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Special Section:
Geosystem science at the AGU centennial: A theme dedicate to Alexander von Humboldt 250th anniversary

Key Points:
- Alexander von Humboldt's role as one of the founders of geomagnetism is presented
- Current understanding of the various aspects of geomagnetism and paleomagnetism is summarized
- Grand challenges in geomagnetism and its societal relevance are outlined

Correspondence to:
M. Korte,
monika@gfz-potsdam.de

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Geomagnetism: From Alexander von Humboldt to Current Challenges

Monika Korte[1] and Mioara Mandea[2]

[1]GFZ—German Research Centre for Geosciences, Potsdam, Germany, [2]CNES—Centre National d'Etudes Spatiales, Paris, France

Abstract The Earth's magnetic field shields our habitat against potentially harmful charged particles from outer space. Moreover, it is an important source of information about Earth's deep interior and geological history, both inaccessible to direct observations. Geomagnetism, the study of all aspects of the Earth's magneticfield, formed as a field of natural sciences in the early nineteenth century, largely under the influence of two prominent polymaths, Alexander von Humboldt and Carl Friedrich Gauss. On the occasion of the AGU 2019 centennial and Alexander von Humboldt's 250th anniversary, we link Humboldt's activities in geomagnetism with modern research in this domain and its challenges. Based on magnetic field observations during his scientific journeys, Alexander von Humboldt determined the increase of magnetic intensity with distance from the equator. He initiated coordinated observations across the globe and thus laid the foundation for international data exchange and collaboration. Observation is a prerequisite to a better understanding of the Earth's magnetic field with its various sources from the Earth's core, lithosphere, and electrical current systems outside the Earth, with a multitude of applications from navigation, exploration, natural hazard assessment, and study of Earth's evolution. A full understanding of the physical processes underlying the various geomagnetic field sources is mandatory to tackle the challenge of forecasting the future geomagnetic field evolution and to take advantage of the information that the geomagnetic field can provide about the Earth's history, geological and tectonic conditions and processes, and the near-Earth's space environment.

Plain Language Summary Earth's magnetic field shields our planet against highly energetic particles from the Sun and outer space, which threaten modern technology. The main part of the magnetic field originates from dynamical processes in the Earth's outer, fluid core, and changes slowly. Additional contributions are due to magnetized rocks in the uppermost parts of the Earth. Moreover, several quickly varying electrical current systems flowing at distances from approximately 60 km to several Earth's radii around our planet contribute to geomagnetic field observations. Alexander von Humboldt played an important role in establishing the science of geomagnetism. He described the systematic change of magnetic field strength with distance from the equator, and he initiated synchronized magnetic field observations worldwide. Since that time, significant progress has been made in understanding the various geomagnetic field sources, and we have recognized applications ranging from understanding the Earth's geological history, exploration for natural resources, natural hazard assessment, navigation, and protection against adverse space weather influences. 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.

1. Historical Introduction

Geomagnetism, the science about the Earth's magnetic field, has a long, rich, and international history (see, e.g., Kono, 2015, for more details on the following). The attractive force of natural magnets was already known to ancient Greek philosophers, a couple of centuries BCE. North-/south-pointing devices, predecessors of modern magnetic compasses, were used by the ancient Chinese from at least the second century CE. The *Epistola* by the thirteenth century French scholar Petrus Peregrinus can be considered the first scientific treatise, providing compelling conclusions about the properties of a natural magnet from observations and experiments. Another seminal publication is *De Magnete* by William Gilbert in Britain (1600), who wrote

