

Magnetic monitoring of Earth and space

Jeffrey J. Love

With data provided by magnetic observatories, geophysicists can gain insights into our planet's interior and nearby space environment without even leaving the ground.

feature
article

Jeffrey Love (jlove@usgs.gov) is the US Geological Survey adviser for geomagnetic research and a member of the Intermagnet executive council.

For centuries, navigators of the world's oceans have been familiar with an effect of Earth's magnetic field: It imparts a directional preference to the needle of a compass. Although in some settings magnetic orientation remains important, the modern science of geomagnetism has emerged from its romantic nautical origins and developed into a subject of great depth and diversity. The geomagnetic field is used to explore the dynamics of Earth's interior and its surrounding space environment, and geomagnetic data are used for geophysical mapping, mineral exploration, risk mitigation, and other practical applications. A global distribution of ground-based magnetic observatories supports those pursuits by providing accurate records of the magnetic-field direction and intensity at fixed locations and over long periods of time.

Magnetic observatories were first established in the early 19th century in response to the influence of Alexander von Humboldt and Carl Friedrich Gauss. Since then, magnetic measurement has advanced significantly, progressing from simple visual readings of magnetic survey instruments to include automatic photographic measurement and modern electronic acquisition. To satisfy the needs of the scientific community, observatories are being upgraded to collect data that meet ever more stringent standards, to achieve higher acquisition frequencies, and to disseminate data in real time.

To appreciate why data from magnetic observatories can be used for so many purposes, one needs only to recall that the geomagnetic field is a continuum, connecting the different parts of Earth to each other and to nearby space. Beneath our feet and above our heads, electric currents generate magnetic fields that contribute to the totality of the geomagnetic field measured at an observatory on Earth's surface. The many physical processes that operate in each geophysical domain give rise to a complicated field that exhibits a wide variety of time-dependent behavior.¹ In this article I review the status of the global community of magnetic observatories, show how Earth and space can be monitored for purposes of scientific understanding and practical application, and highlight the role played by magnetic observatories in the history of geomagnetism research.

Measurement and data

To support a wide range of geophysical studies, magnetic observatories such as that shown in figure 1 need to produce accurate measurements of the geomagnetic field over a wide range of time scales. The longest time scale is defined by the lifetime of the observatory. Naturally, that depends on many practical factors, including long-term funding and staffing.

Some observatories operate for only a few years, but others, such as the Sodankylä Geophysical Observatory in Finland and the Apia Observatory in Samoa, have operated continuously for well over a century. The shortest time scale of relevance is the time between sequential measurements. Older analog photographic systems typically produce data with a one-hour cadence. Modern digital systems provide data at much higher acquisition rates. These days, one-minute-average data is a standard observatory product, but one-second-average data production is becoming more common. As an example, the Kakioka Magnetic Observatory in Japan has produced one-second data continuously since 1983—a record of magnetic-field variation over time scales spanning almost nine orders of magnitude.

To reliably produce a long-period geomagnetic time series, an observatory must operate under carefully controlled conditions.² Typically, the site of an observatory is large enough to isolate the measurements from most sources of anthropogenic magnetic interference, and many observatories are in relatively remote locations. Buildings on the site provide stable operating conditions for the sensors, calibration systems, and associated instrument and data-acquisition electronics.

A modern observatory has a fluxgate magnetometer, which gives vectorial data conventionally expressed in terms of either the Cartesian components (X [north], Y [east], and Z [down]) or the horizontal-polar components (horizontal intensity $H = [X^2 + Y^2]^{1/2}$, declination $D = \arctan[Y/X]$, and Z [down]). Note that declination is the direction in which a compass needle points. More formally, it is the angle of the direction of the magnetic field's horizontal component. A well-run observatory will produce fluxgate data that show little drift in accuracy—usually less than 20 nanotesla annually. For many real-time nonresearch applications, that standard of accuracy is sufficient.

But more stringent ionospheric and magnetospheric research projects, as well as long-term mapping of the global magnetic field, require more accurate data. For that reason a modern magnetic observatory has a proton precession magnetometer that measures the total absolute field intensity $F = (X^2 + Y^2 + Z^2)^{1/2}$. An observatory also has a pier-mounted theodolite, a familiar surveying instrument, but one having a small fluxgate fixed to its telescope. About once a week, an observer visits the site and makes a series of measurements using the theodolite to obtain D and the inclination $I = \arctan(Z/H)$. Those absolute magnetic-direction data are then used to calibrate the fluxgate data, so as to compensate for long-term drift

