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EDITORIAL

Geomagnetism through core-crust-space: Discoveries over Time

Kusumita Arora
CSIR-National Geophysical Research Institute, Uppal Road, Hyderabad - 500 007, India
E-mail: *karora@ngri.res.in*

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THE BEGINNINGS

The knowledge of magnetic properties of some natural materials existed several centuries before the phenomenon was investigated and understood. Magnetism is claimed to have been known in Greece as early as 2000 B.C. From about 1000 B.C. the Chinese and the Scandinavians had adopted the use of a compass made of lodestone and iron for navigation, particularly under conditions of low visibility. The beginnings of systematic observations of this physical property is documented by the works of Pliny the Elder in Rome in early A.D.s, by Petrus Peregrinus in France in 1200s and then by William Gilbert in England in 1600. Gilbert discovered that magnets could be made out of iron and these could lose their magnetism on heating. He also discovered that the Earth itself behaved like a magnet, based on experiments using a spherical magnetic lodestone (known as a terella, or "little Earth") and a freely pivoting miniature compass needle (or *versorium*). By studying how the dip of a *versorium* varies at different points around a terella, Gilbert successfully predicted that this relationship between dip and latitude on a terella models the dip of a compass needle around the Earth, thus giving birth to the study of *geomagnetism*, the oldest branch of Earth Science. With the proliferation of space exploration and satellites, astronomers have found that not only individual stars and planets, but the whole Universe is magnetic, possibly representing primordial cosmic magnetism.

Eighteenth century onward, the phenomenon of electricity, static and current, was discovered by physicists such as Charles Augustine de Coulomb in 1785, followed by George Ohm in 1827. The observations of Hans Christian Oersted and mathematical theory developed by Andre Marie Ampere around this time revealed the relationships between electricity and magnetism. Anecdote goes that Professor Hans Oersted at the University of Copenhagen happened to leave a compass next to a conducting wire during a lecture and noticed that the current was deflecting the compass; an example of a discovery before a live audience. Research over the next century established that electricity and magnetism are different manifestations of the same fundamental property of materials: changing electric field creates a magnetic field, and a changing magnetic field (moving/expanding/oscillating/rotating) creates an electric field, which is called induction and was discovered by Michael Faraday in 1831-1832, further formalised by James Clerk Maxwell in 1873. Over the years, Earth's magnetic properties were studied in the light of these advances in physics, leading to the understanding of our planet as well as proliferating applications ranging from navigation, understanding the Earth's geological history, exploration for natural resources, natural hazard assessment and protection against adverse space weather influences. Magnetometers are also used for the measurement of biological fields, e.g. brain, heart, or muscles. Objects can be detected by looking at the way the magnetic field is distorted around objects. This has utility in defence, security, traffic monitoring, and a number of other industries.

Surface Measurements through Geomagnetic Observatory Network

During the eighteenth century Edmond Halley of the Royal Navy made major advances in making measurements of the departures of magnetic north from the geographic north (declination) in the Atlantic Ocean using a compass. James Cook of the British Royal Navy, further expanded the measurements in the Pacific Ocean on his voyages to New Zealand and Australia. Based on magnetic field observations during his journeys to the America's in the early nineteenth century, Alexander von Humboldt determined the increase of magnetic intensity with distance from the Equator and defined the magnetic equator. Alexander von Humboldt and Carl Friedrich Gauss laid the foundation of long term geomagnetic measurements and setup a network on magnetic observatories in different parts of the world to initiate coordinated observations of temporal variations of the field across the globe (France, UK, Germany, Siberia, Central Asia), one of the first examples of international cooperation in science. His observations led to initial linkages of weakening of the field and appearance of auroras; he coined the term *magnetic storm*. In 1841, magnetic storms were recorded at Toronto, Cape of Good Hope, Prague and Tasmania. In 1828, Humboldt arranged for magnetic field observations in an underground mine to find out if the daily variations below ground were the same as above and whether the Sun has an influence on observations. Gauss and Wilhelm Weber later founded the *Göttingen magnetic association*; the Colaba-Alibag observatory in Mumbai was initiated in 1840 as part of this programme. The publication series 'Results from the observations of the magnetic association' with worldwide observational results, graphics and scientific articles were the basis for later worldwide distributed geomagnetic observatory yearbooks and global data collections that still are essential for mapping and studying a global phenomenon such as the geomagnetic field. Gauss derived a method to determine the absolute intensity of the field from the collection of measurements, in 1832. He also developed the method of spherical harmonic analysis that is used for modelling and global mapping of the geomagnetic field.