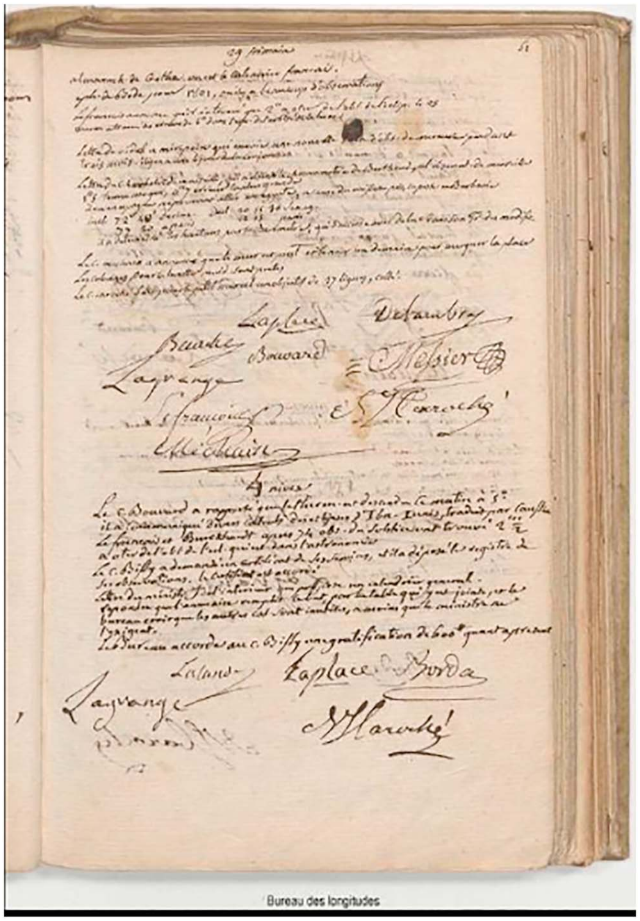

Figure 1. Minutes of the Bureau des Longitudes' meeting of 19 December 1798, where declination and inclination observations made by Humboldt in Marseilles and Paris are noted.

about "magnets, magnetic materials, and the Earth as a large magnet." At the beginning of the seventeenth century, a debate on local versus global departures of the field from that of an axial dipole pitted William Gilbert against Guillaume le Nautonier (Mandea & Mayaud, 2004). Gilbert's work terminated long-lasting discussions, and Earth's magnetism was recognized as a property of the whole globe. During this century, the number of measurements of magnetic directional elements increased.

It is unclear when knowledge about the magnetic compass reached Europe, but the usefulness of declination (the deviation of magnetic from geographic north) and its regional variability for, in particular seafaring, navigation were recognized after Christopher Columbus' voyage at the end of the fifteenth century (e.g., Kono, 2015). The British astronomer Edmund Halley charted declination in the Atlantic and published the first magnetic map in 1701. Although inclination, the deviation of magnetic field lines from the horizontal plane, was noticed by the German instrument maker Georg Hartmann and the British mariner Robert Norman in the sixteenth century, it was not measured much until the late eighteenth century.

In the following, we focus on the fundamental role for modern geomagnetism played by Alexander von Humboldt (1769–1859), whose 250th anniversary falls together with the AGU centennial. Born in Berlin, Germany, Alexander von Humboldt was a cosmopolitan, polyglot, and lived as a world citizen in London, Rome, Paris, and Vienna. Both he and his brother Wilhelm (1767–1835) were present in the circles of the greatest minds of their time, such as Goethe, Schiller, Madame de Stael, Madame Recamier, and Chateaubriand, and recognized scientists, such as Arago, Gay-Lussac, Laplace, and Lagrange (Schiavon & Rollet, 2017).

Alexander von Humboldt's scientific career began when he enrolled at the University of Goettingen in 1789. Here, under the influence of the lessons of Blumenbach and thanks to geological excursions in the Harz Mountains, the first germs of his vocation developed. In the spring of 1790, he made a study trip through Belgium, Holland, England, and France together with Georg Forster and moved to Freiberg in 1791. Appointed in 1792 to serve as an assessor in the Berlin Mines Council and appointed thereafter as director general of the mines of Franconia, he fulfilled these functions for 5 years. However, this did not prevent him to continue his scientific research and to carry out some new botanical and geological explorations in Switzerland, Tyrol, and Lombardy.

