**Geomagnetic variations**

Variations in the natural magnetic field measured at the Earth's surface and elsewhere in the Earth's magnetosphere (for example, at the geostationary orbit). These are field changes with periodicities from about 0.3 second to hundreds of years. (These boundaries are set to distinguish geomagnetic variations from the quasipermanent field and higher-frequency waves.) Many of these observed variations—from very short periods (seconds, minutes, hours) to daily, seasonal, semiannual, solar-cycle (11-year), and secular (~60–80 years) periods—arise from sources that either are external to the Earth (but superposed upon the larger, mainly dipolar field) or internal to the Earth (the magnetic-dipole and higher-harmonic trends and variations on the scales of hundreds and even thousands years). The daily and seasonal motions of the atmosphere at ionospheric altitudes cause field variations that are smooth in form and relatively predictable, given the time and location of the observation. During occasions of high solar–terrestrial disturbance activity that give rise to aurorae (northern and southern lights) at high latitudes, very large geomagnetic variations occur that even mask the quiet daily changes. These geomagnetic variations are so spectacular in size and global extent that they have been named geomagnetic storms and substorms, with the latter generally limited to the polar regions.

**Solar quiet-time variations**

The recurrent patterns of daily geomagnetic field changes (Fig. 1) arise in the upper atmosphere through dynamo current processes occurring at 100–120-km (60–75-mi) altitudes in the E and lower F regions of the ionosphere. The charged particles of the daytime ionosphere are driven by thermotidal and wind forces through the main geomagnetic field to form a local current, extending primarily over the sunlit side of the Earth.

Annual picture of the midmonth daily variations of quiet-time geomagnetic field, in local time, for the Northern Hemisphere from the Equator (0°) to 80° latitude displayed for H, D, and Z field components. The scale size between baselines is 50 nanotesla. (1 nT = 1 × 10⁻⁹ tesla = 1 gamma—a geomagnetic induction unit used in the past.)

The ionization and the tidal and wind forces vary with time of day and season; the tidal and wind forces are dependent upon geographic location. However, the Earth's main field is offset from the geographic axis alignment and thus provides some geomagnetic coordinate organization to solar quiet-time (Sq) variations. Because the Earth's interior composition is electrically conducting, the solar quiet-time current in the ionosphere causes a secondary current to be induced within the Earth; the magnetic field variations generated by these two currents are observed at the Earth's surface. In addition, a resolution of these external and internal parts of the observed fields can be used to calculate the remote deep-earth electrical conductivity profiles.
**Figure 2** illustrates the computed “equivalent” external \(Sq\) current patterns in the ionosphere and those induced in the Earth (internal) for the summer and winter months of the Northern Hemisphere that could provide the observed fields. The denser the contours, the higher the surface field contribution.

Streamlines for the equivalent external ionospheric source currents (top) and internal induced currents (bottom) for solar quiet-time \((Sq)\) variations of the geomagnetic field in the Northern Hemisphere for midmonth quiet conditions, in June and December. Each pattern, in local time versus geomagnetic (dipole) latitude coordinates, shows the equivalent current contours, with \(10^{-4}\) ampere flowing in the region between contour lines. Arrows indicate the required flow direction. The midnight zero level that is assumed for the display has no effect on the current pattern.

The right-hand rule (with the right hand wrapped around the current vector and the thumb pointing in the current direction, the fingers point in the resulting magnetic field direction) can be applied showing the daily changes of field illustrated by Fig. 1. Near the Equator, the (almost) horizontal orientation of the main geomagnetic field lines causes an especially high ionospheric conductivity for the \(Sq\) system; as a result, there arises an intense eastward daytime current called the equatorial electrojet. In the polar cap region, there are quiet-time, Birkeland field-aligned currents flowing between the magnetosphere and ionosphere that add to the dynamo source of quiet-time geomagnetic field variations. Because magnetospheric behavior is sensitive to the direction of the interplanetary magnetic field (IMF) arriving with the solar wind particles blown out from the Sun, and because polar region field lines reach the outer parts of the magnetosphere, a signature of this interplanetary field is embedded in the polar cap \(Sq\) records. See also: Atmospheric tides; Geomagnetism; Ionosphere; Magnetosphere; Solar wind

**Lunar variations**

The seonidiurnal lunar tidal oscillations of the atmosphere drag the E-region ionization through the main field of the Earth and produce another dynamo current, \(L\). The fields of this current are quite small, less than 10% of the \(Sq\) amplitude, and so special analytical methods are required to isolate their contribution to the observed geomagnetic records. The lunar tidal “day” is 50.5 minutes longer than the solar day, and the global \(L\)-amplitude patterns depend upon the twice-daily lunar tidal forces on the atmosphere, the E- and F-region ionization, and the direction and magnitude of the main magnetic field of the Earth.

