Cambridge University Press
978-1-108-41848-5 — Geomagnetism, Aeronomy and Space Weather
Edited by Mioara Mandea , Monika Korte , Andrew Yau , Eduard Petrovsky
Excerpt
More Information

PART I

Introduction

Cambridge University Press
978-1-108-41848-5 — Geomagnetism, Aeronomy and Space Weather
Edited by Mioara Mandea , Monika Korte , Andrew Yau , Eduard Petrovsky
Excerpt
More Information

1
Objectives of Geomagnetic and Aeronomy Studies

David Kerridge

Magnetism was discovered in antiquity as the remarkable ability of a type of black rock, lodestone, to attract iron and to both attract and repel other lumps of lodestone. This was followed by the discovery that, when free to rotate, a piece of lodestone turns and aligns itself in a particular direction. The Earth's magnetic field entered human service when this directive property was made useful through the invention of the compass around a thousand years ago, most probably in China. There is evidence that the Chinese also found that the compass direction deviated from true north–south and so discovered what today is termed *magnetic declination*, the angle between true and magnetic north (Needham, 1962). The compass, as a navigational tool, later became invaluable to mariners in their voyages of exploration and trade (Jonkers et al., 2003). (It is interesting to note the geomagnetic field is now used as a directional reference in high-accuracy drilling for production of hydrocarbons and that many of today's ubiquitous smartphones have in-built magnetic sensors and global geomagnetic field models, putting magnetic navigational capability into the hands of people worldwide.)

The invention of the compass was a technological achievement, and the properties of lodestone stimulated curiosity and the beginning of scientific investigation, notably by Petrus Peregrinus, who introduced the concept of magnetic poles in his letter of 1269. William Gilbert (1600) acknowledged Peregrinus' influence when he published the results of years of careful investigation into the properties of a spherical lodestone in his book *De Magnete*. Gilbert vigorously advocated discovery through meticulous experimentation and measurement, and *De Magnete* is often cited as the first scientific textbook. From the evidence of his experiments, he made the revolutionary claim that the Earth itself is magnetic, and it is not unreasonable to suggest that Gilbert's identification of magnetism as a planetary property was the starting point for geomagnetic science.

The pivoted magnetised needle was developed into a scientific instrument with the aim of discovering more about the behaviour of the geomagnetic field. In 1635 Gellibrand noted the slow drift of the direction of the compass in London over several years, so discovering the secular variation of declination. Graham, in London, around 1722, observed diurnal declination changes and, in collaboration with Celsius in Uppsala in 1741, showed that rapid, large changes were observed at the same time in the two locations, and discovered their correlation with the aurora. The connection between solar activity and major geomagnetic disturbances was firmly established in 1859 when Richard Carrington observed a spectacular white-light solar flare, which was followed by a large magnetic storm about 18 hours later (Carrington, 1859). (The term *magnetischer Sturm*, 'magnetic storm', was first used by von Humboldt.)

Knowledge of geographical changes in declination was vital to navigators, who relied on it to make compass corrections as they travelled, particularly on long ocean voyages. Halley was given command of the Royal Navy ship *Paramore* in 1698–1700, surveyed the Atlantic Ocean, and published his famous contour charts of magnetic variation (declination) throughout the Atlantic in 1701.

The nineteenth century saw rapid progress in experimental investigations of electricity and magnetism. Volta reported his invention of the voltaic pile in 1800. Ørsted (1820) established the intimate link between electricity and magnetism, and Ampère (1820) and Biot and Savart (1820) made fundamental discoveries about electrical currents and magnetic fields. Faraday discovered electromagnetic induction in 1831 and introduced the concept of magnetic field lines of force (Faraday, 1852). Maxwell (1873a, 1873b) gave a unified mathematical formulation of the experimental results, and his equations of electromagnetism continue to provide the foundation for theoretical investigations of the geomagnetic (and geoelectric) field.

