

# GEOMAGNETISM TUTORIAL

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# *Geomagnetism Tutorial*

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## I. INTRODUCTION

This tutorial is written for amateur radio astronomers and amateur radio operators who wish to understand the causes and characteristics of Earth's magnetic field and how it is affected by solar activity.

In 1600 William Gilbert published the first scientific study of Earth's magnetic field in *De Magnete*. [Gilbert] However, in spite of this and a huge amount of subsequent work and the practical use of Earth's magnetic field for compass navigation for perhaps a thousand years, our understanding of the origin of Earth's magnetic field still is incomplete. We call the study of Earth's magnetic field the study of *geomagnetism* and we use *geomagnetometers* to measure it. The results of our measurements are shown on *magnetograms* (Fig. 1).

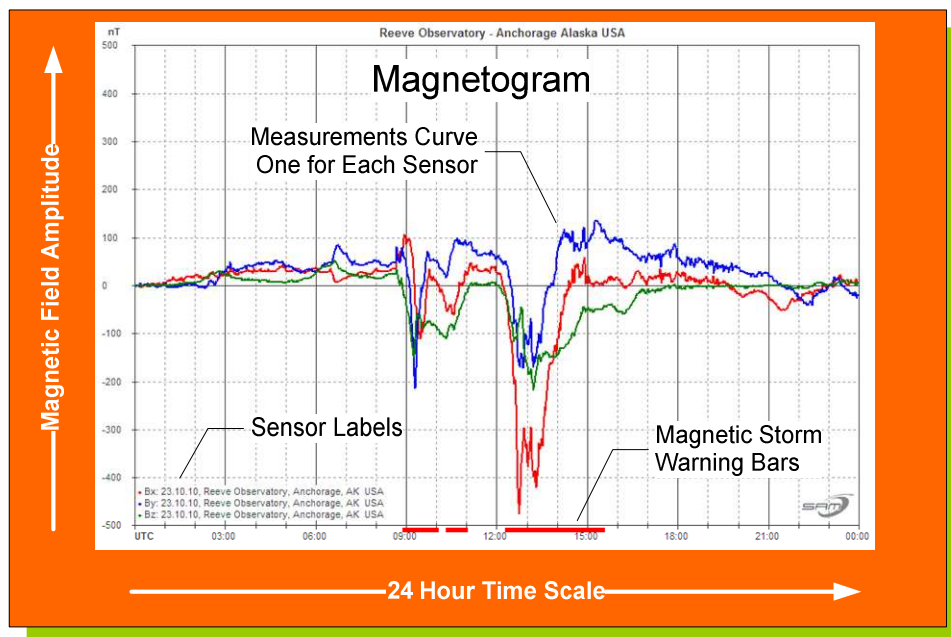


Fig. 1

A magnetogram shows the magnetic field amplitude on the vertical scale with respect to time on the horizontal scale. This magnetogram was produced by the Simple Aurora Monitor, SAM-III. Annotations have been added to indicate other features of this magnetogram

Amateur radio astronomers can study Earth's magnetic field and its variability by using instrumentation well within their financial reach and technical capabilities. At least one magnetometer system has alarm capabilities that can be used to indicate aurora viewing and radio propagation opportunities associated with geomagnetic storms and disturbances. Live magnetometer data can be viewed online.<sup>1</sup>

<sup>1</sup> For example, see [www.reeve.com/SAM/SAM\\_simple.html](http://www.reeve.com/SAM/SAM_simple.html) and [www.sam-magnetometer.net/](http://www.sam-magnetometer.net/)

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## II. MAGNETIC QUANTITIES AND UNITS OF MEASURE

There are two basic magnetic quantities and one constant from which all other magnetic quantities are derived: [NBS]

- Magnetic induction,  $B$  (often called magnetic flux density). It measures the mechanical force experienced by a current-carrying conductor in a magnetic field
- Magnetic field strength,  $H$  (often called magnetizing force, magnetizing field or magnetic intensity). It measures the ability of an electric current to produce magnetic induction at a given point
- Magnetic constant,  $\Gamma_m$  (for air or vacuum,  $\Gamma_m = \mu_0 = B/H$ ). It is the ratio of the magnetic induction to the corresponding magnetic field strength in a material or in a vacuum. The magnetic constant also is called *permeability*, and  $\mu_0$  is the permeability of free space.

The units of measure for these magnetic quantities are given in Table 1.

One of the unfortunate results of early studies of magnetism was the naming of the units of measure. The name magnetic field strength for  $H$  probably is more appropriate to  $B$ , the magnetic induction. Magnetic field sensors actually measure the induction of the field. A typical sensor can be thought of as the secondary of a transformer in which Earth's core is the primary.

Another difficult legacy arises from the various systems of units. In the CGS (centimeter, gram, second) system,  $H$  and  $B$  have identical values but, of course, different units. In the SI (International System of Units),  $B$  and  $H$  are in the ratio of  $4\pi \cdot 10^{-7}$  H/m. One of the additional problems associated with the use of magnetic units is that the simple ratio relationships mentioned here are true only in air and vacuum and where ferromagnetic materials are not involved.

Table 1 – Magnetic quantities and units of measure

Quantity	Common unit	Alternate units and remarks	Dimensions
$B$	tesla (T)	gamma (= 1 nT = $10^{-9}$ T) weber/m <sup>2</sup> (= 1 T) gauss (= 100,000 nT)	$M \cdot T^{-2} \cdot I^{-1}$
$H$	ampere-turn/meter (A/m)	oersted (= $10^3/4\pi$ A/m)	$I \cdot L^{-1}$
$\Gamma_m$	henry/meter (H/m)	In air or vacuum, $\Gamma_m = \mu_0 = 4\pi \times 10^{-7}$ H/m	$L \cdot M \cdot T^{-2} \cdot I^{-2}$

Table notes:

1. Confusion often arises in the use of units for magnetic induction  $B$  and magnetic field strength  $H$ . In the science of geomagnetism, the magnetic field strength frequently is expressed in units of gauss despite international agreement in the International System of Units (SI) to use ampere-turn/meter. Also, in geomagnetism a smaller unit, lower-case gamma ( $\gamma$ ) frequently is used with long-term (secular) and transient variations. 1  $\gamma$  = 1 nT
2. Dimensions are mass ( $M$ ), time ( $T$ ), current ( $I$ ), and length ( $L$ )

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## III. THE MAGNETIC DIPOLE

Theoretical and experimental studies have shown that the magnetic properties of materials result from the motions of electric charges within them, either rotation in orbits or spins about their axis. These motions constitute electric currents and thereby produce magnetic fields.

In electricity the simplest structure is the isolated charge. If two opposite charges are placed near each other, they form an electric dipole, characterized by an electric dipole moment. The electric dipole moment indicates the orientation of the charges. In magnetism, isolated magnetic poles apparently do not exist, and the simplest magnetic structure is the magnetic dipole, characterized by a magnetic dipole moment, or just magnetic moment. Earth's magnetic field, as measured at the surface, is very similar to the field from a magnetic dipole (Fig. 2).

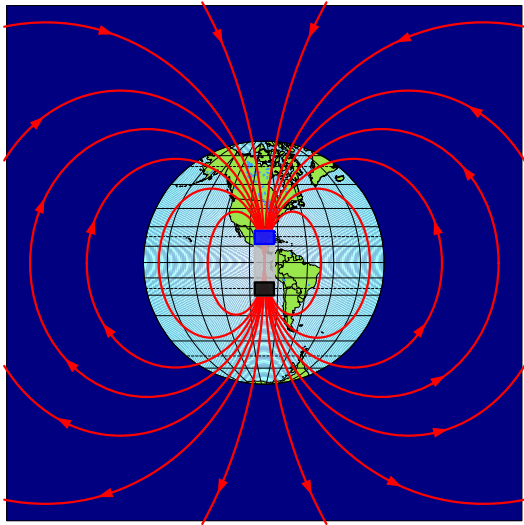


Fig. 2

The geomagnetic field at Earth's surface appears as if the field is developed by a magnetic dipole near Earth's center as indicated by the bar magnet.

The magnetic moment of a moving electric charge is a vector pointed along the spin axis or normal to the orbital plane. Its magnitude is the product of the equivalent current and the area enclosed by its path. The magnetic moment of a body is the vector sum of its internal moments. Various symbols have been used for the magnetic moment including  $M$ ,  $m$  and  $\mu$ . The units are ampere-meter<sup>2</sup> (A-m<sup>2</sup>) and dimensions are  $I \cdot L^2$ .

A loop of wire or coil of wire (solenoid) carrying an electrical current and a bar magnet are examples of magnetic dipoles. The magnetic induction,  $B$ , due to a dipole at a distant point along its axis in line with the magnetic north and south poles, in terms of the dipole moment, is

$$B = \frac{\mu_0 \cdot M}{2 \cdot \pi \cdot r^3}$$

where  $B$  = magnetic induction (T)

$\mu_0$  = magnetic constant (H/m)

$M$  = magnetic moment (A-m<sup>2</sup>)

$r$  = distance from dipole center (m)

The magnetic induction at a distant point along a magnetic dipole's perpendicular bisector (magnetic equator) is

$$B = \frac{\mu_0 \cdot M}{4 \cdot \pi \cdot r^3}$$

The foregoing equations show that the magnetic induction drops quite rapidly with distance from the magnetic dipole center. For example, if we double the distance, the magnetic induction is reduced by a factor of 1/8. We can rearrange the second equation to calculate the approximate

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dipole moment of Earth's field at the equator. The average magnetic induction ( $B$ ) at the equator is approximately 31,000 nT and Earth's radius is approximately 6,378 km. Substituting these values

$$M = \frac{4\pi \cdot r^3 \cdot B}{\mu_0} = \frac{4\pi \cdot (6.378 \cdot 10^6)^3 \cdot 3.1 \cdot 10^{-5}}{4\pi \cdot 10^{-7}} \approx 8 \cdot 10^{22} \text{ A}\cdot\text{m}^2$$

If we assume the outer core is a single turn conductive iron loop, we can calculate the current in that loop from

$$I = \frac{M}{\pi \cdot r_{oc}^2}$$

where  $M$  was previously calculated and  $r_{oc}$  is the radius of Earth's outer core, roughly 3,000 km. With these simplifying assumptions, the current in the core is on the order of  $2.8 \cdot 10^9$  A (2.8 billion amperes).

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## IV. THE MAGNETIC ENVIRONMENT

In our universe, magnetic field amplitudes range over many orders of magnitudes (Table 2). Although our main concern is Earth's magnetic field, it is interesting and instructive to also consider extraterrestrial magnetic fields. In the far reaches of outer-space – the inter-stellar medium (ISM) – a small magnetic field exists due to the polarization of light by magnetically oriented dust particles. The magnetic induction is on the order of 1 nT, or about one-billionth that of the strongest permanent magnets on Earth.

Within the solar system – the inter-planetary medium (IPM) – the Sun's magnetic field is on the order of 5 nT at a distance of 1 astronomical unit (AU), the average distance of Earth to the Sun (approximately 150 million km). This magnetic field is caused by the plasma – neutral hydrogen atoms, protons and electrons – that makes up the solar wind. The orientation of this field is away from or toward the Sun and is heavily influenced by solar activity such as sunspots, coronal mass ejections (CME), coronal hole high-speed streams (CHSS) and certain types of solar flares.

Table 2 – The magnetic field environment

Environment	$B$ (T)
Surface of neutron stars	$10^8$
Pulsed electromagnets	10
Strongest permanent magnets	1
Refrigerator magnet	$10^{-2}$
Sun's magnetic field at poles	$10^{-2}$
Jupiter's magnetic field at poles	$10^{-3}$
Earth's magnetic field at poles	$10^{-4}$
Stray fields from electric machinery	$10^{-5}$
Urban magnetic noise level	$10^{-6}$
Inter-stellar medium	$10^{-9}$
Magneto-cardiograms	$10^{-10}$
Heartbeat	$10^{-11}$
Human brain	$10^{-12}$

Earth's main magnetic field creates a volume called the *magnetosphere* in the space surrounding Earth (Fig. 3). Without the solar wind, the shape of the magnetosphere would be the shape of Earth's undisturbed dipole field in space. However, the solar wind compresses the side toward the Sun to about 10 Earth radii and stretches it like a tail on the other side to more than 100 Earth radii. The magnetosphere deflects the flow of most solar wind particles around Earth. However, some charged particles are trapped and guided by the magnetosphere causing aurora in a halo-shaped region around the poles (*auroral zone*). The magnetic induction in the magnetosphere varies from around 10 nT to 60,000 nT.

Closer to Earth, the Van Allen radiation belts extend from around 3 to 10 Earth radii and consist of a torus of charged particles (protons and electrons) that move along Earth's magnetic field lines and are reflected back and forth by the high-intensity fields near the north and south poles. The outer Van Allen belts derive their energy from the solar wind. The system circulates along the geomagnetic equator causing a *ring current*. These currents generate their own magnetic field, which can be as strong as 80 nT. [Backus] Further, "The ring current is like the Van Allen belt, surrounding Earth like a doughnut. The current is directed westward. In the vicinity of Earth, the current produces a field parallel to Earth's magnetic axis, pointing from north to south.