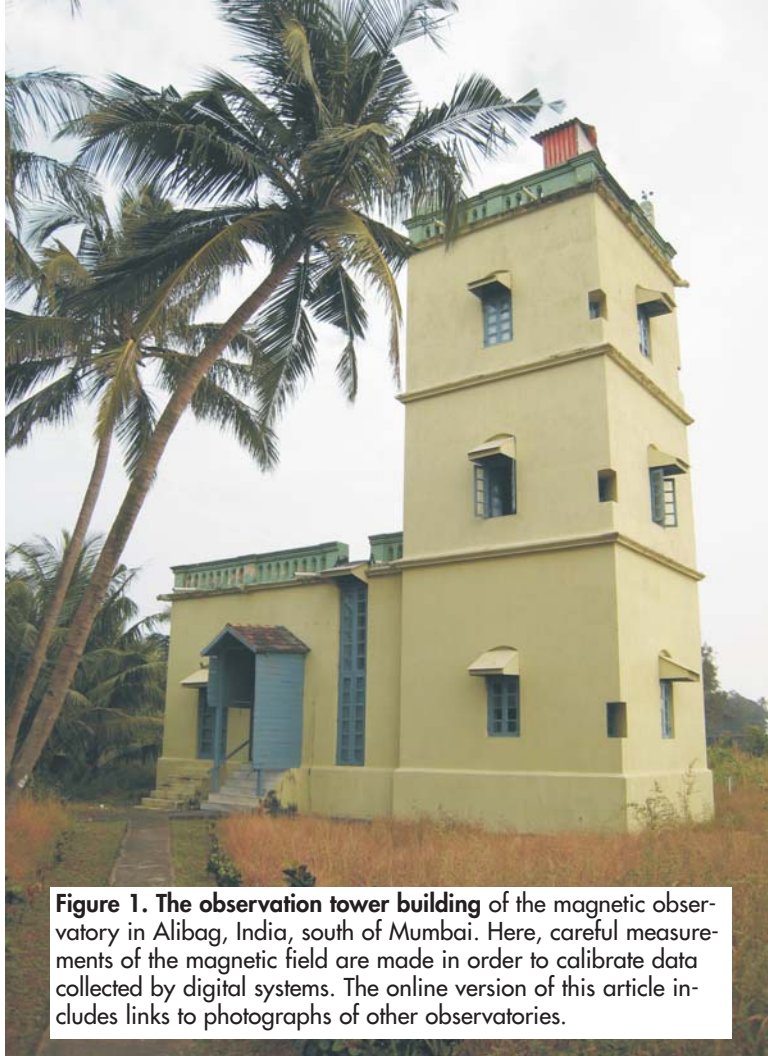


Figure 1. The observation tower building of the magnetic observatory in Alibag, India, south of Mumbai. Here, careful measurements of the magnetic field are made in order to calibrate data collected by digital systems. The online version of this article includes links to photographs of other observatories.

A global network

Approximately 170 magnetic observatories operate worldwide. Most are supported by national governments, some by universities, and a few by private companies. During the International Geophysical Year in 1957–58, many new observatories were established as part of a coordinated effort to enhance the global collection of geophysical data, and many existing observatories were improved (see the article by Fae L. Korsmo, *PHYSICS TODAY*, July 2007, page 38). Today about 120 observatories produce and routinely report digital data with an acquisition cadence of one minute or better; figure 2 shows where they are located around the globe. The remaining 50 or so observatories use older, analog systems or report their data only years after acquisition. Note that the geographic distribution of observatories is far from uniform, with a general sparsity in, for example, the Southern Hemisphere and in the central Pacific. To promote observatory operation according to consistent standards and to facilitate the prompt dissemination of digital data, the international observatory network organization Intermagnet (<http://www.intermagnet.org>) was formed in 1987. As of January 2008, 42 countries and 108 observatories participate in and follow the modern standards set by Intermagnet.

Ground-based fluxgate networks, sometimes called variometer networks, and satellite-based magnetometers fill niches that are complementary to that filled by the observatories. Most fluxgate networks are maintained by universities and various national governmental programs; they typically operate for a few years for space-physics research. Because of their more specialized nature, the networks do not need the laborious standards adopted by full-fledged magnetic observatories. Satellite magnetometers measure the part of Earth's magnetic field that is in space; over the course of many orbits, they can provide good global coverage, albeit from only a relatively small number of locations at any particular time.

in the fluxgate magnetometer. Production of definitive observatory data involve processing. The resulting data have an absolute accuracy of better than 5 nT, which permits meaningful analysis of magnetic variation that can occur over time scales ranging from the acquisition cadence out to the observatory's lifetime.

Fluxgate magnetometers and proton precession magnetometers are the two types most commonly used in magnetic observatories. The Quick Study by Uli Auster on page 76 describes how they work and includes a photo of a theodolite with fluxgate.

In the future almost all users of observatory data will expect greater accuracy, and many will require real-time magnetic-observatory data streams and easier access to data from all parts of the globe. Demand for higher-frequency data acquisition will increase, especially from space physicists. To meet those needs, the international programs that support magnetic observatories will have to be even better integrated than they are today. Older observatories will need to be modernized and all parts of observatory operations made more automatic.

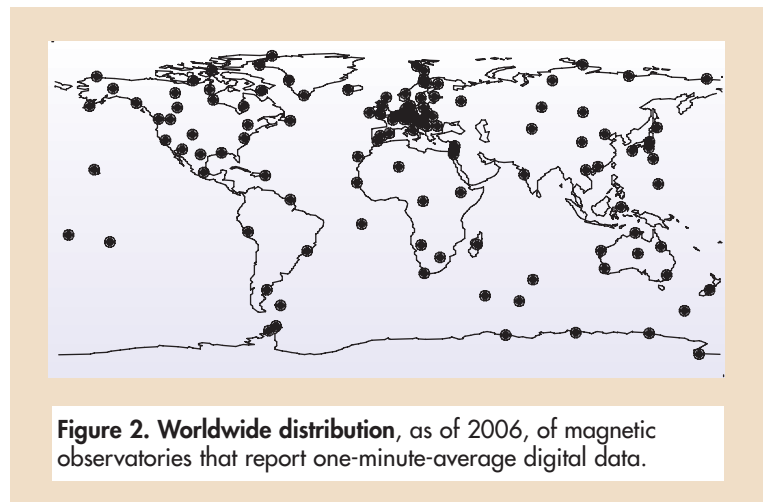


Figure 2. Worldwide distribution, as of 2006, of magnetic observatories that report one-minute-average digital data.

