average; see also Polar drift). Members of the 2007 expedition to locate the magnetic north pole wrote that such expeditions have become logistically difficult, as the pole moves farther away from inhabited locations. They expect that in the future, the magnetic pole position will be obtained from satellite data instead of ground surveys.[11]

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.[12] This effect is due to disturbances of the geomagnetic field by charged particles from the Sun.



The movement of Earth's north magnetic pole across the Canadian arctic.

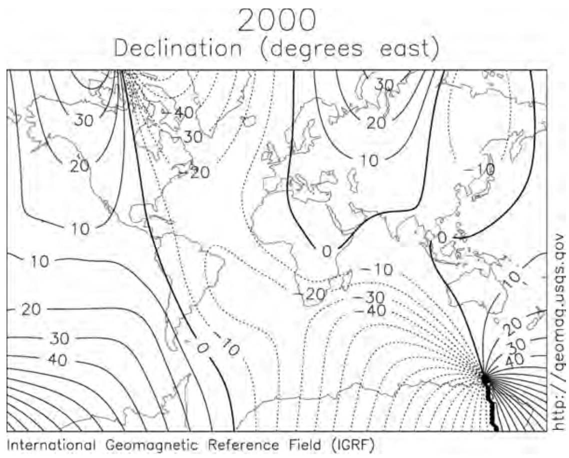


Speed of the north magnetic pole according to the IGRF-12 model.

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 Sue Stockdale 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, and certified its location by magnetometer and theodolite at 78°35.7′N 104°11.9′W / 78.5950°N 104.1983°W.*[15]

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 / 78.5950°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 (and their support and camera team) became the first people in history to reach this location in a car.*[16]

8.4 Magnetic north and magnetic declination



Magnetic declination from true north in 2000.

Main article: Magnetic declination

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 local angular difference between magnetic north and true north 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 North America 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.

8.5 North Geomagnetic Pole

Main article: 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 10° 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.*[17]

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 magnetic *south* 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,*[17] but it is now drifting away from North America and toward Siberia.

8.6 Geomagnetic reversal

Main article: Geomagnetic reversal

Over the life of the Earth, the orientation of Earth's magnetic field has reversed many 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.*[18]

8.7 See also

- South Magnetic Pole
- North Pole
- Polar alignment

8.8 Notes and references

[1] Merrill, Ronald T.; McElhinny, Michael W.; McFadden, Phillip L. (1996). "Chapter 8". *The magnetic field of the earth: paleomagnetism, the core, and the deep mantle*. Academic Press. ISBN 978-0-12-491246-5.

[2] World Data Center for Geomagnetism, Kyoto. "Magnetic North, Geomagnetic and Magnetic Poles". Retrieved 2012-07-03.

[3] North Magnetic Pole Moving East Due to Core Flux, National Geographic, December 24, 2009

[4] "The Magnetic North Pole". *Ocean bottom magnetology laboratory*. Woods Hole Oceanographic Institution. Retrieved 2017-02-06.

[5] Serway, Raymond A.; Chris Vuille (2006). *Essentials of college physics*. USA: Cengage Learning. p. 493. ISBN 0-495-10619-4. Retrieved 2012-04-19.

[6] Russell, Randy. "Earth's Magnetic Poles". *Windows to the Universe*. National Earth Science Teachers Association. Retrieved 2012-04-19.

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[8] History of Expeditions to the North Magnetic Pole, Natural Resources Canada

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[10] Wack, Fred John (1992). *The Secret Explorers: Saga of the 46th/72nd Reconnaissance Squadrons*. Seeger's Print.

[11] L. R. Newitt, A. Chulliat, and J.-J. Orgeval, Location of the North Magnetic Pole in April 2007, Earth Planets Space, 61, 703–710, 2009

[12] Geomagnetism —Daily Movement of the North Magnetic Pole, Natural Resources Canada

[13] "Geomagnetism, North Magnetic Pole". *Geological Survey of Canada*. Natural Resources Canada. Archived from the original on 2010-03-26. Retrieved 11 January 2009.

[14] "Poles and Directions". Australian Antarctic Division. 2011. Retrieved 2017-02-06.

[15] 1996 Certified Position of the Magnetic North Pole, Jock Wishart, Polar Race organiser

[16] "Polar Challenge". *Top Gear*. 25 July 2007. 0:22 minutes in. BBC Two. Retrieved 19 April 2012.

[17] "Geomagnetism Frequently Asked Questions". National Geophysical Data Center. Retrieved 19 April 2012.

[18] Earth's Inconstant Magnetic Field – NASA Science

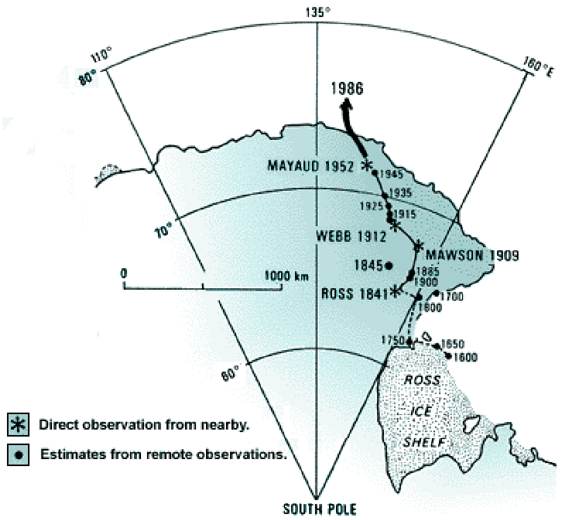
8.9 External links

- "Wandering of the geomagnetic poles" . *Geomagnetism*. National Geophysical Data Center. Retrieved 19 April 2012.
- "Geomagnetism" . Natural Resources Canada. April 1, 2012. Retrieved 19 April 2012.
- Map of pole's wandering
- "North Magnetic Pole could be leaving Canada" . *CNN.com*. 20 March 2002. Retrieved 19 April 2012.
- "Magnetic pole drifting fast" . *BBC News*. 12 December 2005. Retrieved 19 April 2012.
- Nemiroff, R.; Bonnell, J., eds. (25 November 2002). "The Earth's magnetic field" . *Astronomy Picture of the Day*. NASA. Retrieved 2012-04-19.

Chapter 9

South Magnetic Pole

"Magnetic south" redirects here. For other uses, see Magnetic South (disambiguation).
For additional general information about the Earth's magnetic poles, see North Magnetic Pole.



Locations of South Magnetic Pole from direct observation and model prediction.[*][1]*

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

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

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 / 64.53000°S 137.86000°E,[*][2] placing it off the coast of Antarctica, between Adelie Land and Wilkes Land. In 2015 it lay at 64°17′S 136°35′E / 64.28°S 136.59°E (est).[*][3] That point lies outside the Antarctic Circle. Due to polar drift, the pole is moving northwest by about 10 to 15 kilometers per year. Its current distance from the actual Geographic South Pole is approximately 2860 km.[*][1] The nearest permanent science station is Dumont d'Urville Station. Wilkes Land contains a large gravitational mass concentration.

9.1 Expeditions

Early unsuccessful attempts to reach the magnetic south pole included those of French explorer Dumont d'Urville (1837–40), American Charles Wilkes (expedition of 1838–42) and Briton James Clark Ross (expedition of 1839 to 1843).[*][7]

The first calculation of the magnetic inclination to locate the magnetic South Pole was made on January 23, 1838 by the hydrographer Clément Adrien Vincendon-Dumoulin, a member of the Dumont d'Urville expedition in Antarctica and Oceania on the corvettes "L'Astrolabe" and "Zélée" in 1837-1840, which discovered Adelie Land.

On 16 January 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,[*][8] which was at that time located on land. However, there is now some doubt as to whether their location was correct.[*][9] The approximate position of the pole on 16 January 1909 was 72°15′S 155°09′E / 72.25°S 155.15°E.[*][10]

9.2 Fits to global data sets

The South Magnetic Pole has also been estimated by fits to global sets of data such as the World Magnetic Model (WMM) and the International Geomagnetic Reference Model (IGRF).[*][1] For earlier years back to about 1600, the model GUFM1 is used, based on a compilation of data from ship logs.[*][11]

9.3 South Geomagnetic Pole

Main article: 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,*[12] 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.

9.4 See also

- North Magnetic Pole
- Polar alignment

9.5 References

[1] NOAA National Geophysical Data Center. "Wandering of the Geomagnetic Poles". Retrieved October 10, 2011.

[2] "Geomagnetism Frequently Asked Questions". NGDC. Retrieved 11 January 2009.

[3] British Geological Survey - Magnetic Poles

[4] "Geomagnetism, North Magnetic Pole". *Geological Survey of Canada*. Natural Resources Canada. Retrieved 11 January 2009.

[5] World Data Center for Geomagnetism, Kyoto. "Magnetic North, Geomagnetic and Magnetic Poles". Retrieved 2012-07-03.

[6] "Poles and Directions". Australian Antarctic Division. 2011. Retrieved October 11, 2011.

[7] *Antarctic Treaty System: an Assessment*, p. 90, US National Research Council, 1986

[8] "FAQs from primary schools - British Antarctic Survey". Antarctica.ac.uk. 2011-03-11. Retrieved 2012-11-09.

[9] "The Magnetic South Pole". *Ocean Bottom Magnetology Laboratory*. Woods Hole Oceanographic Institute. Retrieved October 11, 2011.

[10] Shackleton, Roland Huntford

[11] Jackson, Andrew; Jonkers, Art R. T.; Walker, Matthew R. (2000). "Four centuries of geomagnetic secular variation from historical records". *Philosophical Transactions of the Royal Society A*. **358** (1768): 957–990. doi:10.1098/rsta.2000.0569.

[12] "Geomagnetism Frequently Asked Questions". Ngdc.noaa.gov. Retrieved 2012-11-09.

- Barton, Charles (2002). "Survey tracks current position of South Magnetic Pole". *EOS*. **83** (27): 291. doi:10.1029/2002EO000210.

9.6 External links

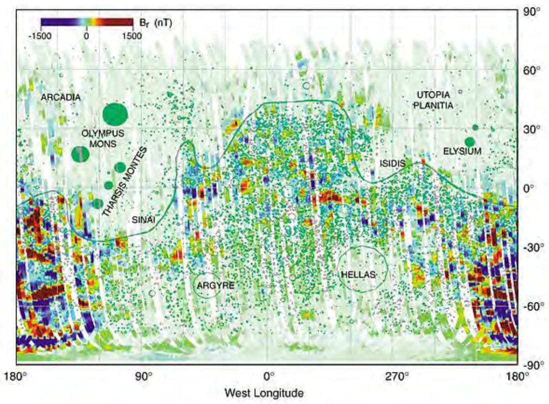
- Australian Antarctic Division

Chapter 10

Magnetic anomaly

For more details on this topic, see Magnetic striping.

In geophysics, a **magnetic anomaly** is a local variation in the Earth's magnetic field resulting from variations in the chemistry or magnetism of the rocks. Mapping of variation over an area is valuable in detecting structures obscured by overlying material. The magnetic variation in successive bands of ocean floor parallel with mid-ocean ridges is important evidence supporting the theory of seafloor spreading, central to plate tectonics.



Satellite measurements of the radial magnetic field on Mars.

10.1 Measurement

Magnetic anomalies are generally a small fraction of the magnetic field. The total field ranges from 25,000 to 65,000 nanoteslas (nT).*[1] To measure anomalies, magnetometers need a sensitivity of 10 nT or less. There are three main types of magnetometer used to measure magnetic anomalies:*[2]*:162–164*[3]*:77–79

1. The fluxgate magnetometer was developed during World War II to detect submarines.*[3]*:75*[4] It measures the component along a particular axis of the sensor, so it needs to be oriented. On land, it is often oriented vertically, while in aircraft, ships and satellites it is usually oriented so the axis is in the direction of the field. It measures the magnetic field continuously, but drifts over time. One way to correct for drift is to take repeated measurements at the same place during the survey.*[2]*:163–165*[3]*:75–77

2. The proton precession magnetometer measures the strength of the field but not its direction, so it does not need to be oriented. Each measurement takes a second or more. It is used in most ground surveys except for boreholes and high-resolution gradiometer surveys.*[2]*:163–165*[3]*:77–78

3. Optically pumped magnetometers, which use alkali gases (most commonly rubidium and cesium) have high sample rates and sensitivities of 0.001 nT or less, but are more expensive than the other types of magnetometers. They are used on satellites and in most aeromagnetic surveys.*[3]*:78–79

10.2 Data acquisition

10.2.1 Ground-based

In ground-based surveys, measurements are made at a series of stations, typically 15 to 60 m apart. Usually a proton precession magnetometer is used and it is often mounted on a pole. Raising the magnetometer reduces the influence of small ferrous objects that were discarded by humans. To further reduce unwanted signals, they do not carry objects such as keys, knives or compasses. In addition, objects such as motor vehicles, railway lines, and barbed wire fences are avoided. If some such contaminant is overlooked, it often shows up as a sharp spike in the anomaly, so such features are treated with suspicion. The main application for ground-based surveys is detailed search for minerals.*[2]*:163*[3]*:83–84

10.2.2 Aeromagnetic

Main article: Aeromagnetic survey

Airborne magnetic surveys are often used in oil surveys to provide preliminary information for seismic surveys. In some countries such as Canada, government agencies

This helicopter is equipped with a magnetometer array. It flies six feet above ground at speeds of 30 to 40 mph.

have made systematic surveys of large areas. The survey generally involves making a series of parallel runs at a constant height and intervals of anywhere from a hundred meters to several kilometers. These are crossed by occasional tie lines, perpendicular to the main survey, to check for errors. The plane is a source of magnetism, so sensors are either mounted on a boom (as in the figure) or towed behind on a cable. Aeromagnetic surveys have a lower spatial resolution of ground surveys, but this can be an advantage for a regional survey of deeper rocks.*[2]*:166*[3]*:81–83

10.2.3 Shipborne

In shipborne surveys, a magnetometer is towed a few hundred meters behind a ship in a device called a *fish*. The sensor is kept at a constant depth of about 15 m. Otherwise, the procedure is similar to that used in aeromagnetic surveys.*[2]*:167*[3]*:83

10.2.4 Spacecraft

American and Russian satellites began measuring the Earth's field in the 1960s.*[5] In the fall of 1979, Magsat was launched and jointly operated by NASA and USGS until the spring of 1980. It had a cesium vapor scalar magnetometer and a fluxgate vector magnetometer.*[6] CHAMP, a German satellite, made precise gravity and magnetic measurements from 2001 to 2010.*[7]*[8] A Danish satellite, Ørsted, was launched in 1999 and is still in operation, while the Swarm mission of the European Space Agency involves a "constellation" of three satellites that were launched in November, 2013.*[9]*[10]*[11]

10.3 Data reduction

There are two main corrections that are needed for magnetic measurements. The first is remove short-term variations in the field from external sources. There are *diurnal variations* that have a period of 24 hours and magnitudes of up to 30 nT, probably from the action of the solar wind on the ionosphere.*[3]*:72 In addition, magnetic storms can have peak magnitudes of 1000 nT and can last for several days. Their contribution can be measured by returning to a base station repeatedly or by having another magnetometer that periodically measures the field at a fixed location.*[2]*:167

The anomaly is the local contribution to the magnetic field, so the main geomagnetic field must be subtracted from it. Usually the International Geomagnetic Reference Field is used for this purpose. This is a large-scale, time-averaged mathematical model of the Earth's field based on measurements from satellites, magnetic observatories and other surveys.*[2]*:167

Some corrections that are needed for gravity anomalies are less important for magnetic anomalies. For example, the vertical gradient of the magnetic field is 0.03 nT/m or less, so an elevation correction is generally not needed.*[2]*:167

10.4 Interpretation

The magnetization in the surveyed rock is a vector sum of induced and remanent magnetization:

$$\mathbf{M} = \mathbf{M}_{\mathrm{i}} + \mathbf{M}_{\mathrm{r}}.$$

The induced magnetization of many minerals is the product of the ambient magnetic field and their magnetic susceptibility χ:

$$\mathbf{M}_{\mathrm{i}} = \chi \mathbf{H}.$$

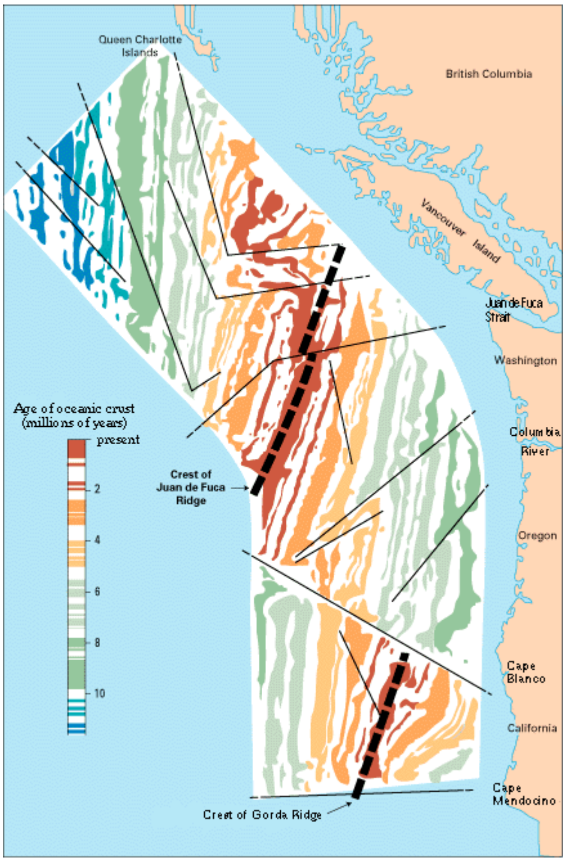
Some susceptibilities are given in the table.

Minerals that are diamagnetic or paramagnetic only have an induced magnetization. Ferromagnetic minerals such as magnetite also can carry a remanent magnetization or remanence. This remanence can last for millions of years, so it may be in a completely different direction from the present Earth's field. If a remanence is present, it is difficult to separate from the induced magnetization unless samples of the rock are measured. The ratio of the magnitudes, $Q = M_r/M_i$, is called the Koenigsberger ratio.*[2]*:172–173*[12]

10.5 Applications

10.5.1 Ocean floor stripes

Magnetic surveys over the oceans have revealed a characteristic pattern of anomalies around mid-ocean ridges.



Magnetic anomalies around the Juan de Fuca and Gorda Ridges, off the west coast of North America, color coded by age.

They involve a series of positive and negative anomalies in the intensity of the magnetic field, forming stripes running parallel to each ridge. They are often symmetric about the axis of the ridge. The stripes are generally tens of kilometers wide, and the anomalies are a few hundred nanoteslas. The source of these anomalies is primarily permanent magnetization carried by titanomagnetite minerals in basalt and gabbros. They are magnetized when ocean crust is formed at the ridge. As magma rises to the surface and cools, the rock acquires a thermoremanent magnetization in the direction of the field. Then the rock is carried away from the ridge by the motions of the tectonic plates. Every few hundred thousand years, the direction of the magnetic field reverses. Thus, the pattern of stripes is a global phenomenon and can be used to calculate the velocity of seafloor spreading.*[13]*[14]

10.6 In fiction

In the *Space Odyssey* series by Arthur C. Clarke, a series of monoliths are left by extraterrestrials for humans to find them. One near the crater Tycho is found by its unnaturally powerful magnetic field and named *Tycho Magnetic Anomaly 1* (TMA-1).*[15] One orbiting Jupiter is named TMA-2, and one in the Olduvai Gorge is found in 2513 and retroactively named TMA-0 because it was first encountered by primitive humans.

10.7 See also

- Bangui magnetic anomaly
- Geomagnetic reversal
- Kursk Magnetic Anomaly
- Magnetic anomaly detector
- South Atlantic Anomaly
- Temagami Magnetic Anomaly
- World Digital Magnetic Anomaly Map (WDMAM)

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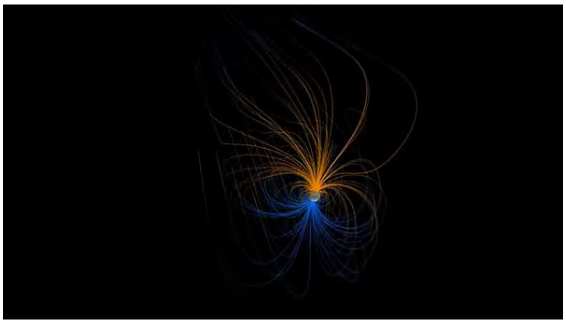
10.10 External links

- Magnetic field of the lithosphere (CIRES)
- Magnetic anomaly maps and data for North America (USGS)
- World Digital Magnetic Anomaly Map: info
- Magnetic anomaly map of the world
- Asteroids may have delivered magnetic material to the Moon

Chapter 11

Magnetosphere



A rendering of the magnetic field lines of Earth's magnetosphere

A **magnetosphere** is the region of space surrounding an astronomical object in which charged particles are controlled by that object's magnetic field.*[1]*[2] The magnetic field near the surface of many astronomical objects resembles that of a dipole. The field lines farther away from the surface can be significantly distorted by the flow of electrically conducting plasma emitted from a nearby star (e.g. the solar wind from the Sun).*[3]*[4]

11.1 History

Main article: Magnetosphere chronology

Study of Earth's magnetosphere began in 1600, when William Gilbert discovered that the magnetic field on the surface of Earth resembled that on a terrella, a small, magnetized sphere. In the 1940s, Walter M. Elsasser proposed the model of dynamo theory, which attributes Earth's magnetic field to the motion of Earth's iron outer core. Through the use of magnetometers, scientists were able to study the variations in Earth's magnetic field as functions of both time and latitude and longitude. Beginning in the late 1940s, rockets were used to study cosmic rays. In 1958, Explorer 1, the first of the Explorer series of space missions, was launched to study the intensity of cosmic rays above the atmosphere and measure the fluctuations in this activity. This mission observed the existence of the Van Allen radiation belt (located in the inner region of Earth's magnetosphere), with the Explorer 3 mission later that year definitively proving its existence. Also in 1958, Eugene Parker proposed the idea of the solar wind. The term 'magnetosphere' was proposed by Thomas Gold in 1959. The Explorer 12 mission (1961) led to the observation by Cahill and Amazeen in 1963 of a sudden decrease in the strength of the magnetic field near the noon meridian, later named the magnetopause. In 1983, the International Cometary Explorer observed the magnetotail, or the distant magnetic field.*[4]

11.2 Types

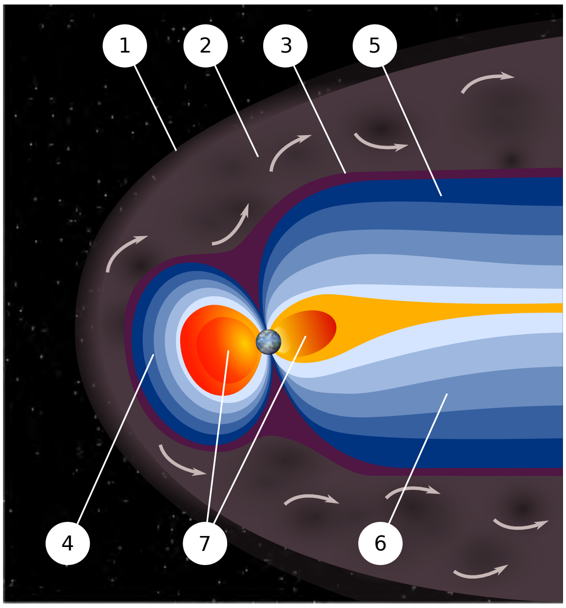
The structure and behavior of magnetospheres are dependent on several variables: the type of astronomical object, the nature of sources of plasma and momentum, the period of the object's spin, the nature of the axis about which the object spins, the axis of the magnetic dipole, and the magnitude and direction of the flow of solar wind.

The distance at which a planet can withstand the solar wind pressure is called the Chapman–Ferraro distance. This is modeled by a formula wherein R_P represents the radius of the planet, B_{surf} represents the magnetic field on the surface of the planet at the equator, and V_{SW} represents the velocity of the solar wind:

$$R_{CF} = R_P \left(\frac{B_{surf}^2}{\mu_0 \rho V_{SW}^2} \right)^{\frac{1}{6}}$$

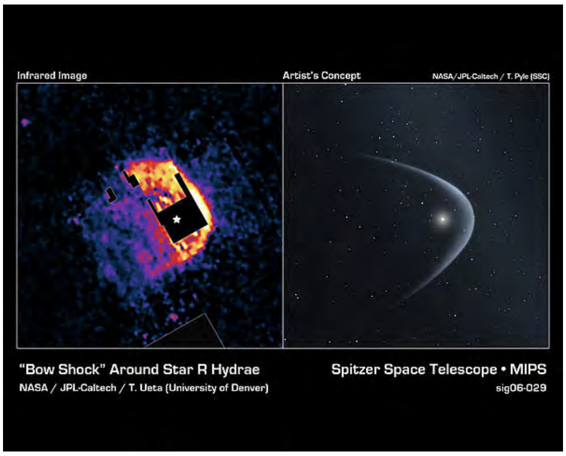
A magnetosphere is classified as "intrinsic" when $R_{CF} \gg R_P$, or when the primary opposition to the flow of solar wind is the magnetic field of the object. Mercury, Earth, Jupiter, Ganymede, Saturn, Uranus, and Neptune exhibit intrinsic magnetospheres. A magnetosphere is classified as "induced" when $R_{CF} \ll R_P$, or when the solar wind is not opposed by the object's magnetic field. In this case, the solar wind interacts with the atmosphere or ionosphere of the planet (or surface of the planet, if the planet has no atmosphere). Venus has an induced magnetic field, which means that because Venus appears to have no internal dynamo effect, the only magnetic field present is that formed by the solar wind's wrapping around the physical obstacle of Venus (see also Venus' induced magnetosphere). When $R_{CF} \approx R_P$, the planet itself and its magnetic field both contribute. It is possible that Mars is of this type.*[5]

11.3 Structure



An artist's rendering of the structure of a magnetosphere: 1) Bow shock. 2) Magnetosheath. 3) Magnetopause. 4) Magnetosphere. 5) Northern tail lobe. 6) Southern tail lobe. 7) Plasmasphere.

11.3.1 Bow shock



Infrared image and artist's concept of the bow shock around R Hydrae

Main article: Bow shock

The bow shock forms the outermost layer of the magnetosphere; the boundary between the magnetosphere and the ambient medium. For stars, this is usually the boundary between the stellar wind and interstellar medium; for planets, the speed of the solar wind there decreases as it approaches the magnetopause.*[6]

11.3.2 Magnetosheath

Main article: Magnetosheath

The magnetosheath is the region of the magnetosphere between the bow shock and the magnetopause. It is formed mainly from shocked solar wind, though it contains a small amount of plasma from the magnetosphere.*[7] It is an area exhibiting high particle energy flux, where the direction and magnitude of the magnetic field varies erratically. This is caused by the collection of solar wind gas that has effectively undergone thermalization. It acts as a cushion that transmits the pressure from the flow of the solar wind and the barrier of the magnetic field from the object.*[4]

11.3.3 Magnetopause

Main article: Magnetopause

The magnetopause is the area of the magnetosphere wherein the pressure from the planetary magnetic field is balanced with the pressure from the solar wind.*[3] It is the convergence of the shocked solar wind from the magnetosheath with the magnetic field of the object and plasma from the magnetosphere. Because both sides of this convergence contain magnetized plasma, the interactions between them are complex. The structure of the magnetopause depends upon the Mach number and beta of the plasma, as well as the magnetic field.*[8] The magnetopause changes size and shape as the pressure from the solar wind fluctuates.*[9]

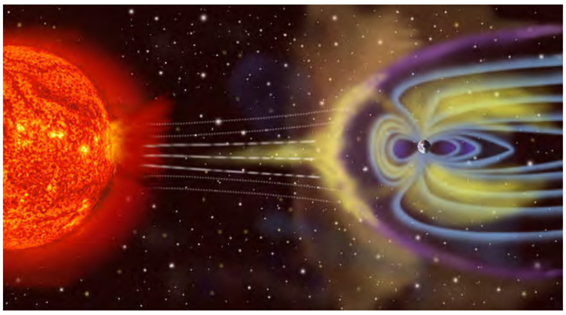
11.3.4 Magnetotail

Opposite the compressed magnetic field is the magnetotail, where the magnetosphere extends far beyond the astronomical object. It contains two lobes, referred to as the northern and southern tail lobes. Magnetic field lines in the northern tail lobe point towards the object while those in the southern tail lobe point away. The tail lobes are almost empty, with few charged particles opposing the flow of the solar wind. The two lobes are separated by a plasma sheet, an area where the magnetic field is weaker and the density of charged particles is higher.*[10]

11.3.5 Earth's magnetosphere

See also: Earth's magnetic field § Magnetosphere

Over Earth's equator, the magnetic field lines become almost horizontal, then return to reconnect at high latitudes. However, at high altitudes, the magnetic field is significantly distorted by the solar wind and its solar magnetic field. On the dayside of Earth, the magnetic field is significantly compressed by the solar wind to



Artist's rendition of Earth's magnetosphere

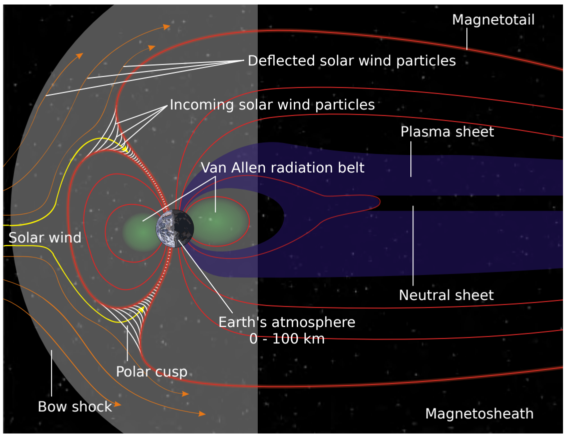


Diagram of Earth's magnetosphere

a distance of approximately 65,000 kilometers (40,000 mi). Earth's bow shock is about 17 kilometers (11 mi) thick*[11] and located about 90,000 kilometers (56,000 mi) from Earth.*[12] The magnetopause exists at a distance of several hundred kilometers above Earth's surface. Earth's magnetopause has been compared to a sieve because it allows solar wind particles to enter. Kelvin–Helmholtz instabilities occur when large swirls of plasma travel along the edge of the magnetosphere at a different velocity from the magnetosphere, causing the plasma to slip past. This results in magnetic reconnection, and as the magnetic field lines break and reconnect, solar wind particles are able to enter the magnetosphere.*[13] On Earth's nightside, the magnetic field extends in the magnetotail, which lengthwise exceeds 6,300,000 kilometers (3,900,000 mi).*[3] Earth's magnetotail is the primary source of the polar aurora.*[10] Also, NASA scientists have suggested that Earth's magnetotail might cause "dust storms" on the Moon by creating a potential difference between the day side and the night side.*[14]

11.3.6 Other objects

The magnetosphere of Jupiter is the largest planetary magnetosphere in the Solar System, extending up to 7,000,000 kilometers (4,300,000 mi) on the dayside and almost to the orbit of Saturn on the nightside.*[15] Jupiter's magnetosphere is stronger than Earth's by an order of magnitude, and its magnetic moment is approximately 18,000 times larger.*[16] Pluto, on the other hand, has no magnetic field.*[17]

11.4 See also

Geomagnetism – Wikipedia book

- Plasma physics

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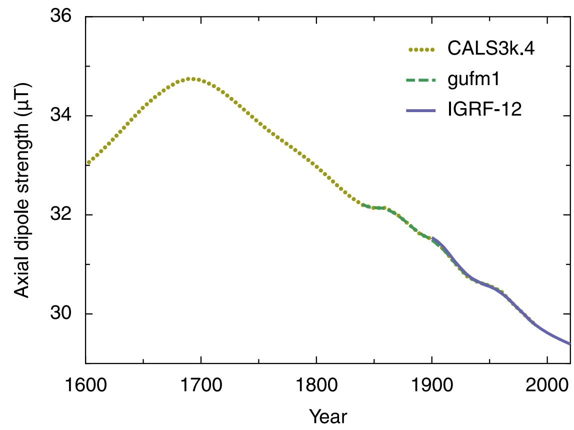
Chapter 12

Geomagnetic secular variation

Geomagnetic secular variation refers to changes in the Earth's magnetic field on time scales of about a year or more. These changes mostly reflect changes in the Earth's interior, while more rapid changes mostly originate in the ionosphere or magnetosphere.*[1]

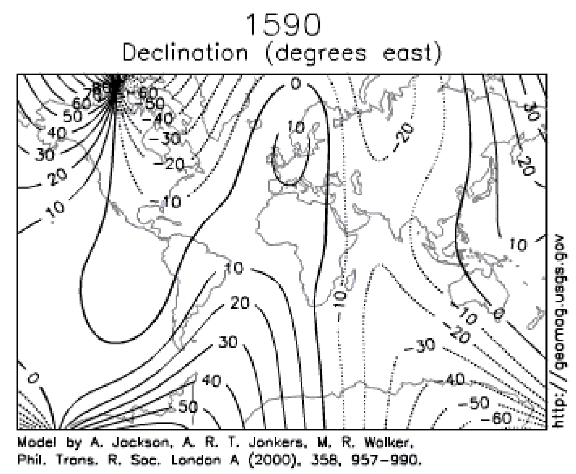


Strength of the axial dipole component of Earth's magnetic field from 1600 to 2020, according to three models.

12.1 Introduction

The geomagnetic field changes on time scales from milliseconds to millions of years. Shorter time scales mostly arise from currents in the ionosphere and magnetosphere, and some changes can be traced to geomagnetic storms or daily variations in currents. Changes over time scales of a year or more mostly reflect changes in the Earth's interior, particularly the iron-rich core. These changes are referred to as *secular variation*.*[1]

12.2 Recent change



Estimated declination contours by year, 1590 to 1990 (click to see variation).

Secular variation can be observed in measurements at magnetic observatories, some of which have been around for hundreds of years (the Kew Observatory, for example). Over such a time scale, magnetic declination is observed to vary over tens of degrees.*[1] A movie on the right shows how global declinations have changed over the last few centuries.*[2]

To analyze global patterns of change in the geomagnetic field, geophysicists fit the field data to a spherical harmonic expansion (see International Geomagnetic Reference Field). The terms in this expansion can be divided into a dipolar part, like the field around a bar magnet, and a nondipolar part. The dipolar part dominates the geomagnetic field and determines the direction of the geomagnetic poles. The direction and intensity of the dipole change over time.*[1] Over the last two centuries the dipole strength has been decreasing at a rate of about 6.3% per century. At this rate of decrease, the field would reach zero in about 1600 years.*[3] However, this strength is about average for the last 7 thousand years, and the current rate of change is not unusual.*[4]

A prominent feature in the non-dipolar part of the secular variation is a *westward drift* at a rate of about 0.2 degrees per year.*[3] This drift is not the same everywhere and has varied over time. The globally averaged drift has been westward since about 1400 AD but eastward between about 1000 AD and 1400 AD.*[5]

12.3 Paleomagnetic secular variation

Changes that predate magnetic observatories are recorded in archaeological and geological materials. Such changes are referred to as *paleomagnetic secular variation* or *paleosecular variation (PSV)*. The records typically include long periods of small change with occasional large changes reflecting geomagnetic excursions and geomagnetic reversals.*[6]

12.4 See also

- Geomagnetic jerk
- Secular variation

12.5 Notes

[1] Merrill, McElhinny & McFadden 1996, Ch. 2

[2] Jackson, Jonkers & Walker 2000

[3] CGS 2011

[4] Constable 2007

[5] Dumberry & Finlay 2007

[6] Tauxe 1998, Ch. 1

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Chapter 13

Geomagnetic excursion

A **geomagnetic excursion**, like a geomagnetic reversal, is a significant change in the Earth's magnetic field. Unlike reversals however, an excursion does not permanently change the large-scale orientation of the field, but rather represents a dramatic, typically short-lived decrease in field intensity, with a variation in pole orientation of up to 45 degrees from the previous position. These events, which typically last a few thousand to a few tens of thousands of years, often involve declines in field strength to between 0 and 20% of normal. Excursions, unlike reversals, are generally not recorded around the entire globe. This is partially due to them not being recorded well within the sedimentary record, but also because they likely do not extend through the entire geomagnetic field. One of the first excursions to be studied was the Laschamp event, dated at around 40,000 years ago. This event was a complete reversal of polarity, however, as it later turned out, though with the reversed field 5% of the normal strength*[1] Since this event has also been seen in sites around the globe, it is suggested as one of the few examples of a truly global excursion.*[2]

13.1 Causes

Scientific opinion is divided on what causes geomagnetic excursions. The dominant theory is that they are an inherent aspect of the dynamo processes that maintain the Earth's magnetic field. In computer 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. In such cases, this spontaneous disorganization can cause decreases in the magnetic field as perceived at the Earth's surface. In truth, under this scenario, the Earth's magnetic field intensity does not significantly change in the core itself, but rather energy is transferred from a dipole configuration to higher order multipole moments which decay more rapidly with the distance from the Earth's core, so that the expression of such a magnetic field at the surface of the Earth would be considerably less, even without significant changes in the strength of the deep field. This scenario is supported by observed tangling and spontaneous disorganizations in the solar magnetic field. However, this process in the sun invariabily leads to a reversal of the solar magnetic field (see: solar cycle), and has never been observed such that the field would recover without large scale changes in field orientation.

The work of David Gubbins suggests that excursions occur when the magnetic field is reversed only within the liquid outer core; reversals occur when the inner core is also affected.*[3] This fits well with observations of events within the current chron of reversals taking 3–7000 years to complete, while excursions typically last 500–3000 years. However, this timescale does not hold true for all events, and the need for separate generation of fields has been contested, since the changes can be spontaneously generated in mathematical models.

A minority opinion, held by such figures as Richard A. Muller, is that geomagnetic excursions are not spontaneous processes but rather triggered by external events which directly disrupt the flow in the Earth's core. Such processes may include the arrival of continental slabs carried down into the mantle by the action of plate tectonics at subduction zones, the initiation of new mantle plumes from the core-mantle boundary, and possibly mantle-core shear forces and displacements resulting from very large impact events. Supporters of this theory hold that any of these events lead to a large scale disruption of the dynamo, effectively turning off the geomagnetic field for a period of time necessary for it to recover.

Except for recent periods of the geologic past, it is not well known how frequently geomagnetic excursions occur. Unlike geomagnetic reversals, which are easily detected by the change in field direction, the relatively short-lived excursions can be easily overlooked in long duration, coarsely resolved, records of past geomagnetic field intensity. Present knowledge suggests that they are around ten times more abundant than reversals, with up to 12 excursions documented within the current reversal period Brunhes–Matuyama reversal.

13.2 Effects

Due to the weakening of the magnetic field, particularly during the transition period, greater amounts of radiation would be able to reach the Earth, increasing production of beryllium 10 and levels of carbon 14.*[4] However, it is likely that nothing serious would occur, as the human species has certainly lived through at least one such event; *Homo erectus* and possibly *Homo heidelbergensis* lived through the Matuyama reversal with no known ill effect, and excursions are shorter lived and do not result in permanent changes to the magnetic field. The major hazard to modern society is likely to be similar to those associated with geomagnetic storms, where satellites and power supplies may be damaged, although compass navigation would also be affected. Some forms of life which are thought to navigate based on magnetic fields may be disrupted, but again it is suggested that these species have survived excursions in the past. Since excursion periods are not always global, any effect might well only be experienced in certain places, with others relatively unaffected. The time period involved could be as little as a century, or as much as 10,000 years.

13.2.1 Possible relationship to climate

There is evidence that geomagnetic excursions may be associated with episodes of rapid short-term climatic cooling during periods of continental glaciation (ice ages).*[5]

13.3 See also

- *Geomagnetism* – Wikipedia book

13.4 Notes and references

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Chapter 14

Geomagnetic reversal

"Magnetic reversal" redirects here. For switching of a magnet, see Magnetization reversal.
"Polarity reversal" redirects here. For a seismic anomaly, see Polarity reversal (seismology).

A **geomagnetic reversal** is a change in a planet's magnetic field such that the positions of magnetic north and magnetic south are interchanged, while geographic north and geographic south remain the same. 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 the opposite. These periods are called *chrons*.

The time spans of chrons are randomly distributed with most being between 0.1 and 1 million years with an average of 450,000 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, and may have happened very quickly, within a human lifetime.*[1]

A brief complete reversal, known as the Laschamp event, occurred only 41,000 years ago during the last glacial period. That reversal lasted only about 440 years with the actual change of polarity lasting around 250 years. During this change the strength of the magnetic field weakened to 5% of its present strength.*[2] Brief disruptions that do not result in reversal are called geomagnetic excursions.

14.1 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 by Motonori Matuyama in the 1920s; he observed that rocks with reversed fields 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.*[3]*[4]

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. In the absence of reliable methods for obtaining absolute ages for rocks, it was thought that reversals occurred approximately every million years.*[3]*[4]

The next major advance in understanding reversals came when techniques for radiometric dating were developed in the 1950s. Allan Cox and Richard Doell, at the United States Geological Survey, wanted to know whether reversals occurred at regular intervals, and invited the geochronologist Brent Dalrymple to join their group. They produced the first magnetic-polarity time scale in 1959. As they accumulated data, they continued to refine this scale in competition with Don Tarling and Ian McDougall at the Australian National University. A group led by Neil Opdyke at the Lamont-Doherty Geological Observatory showed that the same pattern of reversals was recorded in sediments from deep-sea cores.*[4]

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 were plotted on a map did it become apparent that remarkably regular and continuous magnetic stripes appeared on the ocean floors.*[3]*[4]

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: new sea floor is magnetized in the direction of the then-current field. Thus, sea floor spreading from a central ridge will produce pairs of magnetic stripes parallel to the ridge.*[5] 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*.*[3] The Morley–Vine–Matthews hypothesis was the first key scientific test of the seafloor spreading theory of continental drift.*[4]

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.*[3]*[4]

14.2 Observing past fields

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.

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*[5]*[6] which soon led to the development of the theory of plate tectonics. The relatively constant rate at which the sea floor spreads results in substrate "stripes" from which past magnetic field polarity can be inferred from data gathered from towing a magnetometer along the sea floor.

Because no existing unsubducted sea floor (or sea floor thrust onto continental plates) is more than about 180 million years (Ma) old, 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. These rocks can preserve a record of the field if it is not later erased by chemical, physical or biological change.

Because the magnetic field is global, similar patterns of magnetic variations at different sites may be used to correlate age in different locations. In the past four decades much paleomagnetic data about seafloor ages (up to ~250 Ma) has been collected and is useful in estimating the age of geologic sections. Not an independent dating method, it depends on "absolute" age dating methods like radioisotopic systems to derive numeric ages. It has become especially useful to metamorphic and igneous geologists where index fossils are seldom available.

14.3 Geomagnetic polarity time scale

Further information: Magnetostratigraphy

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.*[7]*[8]

14.3.1 Changing frequency 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.*[9]

14.3.2 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.

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.*[10]

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.*[10] 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.*[11]

The Ordovician is suspected to have hosted another superchron, called the *Moyero Reverse Superchron*, lasting more than 20 million years (485 to 463 million years ago). Thus far, this possible superchron has only been found in the Moyero river section north of the polar circle in Siberia.*[12] Moreover, the best data from elsewhere in the world do not show evidence for this superchron.*[13]

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 called the *Jurassic Quiet Zone*, 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, causing the geomagnetic signal to be attenuated between the seabed and the surface.*[13]

14.3.3 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.*[14] 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.*[10] 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.*[15] However, these results are probably artifacts of an analysis using sliding windows to determine reversal rates.*[16]

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 tens of thousands of years after a reversal. This could be due to an inhibition in the underlying mechanism, or it could just mean that some shorter polarity intervals have been missed.*[10] 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.*[17]*[18] The data are also consistent with a deterministic, but chaotic, process.*[19]

14.4 Character of transitions

14.4.1 Duration

Most estimates for the duration of a polarity transition are between 1,000 and 10,000 years,*[10] but some estimates are as quick as a human lifetime.*[1] Studies of 15-million-year-old lava flows on Steens Mountain, Oregon, indicate that the Earth's magnetic field is capable of shifting at a rate of up to 6 degrees per day.*[20] This was initially met with skepticism from paleomagnetists. Even if changes occur that quickly in the core, the mantle, which is a semiconductor, is thought to remove variations with periods less than a few months. A variety of possible rock magnetic mechanisms were proposed that would lead to a false signal.*[21] However, paleomagnetic studies of other sections from the same region (the Oregon Plateau flood basalts) give consistent results.*[22]*[23] It appears that the reversed-to-normal polarity transition that marks the end of Chron C5Cr (16.7 million years ago) contains a series of reversals and excursions.*[24] In addition, geologists Scott Bogue of Occidental College and Jonathan Glen of the US Geological Survey, sampling lava flows in Battle Mountain, Nevada, found evidence for a brief, several-year-long interval during a reversal when the field direction changed by over 50 degrees. The reversal was dated to approximately 15 million years ago.*[25]*[26]

14.4.2 Magnetic field

The magnetic field will not vanish completely, but many poles might form chaotically in different places during reversal, until it stabilizes again.*[27]*[28]

14.5 Causes

The magnetic field of the Earth, and of other planets that have magnetic fields, is 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.*[10] In simulations of planetary dynamos, reversals often emerge spontaneously from the underlying dynamics. For example, Gary Glatzmaier and collaborator Paul Roberts of UCLA ran a numerical model of the coupling between electromagnetism and fluid dynamics in the Earth's interior. Their simulation reproduced key features of the magnetic field over more than 40,000 years of simulated time and the computer-generated field reversed itself.*[29]*[30] Global field reversals at irregular intervals have also been observed in the laboratory liquid metal experiment “VKS2” .*[31]

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.*[32]

14.5.1 Hypothesized triggers

Some scientists, such as Richard A. Muller, think 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*[33]*[34] 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.*[35] Supporters of this hypothesis 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 half the recoveries become reversals. However, the proposed mechanism does not appear to work in a quantitative model, and the evidence from stratigraphy for a correlation between reversals and impact events is weak. There is no evidence for a reversal connected with the impact event that caused the Cretaceous–Paleogene extinction event.*[36]

14.6 Effects on biosphere

Shortly after the first geomagnetic polarity time scales were produced, scientists began exploring the possibility that reversals could be linked to extinctions. Most such proposals rest on the assumption that the Earth's magnetic field would be much weaker during reversals. Possibly the first such hypothesis was that high energy particles trapped in the Van Allen radiation belt could be liberated and bombard the Earth.*[37]*[38] Detailed calculations confirm that, if the Earth's dipole field disappeared entirely (leaving the quadrupole and higher components), most of the atmosphere would become accessible to high energy particles, but would act as a barrier to them, and cosmic ray collisions would produce secondary radiation of beryllium-10 or chlorine-36. An increase of beryllium-10 was noted in a 2012 German study showing a peak of beryllium-10 in Greenland ice cores during a brief complete reversal 41,000 years ago which led to the magnetic field strength dropping to an estimated 5% of normal during the reversal.*[2] There is evidence that this occurs both during secular variation*[39]*[40] and during reversals.*[41]*[42]

Another hypothesis by McCormac and Evans assumes that the Earth's field disappears entirely during reversals.*[43] They argue that the atmosphere of Mars may have been eroded away by the solar wind because it had no magnetic field to protect it. They predict that ions would be stripped away from Earth's atmosphere above 100 km. However, paleointensity measurements show that the magnetic field has not disappeared during reversals. Based on paleointensity data for the last 800,000 years,*[44] the magnetopause is still estimated to have been at about 3 Earth radii during the Brunhes-Matuyama reversal.*[37] Even if the internal magnetic field did disappear, the solar wind can induce a magnetic field in the Earth's ionosphere sufficient to shield the surface from energetic particles.*[45]

Hypotheses have also been advanced linking reversals to mass extinctions.*[46] Many such arguments were based on an apparent periodicity in the rate of reversals; more careful analyses show that the reversal record is not periodic.*[16] It may be, however, that the ends of superchrons have caused vigorous convection leading to widespread volcanism, and that the subsequent airborne ash caused extinctions.*[47]

Tests of correlations between extinctions and reversals are difficult for a number of reasons. Larger animals are too scarce in the fossil record for good statistics, so paleontologists have analyzed microfossil extinctions. Even microfossil data can be unreliable if there are hiatuses in the fossil record. It can appear that the extinction occurs at the end of a polarity interval when the rest of that polarity interval was simply eroded away.*[21] Statistical analysis shows no evidence for a correlation between reversals and extinctions.*[48]*[37]

14.7 See also

- *Geomagnetism* – Wikipedia book
- Magnetic anomaly
- South Atlantic Anomaly

14.8 References

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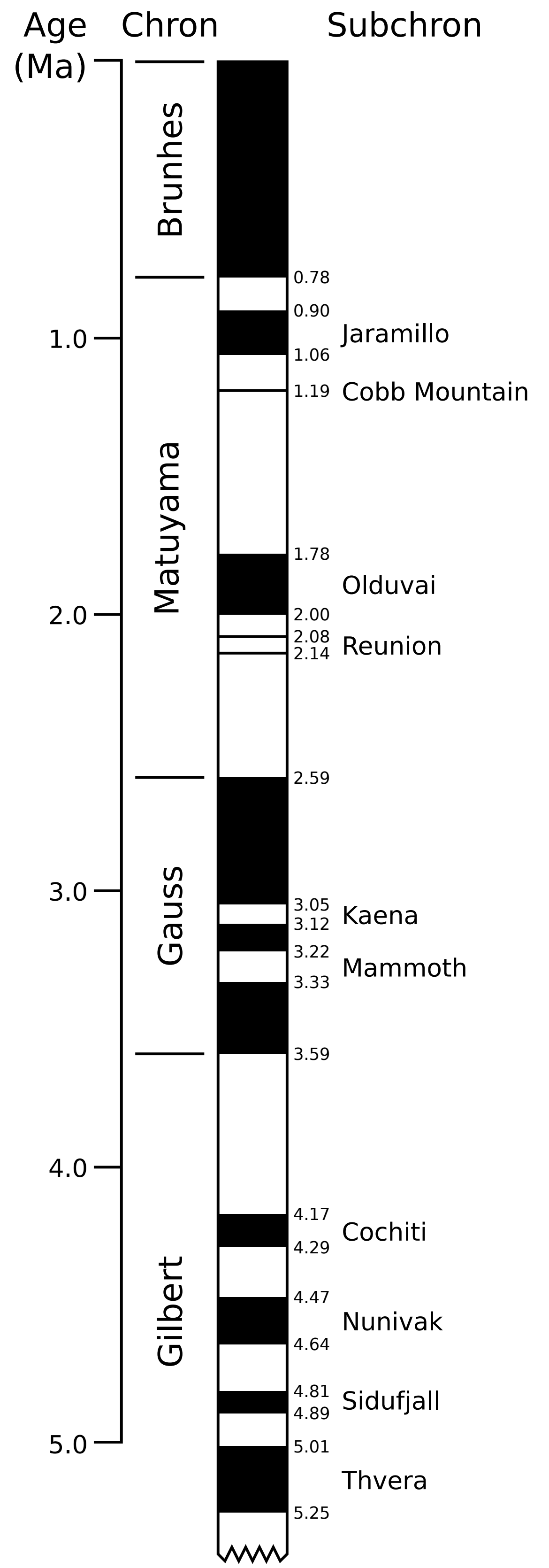
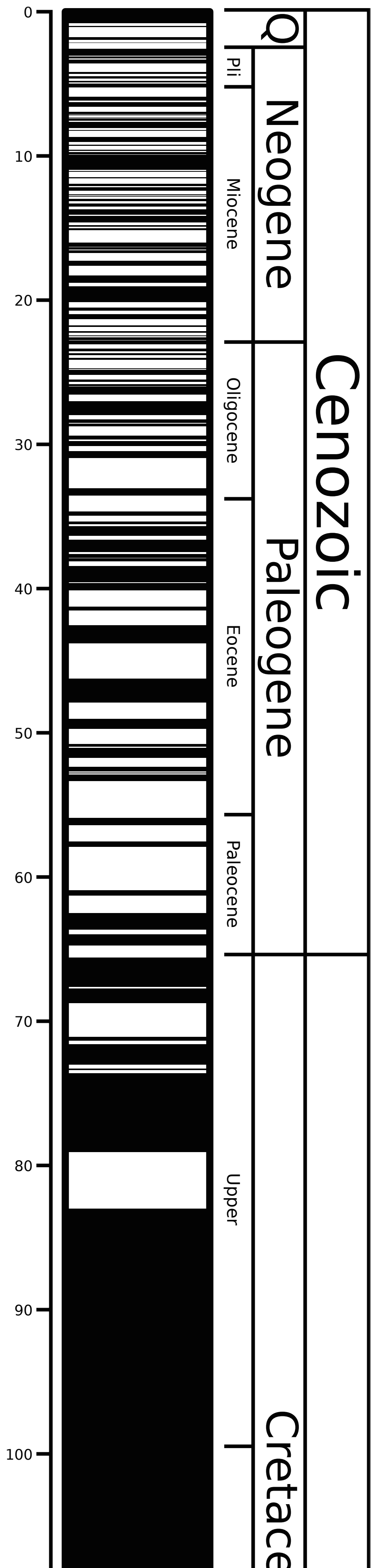
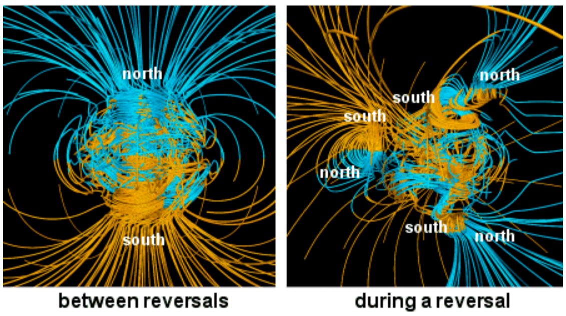
14.10 External links

- How geomagnetic reversals are related to intensity
- "Look down, look up, look out!", *The Economist*, May 10 2007
- "Ships' logs give clues to Earth's magnetic decline" , *New Scientist*, May 11 2006
- Simple explanation of geomagnetic reversal, *physics.org*, accessed Nov 2 2012



Geomagnetic polarity during the last 5 million years (Pliocene and Quaternary, late Cenozoic Era). Dark areas denote periods where the polarity matches today's normal polarity; light areas denote periods where that polarity is reversed.





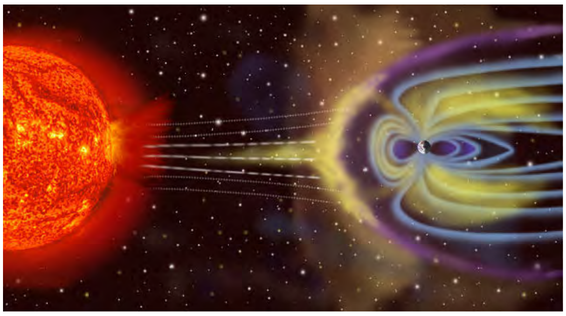
NASA computer simulation using the model of Glatzmaier and Roberts.[*][29] *The tubes represent magnetic field lines, blue when the field points towards the center and yellow when away. The rotation axis of the Earth is centered and vertical. The dense clusters of lines are within the Earth's core.*[*][28]

Chapter 15

Geomagnetic storm

This article is about disturbances within Earth's magnetosphere. For other uses of "magnetic storm", see Magnetic storm (disambiguation).

A **geomagnetic storm** is a temporary disturbance of



Artist's depiction of solar wind particles interacting with Earth's magnetosphere. Sizes are not to scale.

the Earth's magnetosphere caused by a solar wind shock wave and/or cloud of magnetic field that interacts with the Earth's magnetic field. The increase in the solar wind pressure initially compresses the magnetosphere. The solar wind's magnetic field interacts with the Earth's magnetic field and transfers an increased energy into the magnetosphere. Both interactions cause an increase in plasma movement 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 creates a magnetic force that pushes out the boundary between the magnetosphere and the solar wind. The disturbance in the interplanetary medium that drives the storm may be due to a solar coronal mass ejection (CME) or a high speed stream (co-rotating interaction region or CIR)*[1] 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, while CIR driven storms are more common during the minimum of the solar cycle.

Several space weather phenomena tend to be associated with or are caused by a geomagnetic storm. These include: solar energetic Particle (SEP) events, geomagnetically induced currents (GIC), ionospheric disturbances that cause radio and radar scintillation, disruption of navigation by magnetic compass and auroral displays at much lower latitudes than normal. In 1989, a geomagnetic storm energized ground induced currents that disrupted electric power distribution throughout most of the province of Quebec*[2] and caused aurorae as far south as Texas.*[3]

15.1 History

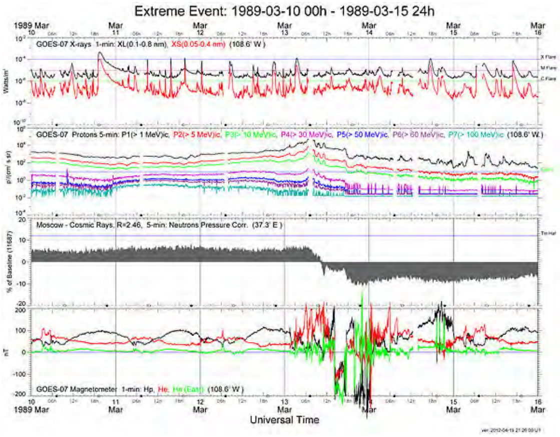
In 1931, Sydney Chapman and Vincenzo C. A. Ferraro wrote an article, *A New Theory of Magnetic Storms*, that sought to explain the phenomenon.*[4] They argued that whenever the Sun emits a solar flare it also emits a plasma cloud, now known as a coronal mass ejection. This plasma will travel at a velocity such that it reaches Earth within 113 days, though we now know this journey takes 1 to 5 days. The cloud then compresses the Earth's magnetic field and thus increases this field at the Earth's surface.*[5]

15.2 Definition

A geomagnetic storm is defined*[6] by changes in the Dst*[7] (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.*[8] During quiet times, Dst is between +20 and −20 nano-Tesla (nT).

A geomagnetic storm has three phases:*[6] initial, main and recovery. 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 2–8 hours. The recovery phase is when Dst changes from its minimum value to its quiet time value. The recovery phase may last 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).*[9]



GOES-7 monitors the space weather conditions during the Great Geomagnetic storm of March 1989, the Moscow neutron monitor recorded the passage of a CME as a drop in levels known as a Forbush decrease.[13]*

15.3 Historical occurrences

The first scientific observation of the effects of a geomagnetic storm occurred early in the 19th century: From May 1806 until June 1807, Alexander von Humboldt recorded the bearing of a magnetic compass in Berlin. On 21 December 1806, he noticed that his compass had become erratic during a bright auroral event.*[10]

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, with the largest flare on September 1. This is referred to as the Solar storm of 1859 or the Carrington Event. It can be assumed that a massive coronal mass ejection (CME) was launched from the Sun and reached the Earth within eighteen hours—a trip that normally takes three to four days. The horizontal field was reduced by 1600 nT as recorded by the Colaba Observatory. It is estimated that Dst would have been approximately −1760 nT.*[11] Telegraph wires in both the United States and Europe experienced induced voltage increases (emf), in some cases even delivering shocks to telegraph operators and igniting fires. Aurorae were seen as far south as Hawaii, Mexico, Cuba and Italy—phenomena that are usually only visible in polar regions. 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, notably the aurora of November 17, 1882 and the May 1921 geomagnetic storm, both with disruption of telegraph service and initiation of fires, and 1960, when widespread radio disruption was reported.*[12]

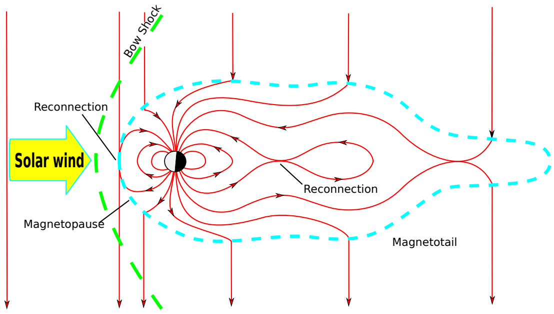
The March 1989 geomagnetic storm caused the collapse of the Hydro-Québec power grid in seconds as equipment protection relays tripped in a cascading sequence.*[2]*[14] Six million people were left without power for nine hours. The storm caused aurorae as far south as Texas.*[3] The storm causing this event was the result of a coronal mass ejected from the Sun on March 9, 1989.*[15] The minimum of Dst was −589 nT.

On July 14, 2000, an X5 class flare erupted (known as the Bastille Day event) and a coronal mass was launched directly at the Earth. A geomagnetic super storm occurred on July 15–17; the minimum of the Dst index was −301 nT. Despite the storm's strength, no power distribution failures were reported.*[16] The Bastille Day event was observed by Voyager 1 and Voyager 2,*[17] thus it is the farthest out in the Solar System that a solar storm has been observed.

Seventeen major flares erupted on the Sun between 19 October and 5 November 2003, including perhaps the most intense flare ever measured on the GOES XRS sensor—a huge X28 flare,*[18] resulting in an extreme radio blackout, on 4 November. These flares were associated with CME events that caused three geomagnetic storms between 29 October and 2 November, during which the second and third storms were initiated before the previous storm period had fully recovered. The minimum Dst values were −151, −353 and −383 nT. Another storm in this sequence occurred on 4–5 November with a minimum Dst of −69 nT. The last geomagnetic storm was weaker than the preceding storms, because the active region on the Sun had rotated beyond the meridian where the central portion CME created during the flare event passed to the side of the Earth. The whole sequence became known as the Halloween Solar Storm.*[19] The Wide Area Augmentation System (WAAS) operated by the Federal Aviation Administration (FAA) was offline for approximately 30 hours due to the storm.*[20] The Japanese ADEOS-2 satellite was severely damaged and the operation of many other satellites were interrupted due to the storm.*[21]

15.4 Interactions with planetary processes

The solar wind also carries with it the Sun's magnetic field. This field will have either a North or South orien-



Magnetosphere in the near-Earth space environment.

tation. 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 becomes unstable, fragments, and may even disappear. In the northern and southern pole regions of the Earth, auroras are observable.

15.5 Instruments

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 move with the 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.*[22]
- Electric sensors at the ends of opposing booms are used to measure potential differences between separated points, to derive electric fields 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 determine the electron density profile—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).
- Particle detectors include a Geiger counter, as was used for the original observations of the Van Allen radiation belt. Scintillator detectors came later, and still later "channeltron" electron multipliers 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 need to be taken into account. So far the results are difficult to interpret, and certain assumptions are needed to cover small-scale phenomena.

15.6 Geomagnetic storm effects

15.6.1 Disruption of electrical systems

It has been suggested that a geomagnetic storm on the scale of the solar storm of 1859 today would cause billions or even trillions of dollars of damage to satellites, power grids and radio communications, and could cause electrical blackouts on a massive scale that might not be repaired for weeks, months, or even years.*[20]

15.6.2 Communications

High frequency (3–30 MHz) communication systems use the ionosphere to reflect radio signals over long distances. Ionospheric storms can affect radio communication at all latitudes. Some 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.

Military detection or early warning systems operating in the high frequency range 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. Also 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, high levels of noise can occur on air-control radio frequencies. This can also happen on UHF and SHF satellite communications, when an Earth station, a satellite and the Sun are in alignment. In order to prevent unnecessary maintenance on satellite communications systems aboard aircraft AirSatOne provides a live feed for geophysical events from NOAA's Space Weather Prediction Center. AirSatOne's live feed*[23] allows users to view observed and predicted space storms. Geophysical Alerts are important to flight crews and maintenance personnel to determine if any upcoming activity or history has or will have an effect on satellite communications, GPS navigation and HF Communications.

Telegraph lines in the past were affected by geomagnetic storms. Telegraphs used a single long wire for the data line, stretching for many miles, using the ground as the return wire and 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 diminished the signal, when subtracted from the battery polarity, or to overly strong and spurious signals when added to it; some operators 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.*[24]

Damage to communications satellites can disrupt non-terrestrial telephone, television, radio and Internet links.*[25] The National Academy of Sciences reported in 2008 on possible scenarios of widespread disruption in the 2012–2013 solar peak.*[26]

15.6.3 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 was 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.

15.6.4 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, causing satellites to slow and change orbit slightly. Low Earth Orbit satellites that are not repeatedly boosted to higher orbits slowly fall and eventually burn up.

Skylab's 1979 destruction is an example of a spacecraft reentering Earth's atmosphere prematurely 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 physically damage 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 differentially charge portions of the spacecraft. 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.

15.6.5 Mains electricity 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 influenced telephone and telegraph lines before fiber optics, see above) on all long transmission lines. 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, especially in modern high-voltage, low-resistance lines. The European grid consists mainly of shorter transmission circuits, which are less vulnerable to damage.*[27]*[28]

The (nearly direct) currents induced in these lines from geomagnetic storms are harmful to electrical transmission equipment, especially transformers—inducing core saturation, constraining their performance (as well as tripping various safety devices), and causing coils and cores to heat up. In extreme cases, this heat can disable or destroy them, even inducing a chain reaction that can overload transformers.*[29]*[30] Most generators are connected to the grid via transformers, isolating them from the induced currents on the grid, making them much less susceptible to damage due to geomagnetically induced current. However, a transformer that is subjected to this will act as an unbalanced load to the generator, causing negative sequence current in the stator and consequently rotor heating.

According to a study by Metatech corporation, a storm with a strength comparable to that of 1921 would destroy more than 300 transformers and leave over 130 million people without power in the United States, costing several trillion dollars.*[31] The Daily Mail even claims that a massive solar flare could knock out electric power for months, but*[32] these predictions are contradicted by a NERC report that concludes that a geomagnetic storm would cause temporary grid instability but no widespread destruction of high-voltage transformers. The report points out that the widely quoted Quebec grid collapse was not caused by overheating transformers but by the near-simultaneous tripping of seven relays.*[33]

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 minimize damage to power transmission equipment, by momentarily disconnecting transformers or by inducing temporary blackouts. Preventative measures also exist, including preventing the inflow of GICs into the grid through the neutral-to-ground connection.*[27]

15.6.6 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.

15.6.7 Pipelines

Rapidly fluctuating geomagnetic fields can produce geomagnetically induced currents in pipelines. This can cause multiple problems for pipeline engineers. Pipeline flow meters can transmit erroneous flow information and the corrosion rate of the pipeline is dramatically increased.*[34]*[35] If engineers incorrectly attempt to balance the current during a geomagnetic storm, corrosion rates may increase even more. Pipeline managers thus receive space weather alerts and warnings to allow them to implement defensive measures.

15.6.8 Radiation hazards to humans

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

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

Solar protons with energies greater than 30 MeV are particularly hazardous. In October 1989, the Sun produced enough energetic particles that, an astronaut standing on the Moon at the time, wearing only a space suit, would probably have died; the expected dose would be about 7000 rem.

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 flight paths and altitudes adjusted in order to lower the absorbed dose of the flight crews.*[36]*[37]*[38]

15.7 See also

- A-index
- K-index
- Advanced Composition Explorer
- Electromagnetic pulse
- List of plasma (physics) articles
- List of solar storms
- Magnetar
- Solar and Heliospheric Observatory
- Solar flare
- STEREO
- Van Allen Probes

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15.10 External links

- Live solar and geomagnetic activity data at Spaceweather
- NOAA Space Weather Prediction Center
- Real time magnetograms
- Aurora Watch at Lancaster University
- USGS Geomagnetism program

Links related to power grids:

- Geomagnetic Storm Induced HVAC Transformer Failure is Avoidable
- NOAA Economics —Geomagnetic Storm datasets and Economic Research
- Geomagnetic Storms Can Threaten Electric Power Grid

Chapter 16

Apparent polar wander

Apparent polar wander (APW) is the perceived movement of the Earth's paleo-magnetic poles relative to a continent while regarding the continent being studied as fixed in position.*[1] It is frequently displayed on the present latitude-longitude map as a path connecting the locations of geomagnetic poles, inferred at distinct times using paleomagnetic techniques.

In reality, the relative polar movement can either be polar wandering or continental drift (or a combination of both).*[2] Data from around the globe are needed in order to isolate or distinguish between the two. Nevertheless, the magnetic poles rarely stray far from the geographic poles of the planet. Therefore, the concept of apparent polar wander is very useful in plate tectonics, since it can retrace the relative motion of continents, as well as the formation and break-up of supercontinents.