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Thus, if you are located in the equator, the H (horizontal) component is reduced.<sup>2</sup> On the other hand, if you are at the pole, it (causes) an increase in the Z (vertical) component.”<sup>3</sup>

Another phenomenon is called *electrojet*, an analogy with the jet streams in the stratosphere. Two types of electrojets are considered, auroral and equatorial. The auroral electrojet is a current that flows in the ionosphere in the auroral zone (above 60 deg. geomagnetic latitude). The auroral electrojet “is a concentrated westward current of width of a few hundred kilometers and (current) of a few million amperes. It is located in the evening-midnight-morning sector of the E region of the ionosphere in the auroral zone. In the past, we thought that there were two electrojets, one eastward and other westward oriented, but we think (now) that there is only one. During auroral substorms, the westward electrojet produces a large negative change in the H component, while the corresponding Z component changes depend on the location with respect to the jet, positive in the north, negative in the south.”<sup>4</sup> The equatorial electrojet is a thin electric current layer in the ionosphere over the geomagnetic equator at about 100 to 115 km altitude.



Fig. 3

Earth's magnetosphere and effects of the solar wind. Earth is the small globe in the middle-right. The Sun (not shown) is approximately 150 million kilometers away. The magnetosphere is compressed by the solar wind shock wave on the sunlit side (from upper-right corner). The magnetosphere's tail is pushed out on the nighttime side around 100 Earth radii (toward lower-left corner). The Van Allen belt is the white torus around Earth. (Image source: NASA)

Even closer to Earth, the Sun's ultraviolet light ionizes the outer regions of Earth's atmosphere on its sunlit side causing it to be much more conducting than the

nighttime side. The *ionosphere* extends from as low as 50 km to as high as 1000 km above Earth's surface. Strong electric currents circulate in the sunlit hemisphere with a westward drift. On Earth's surface, the current system associated with this component of the magnetic field follows the Sun as it passes overhead.

On Earth's surface, the field consists of several components, the largest of which is the *main field* or dipole field generated within Earth itself. This ranges from around 20,000 to 65,000 nT depending on the location. Other components, which can make up as much as 10% of the total measured field at the surface, are described later. Under the surface, the magnetic field gets stronger as the observer moves toward Earth's core, the source of the main field.

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<sup>2</sup> Here, H (non-italicized) represents the field's horizontal component and not the magnetic field strength.

<sup>3</sup> Personal communications, Syun Akasofu, International Arctic Research Center, 31 August 2010.

<sup>4</sup> Same as previous.



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## V. TIME SCALES

Earth's magnetic field varies over an extraordinary large span of time scales, from femtoseconds ( $10^{-15} s$ ) to millions or billions of years (10 petaseconds, or  $10^{15} s$ ). The very short time variations are due to sunlight and are of little interest in the study of geomagnetism.

Our interest starts with a time period on the order of milliseconds ( $10^{-3} s$ ). The magnetic field sporadically oscillates with amplitude of a few nanoteslas and frequency in the kilohertz range. The induced electric emissions from these oscillations can be received by simple ultra low and very low frequency (ULF and VLF) receivers and fed into a speaker or headphones. They are found to have a falling tone and are called *whistlers*. Each whistler is the result of a lightning stroke at the other end of the magnetic field lines passing through the observer's detector. The lightning produces a radio wave pulse in the ionosphere that travels along the field line. The frequency components of the pulse disperse as it propagates and its higher frequencies arrive first followed by progressively lower frequencies.

The solar wind excites charged particles in the magnetosphere at their resonant frequencies. These are called *micropulsations* and they have periods of 1 to 300 seconds. Micropulsations can last for several hours and have amplitudes of a few nanoteslas.

As mentioned previously, ring currents follow the Sun as it moves through the sky. An observer at a fixed location would measure a daily variation in the magnetic field. This *diurnal* variation is particularly noticeable on magnetically quiet days. There also are seasonal variations due to the change in the Sun's position, as seen by a fixed observer on Earth, as Earth orbits the Sun (Fig. 4). These variations are quite subtle and required years of observation and study to find. Geomagnetic disturbances tend to occur most frequently in the equinox months of March/April and September/October. They are least common during the solstice months of December/January and June/July.

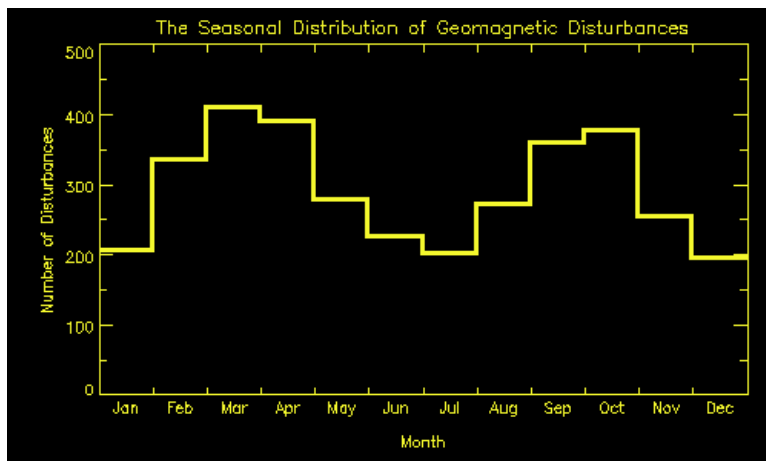


Fig. 4  
Number of geomagnetic disturbances by month taken during the years 1932 to 1994. In this case, a disturbance is indicated by a daily A-index greater than 25 (see Section VIII). Disturbances occur most frequently in the equinox months of March and April and are least common during the solstice months December and January. Source: Australian Space Weather Agency.  
<http://www.ips.gov.au/Educational/3/1/5>

Observers notice that measurements of Earth's magnetic

field also vary with a period of about 27 days, corresponding to the average rotation rate of the Sun itself. In particular, when there are active sunspots, Earth's field may experience wild gyrations due to coronal mass ejections and other activity on the Sun. These tend to recur with a 27 day period as sunspots and coronal holes rotate with the Sun. Depending on the location and the intensity of the solar activity, the magnetic field variations at Earth's surface can reach 2,000 nT. The number of sunspots visible on the sun follows an approximate 11-year cycle (Fig. 5-

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left). A new 11 year sunspot cycle begins when the magnetic polarity of the sunspots has reversed from the previous cycle. The polarity reversal cycle requires 22 years to complete and is called the solar magnetic cycle (Fig. 5-right). Observers see variations in Earth's magnetic field corresponding to these periods.

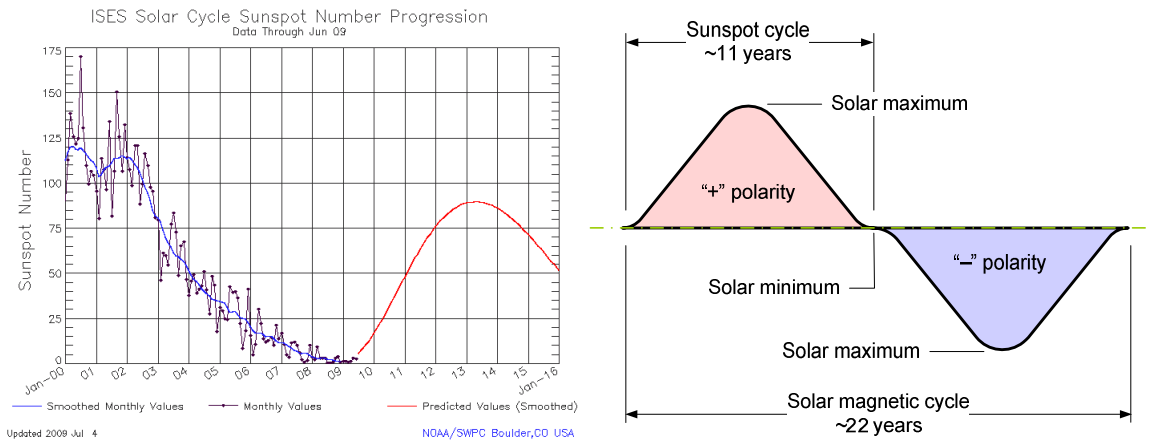


Fig. 5

(Left) Most recent 11 year sunspot cycle and predicted next cycle. (Right) 22 year solar magnetic cycle. Sunspot cycles vary in length and intensity and do not result in a smooth sinusoidal curve

All magnetic field variations discussed so far are related to solar or lightning activity and, with the exception of the sunspot cycle and solar magnetic cycle, have periods less than one year (Fig. 6). Earth's magnetic field also varies over longer time periods due to sources within Earth itself. These are called *secular variations* and are observed as a steady increase or decrease of magnetic field amplitudes at an observatory amounting to a few nanoteslas per year. Secular variations can be modeled by a quadratic polynomial in time.

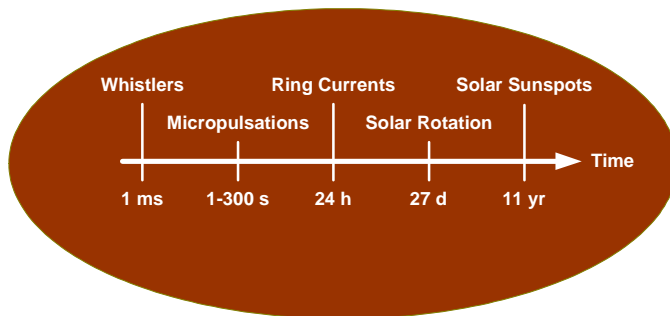


Fig. 6

Geomagnetic field time scales for external geomagnetic field influences

Occasionally, the slope of the secular drift changes rather suddenly; that is, the change takes place in a time period less than one year (Fig. 7). These *magnetic jerks* do not occur periodically, the most recent occurred in 1969, 1979, 1992 and

2003. It is thought they may be caused by differential movement between Earth's core and the outer crust. The 1969 magnetic jerk was not a global phenomenon. It was quite clear in Europe but undetectable at most observatories in North America.

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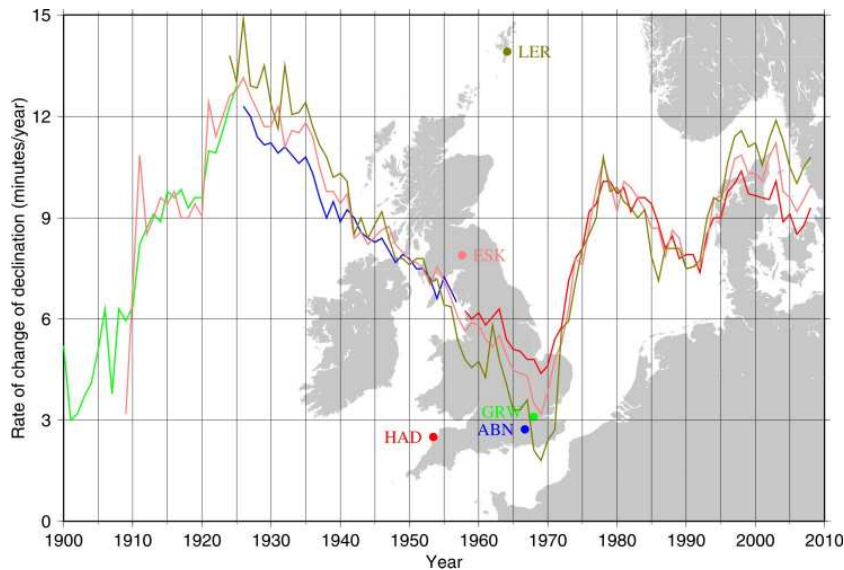


Fig. 7  
Secular variations and magnetic jerks. The magnetic field slowly drifts but occasionally the drift direction changes suddenly (within a one year time period) as shown here for three observatories in the United Kingdom. Image source: British Geological Survey

Earth's field experiences a slow westward drift. The drift rate corresponds to a complete circuit around Earth in about 700 to 2000 years (depending on who is making the calculation), although it is

unlikely that any individual feature of the field survives that long. Earth's field also changes in such a way that its polarity reverses at apparently random times (Fig. 8). The reversals have occurred as frequently as every 10,000 years and as infrequently as every 50 million years. Over the last 25 million years reversals have had an average period of about 100,000 years. However, geological evidence indicates the rate has increased and decreased with a characteristic time of around 100 million years.

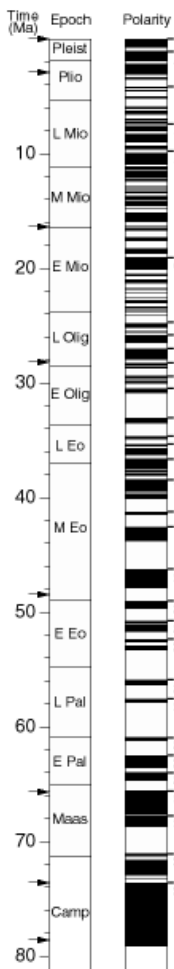


Fig. 8  
Geomagnetic field reversals over the last 80 million years. Geomagnetic field reversals during the last 25 million yr have occurred at an average rate of about once every 100,000 yr. Image source: US Geological Survey

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## VI. BASIC CHARACTERISTICS

Earth's magnetic field consists of *internal* and *external* components. The internal, or main, magnetic field is fairly steady when measured over time periods of days or months but its changes are quite significant when measured over periods of years and centuries. Earth's field also includes external components that represent up to around 10% of the total field measured at Earth's surface.