In Humboldt's mind, all these studies constituted a preparation for a more distant journey. At the end of 1796, his mother having died, he resolved his departure. He resigned his duties as director of mines (1797) and sold several of his properties, and after a few months spent in Jena and Vienna to further perfect his scientific knowledge, he went to Paris to buy the necessary instruments. In Paris, he was already in contact with members of the Bureau des Longitudes (BDL), like Laplace, Delambre, Méchain, Buache, Lagrange, Caroché, Messier, Bouvard, and Lefrançais. As it is noted in the minutes of the meeting of 19 December 1798, Humboldt shared with BDL members declination and inclination measurements made at Marseille and Paris: "Lettre du C. Humboldt de Marseille qui a observé le chronomètre de Berthoud, à l'observatoire de Marseille: 1,5" terme moyen, 0,7" erreur la plus grande. Il va en Espagne, ne pouvant aller en Egypte, à cause du vaisseau pris, la peste en Barbarie. Inclinaisons: 72° 40′ décimales; 77° 20′ à Paris. Déclinaisons : 20° 55′ 30" sexagésimales; 22° 15′ à Paris." (Figure 1; Schiavon & Rollet, 2017). (Letter from C. Humboldt from Marseille who observed, using the chronometer of Berthoud, at the Marseille observatory: 1.5" as average term, with 0.7" the largest error. He goes to Spain, unable to go to Egypt, because the vessel was affected by the plague in Barbaria. Inclinations: 72° 40′; 77° 20′ in Paris. Declinations: 20° 55′ 30"; 22° 15′ in Paris.)

Then he undertook a voyage of exploration to the Americas with the French botanist Bonpland, especially to the Amazon and Cuba, Peru and the Andes, Mexico, and finally the United States. After 5 years (1799–1804) of amassing materials of all kinds and in many fields (botany, zoology, climatology, geography, cartography, geology, etc.), they returned to Paris. Again, interesting information can be found in the old pages: "M. de Humboldt présente une partie des observations qu'il a faites pendant cinq ans en Amérique: des distances de la lune dont il désire qu'on vérifie les calculs et qu'on lui fournisse des correspondantes, des observations de satellites, des longitudes par le chronomètre, des observations barométriques pour 500 hauteurs que M. de Prony a offert de faire calculer par la formule de M. de Laplace qui a égard à la différence qu'exigent les latitudes; sous l'équateur il faut, pour diminuer d'une ligne la hauteur du baromètre, s'élever plus qu'au pôle." (BDL, 19 October 1804). This translates to "M. de Humboldt presents a part of the observations he has made during five years in America: distances from the moon which he wishes to be checked and to provide corresponding values, observations of satellites, longitudes by the chronometer, barometric observations for 500 heights which M. de Prony has offered to calculate by M. de Laplace's formula, in view of the difference required by the latitudes; under the equator it is necessary, to decrease the height of the barometer by one line, to rise more than at the poles." The results of this memorable voyage pushed the limits of geographical and physical knowledge. The preparation and supervision of numerous publications kept Alexander of Humboldt in Paris for more than 20 years, a period during which he refused all the offers made to him by the Prussian Government.

In 1826, Humboldt returned to Prussia, and a year after, he undertook a voyage of exploration to the Ural and Siberia. He lectured at the University of Berlin on famous lessons in physical cosmography a year later. In 1829, he undertook, at the Tsar's request, a new trip, this time to Russian Asia.

Humboldt can be seen as the child of two cultures, German and French. He is also a man of three epochs: the Age of Enlightenment, Romanticism, and the epoch of a new scientific and technical nineteenth century. This explains the coexistence of seemingly contradictory features: on the one hand, his involvement to use the most sophisticated instruments at his time and, on the other hand, his emotion in front of a landscape.