16.1 History

It has been known for a long time that the geomagnetic field varies through time, and records of its direction and magnitude have been kept in different locations since the 1800s.*[2] The technique of drawing apparent polar wander was first developed by Creer et al. (1954), and was a major step taken towards the acceptance of the plate tectonics theory. Since then many discoveries have been made in that field, and apparent polar wander has become better understood with the evolution of the theory and of the Geocentric Axial Dipole (GAD) model. There are over 10,000 paleomagnetic poles recorded in the database today.*[2]

16.2 Paleomagnetic poles

Much research in paleomagnetism is aimed at finding paleomagnetic poles for different continents and at different epochs, in order to assemble them in APWP tracks.*[2] Paleomagnetic poles have the advantage that they should have the same value at each observing locality on the basis of the Geocentric axial dipole (GAD) model.*[3] Thus they can be used to compare paleomagnetic results from widely separated localities.

16.3 Rock magnetism

Fossil magnetization in rocks is key to locate a paleomagnetic pole. At the time of formation, rocks conserve the direction of the magnetic field. The inclination(Im) and declination vectors(Dm) are preserved and therefore the paleolatitude(λp) and paleolongitude(φp) of the pole can be found.*[3]

16.3.1 Blocking temperature

The reason the characteristics of the field are conserved comes from the concept of blocking temperature (also known as closure temperature in geochronology). This temperature is where the system becomes blocked against thermal agitation at lower temperatures.*[3] Therefore, some minerals exhibit remnant magnetization. One problem that arises in the determination of remnant (or fossil) magnetization is that if the temperature rises above this point, the magnetic history is destroyed. However, in theory it should be possible to relate the magnetic blocking temperature to the isotopic closure temperature, such that it could be checked whether or not a sample can be used.*[3]

16.4 APWP tracks

Often, APWP tracks represent the motion of a plate relative to a fixed point (paleomagnetic pole). The usual pattern observed consists of long, gently curved segments linked by short, sharply curved segments. Those respectively correspond to time intervals of constant plate motion versus changing plate motion.*[3]

These segments are described by the rotation about a pivot point, which is called the paleomagnetic Euler pole (“Euler” is pronounced like “oiler”) (see Euler's rotation theorem). The relative motion between two plates is also described by the rotation about an Euler Pole. In recent times it is easier to determine finite rotations as transforms and ridges are respectively perpendicular and parallel to the direction of a finite rotation pole.*[2] In this way reconstructions of the last 200 Ma rely mostly on marine geophysical data. Older than that we run out of seafloor, so other ways have to be used, like paleomagnetic poles and fit of geological observations.

Determining paleomagnetic poles is a complicated process since with increasing time more uncertainties come into play. Reliability of poles has been subject to debate for many years. Paleomagnetic poles are usually a group mean determined from different samples, in order to average out the secular variation over time to respect GAD hypothesis.*[2] The treatment of data is a big step and involves a lot of statistical calculations to obtain a valid paleomagnetic pole.

When applied to continents, it is possible to define finite rotation with paleomagnetic poles; that is, describe the certain motion of a continent based on records of its paleomagnetic poles. However, there are two major problems for constraining finite rotation:*[3]

• Because of random magnetic reversals, the north magnetic pole at a given time could either be in the North or South hemisphere. Without context, it is impossible to know which is the north-seeking direction of the magnetic vectors. Again, in recent times there is often a better context, but after 300Ma it becomes increasingly difficult.

• The paleolongitude cannot be constrained from the pole alone. This is why data from different locations are needed, as it reduces the degrees of freedom. With the apparent polar wander path of high fidelity, however, paleolongitude could be constrained by the paleomagnetic Euler rotations (rotation poles and angles) estimated from the circle modelling to the APWP tracks.*[4]

The goal of much paleomagnetic research is to assemble poles in APWPs for the different continental fragments, which is the first step in reconstructing the paleogeography. The two main issues in this construction are

- 1) The selection of reliable poles (criteria V90, BC02)
- 2) Curve fitting.*[3]

The first issue has been addressed with general selection criteria. The common ones have been described by Van der Voo (1990; V90). These include the uncertainty on ages, the number of samples, positive field tests to constrain the age of magnetization relative to the age of the rock (e.g. fold test), pole positions etc. Besse and Courtillot (2002; BC02) brought some modifications to these criteria for particular applications. Once poles are selected and attributed a certain degree of reliability, the task of curve fitting remains, in order to define apparent polar wander paths. Different approaches have been used for this process: Discrete windows, Key poles, Moving windows, splines, Paleomagnetic Euler pole (PEP) analysis, Master path, inclination-only data. These differ in the way poles are separated, the relative importance attributed to some poles and the general shape of resulting curves.

16.5 See also

- *Geomagnetism* – Wikipedia book

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Chapter 17

Dynamo theory

This article is about a proposed theory for the source of the Earth's magnetic field. For an explanation of the operation of a mechanical dynamo, see Dynamo.

In physics, the **dynamo theory** proposes a mechanism by which a celestial body such as Earth or a star generates a magnetic field. The dynamo theory describes the process through which a rotating, convecting, and electrically conducting fluid can maintain a magnetic field over astronomical time scales. A dynamo is thought to be the source of the Earth's magnetic field, as well as the magnetic fields of other planets.

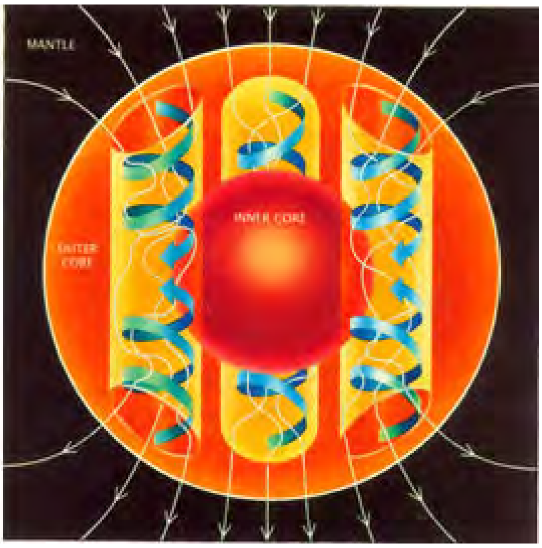

Illustration of the dynamo mechanism that creates the Earth's magnetic field: convection currents of fluid metal in the Earth's outer core, driven by heat flow from the inner core, organized into rolls by the Coriolis force, create circulating electric currents, which generate the magnetic field.[1]*

17.1 History of theory

When William Gilbert published *de Magnete* in 1600, he concluded that the Earth is magnetic and proposed the first hypothesis for the origin of this magnetism: permanent magnetism such as that found in lodestone. In 1919, Joseph Larmor proposed that a dynamo might be generating the field.*[2]*[3] However, even after he advanced his hypothesis, some prominent scientists advanced alternative explanations. Einstein believed that there might be an asymmetry between the charges of the electron and proton so that the Earth's magnetic field would be produced by the entire Earth. The Nobel Prize winner Patrick Blackett did a series of experiments looking for a fundamental relation between angular momentum and magnetic moment, but found none.*[4]*[5]

Walter M. Elsasser, considered a "father" of the presently accepted dynamo theory as an explanation of the Earth's magnetism, proposed that this magnetic field resulted from electric currents induced in the fluid outer core of the Earth. He revealed the history of the Earth's magnetic field through pioneering the study of the magnetic orientation of minerals in rocks.

In order to maintain the magnetic field against ohmic decay (which would occur for the dipole field in 20,000 years), the outer core must be convecting. The convection is likely some combination of thermal and compositional convection. The mantle controls the rate at which heat is extracted from the core. Heat sources include gravitational energy released by the compression of the core, gravitational energy released by the rejection of light elements (probably sulfur, oxygen, or silicon) at the inner core boundary as it grows, latent heat of crystallization at the inner core boundary, and radioactivity of potassium, uranium and thorium.*[6]

At the dawn of the 21st century, numerical modeling of the Earth's magnetic field has not been successfully demonstrated, but appears to be in reach. Initial models are focused on field generation by convection in the planet's fluid outer core. It was possible to show the generation of a strong, Earth-like field when the model assumed a uniform core-surface temperature and exceptionally high viscosities for the core fluid. Computations which incorporated more realistic parameter values yielded magnetic fields that were less Earth-like, but also point the way to model refinements which may ultimately lead to an accurate analytic model. Slight variations in the core-surface temperature, in the range of a few millikelvins, result in significant increases in convective flow and produce more realistic magnetic fields.*[7]*[8]

17.2 Formal definition

Dynamo theory describes the process through which a rotating, convecting, and electrically conducting fluid acts to maintain a magnetic field. This theory is used to explain the presence of anomalously long-lived magnetic fields in astrophysical bodies. The conductive fluid in the geodynamo is liquid iron in the outer core, and in the solar dynamo is ionized gas at the tachocline. Dynamo theory of astrophysical bodies uses magnetohydrodynamic equations to investigate how the fluid can continuously regenerate the magnetic field.*[9]

It was once believed that the dipole, which comprises much of the Earth's magnetic field and is misaligned along the rotation axis by 11.3 degrees, was caused by permanent magnetization of the materials in the earth. This means that dynamo theory was originally used to explain the Sun's magnetic field in its relationship with that of the Earth. However, this hypothesis, which was initially proposed by Joseph Larmor in 1919, has been modified due to extensive studies of magnetic secular variation, paleomagnetism (including polarity reversals), seismology, and the solar system's abundance of elements. Also, the application of the theories of Carl Friedrich Gauss to magnetic observations showed that Earth's magnetic field had an internal, rather than external, origin.

There are three requisites for a dynamo to operate:

- An electrically conductive fluid medium
- Kinetic energy provided by planetary rotation
- An internal energy source to drive convective motions within the fluid.*[10]

In the case of the Earth, the magnetic field is induced and constantly maintained by the convection of liquid iron in the outer core. A requirement for the induction of field is a rotating fluid. Rotation in the outer core is supplied by the Coriolis effect caused by the rotation of the Earth. The Coriolis force tends to organize fluid motions and electric currents into columns (also see Taylor columns) aligned with the rotation axis. Induction or creation of magnetic field is described by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla^2 \mathbf{B} + \nabla \times (\mathbf{u} \times \mathbf{B})$$

where $\mathbf{u}$ is velocity, $\mathbf{B}$ is magnetic field, t is time, and $\eta = 1/(\sigma\mu)$ is the magnetic diffusivity with σ electrical conductivity and μ permeability. The ratio of the second term on the right hand side to the first term gives the Magnetic Reynolds number, a dimensionless ratio of advection of magnetic field to diffusion.

17.2.1 Tidal heating supporting a dynamo

Tidal forces between celestial orbiting bodies cause friction that heats up their interiors. This is known as tidal heating, and it helps keep the interior liquid. A liquid interior that can conduct electricity is required to produce a dynamo. Saturn's Enceladus and Jupiter's Io have enough tidal heating to liquify their inner cores, but they may not create a dynamo because they cannot conduct electricity. *[11] *[12] Mercury, despite its small size, has a magnetic field, because it has a conductive liquid core created by its iron composition and friction resulting from its highly elliptical orbit.*[13] It is theorized that the Moon once had a magnetic field, based on evidence from magnetized lunar rocks, due to its short-lived closer distance to Earth creating tidal heating. *[14] An orbit and rotation of a planet helps provide a liquid core, and supplements kinetic energy that supports a dynamo action.

17.3 Kinematic dynamo theory

In kinematic dynamo theory the velocity field is prescribed, instead of being a dynamic variable. This method cannot provide the time variable behavior of a fully nonlinear chaotic dynamo but is useful in studying how magnetic field strength varies with the flow structure and speed.

Using Maxwell's equations simultaneously with the curl of Ohm's Law, one can derive what is basically the linear eigenvalue equation for magnetic fields (**B**) which can be done when assuming that the magnetic field is independent from the velocity field. One arrives at a critical *magnetic Reynolds number* above which the flow strength is sufficient to amplify the imposed magnetic field, and below which it decays.

The most functional feature of kinematic dynamo theory is that it can be used to test whether a velocity field is or is not capable of dynamo action. By applying a certain velocity field to a small magnetic field, it can be determined through observation whether the magnetic field tends to grow or not in reaction to the applied flow. If the magnetic field does grow, then the system is either capable of dynamo action or is a dynamo, but if the magnetic field does not grow, then it is simply referred to as non-dynamo.

The membrane paradigm is a way of looking at black holes that allows for the material near their surfaces to be expressed in the language of dynamo theory.

17.4 Nonlinear dynamo theory

The kinematic approximation becomes invalid when the magnetic field becomes strong enough to affect the fluid motions. In that case the velocity field becomes affected by the Lorentz force, and so the induction equation is no longer linear in the magnetic field. In most cases this leads to a quenching of the amplitude of the dynamo. Such dynamos are sometimes also referred to as *hydromagnetic dynamos*.*[15] Virtually all dynamos in astrophysics and geophysics are hydromagnetic dynamos.

Numerical models are used to simulate fully nonlinear dynamos. A minimum of 5 equations are needed. They are as follows. The induction equation, see above. Maxwell's equation:

$$\nabla \cdot \mathbf{B} = 0$$

The Boussinesq approximation is often used, in which the continuity equation for conservation of mass is

$$\nabla \cdot \mathbf{u} = 0,$$

and the Navier-Stokes equation for conservation of momentum is

$$\frac{D\mathbf{u}}{Dt} = -\nabla p + \nu \nabla^2 \mathbf{u} + \rho' \mathbf{g} + 2\Omega \times \mathbf{u} + \Omega \times \Omega \times \mathbf{R} + \mathbf{J} \times \mathbf{B},$$

where ν is the kinematic viscosity, ρ' is the density perturbation that provides buoyancy (for thermal convection $\rho' = \alpha \Delta T$), Ω is the rotation rate of the Earth, and $\mathbf{J}$ is the electric current density.

Finally, a transport equation, usually of heat (sometimes of light element concentration):

$$\frac{\partial T}{\partial t} = \kappa \nabla^2 T + \epsilon$$

where T is temperature, $\kappa = k/\rho c_p$ is the thermal diffusivity with k thermal conductivity, c_p heat capacity, and ρ density, and ϵ is an optional heat source. Often the pressure is the dynamic pressure, with the hydrostatic pressure and centripetal potential removed. These equations are then non-dimensionalized, introducing the non-dimensional parameters,

$$Ra = \frac{g\alpha T D^3}{\nu\kappa}, E = \frac{\nu}{\Omega D^2}, Pr = \frac{\nu}{\kappa}, Pm = \frac{\nu}{\eta}$$

where *Ra* is the Rayleigh number, *E* the Ekman number, *Pr* and *Pm* the Prandtl and magnetic Prandtl number. Magnetic field scaling is often in Elsasser number units $B = (\rho\Omega/\sigma)^{1/2}$.

17.5 Numerical models

The equations for the geodynamo are enormously difficult to solve, and the realism of the solutions is limited mainly by computer power. For decades, theorists were confined to *kinematic dynamo* models described above, in which the fluid motion is chosen in advance and the effect on the magnetic field calculated. Kinematic dynamo theory was mainly a matter of trying different flow geometries and seeing whether they could sustain a dynamo.*[16]

The first *self-consistent* dynamo models, ones that determine both the fluid motions and the magnetic field, were developed by two groups in 1995, one in Japan*[17] and one in the United States.*[18]*[19] The latter received significant attention because it successfully reproduced some of the characteristics of the Earth's field, including geomagnetic reversals.*[16]

17.6 See also

- Antidynamo theorem
- Rotating magnetic field

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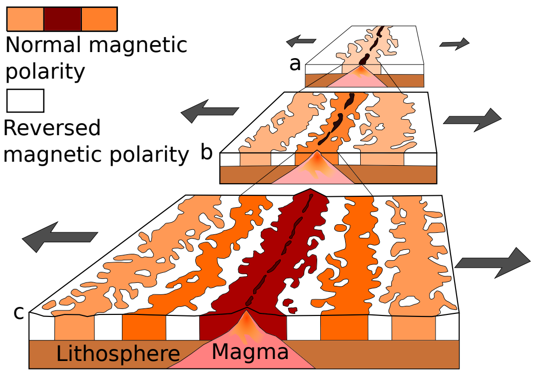
Chapter 18

Paleomagnetism

This article is about the study of paleomagnetism. For other uses, see Paleomagnetism (disambiguation).

Paleomagnetism (or **Palaeomagnetism** in the United Kingdom) is the study of the record of the Earth's magnetic field in rocks, sediment, or archeological materials. Certain minerals in rocks lock-in a record of the direction and intensity of the magnetic field when they form. This record provides information on the past behavior of Earth's magnetic field and the past location of tectonic plates. The record of geomagnetic reversals preserved in volcanic and sedimentary rock sequences (magnetostratigraphy) provides a time-scale that is used as a geochronologic tool. Geophysicists who specialize in paleomagnetism are called *paleomagnetists.*



Magnetic stripes are the result of reversals of the Earth's field and seafloor spreading. New oceanic crust is magnetized as it forms and then it moves away from the ridge in both directions. The models show a ridge (a) about 5 million years ago (b) about 2 to 3 million years ago and (c) in the present.[1]*

Paleomagnetists led the revival of the continental drift hypothesis and its transformation into plate tectonics. Apparent polar wander paths provided the first clear geophysical evidence for continental drift, while marine magnetic anomalies did the same for seafloor spreading. Paleomagnetism continues to extend the history of plate tectonics back in time and are applied to the movement of continental fragments, or terranes.

Paleomagnetism relied heavily on new developments in rock magnetism, which in turn has provided the foundation for new applications of magnetism. These include biomagnetism, magnetic fabrics (used as strain indicators in rocks and soils), and environmental magnetism.

18.1 History

Main article: History of geomagnetism

As early as the 18th century, it was noticed that compass needles deviated near strongly magnetized outcrops. In 1797, Von Humboldt attributed this magnetization to lightning strikes (and lightning strikes do often magnetize surface rocks).*[2]*[3] In the 19th century studies of the direction of magnetization in rocks showed that some recent lavas were magnetized parallel to the Earth's magnetic field. Early in the 20th century, work by David, Brunhes and Mercanton showed that many rocks were magnetized antiparallel to the field. Japanese geophysicist Motonori Matuyama showed that the Earth's magnetic field reversed in the mid-Quaternary, a reversal now known as the Brunhes-Matuyama reversal.*[2]

The British physicist P.M.S. Blackett provided a major impetus to paleomagnetism by inventing a sensitive astatic magnetometer in 1956. His intent was to test his theory that the geomagnetic field was related to the Earth's rotation, a theory that he ultimately rejected; but the astatic magnetometer became the basic tool of paleomagnetism and led to a revival of the theory of continental drift. Alfred Wegener first proposed in 1915 that continents had once been joined together and had since moved apart.*[4] Although he produced an abundance of circumstantial evidence, his theory met with little acceptance for two reasons: (1) no mechanism for continental drift was known, and (2) there was no way to reconstruct the movements of the continents over time. Keith Runcorn*[5] and Edward A. Irving*[6] constructed apparent polar wander paths for Europe and North America. These curves diverged, but could be reconciled if it was assumed that the continents had been in contact up to 200 million years ago. This provided the first clear geophysical evidence for continental drift. Then in 1963, Morley, Vine and Matthews showed that marine magnetic anomalies provided evidence for seafloor spreading.

18.2 Fields of paleomagnetism

Paleomagnetism is studied on a number of scales:

- *Secular variation studies* look at small-scale changes in the direction and intensity of the Earth's magnetic field. The magnetic north pole is constantly shifting relative to the axis of rotation of the Earth. Magnetism is a vector and so magnetic field variation is made up of palaeodirectional measurements of magnetic declination and magnetic inclination and palaeointensity measurements.

- *Magnetostratigraphy* uses the polarity reversal history of the Earth's magnetic field recorded in rocks to determine the age of those rocks. *Reversals* have occurred at irregular intervals throughout Earth history. The age and pattern of these reversals is known from the study of sea floor spreading zones and the dating of volcanic rocks.

18.3 Principles of remanent magnetization

The study of paleomagnetism is possible because iron-bearing minerals such as magnetite may record past directions of the Earth's magnetic field. Magnetic signatures in rocks can be recorded by several different mechanisms.

18.3.1 Thermoremanent magnetization

Main article: Thermoremanent magnetization

Iron-titanium oxide minerals in basalt and other igneous rocks may preserve the direction of the Earth's magnetic field when the rocks cool through the Curie temperatures of those minerals. The Curie temperature of magnetite, a spinel-group iron oxide, is about 580°C, whereas most basalt and gabbro are completely crystallized at temperatures below 900°C. Hence, the mineral grains are not rotated physically to align with the Earth's field, but rather they may record the orientation of that field. The record so preserved is called a thermoremanent magnetization (TRM). Because complex oxidation reactions may occur as igneous rocks cool after crystallization, the orientations of the Earth's magnetic field are not always accurately recorded, nor is the record necessarily maintained. Nonetheless, the record has been preserved well enough in basalts of the ocean crust to have been critical in the development of theories of sea floor spreading related to plate tectonics. TRM can also be recorded in pottery kilns, hearths, and burned adobe buildings. The discipline based on the study of thermoremanent magnetisation in archaeological materials is called archaeomagnetic dating.*[7]

18.3.2 Detrital remanent magnetization

In a completely different process, magnetic grains in sediments may align with the magnetic field during or soon after deposition; this is known as *detrital remanent magnetization* (DRM). If the magnetization is acquired as the grains are deposited, the result is a depositional detrital remanent magnetization (dDRM); if it is acquired soon after deposition, it is a post-depositional detrital remanent magnetization (pDRM).*[8]

18.3.3 Chemical remanent magnetization

See also: Chemical remanent magnetization

In a third process, magnetic grains grow during chemical reactions, and record the direction of the magnetic field at the time of their formation. The field is said to be recorded by *chemical remanent magnetization* (CRM). A common form of chemical remanent magnetization is held by the mineral hematite, another iron oxide. Hematite forms through chemical oxidation reactions of other minerals in the rock including magnetite. Redbeds, clastic sedimentary rocks (such as sandstones) are red because of hematite that formed during sedimentary diagenesis. The CRM signatures in redbeds can be quite useful and they are common targets in magnetostratigraphy studies.*[9]

18.3.4 Isothermal remanent magnetization

See also: Remanence

Remanence that is acquired at a fixed temperature is called *isothermal remanent magnetization (IRM)*. Remanence of this sort is not useful for paleomagnetism, but it can be acquired as a result of lightning strikes. Lightning-induced remanent magnetization can be distinguished by its high intensity and rapid variation in direction over scales of centimeters.*[10]*[9]

IRM is often induced in drill cores by the magnetic field of the steel core barrel. This contaminant is generally parallel to the barrel, and most of it can be removed by heating up to about 400 ℃ or demagnetizing in a small alternating field.

In the laboratory, IRM is induced by applying fields of various strengths and is used for many purposes in rock magnetism.

18.3.5 Viscous remanent magnetization

Main article: Viscous remanent magnetization

Viscous remanent magnetization is remanence that is acquired by ferromagnetic materials by sitting in a magnetic field for some time.

18.4 Paleomagnetic procedure

18.4.1 Collecting samples on land

The oldest rocks on the ocean floor are 200 mya - very young when compared with the oldest continental rocks, which date from 3.8 billion years ago. In order to collect paleomagnetic data dating beyond 200 mya, scientists turn to magnetite-bearing samples on land to reconstruct the Earth's ancient field orientation.

Paleomagnetists, like many geologists, gravitate towards outcrops because layers of rock are exposed. Road cuts are a convenient man-made source of outcrops.

> "And everywhere, in profusion along this half mile of [roadcut], there are small, neatly cored holes ... appears to be a Hilton for wrens and purple martins." *[11]

There are two main goals of sampling:

1. Retrieve samples with accurate orientations, and
2. Reduce statistical uncertainty.

One way to achieve the first goal is to use a rock coring drill that has a pipe tipped with diamond bits. The drill cuts a cylindrical space around some rock. This can be messy - the drill must be cooled with water, and the result is mud spewing out of the hole. Into this space is inserted another pipe with compass and inclinometer attached. These provide the orientations. Before this device is removed, a mark is scratched on the sample. After the sample is broken off, the mark can be augmented for clarity.*[12]

18.5 Applications

Paleomagnetic evidence, both reversals and polar wandering data, was instrumental in verifying the theories of continental drift and plate tectonics in the 1960s and 1970s. Some applications of paleomagnetic evidence to reconstruct histories of terranes have continued to arouse controversies. Paleomagnetic evidence is also used in constraining possible ages for rocks and processes and in reconstructions of the deformational histories of parts of the crust.*[3]

Reversal magnetostratigraphy is often used to estimate the age of sites bearing fossils and hominin remains.*[13] Conversely, for a fossil of known age, the paleomagnetic data can fix the latitude at which the fossil was laid down. Such a *paleolatitude* provides information about the geological environment at the time of deposition.

Paleomagnetic studies are combined with geochronological methods to determine absolute ages for rocks in which the magnetic record is preserved. For igneous rocks such as basalt, commonly used methods include potassium–argon and argon–argon geochronology.

Scientists in New Zealand have found that they are able to figure out the Earth's past magnetic field changes by studying 700- to 800-year-old steam ovens, or hangi, used by the Maori for cooking food.*[14]

18.6 See also

- Geophysics
- Magnetochemistry
- Paleoclimate
- Plate reconstruction
- Rock magnetism

18.7 Notes and references

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[11] McPhee 1988, pp.21-22

[12] Tauxe 1998

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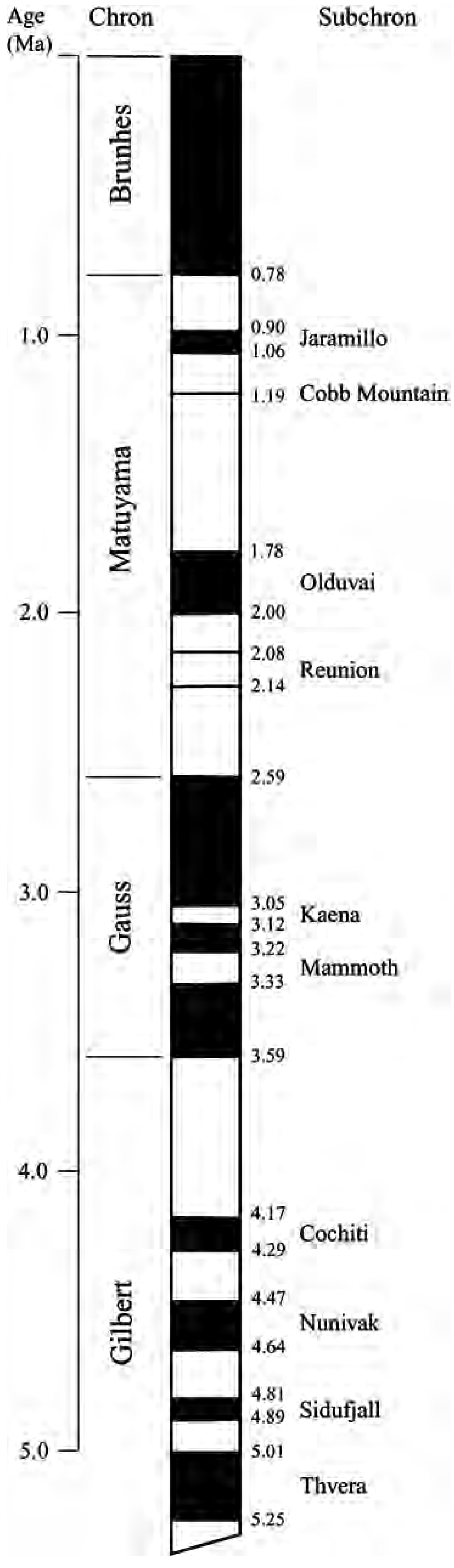
18.9 External links

- Geomagnetism & Paleomagnetism background material
- Paleomagnetic Data from NGDC / WDC Boulder
- The Great Magnet, The Earth
- Paleomagnetic database at the Scripps Institution of Oceanography (MagIC)



Earth's magnetic polarity reversals in last 5 million years. Dark regions represent normal polarity (same as present field); light

Chapter 19

Environmental magnetism

Environmental magnetism is the study of magnetism as it relates to the effects of climate, sediment transport, pollution and other environmental influences on magnetic minerals. It makes use of techniques from rock magnetism and magnetic mineralogy. The magnetic properties of minerals are used as proxies for environmental change in applications such as paleoclimate, paleoceanography, studies of the provenance of sediments, pollution and archeology.*[1] The main advantages of using magnetic measurements are that magnetic minerals are almost ubiquitous and magnetic measurements are quick and non-invasive.

19.1 History

Environmental magnetism was first identified as a distinct field in 1978 and was introduced to a wider audience by the book *Environmental Magnetism* in 1986.*[2]*[3] Since then it has grown rapidly, finding application in and making major contributions to a range of diverse fields, especially paleoclimate, sedimentology, paleoceanography, and studies of particulate pollution.*[4]*[5]

19.2 Fundamentals

Main article: rock magnetism

Environmental magnetism is built on two parts of rock magnetism: magnetic mineralogy, which looks at how basic magnetic properties depend on composition; and magnetic hysteresis, which can provide details on particle size and other physical properties that also affect the hysteresis. Several parameters such as magnetic susceptibility and various kinds of remanence have been developed to represent certain features of the hysteresis.*[6]*[7] These parameters are then used to estimate mineral size and composition. The main contributors to the magnetic properties of rocks are the iron oxides, including magnetite, maghemite, hematite; and iron sulfides (particularly greigite and pyrrhotite). These minerals are strongly magnetic because, at room temperature, they are magnetically ordered (magnetite, maghemite and greigite are ferrimagnets while hematite is a canted antiferromagnet).

To relate magnetic measurements to the environment, environmental magnetists have identified a variety of processes that give rise to each magnetic mineral. These include erosion, transport, fossil fuel combustion, and bacterial formation. The latter includes extracellular precipitation and formation of magnetosomes by magnetotactic bacteria.

19.3 Applications

19.3.1 Paleoclimate

Magnetic measurements have been used to investigate past climate. A classic example is the study of loess, which is windblown dust from the edges of glaciers and semiarid desert margins. In north-central China, blankets of loess that were deposited during glacial periods alternate with paleosols (fossil soils) that formed during warmer and wetter interglacials. The magnetic susceptibility profiles of these sediments have been dated using magnetostratigraphy, which identifies geomagnetic reversals, and correlated with climate indicators such as oxygen isotope stages. Ultimately, this work allowed environmental magnetists to map out the variations in the monsoon cycle during the Quaternary.*[5] Magnetic measurements of lacustrine sediments can also be used to reconstruct the upland surfical processes that were associated with past climate.*[8]

19.4 See also

- Smoke

19.5 Notes

[1] Dekkers 1997

[2] Oldfield et al. 1978

[3] Thompson & Oldfield 1986

[4] Maher & Thompson 1999

[5] Evans & Heller 2003

[6] Dunlop & Özdemir 1997

[7] Maher 1998

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Chapter 20

Magnetostratigraphy

Magnetostratigraphy is a geophysical correlation technique used to date sedimentary and volcanic sequences. The method works by collecting oriented samples at measured intervals throughout the section. The samples are analyzed to determine their *characteristic remanent magnetization* (ChRM), that is, the polarity of Earth's magnetic field at the time a stratum was deposited. This is possible because volcanic flows acquire a thermoremanent magnetization and sediments acquire a depositional remanent magnetization, both of which reflect the direction of the Earth's field at the time of formation. This technique is typically used to date sequences that generally lack fossils or interbedded igneous rock.

20.1 Technique

When measurable magnetic properties of rocks vary stratigraphically they may be the basis for related but different kinds of stratigraphic units known collectively as *magnetostratigraphic units (magnetozones)*.*[1] The magnetic property most useful in stratigraphic work is the change in the direction of the remanent magnetization of the rocks, caused by reversals in the polarity of the Earth's magnetic field. The direction of the remnant magnetic polarity recorded in the stratigraphic sequence can be used as the basis for the subdivision of the sequence into units characterized by their magnetic polarity. Such units are called "magnetostratigraphic polarity units" or chrons.*[2]

If the ancient magnetic field was oriented similar to today's field (North Magnetic Pole near the Geographic North Pole) the strata retain a normal polarity. If the data indicate that the North Magnetic Pole was near the Geographic South Pole, the strata exhibit reversed polarity.

20.1.1 Sampling procedures

Oriented paleomagnetic samples are collected in the field using a rock core drill, or as *hand samples* (chunks broken off the rock face). To average out sampling errors, a minimum of three samples is taken from each sample site.*[3] Spacing of the sample sites within a stratigraphic section depends on the rate of deposition and the age of the section. In sedimentary layers, the preferred lithologies are mudstones, claystones, and very fine-grained siltstones because the magnetic grains are finer and more likely to orient with the ambient field during deposition.*[2]

20.1.2 Analytical procedures

Samples are first analyzed in their natural state to obtain their natural remanent magnetization (NRM). The NRM is then stripped away in a stepwise manner using thermal or alternating field demagnetization techniques to reveal the stable magnetic component.

Magnetic orientations of all samples from a site are then compared and their average magnetic polarity is determined with directional statistics, most commonly Fisher statistics or bootstrapping.*[3] The statistical significance of each average is evaluated. The latitudes of the Virtual Geomagnetic Poles from those sites determined to be statistically significant are plotted against the stratigraphic level at which they were collected. These data are then abstracted to the standard black and white magnetostratigraphic columns in which black indicates normal polarity and white is reversed polarity.

20.1.3 Correlation and ages

Because the polarity of a stratum can only be normal or reversed, variations in the rate at which the sediment accumulated can cause the thickness of a given polarity zone to vary from one area to another. This presents the problem of how to correlate zones of like polarities between different stratigraphic sections. To avoid confusion at least one isotopic age needs to be collected from each section. In sediments, this is often obtained from layers of volcanic ash. Failing that, one can tie a polarity to a biostratigraphic event that has been correlated elsewhere with isotopic ages. With the aid of the independent isotopic age or ages, the local magnetostratigraphic column is correlated with the Global Magnetic Polarity Time Scale (GMPTS).*[1]

Because the age of each reversal shown on the GMPTS is relatively well known, the correlation establishes numerous time lines through the stratigraphic section. These ages provide relatively precise dates for features in the rocks such as fossils, changes in sedimentary rock composition, changes in depositional environment, etc. They also constrain the ages of cross-cutting features such as faults, dikes, and unconformities.

Sediment accumulation rates

Perhaps the most powerful application of these data is to determine the rate at which the sediment accumulated. This is accomplished by plotting the age of each reversal (in millions of years ago) vs. the stratigraphic level at which the reversal is found (in meters). This provides the rate in meters per million years which is usually rewritten in terms of millimeters per year (which is the same as kilometers per million years).*[2]

These data are also used to model basin subsidence rates. Knowing the depth of a hydrocarbon source rock beneath the basin-filling strata allows calculation of the age at which the source rock passed through the generation window and hydrocarbon migration began. Because the ages of cross-cutting trapping structures can usually be determined from magnetostratigraphic data, a comparison of these ages will assist reservoir geologists in their determination of whether or not a play is likely in a given trap.*[4]

Changes in sedimentation rate revealed by magnetostratigraphy are often related to either climatic factors or to tectonic developments in nearby or distant mountain ranges. Evidence to strengthen this interpretation can often be found by looking for subtle changes in the composition of the rocks in the section. Changes in sandstone composition are often used for this type of interpretation.

20.2 See also

- Biostratigraphy
- Chemostratigraphy
- Chronostratigraphy
- Cyclostratigraphy
- Lithostratigraphy
- Tectonostratigraphy

20.3 Notes

[1] Opdyke & Channell 1996, Chapter 5

[2] Butler 1992, Chapter 9

[3] Tauxe 1998, Chapter 3

[4] Reynolds 2002

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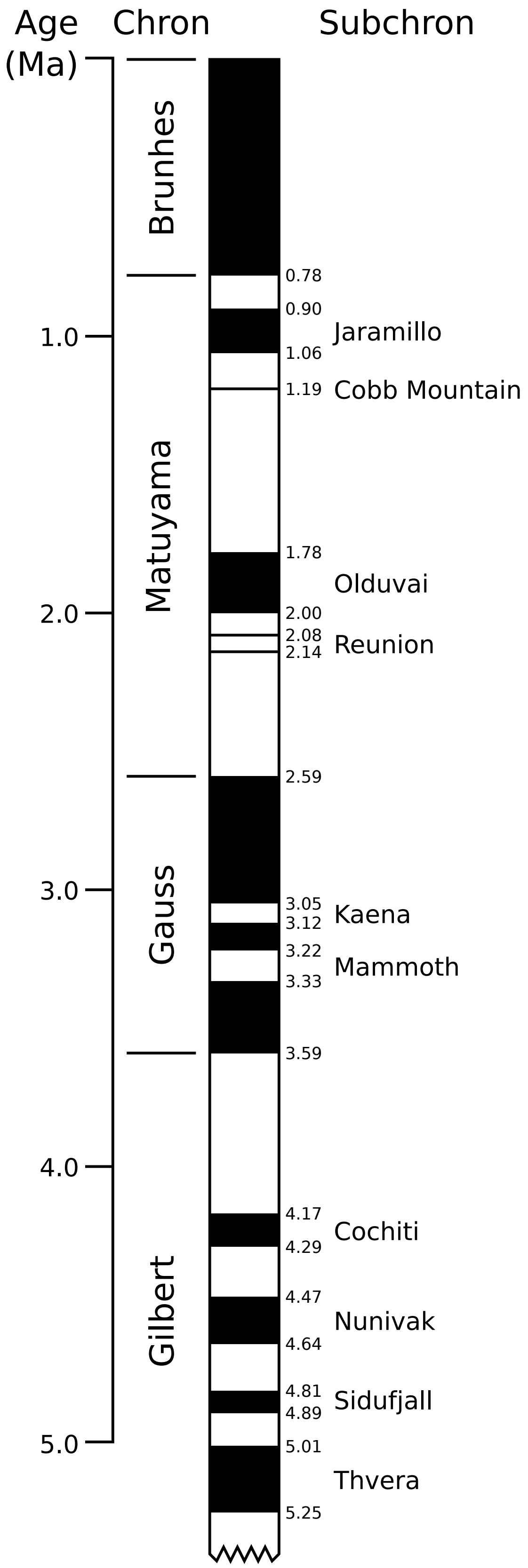


Geomagnetic polarity in late Cenozoic
normal polarity (black)
reverse polarity (white)

Chapter 21

Rock magnetism

A vibrating sample magnetometer, a widely used tool for measuring magnetic hysteresis.

Rock magnetism is the study of the magnetic properties of rocks, sediments and soils. The field arose out of the need in paleomagnetism to understand how rocks record the Earth's magnetic field. This remanence is carried by minerals, particularly certain strongly magnetic minerals like magnetite (the main source of magnetism in lodestone). An understanding of remanence helps paleomagnetists to develop methods for measuring the ancient magnetic field and correct for effects like sediment compaction and metamorphism. Rock magnetic methods are used to get a more detailed picture of the source of distinctive striped pattern in marine magnetic anomalies that provides important information on plate tectonics. They are also used to interpret terrestrial magnetic anomalies in magnetic surveys as well as the strong crustal magnetism on Mars.

Strongly magnetic minerals have properties that depend on the size, shape, defect structure and concentration of the minerals in a rock. Rock magnetism provides non-destructive methods for analyzing these minerals such as magnetic hysteresis measurements, temperature-dependent remanence measurements, Mössbauer spectroscopy, ferromagnetic resonance and so on. With such methods, rock magnetists can measure the effects of past climate change and human impacts on the mineralogy (see environmental magnetism). In sediments, a lot of the magnetic remanence is carried by minerals that were created by magnetotactic bacteria, so rock magnetists have made significant contributions to biomagnetism.

21.1 History

Until the 20th century, the study of the Earth's field (geomagnetism and paleomagnetism) and of magnetic materials (especially ferromagnetism) developed separately.

Rock magnetism had its start when scientists brought these two fields together in the laboratory.*[1] Koenigsberger (1938), Thellier (1938) and Nagata (1943) investigated the origin of remanence in igneous rocks.*[1] By heating rocks and archeological materials to high temperatures in a magnetic field, they gave the materials a thermoremanent magnetization (TRM), and they investigated the properties of this magnetization. Thellier developed a series of conditions (the Thellier laws) that, if fulfilled, would allow the determination of the intensity of the ancient magnetic field to be determined using the Thellier-Thellier method. In 1949, Louis Néel developed a theory that explained these observations, showed that the Thellier laws were satisfied by certain kinds of single-domain magnets, and introduced the concept of blocking of TRM.*[2]

When paleomagnetic work in the 1950s lent support to the theory of continental drift,*[3]*[4] skeptics were quick to question whether rocks could carry a stable remanence for geological ages. *[5] Rock magnetists were able to show that rocks could have more than one component of remanence, some soft (easily removed) and some very stable. To get at the stable part, they took to “cleaning" samples by heating them or exposing them to an alternating field. However, later events, particularly the recognition that many North American rocks had been pervasively remagnetized in the Paleozoic,*[6] showed that a single cleaning step was inadequate, and paleomagnetists began to routinely use stepwise demagnetization to strip away the remanence in small bits.

21.2 Fundamentals

21.2.1 Types of magnetic order

The contribution of a mineral to the total magnetism of a rock depends strongly on the type of magnetic order or disorder. Magnetically disordered minerals (diamagnets and paramagnets) contribute a weak magnetism and have no remanence. The more important minerals for rock magnetism are the minerals that can be magnetically ordered, at least at some temperatures. These are the ferromagnets, ferrimagnets and certain kinds of antiferromagnets. These minerals have a much stronger response to the field and can have a remanence.

Diamagnetism

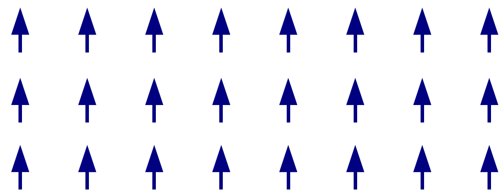
Diamagnetism is a magnetic response shared by all substances. In response to an applied magnetic field, electrons precess (see Larmor precession), and by Lenz's law they act to shield the interior of a body from the magnetic field. Thus, the moment produced is in the opposite direction to the field and the susceptibility is negative. This effect is weak but independent of temperature. A substance whose only magnetic response is diamagnetism is called a diamagnet.

Paramagnetism

Paramagnetism is a weak positive response to a magnetic field due to rotation of electron spins. Paramagnetism occurs in certain kinds of iron-bearing minerals because the iron contains an unpaired electron in one of their shells (see Hund's rules). Some are paramagnetic down to absolute zero and their susceptibility is inversely proportional to the temperature (see Curie's law); others are magnetically ordered below a critical temperature and the susceptibility increases as it approaches that temperature (see Curie-Weiss law).

Ferromagnetism

Collectively, strongly magnetic materials are often referred to as ferromagnets. However, this magnetism can arise as the result of more than one kind of magnetic order. In the strict sense, ferromagnetism refers to magnetic ordering where neighboring electron spins are aligned by

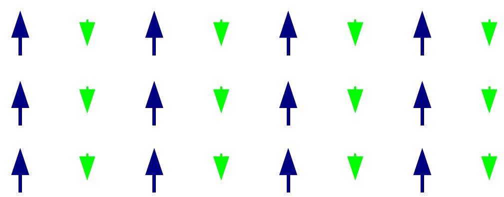


Schematic of parallel spin directions in a ferromagnet.

the exchange interaction. The classic ferromagnet is iron. Below a critical temperature called the Curie temperature, ferromagnets have a spontaneous magnetization and there is hysteresis in their response to a changing magnetic field. Most importantly for rock magnetism, they have remanence, so they can record the Earth's field.

Iron does not occur widely in its pure form. It is usually incorporated into iron oxides, oxyhydroxides and sulfides. In these compounds, the iron atoms are not close enough for direct exchange, so they are coupled by indirect exchange or superexchange. The result is that the crystal lattice is divided into two or more sublattices with different moments.*[1]

Ferrimagnetism

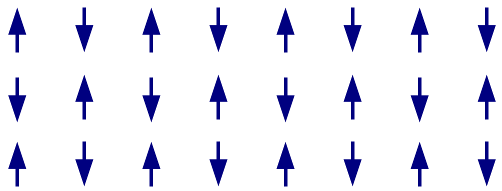


Schematic of unbalanced antiparallel moments in a ferrimagnet.

Ferrimagnets have two sublattices with opposing moments. One sublattice has a larger moment, so there is a net unbalance. Magnetite, the most important of the magnetic minerals, is a ferrimagnet. Ferrimagnets often behave like ferromagnets, but the temperature dependence of their spontaneous magnetization can be quite different. Louis Néel identified four types of temperature dependence, one of which involves a reversal of the magnetization. This phenomenon played a role in controversies over marine magnetic anomalies.

Antiferromagnetism

Antiferromagnets, like ferrimagnets, have two sublattices with opposing moments, but now the moments are equal in magnitude. If the moments are exactly opposed, the magnet has no remanence. However, the moments can



Schematic of alternating spin directions in an antiferromagnet.

be tilted (spin canting), resulting in a moment nearly at right angles to the moments of the sublattices. Hematite has this kind of magnetism.

21.3 Magnetic mineralogy

Main article: Magnetic mineralogy

21.4 Types of remanence

Magnetic remanence is often identified with a particular kind of remanence that is obtained after exposing a magnet to a field at room temperature. However, the Earth's field is not large, and this kind of remanence would be weak and easily overwritten by later fields. A central part of rock magnetism is the study of magnetic remanence, both as natural remanent magnetization (NRM) in rocks obtained from the field and remanence induced in the laboratory. Below are listed the important natural remanences and some artificially induced kinds.

21.4.1 Thermoremanent magnetization (TRM)

Main article: Thermoremanent magnetization

When an igneous rock cools, it acquires a *thermoremanent magnetization (TRM)* from the Earth's field. TRM can be much larger than it would be if exposed to the same field at room temperature (see isothermal remanence). This remanence can also be very stable, lasting without significant change for millions of years. TRM is the main reason that paleomagnetists are able to deduce the direction and magnitude of the ancient Earth's field.*[7]

If a rock is later re-heated (as a result of burial, for example), part or all of the TRM can be replaced by a new remanence. If it is only part of the remanence, it is known as *partial thermoremanent magnetization (pTRM)*. Because numerous experiments have been done modeling different ways of acquiring remanence, pTRM can have other meanings. For example, it can also be acquired in the laboratory by cooling in zero field to a temperature T_1 (below the Curie temperature), applying a magnetic field and cooling to a temperature T_2 , then cooling the rest of the way to room temperature in zero field.

The standard model for TRM is as follows. When a mineral such as magnetite cools below the Curie temperature, it becomes ferromagnetic but is not immediately capable of carrying a remanence. Instead, it is superparamagnetic, responding reversibly to changes in the magnetic field. For remanence to be possible there must be a strong enough magnetic anisotropy to keep the magnetization near a stable state; otherwise, thermal fluctuations make the magnetic moment wander randomly. As the rock continues to cool, there is a critical temperature at which the magnetic anisotropy becomes large enough to keep the moment from wandering: this temperature is called the *blocking temperature* and referred to by the symbol T_B . The magnetization remains in the same state as the rock is cooled to room temperature and becomes a thermoremanent magnetization.

21.4.2 Chemical (or crystallization) remanent magnetization (CRM)

Magnetic grains may precipitate from a circulating solution, or be formed during chemical reactions, and may record the direction of the magnetic field at the time of mineral formation. The field is said to be recorded by *chemical remanent magnetization (CRM)*. The mineral recording the field commonly is hematite, another iron oxide. Redbeds, clastic sedimentary rocks (such as sandstones) that are red primarily because of hematite formation during or after sedimentary diagenesis, may have useful CRM signatures, and magnetostratigraphy can be based on such signatures.

21.4.3 Depositional remanent magnetization (DRM)

Magnetic grains in sediments may align with the magnetic field during or soon after deposition; this is known as detrital remnant magnetization (DRM). If the magnetization is acquired as the grains are deposited, the result is a depositional detrital remanent magnetization (dDRM); if it is acquired soon after deposition, it is a *post-depositional detrital remanent magnetization (pDRM)*.

21.4.4 Viscous remanent magnetization

Main article: Viscous remanent magnetization

Viscous remanent magnetization (VRM), also known as viscous magnetization, is remanence that is acquired by ferromagnetic minerals by sitting in a magnetic field for some time. The natural remanent magnetization of an igneous rock can be altered by this process. To remove this component, some form of stepwise demagnetization must be used.*[1]

21.5 Applications of rock magnetism

- biomagnetism
- environmental magnetism
- magnetic anomalies
- magnetostratigraphy
- paleomagnetic secular variation
- plate tectonics

21.6 See also

- *Geomagnetism* – Wikipedia book

21.7 Notes

[1] Dunlop & Özdemir 1997

[2] Néel 1949

[3] Irving 1956

[4] Runcorn 1956

[5] For example, Sir Harold Jeffreys, in his influential textbook *The Earth*, had the following to say about it:

> “When I last did a magnetic experiment (about 1909) we were warned against careless handling of permanent magnets, and the magnetism was liable to change without much carelessness. In studying the magnetism of rocks the specimen has to be broken off with a geological hammer and then carried to the laboratory. It is supposed that in the process its magnetism does not change to any important extent, and though I have often asked how this comes to be the case I have never received any answer.Jeffreys 1959, p. 371

[6] McCabe & Elmore 1989

[7] Stacey & Banerjee 1974

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21.9 External links

- Institute for Rock Magnetism
- UC Davis FORC Group, Introduction to FORC Diagrams

Chapter 22

Néel relaxation theory

Néel relaxation theory is a theory developed by Louis Néel in 1949*[1] to explain time-dependent magnetic phenomena known as *magnetic viscosity*. It is also called *Néel-Arrhenius theory*, after the Arrhenius equation, and *Néel-Brown theory* after a more rigorous derivation by William Fuller Brown, Jr.*[2] Néel used his theory to develop a model of thermoremanent magnetization in single-domain ferromagnetic minerals that explained how these minerals could reliably record the geomagnetic field. He also modeled frequency-dependent susceptibility and alternating field demagnetization.

22.1 Superparamagnetism

Superparamagnetism occurs in ferromagnetic and ferrimagnetic nanoparticles which are single-domain, i.e. composed of a single magnetic domain. This is possible when their diameter is below 3–50 nm, depending on the materials. In this condition, it is considered that the magnetization of the nanoparticles is a single giant magnetic moment, sum of all the individual magnetic moments carried by the atoms of the nanoparticle. This is what people working in the field of superparamagnetism call the "macro-spin approximation" .

22.2 Mean transition time

Because of the nanoparticle' s magnetic anisotropy, the magnetic moment has usually only two stable orientations antiparallel to each other, separated by an energy barrier. The stable orientations define the magnetic *easy axis* of the nanoparticle. At finite temperature, there is a finite probability for the magnetization to flip and reverse its direction. The mean time between two flips is called the Néel relaxation time τ_N and is given by the Néel-Arrhenius equation:*[1]

$$\tau_{\mathrm{N}} = \tau_0 \exp\left(\frac{KV}{k_{\mathrm{B}}T}\right)$$

where KV is the height of the energy barrier, a product of the magnetic anisotropy energy density K and volume V; k_B is the Boltzmann constant, T the temperature and their product the thermal energy; and τ_0 is a length of time, characteristic of the material, called the *attempt time* or *attempt period* (its reciprocal is called the *attempt frequency*). Typical values for τ_0 are between 10*−9 and 10*−10 seconds.

The Néel relaxation time can be anywhere from a few nanoseconds to years or much longer. In particular, it is an exponential function of the grain volume, which explains why the flipping probability becomes rapidly negligible for bulk materials or large nanoparticles.

22.3 Blocking temperature

Suppose that the magnetization of a single superparamagnetic nanoparticle is measured over a time τ_m. If this time is much greater than the relaxation time τ_N, the nanoparticle magnetization will flip several times during the measurement. In zero field, the measured magnetization will average to zero. If $\tau_m \ll \tau_N$, the magnetization will not flip during the measurement, so the measured magnetization will be equal to the initial magnetization. In the former case, the nanoparticle will appear to be in the superparamagnetic state whereas in the latter case it will be *blocked* in its initial state. The state of the nanoparticle (superparamagnetic or blocked) depends on the measurement time. A transition between superparamagnetism and the blocked state occurs when $\tau_m = \tau_N$. In several experiments, the measurement time is kept constant but the temperature is varied, so the transition between superparamagnetism and blocked state is a function of the temperature. The temperature for which $\tau_m = \tau_N$ is called the *blocking temperature*:

$$T_{\mathrm{B}} = \frac{KV}{k_{\mathrm{B}} \ln\left(\tau_{\mathrm{m}}/\tau_0\right)}$$

For typical laboratory measurements, the value of the logarithm in the previous equation is in the order of 20–25.

22.4 References

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Chapter 23

Thermoremanent magnetization

When an igneous rock cools, it acquires a **thermoremanent magnetization (TRM)** from the Earth's field. TRM can be much larger than it would be if exposed to the same field at room temperature (see isothermal remanence). This remanence can also be very stable, lasting without significant change for millions of years. TRM is the main reason that paleomagnetists are able to deduce the direction and magnitude of the ancient Earth's field.*[1]

23.1 History

As early as the eleventh century, the Chinese were aware that a piece of iron could be magnetized by heating until it was red hot and then quenched in water. While quenching it was oriented in the Earth's field to get the desired polarity. In 1600, William Gilbert published *De Magnete* (1600), a report of a series of meticulous experiments in magnetism. In it, he described the quenching of a steel rod in the direction of the Earth's field, and he may have been aware of the Chinese work.*[2]

In the early 20th century, a few investigators found that igneous rocks had a remanence that was much more intense than remanence acquired in the Earth's field without heating; that heating rocks in the Earth's magnetic field could magnetize them in the direction of the field; and that the Earth's field had reversed its direction in the past.*[3]

23.2 TRM in paleomagnetism

23.2.1 Demagnetization of TRM

It has long been known that a TRM can be removed if it is heated above the Curie temperature T_C of the minerals carrying it. A TRM can also be partially demagnetized by heating up to some lower temperature T_1 and cooling back to room temperature. A common procedure in paleomagnetism is *stepwise demagnetization*, in which the sample is heated to a series of temperatures $T_1, T_2, \ldots$, cooling to room temperature and measuring the remaining remanence in between each heating step. The series of remanences can be plotted in a variety of ways, depending on the application.

23.2.2 Partial TRM

If a rock is later re-heated (as a result of burial, for example), part or all of the TRM can be replaced by a new remanence. If it is only part of the remanence, it is known as *partial thermoremanent magnetization (pTRM)*. Because numerous experiments have been done modeling different ways of acquiring remanence, pTRM can have other meanings. For example, it can also be acquired in the laboratory by cooling in zero field to a temperature T_1 (below the Curie temperature), applying a magnetic field and cooling to a temperature T_2 , then cooling the rest of the way to room temperature in zero field.

23.3 Ideal TRM behavior

23.3.1 The Thellier laws

The ideal TRM is one that can record the magnetic field in such a way that both its direction and intensity can be measured by some process in the lab. Thellier*[4] showed that this could be done if pTRM's satisfied four laws. Suppose that A and B are two non-overlapping temperature intervals. Suppose that M_A is a pTRM that is acquired by cooling the sample to room temperature, only switching the field H on while the temperature is in interval A; M_B has a similar definition. The *Thellier laws* are

- *Linearity*: $M_A(H)$ and $M_B(H)$ are proportional to H when H is not much larger than the present Earth's field.
- *Reciprocity*: M_A can be removed by heating through temperature interval A , and M_B through B .
- *Independence*: M_A and M_B are independent.
- *Additivity*: If $M_{A\cup B}$ is acquired by turning the field on in both temperature intervals, $M_{A\cup B} = M_A + M_B$.

If these laws hold for any non-overlapping temperature intervals A and B, the sample satisfies the Thellier laws.*[5]

23.3.2 A simple model for the Thellier laws

Suppose that a sample has a lot of magnetic minerals, each of which has the following property: It is superparamagnetic until the temperature reaches a *blocking temperature* T_{B} that is independent of magnetic field for small fields. No irreversible changes occur at temperatures below T_{B}. If the resulting TRM is heated in zero field, it becomes superparamagnetic again at an *unblocking temperature* T_{UB} that is equal to T_{B}. Then it is easy to verify that reciprocity, independence and additivity hold. It only remains for linearity to be satisfied for all the Thellier laws to be obeyed.

23.3.3 The Néel model for single-domain TRM

Louis Néel developed a physical model that showed how real magnetic minerals could have the above properties. It applies to particles that are single-domain, having a uniform magnetization that can only rotate as a unit.*[6]

23.4 See also

- Rock magnetism

23.5 Notes

[1] Stacey & Banerjee 1974

[2] Temple 2006, pp. 169–171

[3] Glen 1982

[4] Thellier 1938

[5] Dunlop & Özdemir 1997

[6] Néel 1955

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Chapter 24

Remanence

This article is about magnetic remanence. For the data storage term, see Data remanence.

Remanence or **remanent magnetization** or **residual magnetism** is the magnetization left behind in a ferromagnetic material (such as iron) after an external magnetic field is removed. It is also the measure of that magnetization.*[1] Colloquially, when a magnet is "magnetized" it has remanence.*[2] The remanence of magnetic materials provides the magnetic memory in magnetic storage devices, and is used as a source of information on the past Earth's magnetic field in paleomagnetism.

The equivalent term **residual magnetization** is generally used in engineering applications. In transformers, electric motors and generators a large residual magnetization is not desirable (see also electrical steel) as it is an unwanted contamination, for example a magnetization remaining in an electromagnet after the current in the coil is turned off. Where it is unwanted, it can be removed by degaussing.

Sometimes the term **retentivity** is used for remanence measured in units of magnetic flux density.*[3]

24.1 Types of remanence

24.1.1 Saturation remanence

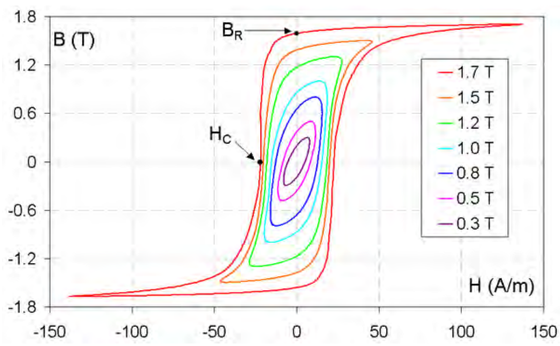

***Fig. 1** A family of AC hysteresis loops for grain-oriented electrical steel (**B**$_r$ denotes* remanence *and **H**$_c$ is the* coercivity*).*

The default definition of magnetic remanence is the magnetization remaining in zero field after a large magnetic field is applied (enough to achieve saturation).*[1] The effect of a magnetic hysteresis loop is measured using instruments such as a vibrating sample magnetometer; and the zero-field intercept is a measure of the remanence. In physics this measure is converted to an average magnetization (the total magnetic moment divided by the volume of the sample) and denoted in equations as $\boldsymbol{M}_{\mathrm{r}}$. If it must be distinguished from other kinds of remanence, then it is called the *saturation remanence* or *saturation isothermal remanence (SIRM)* and denoted by $\boldsymbol{M}_{\mathrm{rs}}$.

In engineering applications the residual magnetization is often measured using a B-H Analyzer, which measures the response to an AC magnetic field (as in Fig. 1). This is represented by a flux density $\boldsymbol{B}_{\mathrm{r}}$. This value of remanence is one of the most important parameters characterizing permanent magnets; it measures the strongest magnetic field they can produce. Neodymium magnets, for example, have a remanence approximately equal to 1.3 teslas.

24.1.2 Isothermal remanence

Often a single measure of remanence does not provide adequate information on a magnet. For example, magnetic tapes contain a large number of small magnetic particles (see magnetic storage), and these particles are not identical. Magnetic minerals in rocks may have a wide range of magnetic properties (see rock magnetism). One way to look inside these materials is to add or subtract small increments of remanence. One way of doing this is first demagnetizing the magnet in an AC field, and then applying a field $\boldsymbol{H}$ and removing it. This remanence, denoted by $\boldsymbol{M}_{\mathrm{r}}(\boldsymbol{H})$, depends on the field.*[4] It is called the *initial remanence**[5] or the *isothermal remanent magnetization (IRM)*.*[6]

Another kind of IRM can be obtained by first giving the magnet a saturation remanence in one direction and then applying and removing a magnetic field in the opposite direction.*[4] This is called *demagnetization remanence* or *DC demagnetization remanence* and is denoted by symbols like $\boldsymbol{M}_{\mathrm{d}}(\boldsymbol{H})$, where $\boldsymbol{H}$ is the *magnitude* of the field.*[7] Yet another kind of remanence can be obtained by demagnetizing the saturation remanence in an ac field. This is called *AC demagnetization remanence* or *alternating field demagnetization remanence* and is denoted by symbols like $\boldsymbol{M}_{\mathrm{af}}(\boldsymbol{H})$.

If the particles are noninteracting single-domain particles with uniaxial anisotropy, there are simple linear relations between the remanences.*[4]

24.1.3 Anhysteretic remanence

Another kind of laboratory remanence is *anhysteretic remanence* or *anhysteretic remanent magnetization (ARM)*. This is induced by exposing a magnet to a large alternating field plus a small dc bias field. The amplitude of the alternating field is gradually reduced to zero to get an *anhysteretic magnetization*, and then the bias field is removed to get the remanence. The anhysteretic magnetization curve is often close to an average of the two branches of the hysteresis loop,*[8] and is assumed in some models to represent the lowest-energy state for a given field.*[9] ARM has also been studied because of its similarity to the write process in some magnetic recording technology*[10] and to the acquisition of natural remanent magnetization in rocks.*[11]

24.2 Examples

24.3 Notes

[1] Chikazumi 1997

[2] Strictly speaking, it is still in the Earth's field, but that has little effect on the remanence of a hard magnet.

[3] "Magnetic Tape Storage and Handling" .

[4] Wohlfarth 1958

[5] McCurrie & Gaunt 1966

[6] Néel 1955

[7] Pfeiffer 1990

[8] Bozorth 1951

[9] Jiles & Atherton 1986

[10] Jaep 1969

[11] Banerjee & Mellema 1974

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24.5 External links

- Coercivity and Remanence in Permanent Magnets
- Magnet Man

24.6 See also

- Coercivity
- Hysteresis
- Rock magnetism
- Thermoremanent magnetization
- Viscous remanent magnetization

Chapter 25

Magnetic susceptibility

In electromagnetism, the **magnetic susceptibility** (Latin: *susceptibilis*, "receptive"; denoted χ) is one measure of the magnetic properties of a material. The susceptibility indicates whether a material is attracted into or repelled out of a magnetic field, which in turn has implications for practical applications. Quantitative measures of the magnetic susceptibility also provide insights into the structure of materials, providing insight into bonding and energy levels.

25.1 Definition of volume susceptibility

See also: Permeability (electromagnetism) § Relative permeability and magnetic susceptibility

Magnetic susceptibility is a dimensionless proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field. A related term is **magnetizability**, the proportion between magnetic moment and magnetic flux density.*[1] A closely related parameter is the permeability, which expresses the total magnetization of material and volume.

The *volume magnetic susceptibility*, represented by the symbol χ_v (often simply χ , sometimes χ_m – magnetic, to distinguish from the electric susceptibility), is defined in the International System of Units —in other systems there may be additional constants —by the following relationship:*[2]

$$\mathbf{M} = \chi_v \mathbf{H}.$$

Here

> **M** is the magnetization of the material (the magnetic dipole moment per unit volume), measured in amperes per meter, and

> **H** is the magnetic field strength, also measured in amperes per meter.

χ_v is therefore a dimensionless quantity.

Using SI units, the magnetic induction **B** is related to **H** by the relationship

$$\mathbf{B} \;=\; \mu_0(\mathbf{H}+\mathbf{M}) \;=\; \mu_0(1+\chi_v)\mathbf{H} \;=\; \mu\mathbf{H}$$

where μ_0 is the magnetic constant (see table of physical constants), and $(1+\chi_v)$ is the relative permeability of the material. Thus the *volume magnetic susceptibility* χ_v and the magnetic permeability μ are related by the following formula:

$$\mu = \mu_0(1+\chi_v)$$

Sometimes*[3] an auxiliary quantity called *intensity of magnetization* (also referred to as *magnetic polarisation* **J**) and measured in teslas, is defined as

$$\mathbf{I} = \mu_0 \mathbf{M}$$

This allows an alternative description of all magnetization phenomena in terms of the quantities **I** and **B**, as opposed to the commonly used **M** and **H**.

Note that these definitions are according to SI conventions. However, many tables of magnetic susceptibility give CGS values (more specifically emu-cgs, short for electromagnetic units, or Gaussian-cgs; both are the same in this context). These units rely on a different definition of the permeability of free space:*[4]

$$\mathbf{B}^{\text{cgs}} \;=\; \mathbf{H}^{\text{cgs}} + 4\pi\mathbf{M}^{\text{cgs}} \;=\; (1+4\pi\chi_v^{\text{cgs}})\mathbf{H}^{\text{cgs}}$$

The dimensionless CGS value of volume susceptibility is multiplied by 4π to give the dimensionless SI volume susceptibility value:*[4]

$$\chi_v^{\text{SI}} = 4\pi\chi_v^{\text{cgs}}$$

For example, the CGS volume magnetic susceptibility of water at 20 °C is −7.19×10*−7 which is −9.04×10*−6 using the SI convention.

In physics it is common (in older literature) to see CGS mass susceptibility given in emu/g, so to convert to SI volume susceptibility we use the conversion *[5]

$$\chi_v^{\text{SI}} = 4\pi\,\rho^{\text{cgs}}\,\chi_m^{\text{cgs}}$$

where ρ^{cgs} is the density given in g/cm^3, or

$$\chi_v^{\text{SI}} = (4\pi \times 10^{-3})\,\rho^{\text{SI}}\,\chi_m^{\text{cgs}}$$

where ρ^{SI} is the density given in kg/m^3.

25.2 Mass susceptibility and molar susceptibility

There are two other measures of susceptibility, the *mass magnetic susceptibility* (χ_{mass} or χ_{g}, sometimes χ_{m}), measured in m^3·kg*−1 in SI or in cm^3·g*−1 in CGS and the *molar magnetic susceptibility* (χ_{mol}) measured in m^3·mol*−1 (SI) or cm^3·mol*−1 (CGS) that are defined below, where ρ is the density in kg·m*−3 (SI) or g·cm*−3 (CGS) and M is molar mass in kg·mol*−1 (SI) or g·mol*−1 (CGS).

$$\chi_{\text{mass}} = \chi_v/\rho$$

$$\chi_{\text{mol}} = M\chi_{\text{mass}} = M\chi_v/\rho$$

25.3 Sign of susceptibility: diamagnetics and other types of magnetism

If χ is positive, a material can be paramagnetic. In this case, the magnetic field in the material is strengthened by the induced magnetization. Alternatively, if χ is negative, the material is diamagnetic. In this case, the magnetic field in the material is weakened by the induced magnetization. Generally, non-magnetic materials are said to be para- or diamagnetic because they do not possess permanent magnetization without external magnetic field. Ferromagnetic, ferrimagnetic, or antiferromagnetic materials have positive susceptibility and possess permanent magnetization even without external magnetic field.

25.4 Experimental methods to determine susceptibility

Volume magnetic susceptibility is measured by the force change felt upon a substance when a magnetic field gradient is applied.*[6] Early measurements are made using the Gouy balance where a sample is hung between the poles of an electromagnet. The change in weight when the electromagnet is turned on is proportional to the susceptibility. Today, high-end measurement systems use a superconductive magnet. An alternative is to measure the force change on a strong compact magnet upon insertion of the sample. This system, widely used today, is called the Evans balance.*[7] For liquid samples, the susceptibility can be measured from the dependence of the NMR frequency of the sample on its shape or orientation.*[8]*[9]*[10]*[11]*[12] Another method using MRI/NMR techniques measures the magnetic field distortion around a sample immersed in water inside an MR scanner. This method is highly accurate for diamagnetic materials with susceptibilities similar to water. *[13]

25.5 Tensor susceptibility

The magnetic susceptibility of most crystals is not a scalar quantity. Magnetic response **M** is dependent upon the orientation of the sample and can occur in directions other than that of the applied field **H**. In these cases, volume susceptibility is defined as a tensor

$$M_i = \chi_{ij} H_j$$

where *i* and *j* refer to the directions (e.g., *x* and *y* in Cartesian coordinates) of the applied field and magnetization, respectively. The tensor is thus rank 2 (second order), dimension (3,3) describing the component of magnetization in the *i*-th direction from the external field applied in the *j*-th direction.