Secular variation and Earth's core

How do geophysicists interpret the abundance of magnetic-observatory data? To answer that question, let us take a tour of magnetic signals. The tour begins deep inside Earth, in the iron core where the majority of the geomagnetic field originates. From there, we trace the magnetic field up to the surface, where the observatories are located. Next, we continue onward and upward through the ionosphere to the magnetosphere. The physics encompassed in the tour is classical and includes electricity and magnetism, fluid mechanics, and plasma dynamics.

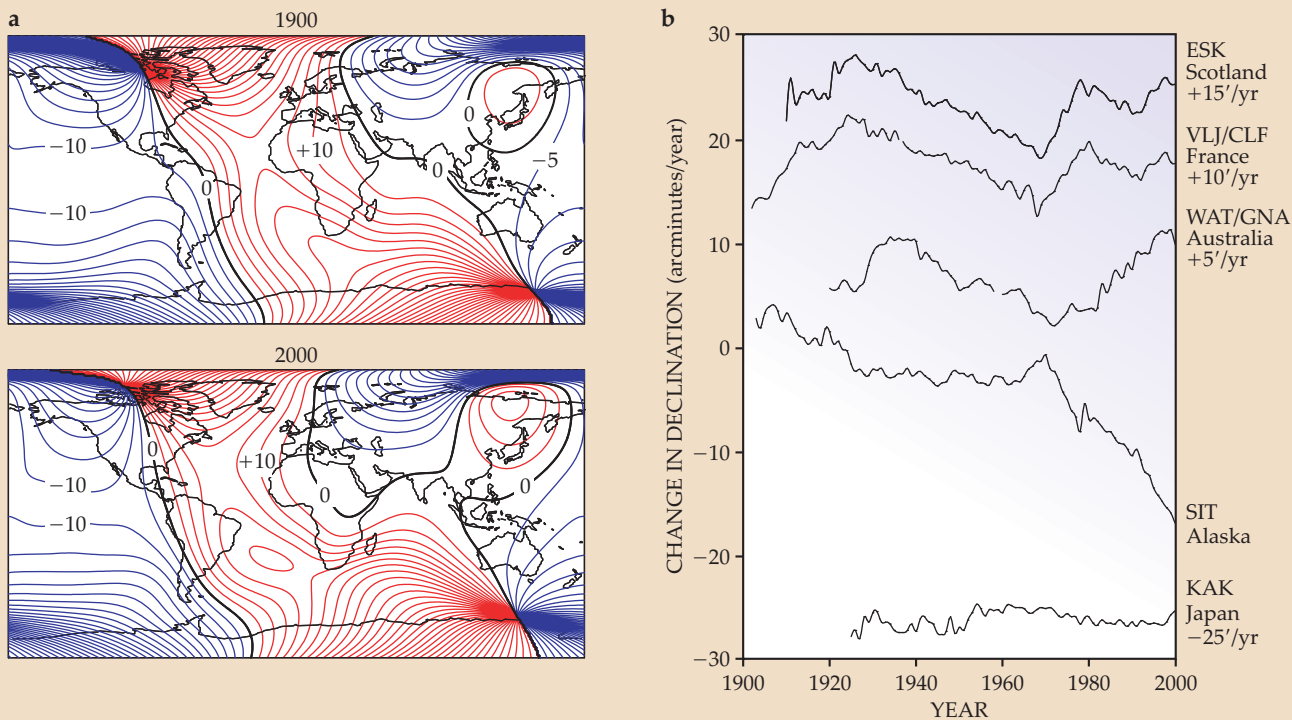


Figure 3. Magnetic declination changes over time. (a) Contour maps of declination D for the years 1900 and 2000 show significant differences over the century. Each contour line represents 5° ; red is declination to the east and blue is to the west. (b) Data from five observatories show the yearly rate of change in declination. Note, in particular, the abrupt changes, or jerks, in the rate of secular variation, around 1970. For clarity of presentation, the data have been separated by the ordinate values listed on the right.

Earth's core lies some 2900 km below the surface. In the outer part of the core, a combination of thermal and chemical buoyancy sustains convective fluid motion and establishes what is essentially a naturally occurring electrical generator. As the electrically conducting core fluid flows through the geomagnetic field, motional induction generates electric currents. Those currents, in turn, generate their own magnetic fields. If it is sufficiently complicated—lacking simple symmetry—the magnetic field that partakes in the motional induction is the same field that is sustained by the induced electric currents. The process is efficient enough to overcome the effects of ohmic dissipation, and so Earth's core is a self-sustaining dynamo.³ The mathematics of the geodynamo is sometimes described as being a bit like that of oceanography and meteorology, but with the additional complication presented by the magnetic field itself. Scientists still don't know or understand many things about dynamo theory; not surprisingly, it is the subject of ongoing research (see the article by Raymond Jeanloz and Barbara Romanowicz, *PHYSICS TODAY*, August 1997, page 22).