The internal field is thought to be generated by dynamo action in Earth's core. Dynamo is an obsolete term used for a rotating machine that generates direct current, but in the field of geomagnetism it is used to describe what is thought to be the rotation of Earth's core with respect to the mantle to produce a self-sustaining magnetic field.

The external field is considered to consist of three separate components: 1) magnetospheric current systems at the magnetopause (boundary between the magnetosphere and the surrounding inter-planetary medium or plasma); 2) magnetospheric currents at the surface that separate the two lobes of the magnetosphere's tail; and 3) a current system above Earth's equatorial region (ring current). Investigators believe the ring current is caused by charged particles in the solar wind that are trapped by the geomagnetic field, enhancing the plasma in the Van Allen belts. The charged particles spiral around and along the magnetic field lines between northern and southern latitudes. Their net motion is mainly westward and equivalent to an electric current in a ring around Earth as previously described. [Chapman]

The external field varies diurnally on the order of a few tens of nanoteslas (Fig. 9) and also experiences seasonal variations. It is the external field that is most affected by solar activity. Magnetic storms associated with the external field last minutes to days with variations of hundreds to thousands of nanoteslas. Some variations are so subtle that they were detected or put on a firm basis only by very detailed and pioneering statistical analysis by S. E. Forbush over a period of many years. [Van Allen]

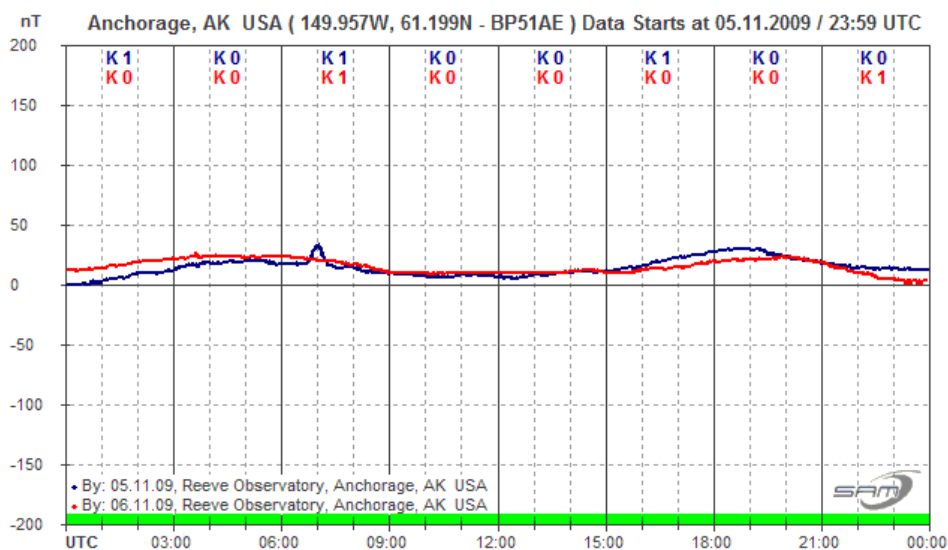


Fig. 9

Diurnal variations in the geomagnetic field on magnetically quiet days in November 2009 at Anchorage, Alaska USA. The “swelling” of the field in the sunlit hemisphere is apparent from



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around 1600 to 2200 UTC. Sunrise and sunset on the days shown were approximately 1640 and 0045 UTC, respectively. The daytime peak migrates back and forth with the seasons

Another component of Earth's magnetic field is the anomalous, induced magnetic field. This is magnetization induced in Earth's crust by the main and external fields and also remnant magnetization in ferromagnetic materials in the upper crust (for example, iron ore deposits). In most places, the induced field is considerably smaller than the other components, but there are locations, for example along the Aleutian Islands and Southeast Alaska coasts, where compass navigation is impaired due to the anomalous field (Fig. 10).

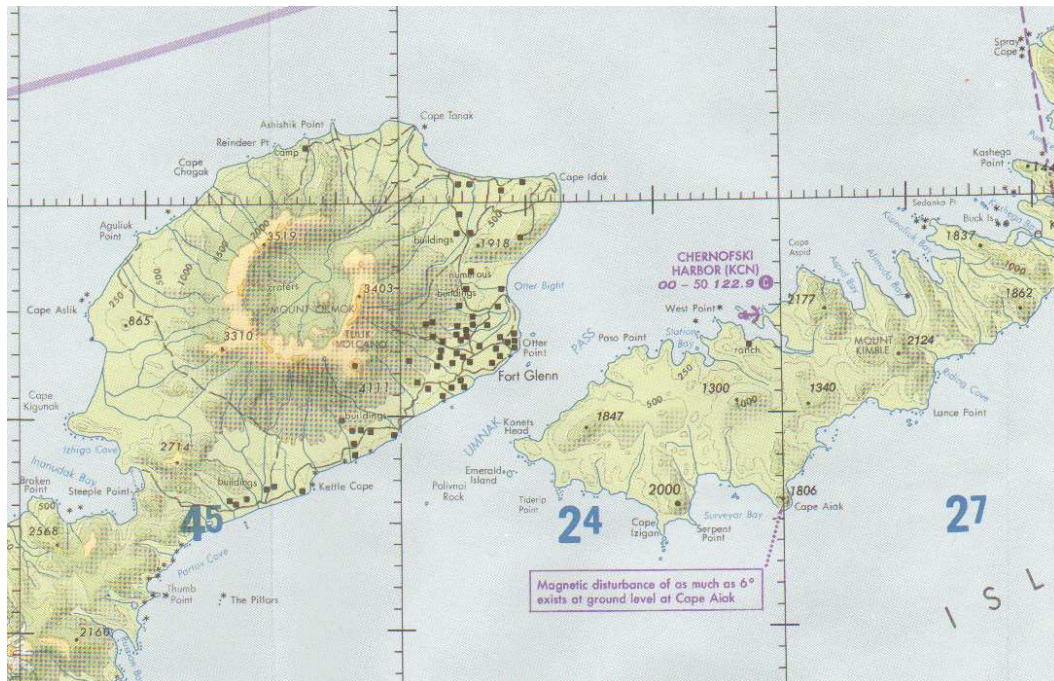


Fig. 10

Anomalous field on the south coast of Unalaska Island in Alaska's Aleutian Island Chain (see mariner warning at lower-right). Image source: US Geological Survey

A subtle component of the anomalous induced field is due to tsunamis, amounting to about 1 nT.[Manoj] This discovery was enabled by the magnetically very quiet conditions that prevailed during the extended solar minimum in 2008-2009 (end of solar cycle 23). As the electrically conducting seawater moves, it generates an electromotive force that induces electric fields, currents and secondary magnetic fields. This effect (motional induction) is proportional to the ocean velocity and strength of the vertical component of Earth's ambient field. Motional induction in the ocean by tides has been observed in land measurements since the 1960s and in satellite measurements.

Seismic measurements have indicated that Earth's core may consist of two layers of iron-nickel (Fig. 11-left). In current magnetic field models, the inner core is solid due to the high pressure from gravity but the outer core, or layer, is liquid. The solid inner core rotates with respect to the outer core and mantle. The temperature gradient between the top and bottom of the outer layer is large enough to cause convection (Fig. 11-right). [Karttunen] The magnetic field as measured on the surface and in near-Earth space cannot be described by a unique model. Therefore, the exact mechanism that produces Earth's magnetic field is unknown, but all the components for

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producing it are in the core – a rotating conductor (inner core) and strong electrical currents (outer layer).

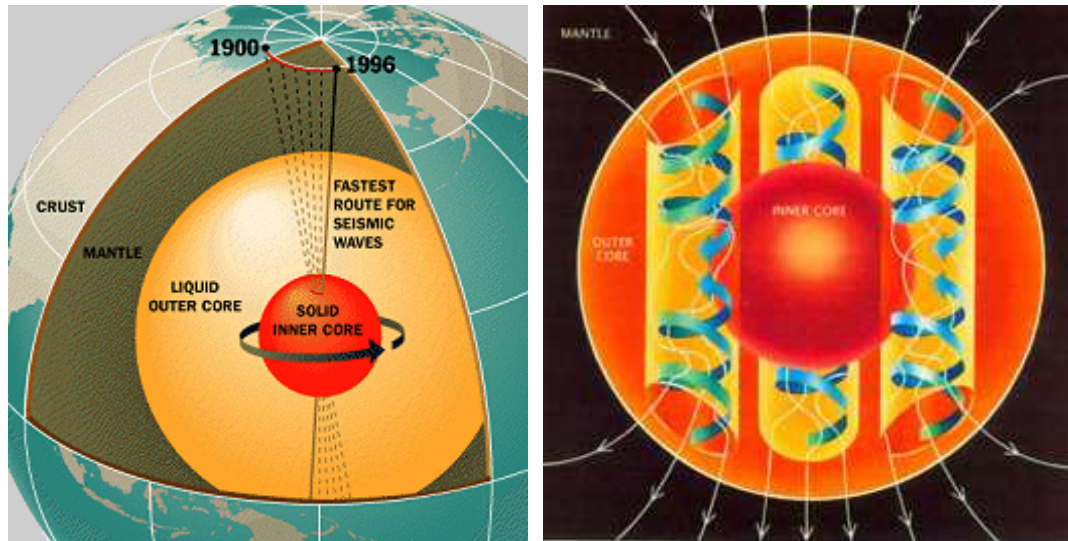


Fig. 11

(Left) Earth's core is thought to consist of two layers of iron-nickel. (Right) Convection currents in Earth's core are thought to be part of the process that produces the geomagnetic field. Image source: NASA

As previously mentioned, Earth's magnetic field as measured on the surface is roughly equivalent to the field of a magnetic dipole. The dipole is not aligned with Earth's geographic poles but is tilted. If the dipole is assumed to be at Earth's center, the best approximation is obtained with the dipole axis tilted about  $11.5^\circ$  (Fig. 12).

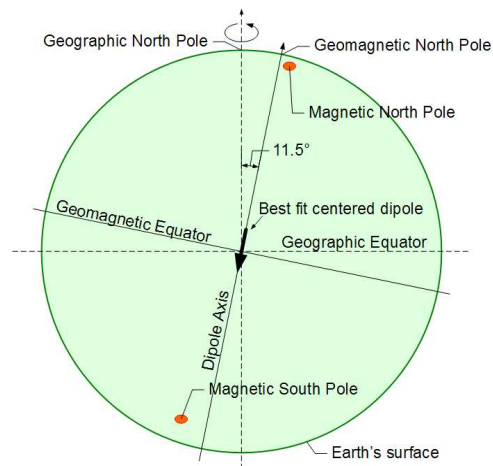


Fig. 12

Alignment of the best-fit centered dipole gives a tilt of  $11.5^\circ$ . The difference between the field from a centered dipole and Earth's actual field can be reduced by offsetting the dipole slightly. Note that the Magnetic North and South Poles are not collocated with the Geomagnetic North and South Poles, the latter based on a dipole model (see text).

The dipole is not centered, and the geographic location of the measured magnetic North Pole is not on the exact opposite side of Earth from the measured magnetic South Pole. The discrepancies between the centered dipole and Earth's actual measured field can be reduced by fitting an eccentric dipole. In 2005 the location of the center of the

eccentric dipole, sometimes known as the magnetic center, was at approximately  $r, \varphi', \lambda = 552$  km,  $22.2^\circ\text{N}$ ,  $141.6^\circ\text{E}$ , where  $r$  is the dipole's distance from Earth's geographic center, and  $\varphi'$  and  $\lambda$  are its geographic latitude and longitude.<sup>5</sup>

Earth's north and south magnetic poles (NMP and SMP) are where the field lines are vertical (measured magnetic inclination is  $+90^\circ$ ). These also are called the *magnetic dip poles*. On the other hand, the geomagnetic poles are based on models such as the International Geomagnetic Reference Field (IGRF) models (for example, the Centered Dipole model and

<sup>5</sup> Calculations from [www.ngdc.noaa.gov/geomag/faqgeom.shtml](http://www.ngdc.noaa.gov/geomag/faqgeom.shtml)



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Eccentric Dipole model). These are *computed* pole positions and may be quite different than the actual *measured* dip poles.

The average magnetic induction at Earth's equator is ~31,000 nT. Over Earth's surface, the field varies from about 20,000 to 65,000 nT depending on the location (Fig. 13). If we look at just the vertical component of the field, the magnetic equator is located where the vertical component is zero (Fig. 14).