25.6 Differential susceptibility

In ferromagnetic crystals, the relationship between **M** and **H** is not linear. To accommodate this, a more general definition of *differential susceptibility* is used

$$\chi_{ij}^d = \frac{\partial M_i}{\partial H_j}$$

where χ_{ij}^d is a tensor derived from partial derivatives of components of **M** with respect to components of **H**. When the coercivity of the material parallel to an applied field is the smaller of the two, the differential susceptibility is a function of the applied field and self interactions, such as the magnetic anisotropy. When the material is not saturated, the effect will be nonlinear and dependent upon the domain wall configuration of the material.

25.7 Susceptibility in the frequency domain

When the magnetic susceptibility is measured in response to an AC magnetic field (i.e. a magnetic field that varies sinusoidally), this is called *AC susceptibility*. AC susceptibility (and the closely related "AC permeability") are complex number quantities, and various phenomena (such as resonances) can be seen in AC susceptibility that cannot in constant-field (DC) susceptibility. In particular, when an AC field is applied perpendicular to the detection direction (called the "transverse susceptibility" regardless of the frequency), the effect has a peak at the ferromagnetic resonance frequency of the material with a given static applied field. Currently, this effect is called the *microwave permeability* or *network ferromagnetic resonance* in the literature. These results are sensitive to the domain wall configuration of the material and eddy currents.

In terms of ferromagnetic resonance, the effect of an ac-field applied along the direction of the magnetization is called *parallel pumping*.

For a tutorial with more information on AC susceptibility measurements, see here (external link).

25.8 Examples

25.9 Sources of confusion in published data

The CRC Handbook of Chemistry and Physics has one of the only published magnetic susceptibility tables. Some of the data (e.g. for Al, Bi, and diamond) is listed as CGS. CGS has caused confusion to some readers. CGS is an abbreviation of (centimeters*grams*second) it represents the form of the units but CGS does not specify units. Correct units of magnetic susceptibility in CGS is cm^3/mol or cm^3/g. **Molar Susceptibility** and **Mass Susceptibility** are both listed in the CRC. Some table have listed magnetic susceptibility of diamagnets as positives. It is important to check the header of the table for the correct units and sign of magnetic susceptibility readings.

25.10 See also

- Curie constant
- Electric susceptibility
- Iron
- Magnetic constant
- Magnetic flux density
- Magnetism
- Magnetochemistry
- Magnetometer
- Maxwell's equations
- Paleomagnetism
- Permeability (electromagnetism)
- Quantitative susceptibility mapping
- Susceptibility weighted imaging

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25.12 External links

- Linear Response Functions in Eva Pavarini, Erik Koch, Dieter Vollhardt, and Alexander Lichtenstein (eds.): DMFT at 25: Infinite Dimensions, Verlag des Forschungszentrum Jülich, 2014 ISBN 978-3-89336-953-9

Chapter 26

Magnetic mineralogy

Magnetic mineralogy is the study of the magnetic properties of minerals. The contribution of a mineral to the total magnetism of a rock depends strongly on the type of magnetic order or disorder. Magnetically disordered minerals (diamagnets and paramagnets) contribute a weak magnetism and have no remanence. The more important minerals for rock magnetism are the minerals that can be magnetically ordered, at least at some temperatures. These are the ferromagnets, ferrimagnets and certain kinds of antiferromagnets. These minerals have a much stronger response to the field and can have a remanence.

Reddish crystals: biotite.

26.1 Weakly magnetic minerals

26.1.1 Non-iron-bearing minerals

Most minerals with no iron content are diamagnetic.*[1] Some such minerals may have a significant positive magnetic susceptibility, for example serpentine,*[2] but this is because the minerals have inclusions containing strongly magnetic minerals such as magnetite. The susceptibility of such minerals is negative and small (Table 1).

26.1.2 Iron-bearing paramagnetic minerals

Most iron-bearing carbonates and silicates are paramagnetic at all temperatures.*[1] Some sulfides are paramagnetic, but some are strongly magnetic (see below). In addition, many of the strongly magnetic minerals discussed below are paramagnetic above a critical temperature (the Curie temperature or Néel temperature). In Table 2 are given susceptibilities for some iron-bearing minerals. The susceptibilities are positive and an order of magnitude or more larger than diamagnetic susceptibilities.

26.2 Strongly magnetic minerals

26.2.1 Iron-titanium oxides

Magnetite-bearing lodestone displaying strong magnetic properties.

Many of the most important magnetic minerals on Earth are oxides of iron and titanium. Their compositions are conveniently represented on a ternary plot with axes corresponding to the proportions of Ti*4+, Fe*2+, and Fe*3+. Important regions on the diagram include the *titanomagnetites*, which form a line of compositions $Fe_{3-x}Ti_xO_4$ for *x* between 0 and 1. At the *x*=0 end is magnetite, while the *x*=1 composition is ulvöspinel. The titanomagnetites have an inverse spinel crystal structure and at high temperatures are a solid solution series. Crystals formed from titanomagnetites by cation-deficient oxidation are called *titanomaghemites*, an important example of which is maghemite. Another series, the *titanohematites*, have hematite and ilmenite as their end members, and so are also called *hemoilmenites*.*[1] The crystal structure of hematite is trigonal-hexagonal. It has the same composition as maghemite; to distinguish between them, their chemical formulae are generally given as γFe_2O_3 for hematite and αFe_2O_3 for maghemite.

26.2.2 Iron sulfides

The other important class of strongly magnetic minerals is the iron sulfides, particularly greigite and pyrrhotite.

26.2.3 Iron alloys

Meteorite slice with intergrowth of kamacite and taenite.

Extraterrestrial environments being low in oxygen, minerals tend to have very little Fe*3+. The primary magnetic phase on the Moon is ferrite, the body-centered cubic (bcc) phase of iron. As the proportion of iron decreases, the crystal structure changes from bcc to face centered cubic (fcc). Nickel iron mixtures tend to exsolve into a mixture of iron-rich kamacite and iron-poor taenite.*[3]*:27

26.3 See also

- Magnetochemistry

26.4 References

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Chapter 27

Magnetite

Magnetite is a mineral and one of the main iron ores. With the chemical formula Fe_3O_4, it is one of the oxides of iron. Magnetite is ferrimagnetic; it is attracted to a magnet and can be magnetized to become a permanent magnet itself.*[5]*[6] It is the most magnetic of all the naturally-occurring minerals on Earth.*[5]*[7] Naturally-magnetized pieces of magnetite, called lodestone, will attract small pieces of iron, which is how ancient peoples first discovered the property of magnetism. Today it is mined as iron ore.

Small grains of magnetite occur in almost all igneous and metamorphic rocks. Magnetite is black or brownish-black with a metallic luster, has a Mohs hardness of 5–6 and leaves a black streak.*[5]

The chemical IUPAC name is iron(II,III) oxide and the common chemical name is **ferrous-ferric oxide**.

27.1 Properties

In addition to igneous rocks, magnetite also occurs in sedimentary rocks, including banded iron formations and in lake and marine sediments as both detrital grains and as magnetofossils. Magnetite nanoparticles are also thought to form in soils, where they probably oxidize rapidly to maghemite. *[8]

27.1.1 Solid solutions

Magnetite has an inverse spinel crystal structure. As a member of the spinel group, it can form solid solutions with similarly structured minerals, including ulvospinel (Fe_2TiO_4), hercynite ($FeAl_2O_4$) and chromite ($FeCr_2O_4$). Titanomagnetite, also known as titaniferous magnetite, is a solid solution between magnetite and ulvospinel that crystallizes in many mafic igneous rocks. Titanomagnetite may undergo oxyexsolution during cooling, resulting in ingrowths of magnetite and ilmenite.

27.1.2 Reactions

Magnetite has been important in understanding the conditions under which rocks form. Magnetite reacts with oxygen to produce hematite, and the mineral pair forms a buffer that can control oxygen fugacity. Commonly, igneous rocks contain solid solutions of both titanomagnetite and hemoilmenite or titanohematite. Compositions of the mineral pairs are used to calculate how oxidizing was the magma (i.e., the oxygen fugacity of the magma): a range of oxidizing conditions are found in magmas and the oxidation state helps to determine how the magmas might evolve by fractional crystallization. Magnetite also is produced from peridotites and dunites by serpentinization.

27.1.3 Magnetic properties

Lodestones were used as an early form of magnetic compass. Magnetite typically carries the dominant magnetic signature in rocks, and so it has been a critical tool in paleomagnetism, a science important in understanding plate tectonics and as historic data for magnetohydrodynamics and other scientific fields.

The relationships between magnetite and other iron-rich oxide minerals such as ilmenite, hematite, and ulvospinel have been much studied; the reactions between these minerals and oxygen influence how and when magnetite preserves a record of the Earth's magnetic field.

At low temperatures, magnetite undergoes a crystal structure phase transition from a monoclinic structure to a cubic structure known as the Verwey transition. The Verwey transition occurs around 121 K and is dependent on grain size, domain state, and the iron-oxygen stoichiometry.*[9] An isotropic point also occurs near the Verwey transition around 130 K, at which point the sign of the magnetocrystalline anisotropy constant changes from positive to negative. *[10] The Curie temperature of magnetite is 858 K (585 °C; 1,085 °F).

A fine textured sample, ~5cm across

Magnetite and other heavy minerals (dark) in a quartz beach sand (Chennai, India).

27.2 Distribution of deposits

Magnetite is sometimes found in large quantities in beach sand. Such black sands (mineral sands or iron sands) are found in various places, such as Lung Kwu Tan of Hong Kong, California of the United States and the west coast of the North Island of New Zealand.[11] The magnetite is carried to the beach via rivers from erosion and is concentrated via wave action and currents. Huge deposits have been found in banded iron formations. These sedimentary rocks have been used to infer changes in the oxygen content of the atmosphere of the Earth.

Large deposits of magnetite are also found in the Atacama region of Chile, Valentines region of Uruguay, Kiruna, Sweden, the Pilbara, Midwest and Northern Goldfields regions in Western Australia, New South Wales in the Tallawang Region, and in the Adirondack region of New York in the United States. Kediet ej Jill, the highest mountain of Mauritania, is made entirely of the mineral.[12] Deposits are also found in Norway, Germany, Italy, Switzerland, South Africa, India, Indonesia, Mexico, Hong Kong, and in Oregon, New Jersey, Pennsylvania, North Carolina, West Virginia, Virginia, New Mexico, Utah, and Colorado in the United States. In 2005, an exploration company, Cardero Resources, discovered a vast deposit of magnetite-bearing sand dunes in Peru. The dune field covers 250 square kilometers (100 sq mi), with the highest dune at over 2,000 meters (6,560 ft) above the desert floor. The sand contains 10% magnetite.[13]

27.3 Biological occurrences

Biomagnetism is usually related to the presence of biogenic crystals of magnetite, which occur widely in organisms.[14] These organisms range from bacteria (e.g., *Magnetospirillum magnetotacticum*) to animals, including humans, where magnetite crystals (and other magnetically-sensitive compounds) are found in different organs, depending on the species.[15][16] Biomagnetites account for the effects of weak magnetic fields on biological systems.[17] There is also a chemical basis for cellular sensitivity to electric and magnetic fields (galvanotaxis).[18]

Pure magnetite particles are biomineralized in magnetosomes, which are produced by several species of magnetotactic bacteria. Magnetosomes consist of long chains of oriented magnetite particle that are used by bacteria for navigation. After the death of these bacteria, the magnetite particles in magnetosomes may be preserved in sediments as magnetofossils.

Several species of birds are known to incorporate magnetite crystals in the upper beak for magnetoreception,[19] which (in conjunction with cryptochromes in the retina) gives them the ability to sense the direction, polarity, and magnitude of the ambient magnetic field.[15][20]

Chitons, a type of mollusk, have a tongue-like structure known as a radula, covered with magnetite-coated teeth, or denticles.[21] The hardness of the magnetite helps in breaking down food, and its magnetic properties may additionally aid in navigation. It has also been proposed that biological magnetite may store information.[22]

27.3.1 Human brain

There is also evidence that magnetite exists in the human brain,[16] where it is theorized to affect long-term memory.[23] Some researchers also suggest that humans possess a magnetic sense,[24] proposing that this could allow certain people to use magnetoreception for navigation.[25] The role of magnetite in the brain is still not well understood, and there has been a general lag in applying more modern, interdisciplinary techniques to the study of biomagnetism.[26]

Electron microscope scans of human brain-tissue samples are able to differentiate between magnetite produced by the body's own cells and magnetite absorbed from airborne pollution, the natural forms being jagged and crystalline, while magnetite pollution occurs as rounded nanoparticles. In some brain samples, the nanoparticle pollution outnumbers the natural particles by as much as 100:1, and such pollution-borne magnetite particles may be linked to abnormal neural deterioration. In one study, the characteristic nanoparticles were found in the brains of 37 people: 29 of these, aged 3 to 85, had lived and died in Mexico City, a significant air pollution hotspot. A further eight, aged 62 to 92, came from Manchester, and some had died with varying severities of neurodegenerative diseases.*[27] According to researchers led by Prof. Barbara Maher at Lancaster University and published in the Proceedings of the National Academy of Sciences, such particles could conceivably contribute to diseases like Alzheimer's disease. Though a causal link has not been established, laboratory studies suggest that iron oxides like magnetite are a component of protein plaques in the brain, linked to Alzheimer's disease.*[28]

27.4 Applications

Due to its high iron content, magnetite has long been a major iron ore.*[29] It is reduced in blast furnaces to pig iron or sponge iron for conversion to steel.

27.4.1 Magnetic recording

Audio recording using magnetic acetate tape was developed in the 1930s. The German magnetophon utilized magnetite powder as the recording medium.*[30] Following World War II, the 3M company continued work on the German design. In 1946, the 3M researchers found they could improve the magnetite-based tape, which utilized powders of cubic crystals, by replacing the magnetite with needle-shaped particles of gamma ferric oxide (γ-Fe_2O_3).*[30]

27.4.2 Catalysis

Magnetite is the catalyst for the industrial synthesis of ammonia.*[31]

27.5 Gallery of magnetite mineral specimens

- Octahedral crystals of magnetite up to 1.8 cm across, on cream colored feldspar crystals, locality: Cerro Huañaquino, Potosí Department, Bolivia (size: 8.4 x 5.2 x 3.2 cm)
- Red gem-like crystals of chondrodite with magnetite, Tilly Foster mine, Brewster, New York (size 2.8 x 2.6 x 2.1 cm)
- Metallic, jet black, complex cubes of magnetite, from the Balmat-Edwards district, St. Lawrence County, New York (field of view, about 4 cm)

27.6 See also

- Bluing (steel), a process in which steel is partially protected against rust by a layer of magnetite
- Buena Vista Iron Ore District
- Corrosion product

- Ferrite
- Greigite
- Maghemite
- Magnesia (in natural mixtures with magnetite)
- Magnetotactic bacteria
- Mill scale
- Mineral redox buffer
- Magnes the shepherd

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27.8 Further reading

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27.9 External links

- Mineral galleries
- Bio-magnetics
- Magnetite mining in New Zealand Accessed 25-Mar-09

Chapter 28

Hematite

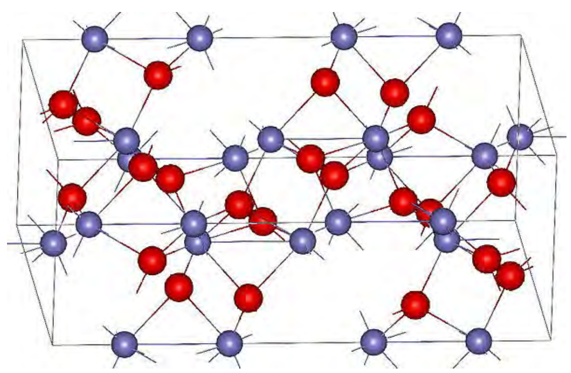
For other uses, see Hematite (disambiguation).

Hematite, also spelled as **haematite**, is the mineral form of iron(III) oxide (Fe_2O_3), one of several iron oxides. Hematite crystallizes in the rhombohedral lattice system, and it has the same crystal structure as ilmenite and corundum. Hematite and ilmenite form a complete solid solution at temperatures above 950 °C (1,740 °F).

Hematite is colored black to steel or silver-gray, brown to reddish brown, or red. It is mined as the main ore of iron. Varieties include *kidney ore*, *martite* (pseudomorphs after magnetite), *iron rose* and *specularite* (specular hematite). While the forms of hematite vary, they all have a rust-red streak. Hematite is harder than pure iron, but much more brittle. Maghemite is a hematite- and magnetite-related oxide mineral.

Huge deposits of hematite are found in banded iron formations. Gray hematite is typically found in places that can have still standing water or mineral hot springs, such as those in Yellowstone National Park in North America. The mineral can precipitate out of water and collect in layers at the bottom of a lake, spring, or other standing water. Hematite can also occur without water, however, usually as the result of volcanic activity.

Clay-sized hematite crystals can also occur as a secondary mineral formed by weathering processes in soil, and along with other iron oxides or oxyhydroxides such as goethite, is responsible for the red color of many tropical, ancient, or otherwise highly weathered soils.



Crystal structure of hematite

28.1 Etymology and history

Main article: Ochre

The name hematite is derived from the Greek word for blood αἷμα *haima,* due to the red coloration found in some varities of hematite. The color of hematite lends itself to use as a pigment. The English name of the stone is derived from Middle French: Hématite Pierre, which was imported from Latin: Lapis Hæmatites around the 15th century, which originated from Ancient Greek: αἱματίτης λίθος (*haimatitēs* lithos, "blood-red stone").

Ochre is a clay that is colored by varying amounts of hematite, varying between 20% and 70%.*[5] Red ochre contains unhydrated hematite, whereas yellow ochre contains hydrated hematite ($Fe_2O_3 \cdot H_2O$). The principal use of ochre is for tinting with a permanent color.*[5]

The red chalk writing of this mineral was one of the earliest in the history of humans. The powdery mineral was first used 164,000 years ago by the Pinnacle-Point man possibly for social purposes.*[6] Hematite residues are also found in graves from 80,000 years ago. Near Rydno in Poland and Lovas in Hungary red chalk mines have been found that are from 5000 BC, belonging to the Linear Pottery culture at the Upper Rhine.*[7]

Rich deposits of hematite have been found on the island of Elba that have been mined since the time of the Etruscans.

28.2 Magnetism

Hematite is an antiferromagnetic material below the Morin transition at 250 kelvin (K) or −9.7 degrees Fahrenheit (°F), and a canted antiferromagnet or weakly ferromagnetic above the Morin transition and below its Néel temperature at 948 K, above which it is paramagnetic.

The magnetic structure of a-hematite was the subject of considerable discussion and debate in the 1950s because it appeared to be ferromagnetic with a Curie temperature of around 1000 K, but with an extremely tiny magnetic moment (0.002 μ_B). Adding to the surprise was a transition with a decrease in temperature at around 260 K to a phase with no net magnetic moment. It was shown that the system is essentially antiferromagnetic, but that the low symmetry of the cation sites allows spin–orbit coupling to cause canting of the moments when they are in the plane perpendicular to the c axis. The disappearance of the moment with a decrease in temperature at 260 K is caused by a change in the anisotropy which causes the moments to align along the c axis. In this configuration, spin canting does not reduce the energy.*[8]*[9] The magnetic properties of bulk hematite differ from their nanoscale counterparts. For example, the Morin transition temperature of hematite decreases with a decrease in the particle size. The suppression of this transition has also been observed in some of the hematite nanoparticles, and the presence of impurities, water molecules and defects in the crystals were attributed to the absence of a Morin transition. Hematite is part of a complex solid solution oxyhydroxide system having various contents of water, hydroxyl groups and vacancy substitutions that affect the mineral's magnetic and crystal chemical properties.*[10] Two other end-members are referred to as protohematite and hydrohematite.

Enhanced magnetic coercivities for hematite have been achieved by dry-heating a 2-line ferrihydrite precursor prepared from solution. Hematite exhibited temperature-dependent magnetic coercivity values ranging from 289 to 5,027 Oe. The origin of these high coercivity values has been interpreted as a consequence of the subparticle structure induced by the different particle and crystallite size growth rates at increasing annealing temperature. These differences in the growth rates are translated into a progressive development of a subparticle structure at the nanoscale. At lower temperatures (350–600 °C), single particles crystallize however; at higher temperatures (600-1000 °C), the growth of crystalline aggregates with a subparticle structure is favored.*[11]

28.3 Mine tailings

Hematite is present in the waste tailings of iron mines. A recently developed process, magnetation, uses magnets to glean waste hematite from old mine tailings in Minnesota's vast Mesabi Range iron district.*[12] Falu red is a pigment used in traditional Swedish house paints. Originally, it was made from tailings of the Falu mine.*[13]

28.4 Mars

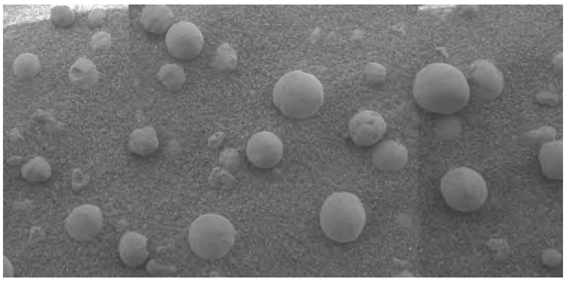


Image mosaic from the Mars Exploration Rover Microscopic Imager shows Hematite spherules partly embedded in rock at the Opportunity landing site. Image is ca. 5 cm (2 in) across.

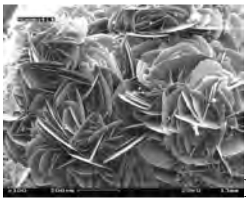
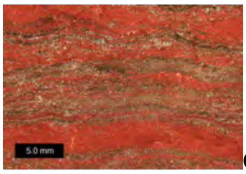
The spectral signature of hematite was seen on the planet Mars by the infrared spectrometer on the NASA Mars Global Surveyor (“MGS”) and 2001 Mars Odyssey spacecraft in orbit around Mars.*[14] The mineral was seen in abundance at two sites*[15] on the planet, the Terra Meridiani site, near the Martian equator at 0° longitude, and the Aram Chaos site near the Valles Marineris.*[16] Several other sites also showed hematite, e.g., Aureum Chaos.*[17] Because terrestrial hematite is typically a mineral formed in aqueous environments or by aqueous alteration, this detection was scientifically interesting enough that the second of the two Mars Exploration Rovers was sent to a site in the Terra Meridiani region designated Meridiani Planum. In-situ investigations by the Opportunity rover showed a significant amount of hematite, much of it in the form of small spherules that were informally named “blueberries” by the science team. Analysis indicates that these spherules are apparently concretions formed from a water solution. “Knowing just how the hematite on Mars was formed will help us characterize the past environment and determine whether that environment was favorable for life” .*[18]

Hematite carving, 5 cm (2 in) long.

28.5 Jewelry

Hematite's popularity in jewelry was at its highest in Europe during the Victorian era. Certain types of hematite or iron oxide-rich clay, especially Armenian bole, have been used in gilding. Hematite is also used in art such as in the creation of intaglio engraved gems. Hematine is a synthetic material sold as *magnetic hematite*.*[19]

28.6 Gallery

- Hematite in a scanning electron microscope, magnification 100x
- Amethyst crystals with hematite inclusions from Thunder Bay, Ontario
- Hematite (blood ore) from Michigan
- Close-up of hematitic banded iron formation specimen from Upper Michigan. Scale bar is 5.0 mm.
- Cypro-Minoan cylinder seal (left) made from hematite with corresponding impression (right), approximately 14th century BC

28.7 See also

- Mill scale
- Mineral redox buffer
- Wüstite

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28.9 External links

- MineralData.org

Chapter 29

Lodestone

For a general description of the mineral itself, see Magnetite.

For other uses, see Lodestone (disambiguation).

A **lodestone** is a naturally magnetized piece of the mineral magnetite.[1][2] They are naturally occurring magnets, which can attract iron. The property of magnetism was first discovered in antiquity through lodestones.[3] Pieces of lodestone, suspended so they could turn, were the first magnetic compasses,[3][4][5][6] and their importance to early navigation is indicated by the name *lodestone*, which in Middle English means 'course stone' or 'leading stone',[7] from the now-obsolete meaning of *lode* as 'journey, way'.[8]

Lodestone attracting small bits of iron

Lodestone in the Hall of Gems of the Smithsonian

Lodestone is one of the few minerals that is found naturally magnetized.[1] Magnetite is black or brownish-black, with a metallic luster, a Mohs hardness of 5.5–6.5 and a black streak.

29.1 Origin

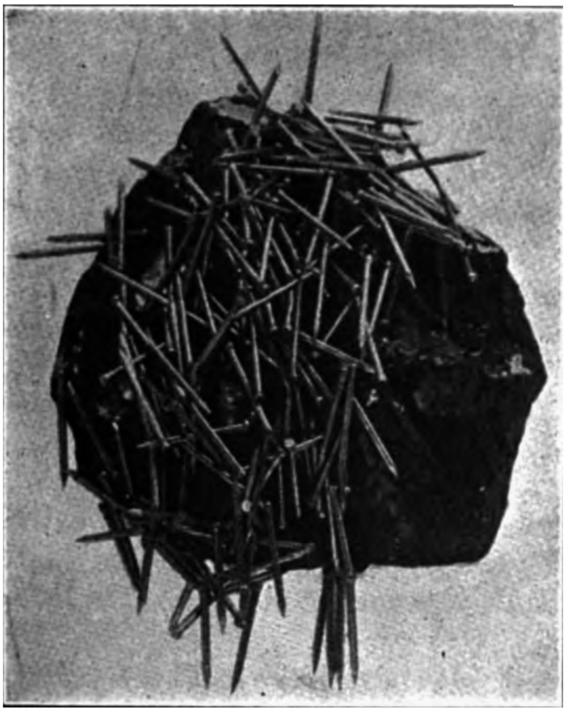
The process by which lodestone is created has long been an open question in geology. Only a small amount of the magnetite on Earth is found magnetized as lodestone. Ordinary magnetite is attracted to a magnetic field like iron and steel is, but does not tend to become magnetized itself; it has too low a magnetic coercivity (resistance to demagnetization) to stay magnetized for long.[9] Microscopic examination of lodestones has found them to be made of magnetite (Fe_3O_4) with inclusions of maghemite (cubic Fe_2O_3), often with impurity metal ions of titanium, aluminium, and manganese.[9][10][11] This inhomogeneous crystalline structure gives this variety of magnetite sufficient coercivity to remain magnetized and thus be a permanent magnet.[9][10][11]

The other question is how lodestones get magnetized. The Earth's magnetic field at 0.5 gauss is too weak to magnetize a lodestone by itself.[9][10] The leading theory is that lodestones are magnetized by the strong magnetic fields surrounding lightning bolts.[9][10][11] This is supported by the observation that they are mostly found near the surface of the Earth, rather than buried at great depth.[10]

29.2 History

One of the first references to lodestone's magnetic properties was made by 6th century BC Greek philosopher Thales of Miletus,[12] whom the ancient Greeks credited with discovering lodestone's attraction to iron and other lodestones.[13] The name *magnet* may come from lodestones found in Magnesia, Anatolia.[14]

The earliest Chinese literary reference to magnetism occurs in a 4th-century BC *Book of the Devil Valley Master* (*Guiguzi*).[15] In the chronicle *Lüshi Chunqiu*, from



Lodestone attracting iron nails

the 2nd century BC, it is explicitly stated that "the lodestone makes iron come or it attracts it." *[16] The earliest mention of a needle's attraction appears in a work composed between 20 and 100 AD, the *Lunheng* (*Balanced Inquiries*): "A lodestone attracts a needle." *[17] Medieval Chinese navigators were using lodestone compasses by the 12th century.

Based on his discovery of an Olmec artifact (a shaped and grooved magnetic bar) in Central America, astronomer John Carlson suggests that lodestone may have been used by the Olmec more than a thousand years prior to the Chinese discovery.*[18] Carlson speculates that the Olmecs, for astrological or geomantic purposes, used similar artifacts as a directional device, or to orient their temples, the dwellings of the living, or the interments of the dead.*[18] Detailed analysis of the Olmec artifact revealed that the "bar" was composed of hematite with titanium lamellae of $Fe_{2-x}Ti_xO_3$ that accounted for the anomalous remanent magnetism of the artifact.*[19]

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29.4 External links

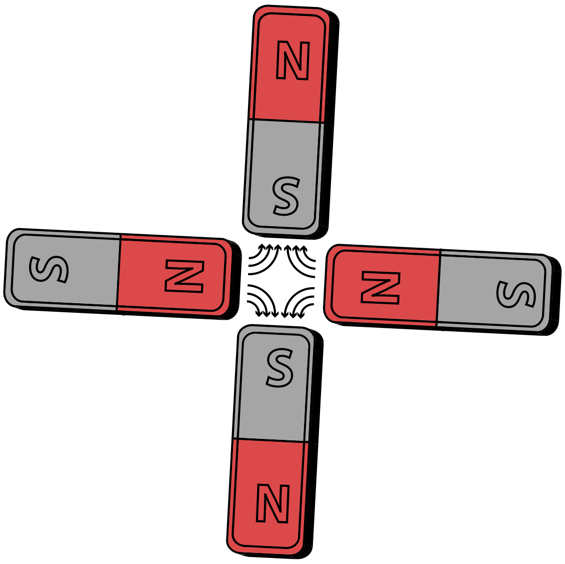
- Lodestone

Chapter 30

Magnetism

"Magnetic" redirects here. For other uses, see Magnetic (disambiguation) and Magnetism (disambiguation).

Magnetism is a class of physical phenomena that are mediated by magnetic fields. Electric currents and the magnetic moments of elementary particles give rise to a magnetic field, which acts on other currents and magnetic moments. The most familiar effects occur in ferromagnetic materials, which are strongly attracted by magnetic fields and can be magnetized to become permanent magnets, producing magnetic fields themselves. Only a few substances are ferromagnetic; the most common ones are iron, nickel and cobalt and their alloys. The prefix *ferro-* refers to iron, because permanent magnetism was first observed in lodestone, a form of natural iron ore called magnetite, Fe_3O_4.



A magnetic quadrupole

Although ferromagnetism is responsible for most of the effects of magnetism encountered in everyday life, all other materials are influenced to some extent by a magnetic field, by several other types of magnetism. Paramagnetic substances such as aluminum and oxygen are weakly attracted to an applied magnetic field; diamagnetic substances such as copper and carbon are weakly repelled; while antiferromagnetic materials such as chromium and spin glasses have a more complex relationship with a magnetic field. The force of a magnet on paramagnetic, diamagnetic, antiferromagnetic materials is usually too weak to be felt, and can be detected only by laboratory instruments, so in everyday life these substances are often described as non-magnetic.

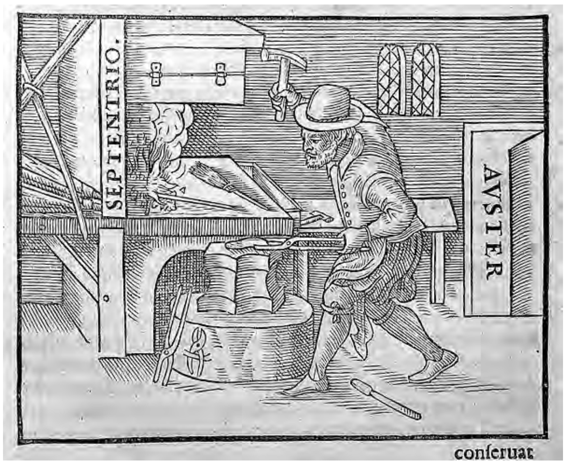
The magnetic state (or magnetic phase) of a material depends on temperature and other variables such as pressure and the applied magnetic field. A material may exhibit more than one form of magnetism as these variables change.

30.1 History

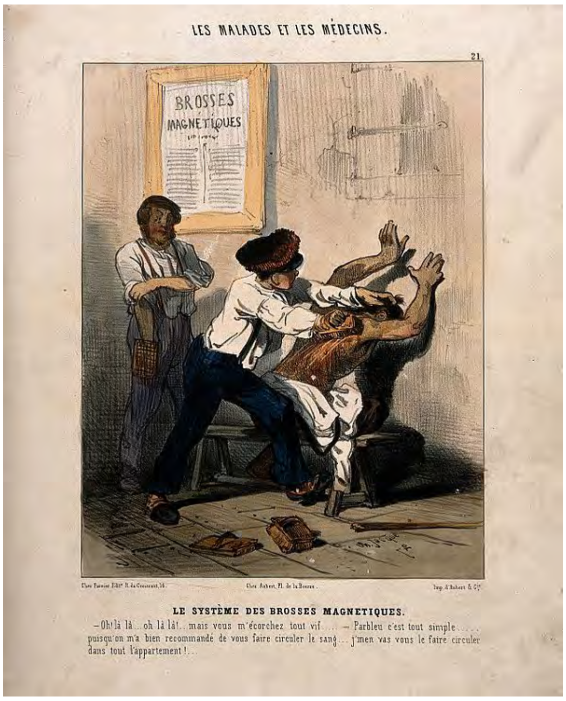
Main article: History of electromagnetism

Magnetism was first discovered in the ancient world,


Lodestone, a natural magnet, attracting iron nails. Ancient humans discovered the property of magnetism from lodestone.



An illustration from Gilbert's 1600 De Magnete *showing one of the earliest methods of making a magnet. A blacksmith holds a piece of red-hot iron in a north-south direction and hammers it as it cools. The magnetic field of the Earth aligns the domains, leaving the iron a weak magnet.*



Drawing of a medical treatment using magnetic brushes. Charles Jacque 1843, France.

when people noticed that lodestones, naturally magnetized pieces of the mineral magnetite, could attract iron.[1] The word *magnet* comes from the Greek term for lodestone, "magnítis líthos" (μαγνήτης λίθος), which means a stone from the region of Magnesia. In ancient Greece, Aristotle attributed the first of what could be called a scientific discussion of magnetism to the philosopher Thales of Miletus, who lived from about 625 BC to about 545 BC.[2] Around the same time, in ancient India, the Indian surgeon Sushruta was the first to make use of the magnet for surgical purposes.[3]

In ancient China, the earliest literary reference to magnetism lies in a 4th-century BC book named after its author, *The Master of Demon Valley*.[4] The 2nd-century BC annals, *Lüshi Chunqiu*, also notes: "The lodestone makes iron approach, or it attracts it." [5] The earliest mention of the attraction of a needle is in a 1st-century work *Lunheng* (*Balanced Inquiries*): "A lodestone attracts a needle." [6] The 11th-century Chinese scientist Shen Kuo was the first person to write – in the *Dream Pool Essays* – of the magnetic needle compass and that it improved the accuracy of navigation by employing the astronomical concept of true north. By the 12th century the Chinese were known to use the lodestone compass for navigation. They sculpted a directional spoon from lodestone in such a way that the handle of the spoon always pointed south.

Alexander Neckam, by 1187, was the first in Europe to describe the compass and its use for navigation. In 1269, Peter Peregrinus de Maricourt wrote the *Epistola de magnete*, the first extant treatise describing the properties of magnets. In 1282, the properties of magnets and the dry compass were discussed by Al-Ashraf, a Yemeni physicist, astronomer, and geographer.[7]

In 1600, William Gilbert published his *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* (*On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth*). In this work he describes many of his experiments with his model earth called the terrella. From his experiments, he concluded that the Earth was itself magnetic and that this was the reason compasses pointed north (previously, some believed that it was the pole star (Polaris) or a large magnetic island on the north pole that attracted the compass).

An understanding of the relationship between electricity and magnetism began in 1819 with work by Hans Christian Ørsted, a professor at the University of Copenhagen, who discovered by the accidental twitching of a compass needle near a wire that an electric current could create a magnetic field. This landmark experiment is known as Ørsted's Experiment. Several other experiments followed, with André-Marie Ampère, who in 1820 discovered that the magnetic field circulating in a closed-path was related to the current flowing through the perimeter of the path; Carl Friedrich Gauss; Jean-Baptiste Biot and Félix Savart, both of whom in 1820 came up with the Biot–Savart law giving an equation for the magnetic field from a current-carrying wire; Michael Faraday, who in 1831 found that a time-varying magnetic flux through a loop of wire induced a voltage, and others finding further links between magnetism and electricity. James Clerk Maxwell synthesized and expanded these insights into Maxwell's equations, unifying electricity, magnetism, and optics into the field of electromagnetism. In 1905, Einstein used these laws in motivating his theory of special relativity,[8] requiring that the laws held true in all inertial reference frames.

Electromagnetism has continued to develop into the 21st century, being incorporated into the more fundamental theories of gauge theory, quantum electrodynamics, electroweak theory, and finally the standard model.

30.2 Sources of magnetism

See also: Magnetic moment

Magnetism, at its root, arises from two sources:

1. Electric current (see *Electron magnetic moment*).
2. Spin magnetic moments of elementary particles. The magnetic moments of the nuclei of atoms are typically thousands of times smaller than the electrons' magnetic moments, so they are negligible in the context of the magnetization of materials. Nuclear magnetic moments are nevertheless very important in other contexts, particularly in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI).

Ordinarily, the enormous number of electrons in a material are arranged such that their magnetic moments (both orbital and intrinsic) cancel out. This is due, to some extent, to electrons combining into pairs with opposite intrinsic magnetic moments as a result of the Pauli exclusion principle (see *electron configuration*), or combining into filled subshells with zero net orbital motion. In both cases, the electron arrangement is so as to exactly cancel the magnetic moments from each electron. Moreover, even when the electron configuration *is* such that there are unpaired electrons and/or non-filled subshells, it is often the case that the various electrons in the solid will contribute magnetic moments that point in different, random directions, so that the material will not be magnetic.

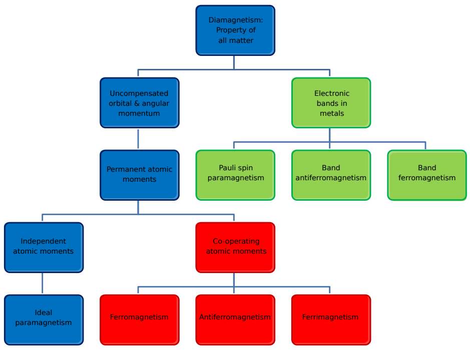
Sometimes, either spontaneously, or owing to an applied external magnetic field—each of the electron magnetic moments will be, on average, lined up. A suitable material can then produce a strong net magnetic field.

The magnetic behavior of a material depends on its structure, particularly its electron configuration, for the reasons mentioned above, and also on the temperature. At high temperatures, random thermal motion makes it more difficult for the electrons to maintain alignment.

30.3 Materials

30.3.1 Diamagnetism

Main article: Diamagnetism



Hierarchy of types of magnetism.[9]*

Diamagnetism appears in all materials, and is the tendency of a material to oppose an applied magnetic field, and therefore, to be repelled by a magnetic field. However, in a material with paramagnetic properties (that is, with a tendency to enhance an external magnetic field), the paramagnetic behavior dominates.*[10] Thus, despite its universal occurrence, diamagnetic behavior is observed only in a purely diamagnetic material. In a diamagnetic material, there are no unpaired electrons, so the intrinsic electron magnetic moments cannot produce any bulk effect. In these cases, the magnetization arises from the electrons' orbital motions, which can be understood classically as follows:

> When a material is put in a magnetic field, the electrons circling the nucleus will experience, in addition to their Coulomb attraction to the nucleus, a Lorentz force from the magnetic field. Depending on which direction the electron is orbiting, this force may increase the centripetal force on the electrons, pulling them in towards the nucleus, or it may decrease the force, pulling them away from the nucleus. This effect systematically increases the orbital magnetic moments that were aligned opposite the field, and decreases the ones aligned parallel to the field (in accordance with Lenz's law). This results in a small bulk magnetic moment, with an opposite direction to the applied field.

Note that this description is meant only as a heuristic; a proper understanding requires a quantum-mechanical description.

Note that all materials undergo this orbital response. However, in paramagnetic and ferromagnetic substances, the diamagnetic effect is overwhelmed by the much stronger effects caused by the unpaired electrons.

30.3.2 Paramagnetism

Main article: Paramagnetism

In a paramagnetic material there are *unpaired electrons*, i.e. atomic or molecular orbitals with exactly one electron in them. While paired electrons are required by the Pauli exclusion principle to have their intrinsic ('spin') magnetic moments pointing in opposite directions, causing their magnetic fields to cancel out, an unpaired electron is free to align its magnetic moment in any direction. When an external magnetic field is applied, these magnetic moments will tend to align themselves in the same direction as the applied field, thus reinforcing it.

30.3.3 Ferromagnetism

Tip of permanent magnet with coins demonstrating ferromagnetism

Main article: Ferromagnetism

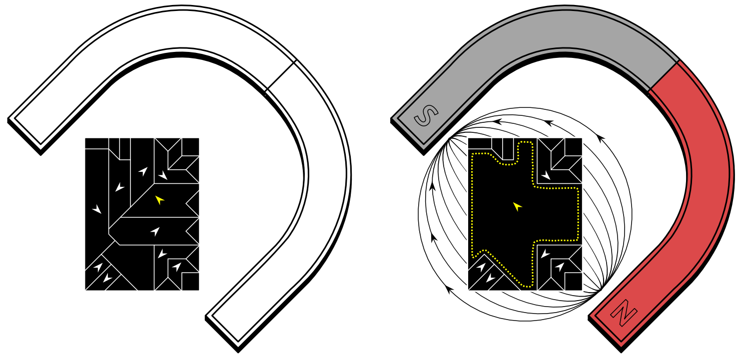
A ferromagnet, like a paramagnetic substance, has unpaired electrons. However, in *addition* to the electrons' intrinsic magnetic moment's tendency to be parallel to an *applied field*, there is also in these materials a tendency for these magnetic moments to orient parallel to *each other* to maintain a lowered-energy state. Thus, even in the absence of an applied field, the magnetic moments of the electrons in the material spontaneously line up parallel to one another.

Every ferromagnetic substance has its own individual temperature, called the Curie temperature, or Curie point, above which it loses its ferromagnetic properties. This is because the thermal tendency to disorder overwhelms the energy-lowering due to ferromagnetic order.

Ferromagnetism only occurs in a few substances; the common ones are iron, nickel, cobalt, their alloys, and some alloys of rare earth metals.

Magnetic domains

Main article: Magnetic domains



Magnetic domains boundaries (white lines) in ferromagnetic material (black rectangle). **Right:** Effect of a magnet on the domains.

The magnetic moments of atoms in a ferromagnetic material cause them to behave something like tiny permanent magnets. They stick together and align themselves into small regions of more or less uniform alignment called magnetic domains or Weiss domains. Magnetic domains can be observed with a magnetic force microscope to reveal magnetic domain boundaries that resemble white lines in the sketch. There are many scientific experiments that can physically show magnetic fields.

When a domain contains too many molecules, it becomes unstable and divides into two domains aligned in opposite directions so that they stick together more stably as shown at the right.

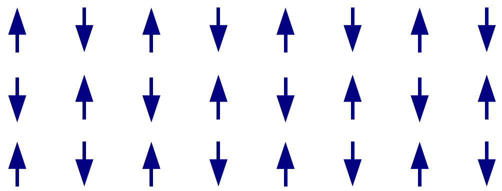
When exposed to a magnetic field, the domain boundaries move so that the domains aligned with the magnetic field grow and dominate the structure (dotted yellow area) as shown at the left. When the magnetizing field is removed, the domains may not return to an unmagnetized state. This results in the ferromagnetic material's being magnetized, forming a permanent magnet.

When magnetized strongly enough that the prevailing domain overruns all others to result in only one single domain, the material is magnetically saturated. When a magnetized ferromagnetic material is heated to the Curie point temperature, the molecules are agitated to the point that the magnetic domains lose the organization and the magnetic properties they cause cease. When the material is cooled, this domain alignment structure spontaneously returns, in a manner roughly analogous to how a liquid can freeze into a crystalline solid.

30.3.4 Antiferromagnetism

Main article: Antiferromagnetism

In an antiferromagnet, unlike a ferromagnet, there is a

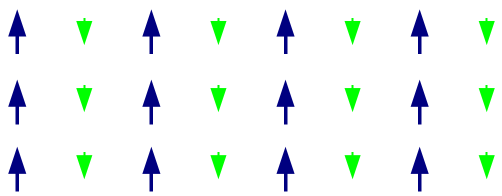


Antiferromagnetic ordering

tendency for the intrinsic magnetic moments of neighboring valence electrons to point in *opposite* directions. When all atoms are arranged in a substance so that each neighbor is 'anti-aligned', the substance is **antiferromagnetic**. Antiferromagnets have a zero net magnetic moment, meaning no field is produced by them. Antiferromagnets are less common compared to the other types of behaviors, and are mostly observed at low temperatures. In varying temperatures, antiferromagnets can be seen to exhibit diamagnetic and ferromagnetic properties.

In some materials, neighboring electrons want to point in opposite directions, but there is no geometrical arrangement in which *each* pair of neighbors is anti-aligned. This is called a spin glass, and is an example of geometrical frustration.

30.3.5 Ferrimagnetism



Ferrimagnetic ordering

Main article: Ferrimagnetism

Like ferromagnetism, **ferrimagnets** retain their magnetization in the absence of a field. However, like antiferromagnets, neighboring pairs of electron spins tend to point in opposite directions. These two properties are not contradictory, because in the optimal geometrical arrangement, there is more magnetic moment from the sublattice of electrons that point in one direction, than from the sublattice that points in the opposite direction.

Most ferrites are ferrimagnetic. The first discovered magnetic substance, magnetite, is a ferrite and was originally believed to be a ferromagnet; Louis Néel disproved this, however, after discovering ferrimagnetism.

30.3.6 Superparamagnetism

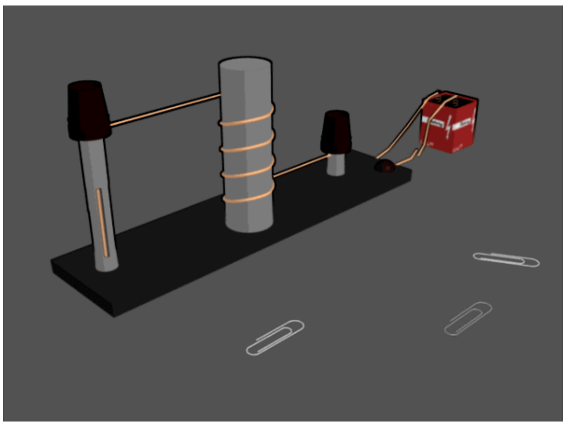
Main article: Superparamagnetism

When a ferromagnet or ferrimagnet is sufficiently small, it acts like a single magnetic spin that is subject to Brownian motion. Its response to a magnetic field is qualitatively similar to the response of a paramagnet, but much larger.

30.3.7 Other types of magnetism

- Metamagnetism
- Molecule-based magnet
- Spin glass

30.4 Electromagnet



An electromagnet attracts paper clips when current is applied creating a magnetic field. The electromagnet loses them when current and magnetic field are removed.

An electromagnet is a type of magnet in which the magnetic field is produced by an electric current. The magnetic field disappears when the current is turned off. Electromagnets usually consist of a large number of closely spaced turns of wire that create the magnetic field. The wire turns are often wound around a magnetic core made from a ferromagnetic or ferrimagnetic material such as iron; the magnetic core concentrates the magnetic flux and makes a more powerful magnet.

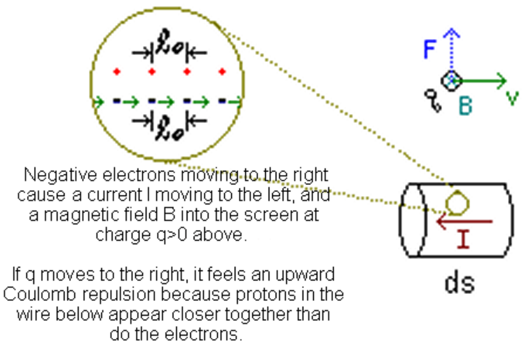
The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be quickly changed by controlling the amount of electric current in the winding. However, unlike a permanent magnet that needs no power, an electromagnet requires a continuous supply of current to maintain the magnetic field.

Electromagnets are widely used as components of other electrical devices, such as motors, generators, relays, loudspeakers, hard disks, MRI machines, scientific instruments, and magnetic separation equipment. Electromagnets are also employed in industry for picking up and moving heavy iron objects such as scrap iron and steel.*[11] Electromagnetism was discovered in 1820.*[12]

30.5 Magnetism, electricity, and special relativity

Main article: Classical electromagnetism and special relativity

As a consequence of Einstein's theory of special relativity, electricity and magnetism are fundamentally interlinked. Both magnetism lacking electricity, and electricity without magnetism, are inconsistent with special relativity, due to such effects as length contraction, time dilation, and the fact that the magnetic force is velocity-dependent. However, when both electricity and magnetism are taken into account, the resulting theory (electromagnetism) is fully consistent with special relativity.*[8]*[13] In particular, a phenomenon that appears purely electric or purely magnetic to one observer may be a mix of both to another, or more generally the relative contributions of electricity and magnetism are dependent on the frame of reference. Thus, special relativity "mixes" electricity and magnetism into a single, inseparable phenomenon called electromagnetism, analogous to how relativity "mixes" space and time into spacetime.



Magnetism from length-contraction.

All observations on electromagnetism apply to what might be considered to be primarily magnetism, e.g. perturbations in the magnetic field are necessarily accompanied by a nonzero electric field, and propagate at the speed of light.

30.6 Magnetic fields in a material

See also: Magnetic field § H and B inside and outside of magnetic materials

In a vacuum,

$$\mathbf{B} = \mu_0 \mathbf{H},$$

where μ_0 is the vacuum permeability.

In a material,

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M}).$$

The quantity $\mu_0\mathbf{M}$ is called *magnetic polarization*.

If the field **H** is small, the response of the magnetization **M** in a diamagnet or paramagnet is approximately linear:

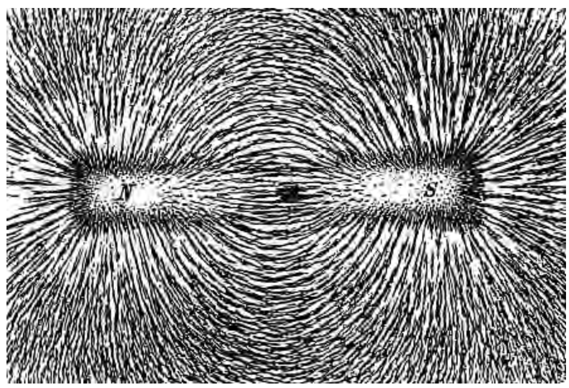
$$\mathbf{M} = \chi \mathbf{H},$$

the constant of proportionality being called the magnetic susceptibility. If so,

$$\mu_0(\mathbf{H} + \mathbf{M}) = \mu_0(1 + \chi)\mathbf{H} = \mu_r \mu_0 \mathbf{H} = \mu \mathbf{H}.$$

In a hard magnet such as a ferromagnet, **M** is not proportional to the field and is generally nonzero even when **H** is zero (see Remanence).

30.7 Magnetic force



Magnetic lines of force of a bar magnet shown by iron filings on paper

Main article: Magnetic field

The phenomenon of magnetism is "mediated" by the magnetic field. An electric current or magnetic dipole creates a magnetic field, and that field, in turn, imparts magnetic forces on other particles that are in the fields.

Maxwell's equations, which simplify to the Biot–Savart law in the case of steady currents, describe the origin and behavior of the fields that govern these forces. Therefore, magnetism is seen whenever electrically charged particles are in motion—for example, from movement of electrons in an electric current, or in certain cases from the orbital motion of electrons around an atom's nucleus. They also arise from "intrinsic" magnetic dipoles arising from quantum-mechanical spin.

The same situations that create magnetic fields—charge moving in a current or in an atom, and intrinsic magnetic dipoles—are also the situations in which a magnetic field has an effect, creating a force. Following is the formula for moving charge; for the forces on an intrinsic dipole, see magnetic dipole.

When a charged particle moves through a magnetic field **B**, it feels a Lorentz force **F** given by the cross product:*[14]

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B})$$

where

q is the electric charge of the particle, and

v is the velocity vector of the particle

Because this is a cross product, the force is perpendicular to both the motion of the particle and the magnetic field. It follows that the magnetic force does no work on the particle; it may change the direction of the particle's movement, but it cannot cause it to speed up or slow down. The magnitude of the force is

$$F = qvB \sin\theta$$

where θ is the angle between **v** and **B**.

One tool for determining the direction of the velocity vector of a moving charge, the magnetic field, and the force exerted is labeling the index finger "V", the middle finger "B" , and the thumb "F" with your right hand. When making a gun-like configuration, with the middle finger crossing under the index finger, the fingers represent the velocity vector, magnetic field vector, and force vector, respectively. See also right hand rule.

30.8 Magnetic dipoles

Main article: Magnetic dipole

A very common source of magnetic field found in nature is a dipole, with a "South pole" and a "North pole", terms dating back to the use of magnets as compasses, interacting with the Earth's magnetic field to indicate North and South on the globe. Since opposite ends of magnets are attracted, the north pole of a magnet is attracted to the south pole of another magnet. The Earth's North Magnetic Pole (currently in the Arctic Ocean, north of Canada) is physically a south pole, as it attracts the north pole of a compass. A magnetic field contains energy, and physical systems move toward configurations with lower energy. When diamagnetic material is placed in a magnetic field, a *magnetic dipole* tends to align itself in opposed polarity to that field, thereby lowering the net field strength. When ferromagnetic material is placed within a magnetic field, the magnetic dipoles align to the applied field, thus expanding the domain walls of the magnetic domains.

30.8.1 Magnetic monopoles

Main article: Magnetic monopole

Since a bar magnet gets its ferromagnetism from electrons distributed evenly throughout the bar, when a bar magnet is cut in half, each of the resulting pieces is a smaller bar magnet. Even though a magnet is said to have a north pole and a south pole, these two poles cannot be separated from each other. A monopole—if such a thing exists—would be a new and fundamentally different kind of magnetic object. It would act as an isolated north pole, not attached to a south pole, or vice versa. Monopoles would carry "magnetic charge" analogous to electric charge. Despite systematic searches since 1931, as of 2010, they have never been observed, and could very well not exist.*[15]

Nevertheless, some theoretical physics models predict the existence of these magnetic monopoles. Paul Dirac observed in 1931 that, because electricity and magnetism show a certain symmetry, just as quantum theory predicts that individual positive or negative electric charges can be observed without the opposing charge, isolated South or North magnetic poles should be observable. Using quantum theory Dirac showed that if magnetic monopoles exist, then one could explain the quantization of electric charge—that is, why the observed elementary particles carry charges that are multiples of the charge of the electron.

Certain grand unified theories predict the existence of monopoles which, unlike elementary particles, are solitons (localized energy packets). The initial results of using these models to estimate the number of monopoles created in the big bang contradicted cosmological observations—the monopoles would have been so plentiful and massive that they would have long since halted the expansion of the universe. However, the idea of inflation (for which this problem served as a partial motivation) was successful in solving this problem, creating models in which monopoles existed but were rare enough to be consistent with current observations.*[16]

30.9 Quantum-mechanical origin of magnetism

In principle all kinds of magnetism originate from specific quantum-mechanical phenomena (e.g. Mathematical formulation of quantum mechanics, in particular the chapters on spin and on the Pauli principle). A successful model was developed already in 1927, by Walter Heitler and Fritz London, who derived quantum-mechanically, how hydrogen molecules are formed from hydrogen atoms, i.e. from the atomic hydrogen orbitals u_A and u_B centered at the nuclei *A* and *B*, see below. That this leads to magnetism is not at all obvious, but will be explained in the following.

According to the Heitler-London theory, so-called two-body molecular σ -orbitals are formed, namely the resulting orbital is:

$$\psi(\mathbf{r}_1,\ \mathbf{r}_2) = \frac{1}{\sqrt{2}}\ (u_A(\mathbf{r}_1)u_B(\mathbf{r}_2) + u_B(\mathbf{r}_1)u_A(\mathbf{r}_2))$$

Here the last product means that a first electron, $\mathbf{r}_1$, is in an atomic hydrogen-orbital centered at the second nucleus, whereas the second electron runs around the first nucleus. This “exchange” phenomenon is an expression for the quantum-mechanical property that particles with identical properties cannot be distinguished. It is specific not only for the formation of chemical bonds, but as we will see, also for magnetism, i.e. in this connection the term exchange interaction arises, a term which is essential for the origin of magnetism, and which is stronger, roughly by factors 100 and even by 1000, than the energies arising from the electrodynamic dipole-dipole interaction.

As for the *spin function* $\chi(s_1, s_2)$, which is responsible for the magnetism, we have the already mentioned Pauli's principle, namely that a symmetric orbital (i.e. with the + sign as above) must be multiplied with an antisymmetric spin function (i.e. with a – sign), and *vice versa*. Thus:

$$\chi(s_1,\ s_2) = \frac{1}{\sqrt{2}}\ (\alpha(s_1)\beta(s_2) - \beta(s_1)\alpha(s_2))$$

I.e., not only u_A and u_B must be substituted by α and β, respectively (the first entity means “spin up” , the second one “spin down”), but also the sign + by the – sign, and finally $\mathbf{r}_i$ by the discrete values s_i (= ±½); thereby we have $\alpha(+1/2) = \beta(-1/2) = 1$ and $\alpha(-1/2) = \beta(+1/2) = 0$. The "singlet state", i.e. the – sign, means: the spins are *antiparallel*, i.e. for the solid we have antiferromagnetism, and for two-atomic molecules one has diamagnetism. The tendency to form a (homoeopolar) chemical bond (this means: the formation of a *symmetric* molecular orbital, i.e. with the + sign) results through the Pauli principle automatically in an *antisymmetric* spin state (i.e. with the – sign). In contrast, the Coulomb repulsion of the electrons, i.e. the tendency that they try to avoid each other by this repulsion, would lead to an *antisymmetric* orbital function (i.e. with the – sign) of these two particles, and complementary to a *symmetric* spin function (i.e. with the + sign, one of the so-called "triplet functions"). Thus, now the spins would be *parallel* (ferromagnetism in a solid, paramagnetism in two-atomic gases).

The last-mentioned tendency dominates in the metals iron, cobalt and nickel, and in some rare earths, which are *ferromagnetic*. Most of the other metals, where the first-mentioned tendency dominates, are *nonmagnetic* (e.g. sodium, aluminium, and magnesium) or *antiferromagnetic* (e.g. manganese). Diatomic gases are also almost exclusively diamagnetic, and not paramagnetic. However, the oxygen molecule, because of the involvement of π-orbitals, is an exception important for the life-sciences.

The Heitler-London considerations can be generalized to the Heisenberg model of magnetism (Heisenberg 1928).

The explanation of the phenomena is thus essentially based on all subtleties of quantum mechanics, whereas the electrodynamics covers mainly the phenomenology.

30.10 Units

30.10.1 SI

30.10.2 Other

- gauss – the centimeter-gram-second (CGS) unit of magnetic field (denoted **B**)
- oersted – the CGS unit of magnetizing field (denoted **H**)
- maxwell – the CGS unit for magnetic flux
- gamma – a unit of *magnetic flux density* that was commonly used before the tesla came into use (1.0 gamma = 1.0 nanotesla)
- μ_0 – common symbol for the permeability of free space (4π×10*−7 newton/(ampere-turn)^2)

30.11 Living things

Some organisms can detect magnetic fields, a phenomenon known as magnetoception. In addition to detection, biomagnetic pheonomena is utilized by organisms in a number of ways. For instance, chitons, a type of marine mollusk, produce magnetite to harden their teeth, and even humans produce magnetite in bodily tissue.*[18] Magnetobiology studies magnetic fields as a medical treatment; fields naturally produced by an organism are known as biomagnetism.

30.12 See also

- Coercivity
- Gravitomagnetism
- Magnetic hysteresis
- Magnetar
- Magnetic bearing
- Magnetic circuit
- Magnetic cooling
- Magnetic field viewing film
- Magnetic stirrer
- Magnetic structure
- Magnetism and temperature
- Micromagnetism
- Neodymium magnet
- Plastic magnet
- Rare-earth magnet
- Spin wave
- Spontaneous magnetization
- Vibrating sample magnetometer

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30.14 Further reading

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30.15 External links

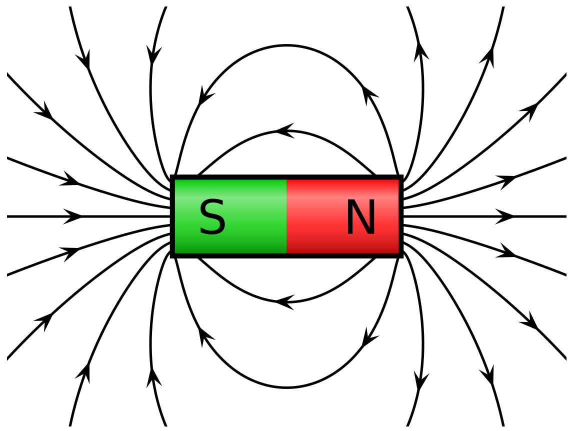
-
- Magnetism on *In Our Time* at the BBC. (listen now)
- The Exploratorium Science Snacks – Snacks about Magnetism
- Electromagnetism - a chapter from an online textbook
- Video: The physicist Richard Feynman answers the question, Why do bar magnets attract or repel each other? on YouTube
- On the Magnet, 1600 First scientific book on magnetism by the father of electrical engineering. Full English text, full text search.
- Magnetism and magnetization - Astronoo

Chapter 31

Magnetic field

For other uses, see Magnetic field (disambiguation).

A **magnetic field** is the magnetic effect of electric currents and magnetic materials. The magnetic field at any given point is specified by both a *direction* and a *magnitude* (or strength); as such it is a vector field.*[nb 1] The term is used for two distinct but closely related fields denoted by the symbols **B** and **H**, where **H** is measured in units of amperes per meter (symbol: A·m*−1 or A/m) in the SI. **B** is measured in teslas (symbol: T) and newtons per meter per ampere (symbol: N·m*−1·A*−1 or N/(m·A)) in the SI. **B** is most commonly defined in terms of the Lorentz force it exerts on moving electric charges.



Magnetic field of an ideal cylindrical magnet with its axis of symmetry inside the image plane. The magnetic field is represented by magnetic field lines, which show the direction of the field at different points.

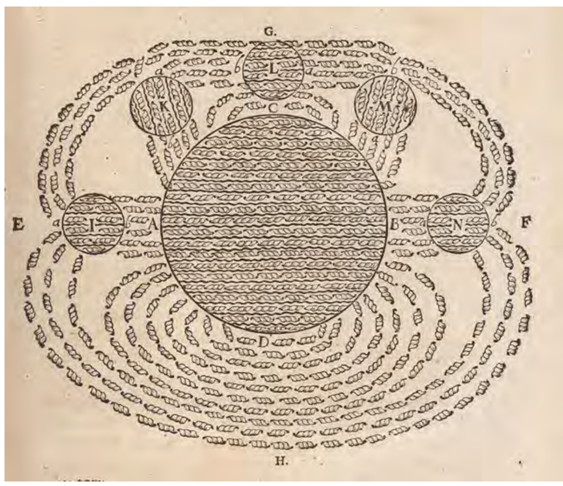
Magnetic fields can be produced by moving electric charges and the intrinsic magnetic moments of elementary particles associated with a fundamental quantum property, their spin.*[1]*[2] In special relativity, electric and magnetic fields are two interrelated aspects of a single object, called the electromagnetic tensor; the split of this tensor into electric and magnetic fields depends on the relative velocity of the observer and charge. In quantum physics, the electromagnetic field is quantized and electromagnetic interactions result from the exchange of photons.

In everyday life, magnetic fields are most often encountered as a force created by permanent magnets, which pull on ferromagnetic materials such as iron, cobalt, or nickel, and attract or repel other magnets. Magnetic fields are widely used throughout modern technology, particularly in electrical engineering and electromechanics. The Earth produces its own magnetic field, which is important in navigation, and it shields the Earth's atmosphere from solar wind. Rotating magnetic fields are used in both electric motors and generators. Magnetic forces give information about the charge carriers in a material through the Hall effect. The interaction of magnetic fields in electric devices such as transformers is studied in the discipline of magnetic circuits.

31.1 History

Main article: History of electromagnetic theory

Although magnets and magnetism were known much earlier, the study of magnetic fields began in 1269 when French scholar Petrus Peregrinus de Maricourt mapped

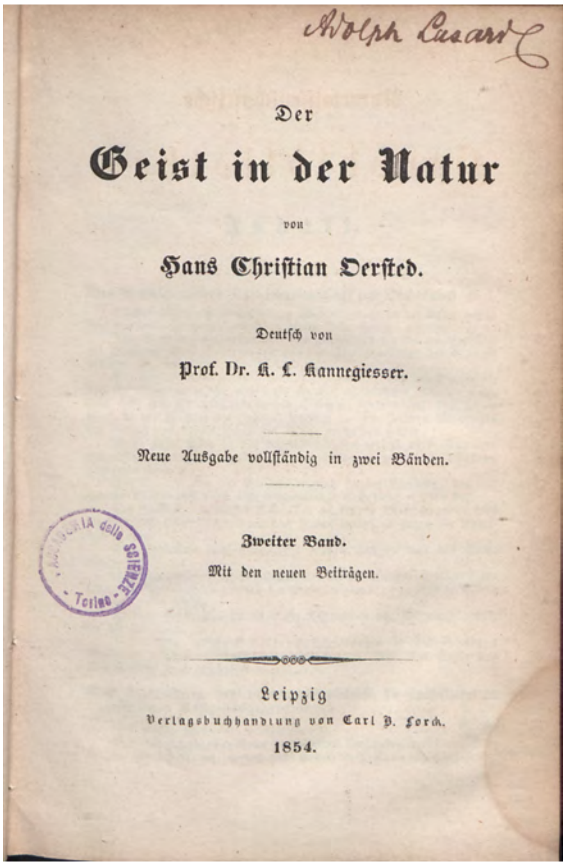


One of the first drawings of a magnetic field, by René Descartes, 1644, showing the Earth attracting lodestones. It illustrated his theory that magnetism was caused by the circulation of tiny helical particles, "threaded parts", through threaded pores in magnets.

out the magnetic field on the surface of a spherical magnet using iron needles.*[nb 2] Noting that the resulting field lines crossed at two points he named those points 'poles' in analogy to Earth's poles. He also clearly articulated the principle that magnets always have both a north and south pole, no matter how finely one slices them.

Almost three centuries later, William Gilbert of Colchester replicated Petrus Peregrinus' work and was the first to state explicitly that Earth is a magnet.*[3] Published in 1600, Gilbert's work, *De Magnete*, helped to establish magnetism as a science.

In 1750, John Michell stated that magnetic poles attract and repel in accordance with an inverse square law.*[4] Charles-Augustin de Coulomb experimentally verified this in 1785 and stated explicitly that the north and south poles cannot be separated.*[5] Building on this force between poles, Siméon Denis Poisson (1781–1840) created the first successful model of the magnetic field, which he presented in 1824.*[6] In this model, a magnetic **H**-field is produced by 'magnetic poles' and magnetism is due to small pairs of north/south magnetic poles.


Der
Geist in der Natur
von
Hans Christian Oersted.
Deutsch von
Prof. Dr. K. L. Kannegiesser.
Neue Ausgabe vollständig in zwei Bänden.
Zweiter Band.
Mit den neuen Beiträgen.
Leipzig
Verlagsbuchhandlung von Carl B. Lorck.
1854.