Carl Friedrich Gauss designed the first magnetometer to record these values, using a permanent bar magnet suspended with a gold fibre. Francis Ronalds and Charles Brooke both developed the magnetograph by continuously recording the movements of the magnet using photography. First fluxgate sensors capable of vector measurements were launched by Aschenbrenner and Goubau in 1936. By the late 1990's sufficient technological advances made in Germany, Denmark, France permitted the sensors to be connected to electronics, which would record the data in digital format. This in turn opened up new avenues of observations and analysis. At present about 180 networked (INTERMAGNET) magnetic observatories are operational over the globe, recording vector and total intensity data 24x7, many in real time. They will continue to be the backbone of observations of the geomagnetic field and its variations.

Measurements from Satellites

The very first satellite magnetic field measurement was accomplished by *a triaxial fluxgate magnetometer onboard Sputnik 3 in 1958.* Early Soviet magnetic satellite missions *Kosmos-49* (1964) and *Kosmos-321* (1970) ventured into measurements of Earth's magnetic fields from space. The U.S. satellite *Magsat* came next and was in orbit for some 7 months in 1979/1980. After 20 years the Danish Ørsted (launched in 1999) and the German CHAMP (2000–2010) satellites provided an unprecedented global data coverage of observations. With observation altitudes between 860 and 250 km, the magnetic field data from these missions brought significant progress for high-resolution core field studies, global mapping of the long-wavelength lithospheric field, and investigations of the various ionospheric and magnetospheric current systems. While higher-orbit Ørsted is still in space, recording only field intensity, the CHAMP mission ended in 2010. At present, the ESA magnetic field satellite mission Swarm is delivering vector data from a constellation of three identical satellites. These missions enabled studies of the recent evolution of the core field, global lithospheric field mapping on scales between 200 and 3000 km, and the altitude-dependent description of the Earth's mantle conductivity and most particularly contributed to first possible observations of currents flowing in the ionosphere that are only detectable by in situ measurements. These include polar cusp, auroral, and inter-hemispheric field-aligned currents, vertical currents at the magnetic equator, F region gravity-driven and plasma-pressure-driven currents, among others. With its constellation of 66 satellites, maps of auroral field-aligned currents derived from magnetometer data of the AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment) project in 2010 have had large impact on the investigations of the polar ionosphere. Data from the recently launched CSES mission of the China Earthquake Administration have provided a candidate model for the International Geomagnetic Reference Field (IGRF-13). Magnetometers in exploratory and observation satellites have been instrumental in mapping the magnetic fields of the Earth, Moon, Sun, Mars, Venus and other planets including attempts to define the shape of Saturn's core. Fluxgate, search-coil and ionized gas magnetometers are the instruments most commonly used for satellite measurements.

Researchers in Canada, the United States, and Europe have developed a new way to remotely measure Earth's magnetic field at altitudes in between the Earth's surface and the much higher altitude of orbiting satellites. Sodium atoms, continually deposited in the mesosphere by meteors, are excited by laser and the light they emit in response is monitored. The excited sodium atoms wobble to produce a periodic fluctuation in the light, that is monitored to determine the magnetic field strength.

SOURCE AND NATURE OF EARTH'S MAGNETIC FIELD IN EARTH'S CORE

As the fields of fridge magnets and lodestones come from electrons spinning around their constituent atoms, more than 90% of the magnetic field measured at Earth's surface originates deep within the Earth, in its conductive outer core, where the strength of the field may be about 50 times stronger. The magnetic field of the Earth is caused by electric currents which are generated by the movement of the conducting material by the thermal convection of the liquid iron inside the Earth and the rotational movement of the Earth in the outer core in a magnetic field. The dynamo effect occurs, when the electrically conductive fluid of the outer core moves helically. The nature of the dynamo effect depends on (i) the velocity of the flow; (ii) the electrical conductivity; (iii) the geometric extension of the currents. The geodynamo was possibly triggered by the inherent instability of the current less state.

The changes of the geomagnetic field over time, namely secular variation, are not constant in time and also vary from place to place. It is expressed as (i) a decrease in the strength of the dipole part of the magnetic field; (ii) a westward drift in the non-dipole part of the magnetic field; (iii) changes in the non-drifting part of the non-dipole field. Archaeomagnetic measurements and global geomagnetic models have revealed that the strength of the dipolar field has been decreasing steadily and is only half of what it was two millennia ago. Since the early eighteenth century, it has been observed from ground measurements that the line of zero declination is slowly moving westward with an average velocity of about 0.2° per year; local values can be different. On the other hand, certain features of the field, e.g. over northern Manitoba, Canada are semi-permanent features with lifetime of millions of years, which experience periodic changes in strength. Many countries, including India have installed a network of repeat stations where measurements are made at regular intervals of 1-5 years to track the finer spatio-temporal details of secular variations. Satellite measurements can also be used for this purpose for the duration of its life.