**Eclipse and solar flare effects**

Temporary conductivity increases in the ionization due to direct x-ray radiation from solar flares, or decreases in ionization due to solar eclipses, can modify the \(Sq\) and \(L\) dynamo currents. Such variations appear as single half-cycle changes in the
geomagnetic field that last from several minutes to about an hour, with maximum amplitudes rarely larger than 10 nanotesla. These small-amplitude variations are best observed on the extremely quiet Sq-condition days. See also: Sun

**Magnetic storms**

Large geomagnetic disturbances (storms) are approximately one-hundredth of the Earth's main-field strength and are caused by shocks the magnetosphere experiences when significant solar wind disturbances (also known as coronal mass ejections, CME) arrive at the Earth's orbit. As a result, solar-wind-charged particles enter the magnetosphere and increase the Earth's ring current at 3.5 to 9 earth radii. The $H$ (magnetic northward) component of the variation field typically shows the greatest amplitudes (**Fig. 3**). See also: Solar corona

Common scale magnetograms for the $H$ component of a geomagnetic storm variation recorded at two groups of stations: the auroral zone (top) and the low-latitude regions (bottom). Gamma ($\gamma$) is the geomagnetic induction unit. (*Records prepared by National Geophysical Data Center, Boulder*)

Many storms have a similar appearance in the $H$ component that is divisible into three parts: sudden commencement, or initial phase; main phase; and recovery phase. The sudden commencements are recorded simultaneously (within minutes) about the entire Earth. Usually there are a sudden onset and then the increase in the northward field strength that may continue for as long as several hours. During the main phase, the $H$ component decreases, and this decrease often lasts longer than the initial phase and is several times larger in amplitude. The follow-on recovery to the quiet-time level takes longer than the other two phases and may even extend to several days. The more intense storms show an increase of both amplitude and duration. At some observatories, only the storm's main phase is observed.

**Storm intensity and occurrence**

The storms are most intense at the latitudes of the nightside auroral zone, where they can be about six to ten times larger than at middle latitudes. They show minimum amplitudes in the region of 20 to 30° geomagnetic latitude on the nightside of the Earth and have a secondary maximum near the dayside equatorial region. At middle latitudes, about 10 storms per year attain a magnitude of over 50 nT; about one or two storms per year attains over 250 nT. There is an increase in activity during the equinoxes, and the storm variation amplitudes are slightly larger in the winter hemisphere. The number and intensity of storms vary with changes in the sunspot number and lag behind the 11-year solar activity cycle by about
a year or two. There are direct relationships of the storms with the solar outbursts and solar magnetic field orientation (which changes every 22 years), as well as the high-velocity solar wind and the interplanetary magnetic field direction.

The planetary-wide geomagnetic activity is measured at each magnetic observatory by the local $K$ index, a quasilogarithmic scale indicating the range of most disturbed components of the geomagnetic field in a 3-hour interval. The $K$ index is obtained from the range of the field changes about the estimated $Sq$ variation during the same period; this value is normalized for the observatory location. An average of the indices from selected world observatories provides a "planetary" index, $Kp$. Storm magnitudes are arranged in size either by their highest $Kp$ value or by the ring current index, $Dst$.

**Polar substorms**

A significant amount of energy can be delivered into the Earth's magnetosphere by a group of related physical processes called polar substorms. These phenomena occur when solar wind blows from the Sun at higher (500–800 km/s) than usual (350–400 km/s) velocities. If the incoming solar wind carries along a southward-directed magnetic field (that is, opposite to the Earth's field at its interface with the solar wind at about 10–12 earth radii distance from the Earth's center) for a prolonged time, a polar substorm can be triggered and then observed in the high-latitude magnetic and ionospheric parameter variations. There follows an explosive precipitation of particles into the midnight sector of the ionosphere, a spectacular increase in aurorae, a massive flow of field-aligned currents to and from the auroral region, and the dramatic development of geomagnetic westward and eastward electrojet currents in the auroral zone ionosphere (Fig. 4) and in the polar cap. These currents give rise to local heating of the high-altitude atmosphere and to the decrease and violent variations of the $H$ magnetic field component seen on the magnetic storm records at auroral latitudes (top four records of Fig. 3). Very short period pulsations (from seconds to minutes) of the geomagnetic field, known as ultralow-frequency (ULF) micropulsations, that are identified with corresponding fluctuations of the auroral luminosity are observed at such times.