Hans Christian Ørsted, Der Geist in der Natur*, 1854*

Three discoveries challenged this foundation of magnetism, though. First, in 1819, Hans Christian Ørsted discovered that an electric current generates a magnetic field encircling it. Then in 1820, André-Marie Ampère showed that parallel wires having currents in the same direction attract one another. Finally, Jean-Baptiste Biot and Félix Savart discovered the Biot–Savart law in 1820, which correctly predicts the magnetic field around any current-carrying wire.

Extending these experiments, Ampère published his own successful model of magnetism in 1825. In it, he showed the equivalence of electrical currents to magnets*[7] and proposed that magnetism is due to perpetually flowing loops of current instead of the dipoles of magnetic charge in Poisson's model.*[nb 3] This has the additional benefit of explaining why magnetic charge can not be isolated. Further, Ampère derived both Ampère's force law describing the force between two currents and Ampère's law, which, like the Biot–Savart law, correctly described the magnetic field generated by a steady current. Also in this work, Ampère introduced the term electrodynamics to describe the relationship between electricity and magnetism.

In 1831, Michael Faraday discovered electromagnetic induction when he found that a changing magnetic field generates an encircling electric field. He described this phenomenon in what is known as Faraday's law of induction. Later, Franz Ernst Neumann proved that, for a moving conductor in a magnetic field, induction is a consequence of Ampère's force law.*[8] In the process he introduced the magnetic vector potential, which was later shown to be equivalent to the underlying mechanism proposed by Faraday.

In 1850, Lord Kelvin, then known as William Thomson, distinguished between two magnetic fields now denoted **H** and **B**. The former applied to Poisson's model and the latter to Ampère's model and induction.*[9] Further, he derived how **H** and **B** relate to each other.

The reason **H** and **B** are used for the two magnetic fields has been a source of some debate among science historians. Most agree that Kelvin avoided **M** to prevent confusion with the SI fundamental unit of length, the Metre, abbreviated “m”. Others believe the choices were purely random.*[10]*[11]

Between 1861 and 1865, James Clerk Maxwell developed and published Maxwell's equations, which explained and united all of classical electricity and magnetism. The first set of these equations was published in a paper entitled *On Physical Lines of Force* in 1861. These equations were valid although incomplete. Maxwell completed his set of equations in his later 1865 paper *A Dynamical Theory of the Electromagnetic Field* and demonstrated the fact that light is an electromagnetic wave. Heinrich Hertz experimentally confirmed this fact in 1887.

The twentieth century extended electrodynamics to include relativity and quantum mechanics. Albert Einstein, in his paper of 1905 that established relativity, showed that both the electric and magnetic fields are part of the same phenomena viewed from different reference frames. (See moving magnet and conductor problem for details about the thought experiment that eventually helped Albert Einstein to develop special relativity.) Finally, the emergent field of quantum mechanics was merged with electrodynamics to form quantum electrodynamics (QED).

31.2 Definitions, units, and measurement

31.2.1 The B-field

The magnetic field can be defined in several equivalent ways based on the effects it has on its environment.

Often the magnetic field is defined by the force it exerts on a moving charged particle. It is known from experiments in electrostatics that a particle of charge q in an electric field **E** experiences a force $\mathbf{F} = q\mathbf{E}$. However, in other situations, such as when a charged particle moves in the vicinity of a current-carrying wire, the force also depends on the velocity of that particle. Fortunately, the velocity dependent portion can be separated out such that the force on the particle satisfies the *Lorentz force law*,

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

Here **v** is the particle's velocity and × denotes the cross product. The vector **B** is termed the magnetic field, and it is *defined* as the vector field necessary to make the Lorentz force law correctly describe the motion of a charged particle. This definition allows the determination of **B** in the following way*[14]

> [T]he command, "Measure the direction and magnitude of the vector **B** at such and such a place," calls for the following operations: Take a particle of known charge q. Measure the force on q at rest, to determine **E**. Then measure the force on the particle when its velocity is **v**; repeat with **v** in some other direction. Now find a **B** that makes the Lorentz force law fit all these results—that is the magnetic field at the place in question.

Alternatively, the magnetic field can be defined in terms of the torque it produces on a magnetic dipole (see magnetic torque on permanent magnets below).

31.2.2 The H-field

In addition to **B**, there is a quantity **H**, which is also sometimes called the *magnetic field*.*[nb 4] In a vacuum, **B** and **H** are proportional to each other, with the multiplicative constant depending on the physical units. Inside a material they are different (see H and B inside and outside of magnetic materials). The term "magnetic field" is historically reserved for **H** while using other terms for **B**. Informally, though, and formally for some recent textbooks mostly in physics, the term 'magnetic field' is used to describe **B** as well as or in place of **H**.*[nb 5] There are many alternative names for both (see sidebar).

31.2.3 Units

In SI units, **B** is measured in teslas (symbol: T) and correspondingly Φ_B (magnetic flux) is measured in webers (symbol: Wb) so that a flux density of 1 Wb/m^2 is 1 tesla. The SI unit of tesla is equivalent to (newton·second)/(coulomb·metre).*[nb 6] In Gaussian-cgs units, **B** is measured in gauss (symbol: G). (The conversion is 1 T = 10,000 G.) One nanotesla is also called a gamma (symbol: γ).*[15] The **H**-field is measured in amperes per metre (A/m) in SI units, and in oersteds (Oe) in cgs units.*[16]

31.2.4 Measurement

The precision attained for a magnetic field measurement for Gravity Probe B experiment is 5 attoteslas (5×10*−18 T);*[17] the largest magnetic field produced in a laboratory is 2.8 kT (VNIIEF in Sarov, Russia, 1998).*[18] The magnetic field of some astronomical objects such as magnetars are much higher; magnetars range from 0.1 to 100 GT (10^8 to 10^{11} T).*[19] See orders of magnitude (magnetic field).

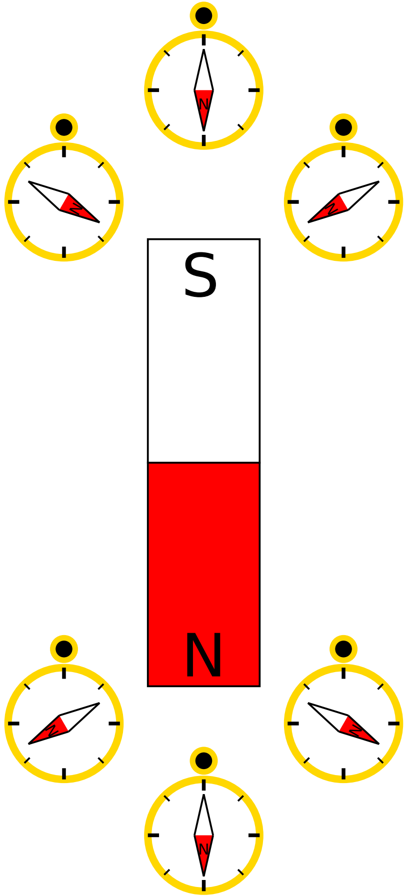
Devices used to measure the local magnetic field are called magnetometers. Important classes of magnetometers include using induction magnetometer (or search-coil magnetometer) which measure only varying magnetic field, rotating coil magnetometer, Hall effect magnetometers, NMR magnetometers, SQUID magnetometers, and fluxgate magnetometers. The magnetic fields of distant astronomical objects are measured through their effects on local charged particles. For instance, electrons spiraling around a field line produce synchrotron radiation that is detectable in radio waves.

31.3 Magnetic field lines

Main article: Field line

Mapping the magnetic field of an object is simple in principle. First, measure the strength and direction of the magnetic field at a large number of locations (or at every point in space). Then, mark each location with an arrow (called a vector) pointing in the direction of the local magnetic field with its magnitude proportional to the strength of the magnetic field.

An alternative method to map the magnetic field is to 'connect' the arrows to form magnetic *field lines*. The direction of the magnetic field at any point is parallel to the



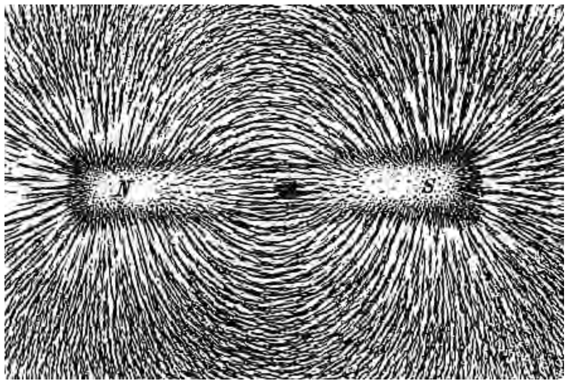
Compasses reveal the direction of the local magnetic field. As seen here, the magnetic field points towards a magnet's south pole and away from its north pole.

direction of nearby field lines, and the local density of field lines can be made proportional to its strength.

Magnetic field lines are like streamlines in fluid flow, in that they represent something continuous, and a different resolution would show more or fewer lines. An advantage of using magnetic field lines as a representation is that many laws of magnetism (and electromagnetism) can be stated completely and concisely using simple concepts such as the 'number' of field lines through a surface. These concepts can be quickly 'translated' to their mathematical form. For example, the number of field lines through a given surface is the surface integral of the magnetic field.

Various phenomena have the effect of "displaying" magnetic field lines as though the field lines were physical phenomena. For example, iron filings placed in a magnetic field, form lines that correspond to 'field lines'.*[nb 7] Magnetic field "lines" are also visually displayed in polar auroras, in which plasma particle dipole interactions create visible streaks of light that line up with the local direction of Earth's magnetic field.

Field lines can be used as a qualitative tool to visualize



The direction of magnetic field lines represented by the alignment of iron filings sprinkled on paper placed above a bar magnet.

magnetic forces. In ferromagnetic substances like iron and in plasmas, magnetic forces can be understood by imagining that the field lines exert a tension, (like a rubber band) along their length, and a pressure perpendicular to their length on neighboring field lines. 'Unlike' poles of magnets attract because they are linked by many field lines; 'like' poles repel because their field lines do not meet, but run parallel, pushing on each other. The rigorous form of this concept is the electromagnetic stress–energy tensor.

31.4 Magnetic field and permanent magnets

Main article: Magnet

Permanent magnets are objects that produce their own persistent magnetic fields. They are made of ferromagnetic materials, such as iron and nickel, that have been magnetized, and they have both a north and a south pole.

31.4.1 Magnetic field of permanent magnets

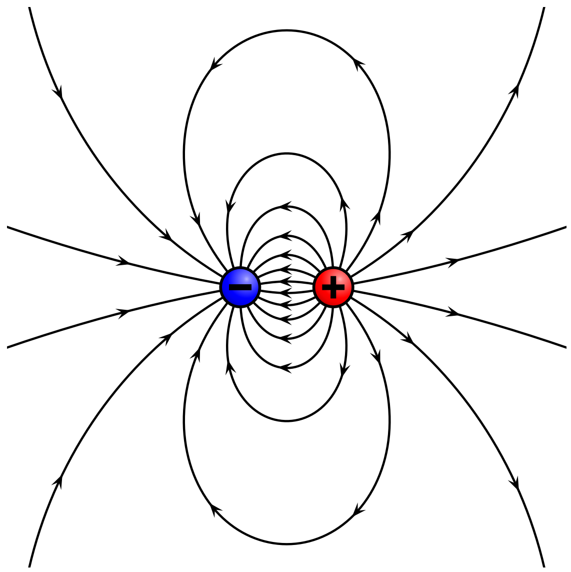
Main articles: Magnetic moment and Two definitions of moment

The magnetic field of permanent magnets can be quite complicated, especially near the magnet. The magnetic field of a small*[nb 8] straight magnet is proportional to the magnet's *strength* (called its magnetic dipole moment **m**). The equations are non-trivial and also depend on the distance from the magnet and the orientation of the magnet. For simple magnets, **m** points in the direction of a line drawn from the south to the north pole of the magnet. Flipping a bar magnet is equivalent to rotating its **m** by 180 degrees.

The magnetic field of larger magnets can be obtained by modelling them as a collection of a large number of small magnets called dipoles each having their own **m**. The magnetic field produced by the magnet then is the net magnetic field of these dipoles. And, any net force on the magnet is a result of adding up the forces on the individual dipoles.

There are two competing models for the nature of these dipoles. These two models produce two different magnetic fields, **H** and **B**. Outside a material, though, the two are identical (to a multiplicative constant) so that in many cases the distinction can be ignored. This is particularly true for magnetic fields, such as those due to electric currents, that are not generated by magnetic materials.

31.4.2 Magnetic pole model and the H-field



*The magnetic pole model: two opposing poles, North (+) and South (−), separated by a distance d produce an **H**-field (lines).*

It is sometimes useful to model the force and torques between two magnets as due to magnetic poles repelling or attracting each other in the same manner as the Coulomb force between electric charges. This is called the Gilbert model of magnetism, after William Gilbert. In this model, a magnetic **H**-field is produced by *magnetic charges* that are 'smeared' around each pole. These *magnetic charges* are in fact related to the magnetization field **M**.

The **H**-field, therefore, is analogous to the electric field **E**, which starts at a positive electric charge and ends at a negative electric charge. Near the north pole, therefore, all **H**-field lines point away from the north pole (whether inside the magnet or out) while near the south pole (whether inside the magnet or out) all **H**-field lines point toward the south pole. A north pole, then, feels a force in the direction of the **H**-field while the force on the south pole is opposite to the **H**-field.

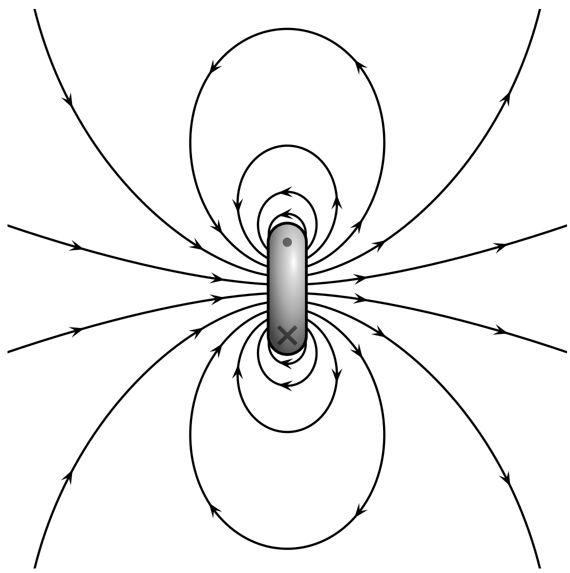
In the magnetic pole model, the elementary magnetic dipole **m** is formed by two opposite magnetic poles of pole strength q_m separated by a small distance vector **d**, such that $\mathbf{m} = q_m \mathbf{d}$. The magnetic pole model predicts correctly the field **H** both inside and outside magnetic materials, in particular the fact that **H** is opposite to the magnetization field **M** inside a permanent magnet.

Since it is based on the fictitious idea of a *magnetic charge density*, the Gilbert model has limitations. Magnetic poles cannot exist apart from each other as electric charges can, but always come in north/south pairs. If a magnetized object is divided in half, a new pole appears on the surface of each piece, so each has a pair of complementary poles. The magnetic pole model does not account for magnetism that is produced by electric currents.

31.4.3 Amperian loop model and the B-field

See also: Gauss's law for magnetism

After Ørsted discovered that electric currents produce a magnetic field and Ampere discovered that electric currents attracted and repelled each other similar to magnets, it was natural to hypothesize that all magnetic fields are due to electric current loops. In this model developed by Ampere, the elementary magnetic dipole that makes up all magnets is a sufficiently small Amperian loop of current I. The dipole moment of this loop is $m = IA$ where A is the area of the loop.



*The Amperian loop model: A current loop (ring) that goes into the page at the x and comes out at the dot produces a **B**-field (lines). The north pole is to the right and the south to the left.*

These magnetic dipoles produce a magnetic **B**-field. One important property of the **B**-field produced this way is that magnetic **B**-field lines neither start nor end (mathematically, **B** is a solenoidal vector field); a field line either extends to infinity or wraps around to form a closed curve.*[nb 9] To date no exception to this rule has been found. (See magnetic monopole below.) Magnetic field lines exit a magnet near its north pole and enter near its south pole, but inside the magnet **B**-field lines continue through the magnet from the south pole back to the north.*[nb 10] If a **B**-field line enters a magnet somewhere it has to leave somewhere else; it is not allowed to have an end point. Magnetic poles, therefore, always come in N and S pairs.

More formally, since all the magnetic field lines that enter any given region must also leave that region, subtracting the 'number'*[nb 11] of field lines that enter the region from the number that exit gives identically zero. Mathematically this is equivalent to:

$$\oint_S \mathbf{B} \cdot \mathrm{d}\mathbf{A} = 0,$$

where the integral is a surface integral over the closed surface S (a closed surface is one that completely surrounds a region with no holes to let any field lines escape). Since d**A** points outward, the dot product in the integral is positive for **B**-field pointing out and negative for **B**-field pointing in.

There is also a corresponding differential form of this equation covered in Maxwell's equations below.

31.4.4 Force between magnets

Main article: Force between magnets

The force between two small magnets is quite complicated and depends on the strength and orientation of both magnets and the distance and direction of the magnets relative to each other. The force is particularly sensitive to rotations of the magnets due to magnetic torque. The force on each magnet depends on its magnetic moment and the magnetic field*[nb 12] of the other.

To understand the force between magnets, it is useful to examine the *magnetic pole model* given above. In this model, the ***H**-field* of one magnet pushes and pulls on *both* poles of a second magnet. If this **H**-field is the same at both poles of the second magnet then there is no net force on that magnet since the force is opposite for opposite poles. If, however, the magnetic field of the first magnet is *nonuniform* (such as the **H** near one of its poles), each pole of the second magnet sees a different field and is subject to a different force. This difference in the two forces moves the magnet in the direction of increasing magnetic field and may also cause a net torque.

This is a specific example of a general rule that magnets are attracted (or repulsed depending on the orientation of the magnet) into regions of higher magnetic field. Any non-uniform magnetic field, whether caused by permanent magnets or electric currents, exerts a force on a small magnet in this way.

The details of the Amperian loop model are different and more complicated but yield the same result: that magnetic dipoles are attracted/repelled into regions of higher magnetic field. Mathematically, the force on a small magnet having a magnetic moment **m** due to a magnetic field **B** is:*[20]

$$\mathbf{F} = \nabla\left(\mathbf{m} \cdot \mathbf{B}\right),$$

where the gradient **∇** is the change of the quantity **m** · **B** per unit distance and the direction is that of maximum increase of **m** ·**B**. To understand this equation, note that the dot product **m** ·**B** = $mB\cos(\theta)$, where m and B represent the magnitude of the **m** and **B** vectors and θ is the angle between them. If **m** is in the same direction as **B** then the dot product is positive and the gradient points 'uphill' pulling the magnet into regions of higher **B**-field (more strictly larger **m** ·**B**). This equation is strictly only valid for magnets of zero size, but is often a good approximation for not too large magnets. The magnetic force on larger magnets is determined by dividing them into smaller regions each having their own **m** then summing up the forces on each of these very small regions.

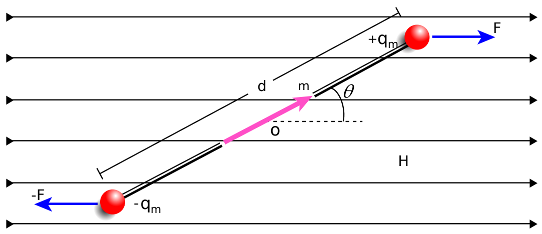
31.4.5 Magnetic torque on permanent magnets

Main article: Magnetic torque

If two like poles of two separate magnets are brought near each other, and one of the magnets is allowed to turn, it promptly rotates to align itself with the first. In this example, the magnetic field of the stationary magnet creates a *magnetic torque* on the magnet that is free to rotate. This magnetic torque **τ** tends to align a magnet's poles with the magnetic field lines. A compass, therefore, turns to align itself with Earth's magnetic field.

Magnetic torque is used to drive electric motors. In one simple motor design, a magnet is fixed to a freely rotating shaft and subjected to a magnetic field from an array of electromagnets. By continuously switching the electric current through each of the electromagnets, thereby flipping the polarity of their magnetic fields, like poles are kept next to the rotor; the resultant torque is transferred to the shaft. See Rotating magnetic fields below.

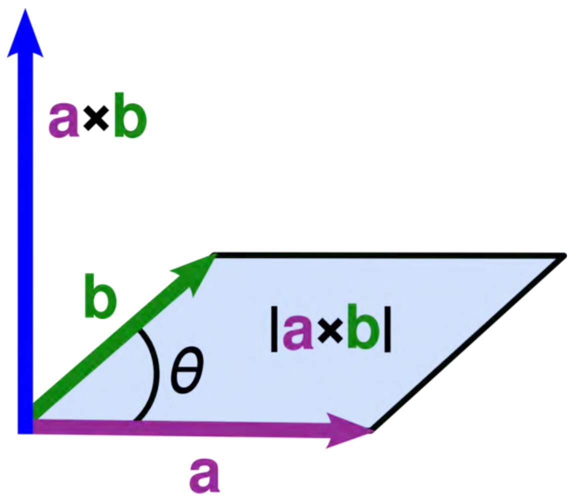
As is the case for the force between magnets, the magnetic pole model leads more readily to the correct equation. Here, two equal and opposite magnetic charges experiencing the same **H** also experience equal and opposite forces. Since these equal and opposite forces are in different locations, this produces a torque proportional to the distance (perpendicular to the force) between them. With the definition of **m** as the pole strength times the



***torque on a dipole**: An **H** field (to right) causes equal but opposite forces on a N pole (+q) and a S pole (−q) creating a torque.*

distance between the poles, this leads to $\tau = \mu_0 m H \sin\theta$, where μ_0 is a constant called the vacuum permeability, measuring 4π×10*−7 V·s/(A·m) and θ is the angle between **H** and **m**.

The Amperian loop model also predicts the same magnetic torque. Here, it is the **B** field interacting with the Amperian current loop through a Lorentz force described below. Again, the results are the same although the models are completely different.



***Cross product**: |**a** × **b**| = a b sinθ.*

Mathematically, the torque $\boldsymbol{\tau}$ on a small magnet is proportional both to the applied magnetic field and to the magnetic moment **m** of the magnet:

$$\boldsymbol{\tau} = \mathbf{m} \times \mathbf{B} = \mu_0 \mathbf{m} \times \mathbf{H},$$

where × represents the vector cross product. Note that this equation includes all of the qualitative information included above. There is no torque on a magnet if **m** is in the same direction as the magnetic field. (The cross product is zero for two vectors that are in the same direction.) Further, all other orientations feel a torque that twists them toward the direction of magnetic field.

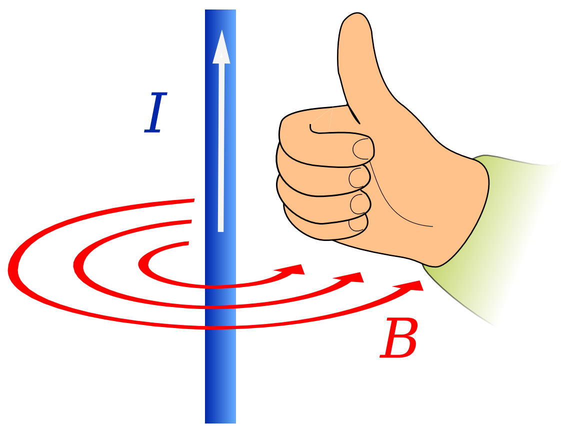
31.5 Magnetic field and electric currents

Currents of electric charges both generate a magnetic field and feel a force due to magnetic B-fields.

31.5.1 Magnetic field due to moving charges and electric currents

Main articles: Electromagnet, Biot–Savart law, and Ampère's law

All moving charged particles produce magnetic fields.



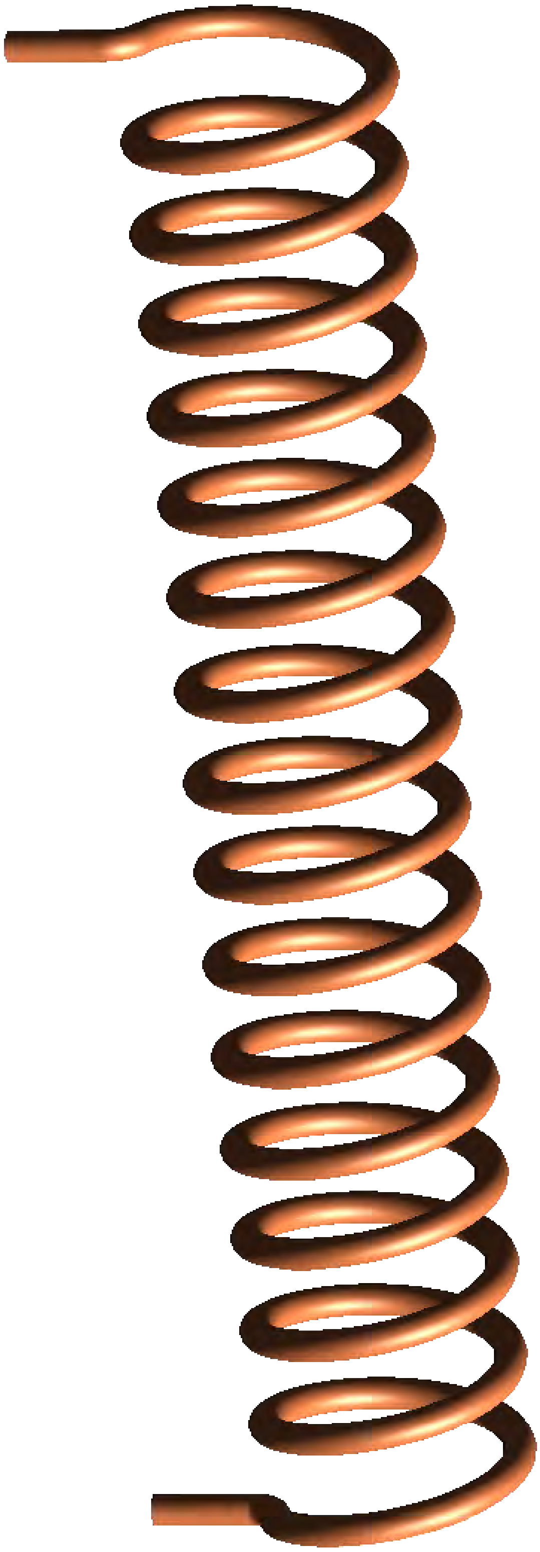
Right hand grip rule: a current flowing in the direction of the white arrow produces a magnetic field shown by the red arrows.

Moving point charges, such as electrons, produce complicated but well known magnetic fields that depend on the charge, velocity, and acceleration of the particles.*[21]

Magnetic field lines form in concentric circles around a cylindrical current-carrying conductor, such as a length of wire. The direction of such a magnetic field can be determined by using the "right hand grip rule" (see figure at right). The strength of the magnetic field decreases with distance from the wire. (For an infinite length wire the strength is inversely proportional to the distance.)

Bending a current-carrying wire into a loop concentrates the magnetic field inside the loop while weakening it outside. Bending a wire into multiple closely spaced loops to form a coil or "solenoid" enhances this effect. A device so formed around an iron core may act as an *electromagnet*, generating a strong, well-controlled magnetic field. An infinitely long cylindrical electromagnet has a uniform magnetic field inside, and no magnetic field outside. A finite length electromagnet produces a magnetic field that looks similar to that produced by a uniform permanent magnet, with its strength and polarity determined by the current flowing through the coil.

The magnetic field generated by a steady current I (a constant flow of electric charges, in which charge neither accumulates nor is depleted at any point)*[nb 13] is described by the *Biot–Savart law*:



Solenoid

$$\mathbf{B} = \frac{\mu_0 I}{4\pi} \int_{\text{wire}} \frac{\mathrm{d}\boldsymbol{\ell} \times \hat{\mathbf{r}}}{r^2},$$

where the integral sums over the wire length where vector $\mathrm{d}\boldsymbol{\ell}$ is the vector line element with direction in the same sense as the current I, μ_0 is the magnetic constant, r is the distance between the location of $\mathrm{d}\boldsymbol{\ell}$ and the location where the magnetic field is calculated, and $\hat{\mathbf{r}}$ is a unit vector in the direction of $\mathbf{r}$. In the case of a sufficiently long wire, this becomes:

$$\mathbf{B} = \frac{\mu_0 I}{2\pi r}$$

where r is the distance from the wire.*[22]

A slightly more general*[23]*[nb 14] way of relating the current I to the **B**-field is through Ampère's law:

$$\oint \mathbf{B} \cdot \mathrm{d}\boldsymbol{\ell} = \mu_0 I_{\text{enc}},$$

where the line integral is over any arbitrary loop and I_{enc} is the current enclosed by that loop. Ampère's law is always valid for steady currents and can be used to calculate the **B**-field for certain highly symmetric situations such as an infinite wire or an infinite solenoid.

In a modified form that accounts for time varying electric fields, Ampère's law is one of four Maxwell's equations that describe electricity and magnetism.

31.5.2 Force on moving charges and current

Force on a charged particle

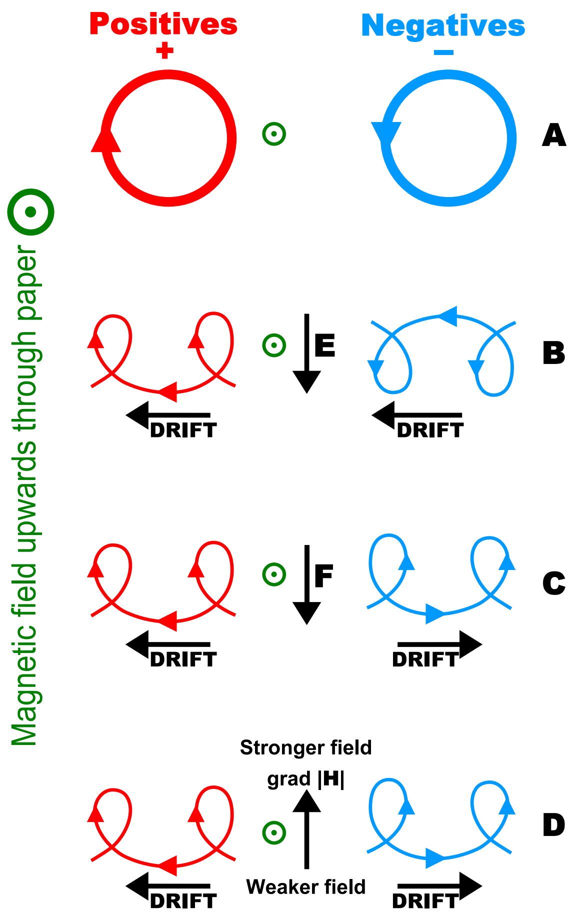
Main article: Lorentz force

A charged particle moving in a **B**-field experiences a *sideways* force that is proportional to the strength of the magnetic field, the component of the velocity that is perpendicular to the magnetic field and the charge of the particle. This force is known as the *Lorentz force*, and is given by

$$\mathbf{F} = q\mathbf{E} + q\mathbf{v} \times \mathbf{B},$$

where **F** is the force, q is the electric charge of the particle, **v** is the instantaneous velocity of the particle, and **B** is the magnetic field (in teslas).

The Lorentz force is always perpendicular to both the velocity of the particle and the magnetic field that created it. When a charged particle moves in a static magnetic field, it traces a helical path in which the helix axis is parallel to the magnetic field, and in which the speed of the particle remains constant. Because the magnetic force is always perpendicular to the motion, the magnetic field can do no work on an isolated charge. It can only do work indirectly, via the electric field generated by a changing magnetic field. It is often claimed that the magnetic force can do work to a non-elementary magnetic dipole, or to charged



Charged particle drifts *in a magnetic field with (A) no net force, (B) an electric field,* ***E****, (C) a charge independent force,* ***F*** *(e.g. gravity), and (D) in a homogeneous magnetic field, grad* ***H****.*

particles whose motion is constrained by other forces, but this is incorrect*[24] because the work in those cases is performed by the electric forces of the charges deflected by the magnetic field.

Force on current-carrying wire

Main article: Laplace force

The force on a current carrying wire is similar to that of a moving charge as expected since a charge carrying wire is a collection of moving charges. A current-carrying wire feels a force in the presence of a magnetic field. The Lorentz force on a macroscopic current is often referred to as the *Laplace force*. Consider a conductor of length ℓ, cross section A, and charge q due to electric current i. If this conductor is placed in a magnetic field of magnitude B that makes an angle θ with the velocity of charges in the conductor, the force exerted on a single charge q is

$$F = qvB\sin\theta,$$

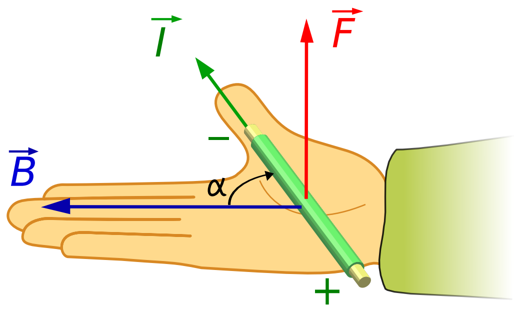
so, for N charges where

$$N = n\ell A$$

the force exerted on the conductor is

$$f = FN = qvBn\ell A\sin\theta = Bi\ell\sin\theta$$

where $i = nqvA$.



The right-hand rule: Pointing the thumb of the right hand in the direction of the conventional current and the fingers in the direction of ***B*** *the force on the current points out of the palm. The force is reversed for a negative charge.*

Direction of force

See also: Right-hand rule

The direction of force on a charge or a current can be determined by a mnemonic known as the *right-hand rule* (see the figure). Using the right hand and pointing the thumb in the direction of the moving positive charge or positive current and the fingers in the direction of the magnetic field the resulting force on the charge points outwards from the palm. The force on a negatively charged particle is in the opposite direction. If both the speed and the charge are reversed then the direction of the force remains the same. For that reason a magnetic field measurement (by itself) cannot distinguish whether there is a positive charge moving to the right or a negative charge moving to the left. (Both of these cases produce the same current.) On the other hand, a magnetic field combined with an electric field *can* distinguish between these, see Hall effect below.

An alternative mnemonic to the right hand rule Flemings's left hand rule.

31.6 Relation between H and B

The formulas derived for the magnetic field above are correct when dealing with the entire current. A magnetic material placed inside a magnetic field, though, generates its own bound current, which can be a challenge to calculate. (This bound current is due to the sum of atomic sized current loops and the spin of the subatomic particles such as electrons that make up the material.) The **H**-field as defined above helps factor out this bound current; but to see how, it helps to introduce the concept of *magnetization* first.

31.6.1 Magnetization

Main article: Magnetization

The *magnetization* vector field **M** represents how strongly a region of material is magnetized. It is defined as the net magnetic dipole moment per unit volume of that region. The magnetization of a uniform magnet is therefore a material constant, equal to the magnetic moment **m** of the magnet divided by its volume. Since the SI unit of magnetic moment is A·m^2, the SI unit of magnetization **M** is ampere per meter, identical to that of the **H**-field.

The magnetization **M** field of a region points in the direction of the average magnetic dipole moment in that region. Magnetization field lines, therefore, begin near the magnetic south pole and ends near the magnetic north pole. (Magnetization does not exist outside of the magnet.)

In the Amperian loop model, the magnetization is due to combining many tiny Amperian loops to form a resultant current called *bound current*. This bound current, then, is the source of the magnetic **B** field due to the magnet. (See Magnetic dipoles below and magnetic poles vs. atomic currents for more information.) Given the definition of the magnetic dipole, the magnetization field follows a similar law to that of Ampere's law:*[25]

$$\oint \mathbf{M} \cdot \mathrm{d}\boldsymbol{\ell} = I_\mathrm{b},$$

where the integral is a line integral over any closed loop and I_b is the 'bound current' enclosed by that closed loop.

In the magnetic pole model, magnetization begins at and ends at magnetic poles. If a given region, therefore, has a net positive 'magnetic pole strength' (corresponding to a north pole) then it has more magnetization field lines entering it than leaving it. Mathematically this is equivalent to:

$$\oint_S \mu_0 \mathbf{M} \cdot \mathrm{d}\mathbf{A} = -q_\mathrm{M}$$

where the integral is a closed surface integral over the closed surface S and q_M is the 'magnetic charge' (in units of magnetic flux) enclosed by S. (A closed surface completely surrounds a region with no holes to let any field lines escape.) The negative sign occurs because the magnetization field moves from south to north.

31.6.2 H-field and magnetic materials

See also: demagnetizing field

In SI units, the H-field is related to the B-field by

$$\mathbf{H} \equiv \frac{\mathbf{B}}{\mu_0} - \mathbf{M}.$$

In terms of the H-field, Ampere's law is

$$\oint \mathbf{H} \cdot \mathrm{d}\boldsymbol{\ell} = \oint \left(\frac{\mathbf{B}}{\mu_0} - \mathbf{M}\right) \cdot \mathrm{d}\boldsymbol{\ell} = I_\mathrm{tot} - I_\mathrm{b} = I_\mathrm{f},$$

where I_f represents the 'free current' enclosed by the loop so that the line integral of **H** does not depend at all on the bound currents.*[26]

For the differential equivalent of this equation see Maxwell's equations. Ampere's law leads to the boundary condition

$$\left(\mathbf{H_1^\parallel} - \mathbf{H_2^\parallel}\right) = \mathbf{K}_\mathrm{f} \times \hat{\mathbf{n}},$$

where $\mathbf{K}_\mathrm{f}$ is the surface free current density and the unit normal $\hat{\mathbf{n}}$ points in the direction from medium 2 to medium 1.*[27]

Similarly, a surface integral of **H** over any closed surface is independent of the free currents and picks out the “magnetic charges” within that closed surface:

$$\oint_S \mu_0 \mathbf{H} \cdot \mathrm{d}\mathbf{A} = \oint_S (\mathbf{B} - \mu_0 \mathbf{M}) \cdot \mathrm{d}\mathbf{A} = 0 - (-q_\mathrm{M}) = q_\mathrm{M},$$

which does not depend on the free currents.

The **H**-field, therefore, can be separated into two*[nb 15] independent parts:

$$\mathbf{H} = \mathbf{H}_0 + \mathbf{H}_\mathrm{d},$$

where $\mathbf{H}_0$ is the applied magnetic field due only to the free currents and $\mathbf{H}_\mathrm{d}$ is the demagnetizing field due only to the bound currents.

The magnetic **H**-field, therefore, re-factors the bound current in terms of “magnetic charges”. The **H** field lines loop only around 'free current' and, unlike the magnetic **B** field, begins and ends near magnetic poles as well.

31.6.3 Magnetism

Main article: Magnetism

Most materials respond to an applied **B**-field by producing their own magnetization **M** and therefore their own **B**-field. Typically, the response is weak and exists only when the magnetic field is applied. The term *magnetism* describes how materials respond on the microscopic level to an applied magnetic field and is used to categorize the magnetic phase of a material. Materials are divided into groups based upon their magnetic behavior:

- Diamagnetic materials*[28] produce a magnetization that opposes the magnetic field.
- Paramagnetic materials*[28] produce a magnetization in the same direction as the applied magnetic field.
- Ferromagnetic materials and the closely related ferrimagnetic materials and antiferromagnetic materials*[29]*[30] can have a magnetization independent of an applied B-field with a complex relationship between the two fields.
- Superconductors (and ferromagnetic superconductors)*[31]*[32] are materials that are characterized by perfect conductivity below a critical temperature and magnetic field. They also are highly magnetic and can be perfect diamagnets below a lower critical magnetic field. Superconductors often have a broad range of temperatures and magnetic fields (the so-named mixed state) under which they exhibit a complex hysteretic dependence of **M** on **B**.

In the case of paramagnetism and diamagnetism, the magnetization **M** is often proportional to the applied magnetic field such that:

$$\mathbf{B} = \mu\mathbf{H},$$

where μ is a material dependent parameter called the permeability. In some cases the permeability may be a second rank tensor so that **H** may not point in the same direction as **B**. These relations between **B** and **H** are examples of constitutive equations. However, superconductors and ferromagnets have a more complex **B** to **H** relation; see magnetic hysteresis.

31.7 Energy stored in magnetic fields

Main article: Magnetic energy
See also: Magnetic hysteresis

Energy is needed to generate a magnetic field both to work against the electric field that a changing magnetic field creates and to change the magnetization of any material within the magnetic field. For non-dispersive materials this same energy is released when the magnetic field is destroyed so that this energy can be modeled as being stored in the magnetic field.

For linear, non-dispersive, materials (such that $\mathbf{B} = \mu\mathbf{H}$ where μ is frequency-independent), the energy density is:

$$u = \frac{\mathbf{B}\cdot\mathbf{H}}{2} = \frac{\mathbf{B}\cdot\mathbf{B}}{2\mu} = \frac{\mu\mathbf{H}\cdot\mathbf{H}}{2}.$$

If there are no magnetic materials around then μ can be replaced by μ_0. The above equation cannot be used for nonlinear materials, though; a more general expression given below must be used.

In general, the incremental amount of work per unit volume δW needed to cause a small change of magnetic field $\delta\mathbf{B}$ is:

$$\delta W = \mathbf{H}\cdot\delta\mathbf{B}.$$

Once the relationship between **H** and **B** is known this equation is used to determine the work needed to reach a given magnetic state. For hysteretic materials such as ferromagnets and superconductors, the work needed also depends on how the magnetic field is created. For linear non-dispersive materials, though, the general equation leads directly to the simpler energy density equation given above.

31.8 Electromagnetism: the relationship between magnetic and electric fields

Main article: Electromagnetism

31.8.1 Faraday's Law: Electric force due to a changing B-field

Main articles: Faraday's law and Magnetic flux

A changing magnetic field, such as a magnet moving through a conducting coil, generates an electric field (and therefore tends to drive a current in such a coil). This is known as *Faraday's law* and forms the basis of many electrical generators and electric motors.

Mathematically, Faraday's law is:

$$\mathcal{E} = -\frac{d\Phi_m}{dt},$$

where ε is the electromotive force (or *EMF*, the voltage generated around a closed loop) and Φ_m is the *magnetic flux*—the product of the area times the magnetic field normal to that area. (This definition of magnetic flux is why **B** is often referred to as *magnetic flux density*.)*[33]*:210

The negative sign represents the fact that any current generated by a changing magnetic field in a coil produces a magnetic field that *opposes* the *change* in the magnetic field that induced it. This phenomenon is known as Lenz's law.

This integral formulation of Faraday's law can be converted*[nb 16] into a differential form, which applies under slightly different conditions. This form is covered as one of Maxwell's equations below.

31.8.2 Maxwell's correction to Ampère's Law: The magnetic field due to a changing electric field

Main article: Maxwell's correction to Ampère's law

Similar to the way that a changing magnetic field generates an electric field, a changing electric field generates a magnetic field. This fact is known as *Maxwell's correction to Ampère's law* and is applied as an additive term to Ampere's law as given above. This additional term is proportional to the time rate of change of the electric flux and is similar to Faraday's law above but with a different and positive constant out front. (The electric flux through an area is proportional to the area times the perpendicular part of the electric field.)

The full law including the correction term is known as the Maxwell–Ampère equation. It is not commonly given in integral form because the effect is so small that it can typically be ignored in most cases where the integral form is used.

The Maxwell term *is* critically important in the creation and propagation of electromagnetic waves. Maxwell's correction to Ampère's Law together with Faraday's law of induction describes how mutually changing electric and magnetic fields interact to sustain each other and thus to form electromagnetic waves, such as light: a changing electric field generates a changing magnetic field, which generates a changing electric field again. These, though, are usually described using the differential form of this equation given below.

31.8.3 Maxwell's equations

Main article: Maxwell's equations

Like all vector fields, a magnetic field has two important mathematical properties that relates it to its *sources*. (For **B** the *sources* are currents and changing electric fields.) These two properties, along with the two corresponding properties of the electric field, make up *Maxwell's Equations*. Maxwell's Equations together with the Lorentz force law form a complete description of classical electrodynamics including both electricity and magnetism.

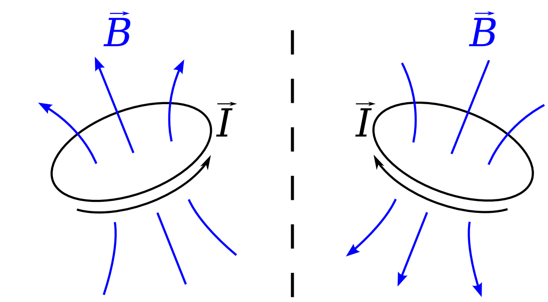
The first property is the divergence of a vector field **A**, ∇ · **A**, which represents how **A** 'flows' outward from a given point. As discussed above, a **B**-field line never starts or ends at a point but instead forms a complete loop. This is mathematically equivalent to saying that the divergence of **B** is zero. (Such vector fields are called solenoidal vector fields.) This property is called Gauss's law for magnetism and is equivalent to the statement that there are no isolated magnetic poles or magnetic monopoles. The electric field on the other hand begins and ends at electric charges so that its divergence is non-zero and proportional to the charge density (See Gauss's law).

The second mathematical property is called the curl, such that ∇ × **A** represents how **A** curls or 'circulates' around a given point. The result of the curl is called a 'circulation source'. The equations for the curl of **B** and of **E** are called the Ampère–Maxwell equation and Faraday's law respectively. They represent the differential forms of the integral equations given above.

The complete set of Maxwell's equations then are:

$$\nabla \cdot \mathbf{B} = 0,$$
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0},$$
$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t},$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

where **J** = complete microscopic current density and ϱ is the charge density.



***Magnetic field, like all pseudovectors, changes sign when reflected in a mirror**: When a current carrying loop (black) is reflected in a mirror (dotted line), its magnetic field (blue) is reflected* and *reversed.*

Technically, **B** is a pseudovector (also called an *axial vector*) due to being defined by a vector cross product. (See diagram.)

As discussed above, materials respond to an applied electric **E** field and an applied magnetic **B** field by producing their own internal 'bound' charge and current distributions that contribute to **E** and **B** but are difficult to calculate. To circumvent this problem, **H** and **D** fields are used to re-factor Maxwell's equations in terms of the *free current density* $\mathbf{J}_\mathrm{f}$ and *free charge density* ρ_f:

$$\begin{aligned}\nabla\cdot\mathbf{B} &= 0,\\ \nabla\cdot\mathbf{D} &= \rho_\mathrm{f},\\ \nabla\times\mathbf{H} &= \mathbf{J}_\mathrm{f}+\frac{\partial\mathbf{D}}{\partial t},\\ \nabla\times\mathbf{E} &= -\frac{\partial\mathbf{B}}{\partial t}.\end{aligned}$$

These equations are not any more general than the original equations (if the 'bound' charges and currents in the material are known). They also must be supplemented by the relationship between **B** and **H** as well as that between **E** and **D**. On the other hand, for simple relationships between these quantities this form of Maxwell's equations can circumvent the need to calculate the bound charges and currents.

31.8.4 Electric and magnetic fields: different aspects of the same phenomenon

Main article: Relativistic electromagnetism

According to the special theory of relativity, the partition of the electromagnetic force into separate electric and magnetic components is not fundamental, but varies with the observational frame of reference: An electric force perceived by one observer may be perceived by another (in a different frame of reference) as a magnetic force, or a mixture of electric and magnetic forces.

Formally, special relativity combines the electric and magnetic fields into a rank-2 tensor, called the *electromagnetic tensor*. Changing reference frames *mixes* these components. This is analogous to the way that special relativity *mixes* space and time into spacetime, and mass, momentum and energy into four-momentum.*[34]

31.8.5 Magnetic vector potential

Main article: Magnetic potential

In advanced topics such as quantum mechanics and relativity it is often easier to work with a potential formulation of electrodynamics rather than in terms of the electric and magnetic fields. In this representation, the *vector potential* **A**, and the scalar potential φ, are defined such that:

$$\begin{aligned}\mathbf{B} &= \nabla\times\mathbf{A},\\ \mathbf{E} &= -\nabla\varphi-\frac{\partial\mathbf{A}}{\partial t}.\end{aligned}$$

The vector potential **A** may be interpreted as a *generalized potential momentum per unit charge**[35] just as φ is interpreted as a *generalized potential energy per unit charge*.

Maxwell's equations when expressed in terms of the potentials can be cast into a form that agrees with special relativity with little effort.*[36] In relativity **A** together with φ forms the four-potential, analogous to the four-momentum that combines the momentum and energy of a particle. Using the four potential instead of the electromagnetic tensor has the advantage of being much simpler—and it can be easily modified to work with quantum mechanics.

31.8.6 Quantum electrodynamics

See also: Standard Model and quantum electrodynamics

In modern physics, the electromagnetic field is understood to be not a *classical* field, but rather a quantum field; it is represented not as a vector of three numbers at each point, but as a vector of three quantum operators at each point. The most accurate modern description of the electromagnetic interaction (and much else) is *quantum electrodynamics* (QED),*[37] which is incorporated into a more complete theory known as the *Standard Model of particle physics*.

In QED, the magnitude of the electromagnetic interactions between charged particles (and their antiparticles) is computed using perturbation theory. These rather complex formulas produce a remarkable pictorial representation as Feynman diagrams in which virtual photons are exchanged.

Predictions of QED agree with experiments to an extremely high degree of accuracy: currently about 10*−12 (and limited by experimental errors); for details see precision tests of QED. This makes QED one of the most accurate physical theories constructed thus far.

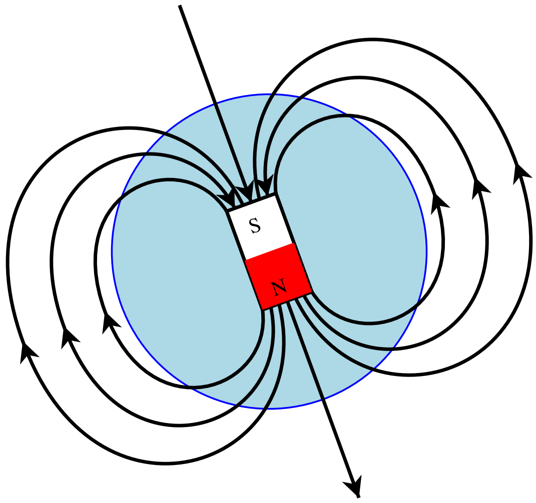
All equations in this article are in the classical approximation, which is less accurate than the quantum description mentioned here. However, under most everyday circumstances, the difference between the two theories is negligible.

31.9 Important uses and examples of magnetic field

31.9.1 Earth's magnetic field

Main article: Earth's magnetic field

The Earth's magnetic field is thought to be produced by



A sketch of Earth's magnetic field representing the source of the field as a magnet. The geographic north pole of Earth is near the top of the diagram, the south pole near the bottom. The south pole of that magnet is deep in Earth's interior below Earth's North Magnetic Pole.

convection currents in the outer liquid of Earth's core. The Dynamo theory proposes that these movements produce electric currents that, in turn, produce the magnetic field.*[38]

The presence of this field causes a compass, placed anywhere within it, to rotate so that the "north pole" of the magnet in the compass points roughly north, toward Earth's North Magnetic Pole. This is the traditional definition of the "north pole" of a magnet, although other equivalent definitions are also possible.

One confusion that arises from this definition is that, if Earth itself is considered as a magnet, the *south* pole of that magnet would be the one nearer the north magnetic pole, and vice versa. The north magnetic pole is so-named not because of the polarity of the field there but because of its geographical location. The north and south poles of a permanent magnet are so-called because they are "north-seeking" and "south-seeking", respectively.*[39]*[40]

The figure is a sketch of Earth's magnetic field represented by field lines. For most locations, the magnetic field has a significant up/down component in addition to the north/south component. (There is also an east/west component, as Earth's magnetic and geographical poles do not coincide.) The magnetic field can be visualised as a bar magnet buried deep in Earth's interior.

Earth's magnetic field is not constant—the strength of the field and the location of its poles vary. Moreover, the poles periodically reverse their orientation in a process called geomagnetic reversal. The most recent reversal occurred 780,000 years ago.

31.9.2 Rotating magnetic fields

Main articles: Rotating magnetic field and Alternator

The *rotating magnetic field* is a key principle in the operation of alternating-current motors. A permanent magnet in such a field rotates so as to maintain its alignment with the external field. This effect was conceptualized by Nikola Tesla, and later utilized in his, and others', early AC (alternating current) electric motors.

A rotating magnetic field can be constructed using two orthogonal coils with 90 degrees phase difference in their AC currents. However, in practice such a system would be supplied through a three-wire arrangement with unequal currents.

This inequality would cause serious problems in standardization of the conductor size and so, to overcome it, three-phase systems are used where the three currents are equal in magnitude and have 120 degrees phase difference. Three similar coils having mutual geometrical angles of 120 degrees create the rotating magnetic field in this case. The ability of the three-phase system to create a rotating field, utilized in electric motors, is one of the main reasons why three-phase systems dominate the world's electrical power supply systems.

Synchronous motors use DC-voltage-fed rotor windings, which lets the excitation of the machine be controlled—and induction motors use short-circuited rotors (instead of a magnet) following the rotating magnetic field of a multicoiled stator. The short-circuited turns of the rotor develop eddy currents in the rotating field of the stator, and these currents in turn move the rotor by the Lorentz force.

In 1882, Nikola Tesla identified the concept of the rotating magnetic field. In 1885, Galileo Ferraris independently researched the concept. In 1888, Tesla gained U.S. Patent 381,968 for his work. Also in 1888, Ferraris published his research in a paper to the *Royal Academy of Sciences* in Turin.

31.9.3 Hall effect

Main article: Hall effect

The charge carriers of a current-carrying conductor placed in a transverse magnetic field experience a sideways Lorentz force; this results in a charge separation in a direction perpendicular to the current and to the magnetic field. The resultant voltage in that direction is proportional to the applied magnetic field. This is known as the *Hall effect*.

The *Hall effect* is often used to measure the magnitude of a magnetic field. It is used as well to find the sign of the dominant charge carriers in materials such as semiconductors (negative electrons or positive holes).

31.9.4 Magnetic circuits

Main article: Magnetic circuit

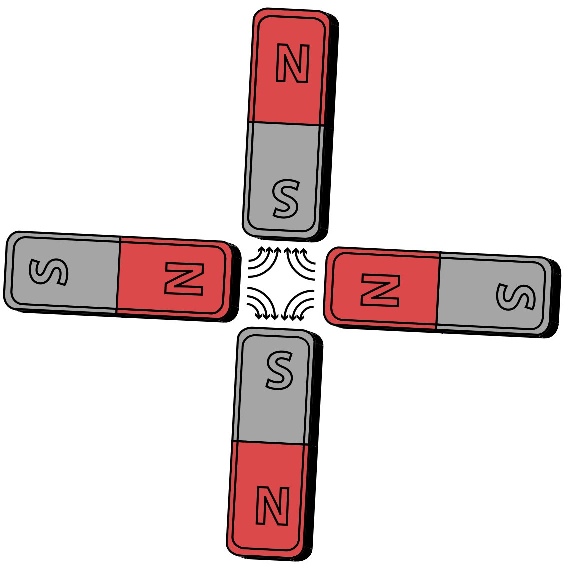
An important use of **H** is in *magnetic circuits* where **B** = μ**H** inside a linear material. Here, μ is the magnetic permeability of the material. This result is similar in form to Ohm's law **J** = σ**E**, where **J** is the current density, σ is the conductance and **E** is the electric field. Extending this analogy, the counterpart to the macroscopic Ohm's law (*I* = *V/R*) is:

$$\Phi = \frac{F}{R_\mathrm{m}},$$

where $\Phi = \int \mathbf{B} \cdot \mathrm{d}\mathbf{A}$ is the magnetic flux in the circuit, $F = \int \mathbf{H} \cdot \mathrm{d}\boldsymbol{\ell}$ is the magnetomotive force applied to the circuit, and R_m is the reluctance of the circuit. Here the reluctance R_m is a quantity similar in nature to resistance for the flux.

Using this analogy it is straightforward to calculate the magnetic flux of complicated magnetic field geometries, by using all the available techniques of circuit theory.

31.9.5 Magnetic field shape descriptions



Schematic quadrupole magnet ("four-pole") magnetic field. There are four steel pole tips, two opposing magnetic north poles and two opposing magnetic south poles.

- An *azimuthal* magnetic field is one that runs east–west.
- A *meridional* magnetic field is one that runs north–south. In the solar dynamo model of the Sun, differential rotation of the solar plasma causes the meridional magnetic field to stretch into an azimuthal magnetic field, a process called the *omega-effect*. The reverse process is called the *alpha-effect*.*[41]
- A *dipole* magnetic field is one seen around a bar magnet or around a charged elementary particle with nonzero spin.
- A *quadrupole* magnetic field is one seen, for example, between the poles of four bar magnets. The field strength grows linearly with the radial distance from its longitudinal axis.
- A *solenoidal* magnetic field is similar to a dipole magnetic field, except that a solid bar magnet is replaced by a hollow electromagnetic coil magnet.
- A *toroidal* magnetic field occurs in a doughnut-shaped coil, the electric current spiraling around the tube-like surface, and is found, for example, in a tokamak.
- A *poloidal* magnetic field is generated by a current flowing in a ring, and is found, for example, in a tokamak.
- A *radial* magnetic field is one in which field lines are directed from the center outwards, similar to the spokes in a bicycle wheel. An example can be found in a loudspeaker transducers (driver).*[42]
- A *helical* magnetic field is corkscrew-shaped, and sometimes seen in space plasmas such as the Orion Molecular Cloud.*[43]

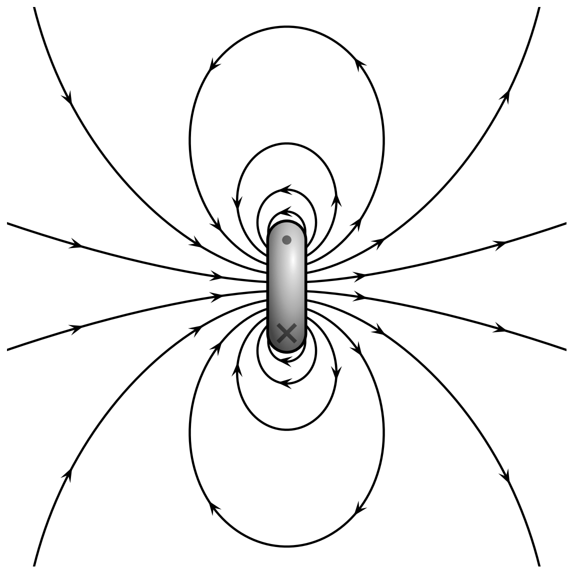
31.9.6 Magnetic dipoles

Main article: Magnetic dipole
See also: Spin magnetic moment and Micromagnetism

The magnetic field of a magnetic dipole is depicted in the figure. From outside, the ideal magnetic dipole is identical to that of an ideal electric dipole of the same strength. Unlike the electric dipole, a magnetic dipole is properly modeled as a current loop having a current *I* and an area *a*. Such a current loop has a magnetic moment of:

$$m = Ia,$$

where the direction of **m** is perpendicular to the area of the loop and depends on the direction of the current using the right-hand rule. An ideal magnetic dipole is modeled as a real magnetic dipole whose area *a* has been reduced to zero and its current *I* increased to infinity such that the



Magnetic field lines around a " magnetostatic dipole" pointing to the right.

product $m = Ia$ is finite. This model clarifies the connection between angular momentum and magnetic moment, which is the basis of the Einstein–de Haas effect *rotation by magnetization* and its inverse, the Barnett effect or *magnetization by rotation*.*[44] Rotating the loop faster (in the same direction) increases the current and therefore the magnetic moment, for example.

It is sometimes useful to model the magnetic dipole similar to the electric dipole with two equal but opposite magnetic charges (one south the other north) separated by distance *d*. This model produces an **H**-field not a **B**-field. Such a model is deficient, though, both in that there are no magnetic charges and in that it obscures the link between electricity and magnetism. Further, as discussed above it fails to explain the inherent connection between angular momentum and magnetism.

31.9.7 Magnetic monopole (hypothetical)

Main article: Magnetic monopole

A *magnetic monopole* is a hypothetical particle (or class of particles) that has, as its name suggests, only one magnetic pole (either a north pole or a south pole). In other words, it would possess a "magnetic charge" analogous to an electric charge. Magnetic field lines would start or end on magnetic monopoles, so if they exist, they would give exceptions to the rule that magnetic field lines neither start nor end.

Modern interest in this concept stems from particle theories, notably Grand Unified Theories and superstring theories, that predict either the existence, or the possibility, of magnetic monopoles. These theories and others have inspired extensive efforts to search for monopoles. Despite these efforts, no magnetic monopole has been observed to date.*[nb 17]

In recent research, materials known as spin ices can simulate monopoles, but do not contain actual monopoles.*[45]*[46]

31.10 See also

31.10.1 General

- Magnetohydrodynamics – the study of the dynamics of electrically conducting fluids
- Magnetic nanoparticles – extremely small magnetic particles that are tens of atoms wide
- Magnetic reconnection – an effect that causes solar flares and auroras
- Magnetic potential – the vector and scalar potential representation of magnetism
- SI electromagnetism units – common units used in electromagnetism
- Orders of magnitude (magnetic field) – list of magnetic field sources and measurement devices from smallest magnetic fields to largest detected
- Upward continuation

31.10.2 Mathematics

- Magnetic helicity – extent to which a magnetic field wraps around itself

31.10.3 Applications

- Dynamo theory – a proposed mechanism for the creation of the Earth's magnetic field
- Helmholtz coil – a device for producing a region of nearly uniform magnetic field
- Magnetic field viewing film – Film used to view the magnetic field of an area
- Maxwell coil – a device for producing a large volume of an almost constant magnetic field
- Stellar magnetic field – a discussion of the magnetic field of stars
- Teltron tube – device used to display an electron beam and demonstrates effect of electric and magnetic fields on moving charges

31.11 Notes

[1] Strictly speaking, a magnetic field is a pseudo vector; pseudo-vectors, which also include torque and rotational velocity, are similar to vectors except that they remain unchanged when the coordinates are inverted.

[2] His *Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt Militem de Magnete*, which is often shortened to *Epistola de magnete*, is dated 1269 C.E.

[3] From the outside, the field of a dipole of magnetic charge has exactly the same form as a current loop when both are sufficiently small. Therefore, the two models differ only for magnetism inside magnetic material.

[4] The letters B and H were originally chosen by Maxwell in his *Treatise on Electricity and Magnetism* (Vol. II, pp. 236–237). For many quantities, he simply started choosing letters from the beginning of the alphabet. See Ralph Baierlein (2000). "Answer to Question #73. S is for entropy, Q is for charge" . *American Journal of Physics*. **68** (8): 691. Bibcode:2000AmJPh..68..691B. doi:10.1119/1.19524.

[5] Edward Purcell, in Electricity and Magnetism, McGraw-Hill, 1963, writes, *Even some modern writers who treat **B** as the primary field feel obliged to call it the magnetic induction because the name magnetic field was historically preempted by **H**. This seems clumsy and pedantic. If you go into the laboratory and ask a physicist what causes the pion trajectories in his bubble chamber to curve, he'll probably answer "magnetic field", not "magnetic induction." You will seldom hear a geophysicist refer to the Earth's magnetic induction, or an astrophysicist talk about the magnetic induction of the galaxy. We propose to keep on calling **B** the magnetic field. As for **H**, although other names have been invented for it, we shall call it "the field **H**" or even "the magnetic field **H**."* In a similar vein, M Gerloch (1983). *Magnetism and Ligand-field Analysis*. Cambridge University Press. p. 110. ISBN 0-521-24939-2. says: "So we may think of both **B** and **H** as magnetic fields, but drop the word 'magnetic' from **H** so as to maintain the distinction ... As Purcell points out, 'it is only the names that give trouble, not the symbols'."

[6] This can be seen from the magnetic part of the Lorentz force law $F = qvB\sin\theta$.

[7] The use of iron filings to display a field presents something of an exception to this picture; the filings alter the magnetic field so that it is much larger along the "lines" of iron, due to the large permeability of iron relative to air.

[8] Here 'small' means that the observer is sufficiently far away that it can be treated as being infinitesimally small. 'Larger' magnets need to include more complicated terms in the expression and depend on the entire geometry of the magnet not just **m**.

[9] Magnetic field lines may also wrap around and around without closing but also without ending. These more complicated non-closing non-ending magnetic field lines are moot, though, since the magnetic field of objects that produce them are calculated by adding the magnetic fields of 'elementary parts' having magnetic field lines that do form closed curves or extend to infinity.

[10] To see that this must be true imagine placing a compass inside a magnet. There, the north pole of the compass points toward the north pole of the magnet since magnets stacked on each other point in the same direction.

[11] As discussed above, magnetic field lines are primarily a conceptual tool used to represent the mathematics behind magnetic fields. The total 'number' of field lines is dependent on how the field lines are drawn. In practice, integral equations such as the one that follows in the main text are used instead.

[12] Either **B** or **H** may be used for the magnetic field outside of the magnet.

[13] In practice, the Biot–Savart law and other laws of magnetostatics are often used even when a current change in time, as long as it does not change too quickly. It is often used, for instance, for standard household currents, which oscillate sixty times per second.

[14] The Biot–Savart law contains the additional restriction (boundary condition) that the B-field must go to zero fast enough at infinity. It also depends on the divergence of **B** being zero, which is always valid. (There are no magnetic charges.)

[15] A third term is needed for changing electric fields and polarization currents; this displacement current term is covered in Maxwell's equations below.

[16] A complete expression for Faraday's law of induction in terms of the electric **E** and magnetic fields can be written as: $\mathcal{E} = -\frac{d\Phi_m}{dt} = \oint_{\partial\Sigma(t)} \left(\mathbf{E}(\mathbf{r},\ t) + \mathbf{v} \times \mathbf{B}(\mathbf{r},\ t)\right) \cdot d\boldsymbol{\ell}$ $= -\frac{d}{dt}\iint_{\Sigma(t)} d\boldsymbol{A} \cdot \mathbf{B}(\mathbf{r},\ t)$, where $\boldsymbol{\partial\Sigma}(t)$ is the moving closed path bounding the moving surface $\boldsymbol{\Sigma}(t)$, and d**A** is an element of surface area of $\boldsymbol{\Sigma}(t)$. The first integral calculates the work done moving a charge a distance $d\boldsymbol{\ell}$ based upon the Lorentz force law. In the case where the bounding surface is stationary, the Kelvin–Stokes theorem can be used to show this equation is equivalent to the Maxwell–Faraday equation.

[17] Two experiments produced candidate events that were initially interpreted as monopoles, but these are now considered inconclusive. For details and references, see magnetic monopole.

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[4] Whittaker 1951, p. 56

[5] Whittaker 1951, p. 59

[6] Whittaker 1951, p. 64

[7] Whittaker 1951, p. 88

[8] Whittaker 1951, p. 222

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31.14 External links

Chapter 32

Magnetic moment

The **magnetic moment** of a magnet is a quantity that determines the torque it will experience in an external magnetic field. A loop of electric current, a bar magnet, an electron, a molecule, and a planet all have magnetic moments.

The magnetic moment may be considered to be a vector having a magnitude and direction. The direction of the magnetic moment points from the south to north pole of the magnet. The magnetic field produced by the magnet is proportional to its magnetic moment. More precisely, the term *magnetic moment* normally refers to a system's **magnetic dipole moment**, which produces the first term in the multipole expansion of a general magnetic field. The dipole component of an object's magnetic field is symmetric about the direction of its magnetic dipole moment, and decreases as the inverse cube of the distance from the object.

32.1 Definition

The magnetic moment is defined as a vector relating the aligning torque on the object from an externally applied magnetic field to the field vector itself. The relationship is given by:*[1]

$$\boldsymbol{\tau} = \boldsymbol{\mu} \times \mathbf{B}$$

where **τ** is the torque acting on the dipole and **B** is the external magnetic field, and **μ** is the magnetic moment.

This definition is based on how one would measure the magnetic moment, in principle, of an unknown sample.

32.2 Units

The unit for magnetic moment is not a base unit in the International System of Units (SI). As the torque is measured in newton-meters (N·m) and the magnetic field in teslas (T), the magnetic moment is measured in newton-meters per tesla. This has equivalents in other base units:*[2]*[3]

$$\mathrm{N{\cdot}m/T} = \mathrm{A{\cdot}m^2} = \mathrm{J/T}$$

where A is amperes and J is joules.