An interesting feature of secular variation is a geomagnetic jerk, which manifests as a distinct change in the rate of secular variation. In a plot of secular acceleration, a jerk shows up as a step change - constant acceleration before the jerk, constant acceleration with a different value after the jerk. The first recorded geomagnetic jerk was in 1969 by Vincent Courtillot and team. Since then, 18-20 jerks have been identified by scientists, the latest being in 2019-2020. Secular variation, like the magnetic field itself, originates in the outer core of the Earth, and is an integral part of the processes which generate the field in the first place. Geomagnetic jerks may represent a reorganization of the secular variation associated with torsional oscillations in the Earth's core. Possible correlations of jerks with LOD and Chandler wobble decadal variations and global temperature changes are under investigation.

CRUSTAL MAGNETISM AND PALEOMAGNETISM

As early as the 18th century, it was noticed that compass needles deviated strongly near magnetized outcrops. In 1797, Von Humboldt attributed this magnetization to lightning strikes. Some elements like iron, cobalt, and nickel, can become magnetized in the presence of a magnetic field and remain so in the absence of that field. As magma solidifies and cools to become rocks, magnetic domains in the magnetic minerals e.g. iron oxides (magnetite, maghemite, haematite, ilmenite), oxyhydroxides (goethite, ferrihydrite, lepidocrocite), and sulphides (greigite, pyrrhotite) become magnetized in the direction of the field at the time and align with the Earth's magnetic field locking in the orientation (dip relative to horizontal) and polarity (field lines pointing out or field lines pointing in). Depending on the nature and concentration of magnetic minerals, rocks are strongly or weakly magnetic. Presence of such rocks makes regions of the Earth's crust magnetic. In such regions, the measured magnetic field values are enhanced from the ambient geomagnetic field by several tens to hundreds nanotesla. Magnetic field patterns on the surface, is thus a proxy for crustal geology and is useful in understanding the structure and composition of the crust. They are apt representations of magmatic and tectonic processes and geological structures, which are generated thereof. With increasing depth, the crustal magnetism is lost because the temperature rises above the Curie temperature of the materials producing the field.

In the oceanic crust, titanomagnetite minerals in basalts and gabbros are magnetised when they are formed at a spreading ridge and produce localised high intensity magnetic field. The continuous process of crust formation thus becomes imprinted with the magnetic signatures of the ambient field, symmetrically on both sides of the spreading centre, which undergoes changes of direction from time to time. Combined with radiometric dating, these patterns have helped to decipher the sequence of reversals of the field up to 250 million years before present. Because this pattern of reversals is non-repeating, it acts like a bar code or finger print with a distinct pattern associated with different time intervals in the geologic past. This code has played a crucial role in establishing the plate tectonic theory.

Paleomagnetism is the branch of geophysics that refers to the study of the Earth's magnetic field using information of magnetic fields preserved in rocks, archaeological materials, or silt. The polarity of the Earth's magnetic field, as well as magnetic field reversals, can thus be determined by examining rocks of various ages or archaeological materials. This record of the strength and direction of Earth's magnetic field is an important source of our knowledge about the location of the tectonic plates, the Earth's evolution through the entire geological history, including the geomagnetic field. Paleomagnetism was first studied in the 1940s when British physicist Patrick M.S. Blackett (1897–1974) invented a system for measuring the minute magnetic fields associated with magnetic minerals. Observations made by David, Brunhes, Mercanton and Matuyama in the ninteenth and twentieth centuries revealed many rocks magnetized parallel and antiparallel to the field. This led to the identification of the Brunhes–Matuyama reversal in the mid-Quaternary.

The origin of magnetic minerals is diverse under different evolutionary processes of the Earth, hence different approaches are adopted to measure the nature and strength of magnetisation acquired by the rocks at different stages of its evolution. Iron-titanium oxide minerals in basalt and other igneous rocks may preserve the direction of the Earth's magnetic field when the rocks cool through the Curie temperatures of those minerals, namely *thermoremanent magnetization*. Magnetic grains in sediments may align with the magnetic field during or soon after deposition; this is known as *detrital remanent magnetization*. When magnetic grains grow during chemical reactions, e.g. haematite, and record the direction of the magnetic field at the time of their formation, this is known as *chemical remanent magnetization*.