Concurrent polar substorm phenomena observed at College, Alaska. (a) Low-energy electron precipitation into the ionosphere measured as the bremsstrahlung x-ray count rate. (b) Geomagnetic field micropulsations recorded by a north-south axis sensor. (c) $H$ component of magnetic field. 1 gamma ($\gamma$) = 1 nT.
The substorm disturbance often proceeds through three stages: (1) the growth phase (of several tens of minutes), representing the time of injection of energy from the nightside magnetosphere; (2) the expansive or explosive phase (several minutes or more), when the disturbance rises to its maximum in amplitude and effective area; and (3) the decay phase (up to an hour or two) as the event subsides. Consecutive substorms can blend (or follow in a sequence) for several hours during the main phase of a magnetic storm. A peak of the substorm activity is usually restricted to a region of less than 5° in latitude and 100° in longitude at the Earth's nightside ionosphere. The ratio of the high- to low-frequency components of the geomagnetic variations decreases rapidly with distance from the disturbance center. Evidence of the substorm is carried to lower latitudes by electric and magnetic fields from the closure of strong auroral-region westward electrojet currents within the ionosphere and from the Birkeland currents of the magnetosphere. The auroral electrojet index, AE, compiled from magnetic records obtained at observatories located in the auroral latitudes, is used as a measure of the substorm intensity. See also: Aurora

Ring current

During the main phase of the magnetic storms and often during the growth phase of the substorms, energetic ions and electrons are fed into a ringlike region at about 3–9 earth radii distance in the equatorial plane of the Earth. There the complicated field and particle interactions generate a westward-flowing ring current due to a charge separation as the energetic protons and electrons move toward the Earth from the magnetospheric tail. By using the right-hand rule, it can be seen that this current causes a worldwide southward field roughly parallel to the Earth's dipole axis. The resulting depression of the measured fields about the entire Earth, particularly apparent at the lower and equatorial latitudes, contributes to the main phase of the geomagnetic storm. With the decay phase of the substorm, the source of maintenance protons disappears; this allows a slow decay of the ring current. This process occurs during the main phase of the magnetic storm, and it lasts a few hours to several days, depending upon the intensity of the substorms that might occur during the storm's main phase. A ring current index, $Dst$, is derived from the storm-time ($st$) disturbance ($D$) field levels of low-latitude stations, with the $Sq$ variation removed from the data and only the axially symmetric contributions to the field being considered. Actually, at the onset of the storm the positive values of $Dst$ represent the compression of the magnetosphere by the solar wind rather than a ring current (which causes negative $Dst$ values). These compression and ring current characteristics can be seen as the initial and recovery phases of the magnetic storms on the low-latitude observatory traces (bottom four) of Fig. 3.

Rapid variations

The geomagnetic spectrum from several minutes to about a third of a second shows activity associated with solar–terrestrial disturbances. The irregularly shaped (on an amplitude–time trace) $Pi$ pulsations are identified with the substorm onset (Fig. 4). The more smoothly varying (continuous) pulsations, $Pc$, also occur in association with the unsettled magnetospheric environment; they are recognized as having special period groups of several minutes ($Pc4$, $Pc5$), about 30 to 15 s ($Pc3$, $Pc2$), and about 0.5 to 5 s ($Pc1$) for which amplitudes near 10, 0.3, and 0.05 nT, respectively, are often reported. These oscillations arise as hydromagnetic waves whose periods and amplitudes are governed by the charged-particle population and main-field configuration within the magnetosphere and by the transmission of energy from the magnetosphere into the ionosphere. All these variations except $Pc1$ are closely associated with auroral luminosity fluctuations. The $Pc1$ micropulsations (Fig. 5) have been shown to arrive at the high-latitude ionosphere as hydromagnetic waves that subsequently propagate in the F-region ionospheric duct to the lower latitudes. The $Pc1$ pulsations occur most frequently during times of high magnetic activity in the week following major substorms.

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Example of $Pc1$ geomagnetic pulsation event recorded at Boulder, Colorado. (a) Frequency-versus-time display of a two-part event. Note the unique rising frequency structure about a midfrequency near 1.5 cycles/s. (b) Amplitude-versus-time representation for no. 1 event and (c) no. 2 event. The beating appearance in the amplitudes is largely due to the overlapping elements of the rising frequency structure.
Bibliography

- F. Lowes et al. (eds.), *Geomagnetism and Paleomagnetism*, 1988

Additional Readings

- The Great Magnet, the Earth
- Exploration of the Earth's Magnetosphere

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