Gauss played an important role in the development of geomagnetism in a number of ways. With Weber he developed a method of making absolute measurements of the strength of the geomagnetic field (Malin, 1982) and supported von Humboldt's efforts to build a network of worldwide magnetic observatories by establishing the Göttingen Magnetic Union in 1836. Gauss applied the method of spherical harmonic analysis to global observations, showing how the method could be used to separate fields originating above and below the Earth's surface. He concluded that the

Cambridge University Press
978-1-108-41848-5 — Geomagnetism, Aeronomy and Space Weather
Edited by Mioara Mandea , Monika Korte , Andrew Yau , Eduard Petrovsky
Excerpt
More Information

geomagnetic field originated largely in the Earth's interior (Gauss, 1839). (Spherical harmonic models remain the standard means of representing the global geomagnetic field, as, for instance, in the International Geomagnetic Reference Field regularly revised and published by IAGA.) Gauss also suggested that the time variations of the field could be due to currents in an electrically conducting layer of the atmosphere.

Maxwell wrote, 'Gauss, as a member of the German Magnetic Union, brought his powerful intellect to bear on the theory of magnetism, and on the methods of observing it, and he not only added greatly to our knowledge of the theory of attractions, but reconstructed the whole of magnetic science as regards the instruments used, the methods of observation and the calculation of the results, so that his memoirs on Terrestrial Magnetism may be taken as models of physical research by all those who are engaged in the measurement of any of the forces in nature'.

In quite different experimental investigations starting in the mid nineteenth century, evidence that magnetised rocks may contain a fossil record of the Earth's magnetic field at the time of their formation emerged. This idea was extended to archaeological materials in the early twentieth century. In 1905 Brunhes found baked clays magnetised in the opposite direction to the present-day field in France and came to the conclusion that the Earth's magnetic field had reversed its polarity in the geological past (Brunhes, 1906). This startling discovery was confirmed in rock samples worldwide and became a vital piece of evidence leading to a revolution in understanding the workings of our planet. Under the assumption that the Earth's magnetic field averages to a geocentric dipole over timescales of around 10 ka, the latitude of the site of a rock sample at the time it acquired its magnetisation can be estimated from the direction of its magnetisation. The changes in latitude of a site deduced from measurements at different geological ages provide strong support for Wegener's proposed continental drift (Wegener, 1929). Marine magnetic surveys have revealed the now-familiar barcode of twinned magnetic stripes showing seafloor spreading (Vine and Matthews, 1963), on either side of the mid-Atlantic ridge, for example. The plate tectonic–driven ocean floor conveyor belt creates a reversal 'egg timer' providing a geomagnetic timescale for around 200 Ma.

As the twentieth century approached, systematic mapping and monitoring of the geomagnetic field had begun, cataloguing its variations in space and time; the physics of electricity and magnetism had been established; and Maxwell's equations gave a mathematical toolkit for theoretical developments. A strong foundation had been laid for the rapid developments in research into the geomagnetic field that followed.

One important reason for progress in the twentieth and twenty-first centuries was the establishment of international organisations allowing scientists to present, share and comment on their results and co-operate and co-ordinate activities. Such organisations played important roles in the International Polar Years in 1882–3 and 1932–3, and the International Geophysical Year in 1957–8, all of which provided impetus for research. The year 1957 was also the start of the space age, and the ability to make scientific measurements on board spacecraft has revolutionised research into the geomagnetic field and much of Earth science in general.

Scientific organisations have to reshape in response to changing research interests, and a pertinent example is that following pressure from upper atmospheric scientists to accommodate their interests, the International Association of Terrestrial Magnetism and Electricity expanded its scope and was renamed the International Association of Geomagnetism and Aeronomy in 1954. This followed the suggestions of Chapman to change 'Terrestrial Magnetism' to 'Geomagnetism', a minor change in terminology, and to adopt his personally invented term 'Aeronomy', which he defined as 'the science of the upper region of the atmosphere where dissociation and ionisation are important' (Chapman, 1938, 1946). Modern aeronomy includes studies of the composition, movement and thermal structure and balance of the atmosphere, naturally including the ionosphere created by the ionising effect of solar ultraviolet radiation.