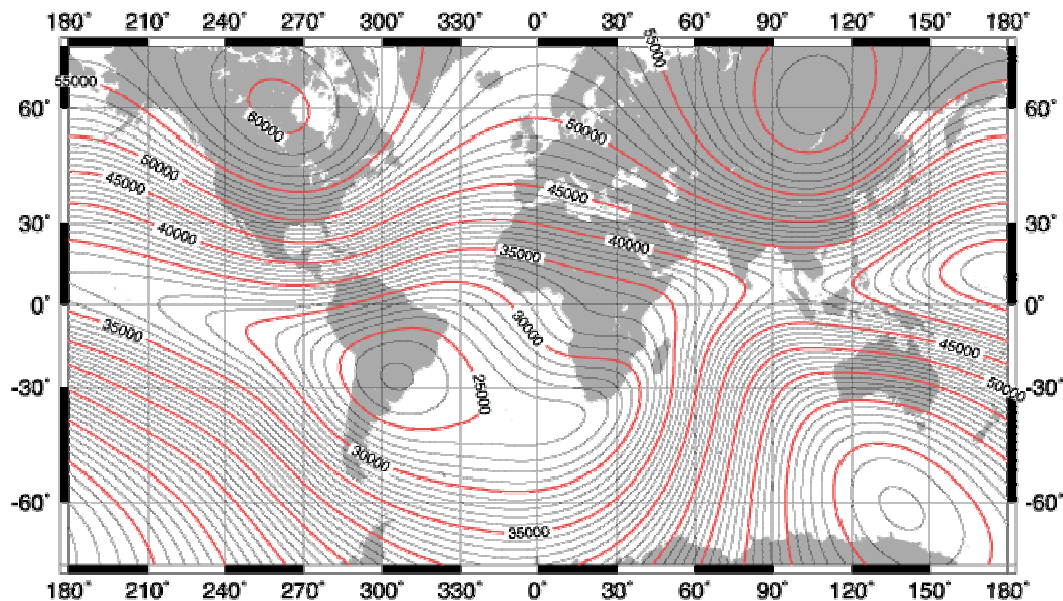


Fig. 13

Earth's total magnetic field in nT for the year 2000. (source: National Geophysical Data Center, NOAA, [www.ngdc.noaa.gov/geomag/](http://www.ngdc.noaa.gov/geomag/))

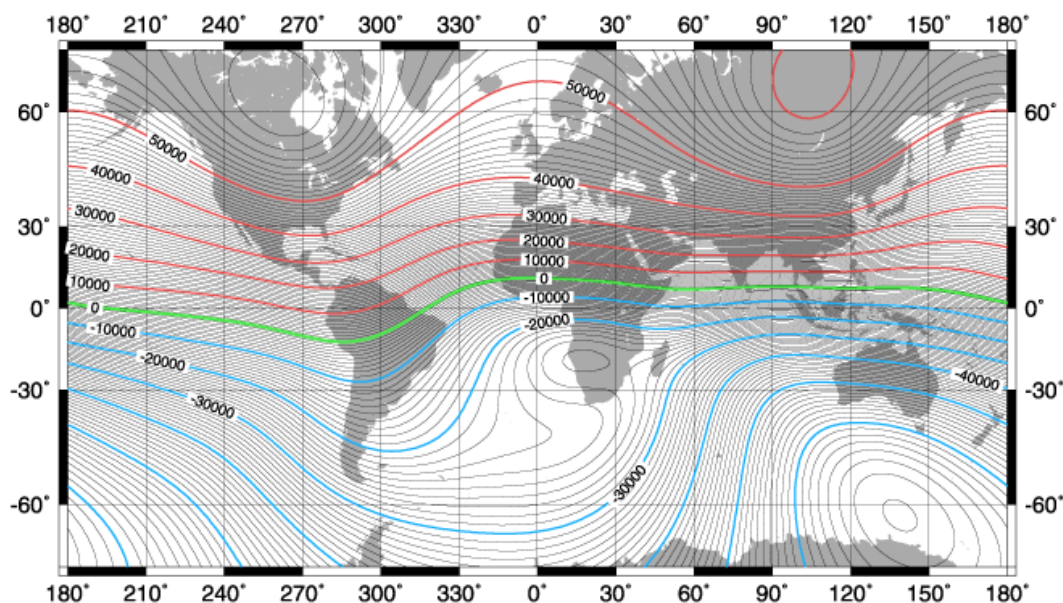


Fig. 14

Vertical component of Earth's magnetic field in nT for the year 2000. The magnetic equator is located along a line

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where the vertical component is zero. (source: National Geophysical Data Center, NOAA, [www.ngdc.noaa.gov/geomag/](http://www.ngdc.noaa.gov/geomag/))

As mentioned above, the field is not constant over time. It varies on a daily basis and on a long-term basis. Long-term variations include complete reversals and wandering (or drift) of the magnetic poles (Fig. 15 and 16).

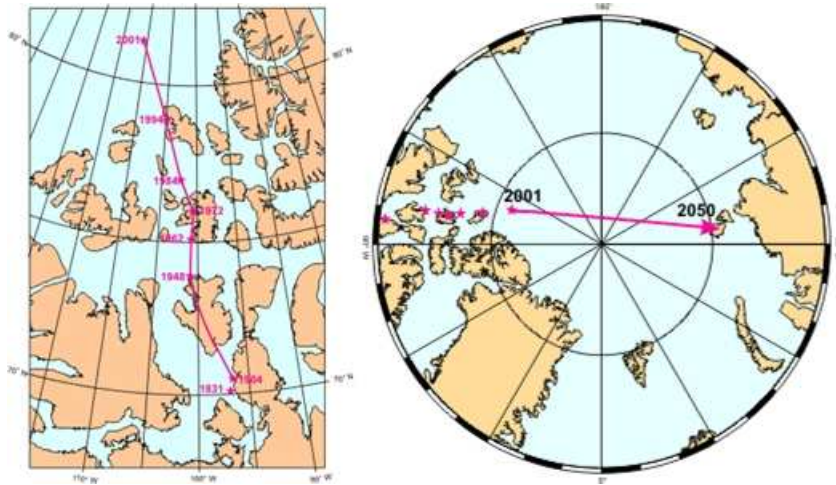


Fig. 15  
(Left) Magnetic north pole movement through northern Canada between 1831 and 2001. (Right) Future estimate. In the right image, the converged black lines indicate the geographic North Pole. Image source: Geological Survey of Canada

In 2001 the North Pole was moving northwest at a rate of about 40 km/yr. Between 2001 and 2005, the North Pole moved from 81.3°N :

110.8°W to 82.7°N : 114.4°W, a great circle distance of about 165 km. Of course, the South Pole wanders as well; however, its movement over long periods is not as well studied as the North Pole. During the 1990s, the North Pole drift rate accelerated for unknown reasons (Fig. 16). The rate had remained less than 15 km/yr over the previous 150 years of observation but accelerated to 55 km/yr by the end of the 1990s. The drift rate peaked at 60 km/yr in 2002, after which it slowly decreased. By contrast, the South Pole drift rate has never exceeded 15 km/yr since observations began.

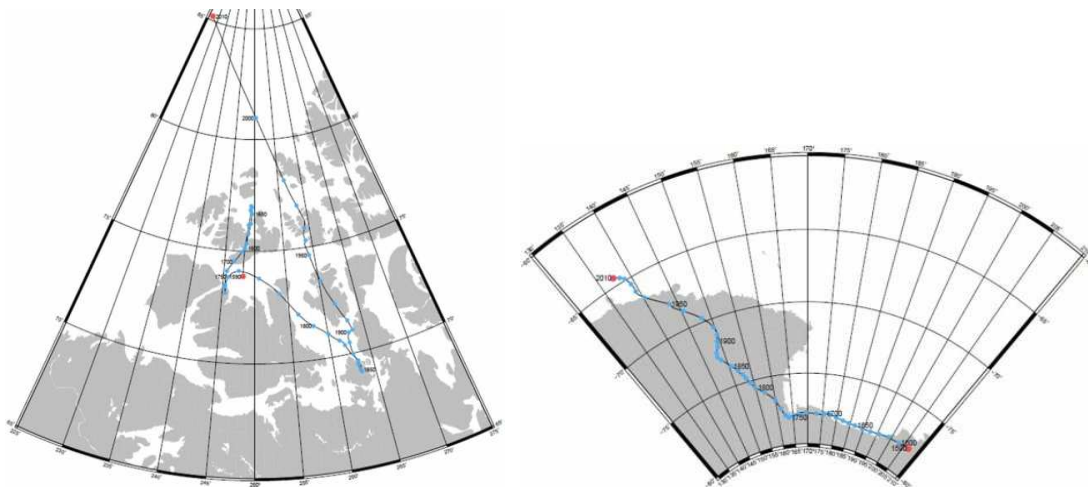


Fig. 16

(Left) Magnetic north pole drift from 1590 to 2010 produced from Uniform Flow Model (UFM) and IGRF-10 magnetic field models. (Right) Magnetic south pole drift from 1590 to 2010. Image source: National Geophysical Data Center

An interesting animation of the field changes and pole wandering can be found at <http://geomag.usgs.gov/faqs.php>. An animation of the total field changes over the last 400 years



# Geomagnetism Tutorial

can be found at [wdc.kugi.kyoto-u.ac.jp/igrf/anime/index.html](http://wdc.kugi.kyoto-u.ac.jp/igrf/anime/index.html). Paleomagnetism studies have shown that, at least for the last 2,000 years, the average position of the geomagnetic poles is indistinguishable from the geographic poles.<sup>6</sup>

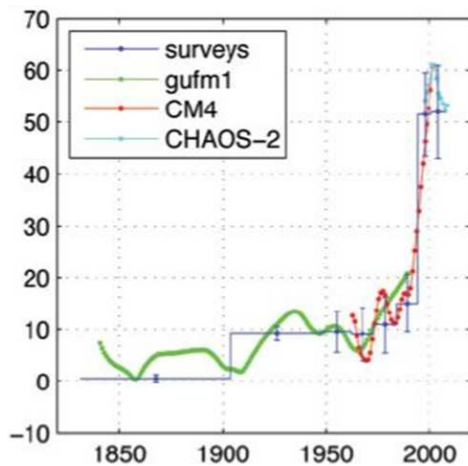


Fig. 16

Average drift rates for the North Magnetic Pole. The vertical scale is drift rate in km/yr. The straight stair-step lines (with error bars) show the observed rate, which sharply rose in the 1990s, peaking at 60 km/yr in 2002. The smooth colored lines are drift rates predicted by the indicated model. Source: [Chulliat, figure 1(a)]

Because the dipole's north and south poles presently are not in the same location as Earth's geographic poles, geomagnetic and geographic coordinates on Earth's surface are considerably different. To provide a consistent framework for study of Earth's field, a system of geomagnetic coordinates has been defined based on the intersections of the modeled dipole axis with Earth's surface. The geographic coordinates of the geomagnetic north and south poles in May 2010 were 79.7 °N : 71.8 °W and 79.7 °S : 108.2 °E. Since the geomagnetic poles are slowly moving, the coordinates are redefined at 5 year intervals (based on the International Geomagnetic Reference Field, presently IGRF-10). A coordinate system converter can be found online.<sup>7</sup> For example, the geographic and geomagnetic coordinates for the Reeve Observatory at Anchorage, Alaska USA in June 2010 were

Geographic: 61.19928 °N : 149.95652 °W

Geomagnetic: 61.74 °N : 263.80 °E

Investigators noticed geomagnetic variations corresponded to the Sun's rotation period. The rotation period was first studied by Richard Carrington in the 1850s and found to be 27.2753 days. Since the Sun is gaseous, has no permanent points of reference and rotates differentially (upper latitudes rotate slower than lower latitudes), this period is an average.

<sup>6</sup> Paleomagnetism is the study of the magnetic properties of rocks and minerals

<sup>7</sup> [wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html](http://wdc.kugi.kyoto-u.ac.jp/igrf/gggm/index.html)

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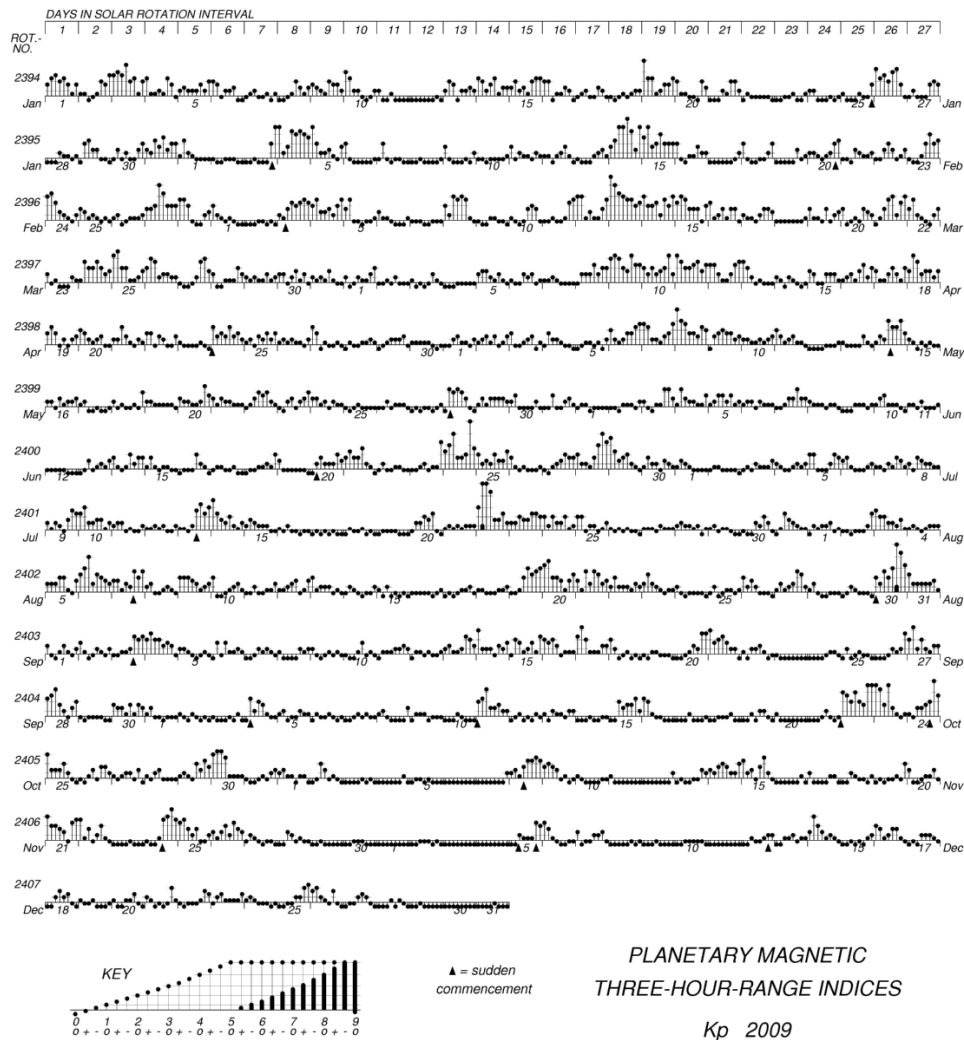


Fig. 17

Bartels Diagram for 2009. The 1st through 27th day of each rotation are shown at the top with the corresponding K-index value for each rotation in a column immediately below. These diagrams aid in the visualization of recurrent solar and magnetic field phenomena. Image source: [wdc.kugi.kyoto-u.ac.jp/kp](http://wdc.kugi.kyoto-u.ac.jp/kp)

Julius Bartels studied the correspondence between the Sun's rotation and the geomagnetic field and in 1934 conceived a system of rotation numbers based on an even 27-day period. [Bartels-34] He assigned Day 1 of Rotation 1 to February 8, 1832 (for reference, day 1 of Rotation 1001 was January 17, 1906 and day 1 of Rotation 2400 was June 12, 2009). He then plotted the Sun's activity based on the 3-hour K-index for each rotation number. This was called the Bartels Diagram, also called Bartels Musical Diagram because of its appearance (Fig. 17).