Part of the magnetic field generated in the core extends outward, passes through the weakly electrically conducting mantle, and reaches the surface. The field at Earth's surface typically has an intensity of 30 000–60 000 nT and is approximately dipolar, with an axis tilted by about 10° with respect to Earth's rotational axis. But the magnetic field also has important ingredients that are nondipolar. One way to appreciate that is to make a map of declination. The compass needle aligns itself with the horizontal direction of the local magnetic field. As figure 3a shows, a compass needle almost never points due north. Indeed, because of the nondipolar field, declination is a complicated function of latitude and longitude. As a result of core convection, the magnetic field also exhibits secular variation over time scales of decades to

millions of years. And so, at a given location, the direction that a compass points changes over time. The two maps of declination in figure 3a show the progression of geomagnetic secular variation over the past century.⁴ Indeed, because the field changes in time, maps of it are updated every five years or so.

Figure 3b shows year-to-year differences in declination measured during the 20th century from five different observatories. The secular variation not only is different in different locations but also occasionally accelerates. An interesting feature of the data is the apparent presence around 1970 of a discontinuous change, or jerk, in the rate of secular variation. Jerks are clearly seen in the European and Australian data. On the other hand, a jerk isn't obvious in the Japanese data. And although the Alaskan data show a jerk, it is of the opposite sign of that for Europe and Australia.

Clearly, a global description of the secular variation is complicated. Still, geophysicists have made progress in relating jerks and secular variation to decade-scale changes in Earth's rotational rate that arise from exchanges of angular momentum between the core and mantle. With certain assumptions, core angular momentum can be deduced from geomagnetic secular variation models. Then, assuming that Earth's total angular momentum is conserved, one can estimate the changes that should have occurred in the mantle angular momentum over the past century or so. Predicted variations in the length of a day are close to those actually observed, and that gives researchers some confidence that their theories are reasonable.

Crust, ocean, and mantle

Time-dependent magnetic-field variations sustained by currents in the ionosphere and magnetosphere induce electric currents in the crust, ocean, and mantle.⁵ Those currents, in

turn, generate internal magnetic fields. The skin depth to which the induced currents diffusively penetrate is a function of Earth's subsurface electrical conductivity and the frequency of the overhead magnetic-field variations. So, for example, magnetic variations with periods ranging from a second to tens of minutes penetrate into the crust some 20–100 km. An observatory, of course, measures the total magnetic field, a superposition of the external, inducing field and the internal, induced field. Mathematical separation of the two requires a large number of simultaneous measurements, densely distributed across Earth's surface; it is a task not ideally suited to the relatively sparse distribution of magnetic observatories. For that reason, detailed regional studies of Earth's conductivity structure often involve the deployment of temporary arrays of sensors to measure both the magnetic field at Earth's surface and the induced electric field in the crust.

Qualitative insight into geomagnetic induction can be obtained through direct inspection of observatory data. Figure 4 shows magnetograms from four European observatories that recorded a large magnetic storm. Each observatory shows a similar variation in H . Most of that is the magnetic signature of a large-scale, overhead ionospheric and magnetospheric current system sustained during the storm.

In contrast, the magnetogram traces in Z vary significantly from site to site, due to localized subsurface differences in electrical conductivity in the vicinity of each observatory. Note, for example, the Z traces for the two Spanish observatories: San Pablo Toledo (SPT), in the center of Spain, and Ebro (EBR), on the coast. Much of the variation in Z reflected in the Ebro magnetogram comes from electric currents induced in the Mediterranean Sea. Since ocean water is a good electrical conductor compared with dry rock and hydrated sediments, the nearby coastal inlets and sea-depth variations establish a local conductivity heterogeneity; the result is the complicated electromagnetic response seen in the data. On the other hand, differences in Z variation between the Italian and Romanian observatories are related to local geology. Both areas are tectonically complicated, but the formation of the Carpathian Mountains created a zone of active rock metamorphism and unusually high electrical conductivity that is manifested in the complexity of the lowest trace.

Quiet time variation and the ionosphere

Above Earth's surface the magnetic field threads its way through the ionosphere, the electrically conducting part of the upper atmosphere where solar radiation maintains partial ionization.⁶⁷ The degree of ionization is a function of altitude, latitude, time of day, season, and solar-cycle phase. At altitudes of 90–300 km or so, winds driven by day–night temperature differences and tides driven by the gravity of the Moon and Sun sustain motional induction. During quiet times, when the magnetic field is relatively undisturbed by solar activity, the electric currents of the ionospheric dynamo give a distinct diurnal variation to observatory magnetograms, as evidenced in figure 5a. A detailed Fourier analysis of longer time series reveals frequencies corresponding to coupled modulations driven by the solar cycle, Earth's orbit around the Sun, the Moon's orbit around Earth, and Earth's rotation. Through application of Ampère's law, the corresponding ionospheric currents can be mapped;⁸ figure 5b reveals that the quiet-time current system is dominated by two day-side current gyres. Earth's rotation under that current system gives rise to the quiet-time daily variation of the magnetic field.