We now understand that the Earth generates its main magnetic field in the fluid part of the core by dynamo action and that the interaction of the field with the solar wind plasma creates a cavity in space, a dynamic magnetic environment, the magnetosphere, with its boundary at a distance of about 10 Earth radii on the sunward side of the Earth and extending well beyond the Moon's orbit on the anti-sunward side. Within the magnetosphere are complex arrangements of electric and magnetic fields controlling a variety of current systems and charged particle populations. Time-varying magnetic fields from within the magnetosphere–ionosphere system induce electric fields in the solid Earth and the oceans, driving electric currents, which, in turn, create secondary magnetic fields. The magnetisation of rocks, which has both induced and remanent components, creates additional fields. Consequently, any instrumental measurement is the composition of fields from all these sources. So, while the core field is the inherent and dominant magnetic field, geomagnetism can be said to encompass the study of geomagnetic fields in the plural.

Geomagnetism has the benefit of long instrumental records, starting with declination observations made more than 400 years ago and observatory records extending over the last 170 years. These data have, among other things, shown that the dipole moment of the geomagnetic field is now decreasing at around 6% per century, provided evidence that the main field is implicated in length-of-day changes through core–mantle coupling (Holme and de

Cambridge University Press
978-1-108-41848-5 — Geomagnetism, Aeronomy and Space Weather
Edited by Mioara Mandea , Monika Korte , Andrew Yau , Eduard Petrovsky
Excerpt
More Information

Viron, 2013) and enabled the evolution of flow patterns at the core surface to be estimated (Holme, 2009). The powerful combination of data from ground-based magnetic observatories and a series of magnetic survey satellites over the last few decades has helped to improve mapping the fluid flow at the surface of the core and understanding of the role of waves in generating the secular variation of the field. A particular challenge is to forecast the evolution of the core field based on this understanding.

Probing the Earth's interior is a major challenge for all areas of the Earth sciences, as structure, material properties and processes must be inferred from remote measurements because the interior cannot be instrumented (the deepest drilled borehole penetrates to less than 13 km below the surface). Combining results from different types of observation helps to reduce ambiguities in interpretations in such inverse problems. For the core, seismology, geodesy, geochemistry and thermodynamics and high-pressure and high-temperature laboratory experiments provide information on structure, composition, physical properties and mechanical and thermal boundary conditions relevant to the dynamo problem.

A great deal of progress has been made in recent years in mathematical modelling of the dynamo process. The feasibility of dynamo action in an homogeneous electrical conductor such as the Earth's core was difficult to establish and only proved theoretically through independent work by Backus (1958) and Herzenberg (1958). Early dynamo models prescribed the form of core motions, but, following the pioneering work of Glatzmaier and Roberts (1995), now there are self-consistent models including the equation of motion for the core fluid that attempt to incorporate constraints based on understanding gained from geophysical data and are capable of producing magnetic fields with characteristics similar to the geomagnetic field, including polarity inversions. However, while recent models exhibit Earth-like behaviour in a qualitative sense, working fully in the Earth's parameter regime is beyond current computational ability and remains a major challenge.

Induction studies, based on surface measurements of magnetic and electric fields, allow estimation of the spatial distribution of electrical conductivity within the Earth's interior, from the crust and lithosphere to the deep mantle. This can complement results from seismology, allowing better definition of thermal and geological structures. Joint inversion of data, including links between electrical conductivity and physical parameters controlling seismic wave propagation, is a promising area of research. Conductivity is sensitive to fluid content, and induction studies can play a part in volcanic hazard assessment by using conductivity contrasts to map magma distributions (Desissa et al., 2013).