In the CGS system, there are several different sets of electromagnetism units, of which the main ones are ESU, Gaussian, and EMU. Among these, there are two alternative (non-equivalent) units of magnetic dipole moment:

1 statA·cm^2 = 3.33564095×10*−14 A·m^2 (ESU)

1 erg/G = 1 abA·cm^2 = 10*−3 A·m^2 (Gaussian and EMU),

where statA is statamperes, cm is centimeters, erg is ergs, G is gauss and abA is abamperes. The ratio of these two non-equivalent CGS units (EMU/ESU) is equal to the speed of light in free space, expressed in cm·s*−1.

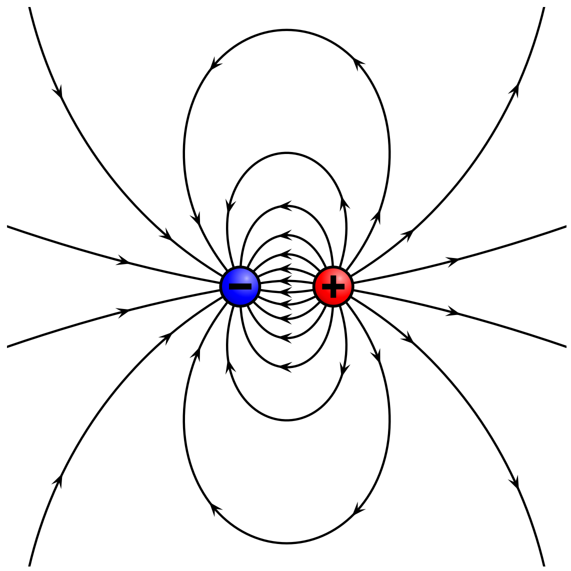
All formulae in this article are correct in SI units; they may need to be changed for use in other unit systems. For example, in SI units, a loop of current with current I and area A has magnetic moment IA (see below), but in Gaussian units the magnetic moment is *IA*/*c*.

32.3 Two representations of the cause of the magnetic moment

The preferred classical explanation of a magnetic moment has changed over time. Before the 1930s, textbooks explained the moment using hypothetical magnetic point charges. Since then, most have defined it in terms of Ampèrian currents.*[4] In magnetic materials, the cause of the magnetic moment are the spin and orbital angular momentum states of the electrons, and varies depending on whether atoms in one region are aligned with atoms in another.

32.3.1 Magnetic pole representation

The sources of magnetic moments in materials can be represented by poles in analogy to electrostatics. Consider a bar magnet which has magnetic poles of equal



An electrostatic analog for a magnetic moment: two opposing charges separated by a finite distance.

magnitude but opposite polarity. Each pole is the source of magnetic force which weakens with distance. Since magnetic poles always come in pairs, their forces partially cancel each other because while one pole pulls, the other repels. This cancellation is greatest when the poles are close to each other i.e. when the bar magnet is short. The magnetic force produced by a bar magnet, at a given point in space, therefore depends on two factors: the strength p of its poles (**magnetic pole strength**), and the vector **l** separating them. The moment is related to the fictitious poles as*[4]

$$\mu = p\boldsymbol{l}.$$

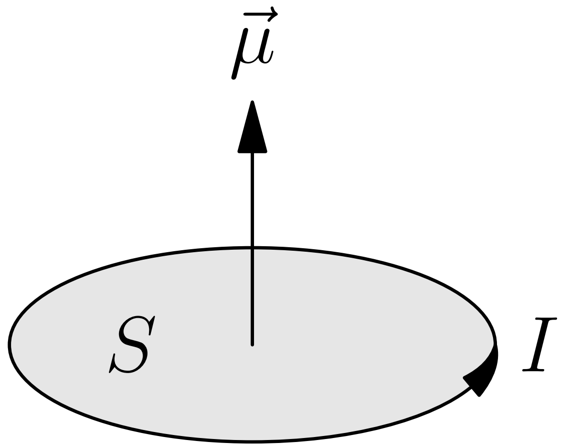
It points in the direction from South to North pole. The analogy with electric dipoles should not be taken too far because magnetic dipoles are associated with angular momentum (see Magnetic moment and angular momentum). Nevertheless, magnetic poles are very useful for magnetostatic calculations, particularly in applications to ferromagnets.*[4] Practitioners using the magnetic pole approach generally represent the magnetic field by the irrotational field **H**, in analogy to the electric field **E**.

32.3.2 Integral representation

We start from the definition of the differential magnetic moment pseudovector:

$$\boldsymbol{\mu} = \tfrac{1}{2}\mathbf{r} \times \mathbf{j}$$

where × is the vector cross product, **r** is the position vector, and **j** is the electric current density. It is very similar to the differential angular momentum, defined as:



*Moment **μ** of a planar current having magnitude **I** and enclosing an area **S***

$$\boldsymbol{l} = \mathbf{r} \times (\rho\mathbf{v})$$

where ρ is the mass density and **v** is the velocity vector. Like in every pseudovector, by convention the direction of the cross product is given by the right hand grip rule. *[5] Practitioners using the current loop model generally represent the magnetic field by the solenoidal field **B**, analogous to the electrostatic field **D**.

The integral magnetic moment of a charge distribution is therefore:

$$\mathbf{M} = \frac{1}{2}\iiint_V \mathbf{r} \times \mathbf{j}\,\mathrm{d}V,$$

Let us start with a point particle; in this simple situation the magnetic moment is:

$$\mathbf{M} = \tfrac{1}{2}q\,\mathbf{r} \times \mathbf{v}$$

where **r** is the position of the electric charge q relative to the center of the circle and **v** is the instantaneous velocity of the charge, giving an electric current density **j**.

On the other hand, for a point particle the angular momentum is defined as:

$$\boldsymbol{L} = \mathbf{r} \times \mathbf{p} = m\mathbf{r} \times \mathbf{v}$$

and in the planar case:

$$\mathbf{M} = \frac{1}{2}\iint_S \mathbf{r} \times \mathbf{j}\,\mathrm{d}S,$$

by defining the electric current with a vector area **S** (the x-, y-, and z-coordinates of this vector are the areas of projections of the loop onto the yz-, zx-, and xy-planes):

$\mathbf{M} = \frac{1}{2} I \int_{\partial S} \mathbf{r} \times d\mathbf{r}.$

Then by Stokes' theorem, integral magnetic moment then becomes expressible as:

$\mathbf{M} = I\mathbf{S}.$

The factor 1/2 in our definition above is only due to historical reason: the old definition of the magnetic moment was this last integral equation. If one had started from a differential definition:

$\boldsymbol{\mu} = \mathbf{r} \times \mathbf{j}$

then the coherent integral expression would have been:

$\mathbf{M} = 2I\mathbf{S}.$

Magnetic moment of a solenoid

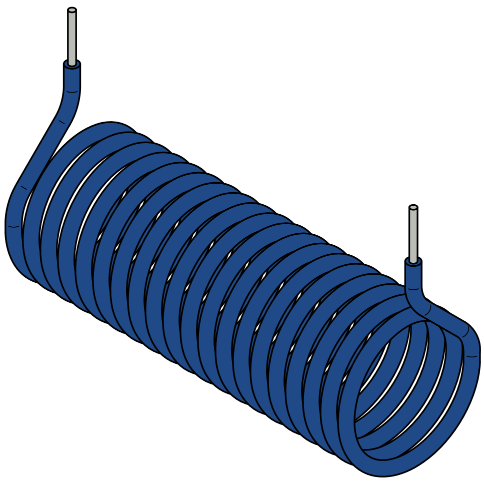


Image of a solenoid

A generalization of the above current loop is a coil, or solenoid. Its moment is the vector sum of the moments of individual turns. If the solenoid has N identical turns (single-layer winding) and vector area **S**,

$\boldsymbol{\mu} = NI\mathbf{S}.$

32.4 Magnetic moment and angular momentum

The magnetic moment has a close connection with angular momentum called the **gyromagnetic effect**. This effect is expressed on a macroscopic scale in the Einstein-de Haas effect, or "rotation by magnetization," and its inverse, the Barnett effect, or "magnetization by rotation." *[1] In particular, when a magnetic moment is subject to a torque in a magnetic field that tends to align it with the applied magnetic field, the moment precesses (rotates about the axis of the applied field). This is a consequence of the concomitance of magnetic moment and angular momentum, that in case of charged massive particles corresponds to the concomitance of charge and mass in a particle.

Viewing a magnetic dipole as a rotating charged particle brings out the close connection between magnetic moment and angular momentum. Both the magnetic moment and the angular momentum increase with the rate of rotation. The ratio of the two is called the gyromagnetic ratio and is simply the half of the charge-to-mass ratio.*[6] *[7]

For a spinning charged solid with a uniform charge density to mass density ratio, the gyromagnetic ratio is equal to half the charge-to-mass ratio. This implies that a more massive assembly of charges spinning with the same angular momentum will have a proportionately weaker magnetic moment, compared to its lighter counterpart. Even though atomic particles cannot be accurately described as spinning charge distributions of uniform charge-to-mass ratio, this general trend can be observed in the atomic world, where the intrinsic angular momentum (spin) of each type of particle is a constant: a small half-integer times the reduced Planck constant ħ. This is the basis for defining the magnetic moment units of Bohr magneton (assuming charge-to-mass ratio of the electron) and nuclear magneton (assuming charge-to-mass ratio of the proton).

32.5 Effects of an external magnetic field on a magnetic moment

32.5.1 Force on a moment

See also: force between magnets

A magnetic moment in an externally produced magnetic field has a potential energy U:

$U = -\boldsymbol{\mu} \cdot \mathbf{B}$

In a case when the external magnetic field is non-uniform, there will be a force, proportional to the magnetic field gradient, acting on the magnetic moment itself. There has been some discussion on how to calculate the force acting on a magnetic dipole. There are two expressions for the force acting on a magnetic dipole, depending on whether the model used for the dipole is a current loop or two monopoles (analogous to the electric dipole).*[8] The force obtained in the case of a current loop model is

$$\mathbf{F}_{\text{loop}} = \nabla (\boldsymbol{\mu} \cdot \mathbf{B})$$

In the case of a pair of monopoles being used (i.e. electric dipole model)

$$\mathbf{F}_{\text{dipole}} = (\boldsymbol{\mu} \cdot \nabla) \mathbf{B}$$

and one can be put in terms of the other via the relation

$$\mathbf{F}_{\text{loop}} = \mathbf{F}_{\text{dipole}} + \boldsymbol{\mu} \times (\nabla \times \mathbf{B})$$

In all these expressions $\boldsymbol{\mu}$ is the dipole and $\mathbf{B}$ is the magnetic field at its position. Note that if there are no currents or time-varying electrical fields $\nabla \times \mathbf{B} = 0$ and the two expressions agree.

An electron, nucleus, or atom placed in a uniform magnetic field will precess with a frequency known as the Larmor frequency. See Resonance.

32.6 Magnetic dipoles

Main article: Magnetic dipole
See also: Dipole

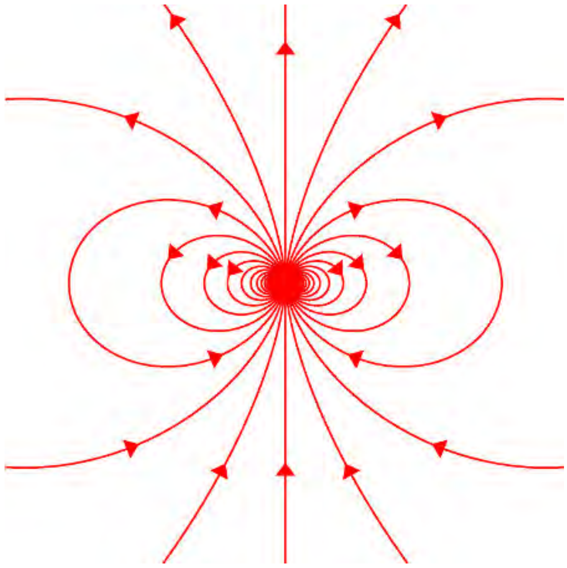
A magnetic dipole is the limit of either a current loop or a pair of poles as the dimensions of the source are reduced to zero while keeping the moment constant. As long as these limits only apply to fields far from the sources, they are equivalent. However, the two models give different predictions for the internal field (see below).

32.6.1 External magnetic field produced by a magnetic dipole moment

Any system possessing a net magnetic dipole moment $\mathbf{m}$ will produce a dipolar magnetic field (described below) in the space surrounding the system. While the net magnetic field produced by the system can also have higher-order multipole components, those will drop off with distance more rapidly, so that only the dipolar component will dominate the magnetic field of the system at distances far away from it.

The vector potential of magnetic field produced by magnetic moment $\mathbf{m}$ is

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi} \frac{\mathbf{m} \times \mathbf{r}}{|\mathbf{r}|^3}$$



Magnetic field lines around a "magnetostatic dipole". The magnetic dipole itself is located in the center of the figure, seen from the side, and pointing upward.

and magnetic flux density is

$$\mathbf{B}(\mathbf{r}) = \nabla \times \mathbf{A} = \frac{\mu_0}{4\pi} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right).$$

Alternatively one can obtain the scalar potential first from the magnetic pole perspective,

$$\psi(\mathbf{r}) = \frac{\mathbf{m} \cdot \mathbf{r}}{4\pi |\mathbf{r}|^3},$$

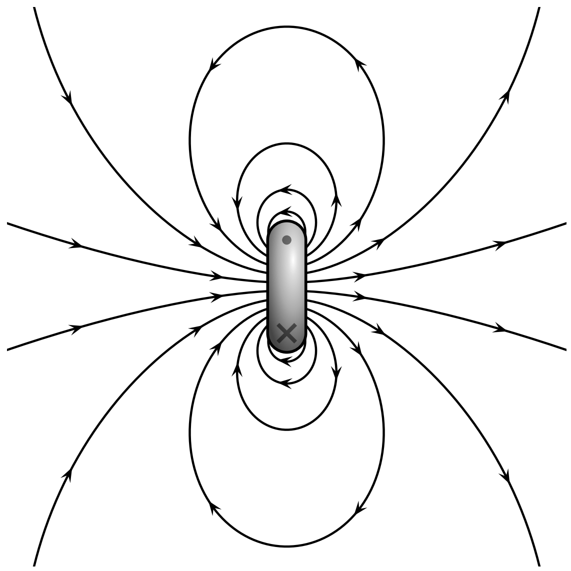
and hence magnetic field strength is

$$\mathbf{H}(\mathbf{r}) = -\nabla \psi = \frac{1}{4\pi} \left(\frac{3\mathbf{r}(\mathbf{m} \cdot \mathbf{r})}{|\mathbf{r}|^5} - \frac{\mathbf{m}}{|\mathbf{r}|^3} \right).$$

The magnetic field of an ideal magnetic dipole is depicted on the right.

32.6.2 Internal magnetic field of a dipole

The two models for a dipole (current loop and magnetic poles) give the same predictions for the magnetic field far from the source. However, inside the source region they give different predictions. The magnetic field between poles (see figure for Magnetic pole definition) is in the opposite direction to the magnetic moment (which points from the negative charge to the positive charge), while inside a current loop it is in the same direction (see the figure to the right). Clearly, the limits of these fields must also be different as the sources shrink to zero size. This distinction only matters if the dipole limit is used to calculate fields inside a magnetic material.*[4]



The magnetic field of a current loop

If a magnetic dipole is formed by making a current loop smaller and smaller, but keeping the product of current and area constant, the limiting field is

$$\mathbf{B}(\mathbf{x}) = \frac{\mu_0}{4\pi}\left[\frac{3\mathbf{n}(\mathbf{n}\cdot\mathbf{m})-\mathbf{m}}{|\mathbf{x}|^3} + \frac{8\pi}{3}\mathbf{m}\delta(\mathbf{x})\right].$$

Unlike the expressions in the previous section, this limit is correct for the internal field of the dipole.*[4]*[9]

If a magnetic dipole is formed by taking a "north pole" and a "south pole", bringing them closer and closer together but keeping the product of magnetic pole-charge and distance constant, the limiting field is*[4]

$$\mathbf{H}(\mathbf{x}) = \frac{1}{4\pi}\left[\frac{3\mathbf{n}(\mathbf{n}\cdot\mathbf{m})-\mathbf{m}}{|\mathbf{x}|^3} - \frac{4\pi}{3}\mathbf{m}\delta(\mathbf{x})\right].$$

These fields are related by $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$, where $\mathbf{M}(\mathbf{x}) = \mathbf{m}\delta(\mathbf{x})$ is the magnetization.

32.6.3 Forces between two magnetic dipoles

See also: Magnetic dipole–dipole interaction

As discussed earlier, the force exerted by a dipole loop with moment $\mathbf{m}_1$ on another with moment $\mathbf{m}_2$ is

$$\mathbf{F} = \nabla\left(\mathbf{m}_2\cdot\mathbf{B}_1\right),$$

where $\mathbf{B}_1$ is the magnetic field due to moment $\mathbf{m}_1$. The result of calculating the gradient is*[10]*[11]

$$\mathbf{F}(\mathbf{r},\mathbf{m}_1,\mathbf{m}_2) = \frac{3\mu_0}{4\pi|\mathbf{r}|^4}\left(\mathbf{m}_2(\mathbf{m}_1\cdot\hat{\mathbf{r}}) + \mathbf{m}_1(\mathbf{m}_2\cdot\hat{\mathbf{r}}) + \hat{\mathbf{r}}(\mathbf{m}_1\cdot\mathbf{m}_2) - 5\hat{\mathbf{r}}(\mathbf{m}\right.$$

where $\hat{\mathbf{r}}$ is the unit vector pointing from magnet 1 to magnet 2 and r is the distance. An equivalent expression is*[11]

$$\mathbf{F} = \frac{3\mu_0}{4\pi|\mathbf{r}|^4}\left((\hat{\mathbf{r}}\times\mathbf{m}_1)\times\mathbf{m}_2 + (\hat{\mathbf{r}}\times\mathbf{m}_2)\times\mathbf{m}_1 - 2\hat{\mathbf{r}}(\mathbf{m}_1\cdot\mathbf{m}_2) + 5\hat{\mathbf{r}}(\hat{\mathbf{r}}\times\right.$$

The force acting on $\mathbf{m}_1$ is in the opposite direction.

The torque of magnet 1 on magnet 2 is

$$\boldsymbol{\tau} = \mathbf{m}_2\times\mathbf{B}_1.$$

32.7 Examples of magnetic moments

32.7.1 Two kinds of magnetic sources

Fundamentally, contributions to any system's magnetic moment may come from sources of two kinds: motion of electric charges, such as electric currents; and the intrinsic magnetism of elementary particles, such as the electron.

Contributions due to the sources of the first kind can be calculated from knowing the distribution of all the electric currents (or, alternatively, of all the electric charges and their velocities) inside the system, by using the formulas below. On the other hand, the magnitude of each elementary particle's intrinsic magnetic moment is a fixed number, often measured experimentally to a great precision. For example, any electron's magnetic moment is measured to be −9.284764×10*−24 J/T.*[12] The direction of the magnetic moment of any elementary particle is entirely determined by the direction of its spin, with the negative value indicating that any electron's magnetic moment is antiparallel to its spin.

The net magnetic moment of any system is a vector sum of contributions from one or both types of sources. For example, the magnetic moment of an atom of hydrogen-1 (the lightest hydrogen isotope, consisting of a proton and an electron) is a vector sum of the following contributions:

1. the intrinsic moment of the electron,
2. the orbital motion of the electron around the proton,
3. the intrinsic moment of the proton.

Similarly, the magnetic moment of a bar magnet is the sum of the contributing magnetic moments, which include the intrinsic and orbital magnetic moments of the unpaired electrons of the magnet's material and the nuclear magnetic moments.

32.7.2 Magnetic moment of an atom

For an atom, individual electron spins are added to get a total spin, and individual orbital angular momenta are added to get a total orbital angular momentum. These two then are added using angular momentum coupling to get a total angular momentum. The magnitude of the atomic dipole moment is then*[13]

$$m_{\text{Atom}} = g_J \mu_B \sqrt{j(j+1)}$$

where j is the total angular momentum quantum number, g_J is the Landé *g*-factor, and μ_B is the Bohr magneton. The component of this magnetic moment along the direction of the magnetic field is then*[14]

$$m_{\text{Atom}}(z) = -m g_J \mu_B$$

where m is called the magnetic quantum number or the *equatorial* quantum number, which can take on any of 2*j* + 1 values:*[15]

$$-j, -(j-1) \cdots 0 \cdots +(j-1), +j\ .$$

The negative sign occurs because electrons have negative charge.

Due to the angular momentum, the dynamics of a magnetic dipole in a magnetic field differs from that of an electric dipole in an electric field. The field does exert a torque on the magnetic dipole tending to align it with the field. However, torque is proportional to rate of change of angular momentum, so precession occurs: the direction of spin changes. This behavior is described by the Landau–Lifshitz–Gilbert equation:*[16]*[17]

$$\frac{1}{\gamma}\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = \mathbf{m} \times \mathbf{H}_{\text{eff}} - \frac{\lambda}{\gamma m}\mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

where γ is the gyromagnetic ratio, **m** is the magnetic moment, λ is the damping coefficient and $\mathbf{H}_{\text{eff}}$ is the effective magnetic field (the external field plus any self-induced field). The first term describes precession of the moment about the effective field, while the second is a damping term related to dissipation of energy caused by interaction with the surroundings.

32.7.3 Magnetic moment of an electron

See also: Anomalous magnetic dipole moment

Electrons and many elementary particles also have intrinsic magnetic moments, an explanation of which requires a quantum mechanical treatment and relates to the intrinsic angular momentum of the particles as discussed in the article Electron magnetic moment. It is these intrinsic magnetic moments that give rise to the macroscopic effects of magnetism, and other phenomena, such as electron paramagnetic resonance.

The magnetic moment of the electron is

$$\mathbf{m}_S = -\frac{g_S \mu_B \mathbf{S}}{\hbar},$$

where μ_B is the Bohr magneton, **S** is electron spin, and the *g*-factor g_S is 2 according to Dirac's theory, but due to quantum electrodynamic effects it is slightly larger in reality: 2.00231930436. The deviation from 2 is known as the anomalous magnetic dipole moment.

Again it is important to notice that **m** is a negative constant multiplied by the spin, so the magnetic moment of the electron is antiparallel to the spin. This can be understood with the following classical picture: if we imagine that the spin angular momentum is created by the electron mass spinning around some axis, the electric current that this rotation creates circulates in the opposite direction, because of the negative charge of the electron; such current loops produce a magnetic moment which is antiparallel to the spin. Hence, for a positron (the anti-particle of the electron) the magnetic moment is parallel to its spin.

32.7.4 Magnetic moment of a nucleus

See also: Nuclear magnetic moment

The nuclear system is a complex physical system consisting of nucleons, i.e., protons and neutrons. The quantum mechanical properties of the nucleons include the spin among others. Since the electromagnetic moments of the nucleus depend on the spin of the individual nucleons, one can look at these properties with measurements of nuclear moments, and more specifically the nuclear magnetic dipole moment.

Most common nuclei exist in their ground state, although nuclei of some isotopes have long-lived excited states. Each energy state of a nucleus of a given isotope is characterized by a well-defined magnetic dipole moment, the magnitude of which is a fixed number, often measured experimentally to a great precision. This number is very sensitive to the individual contributions from nucleons, and a measurement or prediction of its value can reveal important information about the content of the nuclear wave function. There are several theoretical models that predict the value of the magnetic dipole moment and a number of experimental techniques aiming to carry out measurements in nuclei along the nuclear chart.

32.7.5 Magnetic moment of a molecule

Any molecule has a well-defined magnitude of magnetic moment, which may depend on the molecule's energy state. Typically, the overall magnetic moment of a molecule is a combination of the following contributions, in the order of their typical strength:

- magnetic moments due to its unpaired electron spins (paramagnetic contribution), if any
- orbital motion of its electrons, which in the ground state is often proportional to the external magnetic field (diamagnetic contribution)
- the combined magnetic moment of its nuclear spins, which depends on the nuclear spin configuration.

Examples of molecular magnetism

- The dioxygen molecule, O_2, exhibits strong paramagnetism, due to unpaired spins of its outermost two electrons.
- The carbon dioxide molecule, CO_2, mostly exhibits diamagnetism, a much weaker magnetic moment of the electron orbitals that is proportional to the external magnetic field. The nuclear magnetism of a magnetic isotope such as ^{13}C or ^{17}O will contribute to the molecule's magnetic moment.
- The dihydrogen molecule, H_2, in a weak (or zero) magnetic field exhibits nuclear magnetism, and can be in a para- or an ortho- nuclear spin configuration.
- Many transition metal complexes are magnetic. The spin-only formula is a good first approximation for high-spin complexes of first-row transition metals.*[18]

32.7.6 Elementary particles

In atomic and nuclear physics, the Greek symbol μ represents the magnitude of the magnetic moment, often measured in Bohr magnetons or nuclear magnetons, associated with the intrinsic spin of the particle and/or with the orbital motion of the particle in a system. Values of the intrinsic magnetic moments of some particles are given in the table below:

For relation between the notions of magnetic moment and magnetization see magnetization.

32.8 See also

- Electric dipole moment
- Electron magnetic moment
- Magnetic susceptibility
- Magnetic dipole-dipole interaction
- Moment (physics)
- Neutron magnetic moment
- Orbital magnetization
- Proton magnetic moment

32.9 References and notes

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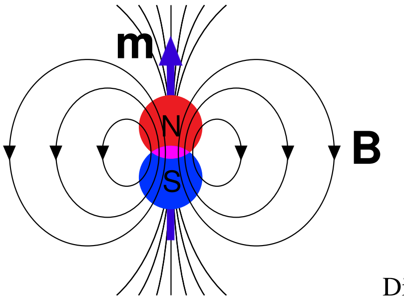
32.10 External links

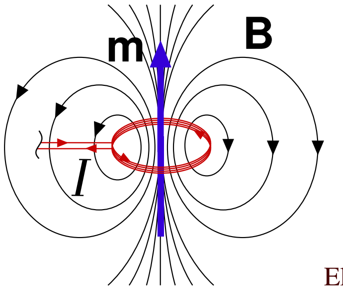
- Bowtell, Richard (2009). "μ – Magnetic Moment” . *Sixty Symbols*. Brady Haran for the University of Nottingham.

Chapter 33

Magnetic dipole

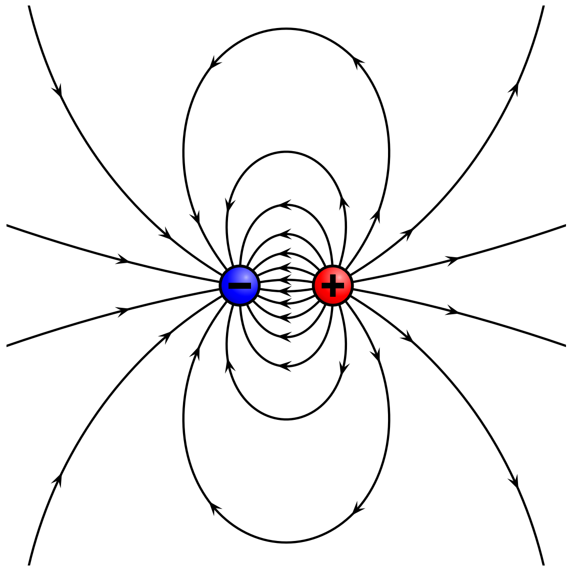


Dipole moment **m**.

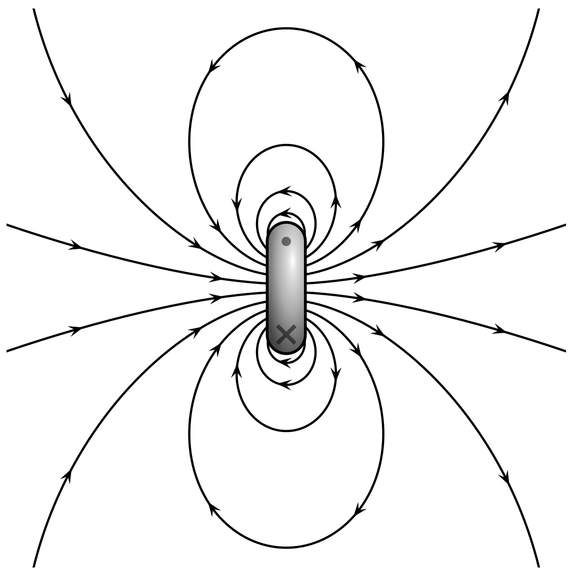


Electric current *I*.

The **magnetic field** and **magnetic moment**, due to natural magnetic dipoles (left), or an electric current (right). Either generates the same field profile.* [1]



An electrostatic analogue for a magnetic moment: two opposing charges separated by a finite distance. Each arrow represents the direction of the field vector at that point.



The magnetic field of a current loop. The ring represents the current loop, which goes into the page at the x and comes out at the dot.

A **magnetic dipole** is the limit of either a closed loop of electric current or a pair of poles as the dimensions of the source are reduced to zero while keeping the magnetic moment constant. It is a magnetic analogue of the electric dipole, but the analogy is not complete. In particular, a magnetic monopole, the magnetic analogue of an electric charge, has never been observed. Moreover, one form of magnetic dipole moment is associated with a fundamental quantum property—the spin of elementary particles.

The magnetic field around any magnetic source looks increasingly like the field of a magnetic dipole as the distance from the source increases.

33.1 External magnetic field produced by a magnetic dipole moment

In classical physics, the magnetic field of a dipole is calculated as the limit of either a current loop or a pair of charges as the source shrinks to a point while keeping the magnetic moment **m** constant. For the current loop, this limit is most easily derived for the vector potential. Outside of the source region, this potential is (in SI units) *[2]

$$\mathbf{A}(\mathbf{r}) = \frac{\mu_0}{4\pi r^2}\frac{\mathbf{m}\times\mathbf{r}}{r} = \frac{\mu_0}{4\pi}\frac{\mathbf{m}\times\mathbf{r}}{r^3},$$

with $4\pi r^2$ being the surface of a sphere of radius *r*;

and the magnetic flux density (strength of the B-field) in teslas is

$$\mathbf{B}(\mathbf{r}) = \nabla\times\mathbf{A} = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right).$$

In spherical coordinates with the magnetic moment aligned with the axis, this relation can be expressed as

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\frac{|\mathbf{m}|}{|\mathbf{r}|^3}\left(2\cos\theta\,\hat{\mathbf{r}} + \sin\theta\,\hat{\boldsymbol{\theta}}\right).$$

Alternatively one can obtain the scalar potential first from the magnetic pole limit,

$$\psi(\mathbf{r}) = \frac{\mathbf{m}\cdot\mathbf{r}}{4\pi r^3},$$

and hence the magnetic field strength (or strength of the H-field) in ampere-turns per meter is

$$\mathbf{H}(\mathbf{r}) = -\nabla\psi = \frac{1}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right) = \mathbf{B}/\mu_0.$$

The magnetic field is symmetric under rotations about the axis of the magnetic moment.

33.2 Internal magnetic field of a dipole

See also: Magnetic moment § Magnetic pole definition

The two models for a dipole (current loop and magnetic poles) give the same predictions for the magnetic field far from the source. However, inside the source region they give different predictions. The magnetic field between poles is in the opposite direction to the magnetic moment (which points from the negative charge to the positive charge), while inside a current loop it is in the same direction (see the figure to the right). Clearly, the limits of these fields must also be different as the sources shrink to zero size. This distinction only matters if the dipole limit is used to calculate fields inside a magnetic material.

If a magnetic dipole is formed by making a current loop smaller and smaller, but keeping the product of current and area constant, the limiting field is

$$\mathbf{B}(\mathbf{x}) = \frac{\mu_0}{4\pi}\left[\frac{3\mathbf{n}(\mathbf{n}\cdot\mathbf{m}) - \mathbf{m}}{|\mathbf{x}|^3} + \frac{8\pi}{3}\mathbf{m}\delta(\mathbf{x})\right],$$

where **n=x/|x|** is a unit vector, and δ(**x**) is the Dirac delta function in three dimensions. Unlike the expressions in the previous section, this limit is correct for the internal field of the dipole.

If a magnetic dipole is formed by taking a "north pole" and a "south pole", bringing them closer and closer together but keeping the product of magnetic pole-charge and distance constant, the limiting field is

$$\mathbf{H}(\mathbf{x}) = \frac{1}{4\pi}\left[\frac{3\mathbf{n}(\mathbf{n}\cdot\mathbf{m}) - \mathbf{m}}{|\mathbf{x}|^3} - \frac{4\pi}{3}\mathbf{m}\delta(\mathbf{x})\right].$$

These fields are related by $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$, where

$$\mathbf{M}(\mathbf{x}) = \mathbf{m}\delta(\mathbf{x})$$

is the magnetization.

33.3 Forces between two magnetic dipoles

See also: Force between magnets § Magnetic dipole-dipole interaction

The force **F** exerted by one dipole moment $\mathbf{m}_1$ on another $\mathbf{m}_2$ separated in space by a vector **r** can be calculated using:*[3]

$$\mathbf{F} = \nabla\left(\mathbf{m}_2\cdot\mathbf{B}_1\right),$$

or *[4]*[5]

$$\mathbf{F}(\mathbf{r},\mathbf{m}_1,\mathbf{m}_2) = \frac{3\mu_0}{4\pi r^5}\Bigg[(\mathbf{m}_1\cdot\mathbf{r})\mathbf{m}_2 + (\mathbf{m}_2\cdot\mathbf{r})\mathbf{m}_1 + (\mathbf{m}_1\cdot\mathbf{m}_2)\mathbf{r} - \frac{5(\mathbf{m}_1\cdot}{}$$

where r is the distance between dipoles. The force acting on $\mathbf{m}_1$ is in the opposite direction.

The torque can be obtained from the formula

$$\boldsymbol{\tau} = \mathbf{m}_2\times\mathbf{B}_1.$$

33.4 Dipolar fields from finite sources

See also: Near and far field

The magnetic scalar potential ψ produced by a finite source, but external to it, can be represented by a multipole expansion. Each term in the expansion is associated with a characteristic moment and a potential having a characteristic rate of decrease with distance r from the source. Monopole moments have a 1/r rate of decrease, dipole moments have a $1/r^2$ rate, quadrupole moments have a $1/r^3$ rate, and so on. The higher the order, the faster the potential drops off. Since the lowest-order term observed in magnetic sources is the dipolar term, it dominates at large distances. Therefore, at large distances any magnetic source looks like a dipole with the same magnetic moment.

33.5 Notes

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Chapter 34

Ferromagnetism

Not to be confused with Ferrimagnetism; for an overview see Magnetism.

A magnet made of alnico, an iron alloy, with its keeper. Ferromagnetism is the theory which explains how materials become magnets.

Ferromagnetism is the basic mechanism by which certain materials (such as iron) form permanent magnets, or are attracted to magnets. In physics, several different types of magnetism are distinguished. Ferromagnetism (including ferrimagnetism)*[1] is the strongest type: it is the only one that typically creates forces strong enough to be felt, and is responsible for the common phenomena of magnetism in magnets encountered in everyday life. Substances respond weakly to magnetic fields with three other types of magnetism, paramagnetism, diamagnetism, and antiferromagnetism, but the forces are usually so weak that they can only be detected by sensitive instruments in a laboratory. An everyday example of ferromagnetism is a refrigerator magnet used to hold notes on a refrigerator door. The attraction between a magnet and ferromagnetic material is "the quality of magnetism first apparent to the ancient world, and to us today" .*[2]

Permanent magnets (materials that can be magnetized by an external magnetic field and remain magnetized after the external field is removed) are either ferromagnetic or ferrimagnetic, as are the materials that are noticeably attracted to them. Only a few substances are ferromagnetic. The common ones are iron, nickel, cobalt and most of their alloys, some compounds of rare earth metals, and a few naturally occurring minerals, including some varieties of lodestone (magnetite is considered ferrimagnetic, rather than ferromagnetic).

Ferromagnetism is very important in industry and modern technology, and is the basis for many electrical and electromechanical devices such as electromagnets, electric motors, generators, transformers, and magnetic storage such as tape recorders, and hard disks.

34.1 History and distinction from ferrimagnetism

Historically, the term *ferromagnetism* was used for any material that could exhibit spontaneous magnetization: a net magnetic moment in the absence of an external magnetic field. This general definition is still in common use. More recently, however, different classes of spontaneous magnetization have been identified when there is more than one magnetic ion per primitive cell of the material, leading to a stricter definition of "ferromagnetism" that is often used to distinguish it from ferrimagnetism. In particular,

- a material is "ferromagnetic" in this narrower sense only if *all* of its magnetic ions add a positive contribution to the net magnetization.
- If some of the magnetic ions *subtract* from the net magnetization (if they are partially *anti*-aligned), then the material is "ferrimagnetic" .*[3]
- If the moments of the aligned and anti-aligned ions balance completely so as to have zero net magnetization, despite the magnetic ordering, then it is an antiferromagnet.

These alignment effects only occur at temperatures below a certain critical temperature, called the Curie temperature (for ferromagnets and ferrimagnets) or the Néel temperature (for antiferromagnets).

Among the first investigations of ferromagnetism are the pioneering works of Aleksandr Stoletov on measurement of the magnetic permeability of ferromagnetics, known as the Stoletov curve.

34.2 Ferromagnetic materials

See also: Category:Ferromagnetic materials

The table on the right lists a selection of ferromagnetic and ferrimagnetic compounds, along with the temperature above which they cease to exhibit spontaneous magnetization (see Curie temperature).

Ferromagnetism is a property not just of the chemical make-up of a material, but of its crystalline structure and microstructure. There are ferromagnetic metal alloys whose constituents are not themselves ferromagnetic, called Heusler alloys, named after Fritz Heusler. Conversely there are non-magnetic alloys, such as types of stainless steel, composed almost exclusively of ferromagnetic metals.

Amorphous (non-crystalline) ferromagnetic metallic alloys can be made by very rapid quenching (cooling) of a liquid alloy. These have the advantage that their properties are nearly isotropic (not aligned along a crystal axis); this results in low coercivity, low hysteresis loss, high permeability, and high electrical resistivity. One such typical material is a transition metal-metalloid alloy, made from about 80% transition metal (usually Fe, Co, or Ni) and a metalloid component (B, C, Si, P, or Al) that lowers the melting point.

A relatively new class of exceptionally strong ferromagnetic materials are the rare-earth magnets. They contain lanthanide elements that are known for their ability to carry large magnetic moments in well-localized f-orbitals.

34.2.1 Actinide ferromagnets

A number of actinide compounds are ferromagnets at room temperature or exhibit ferromagnetism upon cooling. PuP is a paramagnet with cubic symmetry at room temperature, but which undergoes a structural transition into a tetragonal state with ferromagnetic order when cooled below its T_C = 125 K. In its ferromagnetic state, PuP's easy axis is in the <100> direction.*[6]

In $NpFe_2$ the easy axis is <111>.*[7] Above $T_C \approx 500$ K $NpFe_2$ is also paramagnetic and cubic. Cooling below the Curie temperature produces a rhombohedral distortion wherein the rhombohedral angle changes from 60° (cubic phase) to 60.53°. An alternate description of this distortion is to consider the length *c* along the unique trigonal axis (after the distortion has begun) and *a* as the distance in the plane perpendicular to *c*. In the cubic phase this reduces to *c/a* = 1.00. Below the Curie temperature

$$\frac{c}{a} - 1 = -(120 \pm 5) \times 10^{-4}$$

which is the largest strain in any actinide compound.*[8] $NpNi_2$ undergoes a similar lattice distortion below T_C = 32 K, with a strain of (43 ± 5) × 10*−4.*[8] $NpCo_2$ is a ferrimagnet below 15 K.

34.2.2 Lithium gas

In 2009, a team of MIT physicists demonstrated that a lithium gas cooled to less than one kelvin can exhibit ferromagnetism.*[9] The team cooled fermionic lithium-6 to less than 150 nK (150 billionths of one kelvin) using infrared laser cooling. This demonstration is the first time that ferromagnetism has been demonstrated in a gas.

34.3 Explanation

The Bohr–van Leeuwen theorem, discovered in the 1910s, showed that classical physics theories are unable to account for any form of magnetism, including ferromagnetism. Magnetism is now regarded as a purely quantum mechanical effect. Ferromagnetism arises due to two effects from quantum mechanics: spin and the Pauli exclusion principle.*[10]

34.3.1 Origin of magnetism

One of the fundamental properties of an electron (besides that it carries charge) is that it has a magnetic dipole moment, i.e., it behaves like a tiny magnet. This dipole moment comes from the more fundamental property of the electron that it has quantum mechanical spin. Due to its quantum nature, the spin of the electron can be in one of only two states; with the magnetic field either pointing "up" or "down" (for any choice of up and down). The spin of the electrons in atoms is the main source of ferromagnetism, although there is also a contribution from the orbital angular momentum of the electron about the nucleus. When these magnetic dipoles in a piece of matter are aligned, (point in the same direction) their individually tiny magnetic fields add together to create a much larger macroscopic field.

However, materials made of atoms with filled electron shells have a total dipole moment of zero, because the electrons all exist in pairs with opposite spin, every electron's magnetic moment is cancelled by the opposite moment of the second electron in the pair. Only atoms with partially filled shells (i.e., unpaired spins) can have a net magnetic moment, so ferromagnetism only occurs in materials with partially filled shells. Because of Hund's rules, the first few electrons in a shell tend to have the same spin, thereby increasing the total dipole moment.

These unpaired dipoles (often called simply "spins" even though they also generally include angular momentum) tend to align in parallel to an external magnetic field, an effect called paramagnetism. Ferromagnetism involves an additional phenomenon, however: in a few substances the dipoles tend to align spontaneously, giving rise to a spontaneous magnetization, even when there is no applied field.

34.3.2 Exchange interaction

Main article: Exchange interaction

When two nearby atoms have unpaired electrons, whether the electron spins are parallel or antiparallel affects whether the electrons can share the same orbit as a result of the quantum mechanical effect called the exchange interaction. This in turn affects the electron location and the Coulomb (electrostatic) interaction and thus the energy difference between these states.

The exchange interaction is related to the Pauli exclusion principle, which says that two electrons with the same spin cannot also have the same "position". Therefore, under certain conditions, when the orbitals of the unpaired outer valence electrons from adjacent atoms overlap, the distributions of their electric charge in space are farther apart when the electrons have parallel spins than when they have opposite spins. This reduces the electrostatic energy of the electrons when their spins are parallel compared to their energy when the spins are anti-parallel, so the parallel-spin state is more stable. In simple terms, the electrons, which repel one another, can move "further apart" by aligning their spins, so the spins of these electrons tend to line up. This difference in energy is called the exchange energy.

This energy difference can be orders of magnitude larger than the energy differences associated with the magnetic dipole-dipole interaction due to dipole orientation,*[11] which tends to align the dipoles antiparallel. In certain doped semiconductor oxides RKKY interactions have been shown to bring about periodic longer-range magnetic interactions, a phenomenon of significance in the study of spintronic materials.*[12]

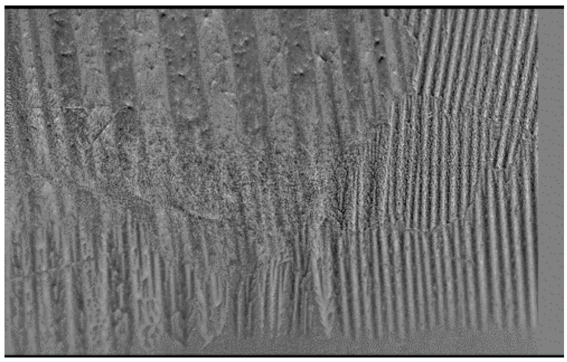
The materials in which the exchange interaction is much stronger than the competing dipole-dipole interaction are frequently called *magnetic materials*. For instance, in iron (Fe) the exchange force is about 1000 times stronger than the dipole interaction. Therefore, below the Curie temperature virtually all of the dipoles in a ferromagnetic material will be aligned. In addition to ferromagnetism, the exchange interaction is also responsible for the other types of spontaneous ordering of atomic magnetic moments occurring in magnetic solids, antiferromagnetism and ferrimagnetism. There are different exchange interaction mechanisms which create the magnetism in different ferromagnetic, ferrimagnetic, and antiferromagnetic substances. These mechanisms include direct exchange, RKKY exchange, double exchange, and superexchange.

34.3.3 Magnetic anisotropy

Main article: Magnetic anisotropy

Although the exchange interaction keeps spins aligned, it does not align them in a particular direction. Without magnetic anisotropy, the spins in a magnet randomly change direction in response to thermal fluctuations and the magnet is superparamagnetic. There are several kinds of magnetic anisotropy, the most common of which is magnetocrystalline anisotropy. This is a dependence of the energy on the direction of magnetization relative to the crystallographic lattice. Another common source of anisotropy, inverse magnetostriction, is induced by internal strains. Single-domain magnets also can have a *shape anisotropy* due to the magnetostatic effects of the particle shape. As the temperature of a magnet increases, the anisotropy tends to decrease, and there is often a blocking temperature at which a transition to superparamagnetism occurs.*[13]

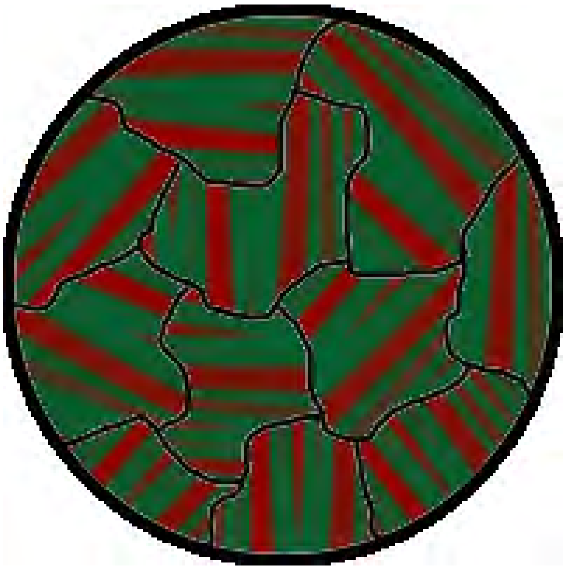
34.3.4 Magnetic domains



Electromagnetic dynamic magnetic domain motion of grain oriented electrical silicon steel

Main article: Magnetic domain

The above would seem to suggest that every piece of ferromagnetic material should have a strong magnetic field, since all the spins are aligned, yet iron and other ferromagnets are often found in an "unmagnetized" state. The reason for this is that a bulk piece of ferromagnetic material is divided into tiny regions called *magnetic domains**[14] (also known as *Weiss domains*). Within each domain, the spins are aligned, but (if the bulk material



Kerr micrograph of metal surface showing magnetic domains, with red and green stripes denoting opposite magnetization directions.

is in its lowest energy configuration, i.e. *unmagnetized*), the spins of separate domains point in different directions and their magnetic fields cancel out, so the object has no net large scale magnetic field.*[15]

Ferromagnetic materials spontaneously divide into magnetic domains because the *exchange interaction* is a short-range force, so over long distances of many atoms the tendency of the magnetic dipoles to reduce their energy by orienting in opposite directions wins out. If all the dipoles in a piece of ferromagnetic material are aligned parallel, it creates a large magnetic field extending into the space around it. This contains a lot of magnetostatic energy. The material can reduce this energy by splitting into many domains pointing in different directions, so the magnetic field is confined to small local fields in the material, reducing the volume of the field. The domains are separated by thin domain walls a number of molecules thick, in which the direction of magnetization of the dipoles rotates smoothly from one domain's direction to the other.

34.3.5 Magnetized materials

Thus, a piece of iron in its lowest energy state ("unmagnetized") generally has little or no net magnetic field. However, the magnetic domains in a material are not fixed in place; they are simply regions where the spins of the electrons have aligned spontaneously due to their magnetic fields, and thus can be altered by an external magnetic field. If a strong enough external magnetic field is applied to the material, the domain walls will move by the process of the spins of the electrons in atoms near the wall in one domain turning under the influence of the external field to face in the same direction as the electrons in the other domain, thus reorienting the domains so more of the dipoles

Moving domain walls in a grain of silicon steel caused by an increasing external magnetic field in the "downward" direction, observed in a Kerr microscope. White areas are domains with magnetization directed up, dark areas are domains with magnetization directed down.

are aligned with the external field. The domains will remain aligned when the external field is removed, creating a magnetic field of their own extending into the space around the material, thus creating a "permanent" magnet. The domains do not go back to their original minimum energy configuration when the field is removed because the domain walls tend to become 'pinned' or 'snagged' on defects in the crystal lattice, preserving their parallel orientation. This is shown by the Barkhausen effect: as the magnetizing field is changed, the magnetization changes in thousands of tiny discontinuous jumps as the domain walls suddenly "snap" past defects.

This magnetization as a function of the external field is described by a hysteresis curve. Although this state of aligned domains found in a piece of magnetized ferromagnetic material is not a minimal-energy configuration, it is metastable, and can persist for long periods, as shown by samples of magnetite from the sea floor which have maintained their magnetization for millions of years.

Heating and then cooling (annealing) a magnetized material, subjecting it to vibration by hammering it, or applying a rapidly oscillating magnetic field from a degaussing coil tends to release the domain walls from their pinned state, and the domain boundaries tend to move back to a lower energy configuration with less external magnetic field, thus *demagnetizing* the material.

Commercial magnets are made of "hard" ferromagnetic or ferrimagnetic materials with very large magnetic anisotropy such as alnico and ferrites, which have a very strong tendency for the magnetization to be pointed along one axis of the crystal, the "easy axis". During manufacture the materials are subjected to various metallurgical processes in a powerful magnetic field, which aligns the crystal grains so their "easy" axes of magnetization all point in the same direction. Thus the magnetization, and the resulting magnetic field, is "built in" to the crystal structure of the material, making it very difficult to demagnetize.

34.3.6 Curie temperature

Main article: Curie temperature

As the temperature increases, thermal motion, or entropy, competes with the ferromagnetic tendency for dipoles to align. When the temperature rises beyond a certain point, called the Curie temperature, there is a second-order phase transition and the system can no longer maintain a spontaneous magnetization, so its ability to be magnetized or attracted to a magnet disappears, although it still responds paramagnetically to an external field. Below that temperature, there is a spontaneous symmetry breaking and magnetic moments become aligned with their neighbors. The Curie temperature itself is a critical point, where the magnetic susceptibility is theoretically infinite and, although there is no net magnetization, domain-like spin correlations fluctuate at all length scales.

The study of ferromagnetic phase transitions, especially via the simplified Ising spin model, had an important impact on the development of statistical physics. There, it was first clearly shown that mean field theory approaches failed to predict the correct behavior at the critical point (which was found to fall under a *universality class* that includes many other systems, such as liquid-gas transitions), and had to be replaced by renormalization group theory.

34.4 See also

- Ferromagnetic material properties
- Diamagnetism
- Thermo-magnetic motor
- Orbital magnetization
- Stoner criterion

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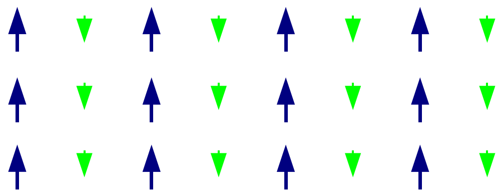
34.6 External links

- Electromagnetism – a chapter from an online textbook
- Sandeman, Karl (January 2008). "Ferromagnetic Materials". *DoITPoMS*. Dept. of Materials Sci. and Metallurgy, Univ. of Cambridge. Retrieved 2008-08-27. Detailed nonmathematical description of ferromagnetic materials with animated illustrations
- Magnetism: Models and Mechanisms in E. Pavarini, E. Koch, and U. Schollwöck: Emergent Phenomena in Correlated Matter, Jülich 2013, ISBN 978-3-89336-884-6

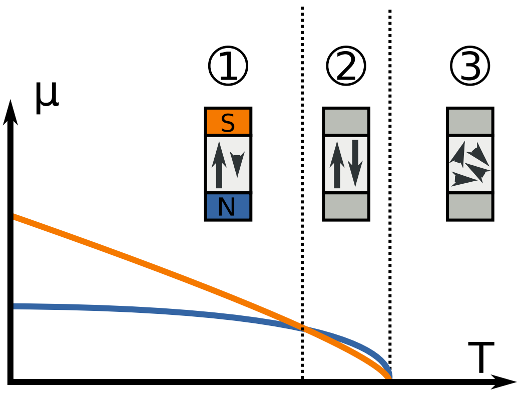
Chapter 35

Ferrimagnetism

Not to be confused with ferromagnetism; for an overview see magnetism



Ferrimagnetic ordering



⍰ Below the magnetization compensation point, ferrimagnetic material is magnetic. ⍰ At the compensation point, the magnetic components cancel each other and the total magnetic moment is zero. ⍰ Above the Curie point, the material loses magnetism.

In physics, a **ferrimagnetic** material is one that has populations of atoms with opposing magnetic moments, as in antiferromagnetism; however, in ferrimagnetic materials, the opposing moments are unequal and a spontaneous magnetization remains.*[1] This happens when the populations consist of different materials or ions (such as $Fe^{*}2+$ and $Fe^{*}3+$).

Ferrimagnetism is exhibited by ferrites and magnetic garnets. The oldest known magnetic substance, magnetite (iron(II,III) oxide; Fe_3O_4), is a ferrimagnet; it was originally classified as a ferromagnet before Néel's discovery of ferrimagnetism and antiferromagnetism in 1948.*[2]

Known ferrimagnetic materials include YIG (yttrium iron garnet), cubic ferrites composed of iron oxides and other elements such as aluminum, cobalt, nickel, manganese and zinc, hexagonal ferrites such as $PbFe_{12}O_{19}$ and $BaFe_{12}O_{19}$, and pyrrhotite, $Fe_{1-x}S$.*[3]

35.1 Effects of temperature

Ferrimagnetic materials are like ferromagnets in that they hold a spontaneous magnetization below the Curie temperature, and show no magnetic order (are paramagnetic) above this temperature. However, there is sometimes a temperature *below* the Curie temperature at which the two opposing moments are equal, resulting in a net magnetic moment of zero; this is called the *magnetization compensation point*. This compensation point is observed easily in garnets and rare earth-transition metal alloys (RE-TM). Furthermore, ferrimagnets may also have an *angular momentum compensation point* at which the net angular momentum vanishes. This compensation point is a crucial point for achieving high speed magnetization reversal in magnetic memory devices.*[4]

35.2 Properties

Ferrimagnetic materials have high resistivity and have anisotropic properties. The anisotropy is actually induced by an external applied field. When this applied field aligns with the magnetic dipoles it causes a net magnetic dipole moment and causes the magnetic dipoles to precess at a frequency controlled by the applied field, called *Larmor* or *precession frequency*. As a particular example, a microwave signal circularly polarized in the same direction as this precession strongly interacts with the magnetic dipole moments; when it is polarized in the opposite direction the interaction is very low. When the interaction is strong, the microwave signal can pass through the material. This directional property is used in the construction of microwave devices like isolators, circulators and gyrators. Ferrimagnetic materials are also used to produce optical isolators and circulators. Ferrimagnetic minerals in various rock types are used to study ancient geomagnetic properties of Earth and other planets. That field of study is known as paleomagnetism.

35.3 Molecular ferrimagnets

Ferrimagnetism can also occur in molecular magnets. A classic example is a dodecanuclear manganese molecule with an effective spin of S = 10 derived from antiferromagnetic interaction on Mn(IV) metal centres with Mn(III) and Mn(II) metal centres.*[5]

35.4 See also

- Orbital magnetization
- Anisotropy energy

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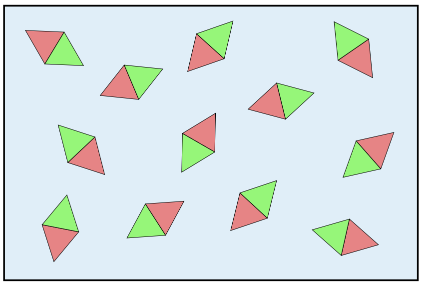
Chapter 36

Paramagnetism



Simple illustration of a paramagnetic probe made up from miniature magnets.

When liquid oxygen is poured from a beaker into a strong magnet, the oxygen is temporarily suspended between the magnet poles owing to its paramagnetism.

Paramagnetism is a form of magnetism whereby certain materials are attracted by an externally applied magnetic field, and form internal, induced magnetic fields in the direction of the applied magnetic field. In contrast with this behavior, diamagnetic materials are repelled by magnetic fields and form induced magnetic fields in the direction opposite to that of the applied magnetic field.*[1] Paramagnetic materials include most chemical elements and some compounds;*[2] they have a relative magnetic permeability greater than or equal to 1 (i.e., a non-negative magnetic susceptibility) and hence are attracted to magnetic fields. The magnetic moment induced by the applied field is linear in the field strength and rather weak. It typically requires a sensitive analytical balance to detect the effect and modern measurements on paramagnetic materials are often conducted with a SQUID magnetometer.

Paramagnetic materials have a small, positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Paramagnetic properties are due to the presence of some unpaired electrons, and from the realignment of the electron paths caused by the external magnetic field. Paramagnetic materials include magnesium, molybdenum, lithium, and tantalum.

Unlike ferromagnets, paramagnets do not retain any magnetization in the absence of an externally applied magnetic field because thermal motion randomizes the spin orientations. (Some paramagnetic materials retain spin disorder even at absolute zero, meaning they are paramagnetic in the ground state, i.e. in the absence of thermal motion.) Thus the total magnetization drops to zero when the applied field is removed. Even in the presence of the field there is only a small induced magnetization because only a small fraction of the spins will be oriented by the field. This fraction is proportional to the field strength and this explains the linear dependency. The attraction experienced by ferromagnetic materials is non-linear and much stronger, so that it is easily observed, for instance, in the attraction between a refrigerator magnet and the iron of the refrigerator itself.

36.1 Relation to electron spins

Constituent atoms or molecules of paramagnetic materials have permanent magnetic moments (dipoles), even in the absence of an applied field. The permanent moment generally is due to the spin of unpaired electrons in atomic or molecular electron orbitals (see Magnetic moment). In pure paramagnetism, the dipoles do not interact with one another and are randomly oriented in the absence of an external field due to thermal agitation, resulting in zero net magnetic moment. When a magnetic field is applied, the dipoles will tend to align with the applied field, resulting in a net magnetic moment in the direction of the applied field. In the classical description, this alignment can be understood to occur due to a torque being provided on the magnetic moments by an applied field, which tries to align the dipoles parallel to the applied field. However, the true origins of the alignment can only be understood via the quantum-mechanical properties of spin and angular momentum.

If there is sufficient energy exchange between neighbouring dipoles they will interact, and may spontaneously align or anti-align and form magnetic domains, resulting in ferromagnetism (permanent magnets) or antiferromagnetism, respectively. Paramagnetic behavior can also be observed in ferromagnetic materials that are above their Curie temperature, and in antiferromagnets above their Néel temperature. At these temperatures, the available thermal energy simply overcomes the interaction energy between the spins.

In general, paramagnetic effects are quite small: the magnetic susceptibility is of the order of $10^{*}-3$ to $10^{*}-5$ for most paramagnets, but may be as high as $10^{*}-1$ for synthetic paramagnets such as ferrofluids.

36.1.1 Delocalization

In conductive materials the electrons are delocalized, that is, they travel through the solid more or less as free electrons. Conductivity can be understood in a band structure picture as arising from the incomplete filling of energy bands. In an ordinary nonmagnetic conductor the conduction band is identical for both spin-up and spin-down electrons. When a magnetic field is applied, the conduction band splits apart into a spin-up and a spin-down band due to the difference in magnetic potential energy for spin-up and spin-down electrons. Since the Fermi level must be identical for both bands, this means that there will be a small surplus of the type of spin in the band that moved downwards. This effect is a weak form of paramagnetism known as *Pauli paramagnetism*.

The effect always competes with a diamagnetic response of opposite sign due to all the core electrons of the atoms. Stronger forms of magnetism usually require localized rather than itinerant electrons. However, in some cases a band structure can result in which there are two delocalized sub-bands with states of opposite spins that have different energies. If one subband is preferentially filled over the other, one can have itinerant ferromagnetic order. This situation usually only occurs in relatively narrow (d-)bands, which are poorly delocalized.

s and p electrons

Generally, strong delocalization in a solid due to large overlap with neighboring wave functions means that there will be a large Fermi velocity; this means that the number of electrons in a band is less sensitive to shifts in that band's energy, implying a weak magnetism. This is why s- and p-type metals are typically either Pauli-paramagnetic or as in the case of gold even diamagnetic. In the latter case the diamagnetic contribution from the closed shell inner electrons simply wins from the weak paramagnetic term of the almost free electrons.

d and f electrons

Stronger magnetic effects are typically only observed when d or f electrons are involved. Particularly the latter are usually strongly localized. Moreover, the size of the magnetic moment on a lanthanide atom can be quite large as it can carry up to 7 unpaired electrons in the case of gadolinium(III) (hence its use in MRI). The high magnetic moments associated with lanthanides is one reason why superstrong magnets are typically based on elements like neodymium or samarium.

Molecular localization

Of course the above picture is a *generalization* as it pertains to materials with an extended lattice rather than a molecular structure. Molecular structure can also lead to localization of electrons. Although there are usually energetic reasons why a molecular structure results such that it does not exhibit partly filled orbitals (i.e. unpaired spins), some non-closed shell moieties do occur in nature. Molecular oxygen is a good example. Even in the frozen solid it contains di-radical molecules resulting in paramagnetic behavior. The unpaired spins reside in orbitals derived from oxygen p wave functions, but the overlap is limited to the one neighbor in the O_2 molecules. The distances to other oxygen atoms in the lattice remain too large to lead to delocalization and the magnetic moments remain unpaired.

36.2 Curie's law

Main article: Curie's law

For low levels of magnetization, the magnetization of paramagnets follows what is known as Curie's law, at least approximately. This law indicates that the susceptibility, χ , of paramagnetic materials is inversely proportional to their temperature, i.e. that materials become more magnetic at lower temperatures. The mathematical expression is:

$$\boldsymbol{M} = \chi \boldsymbol{H} = \frac{C}{T}\boldsymbol{H}$$

where:

M is the resulting magnetization

χ is the magnetic susceptibility

H is the auxiliary magnetic field, measured in amperes/meter

T is absolute temperature, measured in kelvins

C is a material-specific Curie constant

Curie's law is valid under the commonly encountered conditions of low magnetization ($\mu_B H \lesssim k_B T$), but does not apply in the high-field/low-temperature regime where saturation of magnetization occurs ($\mu_B H \gtrsim k_B T$) and magnetic dipoles are all aligned with the applied field. When the dipoles are aligned, increasing the external field will not increase the total magnetization since there can be no further alignment.

For a paramagnetic ion with noninteracting magnetic moments with angular momentum J, the Curie constant is related the individual ions' magnetic moments,

$$C = \frac{N_A}{3k_B}\mu_{\text{eff}}^2 \text{ where } \mu_{\text{eff}} = g_J \mu_B \sqrt{J(J+1)}$$

The parameter μ_{eff} is interpreted as the effective magnetic moment per paramagnetic ion. If one uses a classical treatment with molecular magnetic moments represented as discrete magnetic dipoles, μ, a Curie Law expression of the same form will emerge with μ appearing in place of μ_{eff}.

When orbital angular momentum contributions to the magnetic moment are small, as occurs for most organic radicals or for octahedral transition metal complexes with d^3 or high-spin d^5 configurations, the effective magnetic moment takes the form ($g_e = 2.0023... \approx 2$),

$\mu_{\text{eff}} \simeq 2\sqrt{S(S+1)}\mu_B = \sqrt{n(n+2)}\mu_B$, where *n* is the number of unpaired electrons. In other transition metal complexes this yields a useful, if somewhat cruder, estimate.

36.3 Examples of paramagnets

Materials that are called “paramagnets” are most often those that exhibit, at least over an appreciable temperature range, magnetic susceptibilities that adhere to the Curie or Curie–Weiss laws. In principle any system that contains atoms, ions, or molecules with unpaired spins can be called a paramagnet, but the interactions between them need to be carefully considered.

36.3.1 Systems with minimal interactions

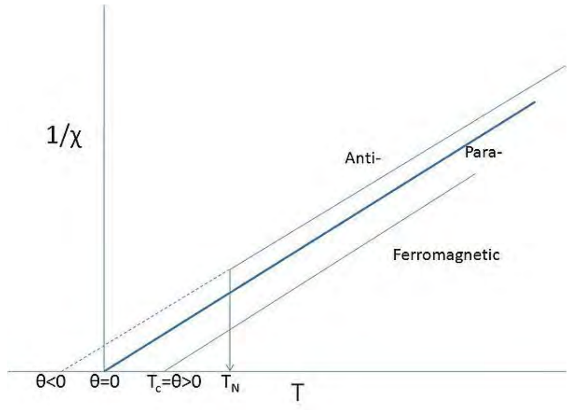
The narrowest definition would be: a system with unpaired spins that *do not interact* with each other. In this narrowest sense, the only pure paramagnet is a dilute gas of monatomic hydrogen atoms. Each atom has one non-interacting unpaired electron. Of course, the latter could be said about a gas of lithium atoms but these already possess two paired core electrons that produce a diamagnetic response of opposite sign. Strictly speaking Li is a mixed system therefore, although admittedly the diamagnetic component is weak and often neglected. In the case of heavier elements the diamagnetic contribution becomes more important and in the case of metallic gold it dominates the properties. Of course, the element hydrogen is virtually never called 'paramagnetic' because the monatomic gas is stable only at extremely high temperature; H atoms combine to form molecular H_2 and in so doing, the magnetic moments are lost (*quenched*), because of the spins pair. Hydrogen is therefore *diamagnetic* and the same holds true for many other elements. Although the electronic configuration of the individual atoms (and ions) of most elements contain unpaired spins, they are not necessarily paramagnetic, because at ambient temperature quenching is very much the rule rather than the exception. The quenching tendency is weakest for f-electrons because *f* (especially 4*f*) orbitals are radially contracted and they overlap only weakly with orbitals on adjacent atoms. Consequently, the lanthanide elements with incompletely filled 4f-orbitals are paramagnetic or magnetically ordered.*[4]

Thus, condensed phase paramagnets are only possible if the interactions of the spins that lead either to quenching or to ordering are kept at bay by structural isolation of the magnetic centers. There are two classes of materials for which this holds:

- Molecular materials with a (isolated) paramagnetic center.
  - Good examples are coordination complexes of d- or f-metals or proteins with such centers, e.g. myoglobin. In such materials the organic part of the molecule acts as an envelope shielding the spins from their neighbors.
  - Small molecules can be stable in radical form, oxygen O_2 is a good example. Such systems are quite rare because they tend to be rather reactive.
- Dilute systems.
  - Dissolving a paramagnetic species in a diamagnetic lattice at small concentrations, e.g. Nd*3+ in $CaCl_2$ will separate the neodymium ions at large enough distances that they do not interact. Such systems are of prime importance for what can be considered the most sen-

sitive method to study paramagnetic systems: EPR.

36.3.2 Systems with interactions



Idealized Curie–Weiss behavior; N.B. $T_C=\theta$, but T_N is not θ. Paramagnetic regimes are denoted by solid lines. Close to T_N or T_C the behavior usually deviates from ideal.

As stated above, many materials that contain d- or f-elements do retain unquenched spins. Salts of such elements often show paramagnetic behavior but at low enough temperatures the magnetic moments may order. It is not uncommon to call such materials 'paramagnets', when referring to their paramagnetic behavior above their Curie or Néel-points, particularly if such temperatures are very low or have never been properly measured. Even for iron it is not uncommon to say that *iron becomes a paramagnet* above its relatively high Curie-point. In that case the Curie-point is seen as a phase transition between a ferromagnet and a 'paramagnet'. The word paramagnet now merely refers to the linear response of the system to an applied field, the temperature dependence of which requires an amended version of Curie's law, known as the Curie–Weiss law:

$$\boldsymbol{M} = \frac{C}{T-\theta}\boldsymbol{H}$$

This amended law includes a term θ that describes the exchange interaction that is present albeit overcome by thermal motion. The sign of θ depends on whether ferro- or antiferromagnetic interactions dominate and it is seldom exactly zero, except in the dilute, isolated cases mentioned above.

Obviously, the paramagnetic Curie–Weiss description above T_N or T_C is a rather different interpretation of the word "paramagnet" as it does *not* imply the *absence* of interactions, but rather that the magnetic structure is random in the absence of an external field at these sufficiently high temperatures. Even if θ is close to zero this does not mean that there are no interactions, just that the aligning ferro- and the anti-aligning antiferromagnetic ones cancel. An additional complication is that the interactions are often different in different directions of the crystalline lattice (anisotropy), leading to complicated magnetic structures once ordered.