Alexander von Humboldt was fascinated by the discovery of the world, human societies, fauna, and flora of Latin America, Central Asia, and the Sino-Siberian borders. To discover the interaction of human phenomena with geological, biological, and physical phenomena, to relate local facts to general laws, was his ambition. He was a polymath embracing many disciplinary fields. His aim was to understand "was die Welt im Innersten zusammenhält, wie Alles sich zum Ganzen webt, Eins in dem Andern wirkt und lebt." (Bruhns, 1872)—roughly translated "what keeps the innermost of the world together, how all is woven together, one acts and lives in another." Father of modern geography, he laid the foundations of geophysics and seismology, was interested in the effects of electricity, found many botanical species, and listed all the knowledge of the time on terrestrial and celestial phenomena in his seminal and extensive *Kosmos* publication (von Humboldt, 1845).

Humboldt was the first to understand that the climate was the product of a complex game of interactions between the atmosphere, oceans and landmasses, winds, currents, landforms, and the density of terrestrial plant cover. Humboldt also introduced scientific vocabulary, new concepts, and words, such as the isothermal line or magnetic storms ("magnetischen Stürme"). In Berlin, he founded a national association of naturalists and physicists that has served as a model for many similar organizations in Europe and America. He is finally the spiritual father of the first great universal museum in Europe, the Neues Museum in Berlin (Egyptian collections, prehistoric, ethnographic, and antiquities mixed all together in a great place of integration of arts as a common expression of peoples).

Here we outline Humboldt's contributions to geomagnetism (section 2), give a general overview over the present knowledge in the field and its societal relevance (section 3), and the remaining grand challenges (section 4), linking all to Humboldt's views and legacy. We end with a concluding summary in section 5.

2. Humboldt's Contributions to Geomagnetism

Geomagnetism became an established field of natural sciences in the nineteenth century, largely due to the influence of Alexander von Humboldt and his contemporary, the great mathematician Carl Friedrich Gauss (1777–1855). While historical geomagnetic field observations that have been carried out since the sixteenth century were motivated by navigational needs (Jonkers, 2003), Humboldt's interest in the Earth's magnetism resulted from his overarching, cosmic scientific interest to understand all the natural forces working together in and around the Earth (Federhofer, 2014). Indeed, geomagnetism nowadays is one of the few sources