The ability to make observations in space, with single and, more recently, constellations of satellites, has enabled rapid global magnetic surveys to be made, resulting in advances in mapping the core and crustal fields, making 3-D models of mantle conductivity and even detecting the subtle motional induction signals generated by ocean currents (Sabaka et al., 2018).

Space missions have also allowed 3-D exploration of the magnetosphere with *in situ* measurements of electric and magnetic fields and charged particle populations (Ganushkina et al., 2018). This has greatly advanced understanding of, for example, processes transferring energy and particles from the solar wind into the magnetosphere, the role of the polar cusps, links into the ionosphere, the dynamics of the radiation belts, processes in the magnetotail and mechanisms involved in magnetic storms and sub-storms and production of the aurora. Research is showing the importance of treating the magnetosphere, ionosphere and neutral atmosphere as a coupled system.

The significance of research into magnetospheric processes has gained the attention of governments and the public because of the threat posed by 'space weather' events driven by solar disturbances (Cannon, 2013). During magnetic storms, the rapid changes in the Earth's magnetic field induce electric fields in the solid Earth, driving geomagnetically induced currents (GIC) into the low-resistance paths provided by grounded systems. The GIC risk to modern-day ground-based technology became particularly apparent during the magnetic storm of 13 March 1989, when the whole of the Hydro-Québec power grid collapsed, leaving 6 million people without electricity for nine hours. Since mankind has been able to launch satellites, we have gradually populated near-Earth space, with spacecraft providing positioning, navigation and timing, telecommunications and Earth observation services on which modern society relies. Understanding magnetospheric processes helps to build the description of hazards required for risk assessments for these vital space-based assets. This requires prediction in the context of a diminishing core field and in the sense of probability distributions for future events.

Geomagnetic science is flourishing for a number of reasons. The availability of observations with high resolution in time and space is leading to the discovery of new phenomena and giving the ability to test theories, and modern computing power supports data analysis and the development of complex mathematical models, bringing into range questions that have been too difficult to attack in the past. The geomagnetic field permeates all parts of the solid Earth, extends into space and interacts in processes to some degree wherever there is finite electrical conductivity. Consequently, it is a vital part of the scientific jigsaw puzzle that needs to be assembled to provide a complete picture of the Earth system.

(*Note*: Courtillot and le Mouël (2007) and Stern (2002) are excellent sources of information on the historical development of geomagnetism and palaeomagnetism.)

References

Ampère, A.-M. (1820) Mémoire sur l'action mutuelle entre deux courants électriques, un courant électrique et un aimant ou le globe terrestre, et entre deux aimants, *Annales de chimie et de physique*, **15**, pp. 59–75, 170–218.

Backus, G. (1958) A class of self-sustaining dissipative spherical dynamos, *Annals of Physics*, **4**(4), pp. 372–447. doi: 10.1016/0003-4916(58)90054-X.

Biot, J.-B. and Savart, F. (1820) Note sur le Magnétisme de la pile de Volta, *Annales de chimie et de physique*, **15**, pp. 222–3.

Brunhes, B. (1906) Recherches sur la direction d'aimantation des roches volcaniques, *Journal of Physics: Theories and Applications*, **5**(1), pp. 705–24. doi: 10.1051/jphystap:019060050070500.

Cannon, P. (2013) *Extreme Space Weather: Impacts on Engineered Systems and Infrastructure*. London: Royal Academy of Engineering. Available at: www.raeng.org.uk/spaceweather.

Carrington, R. C. (1859) Description of a singular appearance seen in the Sun on September 1, 1859, *Monthly Notices of the Royal Astronomical Society*, **20**(1), pp. 13–15. doi: 10.1093/mnras/20.1.13.

Chapman, S. (1938) Geomagnetism or terrestrial magnetism?, *Journal of Geophysical Research*, **43**(3), p. 321. doi: 10.1029/TE043i003p00321.

Chapman, S. (1946) Some thoughts on nomenclature, *Nature*, **157**, p. 405. doi: 10.1038/157405b0.