It is recognized that the Bartels Rotation system is, perhaps, over-simplified for long-term study. It is like a calendar with no leap years – it falls out of synchronization over time. A more accurate rotation system is based on the Carrington period mentioned above. Carrington Rotation Number 1 started November 9, 1853.

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## VII. GEOMAGNETIC FIELD PARAMETERS

According to the National Geophysical Data Center (NGDC)<sup>8</sup>, Earth's magnetic field is described by seven parameters (Fig. 18):

- Declination ( $D$ , + east of north, angular measurement in degrees)
- Inclination ( $I$ , + down, angular measurement in degrees)
- Horizontal intensity ( $H = \sqrt{X^2 + Y^2}$ , amplitude measurement in nT)
- North component of horizontal intensity ( $X$ , + north, amplitude measurement in nT)
- East component of horizontal intensity ( $Y$ , + east, amplitude measurement in nT)
- Vertical intensity ( $Z$ , + down, amplitude measurement in nT)
- Total intensity ( $F = \sqrt{H^2 + Z^2} = \sqrt{X^2 + Y^2 + Z^2}$ , amplitude measurement in nT)

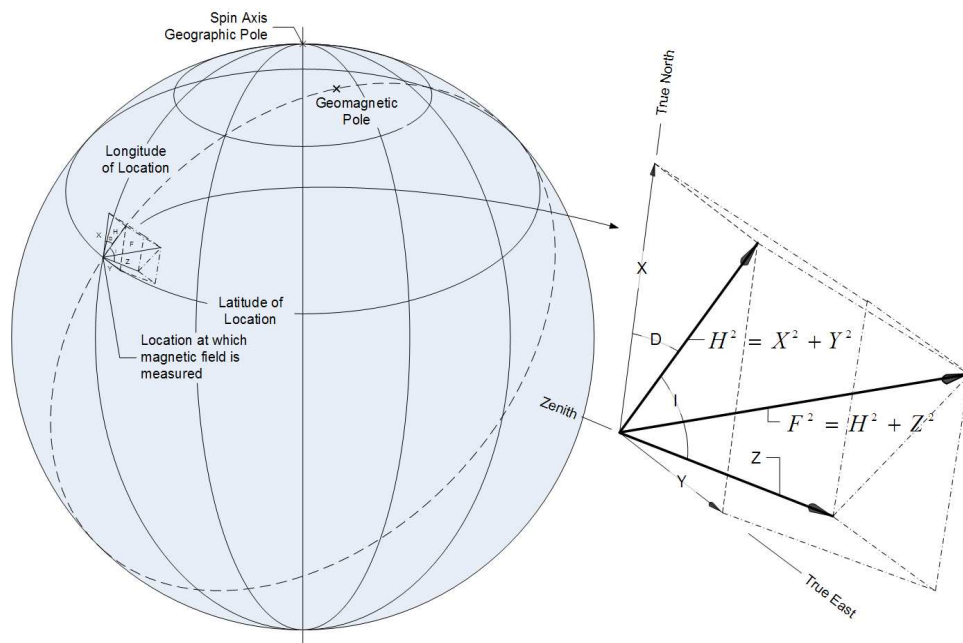


Fig. 18  
Schematic of the seven magnetic field parameters defined by the NGDC

The NGDC calculator gave the following values for March 2, 2010 at the Reeve Observatory in Anchorage (geographic coordinates 61.199 N : 149.956 W):

- Declination,  $D = 18.97^\circ$  changing by  $-0.307^\circ/\text{year}$
- Inclination,  $I = 74.144^\circ$  changing by  $-0.012^\circ/\text{year}$
- North component,  $X = 14,416.14$  nT changing by  $+16.27$  nT/year
- East component,  $Y = 4,955.46$  nT changing by  $-80.63$  nT/year
- Horizontal Intensity,  $H = 15,244.07$  nT changing by  $-10.6$  nT/year
- Vertical component,  $Z = 53,669.56$  nT changing by  $+5.27$  nT/year
- Total Intensity,  $F = 55,792.5$  nT changing by  $+2.18$  nT/year

<sup>8</sup> [www.ngdc.noaa.gov/geomag/faqgeom.shtml](http://www.ngdc.noaa.gov/geomag/faqgeom.shtml)

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As seen in this data, the vertical component at this observatory is, by far, the largest; the total intensity vector is only about  $16^\circ$  from vertical.

Anyone who reads literature associated with geomagnetism soon realizes there are other, often confusing, parameters used to describe Earth's field. For example, many observatories use D in units of nT to indicate the horizontal component aligned with geomagnetic East-West while others use D to indicate Declination in degrees. Geomagnetic literature often lacks symbol and parameter definitions and inconsistent and incorrect use of units of measure, reflecting the confusion mentioned in Sect. II.

Readers may encounter various coordinate systems:

- Geographic coordinates – North (X), East (Y), Vertical down (Z)
- Geographic coordinates – Horizontal intensity (H), Declination (D), Vertical down (Z)
- Geomagnetic coordinates – Magnetic north (H), magnetic east (D), Vertical down (Z)

Geomagnetic latitude and longitude are best defined graphically (Fig. 19).

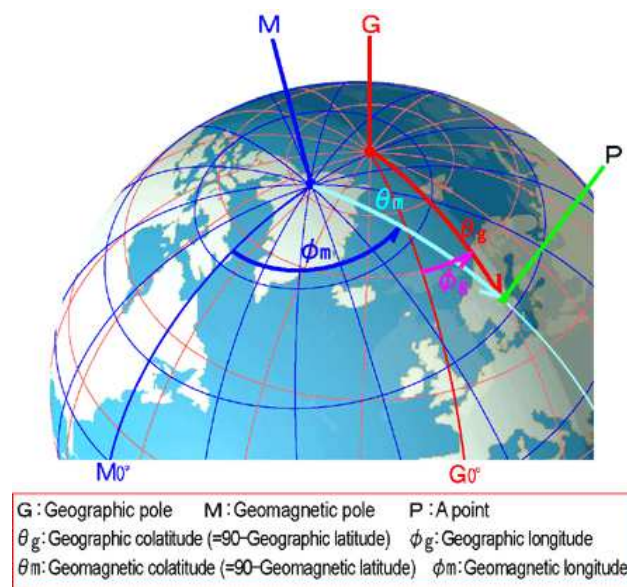


Fig. 19

Definitions of geomagnetic latitude and longitude.  
Source: World Data Center for Geomagnetism, Kyoto  
at [wdc.kugi.kyoto-u.ac.jp/igrf/gggm/gmexp.html](http://wdc.kugi.kyoto-u.ac.jp/igrf/gggm/gmexp.html)

Geomagnetic sensors typically are setup as follows: During initial setup the magnetic sensor axes are oriented in either the geographic or local magnetic coordinate system (that is, with respect to true north and east or with respect to local magnetic north and east). The vertical sensor axis always is exactly vertical.

Earth's main (dipole) field is constantly changing so the geomagnetic coordinate system also changes over time. Using the two horizontal components the observatory determines a slowly varying time dependent declination angle and subsequently rotates the horizontal components into a local magnetic coordinate system for which the magnetic east component (E) is minimized and the magnetic north component (N) is maximized. Note that geomagnetic coordinates are labeled H, D and Z although the units of the D-component can be magnetic induction in nT or an angle in degrees. Also, the D-component is often found to have a significant offset due to changing field over time.

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## VIII. GEOMAGNETIC INDICES

Indices are used in the study of geomagnetism to summarize the large amounts of complex data associated with periodic observations. Many indices have been proposed over the years and several still are in use today. The indices differ in the time scale associated with their determination, for example, hourly, 3-hourly, daily, and so on. We will spend the most time discussing the K-index because it is the most common. We will discuss the related G-scale and Ap-index at the end of this section. An excellent description of geomagnetic indices is found in [Mayaud] and a more detailed description of indices derived from the K-index is found in [Menvielle].

The K-index is an approximately logarithmic measure of magnetic disturbances and consists of ten values, K0 through K9. It is related to the *peak-to-peak* fluctuations of the horizontal magnetic field component observed on a magnetometer during a three-hour interval relative to a quiet day. The vertical component (Z) is excluded from the K-index because it is more affected by underground-induced effects and by field sources farther from the station. The three-hour intervals correspond to Coordinated Universal Time (UTC) 0000 – 0300, 0300 – 0600, . . . , 2100 – 2400.

The conversion from maximum fluctuation in nT to K-index varies from observatory to observatory in such a way that the historical rate of occurrence of each K-index value is about the same at all observatories. The K-index was introduced in 1939 by Julius Bartels.[Bartels-39]

Observatories at higher geomagnetic latitudes routinely experience wider magnetic field fluctuations than lower-latitudes observatories (Fig. 20); therefore, the magnetic field amplitude range corresponding to each K-index value at these higher latitudes is wider. The K-index values also depend on magnetic longitude. Dirk Lummerzheim, Research Professor at Geophysical Institute, University of Alaska - Fairbanks, said “If an existing sensor station is moved across town, it would have a new K-index.”<sup>9</sup> The K-index only can be determined from statistical analysis of data from a long observing period. There is no formula that can be used to determine the limits for the K-index values based on latitude and longitude.

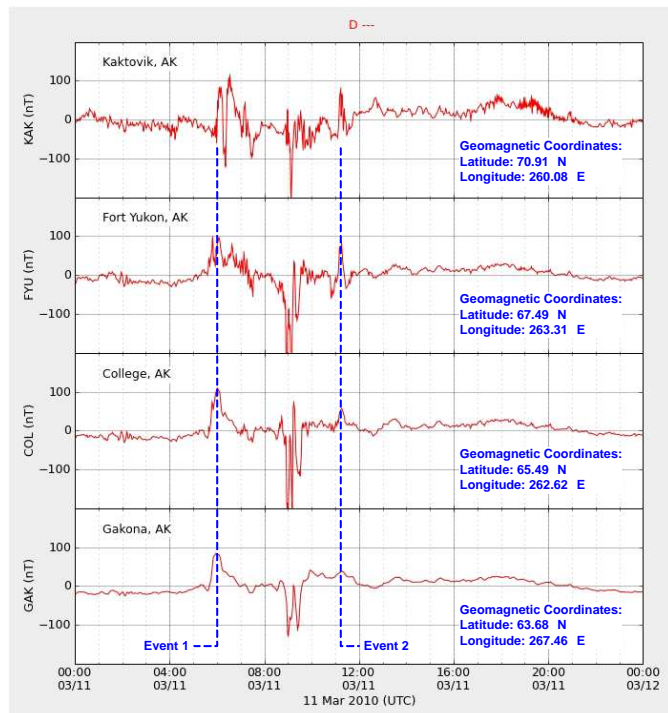


Fig. 20

Geomagnetic variations are more pronounced at high-latitude observatories. These magnetograms show the E-W component for some of stations in the Alaska Magnetometer Chain. The stations are at approximately the same longitude and separated in latitude by about 2 degrees. Two events are marked to illustrate the increase in activity with latitude. Also, it is apparent that the overall charted activity is noisier as latitude is increased

<sup>9</sup> Personal communications May 8, 2009.

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A table is assigned to each observatory, giving the limits, or range, corresponding to each of the ten values of K. The lower limit for K = 9 is 100 times the upper limit for K = 0. The lower limit for K = 9 at a given station generally, but not always, has one of the following values: 300, 350, 500, 600, 750, 1000, 1200, 2000, or 2500.<sup>10</sup> The first applies to magnetically quiet very low latitude observatories, and the last applies to the most disturbed stations in the auroral zone at northern latitudes. The limit 500 is appropriate for mid-latitude stations at about geomagnetic latitude 50°. The K-index table for this latitude is shown in Table 3, left panel.