Randomness of the structure also applies to the many metals that show a net paramagnetic response over a broad temperature range. They do not follow a Curie type law as function of temperature however, often they are more or less temperature independent. This type of behavior is of an itinerant nature and better called Pauli-paramagnetism, but it is not unusual to see, for example, the metal aluminium called a "paramagnet", even though interactions are strong enough to give this element very good electrical conductivity.

36.3.3 Superparamagnets

Some materials show induced magnetic behavior that follows a Curie type law but with exceptionally large values for the Curie constants. These materials are known as superparamagnets. They are characterized by a strong ferromagnetic or ferrimagnetic type of coupling into domains of a limited size that behave independently from one another. The bulk properties of such a system resembles that of a paramagnet, but on a microscopic level they are ordered. The materials do show an ordering temperature above which the behavior reverts to ordinary paramagnetism (with interaction). Ferrofluids are a good example, but the phenomenon can also occur inside solids, e.g., when dilute paramagnetic centers are introduced in a strong itinerant medium of ferromagnetic coupling such as when Fe is substituted in $TlCu_2Se_2$ or the alloy AuFe. Such systems contain ferromagnetically coupled clusters that freeze out at lower temperatures. They are also called mictomagnets.

36.4 See also

- Bohr magneton
- Curie temperature
- Diamagnetism
- Ferromagnetism
- Magnetochemistry

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36.6 Further reading

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36.7 External links

- http://www.ndt-ed.org/EducationResources/CommunityCollege/MagParticle/Physics/MagneticMatls.htm
- Magnetism: Models and Mechanisms in E. Pavarini, E. Koch, and U. Schollwöck: Emergent Phenomena in Correlated Matter, Jülich 2013, ISBN 978-3-89336-884-6

Chapter 37

Curie temperature

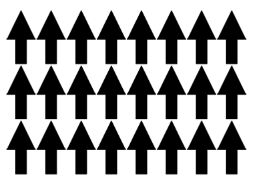


Figure 1. Below the Curie temperature, neighbouring magnetic spins align parallel to each other in ferromagnet in the absence of an applied magnetic field

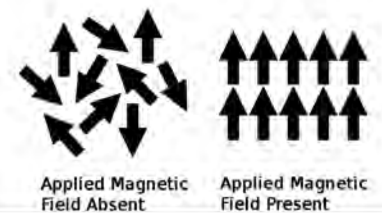


Figure 2. Above the Curie temperature, the magnetic spins are randomly aligned in a paramagnet unless a magnetic field is applied

In physics and materials science, the **Curie temperature** (T_C), or **Curie point**, is the temperature at which certain materials lose their permanent magnetic properties, to be replaced by induced magnetism. The Curie temperature is named after Pierre Curie, who showed that magnetism was lost at a critical temperature.*[1]

The force of magnetism is determined by the magnetic moment, a dipole moment within an atom which originates from the angular momentum and spin of electrons. Materials have different structures of intrinsic magnetic moments that depend on temperature; the Curie temperature is the critical point at which a material's intrinsic magnetic moments change direction.

Permanent magnetism is caused by the alignment of magnetic moments and induced magnetism is created when disordered magnetic moments are forced to align in an applied magnetic field. For example, the ordered magnetic moments (ferromagnetic, Figure 1) change and become disordered (paramagnetic, Figure 2) at the Curie temperature. Higher temperatures make magnets weaker, as spontaneous magnetism only occurs below the Curie temperature. Magnetic susceptibility above the Curie Temperature can be calculated from the Curie–Weiss law, which is derived from Curie's law.

In analogy to ferromagnetic and paramagnetic materials, the Curie temperature can also be used to describe the phase transition between ferroelectricity and paraelectricity. In this context, the order parameter is the *electric* polarisation that goes from a finite value to zero when the temperature is increased above the Curie temperature.

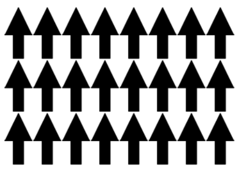
37.1 Magnetic moments

Magnetic moments are permanent dipole moments within the atom which are made up from electron's angular momentum and spin,*[5] by the relation $\mu_l = el/2m_e$ (m_e here is mass of electron),(μ_l = magnetic moment) and (l is angular momentum) this ratio is called as **gyromagnetic ratio**.

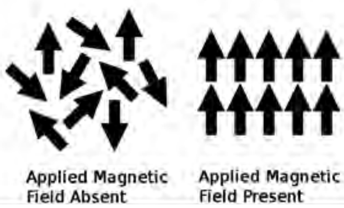
Electrons inside atoms contribute magnetic moments from their own angular momentum and from their orbital momentum around the nucleus. Magnetic moments from the nucleus are insignificant in contrast to magnetic moments from electrons.*[6] Thermal contribution will result in higher energy electrons causing disruption to their order and alignment between dipoles to be destroyed.

Ferromagnetic, paramagnetic, ferrimagnetic and antiferromagnetic materials have different structures of intrinsic magnetic moments. It is at a material's specific Curie temperature where they change properties. The transition from antiferromagnetic to paramagnetic (or vice versa) occurs at the Néel temperature which is analogous to Curie temperature.

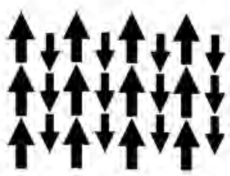
- Orientations of magnetic moments in materials



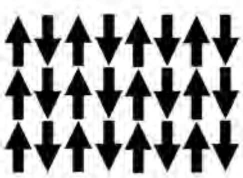
- **Ferromagnetism**: The magnetic moments in a ferromagnetic material. The moments are ordered and of the same magnitude in the absence of an applied magnetic field.



- **Paramagnetism**: The magnetic moments in a paramagnetic material. The moments are disordered in the absence of an applied magnetic field and ordered in the presence of an applied magnetic field.



- **Ferrimagnetism**: The magnetic moments in a ferrimagnetic material. The moments are aligned oppositely and have different magnitudes due to being made up of two different ions. This is in the absence of an applied magnetic field.



- **Antiferromagnetism**: The magnetic moments in an antiferromagnetic material. The moments are aligned oppositely and have the same magnitudes. This is in the absence of an applied magnetic field.

37.2 Materials with magnetic moments that change properties at the Curie temperature

Ferromagnetic, paramagnetic, ferrimagnetic and antiferromagnetic structures are made up of intrinsic magnetic moments. If all electrons within the structure are paired, these moments cancel out due to having opposite spins and angular momentum. Thus even with an applied magnetic field will have different properties and no Curie temperature.*[7]*[8]

37.2.1 Paramagnetic

Main article: Paramagnetism

A material is paramagnetic only above its Curie temperature. Paramagnetic materials are non-magnetic when a magnetic field is absent and magnetic when a magnetic field is applied. When the magnetic field is absent the material has disordered magnetic moments; that is, the atoms are asymmetrical and not aligned. When the magnetic field is present the magnetic moments are temporarily realigned parallel to the applied field;*[9]*[10] the atoms are symmetrical and aligned.*[11] The magnetic moment in the same direction is what causes an induced magnetic field.*[11]*[12]

For paramagnetism this response to an applied magnetic field is positive and known as magnetic susceptibility.*[7] The magnetic susceptibility only applies above the Curie temperature for disordered states.*[13]

Sources of paramagnetism (materials which have Curie temperatures) include:*[14]

- All atoms which have unpaired electrons;
- Atoms where inner shells are incomplete in electrons;
- Free radicals;
- Metals.

Above the Curie temperature the atoms are excited, the spin orientation becomes randomised,*[8] but can be realigned in an applied field, i.e. the material becomes paramagnetic. Below the Curie temperature the intrinsic structure has undergone a phase transition,*[15] the atoms are ordered and the material is ferromagnetic.*[11] The paramagnetic materials' induced magnetic fields are very weak in comparison to ferromagnetic materials' magnetic fields.*[15]

37.2.2 Ferromagnetic

Main article: Ferromagnetism

Materials are only ferromagnetic below their corresponding Curie temperatures. Ferromagnetic materials are magnetic in the absence of an applied magnetic field.

When a magnetic field is absent the material has spontaneous magnetization which is a result of the ordered magnetic moments; that is, for ferromagnetism, the atoms are symmetrical and aligned in the same direction creating a permanent magnetic field.

The magnetic interactions are held together by exchange interactions; otherwise thermal disorder would overcome the weak interactions of magnetic moments. The exchange interaction has a zero probability of parallel electrons occupying the same point in time, implying a preferred parallel alignment in the material.*[16] The Boltzmann factor contributes heavily as it prefers interacting particles to be aligned in the same direction.*[17] This causes ferromagnets to have strong magnetic fields and high Curie temperatures of around 1000 K.*[18]

Below the Curie temperature, the atoms are aligned and parallel, causing spontaneous magnetism; the material is ferromagnetic. Above the Curie temperature the material is paramagnetic, as the atoms lose their ordered magnetic moments when the material undergoes a phase transition.*[15]

37.2.3 Ferrimagnetic

Main article: Ferrimagnetism

Materials are only ferrimagnetic below their corresponding Curie temperature. Ferrimagnetic materials are magnetic in the absence of an applied magnetic field and are made up of two different ions.*[19]

When a magnetic field is absent the material has a spontaneous magnetism which is the result of ordered magnetic moments; that is, for ferrimagnetism one ion's magnetic moments are aligned facing in one direction with certain magnitude and the other ion's magnetic moments are aligned facing in the opposite direction with a different magnitude. As the magnetic moments are of different magnitudes in opposite directions there is still a spontaneous magnetism and a magnetic field is present.*[19]

Similar to ferromagnetic materials the magnetic interactions are held together by exchange interactions. The orientations of moments however are anti-parallel which results in a net momentum by subtracting their momentum from one another.*[19]

Below the Curie temperature the atoms of each ion are aligned anti-parallel with different momentums causing a spontaneous magnetism; the material is ferrimagnetic. Above the Curie temperature the material is paramagnetic as the atoms lose their ordered magnetic moments as the material undergoes a phase transition.*[19]

37.2.4 Antiferromagnetic and the Néel temperature

Main article: Antiferromagnetism

Materials are only antiferromagetic below their corresponding Néel temperature. This is similar to the Curie temperature as above the Néel Temperature the material undergoes a phase transition and becomes paramagnetic.

The material has equal magnetic moments aligned in opposite directions resulting in a zero magnetic moment and a net magnetism of zero at all temperatures below the Néel temperature. Antiferromagnetic materials are weakly magnetic in the absence or presence of an applied magnetic field.

Similar to ferromagnetic materials the magnetic interactions are held together by exchange interactions preventing thermal disorder from overcoming the weak interactions of magnetic moments.*[16]*[20] When disorder occurs it is at the Néel temperature.*[20]

37.3 Curie–Weiss law

The Curie–Weiss law is an adapted version of Curie's law.

The Curie–Weiss law is a simple model derived from a mean-field approximation, this means it works well for the materials temperature, T, much greater than their corresponding Curie temperature, T_C, i.e. $T \gg T_C$; however fails to describe the magnetic susceptibility, χ, in the immediate vicinity of the Curie point because of local fluctuations between atoms.*[21]

Neither Curie's law nor the Curie–Weiss law holds for $T < T_C$.

Curie's law for a paramagnetic material:*[22]

$$\chi = \frac{M}{H} = \frac{M\mu_0}{B} = \frac{C}{T}$$

$$C = \frac{\mu_0 \mu_B^2}{3k_B} N g^2 J(J+1)$$ *[23]

The Curie–Weiss law is then derived from Curie's law to be:

$$\chi = \frac{C}{T - T_C}$$

where:

$$T_C = \frac{C\lambda}{\mu_0}$$

λ is the Weiss molecular field constant.*[23]*[25]

For full derivation see Curie–Weiss law.

37.4 Physics

37.4.1 Approaching Curie temperature from above

As the Curie–Weiss law is an approximation, a more accurate model is needed when the temperature, T, approaches the material's Curie temperature, T_C.

Magnetic susceptibility occurs above the Curie temperature.

An accurate model of critical behaviour for magnetic susceptibility with critical exponent γ:

$$\chi \sim \frac{1}{(T - T_C)^\gamma}$$

The critical exponent differs between materials and for the mean-field model is taken as γ = 1.*[26]

As temperature is inversely proportional to magnetic susceptibility, when T approaches T_C the denominator tends to zero and the magnetic susceptibility approaches infinity allowing magnetism to occur. This is a spontaneous magnetism which is a property of ferromagnetic and ferrimagnetic materials.*[27]*[28]

37.4.2 Approaching Curie temperature from below

Magnetism depends on temperature and spontaneous magnetism occurs below the Curie temperature. An accurate model of critical behaviour for spontaneous magnetism with critical exponent β:

$$M \sim (T - T_C)^\beta$$

The critical exponent differs between materials and for the mean-field model as taken as β = 1/2 where $T \ll T_C$.*[26]

The spontaneous magnetism approaches zero as the temperature increases towards the materials Curie temperature.

37.4.3 Approaching absolute zero (0 kelvins)

The spontaneous magnetism, occurring in ferromagnetic, ferrimagnetic and antiferromagnetic materials, approaches zero as the temperature increases towards the material's Curie temperature. Spontaneous magnetism is at its maximum as the temperature approaches 0 K.*[29] That is, the magnetic moments are completely aligned and at their strongest magnitude of magnetism due to no thermal disturbance.

In paramagnetic materials temperature is sufficient to overcome the ordered alignments. As the temperature approaches 0 K, the entropy decreases to zero, that is, the disorder decreases and becomes ordered. This occurs without the presence of an applied magnetic field and obeys the third law of thermodynamics.*[16]

Both Curie's law and the Curie–Weiss law fail as the temperature approaches 0 K. This is because they depend on the magnetic susceptibility which only applies when the state is disordered.*[30]

Gadolinium sulphate continues to satisfy Curie's law at 1 K. Between 0 and 1 K the law fails to hold and a sudden change in the intrinsic structure occurs at the Curie temperature.*[31]

37.4.4 Ising model of phase transitions

The Ising model is mathematically based and can analyse the critical points of phase transitions in ferromagnetic order due to spins of electrons having magnitudes of ±1/2. The spins interact with their neighbouring dipole electrons in the structure and here the Ising model can predict their behaviour with each other.*[32]*[33]

This model is important for solving and understanding the concepts of phase transitions and hence solving the Curie temperature. As a result, many different dependencies that affect the Curie temperature can be analysed.

For example, the surface and bulk properties depend on the alignment and magnitude of spins and the Ising model can determine the effects of magnetism in this system.

37.4.5 Weiss domains and surface and bulk Curie temperatures

Materials structures consist of intrinsic magnetic moments which are separated into domains called Weiss domains.*[34] This can result in ferromagnetic materials having no spontaneous magnetism as domains could potentially balance each other out.*[34] The position of particles can therefore have different orientations around the surface than the main part (bulk) of the material. This property directly affects the Curie temperature as there can be a bulk Curie temperature T_B and a different sur-

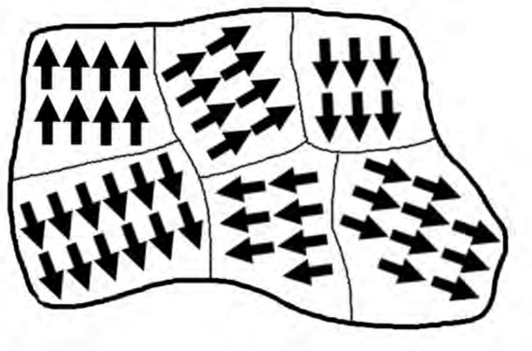


Figure 3. The Weiss domains in a ferromagnetic material; the magnetic moments are aligned in domains.

face Curie temperature T_S for a material.*[35]

This allows for the surface Curie temperature to be ferromagnetic above the bulk Curie temperature when the main state is disordered, i.e. Ordered and disordered states occur simultaneously.*[32]

The surface and bulk properties can be predicted by the Ising model and electron capture spectroscopy can be used to detect the electron spins and hence the magnetic moments on the surface of the material. An average total magnetism is taken from the bulk and surface temperatures to calculate the Curie temperature from the material, noting the bulk contributes more.*[32]*[36]

The angular momentum of an electron is either +ħ/2 or −ħ/2 due to it having a spin of 1/2, which gives a specific size of magnetic moment to the electron; the Bohr magneton.*[37] Electrons orbiting around the nucleus in a current loop create a magnetic field which depends on the Bohr Magneton and magnetic quantum number.*[37] Therefore, the magnetic moments are related between angular and orbital momentum and affect each other. Angular momentum contributes twice as much to magnetic moments than orbital.*[38]

For terbium which is a rare earth metal and has a high orbital angular momentum the magnetic moment is strong enough to affect the order above its bulk temperatures. It is said to have a high anisotropy on the surface, that is it is highly directed in one orientation. It remains ferromagnetic on its surface above its Curie temperature while its bulk becomes ferrimagnetic and then at higher temperatures its surface remains ferrimagnetic above its bulk Néel Temperature before becoming completely disordered and paramagnetic with increasing temperature. The anisotropy in the bulk is different from its surface anisotropy just above these phase changes as the magnetic moments will be ordered differently or ordered in paramagnetic materials.*[35]

37.4.6 Changing a material's Curie temperature

Composite materials

Composite materials, that is, materials composed from other materials with different properties, can change the Curie temperature. For example, a composite which has silver in it can create spaces for oxygen molecules in bonding which decreases the Curie temperature*[39] as the crystal lattice will not be as compact.

The alignment of magnetic moments in the composite material affects the Curie temperature. If the materials moments are parallel with each other the Curie temperature will increase and if perpendicular the Curie temperature will decrease*[39] as either more or less thermal energy will be needed to destroy the alignments.

Preparing composite materials through different temperatures can result in different final compositions which will have different Curie temperatures.*[40] Doping a material can also affect its Curie temperature.*[40]

The density of nanocomposite materials changes the Curie temperature. Nanocomposites are compact structures on a nano-scale. The structure is built up of high and low bulk Curie temperatures, however will only have one mean-field Curie temperature. A higher density of lower bulk temperatures results in a lower mean-field Curie temperature and a higher density of higher bulk temperature significantly increases the mean-field Curie temperature. In more than one dimension the Curie temperature begins to increase as the magnetic moments will need more thermal energy to overcome the ordered structure.*[36]

Particle size

The size of particles in a material's crystal lattice changes the Curie temperature. Due to the small size of particles (nanoparticles) the fluctuations of electron spins become more prominent, this results in the Curie temperature drastically decreasing when the size of particles decrease as the fluctuations cause disorder. The size of a particle also affects the anisotropy causing alignment to become less stable and thus lead to disorder in magnetic moments.*[32]*[41]

The extreme of this is superparamagnetism which only occurs in small ferromagnetic particles and is where fluctuations are very influential causing magnetic moments to change direction randomly and thus create disorder.

The Curie temperature of nanoparticles are also affected by the crystal lattice structure, body-centred cubic (bcc), face-centred cubic (fcc) and a hexagonal structure (hcp) all have different Curie temperatures due to magnetic moments reacting to their neighbouring electron spins. fcc and hcp have tighter structures and as a results have higher Curie temperatures than bcc as the magnetic moments have stronger effects when closer together.*[32] This is known as the coordination number which is the number of nearest neighbouring particles in a structure. This indicates a lower coordination number at the surface of a material than the bulk which leads to the surface becoming less significant when the temperature is approaching the Curie temperature. In smaller systems the coordination number for the surface is more significant and the magnetic moments have a stronger affect on the system.*[32]

Although fluctuations in particles can be minuscule, they are heavily dependent on the structure of crystal lattices as they react with their nearest neighbouring particles. Fluctuations are also affected by the exchange interaction*[41] as parallel facing magnetic moments are favoured and therefore have less disturbance and disorder, therefore a tighter structure influences a stronger magnetism and therefore a higher Curie temperature.

Pressure

Pressure changes a material's Curie temperature. Increasing pressure on the crystal lattice decreases the volume of the system. Pressure directly affects the kinetic energy in particles as movement increases causing the vibrations to disrupt the order of magnetic moments. This is similar to temperature as it also increases the kinetic energy of particles and destroys the order of magnetic moments and magnetism.*[42]

Pressure also affects the density of states (DOS).*[42] Here the DOS decreases causing the number of electrons available to the system to decrease. This leads to the number of magnetic moments decreasing as they depend on electron spins. It would be expected because of this that the Curie temperature would decrease however it increases. This is the result of the exchange interaction. The exchange interaction favours the aligned parallel magnetic moments due to electrons being unable to occupy the same space in time*[16] and as this is increased due to the volume decreasing the Curie temperature increases with pressure. The Curie temperature is made up of a combination of dependencies on kinetic energy and the DOS.*[42]

It is interesting to note that the concentration of particles also affects the Curie temperature when pressure is being applied and can result in a decrease in Curie temperature when the concentration is above a certain percent.*[42]

Orbital ordering

Orbital ordering changes the Curie temperature of a material. Orbital ordering can be controlled through applied strains.*[43] This is a function that determines the wave of a single electron or paired electrons inside the material. Having control over the probability of where the electron will be allows the Curie temperature to be altered. For example, the delocalised electrons can be moved onto the same plane by applied strains within the crystal lattice.*[43]

The Curie temperature is seen to increase greatly due to electrons being packed together in the same plane, they are forced to align due to the exchange interaction and thus increases the strength of the magnetic moments which prevents thermal disorder at lower temperatures.

37.5 Curie temperature in ferroelectric and piezoelectric materials

In analogy to ferromagnetic and paramagnetic materials, the Curie temperature can also be used to describe the temperature where a material's spontaneous electric polarisation changes to induced electric polarisation, or vice versa.*[44]

Electric polarisation is a result of aligned electric dipoles. Aligned electric dipoles are composites of positive and negative charges where all the dipoles are facing in one direction. The charges are separated from their stable placement in the particles and can occur spontaneously, from pressure or an applied electric field.*[45]

Ferroelectric, dielectric (paraelectric) and piezoelectric materials have electric polarisation. In ferroelectric materials there is a spontaneous electric polarisation in the absence of an applied electric field.*[44] In dielectric materials there is electric polarisation aligned only when an electric field is applied.*[45] Piezoelectric materials have electric polarisation due to applied mechanical stress distorting the structure from pressure.*[46]

T_0 is the temperature where ferroelectric materials lose their spontaneous polarisation as a first or second order phase change occurs, that is the internal structure changes or the internal symmetry changes.*[44] In certain cases T_0 is equal to the Curie temperature however the Curie temperature can be 10 kelvins lower than T_0.*[47]

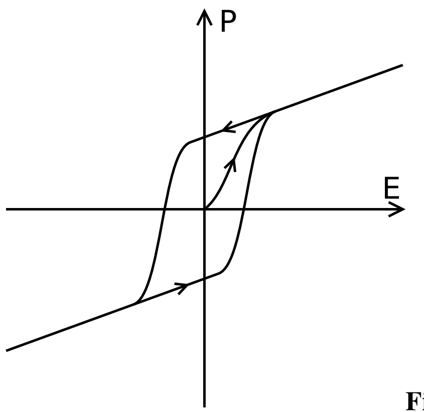


Figure 4. (Below T_0) Ferroelectric polarisation **P** in an applied electric field **E**

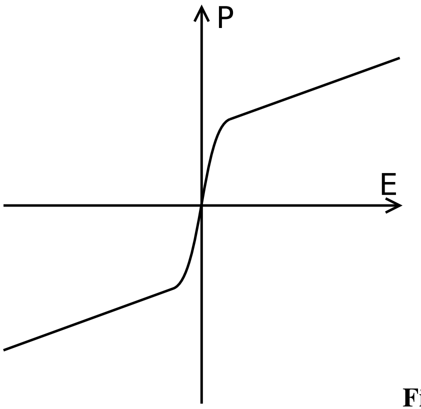


Figure 5. (Above T_0) Dielectric polarisation **P** in an applied electric field **E**

All ferroelectric materials are pyroelectric*[49] and piezoelectric,*[50] but not the converse.

37.5.1 Piezoelectric

An external force applies pressure on particles inside the material which affects the structure of the crystal lattice. Particles in a unit cell become unsymmetrical which allows a net polarisation from each particle. Symmetry would cancel the opposing charges out and there would be no net polarisation.*[51] Below the transition temperature T_0 displacement of electric charges causes polarisation. Above the transition temperature T_0 the structure is cubic and symmetric, causing the material to become dielectric. Electric charges are also agitated and disordered causing the material to have no electric polarisation in the absence of an applied electric field.

37.5.2 Ferroelectric and dielectric

Materials are only ferroelectric below their corresponding transition temperature T_0.*[44] Ferroelectric materials are all piezoelectric and therefore have a spontaneous electric polarisation as the structures are unsymmetrical.

Materials are only dielectric above their corresponding transition temperature T_0.*[52] Dielectric materials have no electric polarisation in the absence of an applied electric field. The electric dipoles are unaligned and have no net polarisation. In analogy to magnetic susceptibility, electric susceptibility only occurs above T_0.

Ferroelectric materials when polarised are influenced under hysteresis (Figure 4); that is they are dependent on their past state as well as their current state. As an electric field is applied the dipoles are forced to align and polarisation is created, when the electric field is removed polarisation remains. The hysteresis loop depends on temperature and as a result as the temperature is increased and reaches T_0 the two curves become one curve as shown in the dielectric polarisation (Figure 5).*[53]

37.5.3 Relative permittivity

A modified version of the Curie–Weiss law applies to the dielectric constant, also known as the relative permittivity:*[47]*[54]

$$\epsilon = \epsilon_0 + \frac{C}{T - T_{\mathrm{C}}}.$$

37.6 Applications

A heat-induced ferromagnetic-paramagnetic transition is used in magneto-optical storage media, for erasing and writing of new data. Famous examples include the Sony Minidisc format, as well as the now-obsolete CD-MO format. Other uses include temperature control in soldering irons,*[55] and stabilizing the magnetic field of tachometer generators against temperature variation.*[56]

37.7 See also

- Ferroelectric effect
- Curie's law

37.8 Notes

[1] “Pierre Curie – Biography” . *Nobelprize.org*. The Nobel Foundation 1903. Retrieved 14 March 2013.

[2] Buschow 2001, p5021, table 1

[3] Jullien 1989, p. 155

[4] Kittel 1986

[5] Hall 1994, p. 200

[6] Jullien 1989, pp. 136–138

[7] Lüth, Harald Ibach, Hans (2009). *Solid-state physics: an introduction to principles of materials science* (4th extensively updated and enlarged ed.). Berlin: Springer. ISBN 978-3-540-93803-3.

[8] Levy 1968, pp. 236–239

[9] Dekker 1958, pp. 217–220

[10] Levy 1968

[11] Fan 1987, pp. 164–165

[12] Dekker 1958, pp. 454–455

[13] Mendelssohn 1977, p. 162

[14] Levy 1968, pp. 198–202

[15] Cusack 1958, p. 269

[16] Hall 1994, pp. 220–221

[17] Palmer 2007

[18] Hall 1994, p. 220

[19] Jullien 1989, pp. 158–159

[20] Jullien 1989, pp. 156–157

[21] Jullien 1989, pp. 153

[22] Hall 1994, pp. 205–206

[23] Levy 1968, pp. 201–202

[24] Kittel 1996, pp. 444

[25] Myers 1997, pp. 334–345

[26] Hall 1994, pp. 227–228

[27] Kittel 1986, pp. 424–426

[28] Spaldin 2010, pp. 52–54

[29] Hall 1994, pp. 225

[30] Mendelssohn 1977, pp. 180–181

[31] Mendelssohn 1977, p. 167

[32] Bertoldi 2012

[33] Brout 1965, pp. 6–7

[34] Jullien 1989, p. 161

[35] Rau 1988

[36] Skomski 2000

[37] Jullien 1989, pp. 138

[38] Hall 1994

[39] Hwang 1998

[40] Jones 2003

[41] López Domínguez 2012

[42] Bose 2011

[43] Sadoc 2010

[44] Myers 1997, pp. 404–405

[45] Jullien 1989, pp. 56–59

[46] Hall 1994, p. 275

[47] Webster 1999

[48] Kovetz 1990, p. 116

[49] Whatmore 1991, pp. 283

[50] Myers 1991, pp. 449

[51] Pascoe 1973, pp. 186–187

[52] Hummel 2001, pp. 189

[53] Pascoe 1973, pp. 190–191

[54] Webster, John G. (1999). *The measurement, instrumentation, and sensors handbook* (Online ed.). Boca Raton, FL: CRC Press published in cooperation with IEEE Press. pp. 6.55–6.56. ISBN 9780849383472.

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[56] Pallàs-Areny & Webster 2001, pp. 262–263

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37.10 External links

- Ferromagnetic Curie Point. Video by Walter Lewin, M.I.T.

Chapter 38

Allan V. Cox

Allan Verne Cox (December 17, 1926 – January 27, 1987) was an American geophysicist. His work on dating geomagnetic reversals, with Richard Doell and Brent Dalrymple, made a major contribution to the theory of plate tectonics. Allan Cox won numerous awards, including the prestigious Vetlesen Prize, and was the president of the American Geophysical Union. He was the author of two books on plate tectonics and over a hundred scientific papers. On January 27, 1987, Cox died in a bicycle accident.

38.1 Biography

Cox began studying chemistry at the University of California, Berkeley. However, after a single quarter he left school and spent three years in the United States Merchant Marine. He returned to Berkeley, but had so little interest in chemistry that his grades were too low to avoid being drafted into the United States Army. When he returned, he switched his major to geology. His research career in geology began in 1950 when he took a position as a field assistant to Clyde Wahrhaftig studying glaciation in the Alaska Range; the pair later had a long romantic relationship.*[1]*[2] For his graduate research at the University of California, Berkeley, Cox concentrated on rock magnetism with John Verhoogen as his supervisor. Verhoogen was one of the few geologists of the time who took the hypothesis of continental drift seriously. His stance made a deep impression on Cox.*[3]

After receiving his Ph.D. in 1959, Cox joined the United States Geological Survey in Menlo Park, California. There he collaborated with another geophysicist, Richard Doell, on rock magnetism. The two were particularly interested in geomagnetic reversals. At the time, very little was known about the timing of reversals. The rock specimens they collected were too young (a few millions of years) to date accurately until the potassium-argon dating method was developed. Cox and Doell arranged for the USGS to hire Brent Dalrymple, a graduate from Berkeley with expertise in this method. The three succeeded in creating the first geomagnetic polarity time scale. This work made possible the first test, by Frederick Vine and Drummond Matthews, of the seafloor spreading hypothesis.*[3]

Cox was hired as a professor at Stanford University in 1967. He became Dean of the School of Earth Sciences in 1979 and demonstrated a talent for administration that was widely acknowledged by his colleagues.*[3]

Cox died in a bicycle accident, colliding with a large redwood tree after falling off a cliff on Tunitas Creek road, in the mountains Northwest of Stanford University. The San Mateo County coroner concluded that Cox's death was a suicide.*[4] Cox was normally very safety conscious and had exceptionally not worn a helmet on that day. Cox's death came five days after he learned he was going to be charged with child molestation. Cox allegedly had molested the mentally disturbed son of one of his graduate students since the boy was fourteen years old. Cox had told the father of the molested child that he would kill himself if the allegations were reported to the police.*[5]

38.2 Honors

Cox was elected to the United States National Academy of Sciences, the American Academy of Arts and Sciences, and the American Philosophical Society.*[3] In 1969 the American Geophysical Union awarded him the John Adam Fleming medal for research in geomagnetism;.*[6] In 1970 he was awarded the prestigious Vetlesen Prize, along with G. Brent Dalrymple, Richard Doell and S. Keith Runcorn, for contributions to geology and geophysics.*[7] In 1976 the Geological Society of America awarded him the Arthur L. Day Medal for the application of physics and chemistry to the solution of geologic problems.*[8] He was the president of the American Geophysical Union from 1978 to 1980.*[9] In 1984 the United States National Academy of Sciences awarded him the Arthur L. Day Prize and Lectureship.

After his death, a number of memorials to him were created. The American Geophysical Union had the annual Allan Cox Lecture from 1998 to 2001; this lecture was replaced by the Edward Bullard lecture.*[10] The Geological Society of America (Geophysics Division) selects a student each year for the Allan V. Cox Student Research Award;*[11] and Stanford University awards the

Allan Cox Medal for Faculty Excellence Fostering Undergraduate Research.*[12]

38.3 Works

38.3.1 Books

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38.4 See also

- *Geomagnetism* – Wikipedia book

38.5 Notes

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[2] "Queer Scientists of Historical Note". National Organization of Gay and Lesbian Scientists and Technical Professionals. 2009. Retrieved 15 November 2013.

[3] Krauskopf 2011

[4] Bill Workman (March 13, 1987). "Stanford Dean killed himself, coroner rules". *San Francisco Chronicle*. The San Mateo County coroner has ruled that Stanford University dean Allan Cox, a world-renowned expert in earthquake studies, committed suicide when he smashed his bicycle into a tree in January. Coroner Paul Jensen said yesterday he has 'conclusive evidence' that Cox, 60, a suspect in a sexual molestation case at the time, killed himself by deliberately riding his bike down a hill and off the road at high speed.

[5] Lisa Lapin (January 30, 1987). "Was death a suicide born of sex probe". *San Jose Mercury News*. p. 1A. 'San Mateo County sheriff's detectives say Cox committed suicide when he struck the redwood head-on during a bicycle ride Tuesday morning, five days after he learned he was to be charged with child molestation. [para break] Cox, the 60-year-old dean of the Stanford earth sciences department, was being investigated on suspicion of repeatedly molesting a friend's teen-age son, according to Lt. Richard McKillip. McKillip said detectives told Cox on Friday that he was under investigation . . .A childless bachelor, he was especially close to the victim's parents and their mentally disturbed 19-year-old son.'

[6] AGU 2011

[7] Lamont-Doherty Earth Observatory 2011

[8] GSA 2011

[9] AGU 1999

[10] AGU Geomagnetism & Paleomagnetism 2011

[11] GSA Geophysics Division 2009

[12] Stanford 2011

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38.7 External links

- National Academy of Sciences Biographical Memoir

Chapter 39

Edmond Halley

Edmond[*][1] (or **Edmund**[*][2]) **Halley**, FRS (pronounced /'ɛdmənd 'hæli/;[*][3][*][4] 8 November [O.S. 29 October] 1656 – 25 January 1742 [O.S. 14 January 1741]) was an English astronomer, geophysicist, mathematician, meteorologist, and physicist who is best known for computing the orbit of Halley's Comet. He was the second Astronomer Royal in Britain, succeeding John Flamsteed.

39.1 Early life

Halley was born in Haggerston, in east London. His father, Edmond Halley Sr., came from a Derbyshire family and was a wealthy soap-maker in London. As a child, Halley was very interested in mathematics. He studied at St Paul's School, and from 1673 at The Queen's College, Oxford. While still an undergraduate, Halley published papers on the Solar System and sunspots.[*][5]

39.2 Career

39.2.1 Publications and inventions

Halley became an assistant to John Flamsteed, the Astronomer Royal at the Greenwich Observatory, in 1675, and among other things, had the job of assigning what is now called Flamsteed numbers to stars.

In 1676, Halley visited the south Atlantic island of Saint Helena and set up an observatory with a large sextant with telescopic sights to catalogue the stars of the southern hemisphere.[*][6] While there he observed a transit of Mercury, and realised that a similar transit of Venus could be used to determine the absolute size of the Solar System.[*][7] He returned to England in May 1678. In the following year he went to Danzig (Gdańsk) on behalf of the Royal Society to help resolve a dispute. Because astronomer Johannes Hevelius did not use a telescope, his observations had been questioned by Robert Hooke. Halley stayed with Hevelius and he observed and verified the quality of Hevelius' observations. In 1679 Halley published the results from his observations on St. Helena as *Catalogus Stellarum Australium* which included details of 341 southern stars.[*][8][*][9] These additions to contemporary star maps earned him comparison with Tycho Brahe: e.g. "the southern Tycho" as described by Flamsteed. Halley was awarded his M.A. degree at Oxford and elected as a Fellow of the Royal Society at the age of 22.

Bust of Halley (Royal Observatory, Greenwich)

In 1686, Halley published the second part of the results from his Helenian expedition, being a paper and chart on trade winds and monsoons. The symbols he used to represent trailing winds still exist in most modern day weather chart representations. In this article he identified solar heating as the cause of atmospheric motions. He also established the relationship between barometric pressure and height above sea level. His charts were an important contribution to the emerging field of information visualisation.*[10]

Halley spent most of his time on lunar observations, but was also interested in the problems of gravity. One problem that attracted his attention was the proof of Kepler's laws of planetary motion. In August 1684, he went to Cambridge to discuss this with Isaac Newton, much as John Flamsteed had done four years earlier, only to find that Newton had solved the problem, at the instigation of Flamsteed with regard to the orbit of comet Kirch, without publishing the solution. Halley asked to see the calculations and was told by Newton that he could not find them, but promised to redo them and send them on later, which he eventually did, in a short treatise entitled, *On the motion of bodies in an orbit*. Halley recognised the importance of the work and returned to Cambridge to arrange its publication with Newton, who instead went on to expand it into his *Philosophiæ Naturalis Principia Mathematica* published at Halley's expense in 1687.*[11] Halley's first calculations with comets were thereby for the orbit of comet Kirch, based on Flamsteed's observations in 1680-1. Although he was to accurately calculate the orbit of the comet of 1682, he was inaccurate in his calculations of the orbit of comet Kirch. They indicated a periodicity of 575 years, thus appearing in the years 531 and 1106, and presumably heralding the death of Julius Caesar in a like fashion in −44 (45 BCE). It is now known to have an orbital period of circa 10,000 years.

In 1691, Halley built a diving bell, a device in which the atmosphere was replenished by way of weighted barrels of air sent down from the surface.*[12] In a demonstration, Halley and five companions dived to 60 feet (18 m) in the River Thames, and remained there for over an hour and a half. Halley's bell was of little use for practical salvage work, as it was very heavy, but he made improvements to it over time, later extending his underwater exposure time to over 4 hours.*[13] Halley suffered one of the earliest recorded cases of middle ear barotrauma. *[12] That same year, at a meeting of the Royal Society, Halley introduced a rudimentary working model of a magnetic compass using a liquid-filled housing to damp the swing and wobble of the magnetised needle.*[14]

In 1691 Halley sought the post of Savilian Professor of Astronomy at Oxford, but, due to being accused of atheism, was opposed by the Archbishop of Canterbury, John Tillotson, and Bishop Stillingfleet. The post went instead to David Gregory, who had the support of Isaac Newton.*[15]

In 1692, Halley put forth the idea of a hollow Earth consisting of a shell about 500 miles (800 km) thick, two inner concentric shells and an innermost core.*[16] He suggested that atmospheres separated these shells, and that each shell had its own magnetic poles, with each sphere rotating at a different speed. Halley proposed this scheme to explain anomalous compass readings. He envisaged each inner region as having an atmosphere and being luminous (and possibly inhabited), and speculated that escaping gas caused the Aurora Borealis.*[17]

In 1693 Halley published an article on life annuities, which featured an analysis of age-at-death on the basis of the Breslau statistics Caspar Neumann had been able to provide. This article allowed the British government to sell life annuities at an appropriate price based on the age of the purchaser. Halley's work strongly influenced the development of actuarial science. The construction of the life-table for Breslau, which followed more primitive work by John Graunt, is now seen as a major event in the history of demography.

The Royal Society censured Halley for suggesting in 1694 that the story of Noah's flood might be an account of a cometary impact.*[18]

Halley's grave

39.2.2 Exploration years

In 1698, Halley was given command of the *Paramour*, a 52 feet (16 m) pink, so that he could carry out investigations in the South Atlantic into the laws governing the variation of the compass. On 19 August 1698, he took command of the ship and, in November 1698, sailed on what was the first purely scientific voyage by an English naval vessel. Unfortunately problems of insubordination arose over questions of Halley's competence to command a vessel. Halley returned the ship to England to proceed against officers in July 1699. The result was a mild rebuke for his men, and dissatisfaction for Halley, who felt the court had been too lenient.*[19] Halley thereafter received a temporary commission as a Captain in the Royal Navy, recommissioned the *Paramour* on 24 August 1699 and sailed again in September 1699 to make extensive observations on the conditions of terrestrial magnetism. This task he accomplished in a second Atlantic voyage which lasted until 6 September 1700, and extended from 52 degrees north to 52 degrees south. The results were published in *General Chart of the Variation of the Compass* (1701). This was the first such chart to be published and the first on which isogonic, or Halleyan, lines appeared.*[20]

The preface to Awnsham and John Churchill's collection

Plaque in South Cloister of Westminster Abbey

of voyages and travels (1704), supposedly written by John Locke or by Halley, made the link.

> "Natural and moral history is embellished with the most beneficial increase of so many thousands of plants it had never before received, so many drugs and spices, such unaccountable diversity. Trade is raised to highest pitch, and this not in a niggard and scanty manner as when the Venetians served all Europe ... the empire of Europe is now extended to the utmost bounds of the Earth."

In November 1703, Halley was appointed Savilian Professor of Geometry at the University of Oxford, his theological enemies, John Tillotson and Bishop Stillingfleet having died, and received an honorary degree of doctor of laws in 1710. In 1705, applying historical astronomy methods, he published *Synopsis Astronomia Cometicae*, which stated his belief that the comet sightings of 1456, 1531, 1607, and 1682 were of the same comet, which he predicted would return in 1758. Halley did not live to witness the comet's return, but when it did, the comet became generally known as Halley's Comet.

By 1706 Halley had learned Arabic and completed the translation started by Edward Bernard*[21] of Books V-VII of Apollonius's *Conics* from copies found at Leiden and the Bodleian Library at Oxford. He also completed a new translation of the first four books from the original Greek that had been started by the late David Gregory. He published these along with his own reconstruction of Book VIII*[22] in the first complete Latin edition in 1710.

In 1716, Halley suggested a high-precision measurement of the distance between the Earth and the Sun by timing the transit of Venus. In doing so, he was following the method described by James Gregory in *Optica Promota* (in which the design of the Gregorian telescope is also described). It is reasonable to assume Halley possessed and had read this book given that the Gregorian design was the principal telescope design used in astronomy in Halley's day.*[23] It is not to Halley's credit that he failed to acknowledge Gregory's priority in this matter. In 1718 he

Edmond Halley's tombstone, re-positioned at the Royal Observatory, Greenwich; he is not buried there, but at St Margaret's, Lee, some 30 minutes' walk away

discovered the proper motion of the "fixed" stars by comparing his astrometric measurements with those given in Ptolemy's *Almagest*. Arcturus and Sirius were two noted to have moved significantly, the latter having progressed 30 arc minutes (about the diameter of the moon) southwards in 1800 years.*[24]

In 1720, together with his friend the antiquarian William Stukeley, Halley participated in the first attempt to scientifically date Stonehenge. Assuming that the monument had been laid out using a magnetic compass, Stukeley and Halley attempted to calculate the perceived deviation introducing corrections from existing magnetic records, and suggested three dates (460 BC, 220 AD and 920 AD), the earliest being the one accepted. These dates were wrong by thousands of years, but the idea that scientific methods could be used to date ancient monuments was revolutionary in its day.*[25]

Halley succeeded John Flamsteed in 1720 as Astronomer Royal, a position Halley held until his death.

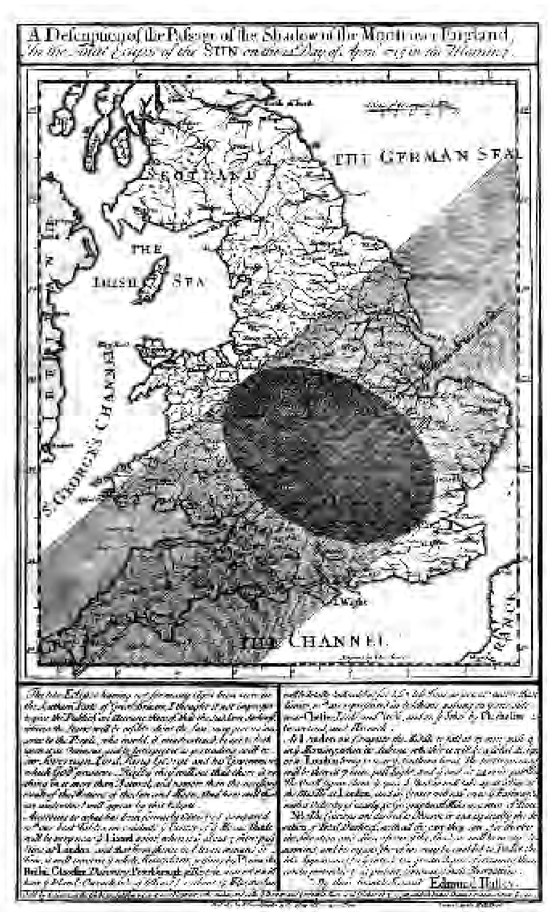
Halley died in 1742 at the age of 85. He was buried in the graveyard of the old church of St Margaret's, Lee (since rebuilt), at Lee Terrace, Blackheath.*[26] He was interred in the same vault as the Astronomer Royal John Pond; the unmarked grave of the Astronomer Royal Nathaniel Bliss is nearby.*[27]

His original tombstone was transferred by the Admiralty when the original Lee church was demolished and rebuilt – it can be seen today on the southern wall of the Camera Obscura at the Royal Observatory, Greenwich. His marked grave can be seen at St Margaret's Church, Lee Terrace.*[28]*[29]

39.3 Personal life

Halley married Mary Tooke in 1682 and settled in Islington. The couple had three children.*[5]

39.4 Named after Edmond Halley



Halley's map of the path of the Solar eclipse of 3 May 1715 across England

- Halley's Comet (orbital period (approximately) 75 years)
- Halley (lunar crater)
- Halley (Martian crater)
- Halley Research Station, Antarctica
- Halley's method, for the numerical solution of equations
- Halley Street, in Blackburn, Victoria, Australia
- Edmund Halley Road, Oxford Science Park, Oxford, OX4 4DQ UK
- Edmund Halley Drive, Reston, Virginia, USA
- Halley Ward, surgical ward at Homerton Hospital East London
- Halley's Mount, Saint Helena (680m high)
- Halley Drive, Hackensack, NJ. Intersects with Comet Way on the campus of Hackensack High School, The home of The Comets
- Rue Edmund Halley, Avignon, France
- The Edmund Halley, A JD Wetherspoon pub in Lee Green London
- Sir Edmond Halley's Restaurant & Freehouse, a pub in Charlotte, North Carolina

39.5 Pronunciation and spelling

There are three pronunciations of the surname *Halley*. The most common, both in Great Britain*[3] and in the United States,*[4] is /'hæli/. This is the personal pronunciation used by most Halleys living in London today.*[30] The alternative /'heɪli/ is often preferred for the man and the comet by those who grew up with rock and roll singer Bill Haley, who called his backing band his “Comets” after the common pronunciation of Halley's Comet in the United States at the time.*[31] Colin Ronan, one of Halley's biographers, preferred /'hɔːli/. Contemporary accounts spell his name *Hailey, Hayley, Haley, Haly, Halley, Hawley* and *Hawly*, and presumably pronunciations varied similarly.*[32]

As for his given name, although the spelling “Edmund” is quite common, “Edmond” is what Halley himself used, according to a 1902 article,*[1] though a 2007 *International Comet Quarterly* article disputes this, commenting that in his published works, he used “Edmund” 22 times and “Edmond” only 3 times,*[33] with several other variations used as well, such as the Latinised “Edmundus”. Much of the debate stems from the fact that, in Halley's own time, English spelling conventions were not yet standardised, and so he himself used multiple spellings.*[2]

39.6 See also

- *Geomagnetism* – Wikipedia book
- History of geomagnetism

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39.9 External links

- Edmond Halley Biography (SEDS)
- A Halley Odyssey
- The National Portrait Gallery (London) has several portraits of Halley: Search the collection
- Halley, Edmond, An Estimate of the Degrees of the Mortality of Mankind (1693)
- Halley, Edmond, Some Considerations about the Cause of the Universal Deluge (1694)
- Material on Halley's life table for Breslau on the Life & Work of Statisticians site: Halley, Edmond
- Halley, Edmund, Considerations on the Changes of the Latitudes of Some of the Principal Fixed Stars (1718) – Reprinted in R. G. Aitken, *Edmund Halley and Stellar Proper Motions* (1942)
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Chapter 40

Carl Friedrich Gauss

"Gauss" redirects here. For things named after Carl Friedrich Gauss, see List of things named after Carl Friedrich Gauss. For other persons or things named Gauss, see Gauss (disambiguation).

Johann Carl Friedrich Gauss (/ɡaʊs/; German: *Gauß*, pronounced [ɡaʊs]; Latin: *Carolus Fridericus Gauss*) (30 April 1777 Braunschweig – 23 February 1855 Göttingen) was a German mathematician who contributed significantly to many fields, including number theory, algebra, statistics, analysis, differential geometry, geodesy, geophysics, mechanics, electrostatics, astronomy, matrix theory, and optics.

Sometimes referred to as the *Princeps mathematicorum**[1] (Latin, "the foremost of mathematicians") and "greatest mathematician since antiquity", Gauss had an exceptional influence in many fields of mathematics and science and is ranked as one of history's most influential mathematicians.*[2]

40.1 Personal life

40.1.1 Early years

Statue of Gauss at his birthplace, Brunswick

Johann Carl Friedrich Gauss was born on 30 April 1777 in Brunswick (Braunschweig), in the Duchy of Brunswick-Wolfenbüttel (now part of Lower Saxony, Germany), as the son of poor working-class parents.*[3] His mother was illiterate and never recorded the date of his birth, remembering only that he had been born on a Wednesday, eight days before the Feast of the Ascension, which itself occurs 39 days after Easter. Gauss later solved this puzzle about his birthdate in the context of finding the date of Easter, deriving methods to compute the date in both past and future years.*[4] He was christened and confirmed in a church near the school he attended as a child.*[5]

Gauss was a child prodigy. A contested story relates that, when he was eight, he figured out how to add up all the numbers from 1 to 100.*[6]*[7] There are many other anecdotes about his precocity while a toddler, and he made his first ground-breaking mathematical discoveries while still a teenager. He completed *Disquisitiones Arithmeticae*, his magnum opus, in 1798 at the age of 21, though it was not published until 1801. This work was fundamental in consolidating number theory as a discipline and has shaped the field to the present day.

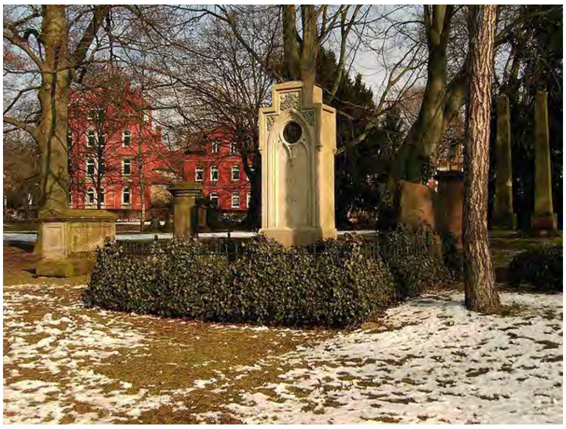
Gauss's intellectual abilities attracted the attention of the Duke of Brunswick,*[2] who sent him to the Collegium Carolinum (now Braunschweig University of Technology), which he attended from 1792 to 1795, and to the University of Göttingen from 1795 to 1798. While at university, Gauss independently rediscovered several important theorems.*[8] His breakthrough occurred in 1796 when he showed that a regular polygon can be constructed by compass and straightedge if and only if the number of sides is the product of distinct Fermat primes and a power of 2. This was a major discovery in an important field of mathematics; construction problems had occupied mathematicians since the days of the Ancient Greeks, and the discovery ultimately led Gauss to choose mathematics instead of philology as a career. Gauss was so pleased by this result that he requested that a regular heptadecagon be inscribed on his tombstone. The stonemason declined, stating that the difficult construction would essentially look like a circle.*[9]

The year 1796 was most productive for both Gauss and number theory. He discovered a construction of the heptadecagon on 30 March.*[10] He further advanced modular arithmetic, greatly simplifying manipulations in number theory. On 8 April he became the first to prove the quadratic reciprocity law. This remarkably general law allows mathematicians to determine the solvability of any quadratic equation in modular arithmetic. The prime number theorem, conjectured on 31 May, gives a good understanding of how the prime numbers are distributed among the integers.

Gauss also discovered that every positive integer is representable as a sum of at most three triangular numbers on 10 July and then jotted down in his diary the note: "ΕΥΡΗΚΑ! num = Δ + Δ' + Δ". On October 1 he published a result on the number of solutions of polynomials with coefficients in finite fields, which 150 years later led to the Weil conjectures.

40.1.2 Later years and death

Gauss on his deathbed (1855) Daguerreotype



Grave of Gauss at Albani Cemetery in Göttingen, Germany.

In 1831 Gauss developed a fruitful collaboration with the physics professor Wilhelm Weber, leading to new knowledge in magnetism (including finding a representation for the unit of magnetism in terms of mass, charge, and time) and the discovery of Kirchhoff's circuit laws in electricity. It was during this time that he formulated his namesake law. They constructed the first electromechanical telegraph in 1833, which connected the observatory with the institute for physics in Göttingen. Gauss ordered a magnetic observatory to be built in the garden of the observatory, and with Weber founded the "Magnetischer Verein" (*magnetic club* in German), which supported measurements of Earth's magnetic field in many regions of the world. He developed a method of measuring the horizontal intensity of the magnetic field which was in use well into the second half of the 20th century, and worked out the mathematical theory for separating the inner and outer (magnetospheric) sources of Earth's magnetic field.

In 1840, Gauss published his influential *Dioptrische Untersuchungen*,*[11] in which he gave the first systematic analysis on the formation of images under a paraxial approximation (Gaussian optics).*[12] Among his results, Gauss showed that under a paraxial approximation an optical system can be characterized by its cardinal points*[13] and he derived the Gaussian lens formula.*[14]

In 1845, he became associated member of the Royal Institute of the Netherlands; when that became the Royal Netherlands Academy of Arts and Sciences in 1851, he joined as a foreign member.*[15]

In 1854, Gauss selected the topic for Bernhard Riemann's Habilitationvortrag, *Über die Hypothesen, welche der Geometrie zu Grunde liegen*.*[16] On the way home from Riemann's lecture, Weber reported that Gauss was full of praise and excitement.*[17]

Gauss died in Göttingen, (then Kingdom of Hanover and now Lower Saxony) on 23 February 1855*[3] and is interred in the Albani Cemetery there. Two individuals gave eulogies at his funeral: Gauss's son-in-law Heinrich Ewald and Wolfgang Sartorius von Waltershausen, who was Gauss's close friend and biographer. His brain was preserved and was studied by Rudolf Wagner who found its mass to be 1,492 grams (slightly above average) and the cerebral area equal to 219,588 square millimeters*[18] (340.362 square inches). Highly developed convolutions were also found, which in the early 20th century were suggested as the explanation of his genius.*[19]

40.1.3 Religious views

Gauss was a Lutheran Protestant, a member of the St. Albans Evangelical Lutheran church in Göttingen.*[20] Potential evidence that Gauss believed in God comes from his response after solving a problem that had previously defeated him: "Finally, two days ago, I succeeded—not on account of my hard efforts, but by the grace of the Lord." *[21] One of his biographers G. Waldo Dunnington describes Gauss's religious views in these terms:

> For him science was the means of exposing the immortal nucleus of the human soul. In the days of his full strength it furnished him recreation and, by the prospects which it opened up

> to him, gave consolation. Toward the end of his life it brought him confidence. Gauss' God was not a cold and distant figment of metaphysics, nor a distorted caricature of embittered theology. To man is not vouchsafed that fullness of knowledge which would warrant his arrogantly holding that his blurred vision is the full light and that there can be none other which might report truth as does his. For Gauss, not he who mumbles his creed, but he who lives it, is accepted. He believed that a life worthily spent here on earth is the best, the only, preparation for heaven. Religion is not a question of literature, but of life. God's revelation is continuous, not contained in tablets of stone or sacred parchment. A book is inspired when it inspires. The unshakeable idea of personal continuance after death, the firm belief in a last regulator of things, in an eternal, just, omniscient, omnipotent God, formed the basis of his religious life, which harmonized completely with his scientific research.*[22]

Apart from his correspondence, there are not many known details about Gauss' personal creed. Many biographers of Gauss disagree with his religious stance, with Bühler and others considering him a deist with very unorthodox views,*[23]*[24]*[25] while Dunnington (though admitting that Gauss did not believe literally in all Christian dogmas and that it is unknown what he believed on most doctrinal and confessional questions) points out that he was, at least, a nominal Lutheran.*[26]

In connection to this, there is a record of a conversation between Rudolf Wagner and Gauss, in which they discussed William Whewell's book *Of the Plurality of Worlds*. In this work, Whewell had discarded the possibility of existing life in other planets, on the basis of theological arguments, but this was a position with which both Wagner and Gauss disagreed. Later Wagner explained that he did not fully believe in the Bible, though he confessed that he "envied" those who were able to easily believe.*[23]*[27] This later led them to discuss the topic of faith, and in some other religious remarks, Gauss said that he had been more influenced by theologians like Lutheran minister Paul Gerhardt than by Moses.*[28] Other religious influences included Wilhelm Braubach, Johann Peter Süssmilch, and the New Testament.*[29]

Dunnington further elaborates on Gauss's religious views by writing:

> Gauss' religious consciousness was based on an insatiable thirst for truth and a deep feeling of justice extending to intellectual as well as material goods. He conceived spiritual life in the whole universe as a great system of law penetrated by eternal truth, and from this source he gained the firm confidence that death does not end all.*[30]

Gauss declared he firmly believed in the afterlife, and saw spirituality as something essentially important for human beings.*[31] He was quoted stating: "*The world would be nonsense, the whole creation an absurdity without immortality,*" *[32] and for this statement he was severely criticized by the atheist Eugen Dühring who judged him as a narrow superstitious man.*[33]

Though he was not a church-goer,*[34] Gauss strongly upheld religious tolerance, believing "that one is not justified in disturbing another's religious belief, in which they find consolation for earthly sorrows in time of trouble." *[2] When his son Eugene announced that he wanted to become a Christian missionary, Gauss approved of this, saying that regardless of the problems within religious organizations, missionary work was "a highly honorable" task.*[35]

40.1.4 Family

Gauss's daughter Therese (1816–1864)

Gauss's personal life was overshadowed by the early death of his first wife, Johanna Osthoff, in 1809, soon followed by the death of one child, Louis. Gauss plunged into a depression from which he never fully recovered. He married again, to Johanna's best friend, Friederica Wilhelmine Waldeck, commonly known as Minna. When his second wife died in 1831 after a long illness,*[36] one of his daughters, Therese, took over the household and cared for Gauss for the rest of his life. His mother lived in his house from 1817 until her death in 1839.*[2]

Gauss had six children. With Johanna (1780–1809), his children were Joseph (1806–1873), Wilhelmina (1808–

1846) and Louis (1809–1810). With Minna Waldeck he also had three children: Eugene (1811–1896), Wilhelm (1813–1879) and Therese (1816–1864). Eugene shared a good measure of Gauss's talent in languages and computation.*[37] Therese kept house for Gauss until his death, after which she married.

Gauss eventually had conflicts with his sons. He did not want any of his sons to enter mathematics or science for "fear of lowering the family name", as he believed none of them would surpass his own achievements.*[37] Gauss wanted Eugene to become a lawyer, but Eugene wanted to study languages. They had an argument over a party Eugene held, which Gauss refused to pay for. The son left in anger and, in about 1832, emigrated to the United States, where he was quite successful. While working for the American Fur Company in the Midwest, he learned the Sioux language. Later, he moved to Missouri and became a successful businessman. Wilhelm also moved to America in 1837 and settled in Missouri, starting as a farmer and later becoming wealthy in the shoe business in St. Louis. It took many years for Eugene's success to counteract his reputation among Gauss's friends and colleagues. See also the letter from Robert Gauss to Felix Klein on 3 September 1912.

40.1.5 Personality

Carl Gauss was an ardent perfectionist and a hard worker. He was never a prolific writer, refusing to publish work which he did not consider complete and above criticism. This was in keeping with his personal motto *pauca sed matura* ("few, but ripe"). His personal diaries indicate that he had made several important mathematical discoveries years or decades before his contemporaries published them. Mathematical historian Eric Temple Bell said that if Gauss had published all of his discoveries in a timely manner, he would have advanced mathematics by fifty years.*[38]

Though he did take in a few students, Gauss was known to dislike teaching. It is said that he attended only a single scientific conference, which was in Berlin in 1828. However, several of his students became influential mathematicians, among them Richard Dedekind and Bernhard Riemann.

On Gauss's recommendation, Friedrich Bessel was awarded an honorary doctor degree from Göttingen in March 1811.*[39] Around that time, the two men engaged in an epistolary correspondence.*[40] However, when they met in person in 1825, they quarrelled; the details are not known.*[41]

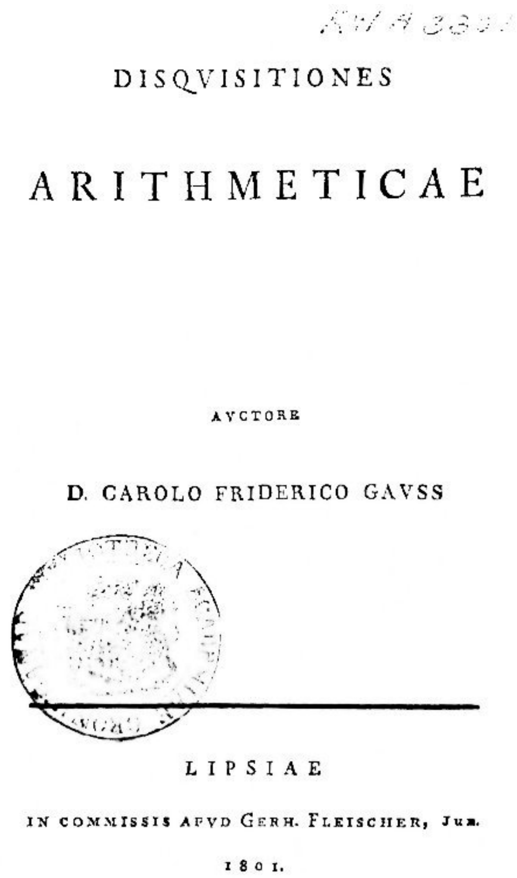
Before she died, Sophie Germain was recommended by Gauss to receive her honorary degree; she never received it.*[42]

Gauss usually declined to present the intuition behind his often very elegant proofs—he preferred them to appear "out of thin air" and erased all traces of how he discovered them. This is justified, if unsatisfactorily, by Gauss in his *Disquisitiones Arithmeticae*, where he states that all analysis (i.e., the paths one travelled to reach the solution of a problem) must be suppressed for sake of brevity.

Gauss supported the monarchy and opposed Napoleon, whom he saw as an outgrowth of revolution.

40.2 Careers and achievements

40.2.1 Algebra


DISQVISITIONES

ARITHMETICAE

AVCTORE

D. CAROLO FRIDERICO GAVSS

LIPSIAE

IN COMMISSIS APVD GERH. FLEISCHER, Jun.

1801.

Title page of Gauss's Disquisitiones Arithmeticae

In his 1799 doctorate in absentia, *A new proof of the theorem that every integral rational algebraic function of one variable can be resolved into real factors of the first or second degree*, Gauss proved the fundamental theorem of algebra which states that every non-constant single-variable polynomial with complex coefficients has at least one complex root. Mathematicians including Jean le Rond d'Alembert had produced false proofs before him, and Gauss's dissertation contains a critique of d'Alembert's work. Ironically, by today's standard, Gauss's own attempt is not acceptable, owing to implicit use of the

Jordan curve theorem. However, he subsequently produced three other proofs, the last one in 1849 being generally rigorous. His attempts clarified the concept of complex numbers considerably along the way.

Gauss also made important contributions to number theory with his 1801 book *Disquisitiones Arithmeticae* (Latin, Arithmetical Investigations), which, among other things, introduced the symbol ≡ for congruence and used it in a clean presentation of modular arithmetic, contained the first two proofs of the law of quadratic reciprocity, developed the theories of binary and ternary quadratic forms, stated the class number problem for them, and showed that a regular heptadecagon (17-sided polygon) can be constructed with straightedge and compass.

40.2.2 Astronomy

Gauss's portrait published in Astronomische Nachrichten *1828*

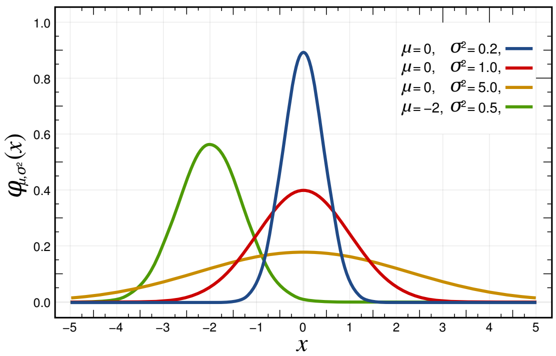
In the same year, Italian astronomer Giuseppe Piazzi discovered the dwarf planet Ceres. Piazzi could only track Ceres for somewhat more than a month, following it for three degrees across the night sky. Then it disappeared temporarily behind the glare of the Sun. Several months later, when Ceres should have reappeared, Piazzi could not locate it: the mathematical tools of the time were not able to extrapolate a position from such a scant amount of data—three degrees represent less than 1% of the total orbit.

Gauss, who was 24 at the time, heard about the problem and tackled it. After three months of intense work, he predicted a position for Ceres in December 1801—just about a year after its first sighting—and this turned out to be accurate within a half-degree when it was rediscovered by Franz Xaver von Zach on 31 December at Gotha, and one day later by Heinrich Olbers in Bremen.

Gauss's method involved determining a conic section in space, given one focus (the Sun) and the conic's intersection with three given lines (lines of sight from the Earth, which is itself moving on an ellipse, to the planet) and given the time it takes the planet to traverse the arcs determined by these lines (from which the lengths of the arcs can be calculated by Kepler's Second Law). This problem leads to an equation of the eighth degree, of which one solution, the Earth's orbit, is known. The solution sought is then separated from the remaining six based on physical conditions. In this work Gauss used comprehensive approximation methods which he created for that purpose.*[43]

One such method was the fast Fourier transform. While this method is traditionally attributed to a 1965 paper by J. W. Cooley and J. W. Tukey, Gauss developed it as a trigonometric interpolation method. His paper, *Theoria Interpolationis Methodo Nova Tractata*,*[44] was only published posthumously in Volume 3 of his collected works. This paper predates the first presentation by Joseph Fourier on the subject in 1807.*[45]

Zach noted that "without the intelligent work and calculations of Doctor Gauss we might not have found Ceres again". Though Gauss had up to that point been financially supported by his stipend from the Duke, he doubted the security of this arrangement, and also did not believe pure mathematics to be important enough to deserve support. Thus he sought a position in astronomy, and in 1807 was appointed Professor of Astronomy and Director of the astronomical observatory in Göttingen, a post he held for the remainder of his life.



Four Gaussian distributions in statistics

The discovery of Ceres led Gauss to his work on a theory of the motion of planetoids disturbed by large planets, eventually published in 1809 as *Theoria motus corporum coelestium in sectionibus conicis solem ambientum* (Theory of motion of the celestial bodies moving in conic sections around the Sun). In the process, he so streamlined the cumbersome mathematics of 18th century orbital prediction that his work remains a cornerstone of astronomical computation. It introduced the Gaussian gravitational constant, and contained an influential treatment of the method of least squares, a procedure used in all sciences to this day to minimize the impact of measurement error.

Gauss proved the method under the assumption of normally distributed errors (see Gauss–Markov theorem; see also Gaussian). The method had been described earlier by Adrien-Marie Legendre in 1805, but Gauss claimed that he had been using it since 1794 or 1795.*[46] In the history of statistics, this disagreement is called the “priority dispute over the discovery of the method of least squares.” *[47]

40.2.3 Geodetic survey

Geodetic survey stone in Garlste (now Garlstedt)

In 1818 Gauss, putting his calculation skills to practical use, carried out a geodetic survey of the Kingdom of Hanover, linking up with previous Danish surveys. To aid the survey, Gauss invented the heliotrope, an instrument that uses a mirror to reflect sunlight over great distances, to measure positions.