Courtillot, V. and Le Mouël, J.-L. (2007) The study of Earth's magnetism (1269–1950): a foundation by Peregrinus and subsequent development of geomagnetism and paleomagnetism, *Reviews of Geophysics*, **45**(3). doi: 10.1029/2006RG000198.

Desissa, M., Johnson, N. E., Whaler, K. A., Hautot, S., Fisseha, S., Dawes, G. J. K. et al. (2013) A mantle magma reservoir beneath an incipient mid-ocean ridge in Afar, Ethiopia, *Nature Geoscience*, **6**(10), pp. 861–5. doi: 10.1038/ngeo1925.

Faraday, M. (1852) On the physical character of the lines of magnetic force, *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, **3**(20), pp. 401–28. doi: 10.1080/14786445208647033.

Ganushkina, N. Y., Liemohn, M. W. and Dubyagin, S. (2018) Current systems in the Earth's magnetosphere, *Reviews of Geophysics*, **56**(2), pp. 309–32. doi: 10.1002/2017RG000590.

Gauss, C. F. (1839) Allgemeine Theorie des Erdmagnetismus, Resultate aus den Beobachtungen des magnetischen Vereins im Yahr 1838, pp. 1–57.

Gilbert, W. (1600) *De Magnete*. London: Peter Short. doi: 10.5479/sil.113709.39088016899940.

Glatzmaier, G. A. and Roberts, P. H. (1995) A three-dimensional self-consistent computer simulation of a geomagnetic field reversal, *Nature*, **377**, pp. 203–9. doi: 10.1038/377203a0.

Herzenberg, A. (1958) Geomagnetic dynamos, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **250**(986), pp. 543–83. doi: 10.1098/rsta.1958.0007.

Holme, R. (2009) Large-scale flow in the core, in Olson, P. and Schubert, G. (eds) *Treatise on Geophysics: Vol. 8. Core Dynamics*. Amsterdam: Elsevier, pp. 107–30.

Holme, R. and de Viron, O. (2013) Characterization and implications of intradecadal variations in length of day, *Nature*, **499** (7457), pp. 202–4. doi: 10.1038/nature12282.

Jonkers, A. R. T., Jackson, A. and Murray, A. (2003) Four centuries of geomagnetic data from historical records, *Reviews of Geophysics*, **41**(2). doi: 10.1029/2002RG000115.

Malin, S. R. C. (1982) Sesquicentenary of Gauss's first measurement of the absolute value of magnetic intensity, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **306**(1492), pp. 5–8. doi: 10.1098/rsta.1982.0060.

Maxwell, J. C. (1873a) *A Treatise on Electricity and Magnetism*, vol. 1, 1st edn. Oxford: Clarendon Press.

Maxwell, J. C. (1873b) *A Treatise on Electricity and Magnetism*, vol. 2, 1st edn. Oxford: Clarendon Press.

Needham, J. (1962) *Science and Civilisation in China: Vol. 4. Physics and Physical Technology, Part 1*, 1st edn. Cambridge: Cambridge University Press.

Ørsted, H. C. (1820) Experiments on the effect of a current of electricity on the magnetic needle, *Annals of Philosophy*, **16**, pp. 273–6.

Sabaka, T. J., Tøffner-Clausen, L, Olsen, N & Finlay, C.C., (2018) A comprehensive model of Earth's magnetic field determined from 4 years of Swarm satellite observations, *Earth, Planets and Space*, **70**(1), p. 130. doi: 10.1186/s40623-018-0896-3.

Stern, D. P. (2002) A millennium of geomagnetism, *Reviews of Geophysics*, **40**(3), p. 1007. doi: 10.1029/2000RG000097.

Vine, F. J. and Matthews, D. H. (1963) Magnetic anomalies over oceanic ridges, *Nature*, **199**(4897), pp. 947–9. doi: 10.1038/199947a0.

Wegener, A. (1929) *Die Entstehung der Kontinente und Ozeane*. 4th edn. Braunschweig: Friedrich Vieweg.