Table 3 – K-index values for various K9 limits

Mid-latitudes ~50 °N K9 > 500		Example K9 > 1000		College, Alaska ~65 °N K9 > 2500	
K	Range (nT)	K	Range (nT)	K	Range (nT)
K0	0 – 5	K0	0 – 10	K0	0 – 25
K1	5 – 10	K1	10 – 20	K1	25 – 50
K2	10 – 20	K2	20 – 40	K2	50 – 100
K3	20 – 40	K3	40 – 80	K3	100 – 200
K4	40 – 70	K4	80 – 140	K4	200 – 350
K5	70 – 120	K5	140 – 240	K5	350 – 600
K6	120 – 200	K6	240 – 400	K6	600 – 1000
K7	200 – 330	K7	400 – 660	K7	1000 – 1650
K8	330 – 500	K8	660 – 1000	K8	1650 – 2500
K9	> 500	K9	> 1000	K9	> 2500

It can be seen that the ranges double for K = 0 through K = 3. The ranges then increase more slowly because, if doubled, the index would become too coarse and the higher indices, K = 8 and K = 9, never would be reached. For other geomagnetic latitudes, the range limits are scaled up or down proportionately to the lower limit for K = 9. For example, if the lower limit for K = 9 is 1000, then the K-index range is as shown in the middle panel of the table. For College, Alaska, at 65.48°N geomagnetic latitude, about 400 km north of the Reeve Observatory in Anchorage, the lower limit for K = 9 is 2500 and is shown in the right panel.

The weighted average of the K-index values for a network of geomagnetic observatories is used to derive a *planetary* K-index, or Kp-index. There are two Kp indices in use today. One is an estimated Kp-index determined by the Space Weather Prediction Center<sup>11</sup> and the other at the international level by the Helmholtz Centre in Potsdam<sup>12</sup>.

The Potsdam Kp-index is based on 13 observatories around the world. It is not reported in real time and cannot be used for space operations where there is a need for immediate warning of geomagnetic disturbances related to solar events. Therefore, the Space Weather Prediction Center uses near real-time estimates from the US Air Force based on a network of observatories, most of which are in North America. The Australian Space Weather Agency produces an estimated regional K-index for Australia.<sup>13</sup>

<sup>10</sup> These values were used when the number of observatories was small. There are no apparent limitations in the use of intermediate values in modern magnetometer networks.

<sup>11</sup> [www.swpc.noaa.gov/info/Kindex.html](http://www.swpc.noaa.gov/info/Kindex.html)

<sup>12</sup> [www-app3.gfz-potsdam.de/kp\\_index/index.html](http://www-app3.gfz-potsdam.de/kp_index/index.html)

<sup>13</sup> [www.ips.gov.au/Geophysical/1/3/1](http://www.ips.gov.au/Geophysical/1/3/1)

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Amateur radio astronomers may not be interested in or equipped to perform the detailed analysis required to develop a K-index for their stations. For that type of work an approximation is sufficient. A *local* K-index may be approximated from a nearby magnetometer station that already has a K-index. Alternately, a local K-index may be approximated by using field data from a nearby magnetometer station and working backward from the planetary Kp-index as follows:<sup>14</sup>

1. Determine the Kp-index values for several 3-hour time periods over several days. If possible, find a dozen or so periods for each Kp-index value, Kp = 0 through Kp = 9. Days when Kp is high (Kp = 8 and Kp = 9) are relatively rare (a few days in an 11 year solar cycle) compared to lower Kp values, so it may not be possible to find very many times when the Kp-index is high
2. Determine the field values (nT) at a nearby magnetometer station corresponding to the same time periods and days.
3. For each Kp-index value, compare the range of corresponding field values to the range limits, or multiples of the range limits, described above (the multiple is the same for each Kp-index value and does not have to be an integer)
4. Assign the appropriate range limits to each local K-index value so they resemble the Kp-index to the extent possible

The US National Oceanic and Atmospheric Administration (NOAA) simplified the K-index and Kp-index into a G-scale to help people involved in space programs to understand the significance of geomagnetic storms. Variations in Earth's magnetic field, and particularly magnetic storms, can affect space operations in many ways (discussed in the next section).

The G-scale uses near-real time estimates of the Kp-index and contains five categories (G1 to G5) to indicate geomagnetic storms for space weather reporting purposes (Table 4). The G0 category corresponds to K = 0 to K = 4. It is a below-storm category and not reported. NOAA reports geomagnetic storms on the web.<sup>15</sup>

Table 4

NOAA space weather scale for geomagnetic storms. See original source for effects associated with the G-scale.  
(source: [www.swpc.noaa.gov/NOAA\\_scales/index.html#GeomagneticStorms](http://www.swpc.noaa.gov/NOAA_scales/index.html#GeomagneticStorms))

Category	Physical measure	Average frequency
Scale Descriptor		(1 cycle = 11 years)
G5 Extreme	Kp = 9	4 per cycle (4 days per cycle)
G4 Severe	Kp = 8 and 9–	100 per cycle (60 days per cycle)
G3 Strong	Kp = 7	200 per cycle (130 days per cycle)
G2 Moderate	Kp = 6	600 per cycle (360 days per cycle)
G1 Minor	Kp = 5	1700 per cycle (900 days per cycle)
G0 Below storm	Kp = 0 to 4	N/A

<sup>14</sup> Dirk Lummerzheim at the Geophysical Institute, University of Alaska Fairbanks suggested this procedure, and it is the one used at Reeve Observatory to set the K-index.

<sup>15</sup> [www.swpc.noaa.gov/SWN/index.html](http://www.swpc.noaa.gov/SWN/index.html)



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Another index that currently is used is the planetary A-index (Ap-index). It is based on the K-index and frequently is mentioned in propagation summaries and forecasts published by the American Radio Relay League (ARRL).<sup>16</sup>

The A-index indicates a daily average level for geomagnetic activity, but it is not a simple average of a set of K-indices because of the non-linear, quasi-logarithmic nature of the K-index. Instead, the K-index at an observatory is converted to a linear scale called the "equivalent three hourly range" a-index (with a lowercase "a"). The daily A-index is the average of eight "a" indices. The following table illustrates the conversion between K-index and a-index.

<b>K =</b>	0	1	2	3	4	5	6	7	8	9
<b>a =</b>	0	3	7	15	27	48	80	140	240	400

An example will illustrate the derivation of the A-index from the K-indices for one day. There are eight K-index values for each 24 hour period. The K-index for each period is converted to an a-index (note lower case) and the eight a-indices are then averaged to find the A-index. The planetary Ap-index takes into account a group of observatories (rather than just one) and actually is calculated as a running average of eight 3-hour periods.

<b>Time period (UTC)</b>	0-3	3-6	6-9	9-12	12-15	15-18	18-21	21-24
<b>K-index</b>	3	5	7	4	3	2	1	1
<b>a-index</b>	15	48	140	27	15	7	3	3
<b>A-index</b>	$(15 + 48 + 140 + 27 + 15 + 7 + 3 + 3)/8 = \mathbf{32.25}$							

The a-indices at a given observatory can be converted into amplitude units of nT by multiplying them by a conversion factor that is specific to that observatory. The conversion factor is found dividing the observatory's lower limit for K9 by 250. For example, say the lower limit of K9 at a northern latitude observatory is K = 1000 nT. In this case, the conversion factor is  $1000/250 = 4$ . From the table above, for a K-index of 3, the associated a-index is 15 and for a K-index of 4, the associated a-index is 27. The equivalent amplitudes are  $4 \cdot 15 = 60$  nT and  $4 \cdot 27 = 108$  nT

The Ap-index and Kp-index are not the only indices used in the study of geomagnetism, but the K-index, by far, is the one most commonly used to describe geomagnetic activity.

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<sup>16</sup> For example, see [www.arrl.org/w1aw-bulletins-archive/](http://www.arrl.org/w1aw-bulletins-archive/)



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## IX. GEOMAGNETIC STORMS AND DISTURBANCES

A geomagnetic storm occurs when there is a period of rapid magnetic field variation. Generally, there are two main causes:

- First, the Sun occasionally emits a *coronal mass ejection* (CME), which is a strong surge in the emission of charged particles with a resulting increase in the velocity and density of the solar wind (Fig. 21-left). A CME must be directed at Earth for it to disturb the geomagnetic field. When the surge hits Earth's magnetosphere, usually 2 – 5 days after the solar event, the magnetic field is disturbed and oscillates. This in turn generates electric currents in Earth's ionosphere and near-Earth space environment. The electric currents in turn generate additional magnetic-field variations. An example of CME impact on the geomagnetic field is shown later in this section;
- Second, large regions on the Sun's corona become cooler indicating that the Sun's magnetic field lines are stretching far out into the inter-planetary medium (Fig. 21-right). These field lines may directly link with Earth's magnetic field, a process called *magnetic reconnection*. Charged particles can then travel along the magnetic field lines and enter Earth's magnetosphere. The resulting current causes the geomagnetic field to vary. An example of the effect of coronal hole high-speed streams on the geomagnetic field was shown in Sect. I. Magnetic reconnection is an ongoing process and the magnitude of its effects depend on plasma pressure, the magnetic field and its direction and other factors. Sometimes the CME and direct linkage occur at the same time leading to a very large geomagnetic storm.

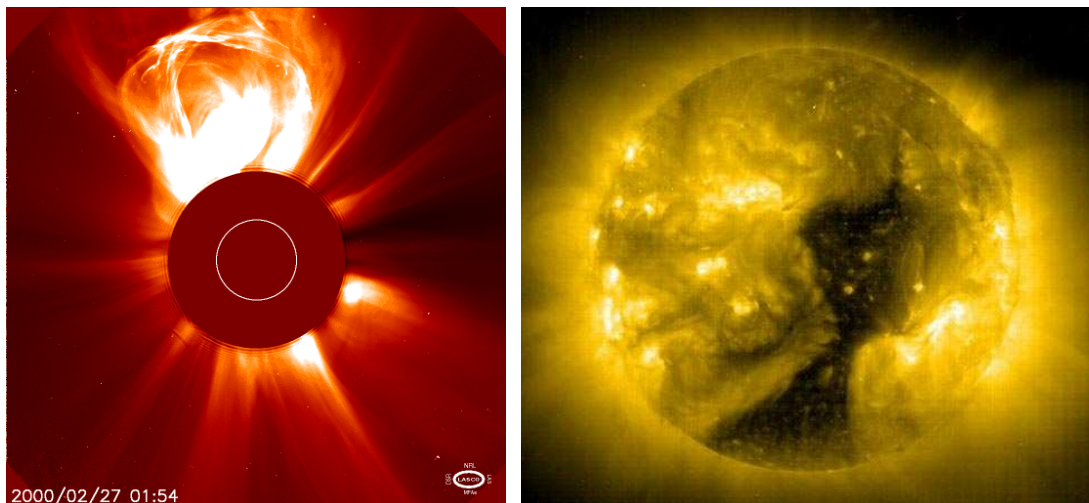


Fig. 21

(Left) Coronal mass ejection (CME) in upper part of image. A huge explosion on the Sun ejects charged particles that, when directed at Earth, interact with and disturb the geomagnetic field. CMEs are often associated with large solar flares. The disk in the center is part of the imaging device, and the white circle in the middle corresponds to the Sun. Image source: NASA. (Right) Coronal hole high-speed stream. The large dark region in the image indicates less dense and colder plasma in the Sun's corona where the solar magnetic field lines are able to stretch far out into the inter-planetary medium. These field lines may connect with Earth's magnetic field, causing a geomagnetic disturbance. During periods of sunspot minimum, the coronal holes usually are found in the Sun's polar regions, but as solar activity increases the coronal holes can be found at all latitudes. Image source: NASA

Sunspots indicate solar activity that also can affect the geomagnetic field (Fig. 22). While sunspots themselves do not cause geomagnetic storms (it is the solar activity associated with the sunspots), there is a direct correlation between the sunspot number and geomagnetic activity. Sunspot cycles are numbered based on an arbitrary starting point. The cycles themselves

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probably have existed as long as the Sun but were not given numbers until the 1700s. Cycle 23 ended in late 2008. Aurora observers have long noted that the brilliance and frequency of aurora is related to the sunspot number.