40.2.4 Non-Euclidean geometries

Gauss also claimed to have discovered the possibility of non-Euclidean geometries but never published it. This discovery was a major paradigm shift in mathematics, as it freed mathematicians from the mistaken belief that Euclid's axioms were the only way to make geometry consistent and non-contradictory.

Research on these geometries led to, among other things, Einstein's theory of general relativity, which describes the universe as non-Euclidean. His friend Farkas Wolfgang Bolyai with whom Gauss had sworn “brotherhood and the banner of truth” as a student, had tried in vain for many years to prove the parallel postulate from Euclid's other axioms of geometry.

Bolyai's son, János Bolyai, discovered non-Euclidean geometry in 1829; his work was published in 1832. After seeing it, Gauss wrote to Farkas Bolyai: “To praise it would amount to praising myself. For the entire content of the work ... coincides almost exactly with my own meditations which have occupied my mind for the past thirty or thirty-five years.”

This unproved statement put a strain on his relationship with Bolyai who thought that Gauss was “stealing” his idea.*[48]

Letters from Gauss years before 1829 reveal him obscurely discussing the problem of parallel lines. Waldo Dunnington, a biographer of Gauss, argues in *Gauss, Titan of Science* that Gauss was in fact in full possession of non-Euclidean geometry long before it was published by Bolyai, but that he refused to publish any of it because of his fear of controversy.*[49]*[50]

40.2.5 Theorema Egregium

The geodetic survey of Hanover, which required Gauss to spend summers traveling on horseback for a decade,*[51] fueled Gauss's interest in differential geometry and topology, fields of mathematics dealing with curves and surfaces. Among other things he came up with the notion of Gaussian curvature. This led in 1828 to an important theorem, the Theorema Egregium (*remarkable theorem*), establishing an important property of the notion of curvature. Informally, the theorem says that the curvature of a surface can be determined entirely by measuring angles and distances on the surface.

That is, curvature does not depend on how the surface might be embedded in 3-dimensional space or 2-dimensional space.

In 1821, he was made a foreign member of the Royal Swedish Academy of Sciences. Gauss was elected a Foreign Honorary Member of the American Academy of Arts and Sciences in 1822.*[52]

40.3 Appraisal of Gauss

The British mathematician Henry John Stephen Smith (1826–1883) gave the following appraisal of Gauss: If we except the great name of Newton it is probable that no mathematicians of any age or country have ever surpassed Gauss in the combination of an abundant fertility of invention with an absolute rigorousness in demonstration, which the ancient Greeks themselves might have envied. It may seem paradoxical, but it is probably nevertheless true that it is precisely the efforts after logical perfection of form which has rendered the writings of Gauss open to the charge of obscurity and unnecessary difficulty. Gauss says more than once that, for brevity, he gives only the synthesis, and suppresses the analysis of his propositions.

If, on the other hand, we turn to a memoir of Euler's, there is a sort of free and luxuriant gracefulness about the whole performance, which tells of the quiet pleasure which Euler must have taken in each step of his work. It is not the least of Gauss' claims to the admiration of mathematicians, that, while fully penetrated with a sense of the vastness of the science, he exacted the utmost rigorousness in every part of it, never passed over a difficulty, as if it did not exist, and never accepted a theorem as true beyond the limits within which it could actually be demonstrated.*[53]

German 10-Deutsche Mark Banknote (1993; discontinued) featuring Gauss

Gauss (aged about 26) on East German stamp produced in 1977. Next to him: heptadecagon, compass and straightedge.

40.4 Anecdotes

There are several stories of his early genius. According to one, his gifts became very apparent at the age of three when he corrected, mentally and without fault in his calculations, an error his father had made on paper while calculating finances.

Another story has it that in primary school after the young Gauss misbehaved, his teacher, J.G. Büttner, gave him a task: add a list of integers in arithmetic progression; as the story is most often told, these were the numbers from 1 to 100. The young Gauss reputedly produced the correct answer within seconds, to the astonishment of his teacher and his assistant Martin Bartels.

Gauss's presumed method was to realize that pairwise addition of terms from opposite ends of the list yielded identical intermediate sums: 1 + 100 = 101, 2 + 99 = 101, 3 + 98 = 101, and so on, for a total sum of 50 × 101 = 5050. However, the details of the story are at best uncertain (see*[7] for discussion of the original Wolfgang Sartorius von Waltershausen source and the changes in other versions); some authors, such as Joseph Rotman in his book *A first course in Abstract Algebra*, question whether it ever happened.

According to Isaac Asimov, Gauss was once interrupted in the middle of a problem and told that his wife was dying. He is purported to have said, "Tell her to wait a moment till I'm done." *[54] This anecdote is briefly discussed in G. Waldo Dunnington's *Gauss, Titan of Science* where it is suggested that it is an apocryphal story.

He referred to mathematics as "the queen of sciences" *[55] and supposedly once espoused a belief in the necessity of immediately understanding Euler's identity as a benchmark pursuant to becoming a first-class mathematician.*[56]

40.5 Commemorations

From 1989 through 2001, Gauss's portrait, a normal distribution curve and some prominent Göttingen buildings were featured on the German ten-mark banknote. The reverse featured the approach for Hanover. Germany has also issued three postage stamps honoring Gauss. One (no. 725) appeared in 1955 on the hundredth anniversary of his death; two others, nos. 1246 and 1811, in 1977, the 200th anniversary of his birth.

Daniel Kehlmann's 2005 novel *Die Vermessung der Welt*, translated into English as *Measuring the World* (2006), explores Gauss's life and work through a lens of historical fiction, contrasting them with those of the German explorer Alexander von Humboldt. A film version directed by Detlev Buck was released in 2012.*[57]

In 2007 a bust of Gauss was placed in the Walhalla temple.*[58]

Things named in honor of Gauss include:

- The Normal Distribution, Gaussian statistics (the bell curve)
- Gauss's Theorem, The Divergence Theorem
- The Gauss Prize, one of the highest honors in mathematics
- Gauss's Law and Gauss's law for magnetism, two of Maxwell's four equations.
- Degaussing, the process of eliminating a magnetic field
- The CGS unit for magnetic field was named gauss in his honour

- The crater Gauss on the Moon*[59]
- Asteroid 1001 Gaussia
- The ship *Gauss*, used in the Gauss expedition to the Antarctic
- Gaussberg, an extinct volcano discovered by the above-mentioned expedition
- Gauss Tower, an observation tower in Dransfeld, Germany
- In Canadian junior high schools, an annual national mathematics competition (Gauss Mathematics Competition) administered by the Centre for Education in Mathematics and Computing is named in honour of Gauss
- In University of California, Santa Cruz, in Crown College, a dormitory building is named after him
- The Gauss Haus, an NMR center at the University of Utah
- The Carl-Friedrich-Gauß School for Mathematics, Computer Science, Business Administration, Economics, and Social Sciences of Braunschweig University of Technology
- The Gauss Building at the University of Idaho (College of Engineering)
- The Carl-Friedrich-Gauss Gymnasium (a school for grades 5–13) in Worms, Germany
- The 'Gauss House', a common room in the University of Sussex Mathematical and Physical Sciences department.

In 1929 the Polish mathematician Marian Rejewski, who helped to solve the German Enigma cipher machine in December 1932, began studying actuarial statistics at Göttingen. At the request of his Poznań University professor, Zdzisław Krygowski, on arriving at Göttingen Rejewski laid flowers on Gauss's grave.*[60]

40.6 Writings

- 1799: Doctoral dissertation on the fundamental theorem of algebra, with the title: *Demonstratio nova theorematis omnem functionem algebraicam rationalem integram unius variabilis in factores reales primi vel secundi gradus resolvi posse* (“New proof of the theorem that every integral algebraic function of one variable can be resolved into real factors (i.e., polynomials) of the first or second degree”)
- 1801: *Disquisitiones Arithmeticae* (Latin). A German translation by H. Maser “Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 1–453. English translation by Arthur A. Clarke “Disquisitiones Arithmeticae (Second, corrected edition)". New York: Springer. 1986. ISBN 0-387-96254-9..
- 1808: “Theorematis arithmetici demonstratio nova” . Göttingen: Commentationes Societatis Regiae Scientiarum Gottingensis. 16.. German translation by H. Maser “Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 457–462 [Introduces Gauss's lemma, uses it in the third proof of quadratic reciprocity]
- 1809: *Theoria Motus Corporum Coelestium in sectionibus conicis solem ambientium* (Theorie der Bewegung der Himmelskörper, die die Sonne in Kegelschnitten umkreisen), *Theory of the Motion of Heavenly Bodies Moving about the Sun in Conic Sections* (English translation by C. H. Davis), reprinted 1963, Dover, New York.
- 1811: “Summatio serierun quarundam singularium” . Göttingen: Commentationes Societatis Regiae Scientiarum Gottingensis.. German translation by H. Maser “Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 463–495 [Determination of the sign of the quadratic Gauss sum, uses this to give the fourth proof of quadratic reciprocity]
- 1812: *Disquisitiones Generales Circa Seriem Infinitam* $1+\frac{\alpha\beta}{\gamma.1}+\text{etc.}$
- 1818: “Theorematis fundamentallis in doctrina de residuis quadraticis demonstrationes et amplicationes novae” . Göttingen: Commentationes Societatis Regiae Scientiarum Gottingensis.. German translation by H. Maser “Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 496–510 [Fifth and sixth proofs of quadratic reciprocity]
- 1821, 1823 and 1826: *Theoria combinationis observationum erroribus minimis obnoxiae*. Drei Abhandlungen betreffend die Wahrscheinlichkeitsrechnung als Grundlage des Gauß'schen Fehlerfortpflanzungsgesetzes. (Three essays concerning the calculation of probabilities as the basis of the Gaussian law of error propagation) English translation by G. W. Stewart, 1987, Society for Industrial Mathematics.

- 1827: *Disquisitiones generales circa superficies curvas*, Commentationes Societatis Regiae Scientiarum Gottingesis Recentiores. Volume **VI**, pp. 99–146. "General Investigations of Curved Surfaces" (published 1965) Raven Press, New York, translated by A.M.Hiltebeitel and J.C.Morehead.
- 1828: "Theoria residuorum biquadraticorum, Commentatio prima" . Göttingen: Commentationes Societatis Regiae Scientiarum Gottingensis. 6.. German translation by H. Maser "Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 511–533 [Elementary facts about biquadratic residues, proves one of the supplements of the law of biquadratic reciprocity (the biquadratic character of 2)]
- 1832: "Theoria residuorum biquadraticorum, Commentatio secunda" . Göttingen: Commentationes Societatis Regiae Scientiarum Gottingensis. 7.. German translation by H. Maser "Untersuchungen über höhere Arithmetik (Disquisitiones Arithmeticae & other papers on number theory) (Second edition)". New York: Chelsea. 1965. ISBN 0-8284-0191-8., pp. 534–586 [Introduces the Gaussian integers, states (without proof) the law of biquadratic reciprocity, proves the supplementary law for 1 + *i*]
- 1843/44: *Untersuchungen über Gegenstände der Höheren Geodäsie. Erste Abhandlung*, Abhandlungen der Königlichen Gesellschaft der Wissenschaften in Göttingen. Zweiter Band, pp. 3–46
- 1846/47: *Untersuchungen über Gegenstände der Höheren Geodäsie. Zweite Abhandlung*, Abhandlungen der Königlichen Gesellschaft der Wissenschaften in Göttingen. Dritter Band, pp. 3–44
- *Mathematisches Tagebuch 1796–1814*, Ostwaldts Klassiker, Verlag Harri Deutsch 2005, mit Anmerkungen von Neumann, ISBN 978-3-8171-3402-1 (English translation with annotations by Jeremy Gray: Expositiones Math. 1984)

Gauss's collective works are online at dz-srv1.sub.uni-goettingen.de Uni-goettingen.de includes German translations of Latin texts and commentaries by various authorities.

40.7 See also

- Carl Friedrich Gauss Prize
- Gaussian elimination
- German inventors and discoverers
- List of topics named after Carl Friedrich Gauss
- Romanticism in science

40.8 Notes

[1] Zeidler, Eberhard (2004). *Oxford Users' Guide to Mathematics*. Oxford, UK: Oxford University Press. p. 1188. ISBN 0-19-850763-1.

[2] Dunnington, G. Waldo. (May 1927). "The Sesquicentennial of the Birth of Gauss" . Archived from the original on 2008-02-26. Retrieved 2005-06-23. *Scientific Monthly* XXIV: 402–414. Retrieved on 29 June 2005. Now available at "The Sesquicentennial of the Birth of Gauss" . Retrieved 23 February 2014. Comprehensive biographical article.

[3] "Carl Friedrich Gauss" . Wichita State University.

[4] "Gauss Birthday Problem" .

[5] Susan Chamberless (2000-03-11). "Letter: WORTHINGTON, Helen to Carl F. Gauss – 1911-07-26" . Susan D. Chambless. Retrieved 2011-09-14.

[6] "Gauss, Carl Friedrich (1777-1855)." (2014). In The Hutchinson Dictionary of scientific biography. Abington, United Kingdom: Helicon.

[7] Brian Hayes (14 November 2009). "Gauss's Day of Reckoning" . American Scientist. doi:10.1511/2006.3.200. Retrieved 30 October 2012.

[8] O'Connor, John J.; Robertson, Edmund F., "Carl Friedrich Gauss" , *MacTutor History of Mathematics archive*, University of St Andrews.

[9] Pappas, Theoni, *Mathematical Snippets*, 2008, p. 42.

[10] Carl Friedrich Gauss §§365–366 in *Disquisitiones Arithmeticae*. Leipzig, Germany, 1801. New Haven, CT: Yale University Press, 1965.

[11] Bühler, Walter Kaufmann (1987). *Gauss: a biographical study*. Springer-Verlag. pp. 144–145. ISBN 0-387-10662-6.

[12] Hecht, Eugene (1987). *Optics*. Addison Wesley. p. 134. ISBN 0-201-11609-X.

[13] Bass, Michael; DeCusatis, Casimer; Enoch, Jay; Lakshminarayanan, Vasudevan (2009). *Handbook of Optics*. McGraw Hill Professional. p. 17.7. ISBN 0-07-149889-3.

[14] Ostdiek, Vern J.; Bord, Donald J. (2007). *Inquiry Into Physics*. Cengage Learning. p. 381. ISBN 0-495-11943-1.

[15] "C.F. Gauss (1797 - 1855)". Royal Netherlands Academy of Arts and Sciences. Retrieved 19 July 2015.

[16] Monastyrsky, Michael (1987). *Riemann, Topology, and Physics*. Birkhäuser. pp. 21–22. ISBN 0-8176-3262-X.

[17] Bühler, Walter Kaufmann (1987). *Gauss: a biographical study*. Springer-Verlag. p. 154. ISBN 0-387-10662-6.

[18] This reference from 1891 (Donaldson, Henry H. (1891). "Anatomical Observations on the Brain and Several Sense-Organs of the Blind Deaf-Mute, Laura Dewey Bridgman" . *The American Journal of Psychology*. E. C. Sanford. **4** (2): 248–294. doi:10.2307/1411270. JSTOR 1411270.) says: "Gauss, 1492 grm. 957 grm. 219588. sq. mm."; i.e. the unit is *square mm*. In the later reference: Dunnington (1927), the unit is erroneously reported as square cm, which gives an unreasonably large area; the 1891 reference is more reliable.

[19] Bardi, Jason (2008). *The Fifth Postulate: How Unraveling A Two Thousand Year Old Mystery Unraveled the Universe*. John Wiley & Sons, Inc. p. 189. ISBN 978-0-470-46736-7.

[20] Guy Waldo Dunnington (1955). *Carl Friedrich Gauss, Titan of Science: A Study of His Life and Work*. Exposition Press, pp. 300

[21] "WikiQuotes" . *WikiQuotes*.

[22] Guy Waldo Dunnington (1955). *Carl Friedrich Gauss, Titan of Science: A Study of His Life and Work*. Exposition Press, pp. 298-301

[23] Bühler, Walter Kaufmann (1987). *Gauss: a biographical study*. Springer-Verlag. p. 153. ISBN 0-387-10662-6.

[24] Gerhard Falk (1995). *American Judaism in Transition: The Secularization of a Religious Community*. University Press of America. p. 121. ISBN 978-0-7618-0016-3. Gauss told his friend Rudolf Wagner, a professor of biology at Gottingen University, that he did not fully believe in the Bible but that he had meditated a great deal on the future of the human soul and speculated on the possibility of the soul being reincarnated on another planet. Evidently, Gauss was a Deist with a good deal of skepticism concerning religion but incorporating a great deal of philosophical interests in the Big Questions, that is. the immortality of the soul, the afterlife and the meaning of man's existence.

[25] Bühler, Walter Kaufmann (1987). *Gauss: a biographical study*. Springer-Verlag. p. 152. ISBN 0-387-10662-6. Closely related to Gauss's political and social views were his religious beliefs. Despite his religious beliefs. Despite his strong roots in the Enlightenment, Gauss was not an atheist, rather a deist with very unorthodox convictions, unorthodox even if measured against the very liberal persuasions of the contemporary Protestant church.

[26] Guy Waldo Dunnington (2004). *Carl Friedrich Gauss: Titan of Science*. MAA. p. 305. ISBN 9780883855478. It is not known just what Gauss believed on most doctrinal and confessional questions. He did not believe literally in all Christian dogmas. Officially he was a member of St. Albans Church (Evangelical Lutheran) in Gottingen. All baptisms, burials, and weddings in his family occurred there. It is also not known whether he attended church regularly or contributed financially. A faculty colleague called Gauss a deist, but there is good reason to believe that this label did not fit well. Gauss possessed strong religious tolerance which he carried over to every belief originating in the depths of the human heart. This tolerance is not to be confused with religious indifference. He took special interest in the religious development of the human race, especially in his own century. With reference to the manifold denominations, which frequently did not agree with his views, he always emphasized that one is not justified in disturbing the faith of others in which they find consolation for earthly sufferings and a safe refuge in days of misfortune

[27] Guy Waldo Dunnington (2004). *Carl Friedrich Gauss: Titan of Science*. MAA. p. 305. ISBN 9780883855478. league, I believe you are more believing in the Bible than I. I am not, and, he added, with the expression of great inner emotion, you are much happier than I. I must say that so often in earlier times when I saw people of the lower classes, simple manual laborers who could believe so rightly with their hearts, I always envied them, and now, he continued, with soft voice and that naive childlike manner peculiar to him, while a tear came into his eye, tell me how does one begin this?...

[28] Guy Waldo Dunnington (2004). *Carl Friedrich Gauss: Titan of Science*. MAA. p. 356. ISBN 9780883855478. I must confess that such old theologians and song writers as Paul Gerhard have always made a great impression on me; a song by Paul Gerhard always exerted a wonderful power on me, much more than, for example, Moses, against whom as a man of God I have all sorts of qualms.

[29] Guy Waldo Dunnington (2004). *Carl Friedrich Gauss: Titan of Science*. MAA. p. 305. ISBN 9780883855478. " Two religious works which Gauss read frequently were Braubach's *Seelenlehre* (Giessen, 1843) and Siissmilch's *Gottliche* (Ordnung gerettet A756); he also devoted considerable time to the New Testament in the original Greek.

[30] Guy Waldo Dunnington; Jeremy Gray; Fritz-Egbert Dohse (2004). *Carl Friedrich Gauss: Titan of Science*. MAA. p. 300. ISBN 978-0-88385-547-8. Gauss' religious consciousness was based on an insatiable thirst for truth and a deep feeling of justice extending to intellectual as well as material goods. He conceived spiritual life in the whole universe as a great system of law penetrated by eternal truth, and from this source he gained the firm confidence that death does not end all.

[31] Morris Kline (1982). *Mathematics: The Loss of Certainty*. Oxford University Press. p. 73. ISBN 978-0-19-503085-3.

[32] Dunnington. 2004:357

[33] Dunnington. 2004:359

[34] "Gauss, Carl Friedrich" . Complete Dictionary of Scientific Biography. 2008. Retrieved 29 July 2012. In seeming contradiction, his religious and philosophical views leaned toward those of his political opponents. He was an uncompromising believer in the priority of empiricism in science. He did not adhere to the views of Kant, Hegel and other idealist philosophers of the day. He was not a churchman and kept his religious views to himself. Moral rectitude and the advancement of scientific knowledge were his avowed principles.

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[39] Bessel never had a university education.

[40] Helmut Koch, *Introduction to Classical Mathematics I: From the Quadratic Reciprocity Law to the Uniformization Theorem*, Springer, p. 90.

[41] Oscar Sheynin, *History of Statistics*, Berlin: NG Verlag Berlin, 2012, p. 88.

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40.10 External links

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- Works by or about Carl Friedrich Gauss at Internet Archive
- "Carl Friedrich Gauss" . *PlanetMath*.
- Complete works
- Gauss and his children
- Gauss biography
- Carl Friedrich Gauss at the Mathematics Genealogy Project
- Carl Friedrich Gauss – Biography at Fermat's Last Theorem Blog
- Gauss: mathematician of the millennium, by Jürgen Schmidhuber
- English translation of Waltershausen's 1862 biography
- Gauss general website on Gauss
- MNRAS **16** (1856) 80 Obituary
- Carl Friedrich Gauss on the 10 Deutsche Mark banknote
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Chapter 41

William Gilbert (astronomer)

For the librettist, see W. S. Gilbert.

William Gilbert (/ˈɡɪlbərt/; 24 May 1544 – 30 November 1603), also known as **Gilberd**, was an English physician, physicist and natural philosopher. He passionately rejected both the prevailing Aristotelian philosophy and the Scholastic method of university teaching. He is remembered today largely for his book *De Magnete* (1600), and is credited as one of the originators of the term "electricity". He is regarded by some as the father of electrical engineering or electricity and magnetism.*[1]

While today he is generally referred to as William Gilbert, he also went under the name of William Gilberd. The latter was used in both his and his father's epitaphs, in the records of the town of Colchester, in the Biographical Memoir that appears in *De Magnete*, and in the name of The Gilberd School in Colchester.

A unit of magnetomotive force, also known as magnetic potential, was named the *Gilbert* in his honour.

41.1 Life and work

William Gilbert M.D. demonstrating his experiments before queen Elizabeth (painting by A. Auckland Hunt).

Gilbert was born in Colchester to Jerome Gilberd, a borough recorder. He was educated at St John's College, Cambridge.*[2] After gaining his MD from Cambridge in 1569, and a short spell as bursar of St John's College, he left to practice medicine in London and travelled on the continent. In 1573, he was elected a Fellow of the Royal College of Physicians. In 1600 he was elected President of the College.*[3] From 1601 until her death in 1603, he was Elizabeth I's own physician, and James VI and I renewed his appointment.*[4]*:30

His primary scientific work—much inspired by earlier works of Robert Norman*[5]*[6]—was *De Magnete, Magneticisque Corporibus, et de Magno Magnete Tellure* (*On the Magnet and Magnetic Bodies, and on the Great Magnet the Earth*) published in 1600. In this work, he describes many of his experiments with his model Earth called the terrella. From these experiments, he concluded that the Earth was itself magnetic and that this was the reason compasses point north (previously, some believed that it was the pole star (Polaris) or a large magnetic island on the north pole that attracted the compass). He was the first to argue, correctly, that the centre of the Earth was iron, and he considered an important and related property of magnets was that they can be cut, each forming a new magnet with north and south poles.

In Book 6, Chapter 3, he argues in support of diurnal rotation, though he does not talk about heliocentrism, stating that it is an absurdity to think that the immense celestial spheres (doubting even that they exist) rotate daily, as opposed to the diurnal rotation of the much smaller Earth. He also posits that the "fixed" stars are at remote variable distances rather than fixed to an imaginary sphere. He states that situated "in thinnest aether, or in the most subtle fifth essence, or in vacuity – how shall the stars keep their places in the mighty swirl of these enormous spheres composed of a substance of which no one knows aught?"

The English word "electricity" was first used in 1646 by Sir Thomas Browne, derived from Gilbert's 1600 New Latin *electricus*, meaning "like amber". The term had been in use since the 13th century, but Gilbert was the first to use it to mean "like amber in its attractive properties". He recognized that friction with these objects removed a so-called "effluvium", which would cause the attraction effect in returning to the object, though he did not realize that this substance (electric charge) was universal to all materials.*[7]

> The electric effluvia differ much from air, and as air is the earth's effluvium, so electric bodies have their own distinctive effluvia; and each peculiar effluvium has its own individual power of leading to union, its own movement to its origin, to its fount, and to the body emitting the effluvium.
> —De Magnete, English translation by Paul Fleury Mottelay, 1893

In his book, he also studied static electricity using amber; amber is called *elektron* in Greek, so Gilbert decided to call its effect the *electric force*. He invented the first electrical measuring instrument, the electroscope, in the form of a pivoted needle he called the *versorium*.*[8]

Like others of his day, he believed that crystal (quartz) was an especially hard form of water, formed from compressed ice:

> Lucid gems are made of water; just as Crystal, which has been concreted from clear water, not always by a very great cold, as some used to judge, and by very hard frost, but sometimes by a less severe one, the nature of the soil fashioning it, the humour or juices being shut up in definite cavities, in the way in which spars are produced in mines.
> —De Magnete, English translation by Silvanus Phillips Thompson, 1900

Gilbert argued that electricity and magnetism were not the same thing. For evidence, he (incorrectly) pointed out that, while electrical attraction disappeared with heat, magnetic attraction did not (although it is proven that magnetism does in fact become damaged and weakened with heat). Hans Christian Ørsted and James Clerk Maxwell showed that both effects were aspects of a single force: electromagnetism. Maxwell surmised this in his *A Treatise on Electricity and Magnetism* after much analysis.

Gilbert's magnetism was the invisible force that many other natural philosophers, such as Kepler, seized upon, incorrectly, as governing the motions that they observed. While not attributing magnetism to attraction among the stars, Gilbert pointed out the motion of the skies was due to earth's rotation, and not the rotation of the spheres, 20 years before Galileo (but 57 years after Copernicus who stated it openly in his work "De revolutionibus orbium coelestium" published in 1543) (see external reference below). Gilbert made the first attempt to map the surface markings on the Moon in the 1590s. His chart, made without the use of a telescope, showed outlines of dark and light patches on the moon's face. Contrary to most of his contemporaries, Gilbert believed that the light spots on the Moon were water, and the dark spots land.*[9]

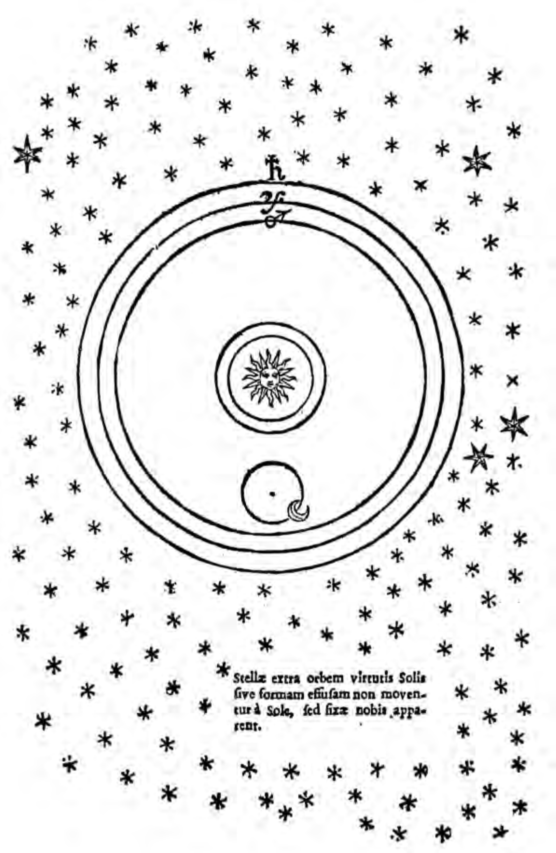

Diagram of the universe appearing on p202 of De Mundo

Besides Gilbert's *De Magnete*, there appeared at Amsterdam in 1651 a quarto volume of 316 pages entitled *De Mundo Nostro Sublunari Philosophia Nova* (New Philosophy about our Sublunary World), edited—some say by his brother William Gilbert Junior, and others say, by the eminent English scholar and critic John Gruter—from two manuscripts found in the library of Sir William Boswell. According to Dr. John Davy, "this work of Gilbert's, which is so little known, is a very remarkable one both in style and matter; and there is a vigor and energy of expression belonging to it very suitable to its originality. Possessed of a more minute and practical knowledge of natural philosophy than Bacon, his opposition to the philosophy of the schools was more searching and particular, and at the same time probably little less efficient." In the opinion of Prof. John Robison, *De Mundo* consists of an attempt to establish a new system of natural philosophy upon the ruins of the Aristotelian doctrine.*[10]

Dr. William Whewell says in his *History of the Inductive Sciences* (1859):*[11]

> Gilbert, in his work, *De Magnete* printed in 1600 has only some vague notions that the magnetic virtue of the earth in some way determines the direction of the earth's axis, the rate of its diurnal rotation, and that of the revolution of the moon about it.*[12] Gilbert died in

> 1603, and in his posthumous work (*De Mundo nostro Sublunari Philosophia nova*, 1631) we have already a more distinct statement of the attraction of one body by another.*[13] "The force which emanates from the moon reaches to the earth, and, in like manner, the magnetic virtue of the earth pervades the region of the moon: both correspond and conspire by the joint action of both, according to a proportion and conformity of motions, but the earth has more effect in consequence of its superior mass; the earth attracts and repels, the moon, and the moon within certain limits, the earth; not so as to make the bodies come together, as magnetic bodies do, but so that they may go on in a continuous course." Though this phraseology is capable of representing a good deal of the truth, it does not appear to have been connected... with any very definite notions of mechanical action in detail.*[14]

Gilbert died on 30 November 1603 in London. His cause of death is thought to have been the bubonic plague.*[15]*[16]

Gilbert was buried in his home town, in Holy Trinity Church, Colchester. His marble wall monument can still be seen in this Saxon church, now deconsecrated and used as a café and market.*[17]

41.2 Commentary on Gilbert

Francis Bacon never accepted Copernican heliocentrism and was critical of Gilbert's philosophical work in support of the diurnal motion of the earth. Bacon's criticism includes the following two statements. The first was repeated in three of his works—*In the Advancement of Learning* (1605), *Novum Organum* (1620) and *De Augmentis* (1623). The more severe second statement is from *History of Heavy and Light Bodies* published after Bacon's death.*[18]

> The Alchemists have made a philosophy out of a few experiments of the furnace and Gilbert our countryman hath made a philosophy out of observations of the lodestone.

> [Gilbert] has himself become a magnet; that is, he has ascribed too many things to that force and built a ship out of a shell.

Thomas Thomson writes in his *History of the Royal Society* (1812):*[19]

> The magnetic laws were first generalized and explained by Dr. Gilbert, whose book on magnetism published in 1600, is one of the finest examples of inductive philosophy that has ever been presented to the world. It is the more remarkable, because it preceded the *Novum Organum* of Bacon, in which the inductive method of philosophizing was first explained.

William Whewell writes in his *History of the Inductive Sciences* (1837/1859):*[20]

> Gilbert... repeatedly asserts the paramount value of experiments. He himself, no doubt, acted up to his own precepts; for his work contains all the fundamental facts of the science [of magnetism], so fully examined, indeed, that even at this day we have little to add to them.

Historian Henry Hallam wrote of Gilbert in his *Introduction to the Literature of Europe in the Fifteenth, Sixteenth, and Seventeenth Centuries* (1848):*[21]

> The year 1600 was the first in which England produced a remarkable work in physical science; but this was one sufficient to raise a lasting reputation to its author. Gilbert, a physician, in his Latin treatise on the magnet, not only collected all the knowledge which others had possessed on that subject, but became at once the father of experimental philosophy in this island, and by a singular felicity and acuteness of genius, the founder of theories which have been revived after the lapse of ages, and are almost universally received into the creed of the science. The magnetism of the earth itself, his own original hypothesis, *nova illa nostra et inaudita de tellure sententia* [our new and unprecedented view of the planet]... was by no means one of those vague conjectures that are sometimes unduly applauded... He relied on the analogy of terrestrial phenomena to those exhibited by what he calls a *terrella*, or artificial spherical magnet. ...Gilbert was also one of our earliest Copernicans, at least as to the rotation of the earth; and with his usual sagacity inferred, before the invention of the telescope, that there are a multitude of fixed stars beyond the reach of our vision.

Walter William Bryant of the Royal Observatory, Greenwich, wrote in his book *Kepler* (1920):

> When Gilbert of Colchester, in his "New Philosophy," founded on his researches in magnetism, was dealing with tides, he did not suggest that the moon attracted the water, but

that "subterranean spirits and humors, rising in sympathy with the moon, cause the sea also to rise and flow to the shores and up rivers". It appears that an idea, presented in some such way as this, was more readily received than a plain statement. This so-called philosophical method was, in fact, very generally applied, and Kepler, who shared Galileo's admiration for Gilbert's work, adopted it in his own attempt to extend the idea of magnetic attraction to the planets.*[22]

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41.4 See also

- History of geomagnetism
- List of geophysicists
- Scientific revolution

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[10] Gilbert (1893) p. xxv

[11] Whewell, William (1859) *History of the Inductive Sciences*. D. Appleton. Vol. 1. p. 394

[12] Gilbert, William *De Magnete*, Book 6, Ch. 6,7

[13] Gilbert, William *De Mundo*, Book 2, Ch. 19

[14] Gilbert (1893) p. 346

[15] William Gilbert. National High Magnetic Field Laboratory

[16] William Gilbert (1544–1603). BBC

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41.7 External links

- The Galileo Project —biography of William Gilbert.
- The Great Magnet, the Earth —website hosted by NASA —*Commemorating the 400th anniversary of* "*De Magnete*" *by William Gilbert of Colchester*.
- Online Galleries, History of Science Collections, University of Oklahoma Libraries High resolution images of works by and/or portraits of William Gilbert in .jpg and .tiff format.
- Works by William Gilbert at Project Gutenberg
- Works by or about William Gilbert at Internet Archive
- On the Magnet —Translation of De Magnete by Silvanus Thompson for the Gilbert Club, London 1900. Full text, free to read and search. Go to page 9 and read Gilbert saying the earth revolves leading to the motion of the skies.
- The Natural Philosophy of William Gilbert and His Predecessors
- De Magnete From the English Printing Collection in the Rare Book and Special Collection Division at the Library of Congress

Chapter 42

Edward A. Irving

Edward A. "Ted"Irving, CM FRSC FRS (27 May 1927 – 25 February 2014) was a geologist and scientist with the Geological Survey of Canada. His studies of paleomagnetism provided the first physical evidence of the theory of continental drift. His efforts contributed to our understanding of how mountain ranges, climate, and life have changed over the past millions of years.*[4]*[7]

42.1 Education

Irving was born and raised in Colne in the Pennine Hills of east Lancashire, England. In 1945, he was conscripted into the British Army. Irving served in the Middle East infantry. In 1948, he began studying geology at the University of Cambridge and obtained his Bachelor of Arts degree in 1951. He spent the next year at Cambridge as a research assistant with Keith Runcorn in the geology and geophysics department before entering the graduate program.*[7]

When Irving started his graduate studies, the history of the Earth's magnetic field was known for the few centuries since the first magnetic observatories had been established. With fellow students Ken Creer and Jan Hospers, he looked to extend this record back in time. Irving used a magnetometer,*[2] recently designed by Patrick Blackett, to analyze the magnetic directions imparted to rocks by their iron minerals. He found large discrepancies between the directions of the present magnetic field direction and those recorded in Precambrian rock in the highlands of Scotland. He surmised the only explanation could be that Scotland had shifted relative to the geomagnetic pole. Irving also determined that India had moved northward by 6000 km and rotated by more than 30°. These results confirmed the predictions Alfred Wegener had put forth in his theory of continental drift in 1912.*[7]*[8]*:146–147

In 1954, Irving attempted to obtain a PhD for his graduate work. Unfortunately the field was so new that his doctoral examiners were not familiar enough with the subject matter to recognize his research achievements. They refused to give him the degree.*[9]*:41–42 Not having a PhD did not stop him from obtaining a position as a research fellow at the Australian National University in Canberra.

42.2 Career

For the next ten years Irving studied Australia's ancient latitudes and published around 30 papers. He was able to demonstrate the continent's southward movement since the Permian period. In 1965, he submitted some of his papers to Cambridge and obtained a ScD, the highest earned degree at the time.*[7]

Irving met his wife Sheila while in Australia. She was a Canadian citizen. In 1964, they moved to Ottawa, Ontario, Canada, and Irving began work as a research officer for Dominion Observatory with the Department of Mines and Technical Surveys. In 1966, Irving returned to England to teach geophysics at the University of Leeds. He returned to Ottawa in 1967 to work as a research scientist in the Earth Physics Branch of the Department of Energy, Mines, and Resources. In 1981, Irving moved to Sidney, British Columbia, to establish a paleomagnetism laboratory at the Pacific Geoscience Centre with the Earth Physics Branch. The branch would later be incorporated into the Geological Survey of Canada. He mapped the movements of Vancouver Island and other parts of the Cordillera that have moved sideways and rotated relative to the Precambrian Canadian Shield.*[7]

In 2005, Irving was semi-retired, investigating the nature of the geomagnetic field in the Precambrian to understand how the crust was being deformed and how the latitudes varied. He and his wife Sheila had four children.*[7] He died during the night of 24 February 2014 in Saanich, British Columbia.*[1]

42.3 Selected works

Irving published a total of 205 papers,*[3] including:

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In addition, he published the first book on paleomagnetism:*[6]

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42.4 Honors and awards

Irving was awarded the Gondwanaland Gold Medal by the Mining, Geological, and Metallurgical Society of India,*[7] the Logan Medal by the Geological Association of Canada (1975),*[10] the Walter H. Bucher Medal by the American Geophysical Union (1979),*[11] the J. Tuzo Wilson Medal by the Canadian Geophysical Union (1984),*[12] the Arthur L. Day Medal by the Geological Society of America (1997),*[13] and the Wollaston Medal by the Geological Society of London (2005).*[3] He was made a fellow of the Royal Society of Canada (FRSC) in 1973 and of the Royal Society of London (FRS) in 1979.*[4]*[14] In 1998 he was elected to the National Academy of Sciences and in 2003 invited to be a Member of the Order of Canada.*[15]*[16]*[17] He received an honorary degree from the University of Victoria in 1999.*[18]

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Chapter 43

Eugene Parker

For the sports agent, see Eugene Parker (sports agent).

Eugene N. Parker (born June 10, 1927) is an American solar astrophysicist who received his B.S. degree in physics from Michigan State University in 1948 and Ph.D. from Caltech in 1951. In the mid-1950s Parker developed the theory on the supersonic solar wind and predicted the Parker spiral shape of the solar magnetic field in the outer solar system. In 1987, Parker proposed that the solar corona might be heated by myriad tiny "nanoflares", miniature brightenings resembling solar flares that would occur all over the surface of the Sun.*[1]*[2]

Parker was elected to the National Academy of Sciences in 1967.*[1] As of early 2005, he was still engaged in active research at the University of Chicago. His daughter and son-in-law are both faculty members at Michigan State University.

Parker spent four years at the University of Utah and has been at the University of Chicago since 1955, where he has held positions in the physics department, the astronomy and astrophysics department and the Enrico Fermi Institute.*[1] He is the leading authority on the solar wind and the effects of magnetic fields in the heliosphere. His work has greatly increased understanding of the solar corona, the solar wind, the magnetic fields of both the Earth and the Sun, and their complex electromagnetic interactions. The theoretical models which he developed in part by looking at comet tails have in recent years been confirmed by spacecraft. His books, especially *Cosmical Magnetic Fields*, have educated generations of investigators. His most recent book includes the effects of magnetic fields of planets, stars, and galaxies on X-ray emissions.*[2]

He also wrote about the dangers of space radiation for future interplanetary missions.

43.1 Honors

- Arctowski Medal of the National Academy of Sciences (1969)*[3]
- Henry Norris Russell Lectureship of the American Astronomical Society (1969)
- George Ellery Hale Prize, American Astronomical Society Solar Physics Division (1978)
- National Medal of Science (1989)*[4]
- William Bowie Medal (1990)*[1]
- Bruce Medal (1997)
- Gold Medal of the Royal Astronomical Society (1992)
- Kyoto Prize (2003)*[5]*[6]
- James Clerk Maxwell Prize (2003) of the American Physical Society. Citation: "For seminal contributions in plasma astrophysics, including predicting the solar wind, explaining the solar dynamo, formulating the theory of magnetic reconnection, and the instability which predicts the escape of the magnetic fields from the galaxy." *[7]
- Member of the Norwegian Academy of Science and Letters.*[8]

43.2 Books

- *Cosmical Magnetic Fields: Their Origin and their Activity*, 1979, Oxford University Press. ISBN 978-0-19-851290-5.
- *Spontaneous Current Sheets in Magnetic Fields: With Applications to Stellar X-rays*, 1994, Oxford University Press. ISBN 978-0-19-507371-3.
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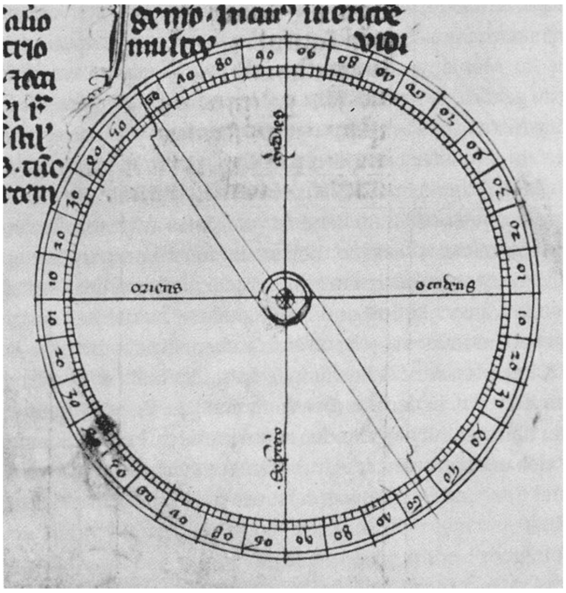
Chapter 44

Petrus Peregrinus de Maricourt



Pivoting compass needle in a 14th-century handcopy of Peter's Epistola de magnete *(1269)*

Petrus Peregrinus de Maricourt (Latin), **Pierre Pelerin de Maricourt** (French), or **Peter Peregrinus of Maricourt***[1] (fl. 1269), was a 13th-century French scholar who conducted experiments on magnetism and wrote the first extant treatise describing the properties of magnets. His work is particularly noted for containing the earliest detailed discussion of freely pivoting compass needles, a fundamental component of the dry compass soon to appear in medieval navigation.*[2]*[3]*[4] He also wrote a treatise on the construction and use of a universal astrolabe.

Peregrinus' text on the magnet is entitled in many of the manuscripts of it *Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt, militem, de magnete* ("Letter of Peter Peregrinus of Maricourt to Sygerus of Foucaucourt, Soldier, on the Magnet") but it is more commonly known by its short title, *Epistola de magnete* ("Letter on the Magnet"). The letter is addressed to an otherwise unknown Picard countryman named Sygerus (Sigerus, Ysaerus) of Foucaucourt, possibly a friend and neighbor of the author; Foucaucourt borders on the home area of Peregrinus around Maricourt, in the present-day *department* of the Somme, near Péronne.

In only one of the 39 surviving manuscript copies the letter also bears the closing legend *Actum in castris in obsidione Luceriæ anno domini 1269º 8º die augusti* ("Done in camp during the siege of Lucera, August 8, 1269"), which might indicate that Peregrinus was in the army of Charles, duke of Anjou and king of Sicily, who in 1269 laid siege to the city of Lucera. However, given that only one manuscript attests this, the evidence is weak.*[5] There is no indication of why Peter received the sobriquet *Peregrinus* (or "pilgrim"), but it suggests that he may have been either a pilgrim at one point or a crusader; and the attack on Lucera of 1269 had been sanctioned as a *crusade* by the Pope. So Petrus Peregrinus may have served in that army.

"You must realize, dearest friend," Peregrinus writes, "that while the investigator in this subject must understand nature and not be ignorant of the celestial motions, he must also be very diligent in the use of his own hands, so that through the operation of this stone he may show wonderful effects." *[6]

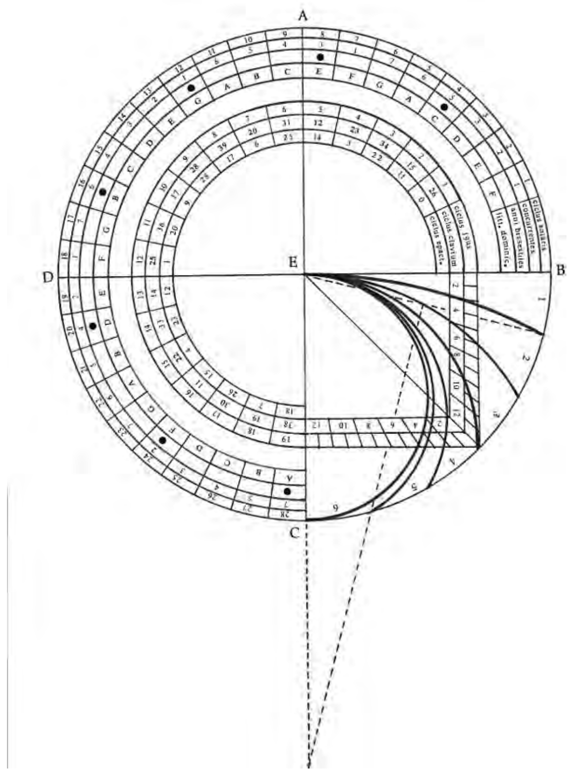
44.1 The content of the *Epistola de magnete*

In his letter of 1269,*[7] Peregrinus explains how to identify the poles of the compasses. He also describes the laws of magnetic attraction and repulsion. The letters also contain a description of an experiment with a repaired magnet, as well as a number of compasses, one of which "you will be able to direct your steps to cities and islands and to any place whatever in the world." Indeed, the increasing perfection of magnetic compasses during the thirteenth century allowed navigators such as Vandino and Ugolino Vivaldi to strike out on voyages to unknown lands.

The *Epistola de magnete* is divided into two parts. *Part One* (10 chapters): This is a section that serves as a model of inductive reasoning based on definite experiences, and setting forth the fundamental laws of magnetism. He did not discover these laws, but presented them in logical order. Part One discusses the physical (but not the occult) properties of the lodestone and provides the first extant written account of the polarity of magnets. He was thus the first to use the word "pole" in this context. He provides methods for determining the north and south poles of a magnet, and he describes the effects magnets have upon one another, showing that like poles repel each other and unlike poles attract each other. He also treats the attraction of iron by lodestones, the magnetization of iron by lodestones, and the ability to reverse the polarity in such an induced magnet. Peregrinus attributed the Earth's magnetism to the action of celestial poles, rather than to the terrestrial poles of the planet itself.*[8]

Part Two (three chapters): This section describes three devices that utilize the properties of magnets. He treats the practical applications of magnets, describing the "wet" floating compass as an instrument in common use, and proposing a new "dry" pivoted compass in some detail. He also attempts to prove that with the help of magnets it is possible to realize perpetual motion (see History of perpetual motion machines). His device is a toothed wheel which passes near a lodestone so that the teeth are alternately attracted by one pole and repelled by the other.

44.2 The universal astrolabe text



Part of the engraving on the back-side de Maricourt's universal astrolabe

The *Nova Compositio Astrolabii Particularis* (found in only 4 manuscripts) describes the construction and use a universal astrolabe which could be used at a variety of latitudes without changing the plates. Unlike al-Zarqālī's more famous universal astrolabe in which vertical halves the heavens were projected onto a plane through the poles, this one had both the northern and southern hemispheres projected onto a plane through the equator (which was also the limit of projection). There are no known surviving astrolabes based on this treatise. The use of such an astrolabe is very complicated, and since it is probable that most sophisticated users were not frequent travelers, they were more likely happier with the traditional (and simpler) stereographic planispheric astrolabe.

44.3 Roger Bacon

The literature often mentions that Peregrinus was praised by Roger Bacon, who called him a "perfect mathematician" and one who valued experience over argument. But the association of the praise with Peregrinus appears only in a marginal gloss to Bacon's *Opus tertium* and only in one of the five manuscripts used in the critical edition, which leads us to conclude that it was a later comment added by someone else. That Bacon's praise was for Peregrinus is open to serious debate.*[9]

44.4 Legacy

The influence of Peregrinus' astrolabe was virtually nil. His reputation derives mainly from his work on magnetism. The *De magnete* became a very popular work from the Middle Ages onwards, as witnessed by the large number of manuscript copies.

The first printed edition of it was issued at Augsburg, in 1558, by Achilles Gasser.*[10] In 1572, Jean Taisner published from the press of Johann Birkmann of Cologne a work entitled *Opusculum perpetua memoria dignissimum, de natura magnetis et ejus effectibus, Item de motu continuo*. This is considered a piece of plagiarism, as Taisnier presents, as though his own, the *Epistola de magnete* of Peregrinus and a treatise on the fall of bodies by Gianbattista Benedetti.

William Gilbert acknowledged his debt to Peregrinus and incorporated this thirteenth-century scientist's experiments on magnetism into his own treatise, called *De magnete*.*[11]

The *Epistola de magnete* was later issued by Guillaume Libri (*Histoire des sciences mathématiques en Italie*, vol 2 [Paris, 1838], pp. 487–505), but, based on only one manuscript, this edition was full of defects; corrected editions were published by Timoteo Bertelli (in *Bulletino di bibliografia e di storia delle scienze matematiche e fisiche pubblicata da B. Boncampagni,* 1 (1868), 70-80)*[12] and G. Hellmann (*Rara magnetica 1269-1599*

[Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus, 10], [Berlin, 1898]) .*[13]

The modern critical edition was prepared by Loris Sturlese and appears in Petrus Peregrinus de Maricourt, *Opera* (Pisa, 1995), pp. 63–89.

A translation into English has been made by Silvanus P. Thompson ("Epistle of Peter Peregrinus of Maricourt, to Sygerus of Foucaucourt, Soldier, concerning the Magnet" , [London: Chiswick Press, 1902]); by Brother Arnold [=Joseph Charles Mertens] ("The Letter of Petrus Peregrinus on the Magnet, A. D. 1269" , with introductory note by Brother Potamian [= M. F. O' Reilly], [New York, 1904]); and H. D. Harradon, ("Some Early Contributions to the History of Geomagnetism - I," in *Terrestrial Magnetism and Atmospheric Electricity* [now *Journal of Geophysical Research*] 48 [1943], 3-17 [text pp. 6–17]).

The modern critical edition of the astrolabe text was prepared by Ron B. Thomson and appears in Petrus Peregrinus de Maricourt, *Opera* (Pisa, 1995), pp. 119–196.

The philosopher and scientist Charles S. Peirce made a thorough study the Epistle of Petrus Peregrinus on the lodestone (MS. No. 7378; See Eisele, C. (1957) The Charles S. Peirce-Simon Newcomb Correspondence. Proceedings of the American Philosophical Society, Vol. 101, No. 5. p. 411).

The European Geosciences Union (EGU) established the **Petrus Peregrinus Medal** in recognition for outstanding scientific contributions in the field of magnetism.*[14]

44.5 See also

- *Geomagnetism* – Wikipedia book
- History of geomagnetism
- History of electromagnetic theory

44.6 Notes

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[6] Jean Gimpel, *The Medieval Machine: The Industrial Revolution of the Middle Ages* (New York, Penguin, 1976), 194-5.

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[14] EGU - Awards & Medals - Petrus Peregrinus Medal

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- Catholic Encyclopedia: Pierre de Maricourt
- Peter Peregrinus at IET Archives
- The letter of Petrus Peregrinus on the magnet, A.D. 1269 (translated 1904)
- Andreas Kleinert, *Wie funktionierte das Perpetuum mobile des Petrus Peregrinus?*, in NTM N.S. 11 (2003), 155–170, abstract

Chapter 45

Keith Runcorn

Stanley Keith Runcorn FRS*[1] (19 November 1922 – 5 December 1995) was a British physicist whose paleomagnetic reconstruction of the relative motions of Europe and America revived the theory of continental drift and was a major contribution to plate tectonics.*[1]*[2]

45.1 Biography

He was born in Southport, Lancashire and graduated in engineering from the University of Cambridge in 1942.

After a period in radar research during the World War II, he joined the Physics Department at the University of Manchester where he did research on aspects of the Earth's magnetic field, taking his Ph.D. under Patrick Blackett in 1949.*[3] This led to his interest in palaeomagnetism, the study of the magnetism of rocks, which he pursued first at the Geophysics Department at the University of Cambridge and later at Newcastle University, where he was appointed to the chair of Physics in 1956. At Newcastle Runcorn developed a strong research group in geophysics, and made substantial contributions to various fields, including convection in the Earth and Moon, the shape and magnetic fields of the Moon and planets, magnetohydrodynamics of the Earth's core, changes in the length of the day, polar wandering, continental drift and plate tectonics.

Runcorn received many honours, including Fellowship of the Royal Society in 1965, the Gold Medal of the Royal Astronomical Society (RAS) and the Fleming medal of the American Geophysical Union. He was also a member of the Pontifical Academy of Science. In 1981, Runcorn became a founding member of the World Cultural Council.*[4]He served as the Sydney Chapman Endowed Chair in Physical Sciences at the University of Alaska from 1989 to 1995. After his retirement in 1988 he continued to be active in various lines of research until his untimely death in San Diego in 1995. In 2007 the RAS named an award – for the year's best PhD thesis in geophysics – the 'Keith Runcorn Prize' in his honour.*[5]

45.2 Death

Runcorn was murdered in his hotel room in San Diego during a lecture trip to the Scripps Institution of Oceanography. Police found that he had been strangled and found evidence of injuries to the head.*[6] Paul Cain, a professional kick-boxer, was later convicted and sentenced to a term of at least 25 years.*[7] Prosecutors argued that Cain killed Runcorn after stealing his wallet and credit cards, having targeted him as an elderly gay man and therefore easy victim. Cain was tried three times in all. The first trial ended with a deadlocked jury; the second with a conviction that was overturned on appeal, on grounds that testimony from Cain's two previous wives as to his violent temper should not have been admitted in evidence.*[8]

45.3 Publications

45.3.1 Refereed journals

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- *Mechanisms of continental drift and plate tectonics* (1980) edited by P. A. Davies and S. K. Runcorn
- *Magnetism, planetary rotation, and convection in the solar system : retrospect and prospect : in honour of Prof. S.K. Runcorn* (1985) edited by W. O'Reilly, S. K. Runcorn
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45.4 See also

- *Geomagnetism* – Wikipedia book
- List of geophysicists

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45.7 External links

- Biography - Newcastle
- UAF Sydney Chapman Endowed Chair in Physical Sciences

Chapter 46

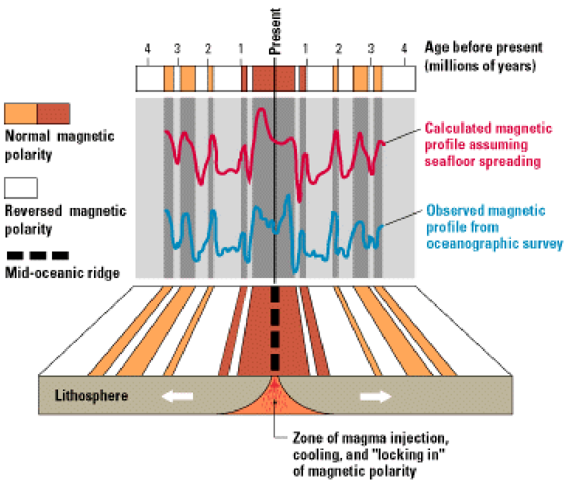
Frederick Vine

Frederick John Vine FRS (born 17 June 1939) is an English marine geologist and geophysicist. He made key contributions to the theory of plate tectonics, helping to show that the seafloor spreads from mid-ocean ridges with a symmetrical pattern of magnetic reversals in the basalt rocks on either side.

46.1 Early life

Vine was born in Chiswick,*[1] London, and educated at Latymer Upper School and St John's College, Cambridge*[2] where he studied Natural Sciences (BA, 1962) and marine geophysics (PhD, 1965).*[3]

46.2 Plate Tectonics



The observed magnetic profile for the sea floor around a mid-oceanic ridge agrees closely with the profile predicted by the Vine–Matthews–Morley hypothesis.

Vine's PhD thesis was on 'Magnetism in the Seafloor', supervised by Drummond Matthews. Having met Harry Hess he was aware of sea floor spreading, where the ocean bed acts as a 'conveyor belt' moving away from the central ridge.*[4] Vine's work, with that of Drummond Matthews and Lawrence Morley of the Geological Survey of Canada, helped put the variations in the magnetic properties of the ocean crust into context in what is now known as the Vine–Matthews–Morley hypothesis. Specifically they supported Dietz's (*Nature* 1961) idea that sea floor spreading was occurring at mid-ocean ridges. Vine and Matthews showed that basalt created at a mid-ocean ridge records earth's current magnetic field polarity (and strength), thus turning Hess's theoretical 'conveyor belt' into a 'tape recorder'.*[4] Furthermore, they showed that magnetic reversals 'frozen' into these rocks, as suggested by Allan Cox (*Nature* 1963),*[5] can be seen as parallel strips as you travel perpendicularly away from the ridge crest.*[4]

46.3 Academic career

Vine worked with E. M. Moores on the Ophiolite in the Troodos mountains of southern Cyprus. He worked with R. A. Livermore and A. G. Smith on the history of the Earth's magnetic field.*[2] He worked on the electrical conductivity of rocks from the lower continental crust with R. G. Ross and P. W. J. Glover, which culminated in 1992 with measurements of the electrical conductivity of graphite-rich amphibolites and granulites at lower crustal temperatures and pressures with a full water saturation and pore fluid pressure.*[6] and graphite-free*[7]

In 1967, Vine became assistant professor of geology and geophysics at Princeton University. In 1970 he moved to the School of Environmental Sciences at the University of East Anglia, becoming Professor there in 1974. He served as Dean from 1977–1980, and again from 1993–1998. Since 1998, he has been a Professorial Fellow of the University of East Anglia.*[2] As of 2008 he was an Emeritus Professor there.*[3]

46.4 Honours

Vine's honours include:

- Day Medal in 1968,*[2]
- Bigsby Medal of the Geological Society of London in 1971,

- Chapman Medal of the Royal Astronomical Society (1973),*[2]
- Fellowship of the Royal Society in March 1974,*[2]
- The Chree Medal and Prize of the Institute of Physics (1977),*[2]
- Hughes Medal of the Royal Society (1982),
- International Balzan Prize (1981).*[2]
- Prestwich Medal of the Geological Society of London in 2007.