SUN AND THE EARTH's MAGNETIC FIELD

The Earth's magnetic field permeates the space around the planet, creating the magnetosphere, as named by Thomas Gold in 1959. This shields the planet and its atmosphere from erosion by the solar wind, coronal mass ejection and other solar phenomena, which are continually hurled into space by the Sun. At the surface of the Earth, the geomagnetic field is dominantly dipolar but several thousand kilometers into space, its shape is determined by the Sun. Solar wind, which was studied initially by Eugene Parker in 1958, compresses the magnetosphere on the sunward side of the Earth to 6-8 times the Earth radius. On the night side the magnetosphere stretches out by several thousand Earth radii. The magnetosphere reacts to the solar forces constantly, thus shielding the planet from irreversible harm. Nevertheless, it is far from impenetrable, and energy, mass, and momentum are transferred from the solar wind to regions inside Earth's magnetosphere. The interaction between the solar wind and Earth's magnetic field, and the underlying atmosphere and ionosphere, creates various regions of fields, plasmas, and currents inside the magnetosphere such as the plasmasphere, the ring current, and radiation belts. The resultant variations of the magnetosphere create what we call "space weather" that can affect technological systems and human activities. For example, the radiation belts can have impacts on the operations of satellites, and particles and currents from the magnetosphere can heat the upper atmosphere and result in satellite drag that can affect the orbits of low-altitude Earth orbiting satellites.

In the Solar System the Sun, Mercury, Jupiter, Saturn, Uranus, Neptune, and Ganymede have magnetospheres. The magnetosphere of Earth has a distinct structure: The *Bowshock* forms the outermost layer, about 90,000 km from the surface of the Earth and acts as boundary between the interplanetary space and geomagnetic field. The *Magnetosheath* is the adjacent layer with high energy flux, where direction and magnitude of magnetic field varies rapidly. The *Magnetopause* is the region next to the Magnetosheath wherein the pressure from the planetary magnetic field is balanced with the pressure from the solar wind. When large swirls of plasma travel along the edge of the magnetosphere driven by geomagnetic disturbances, the plasma can slip past. This results in magnetic reconnection, during which, solar wind particles enter the magnetosphere. Opposite the compressed magnetic field is the *Magnetotail*, where the magnetosphere extends far beyond the astronomical object. It contains two lobes, referred to as the northern and southern tail lobes, separated by a plasma sheet.

The presence of the magnetosphere have enabled the existence of the ionosphere and atmosphere around the Earth. Influences from the magnetosphere cause changes in the ionosphere, which is an electrically conductive layer that prevails between ~80 to 1000 km above the Earth's surface. The ionosphere is formed by partially ionized air (plasma) that surrounds the Earth and constitutes an interface between the neutral upper atmosphere and space plasma. Fluctuations of the magnetosphere and ionosphere influences the propagation and attenuation of electromagnetic waves, which affects communication and navigations systems. Space weather events severely affect GPS signals as well as radio communications during times of turbulence. GPS usage spans farming, construction, exploration, surveying, snow removal and many other applications critical to a functional society; GPS receivers are now in nearly every cell phone and in many automobiles, trucks, and any equipment that moves and needs precision location measurements. Satellite communication is affected by the presence of plasma in the ionosphere, whereby the signals are affected by group delay and phase advance and attenuation due to absorption and scintillation. Furthermore, the drag force on satellites increases during times when the active Sun drives large scale variations in the magnetosphere, thereby adding extra energy into the ionosphere. In such times, the low density layers of air rise and are replaced by higher density layers that were previously at lower altitudes, increasing drag on satellites and changing their orbits. While conspicuous correlations between long term space weather changes and terrestrial climate change patterns are not established, linkages between processes are being investigated, viz. the links between solar minimum and formation of clouds nucleated by cosmic rays.

GEO-ELECTROMAGNETIC INDUCTION

The geomagnetic field is produced by movements of conducting fluids in the Earth's outer core. This field varies constantly under the influence of solar phenomena. The fluctuating geomagnetic field can in turn induce an electric current in conducting materials in the Earth. The study of electromagnetic induction in the Earth has provided a geophysical method for using magnetic and electric field variations observed on the surface to interpret electrical conductivity and earth structure over a wide range of depths. The time varying magnetic field induces telluric currents in the ground to create a secondary magnetic field, which is location dependent; the electrical conductivities of the local formations will determine the current strength.