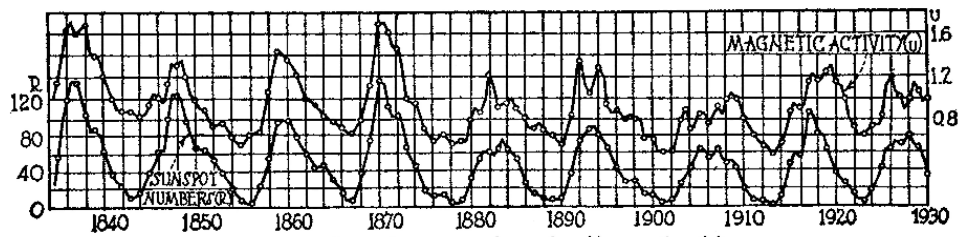


Fig. 22

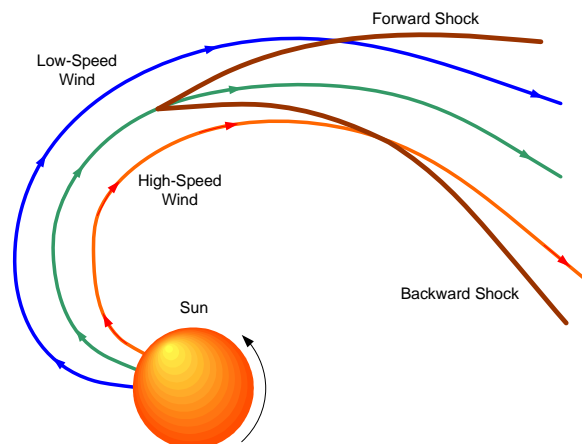
Correlation between sunspot number and geomagnetic field variation, 1834-1930. This chart from 1934 shows how closely the geomagnetic field changes (upper curve and right-hand scale) correspond to the sunspot number (lower curve and left-hand scale), leaving no doubt that the Sun is responsible. In this chart, the geomagnetic activity is measured by the now obsolete U-index, which is reported in variations of tens of nT. Image source: [Stetson] fig. 37

Amateur radio astronomers who study and listen for solar emissions and who also monitor the geomagnetic field can attempt to correlate their data; however, due to the varying delays from the time of a solar event to its effect on the geomagnetic field, correlation of individual events is very difficult, particularly when the Sun is active. The time between a solar event and its effect on the geomagnetic field depends on the solar wind speed.

The solar wind speed depends on many factors associated with the sunspot cycle. During the descending and minimum phases of the sunspot cycle, the solar wind is dominated by coronal hole high-speed streams with speeds in the range of 500 – 800 km/s. The solar wind also has a denser low-speed component with a speed of around 300 km/s associated with the equatorial coronal streamer belt. The overall average speed is in the vicinity of 470 km/s.

The high- and low-speed components form alternating streams in the solar wind flow. They move outward into inter-planetary space in a spiral due to the Sun's rotation. As the streams travel away from the Sun, the high-speed streams overtake the slow-speed flows and create regions of enhanced density and magnetic field called *corotating interaction regions* (CIR) (Fig. 23). When these regions encounter Earth, they can trigger geomagnetic disturbances and storms that recur with a 27-day period.

Fig. 23  
Corotating interaction region. The high-speed flows from coronal hole high-speed streams overtake the slower solar winds, causing regions of denser and rarefied plasma that can interact with the geomagnetic field



In the ascending and maximum phases of the sunspot cycle, the coronal holes shrink and the high-speed flows narrow and weaken resulting in a decrease in the average solar wind speed. At the same time, the ambient solar wind is increasingly disturbed by CMEs. CMEs reach a peak occurrence rate at sunspot maximum and cause non-recurrent geomagnetic storms. The speed of CMEs depends on their characteristics and relative directions to Earth and can vary from a few

# Geomagnetism Tutorial

hundred km/s to over 1,500 km/s (Fig. 24). Therefore, a CME event observed on the Sun may take anywhere from 1 to 9 days to reach Earth, with the average being about four days.

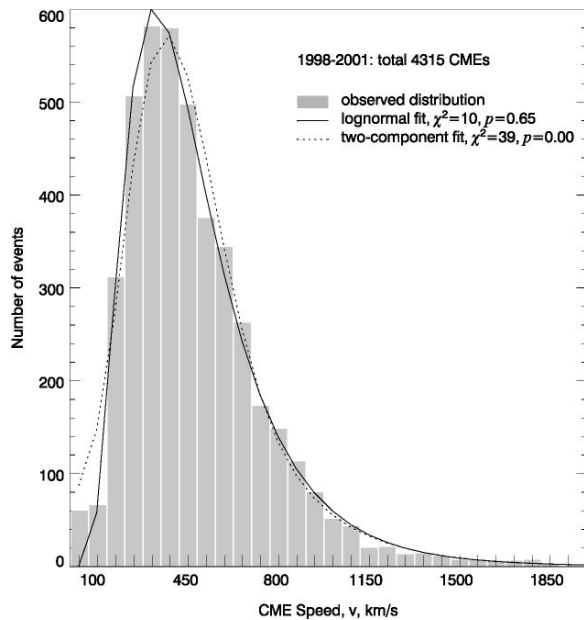


Fig. 24

Speeds of coronal mass ejections from a study of data from the Large Angle and Spectrometric Coronagraph Experiment on board Solar and Heliospheric Observatory (SOHO/LASCO) spacecraft. Image source: [Yurchyshyn]

A CME is a moving mass of three-dimensions (Fig. 25). It has been found that CME speed is a good indicator of the severity of geomagnetic disturbances.[Kilcik] Reports of CMEs sometimes mention a “halo” CME. The term halo indicates that the mass eruption is directed at the imager (typically a spacecraft such as SOHO). As the cloud expands it appears to envelop the Sun and form a halo around it. Animations of halo CME images often show speckles as the energetic particles in the plasma cloud from a related solar flare bombard the electronic detectors in the

spacecraft.

From a technical standpoint, the principal defining property of a geomagnetic storm is the creation of an enhanced ring current formed by ions (mostly protons and oxygen ions) and electrons in the 10-300 keV energy range and usually located between 2 and 7 Earth radii. These produce a magnetic field disturbance which, at the equator, is opposite in direction to Earth’s main (dipole) field. The enhanced ring current can reach upwards of a million amperes and can change Earth’s magnetic field direction by up to 2°. Undisturbed ring currents are primarily caused by strong dawn-to-dusk electric fields associated with the movement of southward-directed inter-planetary magnetic fields (IMF),  $B_s$ , past Earth over a long time period. Energy is transferred from the solar wind by magnetic reconnection between the IMF and Earth’s magnetic field.[Gonzalez]

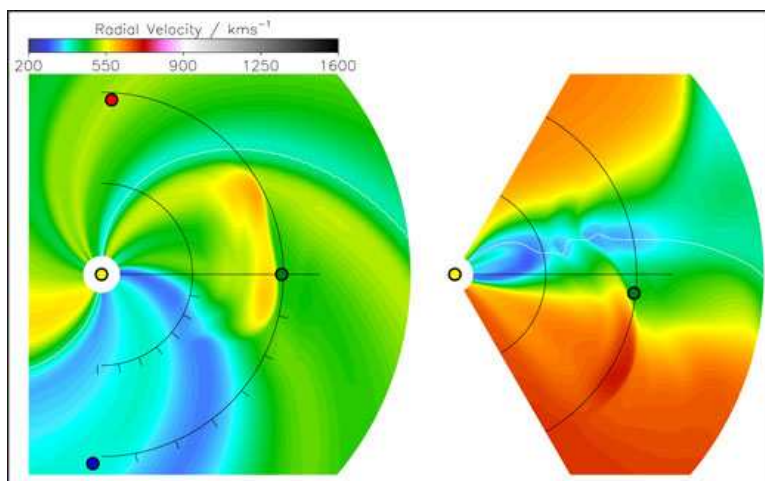


Fig. 25

Model of multiple CME. Sun is the yellow circle with white outline on the left of each image and Earth is the green dot directly to the right of the Sun. The dots above and below the Sun are the respective STEREO spacecraft (A-ahead and B-behind). The left image is looking down on the Sun’s north pole and ecliptic plane and the right image is a north-south slice along the Sun-Earth line. The color indicated in the scale at the top-left depicts speed of the solar wind and CMEs. The redish-orange areas near Earth are CMEs. Image source: [Pizzo]

Geomagnetic storms are extraordinary variations in Earth’s magnetic field, which can last up to several days. Storm conditions are characterized by intensified equatorial ring current and

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expansion of the auroral oval to lower latitudes. The main feature of a storm is an unmistakable decrease of the field's horizontal intensity and its subsequent recovery. Such events are related to the way the magnetosphere interacts with the solar wind.

Some geomagnetic storms, particularly larger ones, begin with the arrival of an interplanetary shock structure, called a *geomagnetic sudden impulse*. The shock front compresses the magnetosphere on the Sun side of Earth and is measured on ground magnetometers as a sudden discontinuous jump in amplitude of the horizontal field component. If the IMF associated with the arrival of a solar-terrestrial disturbance remains northward behind the shock then there usually is no subsequent storm, and the shock stands alone as a *sudden impulse*. If the IMF is directed southward ( $-B_z$ ) behind the shock then a geomagnetic storm usually follows and the impulse is called a *sudden commencement*. Not all geomagnetic storms are preceded by a sudden commencement.

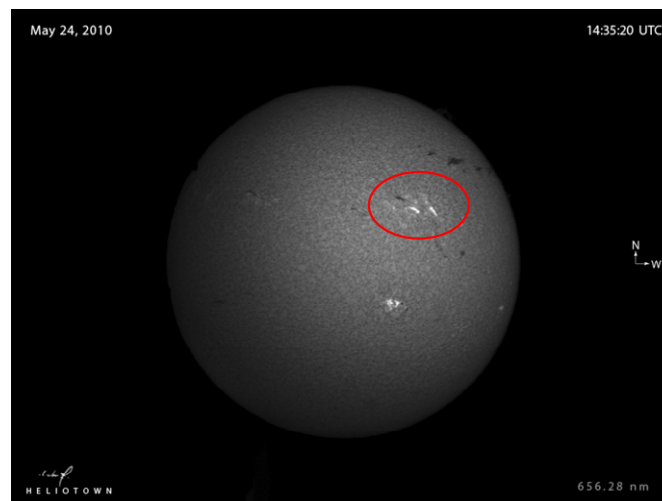
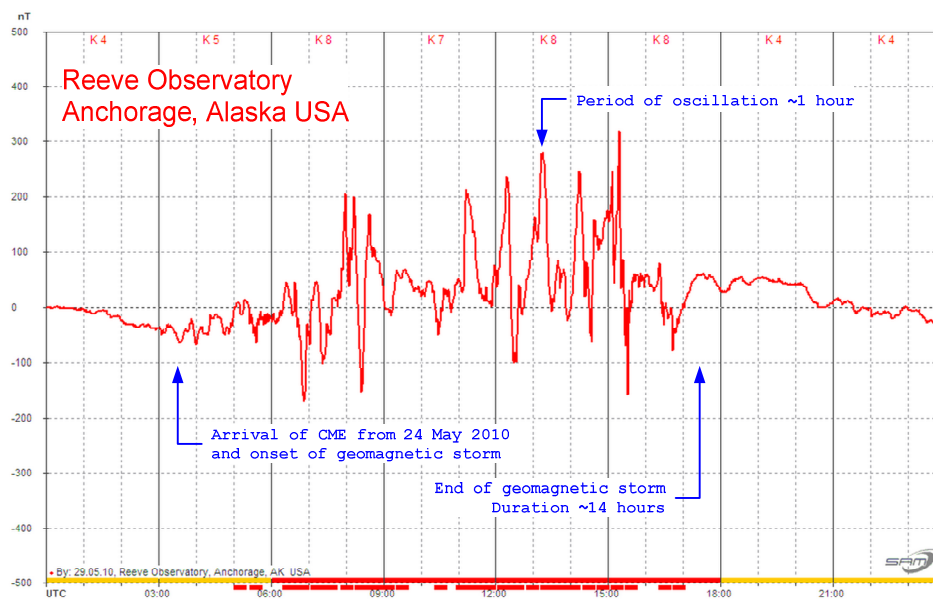


Fig. 25

(Upper) A strong geomagnetic storm was recorded 29 May 2010 at Reeve Observatory in Anchorage, Alaska USA. Compare the vertical scale to the quiet-day magnetogram in Sect. VI. Also, note the red K-index alarm bars along



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the horizontal axis. (Lower) The storm most likely was caused by a CME that occurred 24 May 2010 from the location on the Sun indicated (lower image courtesy of Thomas Ashcraft)

The amplitude variations associated with geomagnetic storms are apparent on magnetograms. One such storm occurred in May 2010 due to arrival of a CME from 24 May (Fig. 25). As for the geomagnetic sudden impulse, the variations are obvious but not nearly as great as for a storm (Fig. 26).