Prominent in Figure 5a is the daily variation in the mag-

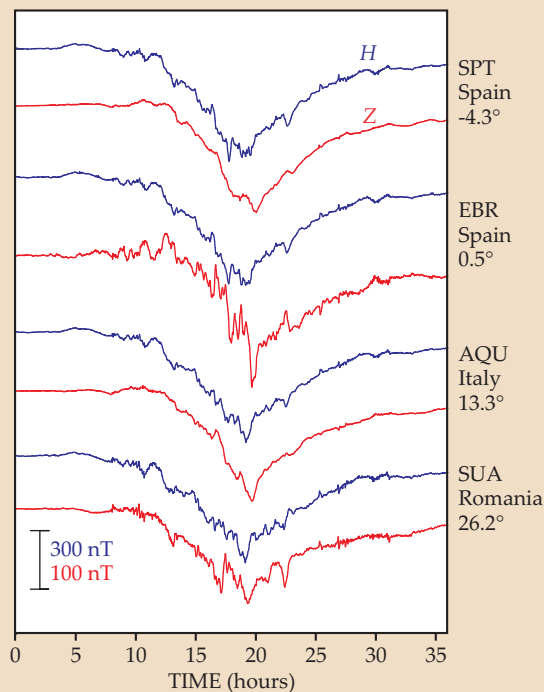


Figure 4. Magnetic-field variation reveals differences in subsurface electrical conductivity. Shown here are magnetograms taken on 20–21 November 2003 at European observatories of specified longitudes. Horizontal-intensity (H , blue) variation is driven by a storm in the magnetosphere. Site-to-site differences in the downward (Z , red) component are due to induced electric currents in the ocean and crust.

netogram from Huancayo, Peru. First observed in the 1920s, soon after the Carnegie Institution of Washington established the Huancayo observatory, the variation is the result of the ionosphere's anisotropic electrical conductivity. On Earth's day side, in a roughly 5°-wide band near the magnetic equator, the horizontal ambient magnetic field and a vertical electrical field maintained by charge separation across the thickness of the ionosphere combine to facilitate the east–west motion of charge carriers. That gives a concentrated flow of daytime electric current toward the east and the observed enhancement of diurnal magnetic variation at observatories like Huancayo that are located very close to the magnetic equator.

Magnetic storms and the magnetosphere

The extent of the geomagnetic field in near-Earth space defines the magnetosphere (see references 7 and 9 and the article by Syun-Ichi Akasofu and Louis J. Lanzerotti, *PHYSICS TODAY*, December 1975, page 28). The shape of the magnetosphere, depicted in figure 6a, is determined by a supersonic solar wind of electrons and ionized hydrogen and helium that moves at speeds of 250–2000 km/s. Inside a resulting shock wave, the magnetic field of the magnetosphere on the Sun side is compressed, with a “magnetopause” at about 10 Earth radii ($10 R_{\oplus}$). On the opposite, night side, the magnetosphere is drawn out into a long tail whose length can exceed $100 R_{\oplus}$.

One can also describe the magnetosphere in terms of its constituent electric currents. The magnetopause is then defined by a surrounding current that flows eastward near the equatorial plane. The magnetotail can be defined in terms of