46.5 Publications

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46.6 See also

- *Geomagnetism* – Wikipedia book
- List of geophysicists

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[4] BBC / Open University broadcast series *Earth Story*, Vine interviewed by Professor Aubrey Manning

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46.8 External links

- Faculty page
- Fred Vine explaining Paleomagnetic reversals on YouTube

46.9 Text and image sources, contributors, and licenses

46.9.1 Text

- **Earth's magnetic field** *Source:* https://en.wikipedia.org/wiki/Earth'{}s_magnetic_field?oldid=771108356 *Contributors:* Bryan Derksen, The Anome, Rmhermen, Ortolan88, Heron, Hephaestos, Stevertigo, Lir, Michael Hardy, Tim Starling, Ezra Wax, Minesweeper, Fcp, Ahoerstemeier, Msablic, Glenn, Raven in Orbit, Pizza Puzzle, Dino, Reddi, Ab384, Dragons flight, Saltine, SEWilco, Shizhao, Denelson83, Robbot, Ke4roh, Schusch, RedWolf, Nurg, Naddy, Pingveno, Bkell, Hadal, Taliswolf, GreatWhiteNortherner, Tea2min, Giftlite, Bogdanb, Mintleaf~enwiki, Art Carlson, Ferkelparade, Herbee, Sunny256, Jorge Stolfi, Croxis, Alanl, Keith Edkins, Quadell, Onco p53, Elembis, Eregli bob, Kiteinthewind, Jossi, Q9, Icairns, GeoGreg, Zfr, Iantresman, Neutrality, Deglr6328, Thorwald, Mindspillage, Cfailde, Vsmith, Smyth, ESkog, Jnestorius, Imhunt, RJHall, JustinWick, Lankiveil, Shanes, AugustinMa, La goutte de pluie, Jonathunder, Hooperbloob, Mdd, A2Kafir, REwhite, Alansohn, Anthony Appleyard, Kessler, Eric Kvaalen, Sabine's Sunbird, Andrewpmk, Riana, Fritzpoll, Wdfarmer, Dschwen, Velella, Jheald, Harej, RJFJR, Dirac1933, Bsadowski1, BDD, Gene Nygaard, Sturmde, Woohookitty, Rocastelo, Duncan.france, MONGO, GregorB, BlaiseFEgan, Frungi, Wdanwatts, MarcoTolo, Sareini, Lawrence King, BD2412, Kbdank71, Saperaud~enwiki, Rjwilmsi, Vary, Ucucha, Fëaluinix, Pfctdayelise, Margosbot~enwiki, Nihiltres, GünniX, ChongDae, Jrtayloriv, Srleffler, Chobot, Krishnavedala, DVdm, Jodine Sparks, YurikBot, Wavelength, RussBot, Jtkiefer, Eleassar, Salsb, NawlinWiki, SEWilcoBot, Muu-karhu, Qrfqr, Crumley, Richardcavell, FF2010, Wbrameld, Lomacar, Algamarga, SmackBot, Jclerman, Kenny56, K-UNIT, Davewild, Ddcampayo, Edgar181, CPatisaul, SmartGuy Old, Gilliam, The Famous Movie Director, ERcheck, Dyvroeth, Heliostellar, Scaife, Bluebot, Jprg1966, Ctbolt, Colonies Chris, Gracenotes, Can't sleep, clown will eat me, Riose, DavidStern, CA geologist, PokeTIJeremy, Henning Makholm, Jwh, Daniel.Cardenas, Pilotguy, Cothrun, 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- **History of geomagnetism** *Source:* https://en.wikipedia.org/wiki/History_of_geomagnetism?oldid=766172092 *Contributors:* Bearcat, Mcapdevila, Rich Farmbrough, LukeSurl, Jennica, Headbomb, Aymatth2, Mild Bill Hiccup, SchreiberBike, AnomieBOT, RockMagnetist, Helpful Pixie Bot, Bibcode Bot, BattyBot, ArmbrustBot, Bender the Bot and Anonymous: 1
- **Compass** *Source:* https://en.wikipedia.org/wiki/Compass?oldid=769918302 *Contributors:* AxelBoldt, The Cunctator, Bryan Derksen, Zundark, Mirwin, PierreAbbat, William Avery, Heron, Comte0, Jinian, Topory, Nommonomanac, Smelialichu, JohnOwens, Michael Hardy, Pit~enwiki, Dante Alighieri, Dcljr, Arpingstone, Alfio, Ahoerstemeier, Kingturtle, Salsa Shark, Ugen64, Glenn, Rossami, Nikai, John K, Raven in Orbit, Loren Rosen, Reddi, Johnh123, Itai, Ringomassa, Populus, Oaktree b, Wetman, Secretlondon, Shantavira, Denelson83, Rogper~enwiki, Robbot, Chris 73, Altenmann, Naddy, Modulatum, Ojigiri~enwiki, Hadal, SpellBott, Tea2min, Ancheta Wis, Giftlite, Tom harrison, IRelayer, Mark.murphy, Everyking, No Guru, Joconnor, Yekrats, Mboverload, Eequor, Brockert, Python eggs, Bobblewik, Peter Ellis, Alexf, Knutux, Sonjaaa, Antandrus, Onco p53, OverlordQ, Bumm13, Icairns, Imjustmatthew, Chmod007, Trevor MacInnis, Zro, Mike Rosoft, Rob cowie, Haiduc, Jiy, Spiko-carpediem~enwiki, EugeneZelenko, Discospinster, Rich Farmbrough, Cfailde, Rama, Mani1, Dmeranda, Stbalbach, Bender235, ESkog, Billlion, Brian0918, LordHarris, Hayabusa future, Mwanner, Sietse Snel, Cacophony, Bobo192, Nigelj, Smalljim, Nyenyec, .:Ajvol:., Man vyi, La goutte de pluie, Nk, Polylerus, Hooperbloob, Nsaa, HasharBot~enwiki, Drf5n, Jumbuck, Musiphil, Alansohn, Anthony Appleyard, Polarscribe, Jeltz, Lord Pistachio, Mlessard, Trjumpet, Ynhockey, Stalefries, Harburg, Wdfarmer, Burwellian, Wtmitchell, Velella, ProhibitOnions, Suruena, Max Naylor, RainbowOfLight, Bsadowski1, Zereshk, Blaxthos, UTSRelativity, Adrian.benko, Oleg Alexandrov, Zntrip, Simetrical, Reinoutr, Woohookitty, Shreevatsa, Scriberius, Aaron McDaid, Armando, Paul Mackay~enwiki, Jeff3000, Damicatz, Philbarker, Gisling, Caiqian, BD2412, Edison, Canderson7, Rjwilmsi, BenWilliamson, Koavf, Kinu, Vary, Salix alba, KharBevNor, LjL, KAM, FlaBot, Nivix, Hottentot, RexNL, Gurch, Bigdottawa, Ahunt, Benjwong, MoRsE, Chobot, Bgwhite, Gwernol, Roboto de Ajvol, Sus scrofa, YurikBot, Wavelength, Hairy Dude, Tznkai, RussBot, Petiatil, Fabartus, Byron Vickers, Lexi Marie, SpuriousQ, Hydrargyrum, Stephenb, CambridgeBayWeather, Rsrikanth05, Shkarter1985, Big Brother 1984, NawlinWiki, Joel7687, Irishguy, Brandon, Ravedave, Voidxor, Bucketsofg, Kortoso, Pablomartinez, Mjsabby, Dv82matt, Wknight94, TransUtopian, Eurosong, Katpatuka, Wiqi55, Anarchyboy, Phgao, Zzuuzz, E Wing, KGasso, Rlhatton, Clay-

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- **Magnetic dip** *Source:* https://en.wikipedia.org/wiki/Magnetic_dip?oldid=735056434 *Contributors:* Robbot, Jheald, JonH, Chobot, Tony1, Jagged 85, Vina-iwbot~enwiki, Tazmaniacs, Chris55, Thalion77, Neelix, Cydebot, SteveMcCluskey, Hazmat2, Yrtgm, VolkovBot, Red Act, Ferengi, Dolphin51, Pointillist, Draeath, XLinkBot, Чръный человек, Addbot, Luckas-bot, Yobot, AnomieBOT, Br77rino, Patchy1, Pps85, Mean as custard, RjwilmsiBot, EmausBot, QEDK, Dgsharp, RockMagnetist, Gareth Griffith-Jones, 7Sidz, 123fudgesticks, Bender the Bot and Anonymous: 16
- **Magnetic declination** *Source:* https://en.wikipedia.org/wiki/Magnetic_declination?oldid=770634918 *Contributors:* Andre Engels, Ahoerstemeier, Plop, Palmpilot900, Lommer, ShaunOfTheLive, SEWilco, Populus, Jerzy, Giftlite, Julianp, Everyking, Rchandra, Icairns, Mormegil, Vsmith, Xezbeth, Mdf, Bobo192, Eric Kvaalen, RoySmith, Ptschett, Pwqn, Peter Hitchmough, Lupinelawyer, Pdn~enwiki, Pfalstad, Trewornan, Obersachse, Jclemens, Filipvr, Heath Johnson, Bubba73, Quuxplusone, BabyNuke, Wrightbus, Chobot, Whosasking, YurikBot, Wormholio, PiAndWhippedCream, Salsb, Cheyne, Vivaldi, JustAddPeter, FF2010, Fibula, Skittle, Richardj311, Mejor Los Indios, Luk, SmackBot, Manoj c, Agateller, Scwlong, Kunnis, Arielco, Magma2, Genedial, Ckatz, SQGibbon, RHB, Hgrobe, Iridescent, Ramskjell, Haus, CmdrObot, BeenAroundAWhile, Marc Salvisberg, MaxEnt, Cydebot, Thijs!bot, Marek69, Dawnseeker2000, AstroLynx, Richard2357, LorenzoB, PrestonH, BenTels, Tina Cordon, LordAnubisBOT, NewEnglandYankee, Stanqo, Sarregouset, Alan U. Kennington, Indubitably, Barneca, Philip Trueman, TXiKiBoT, Rei-bot, UnitedStatesian, Boot Hill, PericlesofAthens, StevenBell, JuanFox, Oxymoron83, Faradayplank, OKBot, Wjwalrus, Petercep, ClueBot, Mild Bill Hiccup, Sv1xv, Draeath, Bruceadler, Aitias, Devadaru, MystBot,

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- **Magnetometer** *Source:* https://en.wikipedia.org/wiki/Magnetometer?oldid=771419473 *Contributors:* TwoOneTwo, Heron, Mbecker, Edward, Tim Starling, Evanherk, Ronz, TUF-KAT, Julesd, Andrewman327, SEWilco, Jeffq, Nurg, Giftlite, 0x0077BE, Bkonrad, Rchandra, Sam Hocevar, Deglr6328, Trevor MacInnis, Zowie, Discospinster, Bender235, Mdf, Kwamikagami, La goutte de pluie, Kjkolb, Novakyu, Congruence, Hooperbloob, Wendell, Alansohn, Wtmitchell, Velella, Wtshymanski, Gene Nygaard, Noz92, Pol098, Jugger90, Smartech~enwiki, Mendaliv, EdDavies, Unused007, Rjwilmsi, Vegaswikian, FlaBot, Neofelis Nebulosa~enwiki, DaGizza, Mrnatural, Hydrargyrum, Van der Hoorn, Gaius Cornelius, Welsh, Topperfalkon, Mysid, NorsemanII, Open2universe, Mike1024, Fram, ThunderBird, NickelShoe, SmackBot, Shoy, Nil Einne, Xaosflux, Jprg1966, Alexmcfire, Zazpot, Arielco, Lambiam, Acrabb, Mh143, Xofc, Rock4arolla, Dicklyon, Geologyguy, Profnick, Tapatio, Peter Horn, Ahdfox, Tawkerbot2, G-W, Chris55, Owen214, Rszasz, Jbusenitz, CmdrObot, Vyznev Xnebara, Zureks, ShelfSkewed, No1lakersfan, Badseed, Supremeknowledge, Altaphon, UncleBubba, Jstuby, Thijs!bot, Epbr123, Headbomb, Missvain, Dawnseeker2000, ReverendG, Jasen betts, Bodragon, Jheiv, TAnthony, Dream Focus, Christopher Cooper, VoABot II, Dulciana, Twarge, David Eppstein, Xenobiotica, Vzapf, GeorgHH, R'n'B, Pdeitiker, J.delanoy, Rod57, WithGLEE, Mlwindsor, Rdfr, Saryakhran, Deor, VolkovBot, The Original Wildbear, Davehi1, Xerxesnine, Gfanari~enwiki, SieBot, Moonriddengirl, Thegreatmichael, Caltas, Kstowers, Flyer22 Reborn, Immo trinks, Stfg, Chem-awb, YSSYguy, ClueBot, Trojancowboy, GorillaWarfare, PipepBot, Mechatronik, LizardJr8, Excirial, Ecov, Arjayay, Thingg, Forbes72, M2o6n0k2e7y3, Addbot, Panthos3, Charliedill, John Chamberlain, Chamal N, TStein, Jubeidono, Numbo3-bot, Ehrenkater, QWerk, Legobot, Luckas-bot, Yobot, AnomieBOT, Polarbear24, Materialscientist, Citation bot, HorridRedThings, ArthurBot, LilHelpa, Abdul qayyum 1986, Anna Frodesiak, J04n, GrouchoBot, Maximumeve, Fotaun, FrescoBot, Originalwana, Seleonov, InternetFoundation, Citation bot 1, Tom.Reding, Tjmoel, Kgrad, Trappist the monk, Philipdaubmeier, Obankston, John of Reading, WikitanvirBot, Rami radwan, Dewritech, Dcirovic, K6ka, RockMagnetist, -revi, Mikhail Ryazanov, ClueBot NG, Anagogist, Smartguy noface1990, David C Bailey, Blairwalker1, Braincricket, Dakrause, Helpful Pixie Bot, Jn52, Bibcode Bot, BG19bot, Bmusician, Magman5, Ducksfordollars, MusikAnimal, IraChesterfield, Cameron6426a, BattyBot, Mdann52, Dexbot, Ironinthepath, AudunVN, Mark viking, Flat Out, ColRad85, Monkbot, Yikkayaya, SkateTier, Brutemenu, Ththeis, Hkeyser, Magnetic models, Γκάλπινος Βασίλης, Peter Tapken, Isambard Kingdom, Abstractdave, ThePercussiveEngineer, Dyfeinstein, Sperth and Anonymous: 243
- **Geomagnetic pole** *Source:* https://en.wikipedia.org/wiki/Geomagnetic_pole?oldid=766629682 *Contributors:* Davemck, Frglee, Cydebot, Hakseng, R'n'B, GeoWriter, TimofKingsland, Truthanado, Goustien, Addbot, Fgnievinski, Abductive, Duoduoduo, RjwilmsiBot, RockMagnetist, Helpful Pixie Bot, Gob Lofa, Ubiquinoid, Blues, Cavit2, Spyglasses, DoomS Dey, Xiopsis and Anonymous: 4
- **North Magnetic Pole** *Source:* https://en.wikipedia.org/wiki/North_Magnetic_Pole?oldid=770599552 *Contributors:* Axlrosen, Skysmith, Lukobe, Dino, Dragons flight, Nnh, Bearcat, Robbot, Mayooranathan, Timvasquez, Giftlite, Beland, D6, Apalsola, Vsmith, Bender235, Shanes, Grutness, Alansohn, Jhertel, Pinar, Mysdaao, Rwendland, Iustinus, Sturmde, Richard Weil, Crosbiesmith, Mu301, Camw, Carcharoth, GregorB, Wisq, Hpka, Rjwilmsi, Tizio, Kolbasz, Drhoss, Chobot, The Rambling Man, Wavelength, Koveras, StuffOfInterest, Christy747, CambridgeBayWeather, JHCaufield, Nikkimaria, SmackBot, Anastrophe, Rolypolyman, Nossac, Colonies Chris, Jdthood, Scwlong, Nakon, Tim riley, Andrei Stroe, Like tears in rain, Caviare, Meco, Mets501, CapitalR, Chetvorno, Bonás, Cydebot, MC10, Paul Heckbert, JesseChisholm, Robertinventor, Ssilvers, Thijs!bot, Epbr123, Ucanlookitup, Headbomb, Nadav1, Hires an editor, JAnDbot, Miti gta, Lost-theory, FaerieInGrey, Stubbleboy, Websterwebfoot, Suestockdale, Gabriel Kielland, Berig, NatureA16, Tntdj, DoctorJava, Ethan c.00, Hugo999, VolkovBot, MichaelSchoenitzer, Kristelwa, DerGolgo, Broadbot, UnitedStatesian, Loyalgadfly, RandomXYZb, Spinningspark, PericlesofAthens, Drumskirun, Zenlax, Scarian, Grundle2600, Faradayplank, Goustien, Lightmouse, Mr. Stradivarius, WordyGirl90, ClueBot, Marklkelly, Nnemo, Heflinator, Maccy69, BumpWit, Alexbot, Johnuniq, DumZiBoT, Mcrules230, Little Mountain 5, Avoided, Addbot, Pietersz~enwiki, Rklear, ChenzwBot, Ehrenkater, مانی, Zorrobot, Greyhood, Luckas-bot, Beeswaxcandle, Marshall Williams2, AnomieBOT, Archon 2488, Jim1138, Stickybombs, ArthurBot, Capricorn42, RibotBOT, Cicero418, Goalsleft2342, Naru12333, Tom.Reding, RedBot, Thinking of England, 1to0to-1, Maciejw, TobeBot, Hutington, Reaper Eternal, Specs112, DARTH SIDIOUS 2, Mean as custard, NameIsRon, Lollypopfred, EmausBot, WikitanvirBot, Wikipelli, OnePt618, Samoojas, RockMagnetist, ClueBot NG, Firebird2099, Vacation9, Calabe1992, Gob Lofa, Petrarchan47, Josiemiajuliet, Mark Arsten, Ggreybeard, Ubiquinoid, BattyBot, Electricmuffin11, Webclient101, Cinderkimberstammy, Makecat-bot, Anirudh2a, Numbermaniac, Frosty, Cavit2, Tobythedog1, XXX8906, Tyr2396, ThatRusskiiGuy, Monkbot, Griffin134, Isambard Kingdom, TWaMoE, Bob9454, Cavit, Trevorhulette, Xiopsis and Anonymous: 172
- **South Magnetic Pole** *Source:* https://en.wikipedia.org/wiki/South_Magnetic_Pole?oldid=770600429 *Contributors:* Mav, Lukobe, Dino, PeterGrecian, Donarreiskoffer, Robbot, Rpyle731, D6, Discospinster, Pmsyyz, Vsmith, Bender235, Bobo192, Grutness, Brookie, BillC, Btyner, Ketiltrout, SchuminWeb, Eubot, Glenn L, Hairy Dude, Wknight94, Nikkimaria, SmackBot, Hugh24, Ohconfucius, Like tears in rain, CapitalR, Cydebot, Robertinventor, Thijs!bot, Headbomb, JAnDbot, Bongwarrior, Zhov, NatureA16, CliffC, R'n'B, Melamed katz, Chiswick Chap, Treisijs, Hugo999, Philip Trueman, Broadbot, Gerbis, Biscuittin, Lewinhodgman, Sfan00 IMG, Hal8999, NuclearWarfare, Saebjorn, Addbot, LaaknorBot, WuBot, Zorrobot, Greyhood, Luckas-bot, Yobot, Legobot II, DiverDave, AnomieBOT, ArthurBot, LilHelpa, Xqbot, Nurnord, DSisyphBot, GrouchoBot, Spesh531, Boris grishenko, Pservini, Tinton5, Full-date unlinking bot, WikitanvirBot, Creolteno, RockMagnetist, ClueBot NG, Gob Lofa, BG19bot, Mangm, Ggreybeard, Ubiquinoid, ThievingBeagles, Marshini Ganesh, Isambard Kingdom and Anonymous: 51
- **Magnetic anomaly** *Source:* https://en.wikipedia.org/wiki/Magnetic_anomaly?oldid=751520012 *Contributors:* Carlossuarez46, Shantavira, Vsmith, Yuriybrisk, Closedmouth, タチコマ robot, SmackBot, P199, G-W, Dawnseeker2000, Mikenorton, Volcanoguy, Pterre, Chienlit, Kurgus, Rosiestep, Piledhigheranddeeper, Jgamleus, Addbot, Yobot, EdwardLane, Dude1818, TobeBot, EmausBot, John of Reading, RockMagnetist, Monkbot, MBlaze Lightning and Anonymous: 14
- **Magnetosphere** *Source:* https://en.wikipedia.org/wiki/Magnetosphere?oldid=761723694 *Contributors:* Trelvis, Bryan Derksen, Roadrunner, SimonP, Heron, Lir, Tim Starling, Vera Cruz, Iluvcapra, Looxix~enwiki, Stan Shebs, TUF-KAT, Kricke, Hike395, Mpt, Reddi, Steinsky, Furrykef, SEWilco, Philopp, Traroth, Jni, Robbot, Justo, Merovingian, Giftlite, Art Carlson, Zinnmann, Jordanh, Bobblewik, Antandrus, Beland, Kaldari, Icairns, Iantresman, Imjustmatthew, Guanabot, Vsmith, Mani1, Bender235, RJHall, El C, Svdmolen, .:Ajvol:., Pearle, Alansohn, Wricardoh~enwiki, Wtmitchell, TaintedMustard, TenOfAllTrades, Gene Nygaard, Redvers, Siafu, Rorschach, Tomem~enwiki, Bhamer, Bluemoose, LocoBurger, Eyreland, FreplySpang, Rjwilmsi, .digamma, Vary, Mike s, Titoxd, Margosbot~enwiki, Nihiltres, DVdm, FrankTobia, YurikBot, Wavelength, Borgx, Retodon8, Sillybilly, Chaser, Van der Hoorn, Welsh, Sir48, E2mb0t~enwiki, Beanyk, DeadEyeArrow, Dddstone, Exodio, Sota767, Sardanaphalus, SmackBot, Cdogsimmons, Onebravemonkey, Oscarthecat, Bakerkb1, Chris the speller, Bluebot, KaragouniS, The Rogue Penguin, Tigerhawkvok, UnKnown X, Njál, OrphanBot, Jmnbatista, Aldaron, DinosaursLoveExistence, DavidStern, Radagast83, Larsenphys, Ixnayonthetimmay, Ck lostsword, Žiga, Breno, JorisvS, GVP Webmaster, Mathias-S, Ckatz,

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- **Geomagnetic secular variation** *Source:* https://en.wikipedia.org/wiki/Geomagnetic_secular_variation?oldid=722708203 *Contributors:* Woohookitty, Headbomb, Faizhaider, Fabrictramp, Katharineamy, Belovedfreak, XLinkBot, Dthomsen8, Yobot, Citation bot, The Legendary Sky Attacker, Neil goldman-schmitt, RockMagnetist, Helpful Pixie Bot, Cavit2, Monkbot and Anonymous: 2
- **Geomagnetic excursion** *Source:* https://en.wikipedia.org/wiki/Geomagnetic_excursion?oldid=763724212 *Contributors:* Michael Hardy, Dragons flight, Rorro, Graeme Bartlett, Rich Farmbrough, Vsmith, Maurreen, La goutte de pluie, Atlant, BRW, Alex.g, Ground Zero, Krótki, SmackBot, Danilot, Rocklaura, Robertinventor, WolfmanSF, Larryisgood, WurmWoode, Mild Bill Hiccup, Director Re, 0XQ, Ost316, Addbot, GrouchoBot, Erik9bot, FrescoBot, Kmb19, RockMagnetist, Bibcode Bot, Dodshe, 93, Monkbot and Anonymous: 3
- **Geomagnetic reversal** *Source:* https://en.wikipedia.org/wiki/Geomagnetic_reversal?oldid=771073340 *Contributors:* AxelBoldt, Wayne Hardman, Michael Hardy, Bogdangiusca, Charles Matthews, Dragons flight, Saltine, SEWilco, Bevo, Shizhao, AnonMoos, Nurg, Wjhonson, Rorro, Rursus, Cyrius, Graeme Bartlett, DocWatson42, Nova77, Onco p53, Sam Hocevar, RevRagnarok, Vsmith, Roo72, Bender235, CDN99, Smalljim, Timecop, Alansohn, Atlant, Bart133, Before My Ken, Duncan.france, Eyreland, SDC, Ashmoo, Graham87, Rjwilmsi, Lars T., Jmcc150, NeonMerlin, Nihiltres, Ewlyahoocom, Intgr, CJLL Wright, YurikBot, Hellbus, Salsb, Anomie, EEMIV, Jessemerriman, Gzabers, Light current, Teentitans!, 2over0, Xaxafrad, Scoutersig, SmackBot, Eskimbot, Gilliam, A. B., Scwlong, Nick Levine, Abyssal, Akijikan, Paul H., Octupole, Adendress, Garry Denke, Swatjester, Titus III, JorisvS, Geeteshgadkari, Jodamn, Miss Matrix, Geologyguy, Paul venter, Dia^, Rezin8, Dorothybaez, Yaris678, Tewapack, Saintrain, Thijs!bot, Second Quantization, Noclevername, Steve Zissou, Mikenorton, Husond, AniRaptor2001, Hello32020, Bongwarrior, VoABot II, Rexfan2, Chris Grose, Iglonghurst, Brusegadi, Dhk, BatteryIncluded, Inhumandecency, Stephenchou0722, Ugajin, Nikpapag, AstroHurricane001, GeoWriter, Noelhunter, Belovedfreak, Pansapiens, Geekdiva, Sgeureka, CardinalDan, VolkovBot, TallNapoleon, Gaianauta, Speaker to wolves, Dominics Fire, Philip Trueman, Zamphuor, Karl07, Robert1947, Maxim, Mazarin07, Spiral5800, Q Science, MCTales, Brianga, Gbawden, StAnselm, Yintan, Crash Underride, LeadSongDog, Chirigami, KritonK, Atif.t2, ClueBot, Daffydavid, Quisqualis, Bchristo, Parkjunwung, Alexbot, Jar mes, Τις, Mlaffs, Aitias, CrackheadMcGee, Misterbeal, Aaron north, Jgamleus, NCDane, Addbot, Xp54321, Pietersz~enwiki, DOI bot, Balabiot, Team4Technologies, Luckas-bot, Yobot, Wikipaddn, AnomieBOT, Rubinbot, Citation bot, Gelvan tullibole 3rd, Gamerdude220, Loveless, Alkibiades231, GrouchoBot, RibotBOT, Look Busy, B767-500, FrescoBot, Craig Pemberton, DivineAlpha, Citation bot 1, PigFlu Oink, I dream of horses, Tom.Reding, Gaussman, IVAN3MAN, Zhernovoi, Adeade00, Marvinandmilo, Reaper Eternal, Losttime17, RjwilmsiBot, Ripchip Bot, John of Reading, GoingBatty, Exok, AManWithNoPlan, Donner60, Puffin, RockMagnetist, Senator2029, Whoop whoop pull up, ClueBot NG, SpikeTorontoRCP, Jack Greenmaven, Widr, Telpardec, Danim, Helpful Pixie Bot, Gob Lofa, Bibcode Bot, Nashhinton, Island Monkey, Danwenlock, Alexbee13, IChangeYourPage, Dodshe, Swbogue, Compfreak7, ZFT, Flobber-dobber, Gorthian, Quristic, BattyBot, Netherzone, Jimw338, Webclient101, Lugia2453, The Quirky Kitty, Rmmalizia, Madreterra, Grant Hatch, Ugog Nizdast, WingTillDie, JaconaFrere, SaraNedrich, Monkbot, Julietdeltalima, Ltbbigtimer, Isambard Kingdom, Detomale, Orange julius 42, WonnE66, GreenC bot, Bear-rings, Ib dropout and Anonymous: 207
- **Geomagnetic storm** *Source:* https://en.wikipedia.org/wiki/Geomagnetic_storm?oldid=770705486 *Contributors:* Ed Poor, Stevertigo, Lir, Nealmcb, Michael Hardy, Glenn, Hike395, Wikiborg, Stone, SEWilco, Indefatigable, Denelson83, Twang, Ke4roh, Taliswolf, Tom harrison, Karn, Everyking, Gilgamesh~enwiki, Dmmaus, Beland, NoPetrol, Paulley, Perey, Kdammers, Vsmith, TerraFrost, Srbauer, RoyBoy, One-dimensional Tangent, MJT1331, Evolauxia, Pearle, Velella, Aurbina, Gene Nygaard, Dejvid, Woohookitty, LOL, Pixeltoo, Rjairam, Eyreland, Wayward, Rjwilmsi, JohnElder, Payo, Chobot, Nylex, YurikBot, Jeffhoy, Hellbus, Hydrargyrum, Shaddack, Salsb, Thane, Ornilnas, NawlinWiki, Ytcracker, Abune, Tevildo, SmackBot, Speight, Yuyudevil, KVDP, Commander Keane bot, Bluebot, Agateller, Persian Poet Gal, RDBrown, Rediahs, Colonies Chris, Rlevse, Zvar, Whpq, Jgoulden, Jmnbatista, DinosaursLoveExistence, Mini-Geek, Vgy7ujm, Tazmaniacs, Jaganath, Nagle, Meco, Mets501, Alan.ca, CapitalR, Tawkerbot2, Cryptic C62, JForget, Runningonbrains, Ruslik0, Michael C Price, Mike1942f, Thijs!bot, Barticus88, RisingStar, Ufwuct, Escarbot, QuiteUnusual, Carolmooredc, Lfstevens, Gordonnovak, Magioladitis, BatteryIncluded, LorenzoB, William James Croft, Johnmarks9, Dbrunner, Info D, Misibacsi, MartinBot, Kiore, Keith D, R'n'B, AstroHurricane001, Personjerry, All Is One, Jesant13, Chiswick Chap, SriMesh, D.M.N., Mokgen, VolkovBot, Philip Trueman, J3gum, Dawaegel, AllGloryToTheHypnotoad, Axpulkki, Conformancenut347, SieBot, Steorra, VVVBot, J-puppy, Dreg, Sanya3, Danoham, StaticGull, Jfromcanada, Martarius, ClueBot, IceUnshattered, Plastikspork, AndersIE, Sv1xv, Djr32, Excirial, Werlebrid44, Muro Bot, Polemos~enwiki, Dthomsen8, Lemchesvej, Starmaker it, Deineka, Addbot, Some jerk on the Internet, Leszek Jańczuk, Sapphosyne, Quantumobserver, Legobot, Luckas-bot, Yobot, Legobot II, Azcolvin429, Examtester, AnomieBOT, Mauro Lanari, Kokichau, Unara, Kingpin13, Citation bot, Thomas Immel, Leijh, Vertikal Design, RibotBOT, Andyyso, Rainald62, Shadowjams, Omar35880, FrescoBot, Krj373, RicHard-59, Pinethicket, Tom.Reding, EdoDodo, Full-date unlinking bot, Bdescham, EmausBot, John of Reading, Abosalahvimto, Ghostofnemo, Immunize, RA0808, Peaceray, QuantumOfHistory, Dcirovic, ZéroBot, Twistoratus, Wikfr, Webbeh, MonoViejo, Anonimski, ChuispastonBot, RockMagnetist, ClueBot NG, Ruckgerm, Flynx, Lynnbwilsoniii, Helpful Pixie Bot, HMSSolent, Bibcode Bot, Richfj, BG19bot, Vagobot, McQuade, Shawn Worthington Laser Plasma, BattyBot, Khazar2, Evaraseac, Bnland, Ultra Venia, Dexbot, Makecatbot, Me, Myself, and I are Here, Jsimmms002, CeeCeeM, DavidLeighEllis, Pokebub22, Marc Bago, 32RB17, Monkbot, Bharding512, Bentank, Perapin, Tetra quark, Isambard Kingdom, KasparBot, Parsley Man, Luca.spogli and Anonymous: 143
- **Apparent polar wander** *Source:* https://en.wikipedia.org/wiki/Apparent_polar_wander?oldid=764343099 *Contributors:* Michael Hardy, Lancevortex, Vsmith, Blaxthos, Wyvern, Rjwilmsi, Dawnseeker2000, Life of Riley, Chris.urs-o, John of Reading, RockMagnetist, Prabhat1729, BG19bot, BarbaraMervin, Hamish59, Pat.beaudry, Enstatite, Monkbot, Ita1986 and Anonymous: 2

- **Dynamo theory** *Source:* https://en.wikipedia.org/wiki/Dynamo_theory?oldid=768295646 *Contributors:* Roadrunner, Ray Van De Walker, Michael Hardy, Tim Starling, Skysmith, Tiles, Stevenj, Pizza Puzzle, Reddi, Quoth-22, Robinh, Davidjonsson, Xanzzibar, David Gerard, Paisa, Art Carlson, Everyking, Niteowlneils, Dvavasour, Onco p53, Zaheen, Vsmith, Bender235, Spoon!, Hurricane111, Remuel, Physicistjedi, Wrs1864, SPUI, Bucephalus, Dirac1933, Gene Nygaard, Joriki, Duncan.france, GregorB, Miken32, Mandarax, Sjakkalle, Rjwilmsi, JHMM13, Williamborg, Geollama, Kortoso, Pr1268, Xaxafrad, Exit2DOS2000, KnightRider~enwiki, Brianwelsch, Westsider, Bluebot, Can't sleep, clown will eat me, Cophus, Onorem, Midnightcomm, Julia431, Vina-iwbot~enwiki, JorisvS, Hemmingsen, Thutch, Twas Now, Chetvorno, Drenaline, Underpants, Satori Son, Thijs!bot, D.H, Icep, Magioladitis, VoABot II, Jbmendelson, Marvin Herndon, Coppertwig, Craigheinke, TXiKiBoT, AxelBrandenburg, UnitedStatesian, James McBride, SieBot, Fox53, Cwkmail, Razimantv, Mild Bill Hiccup, Richerman, Jar mes, Ost316, Addbot, DAEdgerley Ph.D., Yobot, Fraggle81, N3hima, QuantumCyclops, AnomieBOT, Petercascio, AdjustShift, Marshallsumter, Capricorn42, Omnipaedista, RibotBOT, Pederony, Mbejger, FrescoBot, Steve Quinn, Pinethicket, MastiBot, Veqz, IVAN3MAN, Dinamik-bot, Alph Bot, EmausBot, RA0808, Netheril96, Lucas Thoms, Dekker451, ZéroBot, Cogiati, Quondum, Samoojas, RockMagnetist, ClueBot NG, DonaldET3, Widr, Helpful Pixie Bot, Bibcode Bot, Wiki13, Mark Arsten, CitationCleanerBot, MrJohnnyMorales, Droit de Suite, BattyBot, Pratyya Ghosh, Sidelight12, Aellithy, SamanthaPuckettIndo, Franz Scheerer (Olbers), Spencedaddy1121, Elenceq, Radiomansun, Monkbot, SkateTier, MSZ372, Suphanat Isarangkoon Na Ayutthaya, H.dryad, InternetArchiveBot, Dorch and Anonymous: 100
- **Paleomagnetism** *Source:* https://en.wikipedia.org/wiki/Paleomagnetism?oldid=758093377 *Contributors:* William Avery, Rbrwr, Michael Hardy, Robbot, Rursus, Giftlite, Icairns, Avihu, Thorwald, DanielCD, Discospinster, Vsmith, Stevilbot, Florian Blaschke, Eric Kvaalen, Clarphimous, Knowledge Seeker, Grenavitar, David Haslam, Rjwilmsi, FlaBot, Allander, Chobot, Gap, Wavelength, Yamara, MaxD~enwiki, Salsb, Muu-karhu, Tony1, Bota47, Kkmurray, SmackBot, Abyssal, Locutus Borg~enwiki, Smith609, CmdrObot, Antriver, Thijs!bot, Epbr123, John254, Tellyaddict, Uruiamme, Omphacite, Myanw, Mikenorton, DuncanHill, Gcm, Wayne Miller, NatureA16, MarkRoberts, Pharaoh of the Wizards, AstroHurricane001, Belovedfreak, Hanacy, VolkovBot, Rei-bot, Botev, JerrySteal, Oxymoron83, Twinsday, ClueBot, Geologicharka, Mild Bill Hiccup, Vraidente, Jo Weber, 7, ErgoSum88, Addbot, LaaknorBot, DrHerries, SwisterTwister, Jim1138, AdjustShift, Materialscientist, Citation bot, Shirik, Erik9, FrescoBot, Peter Mercator, Steve Quinn, Malahci, Citation bot 1, Pinethicket, ActivExpression, Fama Clamosa, Tbhotch, EmausBot, JayeJaye0!, SDS MT, Bollyjeff, Wackywace, MrZalli, RockMagnetist, EdoBot, Petrb, ClueBot NG, Jack Greenmaven, Polarwander, Helpful Pixie Bot, Cpluhar, Bibcode Bot, Lols03, Gorthian, Alangilchrist, Cyberbot II, EnzaiBot, Njarboe, Makecat-bot, MatthewHoobin, Ginsuloft, Anrnusna, Mpj7, KasparBot, Gaelan, InternetArchiveBot, Entranced98, GreenC bot, KatB2345, Batman$$, Justeditingtoday and Anonymous: 76
- **Environmental magnetism** *Source:* https://en.wikipedia.org/wiki/Environmental_magnetism?oldid=758761820 *Contributors:* Rjwilmsi, Headbomb, EoGuy, Boing! said Zebedee, Citation bot, RockMagnetist, Helpful Pixie Bot, Bibcode Bot, BG19bot, Magmagic and Frankyxl
- **Magnetostratigraphy** *Source:* https://en.wikipedia.org/wiki/Magnetostratigraphy?oldid=767994195 *Contributors:* Vsmith, Thijs!bot, Marek69, Mentifisto, Mikenorton, Ulrichstill, Twinsday, Quisqualis, Awickert, Addbot, SpBot, KamikazeBot, RockMagnetist, Rezabot, Helpful Pixie Bot, BattyBot and Anonymous: 6
- **Rock magnetism** *Source:* https://en.wikipedia.org/wiki/Rock_magnetism?oldid=681686726 *Contributors:* Icairns, Rich Farmbrough, Vsmith, BD2412, Salsb, SmackBot, Mikenorton, MystBot, Addbot, Citation bot, Citation bot 1, Lainestl, RockMagnetist, Polarwander, Helpful Pixie Bot, Bibcode Bot, Gorthian, Snow Blizzard and Anonymous: 7
- **Néel relaxation theory** *Source:* https://en.wikipedia.org/wiki/N%C3%A9el_relaxation_theory?oldid=578788355 *Contributors:* Bgwhite, Gilo1969, RockMagnetist, Bibcode Bot, Op47 and Anonymous: 1
- **Thermoremanent magnetization** *Source:* https://en.wikipedia.org/wiki/Thermoremanent_magnetization?oldid=591946484 *Contributors:* Rich Farmbrough, SmackBot, RjwilmsiBot, RockMagnetist, Saebvn, Helpful Pixie Bot, Bibcode Bot, Vycl1994 and Anonymous: 1
- **Remanence** *Source:* https://en.wikipedia.org/wiki/Remanence?oldid=765886003 *Contributors:* Fubar Obfusco, Michael Hardy, Cimon Avaro, Reddi, Omegatron, Robbot, Moxfyre, Kate, Vsmith, Kross, Bert Hickman, Brownsteve, JIP, MarSch, FlaBot, Anthony81212, Margosbot~enwiki, RussBot, Anomalocaris, Juanpdp, Light current, Amtiss, Chetvorno, Zureks, PamD, Thijs!bot, Royas, Rostislav Lapshin, Rostislav V. Lapshin, Roland Goossens, Estirabot, BOTarate, Addbot, AndersBot, Yobot, AnomieBOT, Materialscientist, Kernel.package, GliderMaven, BenzolBot, Citation bot 1, Vrenator, Armando-Martin, RjwilmsiBot, Ripchip Bot, Primefac, Hoeksas, RockMagnetist, Bibcode Bot, Dexbot, Anrnusna, Mayank2910, Fmadd, Bender the Bot and Anonymous: 18
- **Magnetic susceptibility** *Source:* https://en.wikipedia.org/wiki/Magnetic_susceptibility?oldid=771165832 *Contributors:* DrBob, Heron, Michael Hardy, Looxix~enwiki, Radiojon, Giftlite, Lupin, Fascinet, Aulis Eskola, Icairns, Gianluigi, Shanes, Wtshymanski, Sciurinæ, Gene Nygaard, Duncan.france, DePiep, Rjwilmsi, Nihiltres, Kri, Gaius Cornelius, Salsb, ArséniureDeGallium, Rdrosson, Sbyrnes321, Sebesta, Apple2, Betacommand, Chris the speller, Csoliverez, V1adis1av, Smokefoot, Roy Hoffman, FrozenMan, Politepunk, RahulM18, Zureks, Karenjc, Vectro, Cydebot, Headbomb, JAnDbot, Gcm, Jthorsen3315, Tsuji, Dirac66, SBarnes, XRiffRaffx, Keith D, R'n'B, Adavidb, Skier Dude, Jcwf, Xenonice, Signalhead, Michi zh, Lsyn, BehzadAhmadi, Petergans, Neparis, Ponyo, SieBot, Lightmouse, Sunrise, OKBot, GorillaWarfare, PipepBot, Snigbrook, Jalanpalmer, Jlacount, Brews ohare, JTB01, M.O.X, DumZiBoT, Jytdog, Job Inkop~enwiki, Addbot, AndersBot, زرشک, Matěj Grabovský, Zorrobot, Snaily, Yobot, AnomieBOT, AdjustShift, Materialscientist, Citation bot, LilHelpa, 老陳, Citation bot 1, Just a guy from the KP, Capra Ibex Ibex, Trappist the monk, Floydmitchell, Marie Poise, Woogee, RjwilmsiBot, LMBRPOVOA, EmausBot, WikitanvirBot, Dcirovic, RockMagnetist, Nscozzaro, Bibcode Bot, BG19bot, Nicola.Manini, Jessetjenkins, Mlklt, Jimw338, The Illusive Man, Dexbot, Thepasta, Anrnusna, SirMinkMay, Emergentmatter, TerpeneOtto, Yassuhuhgg and Anonymous: 71
- **Magnetic mineralogy** *Source:* https://en.wikipedia.org/wiki/Magnetic_mineralogy?oldid=753573599 *Contributors:* Vsmith, Egsan Bacon, CmdrObot, GeoWriter, Yobot, John of Reading, RockMagnetist, Dexbot and Anonymous: 1
- **Magnetite** *Source:* https://en.wikipedia.org/wiki/Magnetite?oldid=768437598 *Contributors:* AxelBoldt, Bryan Derksen, Tarquin, Nonenmac, Infrogmation, Llywrch, Stan Shebs, Julesd, Andrewman327, Wik, Robbot, Chris 73, Modulatum, Hadal, Modeha, BenFrantzDale, Timpo, H Padleckas, Icairns, Sam Hocevar, Aramgutang, Deglr6328, DanielCD, Rich Farmbrough, Pmsyyz, Andros 1337, Vsmith, MeltBanana, Dlloyd, Kbh3rd, CanisRufus, Robert P. O'Shea, Fiveless, Bobo192, Iguan0, Stesmo, Smalljim, Slicky, Larry Grossman, Siim, Alansohn, Keenan Pepper, Walkerma, Bart133, Leoadec, RJFJR, Yurivict, Miaow Miaow, Benbest, Rtdrury, Tabletop, Cabhan, CharlesC, V8rik, BD2412, Elvey, JIP, Rjwilmsi, Coemgenus, 25~enwiki, Voretus, Ligulem, The wub, Bhadani, FlaBot, Ground Zero, Margosbot~enwiki, Flowerparty, Nimur, Choess, Chobot, Jaraalbe, WriterHound, YurikBot, Wavelength, Retaggio, Hairy Dude, Loom91, Cate, Shaddack, Janke, Asarelah, TigerPaw2154, Tetracube, 2over0, Xareu bs, CharlesHBennett, Alexandrov, Mejor Los Indios, Crystallina, Ankurdave, SmackBot, KnowledgeOfSelf, Kilo-Lima, WookieInHeat, Canthusus, Ebill, Lovecz, SynergyBlades, Thumperward, MalafayaBot, Philip Howard, AK7, Can't sleep, clown will eat me, Addshore, Nakon, Rolinator, Smokefoot, Rabid9797, SashatoBot, Derek

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Ozone77, Yamaguchi 先生, Aksi great, Gilliam, Hmains, Skizzik, Kmarinas86, Bluebot, Ferix, Keegan, Jprg1966, MalafayaBot, Metacomet, J. Spencer, Octahedron80, Colonies Chris, Hongooi, Royboycrashfan, Can't sleep, clown will eat me, Scott3, KaiserbBot, Snowmanradio, Rrburke, Addshore, Celarnor, Wen D House, Fuhghettaboutit, Rolinator, Rajrajmarley, Akriasas, Knutsi, Danikayser84, DMacks, Where, Daniel.Cardenas, Sadi Carnot, Pilotguy, Yevgeny Kats, Charivari, Wikier.ko, GoldenTorc, DJIndica, Nmnogueira, The undertow, SashatoBot, MusicMaker5376, Petr Kopač, Dr. Sunglasses, Dbtfz, Akendall, UberCryxic, Scientizzle, This user has left wikipedia, JorisvS, Jim.belk, IronGargoyle, Postscript07, 16@r, Grapetonix, Special-T, Mr Stephen, Dicklyon, Geologyguy, Mdanziger, Iridescent, Rpb01r, Casull, Filelakeshoe, Chetvorno, Lahiru k, Harold f, CalebNoble, JForget, Thermochap, Ale jrb, Jaeger5432, Woudloper, El aprendelenguas, Whereizben, Nauticashades, Slazenger, Rossf18, Rifleman 82, Gogo Dodo, Xxanthippe, Pinestone, Chrislk02, Ssilvers, Omicronpersei8, A Mom, PoolDoc, Thijs!bot, Epbr123, ProDigit, Nonagonal Spider, Headbomb, Davidhorman, Dfrg.msc, Nick Number, Mr. Trustegious, Natalie Erin, Mentifisto, Hmrox, AntiVandalBot, Gioto, Widefox, Opelio, Quintote, Gangasudhan, Tim Shuba, Spencer, Sluzzelin, JAnDbot, MER-C, The Transhumanist, Andonic, Mkch, RebelRobot, Kerotan, LittleOldMe, Magioladitis, Bongwarrior, VoABot II, Doodoobutter, C d h, Anthonyramos1, Soulbot, Skew-t, Froid, SwiftBot, Catgut, Allstarecho, LorenzoB, Vssun, Crware, TehBrandon, DerHexer, MartinBot, Halpaugh, Uvainio, Keith D, Kostisl, CommonsDelinker, Science5, Shellwood, J.delanoy, Pharaoh of the Wizards, JA.Davidson, Lone Skeptic, LordAnubisBOT, Ipigott, GhostPirate, Warut, Jcwf, NewEnglandYankee, Mp50967, Vanilluv30, Mufka, FJPB, Cmichael, Usp, JulianB12, Jamesontai, Vanished user 39948282, Rising*From*Ashes, Mike by, Stuart07, Xenonice, Nmgrad, Deor, Thisisborin9, AlnoktaBOT, Al.locke, Station1, WOSlinker, Philip Trueman, Raminmahpour, TXiKiBoT, Oshwah, Paddy-B-Jr, Antoni Barau, Hqb, Z.E.R.O., Anonymous Dissident, Someguy1221, Jackfork, Amog, Tyler Matthews, Pjbcool103, Eubulides, Wenli, Andy Dingley, Spinningspark, Bcfootball, PwncakesN bacon, Ryne1, Insanity Incarnate, Brianga, Fischer.sebastian, TheBendster, ClarkLewis, IndulgentReader, FlyingLeopard2014, EmxBot, Aqwfyj, Biscuittin, Roberdor, SieBot, Tiddly Tom, Caltas, Yintan, Zoragotcha, Keilana, Happysailor, Flyer22 Reborn, Radon210, Sammyk214, Paolo.dL, Rafonseca, Smilesfozwood, Lightmouse, Techman224, Hobartimus, BenoniBot~enwiki, Werldwayd, Mygerardromance, JCPH, Denisarona, Electrodynamicist, ElectronicsEnthusiast, Martarius, De728631, ClueBot, Trojancowboy, Yoduh2007, The Thing That Should Not Be, Fluidchameleon, IceUnshattered, Jan1nad, Drmies, Mild Bill Hiccup, Blanchardb, Otolemur crassicaudatus, Puchiko, Masonm95, Pointillist, Russell4, Mspraveen, Samsee, Excirial, Jusdafax, Ninjackster, Monobi, Eeekster, Lartoven, Brews ohare, Noor Qasmieh, Davdclehn, Erniesaurus, Ottawa4ever, Thingg, AL2TB, Jocelyne Heys-Gerard, Yuwangswisscom, Versus22, Ryalisaivamsi, SoxBot III, Egmontaz, Flutterman, Party, Editorofthewiki, Spitfire, Gnowor, ChucksGay123456789, Mitch Ames, WikHead, SilvonenBot, Khyranleander, HexaChord, Addbot, Xp54321, Proofreader77, American Eagle, S ortiz, Willking1979, Some jerk on the Internet, DOI bot, Bob sagget jr., Ron B. 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Saturn, Lightbot, Gail, Zorrobot, David0811, Legobot, Luckas-bot, Yobot, II MusLiM HyBRiD II, MarcoAurelio, THEN WHO WAS PHONE?, Qui-Gon Jinn, Technobebop, IW.HG, Ykral, Tempodivalse, Synchronism, AnomieBOT, Piano non troppo, Kingpin13, Ulric1313, Flewis, TheFronze05, Materialscientist, Karcih, Granito diaz, The High Fin Sperm Whale, E2eamon, Leif27, Clark89, MauritsBot, Xqbot, Sionus, St.nerol, Capricorn42, Jmundo, Saideepak.budaraju, Abce2, Frosted14, Kyng, Doulos Christos, Shadowjams, Kierkkadon, 老陳, IMNOTARETARDATALL, St. Hubert, Lordyou, GliderMaven, George2001hi, FrescoBot, Paine Ellsworth, Tobby72, S colligan, Nicktfx, HJ Mitchell, Silent78, Yoyo2222, Craig Pemberton, Jakhai1000, Citation bot 1, Pinethicket, I dream of horses, Edderso, PrincessofLlyr, 10metreh, Firozmusthafa, Pudgy78685, A8UDI, Flubber88, Jschnur, Serols, Robo Cop, Reconsider the static, Jauhienij, FoxBot, Tgv8925, TobeBot, Aliwikii, Dinamik-bot, Vrenator, TBloemink, Dan kelley90, Jeffrd10, Diannaa, Pmbeck, Weedwhacker128, Suffusion of Yellow, Splartmaggot, Jesse V., Mean as custard, Slon02, MELISASIMPSONS, EmausBot, Orphan Wiki, WikitanvirBot, Immunize, Octaazacubane, Karteek987, Racerx11, RenamedUser01302013, Dalegudmunsen, Solarra, Tommy2010, Dcirovic, K6ka, Lucas Thoms, Capybara123, Hhhippo, JSquish, John Cline, Fæ, Josve05a, Shuipzv3, Quondum, Crawlbeforeiwalk, EWikist, Wayne Slam, Ownedestroy, Maxrokatanski, Brandmeister, Apocalypse2009, Rigley, John Aplessed, ChuispastonBot, RockMagnetist, Teapeat, 28bot, Sonicyouth86, Petrb, ClueBot NG, Adawg117, Bchaplucian, Alex-engraver, Cntras, The Troll lolololololololol, Helpful Pixie Bot, Stanlste, Strike Eagle, Bibcode Bot, Cmandouble3, Rijinatwiki, MusikAnimal, Changer-guy, JacobTrue, RaulRavndra, Maxellus, Thekillerpenguin, EntangledSpins, Srikar33, Soerfm, CitationCleanerBot, MrBill3, Zedshort, Glacialfox, Millennium bug, ChrisGualtieri, Embrittled, Yammer68, Fizped~enwiki, MadGuy7023, Bluedot951, SoledadKabocha, Denis Fadeev, TwoTwoHello, Numbermaniac, NinjaNightMare12, Reatlas, Harish.awasthi, Trollarc26, DavidLeighEllis, Tobythedog1, Coz12345, !nnovativ, Manul, SpecialPiggy, JaconaFrere, Skr15081997, SufferinSuckatach, Monkbot, Niuthon, Opencooper, Justin15w, Mrmister6123, MacWarcraft, Scarlettail, Trackteur, Shantygoreman, Suraj 967, Martinpalla123, MRD2014, The Last Arietta, Elite Whitesands Force, Tymon.r, RippleStrike, Ak0hlm, KasparBot, Miskiiy, Mf siddiqui, Creadilo, TheDadeOne, Entranced98, Xdxdxd123456789123456789, Rasimmons, Yasmine4correa123, Bender the Bot, 22KAMOLIDDINAKBAROV, Gambler1478 and Anonymous: 978

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Brown, MarcoLittel, NewEnglandYankee, Glmory, SJP, Fylwind, Cometstyles, Treisijs, Nielchiano, Scott Illini, Useight, Lseixas, Idioma-bot, Sheliak, Signalhead, Saryakhran, VolkovBot, Xtremepunker~enwiki, ICE77, JohnBlackburne, Pgavin, Ryan032, LeilaniLad, Barneca, Philip Trueman, PNG crusade bot, Af648, Hy Brasil, TXiKiBoT, Oshwah, Michi zh, Hqb, GDonato, FrstFrs, CaptinJohn, Ocolon, From-cary, Andy Dingley, Meters, Cantiorix, Synthebot, Antixt, Mossd, @pple, Anna512, MCTales, Paverider, Brianga, Thric3, Quantpole, Jwkeohane, SieBot, StAnselm, Armius, Scarian, Claus Ableiter, Da Joe, Dgmyer, Yintan, JerrySteal, Radon210, JD554, Captain Yankee, Oda Mari, Jojalozzo, Momo san, Paolo.dL, Rafonseca, Oxymoron83, Harry-, Hello71, The-G-Unit-Boss, OKBot, Merseyless, Anchor Link Bot, Mygerardromance, Ascidian, Denisarona, Romit3, ClueBot, SirEditALot, Gits (Neo), Snigbrook, Yoduh2007, Fyyer, The Thing That Should Not Be, Matdrodes, Kafka Liz, Luke490, Jagun, DesertAngel, Razimantv, TheOldJacobite, Richerman, Pedantik~enwiki, Dr. Seaweed, DragonBot, Djr32, Excirial, Alexbot, Lartoven, MacedonianBoy, Brews ohare, BSTR, Thingg, Aitias, Venom4u 31, Versus22, Phynicen, Johnuniq, SoxBot III, Egmontaz, DumZiBoT, XLinkBot, H0dges, Mh liv01, WikHead, WikiDao, UnknownForEver, Thatguyflint, HexaChord, Addbot, Cxz111, Mortense, Some jerk on the Internet, Gtakanis, Dgroseth, CharlesChandler, Vishnava, Ndhuang, Stan Sykora, FDT, Download, LaaknorBot, SomeUsr, AndersBot, CUSENZA Mario, Isdarts222, Gingavitus777, TStein, LinkFA-Bot, Numbo3-bot, Kurt.hewett, Tide rolls, Lightbot, સતિષચંદ્ર, Ettrig, Jackelfive, Luckas-bot, Yobot, 2D, Ptbotgourou, Amirobot, The Earwig, Lichen from Hell, محبوب عالم, Tempodivalse, Magog the Ogre, AnomieBOT, KDS4444, DemocraticLuntz, Archon 2488, Sunlight123, Jim1138, Tonyalfrey, Kingpin13, Bishoppowell, Opticron, Materialscientist, Geek1337~enwiki, Citation bot, Citeseer, LilHelpa, Obersachsebot, Xqbot, TinucherianBot II, Wavgfkl, St.nerol, Capricorn42, 4twenty42o, Giggy12345, Anna Frodesiak, NOrbeck, Santista1982, Kenshin9554, Omnipaedista, SassoBot, Locobot, A.amitkumar, Janolaf30, Bekus, Gunnergrady, FrescoBot, LucienBOT, Chrsschm, Nageh, Lookang, Anterior1, Damo0078, Steve Quinn, Marmzok, Sneller2, DivineAlpha, Citation bot 1, Khashishi, Intelligentsium, DrilBot, Pinethicket, I dream of horses, Abductive, El estremeñu, Smuckola, Phasespace, 23790AD, Tagray, Jauhienij, IVAN3MAN, Robvanvee, Gryllida, Sintau.tayua, TobeBot, Trappist the monk, SchreyP, Defender of torch, Diannaa, Hunter360x, UpdateNerd, Xclassmechluv, DARTH SIDIOUS 2, Mean as custard, Pi zza314159, Semmendinger, Noommos, Agent Smith (The Matrix), Bobyorox, Ankid, Vamaviscool123, Deadlyops, EmausBot, Black Shadow, John of Reading, Wisapi, Gfoley4, JasonSaulG, Netheril96, Dcirovic, K6ka, Palle.haastrup, Hhhippo, JSquish, Fæ, 1howardsr1, Flies 1, Ambros-aba, Qniemiec, Quondum, NGPriest, Tolly4bolly, Thine Antique Pen, Maschen, Donner60, Zueignung, Vlus, RockMagnetist, Mni9791, DASHBotAV, G4oep, ClueBot NG, Incompetence, MelbourneStar, SusikMkr, Aniruddha22Paranjpye, Telpardec, Helpful Pixie Bot, B21O303V3941W42371, SzMithrandir, Bibcode Bot, BG19bot, Charon77, Mdmilagre, 1994bhaskar, Kendall-K1, Dlampton, Ushakaron, Wogboy52, MrBill3, Dcntr, JMtB03, ZodTron, Jakebarrington, HueSatLum, Imafjbks, Garamond Lethe, Magnetic7, Jacobymathews99, DeMk9D76, Catalanhost, Dexbot, Cwobeel, Whydowefallbruce?, Frosty, Graphium, Sublimedragon28, Alertboatbanking, Cadillac000, Kyohyi, Epicgenius, Charanwiki2411, Raunakk.chandhoke, Tentinator, DanyCheeto, Spyglasses, YiFeiBot, SpecialPiggy, Franz Scheerer (Olbers), MS398, Monkbot, Keffek, Elgrande12345678, HMSLavender, A Great Catholic Person, Thunt99612, Yixiangp, Samyakj99, Alango1998, Kaleb thoreson, Julietdeltalima, Federico Leva (BEIC), YITYNR, TheHiggsField, Sayambohra, Isambard Kingdom, Krelcoyne, Inorout, KasparBot, PCH333, Boehm, Nourrmourad, CAPTAIN RAJU, Ameilia hope, Linguist111, CLCStudent, Abhishek kandulna, GreenC bot, Fmadd, Spiketrex, Stylez995, JDoe123456789987654321, Mortee, Seph N Haven and Anonymous: 899

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- **Magnetic dipole** *Source:* https://en.wikipedia.org/wiki/Magnetic_dipole?oldid=770769024 *Contributors:* Tim Starling, Bearcat, Oliver Jennrich, Bgwhite, Bdushaw, David s graff, Davius, Facegarden, Geofrod, Drphysics, Jojalozzo, 718 Bot, Brews ohare, Addbot, Wickeynl, Grandfatherclok, Lightbot, Luckas-bot, Redirect fixer, Dcirovic, AsceticRose, Maschen, RockMagnetist, ClueBot NG, MelbourneStar, Helpful Pixie Bot, Snow Blizzard, ChrisGualtieri, Razibot, Ze-aksent, Monkbot, Asm Saikat, Bender the Bot and Anonymous: 20
- **Ferromagnetism** *Source:* https://en.wikipedia.org/wiki/Ferromagnetism?oldid=769451813 *Contributors:* Stokerm, Xaonon, PierreAbbat, Ewen, JohnOwens, Tim Starling, Wapcaplet, Dgrant, Stevenj, Rossami, Rob Hooft, Bemoeial, Phys, Omegatron, Philopp, Pakaran, Pollinator, Twang, Donarreiskoffer, Robbot, Blainster, Wikibot, Giftlite, BenFrantzDale, Wikibob, Guanaco, Eequor, Foobar, Darrien, DÅ‚ugosz, HorsePunchKid, DragonflySixtyseven, Icairns, Sam Hocevar, MementoVivere, Astronouth7303, Piil, Guanabot, Cacycle, Leandros, Xezbeth, Bender235, Nabla, Jonon, West London Dweller, Circeus, Bert Hickman, Bantman, Gene Nygaard, Zereshk, Dan100, Anarcho hipster, Infinoid, Benbest, Macronyx~enwiki, Eras-mus, CharlesC, Vary, FlaBot, Nimur, Novel-Technology, Srleffler, Chobot, Wavelength, Hairy Dude, Charles Gaudette, Hede2000, Salsb, Speedevil, EEMIV, Bota47, Dan Austin, Tonymec, Light current, DardanAeneas, Curpsbot-unicodify, 8472, Itub, SmackBot, Jrockley, Athaler, Ekilfeather, Bduke, Salvor, Complexica, DHN-bot~enwiki, Can't sleep, clown will eat me, Cophus, Rrburke, Wiki me, Stevenmitchell, Bad ideas, Napalm Llama, Peterwhy, John, Iliev, Heimstern, Loodog, Shlomke, Breno, 16@r, Fangfufu, Wizard191, FSHero, Richard75, Tawkerbot2, Chetvorno, Klidge~enwiki, Gbravenclaw, Abiermans, Cydebot, Dl573, Rifleman 82, Xxanthippe, The real dan, Rracecarr, Thijs!bot, MaratIk, Sagaciousuk, MrXow, Headbomb, Marek69, Electron9, Davidmack, Northumbrian, ClassicSC, JAnDbot, Plantsurfer, MSBOT, Bongwarrior, Mtd2006, Sesquiculus1, Dimody, Kopovoi, Adavidb, Gurchzilla, STBotD, Pcordes, Reelrt, Payonel, Philip Trueman, Technopat, Don4of4, Broadbot, Spinningspark,

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- **Ferrimagnetism** *Source:* https://en.wikipedia.org/wiki/Ferrimagnetism?oldid=768757246 *Contributors:* Tim Starling, Stevenj, Furrykef, Phys, Wikibot, Zigger, Fascinet, HorsePunchKid, DragonflySixtyseven, Icairns, Vivacissamamente, Piil, Jag123, Zetawoof, Dan100, Benbest, Rjwilmsi, FlaBot, Srleffler, Tone, Salsb, Prime Entelechy, Bota47, Guillom, Curpsbot-unicodify, SmackBot, Eskimbot, Lovecz, TimBentley, Pieter Kuiper, DHN-bot~enwiki, Logicwax, Iliev, Harej bot, Rifleman 82, הסרפד, Headbomb, Slaweks, JAnDbot, Catslash, Avicennasis, David Eppstein, Rod57, Ryan858, Signalhead, VolkovBot, Larryisgood, Jmrowland, Philip Trueman, A4bot, Petteri Aimonen, Petergans, The-prospector, SieBot, YonaBot, Mimihitam, Yaroslav Blanter, MenoBot, GregVolk, Addbot, Zorrobot, Luckas-bot, Yobot, AnomieBOT, Leaky Lens, Materialscientist, Wavgfkl, Capricorn42, Zhangzhe0101, Mnmngb, FrescoBot, Freddy78, BenzolBot, Trappist the monk, Wikfr, L Kensington, Maschen, Sanku p, RockMagnetist, ClueBot NG, Teammm, WaveJones, Jochen Burghardt, Dough34, Monkbot and Anonymous: 37
- **Paramagnetism** *Source:* https://en.wikipedia.org/wiki/Paramagnetism?oldid=770043911 *Contributors:* Taw, Stokerm, Andre Engels, Heron, Michael Hardy, Tim Starling, Pde, Looxix~enwiki, Ahoerstemeier, Stevenj, Schneelocke, Dcoetzee, Lfh, Phys, Omegatron, Gamera2, Robbot, Humanist, Nick Pisarro, Jr., Dina, Giftlite, Bandy, Troyrock, WhiteDragon, SimonArlott, Icairns, Rakista, Piil, Discospinster, Rich Farmbrough, Joanjoc~enwiki, Eric Kvaalen, Mac Davis, Rebroad, Gene Nygaard, Benbest, Nanite, Kri, YurikBot, Hairy Dude, Salsb, DeadEyeArrow, Someones life, Light current, Profero, SmackBot, Turbos10~enwiki, NCurse, Bduke, Thumperward, Complexica, Silenced, DHN-bot~enwiki, Sbharris, Tsca.bot, Berland, Smokefoot, John, JorisvS, Mgiganteus1, IronGargoyle, Slakr, Beetstra, Koweja, Inquisitus, JoeBot, Quantum7, IvanLanin, Zero sharp, Jdedmond, Tawkerbot2, Markjoseph125, DanielRigal, Electricmic, No1lakersfan, Cydebot, Rifleman 82, Quibik, SimonDeDanser, Thijs!bot, CRON, Marek69, Electron9, Reinpk, JAnDbot, Barek, Eborreson, Murukesh mohanan, Ppxatc, Jcwf, Potatoswatter, VolkovBot, Philip Trueman, TXiKiBoT, Mercurywoodrose, A4bot, BotKung, Cmcnicoll, Petergans, Kbrose, Sonicology, BotMultichill, Mdsam2~enwiki, Oxymoron83, KathrynLybarger, ClueBot, Admiral Norton, The Thing That Should Not Be, Polyamorph, F-402, Lugh23, Estirabot, Brews ohare, Peter.C, Silverplasma, Kruusamägi, HopeChrist, Rangergordon, AlexGWU, Addbot, Samaritan13, AndersBot, Tassedethe, Lightbot, زرشک, Luckas Blade, Luckas-bot, Archon 2488, Jim1138, Piano non troppo, Aaagmnr, Materialscientist, Xqbot, Hammersbach, GrouchoBot, RocketDavid, Freddy78, WikiDonn, Busukxuan, Thevenin77, Gadolinist, EmausBot, Primefac, Dcirovic, Anchananatarajan, Medeis, Donner60, Ls1955, RockMagnetist, ClueBot NG, Robinsoncrusoe, Art and Muscle, BG19bot, MusikAnimal, Cyanoir, Derschueler, Makecat-bot, Bowser2500, Badmonkey717, Walt knocks, KasparBot, Fmadd, Inimesh and Anonymous: 169
- **Curie temperature** *Source:* https://en.wikipedia.org/wiki/Curie_temperature?oldid=769805190 *Contributors:* Tarquin, Robert Foley, Bdesham, Ahoerstemeier, Stevenj, The Anomebot, Archivist~enwiki, EpiVictor, Fredrik, Humanist, Giftlite, Herbee, FrYGuY, Bumm13, Canterbury Tail, Discospinster, Mani1, FirstPrinciples, Kjkolb, Wtshymanski, Linas, Cruccone, Polyparadigm, SCEhardt, Rjwilmsi, Imrehg, Gurubrahma, YurikBot, RobotE, Deeptrivia, Theodolite, Eno-ja, Nathaniel, Monolith2, Algont, Fetofs, Thumperward, Shalom Yechiel, Chlewbot, Spiritia, Robofish, Laogeodritt, NcSchu, Rjgibb, Hgrobe, Skapur, Igoldste, Jcoffland, Phatom87, Cydebot, Thijs!bot, Headbomb, Marek69, Escarbot, Mentifisto, AntiVandalBot, Guy Macon, Hamsterlopithecus, Magioladitis, Meredyth, Jasonbrotherton, Soulbot, David Eppstein, Thibbs, Greenguy1090, Keith D, R'n'B, Lophoole, Trusilver, Roberpl, SirHolo, Gazok, VolkovBot, EmxBot, SieBot, Coffee, AlphaPyro, Flyer22 Reborn, Anchor Link Bot, Sfan00 IMG, ClueBot, DragonBot, Djr32, Jalthaus, Zdravljica, LarryMorseDCOhio, Masher oz, Serrels, XLinkBot, Dthomsen8, Addbot, Mathieu Perrin, Olli Niemitalo, CanadianLinuxUser, LaaknorBot, Ehrenkater, Yungszen, Luckas-bot, Yobot, Amirobot, SwisterTwister, Götz, JackieBot, LilHelpa, Xqbot, GrouchoBot, RibotBOT, DeNoel, Steve Quinn, Ysyoon, DivineAlpha, Roulianne, Trappist the monk, RjwilmsiBot, EmausBot, John of Reading, GoingBatty, Checkingfax, Jaydeepsamant, Nirvanana, Donner60, RockMagnetist, Carmad246, Xanchester, ClueBot NG, This lousy T-shirt, Frietjes, The High Fin Sock Whale, Bibcode Bot, BG19bot, Alf.laylah.wa.laylah, AvocatoBot, Zedshort, Vanischenu, BattyBot, SimmeD, Pratyya Ghosh, SoledadKabocha, Barnex, BreakfastJr, ACGrain, RNLockwood, DavidLeighEllis, Rahsecond, Monkbot, JonFreihage, PiezoJane, Saywrusthegreat, Bender the Bot, Mmax.mani and Anonymous: 120
- **Allan V. Cox** *Source:* https://en.wikipedia.org/wiki/Allan_V._Cox?oldid=740661425 *Contributors:* Dino, Jackol, Forteanajones, Hooperbloob, Richard Arthur Norton (1958-), Etacar11, Rjwilmsi, Bgwhite, Ilanpi, ChemGardener, SmackBot, Haus, Trialsanderrors, Mojo Hand, Waacstats, Twsx, Ekki01, Johnpacklambert, Varnent, GcSwRhIc, Addbot, Mnh, Lightbot, Yobot, Chris.urs-o, Full-date unlinking bot, RjwilmsiBot, ZéroBot, RockMagnetist, Hyperdoctor Phrogghrus, Nasmem, Helpful Pixie Bot, Bibcode Bot, BattyBot, YFdyhbot, Churn and change, Altion33, Einzwitterion, Suspecialcollections, LiamKasbar, Jonarnold1985, KasparBot and Anonymous: 11
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Casliber, Thijs!bot, Headbomb, SGGH, RobotG, Emeraldcityserendipity, Totalnerduk, Kbthompson, NSH001, Dr. Submillimeter, HiToro, Danger, Mikenorton, JAnDbot, Deflective, Leuko, Dricherby, Bencherlite, Connormah, VoABot II, Carlwev, Avjoska, Japo, Vssun, Rif Winfield, Riccardobot, Arjun01, Akulo, Arithmonic, CommonsDelinker, Patar knight, J.delanoy, Skeptic2, Bogey97, OohBunnies!, Hair Commodore, Michael Daly, Chiswick Chap, NewEnglandYankee, Basketdove, Tanaats, Cmichael, KylieTastic, VolkovBot, JohnBlackburne, MenasimBot, Gene Hobbs, Philip Trueman, TXiKiBoT, Oshwah, Ragemanchoo, GcSwRhIc, Crohnie, Omcnew, Billinghurst, Spehizle, AlleborgoBot, Thony C., Ponyo, SieBot, YonaBot, Euryalus, Caltas, CWHughes, Flyer22 Reborn, Antzervos, Swenster101, Benea, COBot, JMOprof, ClueBot, Timeineurope, The Thing That Should Not Be, All Hallow's Wraith, QueenAdelaide, EoGuy, FileMaster, MD1937, P. S. Burton, Jusdafax, SockPuppetForTomruen, Keplerslab, Johnuniq, SoxBot III, Egmontaz, RexxS, BarretB, RogDel, Little Mountain 5, Skarebo, ZooFari, Doug butler, Deineka, Addbot, Kingliam3, Pietersz~enwiki, Ripleyscool, Ironholds, Fluffernutter, Cst17, LaaknorBot, West.andrew.g, Lightbot, TheVixenZozo, Sitehut, Yidle, Luckas-bot, Yobot, AnomieBOT, İnfoCan, Piano non troppo, AdjustShift, Bluerasberry, Giants27, Materialscientist, Citation bot, ArthurBot, LilHelpa, Xqbot, Capricorn42, Mr mo31, JPKos, Coretheapple, Wizardist, Omnipaedista, Krscal, Hersfold tool account, Celuici, MaryBowser, FrescoBot, Anna Roy, Tobby72, VS6507, Rakiko12, Sebastian&kimberly=4ever, Bromley86, Citation bot 1, I dream of horses, Metricmike, LittleWink, Tóraí, Jonesey95, Tom.Reding, Leeney79, GrahamRMcFarlane, Kgrad, Kingleonidas1, ItsZippy, Subhamsudipto, Dyw1969, Oracleofottawa, Daniel Stringer, Onel5969, The Utahraptor, RjwilmsiBot, Hajatvrc, Black85ball, EmausBot, Never give in, Katherine, GoingBatty, Mo ainm, Stephencdickson, Jim Michael, Dcirovic, Jmangrum, K6ka, Checkingfax, Daonguyen95, Smartblondeami, Hazard-SJ, Felix505, Rogerluo18, David J Johnson, Mojowiha, Frenchyjesse, Donner60, Chewings72, RockMagnetist, Pgarret, Taliesin717, Will Beback Auto, ClueBot NG, Gareth Griffith-Jones, ScottSteiner, Antiqueight, Helpful Pixie Bot, Kessy628, Writ Keeper, Jturner87, Paul the alien, Zujua, Jeremyhins, David.moreno72, Darorcilmir, Miszatomic, Ninmacer20, The Illusive Man, ChrisGualtieri, MadGuy7023, JYBot, TowardsTheLight, Kondormari, Aloneinthewild, Holly&lois, Nimetapoeg, Kawaii-Soft, Upsman1023, Lewis Cartmen, CW Nobbs, YiFeiBot, BenEsq, Notthebestusername, OccultZone, JamKaftan, Vieque, JBart2240, Edzavala, Walshy231, Asdklf;, Spideratseds, Mndata, Sundayclose, Isambard Kingdom, DouglasKenney18, KasparBot, CaptainNuts, Kanat.kalybekov, Edmondhalle, Bender the Bot and Anonymous: 371

- **Carl Friedrich Gauss** *Source:* https://en.wikipedia.org/wiki/Carl_Friedrich_Gauss?oldid=769896898 *Contributors:* AxelBoldt, Mav, Zundark, The Anome, Jeronimo, Andre Engels, XJaM, Arvindn, Enchanter, Ben-Zin~enwiki, Olivier, Someone else, Hfastedge, Mathsinger, Bogdan Stanciu, D, Michael Hardy, Dominus, Kku, Menchi, Tannin, Ixfd64, Kalki, Tomi, GTBacchus, Looxix~enwiki, Mdebets, Ahoerstemeier, Stan Shebs, Docu, William M. 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FisherQueen, MartinBot, Kiore, Jay Litman, LedgendGamer, EdBever, Thirdright, J.delanoy, FANSTARbot, Skeptic2, Ali, Kidshare, SureFire, SuperGirl, Catmoongirl, Maurice Carbonaro, Maproom, Ulfalizer, Rufous-crowned Sparrow, Katalaveno, PedEye1, Smeira, DarkFalls, JJ THE NERD, Gurchzilla, Advancewars177, Belovedfreak, NewEnglandYankee, In Transit, Chenel324, Ep3no, Beatpunk, MetsFan76, KylieTastic, DavidCBryant, DorganBot, Jw239, Riaazvgm, Deor, VolkovBot, Ikf5, Indubitably, NikolaiLobachevsky, Themel, Philip Trueman, TXiKiBoT, Klaus Trainer, GimmeBot, Miranda, Rei-bot, Anonymous Dissident, Thewitchkingofangmar, Dr. Leibniz, GcSwRhIc, Sankalpdravid, Pimemorizer, Ocolon, Lradrama, Sintaku, SelketBot, Thelatemail, Smchs, Broadbot, Lou.weird, Omcnew, LeaveSleaves, Pishogue, Maxim, Prb4, M0RD00R, Andy Dingley, Cantiorix, Stephenmitchell, Falcon8765, Spinningspark, Why Not A Duck, Dmcq, AlleborgoBot, Symane, Logan, Ishboyfay, PериclesofAthens, Resurgent insurgent, EmxBot, GirasoleDE, SieBot, 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Nedim Ardoğa, Gui le Roi, Shearsongs78, Shadowjams, Erik9, Thenestorman, 老陳, Green Cardamom, Totemtotemo, FrescoBot, Chicobangs, Dolly1313, Io Herodotus, Telementor, Overminded, Garrybaldi, Carborane, Bull1037, InspectorSands, Weetoddid, Scott A Herbert, Maxus96, WikiMichel, Citation bot 1, Tkuvho, ShadowRangerRIT, I dream of horses, Gaussisaprick, 10metreh, Jonesey95, Plucas58, Tom.Reding, Serols, Loopy loo 1234, Full-date unlinking bot, Hajime create~enwiki, TobeBot, Trappist the monk, Ryan123456789101112131415, Fama Clamosa, Lotje, Miracle Pen, JuanVivar, Mohak12, Reach Out to the Truth, TjBot, Alph Bot, Saruha, DRAGON BOOSTER, Steve03Mills, EmausBot, Orphan Wiki, Acather96, Razor2988, GoingBatty, RA0808, Chriswalt, Sp33dyphil, KHamsun, Tommy2010, Wikipelli, Dcirovic, K6ka, AsceticRose, Solomonfromfinland, Arkenflame, Coubure, Hhhippo, Mz7, 15turnsm, ZéroBot, John Cline, Prayerfortheworld, Hd like apples, XTayax, Alpha Quadrant, H3llBot, Luckychuky, Frochtrup, Tolly4bolly, 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- Kent, D. V.; Gradstein, F. M. (1985). "A Cretaceous and Jurassic geochronology". *Geological Society of America Bulletin*. **96** (11): 1419. doi:10.1130/0016-7606(1985)96<1419:ACAJG>2.0.CO;2. ISSN 0016-7606. *Original artist:*

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