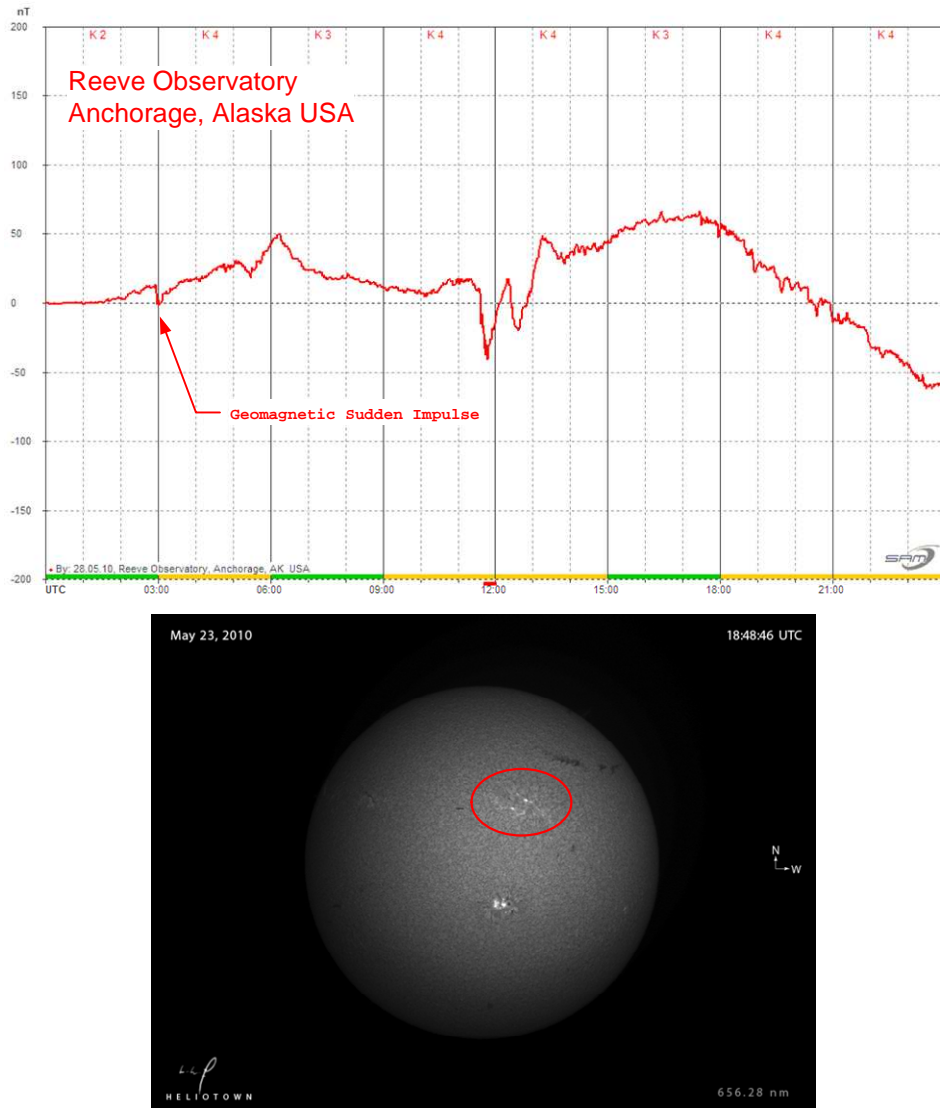


Fig. 26

(Upper) A geomagnetic sudden impulse was recorded at 0300 UTC, 28 May 2010 at Reeve Observatory in Anchorage, Alaska USA. The drop in amplitude was approximately 15 nT. This sudden impulse was identified by an alert issued by Space Weather Prediction Center. (Lower) The sudden impulse most likely was caused by a CME that occurred 23 May from the same location on the Sun as the storm previously described (lower image courtesy of Thomas Ashcraft)

The storm event usually is the effect of enhanced solar-wind pressure associated with a coronal-mass ejection (CME) or coronal hole high-speed stream. For purposes of measurement, a geomagnetic storm occurs when the K-index reaches a threshold of 5 or greater. At least one geomagnetometer (Simple Aurora Monitor, SAM and SAM-III) provides an alarm that is

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triggered by the K-index. When the peak-to-peak amplitude variations within a 3-hour interval reach a preset threshold (in the case of the SAM, the threshold can be set to any of nine K-index values), the alarm is triggered.

The geomagnetic sudden impulse is identified by its characteristic signature in terrestrial magnetometer data. It is most clearly seen at low latitudes, where the field variations are generally less complex than at high latitudes. This means that a sudden impulse can be difficult to identify at high latitude observatories because it may be overshadowed by normal activity. By coincidence, almost all sudden impulses in the 12 month period between May 2009 and May 2010 occurred during otherwise quiet periods and are clearly shown at the Reeve Observatory at 61°N latitude.

A visible manifestation of a geomagnetic storm is *aurora* (Fig. 27-left). Aurora is a luminous glow of the upper atmosphere (from as low as 80 to as high as 600 km) caused by energetic particles from the solar wind, mostly electrons but also protons, that enter the atmosphere from the magnetosphere along Earth's magnetic field lines. As they penetrate the upper atmosphere they collide with air molecules and oxygen and nitrogen atoms. The collisions transfer energy to the molecule or atom, which excites it. An excited atom or molecule returns to a non-excited state (ground state) by emitting a photon, that is, by making light.

Therefore, a geomagnetic storm indicates a good chance for viewing the aurora. Aurora viewing depends on geomagnetic activity and location, with higher latitudes ( $> 60^\circ$ ) being the best. However, during intense geomagnetic storms, aurora may be visible at much lower latitudes (Fig. 27-right). There are several sources of information for aurora viewing; a few are listed in *Further Reading and Study*.

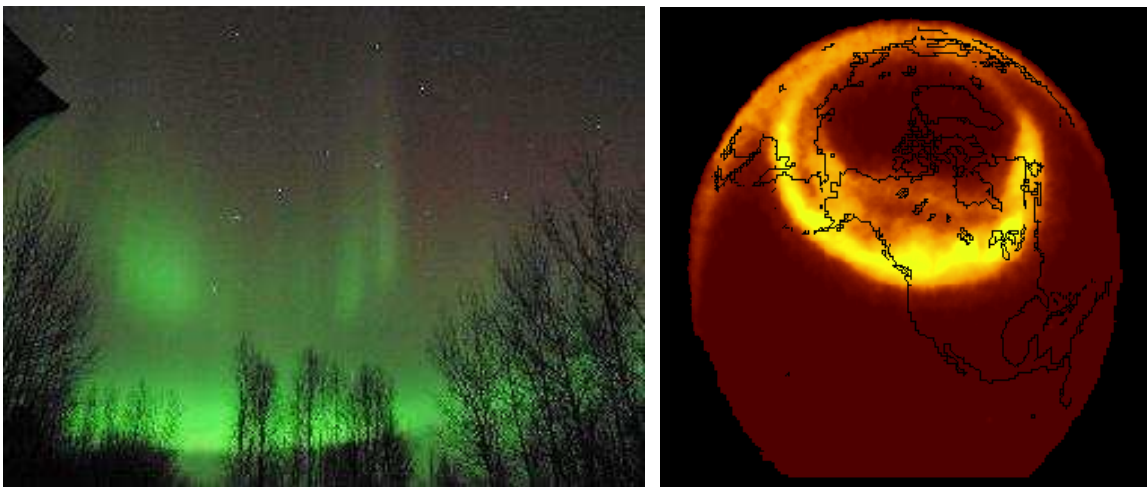


Fig. 27

(Left) Aurora is a visible manifestation of a geomagnetic storm as seen here at ground level. (Right) The aurora normally is seen at higher latitudes ( $> 60^\circ$ ) but during strong geomagnetic storms the auroral oval, shown here, may extend considerably lower. Image source: University of Alaska Geophysical Institute

The effects of solar activity and geomagnetic storms go beyond amateur radio and aurora viewing and are largely deleterious (Fig. 28). For example, rapid variations in the magnetic field can affect ionospheric radio propagation, and changes in the ionosphere can degrade global navigation satellite system (GNSS) performance. The most well-known GNSS is the GPS (Global Positioning System) operated by the US Department of Defense. Magnetic field

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variations can cause ionospheric expansion, which increases the drag on satellites, making their control more difficult, and can expose satellites to damaging static charge build-up and discharge.

Varying magnetic fields can induce currents in long conductors. For example, currents induced in metallic pipelines can increase in the rate of galvanic corrosion. Currents induced in long-haul power transmission lines can result in voltage surges and blackouts as systems trip off line to protect themselves from the over-voltages and over-currents.

Another negative effect of geomagnetic storms is the weakening of the ability of Earth's magnetic field to deflect incoming charged particles from solar bursts and the solar wind, which can increase the risk of biological effects.

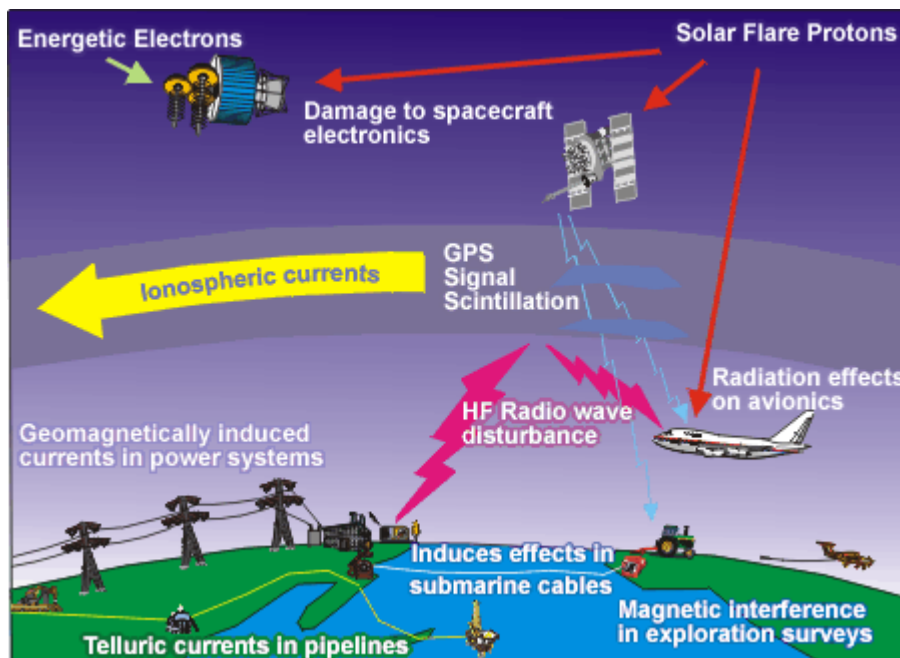


Fig. 28  
Effects of solar activity and related geomagnetic storms.  
Image source: NASA

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## X. *RADIO PROPAGATION EFFECTS*

### Radio Aurora

Radio Aurora is ionospheric ionization associated with auroral disturbances that cause radio reflections.[Davies] Radio aurora reflects or refracts radio waves while the familiar visible aurora is caused by emitted visible and invisible radiation. Visible aurora and radio aurora are separate phenomena that do not necessarily occur at the same time and in the same space, but they do have the same basic origin.

Magazine articles appear frequently that are written about radio aurora from a radio amateur's perspective. See for example [Pocock], [Frank69] and [Frank74]. The solar activity that leads to the radio aurora also leads to geomagnetic field disturbances and thus may be detected by a geomagnetometer.

### Ionospheric Storms

Ionospheric storms are conditions that last several days and are accompanied by additional ionospheric circulating currents and associated geomagnetic disturbances. During normal conditions at mid-latitudes, the variations are a few tenths of one percent of the total geomagnetic field but reach several percent during an ionospheric storm. Large geomagnetic storms are accompanied by ionospheric anomalies including depression of daytime critical frequencies of the F2 layer, radio blackout, and enhanced spread F and sporadic E propagation. [Davies] Ionospheric anomalies also affect global navigation satellite systems (GNSS) such as the Global Positioning System (GPS). These effects and their duration depend on the sunspot cycle. The ionospheric response depends on latitude with conditions nearer the equator and nearer the poles experiencing the most variation. However, a quiet, undisturbed geomagnetic field does not necessarily mean an undisturbed equatorial ionosphere.

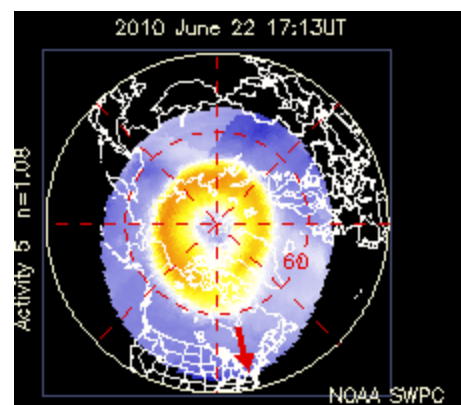
### Polar Cap Absorption

Polar cap absorption (PCA) is ionization at northern latitudes that leads to radio blackouts on trans-polar paths. The blackouts last from hours to days depending on the latitude. PCA events usually are preceded by large solar flares but generally are not accompanied by noticeable changes in geomagnetic or auroral activity except toward the end when an auroral zone geomagnetic storm sets in. Thus, a geomagnetometer may or may not indicate conditions for PCA. The auroral zone is considered to be above 60° geomagnetic latitude and is oval shaped. The current shape and extent of the aurora is available online (Fig. 29).<sup>17</sup>

Fig. 29

The auroral oval expands and contracts with the makeup and speed of the solar wind. Manifestations of the associated geomagnetic activity are radio propagation anomalies. The northern oval is shown here.

Image source: NOAA



<sup>17</sup> Northern oval: [www.swpc.noaa.gov/pmap/](http://www.swpc.noaa.gov/pmap/) ; southern oval: <http://www.ips.gov.au/Geophysical/4/1>



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## *FURTHER READING & STUDY*

- Aurora Viewing Tips, [www.swpc.noaa.gov/Aurora/](http://www.swpc.noaa.gov/Aurora/)
- The Aurora Watcher's Handbook, [www.uaf.edu/uapress/book/displaysingle.html?id=32](http://www.uaf.edu/uapress/book/displaysingle.html?id=32)
- Australian Space Weather Agency,  
[http://www.ips.gov.au/Site\\_Help/1/IPS%20Site%20Map](http://www.ips.gov.au/Site_Help/1/IPS%20Site%20Map)
- US Geological Survey National Geomagnetism Program, [geomag.usgs.gov/](http://geomag.usgs.gov/)
- US Space Weather Prediction Center: <http://www.swpc.noaa.gov/>
- National Geophysical Data Center, [www.ngdc.noaa.gov/geomag/](http://www.ngdc.noaa.gov/geomag/)
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