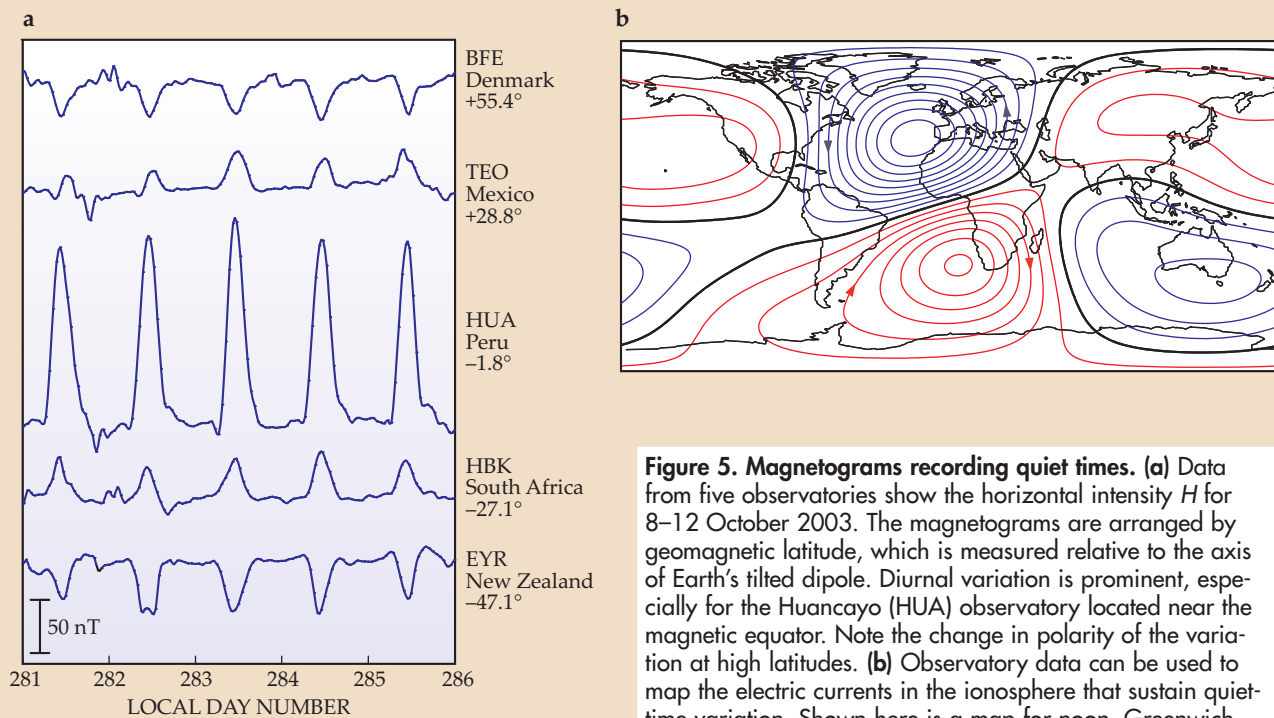


Figure 5. Magnetograms recording quiet times. (a) Data from five observatories show the horizontal intensity H for 8–12 October 2003. The magnetograms are arranged by geomagnetic latitude, which is measured relative to the axis of Earth’s tilted dipole. Diurnal variation is prominent, especially for the Huancayo (HUA) observatory located near the magnetic equator. Note the change in polarity of the variation at high latitudes. (b) Observatory data can be used to map the electric currents in the ionosphere that sustain quiet-time variation. Shown here is a map for noon, Greenwich Mean Time. Contour lines indicate 10-kA increments; more densely packed contour lines indicate higher local current density. Red contours indicate clockwise-circulating current; blue contours, counterclockwise current.

densely packed contour lines indicate higher local current density. Red contours indicate clockwise-circulating current; blue contours, counterclockwise current.

a westward equatorial current sheet. The magnetospheric interior within about 3–6 R_E contains a neutral plasma of 1- to 200-keV hydrogen and oxygen ions and lower-energy electrons. Those particles undergo a complicated dance consisting of cyclotron motion around magnetic-field lines, bounces between mirror points in the Northern and Southern Hemispheres where field lines converge, and a slow migration across field lines due to gradients in the magnetic field. The net result is that ions tend to drift westward and electrons eastward, a contrary motion that gives rise to a westward equatorial ring current.

Along with the solar wind, the interplanetary magnetic field—itsself an extension of the heliomagnetic field—controls the behavior of the magnetosphere. Diffusion allows the interplanetary magnetic field and geomagnetic field to connect, opening the interior of the magnetosphere to interplanetary space. Figure 6a depicts magnetic connection on the magnetosphere’s day side (for additional discussion of magnetic connection, see *PHYSICS TODAY*, October 2001, page 16); on the night side, an opposite process occurs with disconnection of interplanetary and geomagnetic field lines in the magnetotail. With an open magnetosphere, the dragging of field lines across Earth’s polar cap by the solar wind establishes a solar-wind dynamo. That induces convection-like motion of plasma in the magnetosphere and polar ionosphere, and it can energize the ring current.

Occasionally, abrupt ejections or high-speed streams of plasma from the Sun push the magnetosphere into a highly dynamic, time-dependent state called a magnetic storm. That colorful expression was coined by von Humboldt in 1808 to describe occasional periods during which ground-based measurements show large, rapid, and irregular variation of the geomagnetic field. A magnetic storm can last from several hours to several days. Some also exhibit shorter-duration substorms.¹⁰ The cause and effect of substorms is controver-

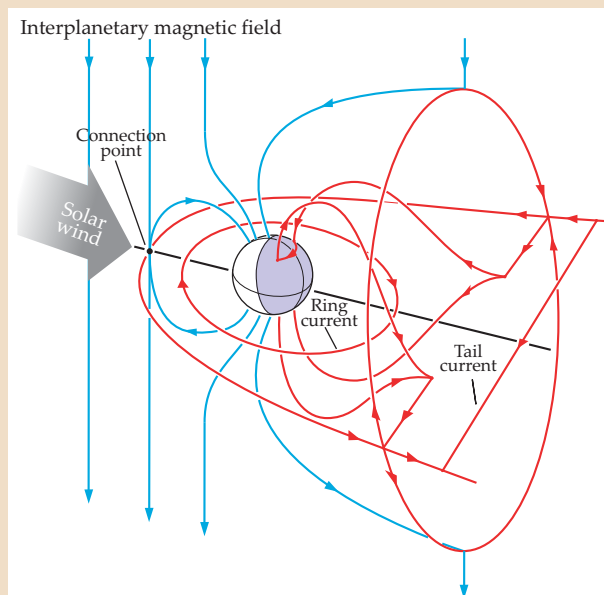
sial, but, generally speaking, substorms result from a temporary buildup of energy in the magnetotail that is released explosively through a sudden collapse of part of the tail current and diversion of current along magnetic-field lines. As a result, the magnetospheric electric circuit closes through the ionosphere, a detour that can give rise to beautiful auroral displays at high latitudes.