Application of this principle to investigate conductivity structure by using the phenomenon of electromagnetic induction within the Earth, was started in Japan in 1948 by Rikitake, in 1950 in Russia by Tikhonov and in 1953 in France by Cagniard. This is called the magnetotelluric (MT) method. The Earth's naturally varying electric and magnetic fields are measured over a wide range of frequencies from 10,000 to 0.0001 Hz. The ratio of the electric field to magnetic field provides simple information about subsurface conductivity. Due to the skin effect, the ratio at higher frequency ranges gives information on the shallow Earth, whereas deeper information is provided by the low frequency range. The ratio is usually represented as both apparent resistivity and phase as functions of frequency. MT measurements can investigate depths from about 300 m down to hundreds of kilometers. The vertical resolution of MT mainly depends on the frequency being measured whereas horizontal resolution of MT mainly depends on the distance between sounding locations. The disciplines of *Geomagnetic depth sounding* (GDS) was pioneered by Schmucker in 1969 to derive lateral conductivity contrasts and *Magneto-variational soundings* (MVS) was initiated in 1984 onward, to derive deep conductivity information of the Earth. Large scale conductors at upper mantle depths have been detected, which contribute to the understanding of tectonic processes.

The oceans play a special role in this induction due to their relatively high conductivity, which leads to large lateral variability in surface conductance. Electric currents that generate secondary fields are induced in the oceans by two different processes: (a) by time varying external magnetic fields, and (b) by the motion of the conducting ocean water through the Earth's main magnetic field. As the electrical conductivity of both seawater and material under the oceans differs considerably from that of the continents, an enhanced effect usually referred to as the "geomagnetic coast effect" (GCE) is observed in data from such locations.

Space weather events also induce currents (i. e. Geomagnetically Induced Currents (GIC) in conductors on the surface of the Earth, most commonly electric transmission grids, buried pipelines and cables, railway tracks. GIC were first observed on the emerging electric telegraph network in 1847–1848 during storm events of Solar cycle in 1850s. Explosion in various conducting networks have made the significance of GIC greater in modern society. The effect is stronger at higher latitudes (tens to hundreds of amperes) and have been studied for necessary mitigation measures in Canadian, Finnish and Scandinavian power grids and pipelines since the 1970s.

ACHIEVEMENTS IN INDIA

Systematic geomagnetic measurements were started at several locations in India as early as the mid-1800s. Fresh impetus was provided by the International Geophysical Year (IGY, 1957-58) and a network of 11-14 long term geomagnetic observatories are operating in the country. In particular, the study of the magnetic Equator and the equatorial Electrojet and its relation to the solar dynamo are special features observable in the sub-continental landmass and has attracted a lot of research. It is critical to emphasise the role of geomagnetic measurements in tracking the solar-terrestrial relation quantifying solar-wind magnetosphere interaction (Magnetic pulsations), magnetic storm (related Dst index), quiet-time ionosphere dynamo, etc. Data from pairs of observatories in low latitude and equatorial region form a valuable resource that has later been critical in testing generation and transmission mechanisms of geomagnetic pulsations. Pioneering work from India on design of time-domain electromagnetic system, resistivity meter, proton precession magnetometer was hailed the world over. Geomagnetic studies in the country diversified to include ground magnetic surveys to map magmatic complexes and configuration of the Deccan Volcanic Province. Aeromagnetic surveys have covered most of the Indian landmass and form the basis for correlation with surface lithology and structural features. Magnetometer array studies in peninsular India and Himalaya, as well as telluric and magnetotelluric studies have proliferated over the last few decades in many parts of the country. From the magnetometer array studies, conductive structures of the crust and lithosphere have shed light on major large scale features. Airborne electromagnetic studies are the present day thrust area, used for mapping aquifer systems on the one hand and for detection of potential zones of mineralization on the other.

CONCLUSION

Geomagnetism became an established field of natural sciences in the nineteenth century. In the initial years the science was driven by curiosity to understand natural phenomena, which led to systematic observations, backed up by theoretical developments. Later, much of the advances were driven by progress in engineering, which produced advanced instruments for observation and advanced computers for analysis and modelling of the data. Main challenges in geomagnetic field research include a clear separation of signals from the individual field contributions and a full understanding of their physical sources, a more complete understanding of the long-term history of the geomagnetic field, and forecasting future field changes. The past decade has seen increasing efforts to combine observations and theory in data assimilation approaches to predict the future geomagnetic core field evolution. India has a strong tradition of study of the geomagnetic field, particularly in the arenas of crustal magnetism and electromagnetic induction. Combined studies on geomagnetism-paleomagnetism-archeomagnetism has immense scope to reveal the evolution of the magnetic field, which can be the basis for predictions of the future of the core field.

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