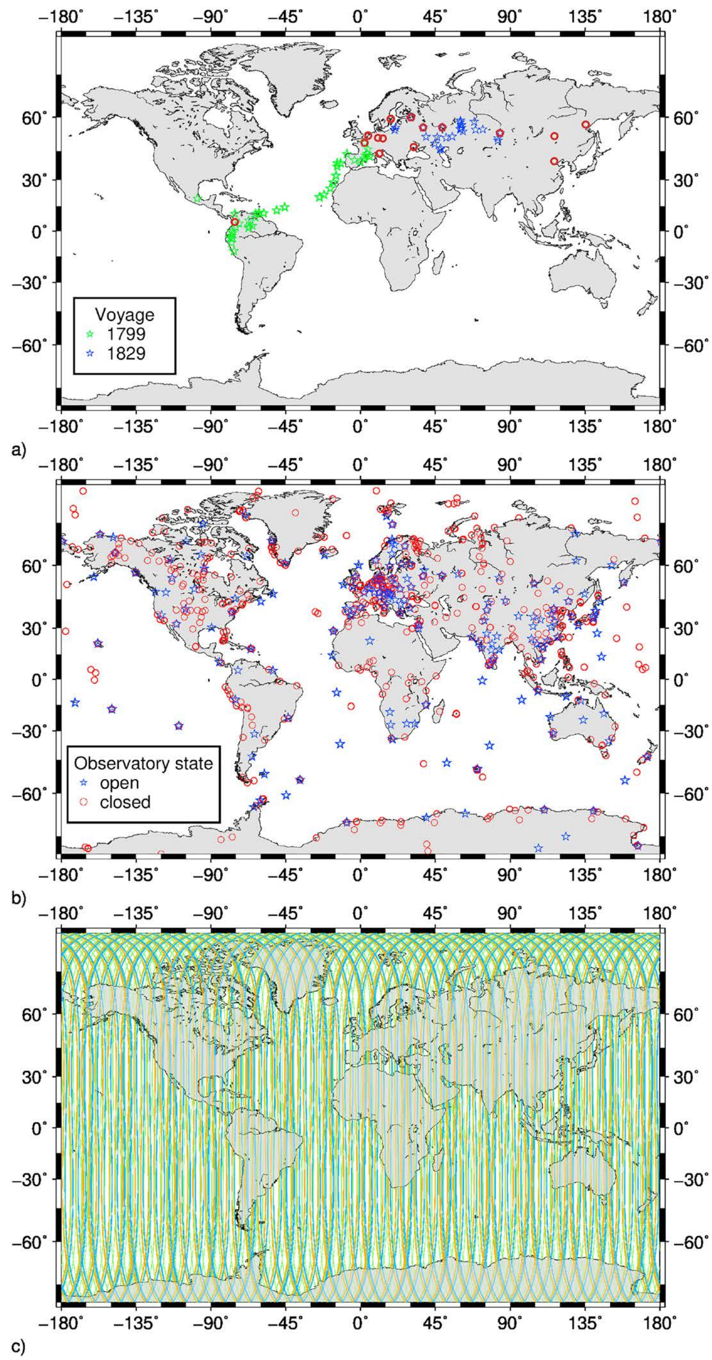

Figure 2. (a) Locations where Alexander von Humboldt carried out magnetic field observations during his journeys to South and Central America in 1799 (green stars) and Russia in 1829 (blue stars) and from where contributions to his magnetic association (1829–1834) of coordinated magnetic field measurements are known (brown circles). (b) Locations of all past (red) and present (blue) geomagnetic observatories that are known within the International Association of Geomagnetism and Aeronomy today. (c) Data coverage obtained from the three *Swarm* satellites (orange = Swarm A; green = Swarm B, blue = Swarm C) after 1 week (June 2016).

of information to learn about the Earth's deep interior, inaccessible to direct observation. Seismology and ultrahigh temperature/pressure experiments are the only other methods that allow empirical inferences about the Earth's deep mantle and core.

2.1. Magnetic Field Observations in Different Parts of the World

Alexander von Humboldt's first introduction to the Earth's magnetic field and its observation probably happened during his studies at the Bergakademie (mining academy) in Freiberg, Germany, in 1791. However, the scientific center at the time was Paris. When Humboldt had moved there in 1798, he joined a group of scientists and was interested in measuring magnetic declination with highly sensitive compasses (Reich, 2011). In the same year, he carried out first inclination measurements with Jean Charles de Borda, who had developed an inclinometer that Humboldt later could take on his voyage to South and Central America (Reich, 2011). He also learned to use a magnetometer that measured the relative magnetic field intensity by oscillation frequency of a magnetic needle. Based on observations in Paris, Marseilles, Nîmes, Madrid, and Valencia, he speculated about a decrease of the magnetic force from north to south (Reich, 2011).

Investigating the distribution of magnetic intensity in varying distances from the magnetic equator, based on a larger number of observations, became one of the goals of Humboldt's first important voyage. He thus was the first to carry out systematic observations of magnetic relative intensity distribution in a classical case of testing a scientific hypothesis by observations with the aim of finding a natural principle (Reich, 2011; Federhofer, 2014). The locations of Humboldt's published measurements are shown in Figure 2. Initially, he found that the magnetic force decreases on mountains and that the magnetic inclination increases with distance from the magnetic equator. Back in Paris, he worked with the mathematician Jean-Baptiste Biot who determined the geomagnetic equator theoretically, and they found a good agreement to Humboldt's observations. With the knowledge of the geomagnetic equator, Humboldt concluded that the magnetic intensity increases from the equator to the poles (Reich, 2011). Humboldt himself considered this last conclusion as the most important result from his voyage to South and Central America (Federhofer, 2014). For a long time, the field intensity measured at the magnetic equator in northern Peru by Humboldt was the reference value for all intensity observations (Honigmann, 1984).

Humboldt soon aimed to supplement his American results with observations from other parts of the world. The main purpose of a journey to Italy together with Joseph Louis Gay-Lussac was to confirm the influence of mountains on the geomagnetic field, but they found only a hardly noticeable influence of the Alps. In 1812, Humboldt proposed a suite of magnetic field measurements toward a considerably improved understanding of geomagnetism as one of the goals of a planned expedition to Siberia, India, and Tibet. However, due to the political situation in Europe, this journey could never be realized.