The Halloween storm

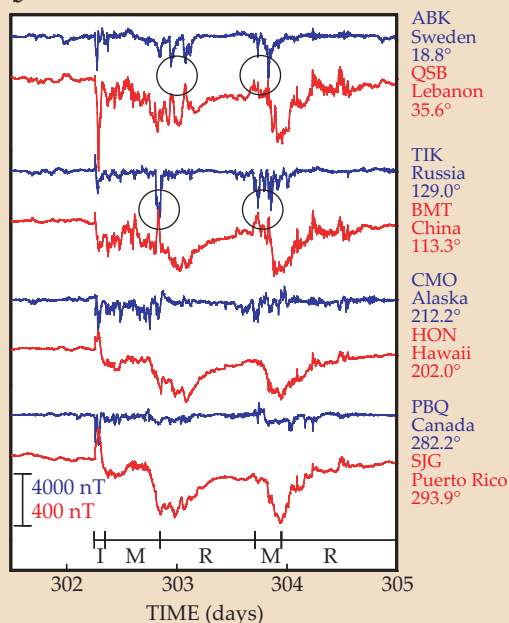
One of the largest magnetic storms on record occurred just before Halloween 2003. Figure 6b shows horizontal-intensity magnetograms of that storm, which was initiated by a coronal mass ejection associated with a large sunspot group. Observatory magnetograms recorded a sudden impulsive change during the distinctive initial phase (I) that resulted from solar-wind compression of the magnetopause and magnetic connection. The following main phase (M) was distinguished by a general decrease in H at low magnetic latitudes, the signature of an increasing equatorial ring current: The westward ring current generates a southward magnetic field in its interior, the Earth side. Since the generated field points opposite to Earth’s prevailing northward dipole field, it decreases H . Indeed, a longitudinal average of the disturbance in H from low-latitude observatories is proportional to the average increase in strength of the ring current. The recovery phase (R) of the storm corresponds to ring-current diminution and a return of low-latitude H to prestorm levels. The Halloween storm is somewhat unusual in that it exhibited two main phases, each followed by a recovery period.

A detailed comparison of low- and high-latitude magnetograms reveals substorm occurrences during the Halloween storm. For example, figure 6b displays data from two comparable longitude pairs of observatories that show intermittent periods of anticorrelation. During those times partial collapse of the ring or tail current gives an increase

a



b



in H at low latitudes, while closure of the current system along field lines and through the ionosphere gives a simultaneous decrease in H at high latitudes. Thus magnetic-observatory data can be used to monitor the electric circuit of the coupled magnetospheric-ionospheric system, notwithstanding that every magnetic storm has its own unique and often complex character.

Space climate and weather

The Sun's dynamo is oscillatory. As a result, the Sun's magnetic polarity reverses once every 11 years or so and sunspot number and solar irradiance wax and wane (see reference 7 and the article by Judith Lean, *PHYSICS TODAY*, June 2005, page 32). Figure 7 shows that magnetic activity, as measured by the monthly standard deviation in H , is modulated in phase with the solar cycle. The spikes in magnetic standard deviation during, for example, the years 1921, 1941, and 1989 correspond to large magnetic storms. The discovery that

Figure 6. Earth's magnetosphere is shaped and controlled by the Sun. (a) Schematic representation of the magnetosphere. Blue lines represent magnetic fields, and red lines represent currents. Magnetic connection is shown on the day side of the magnetosphere, where a southward-pointing interplanetary field merges with a northward-pointing geomagnetic field. (b) Data from eight observatories show the disturbed horizontal intensity H during the Halloween magnetic storm of 28–31 October 2003. The magnetograms are arranged by longitude; red traces correspond to low-magnetic-latitude observatories and blue lines to observatories at high latitudes. The initial (I), main (M), and recovery (R) phases are discussed in the text. The circled anticorrelations between high- and low-latitude magnetograms are indicative of substorms.

magnetic storms are more likely to occur during periods of sunspot maxima and less likely to occur with sunspot minima was one of the most important in the history of space physics. It was made in 1852 by the astronomer and British major general Edward Sabine, who carefully analyzed a long time series of data collected by various magnetic observatories including one located, at the time, in Toronto. In his words, the discovery gave to geomagnetism a “much higher position in the scale of distinct natural forces than was previously assigned to it.”¹¹

Understanding magnetic storms is important for risk mitigation. Storm-induced currents in the crust can be a nuisance for the electric power industry, since they can find their way into power lines and transformers through ground connections.¹² The most prominent example of that particular hazard occurred in March 1989, when a large magnetic storm led to the collapse of the electrical power grid serving the entire Canadian province of Quebec. Magnetic storms interfere with magnetic crustal surveys undertaken for mapping and mineral exploration, and they interfere with in situ magnetic orientation systems used for directional drilling. During magnetic storms, long-distance radio communication can be difficult, and the accuracy of global positioning systems can be reduced. In space, satellite electronics can be damaged and satellite orbital drag enhanced. Astronauts and high-altitude pilots might be subjected to increased radiation.

Since magnetic storms were first identified through ground-based magnetic measurement, it is perhaps not surprising that standard measures of magnetic-storm size are defined using magnetic-observatory data. Real-time observatory data are used for low-cost monitoring or “nowcasting” of space weather. And historical observatory data enable statistical studies of how storms are distributed in time and how big they can be. Because of the potential risk to the activities and infrastructure of our modern, technology-based society, the US federal government supports the interagency National Space Weather Program. Similar programs also exist in Japan and Europe.

The wide-ranging utility of magnetic-observatory data testifies to the importance of programs dedicated to accurate and long-term geophysical measurement. And the data themselves are a lasting legacy of the many hard-working individuals who have supported observatory operations for almost 170 years.

I thank William S. Leith for encouraging me to write this article and Arnaud Chulliat, Carol A. Finn, David J. Kerridge, Stefan Maus, Robert L. McPherron, Lawrence R. Newitt, Leif Svalgaard, Jeremy N. Thomas, and E. William Worthington for reviewing a draft manuscript.

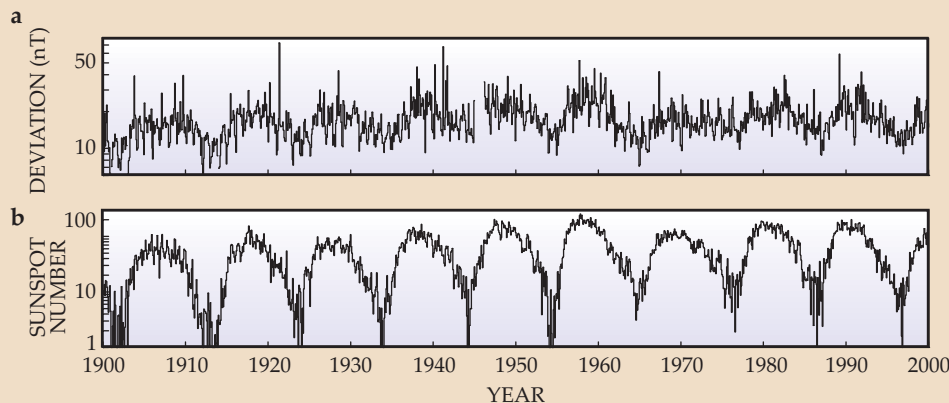


Figure 7. Magnetic activity is driven by the Sun. (a) The monthly standard deviation in the horizontal intensity H as measured at German observatories. **(b)** Monthly averages for sunspot number.

References

1. S. Chapman, J. Bartels, *Geomagnetism*, Clarendon Press, Oxford, UK (1962); S. Matsushita, W. H. Campbell, eds., *Physics of Geomagnetic Phenomena*, Academic Press, New York (1967); J. A. Jacobs, ed., *Geomagnetism*, Academic Press, San Diego, CA (1987–91).
2. J. Jankowski, C. Sucksdorff, *Guide for Magnetic Measurements and Observatory Practice*, International Association of Geomagnetism and Aeronomy, Warsaw, Poland (1996).
3. F. H. Busse, *Annu. Rev. Earth Planet. Sci.* **11**, 241 (1983); P. H. Roberts, A. M. Soward, *Annu. Rev. Fluid Mech.* **24**, 459 (1992).
4. V. Courtillot, J. L. Le Mouél, *Annu. Rev. Earth Planet. Sci.* **16**, 389 (1988); J. Bloxham, D. Gubbins, A. Jackson, *Philos. Trans. R. Soc. London Ser. A* **329**, 415 (1989); S. Maus et al., *Phys. Earth Planet. Inter.* **151**, 320 (2005).
5. I. I. Rokityansky, *Geoelectromagnetic Investigation of Earth's Crust and Mantle*, N. L. Chobotova, G. M. Pestryakov, B. G. Shilman, trans., Springer, New York (1982); F. Simpson, K. Bahr, *Practical Magnetotellurics*, Cambridge U. Press, New York (2005).
6. M. C. Kelley, *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, Academic Press, San Diego, CA (1989); A. D. Richmond, *EOS Trans. Am. Geophys. Union* **77**, 101 (1996); R. A. Heelis, *J. Atmos. Sol.-Terr. Phys.* **66**, 825 (2004).
7. M. G. Kivelson, C. T. Russell, eds., *Introduction to Space Physics*, Cambridge U. Press, New York (1995); G. W. Pröls, *Physics of the Earth's Space Environment: An Introduction*, Springer, New York (2004).
8. S. R. C. Malin, *Philos. Trans. R. Soc. London Ser. A* **274**, 551 (1973); D. E. Winch, *Philos. Trans. R. Soc. London Ser. A* **303**, 1 (1981).
9. D. P. Stern, N. F. Ness, *Annu. Rev. Astron. Astrophys.* **20**, 139 (1982); C. T. Russell, *Annu. Rev. Earth Planet. Sci.* **19**, 169 (1991); J. G. Lyon, *Science* **288**, 1987 (2000).
10. C. T. Russell, R. L. McPherron, *Space Sci. Rev.* **15**, 205 (1973); Y. Kamide et al., *J. Geophys. Res.* **103**, 17705 (1998).
11. E. Sabine, *Proc. R. Soc. London* **8**, 395 (1856–57).
12. J. G. Kappenman et al., *IEEE Trans. Plasma Sci.* **28**, 2114 (2000); D. H. Boteler, *Nat. Hazards* **23**, 101 (2001); R. Pirjola, *Adv. Space Res.* **36**, 2231 (2005). ■