Observing the temporal changes of the geomagnetic field also was of interest to Humboldt. In May 1806, he initiated magnetic declination observations in a summer house in a large garden in Berlin to study the diurnal magnetic field variations (Kellner, 1959). Together with other scientists, he carried out about 6,000 declination measurements over 2 years (Reich et al., 2016).

In 1809, Humboldt met François Arago in Paris, who also had become interested in Earth's magnetism. Together, they worked at the Observatoire de Paris. They carried out further observations of the daily field variations. In 1823, a special small building was constructed for regular magnetic observations (Reich, 2011). It was built from wood, around a stable stone pillar for the observations, and without any use of iron in order to be nonmagnetic. Together with the magnetic observatory at Greenwich (established in 1817), this can be seen as the prototype of modern geomagnetic observatories. When Humboldt returned to Berlin in 1827, he built a comparable magnetic observatory building in the garden of Abraham Mendelssohn Bartholdy, the father of the famous composer, and started regular magnetic field observations there. Later on, he took care to include a magnetic observatory when the astronomical observatory was moved to a new location in 1835. Mandea, Korte, et al. (2010) show by comparison to values obtained from different models that the observations made by von Humboldt and his successors there are of great accuracy.

In 1829, Humboldt finally got the opportunity for another expedition that took him to Siberia and Central Asia. He published the results of 26 widely distributed magnetic field observations afterward (Figure 2), but the main relevance of that journey lies in the initiation of coordinated measurements in different parts of the world (see section 2.3).

2.2. Special Observations

Above we have noted the strong influence of Alexander von Humboldt toward continuously monitoring and understanding the geomagnetic main field. However, through his manifold interests and quest for natural connections, Humboldt contributed to further aspects of geomagnetism. His earliest publication regarding the Earth's magnetism was a short note on the finding that a serpentine rock outcrop in the Fichtel mountains (Germany) had a strong influence on his compass needle (Reich, 2011). Humboldt probably was the first to find that some rocks carry a permanent magnetization. Remarkably, he guessed that a lightning strike caused this magnetization, even before the connections between magnetism and electricity were known (Turner, 2011). Permanent magnetization of rocks, though not from lightning strike but from the geomagnetic core field itself, is the basis for the field of paleomagnetism. Although the discovery that lava flows can be permanently magnetized by the geomagnetic field is ascribed to Achille Delesse, a mineralogist from Besançon (France), in 1849, it took until the early twentieth century before rocks and archeological artifacts that preserved information about the Earth's magnetic field were systematically analyzed, and paleomagnetism became important for the Earth's magnetic field studies, with a wide range of applications (Turner, 2011).

By chance, Humboldt documented strong magnetic field variations during an aurora that was visible in Berlin in December 1806. Humboldt and his assistant Jabbo Oltmanns were recording magnetic field variations for 7 days by observing the magnetic needle once or twice per hour within the framework of observations performed in 1806 and 1807, when the aurora occurred. A connection between aurora and geomagnetic field variations had been found by Olof Peter Hjorter and Anders Celsius in Uppsala, Sweden, in 1741. The connection was already widely accepted at the time, although the linking mechanism of solar wind influence was only found in the early twentieth century by Kristian Birkeland (Federhofer, 2014). Humboldt noted that the magnetic field intensity decreased during the aurora, and he published a detailed documentation of his measurements. Although he did not contribute significantly to the understanding of the phenomenon, he coined a term that is still used today: the magnetic storm. Figure 3 is an example for magnetic storms recorded at different times since Humboldt's observations in the Berlin region. Thanks to Humboldt's efforts of coordinated magnetic field observations around the world (section 2.3), the global simultaneity of these events was proven in September 1841. The strong field variations were observed with 2.5-min sampling according to Humboldt's guidelines at Toronto, the Cape of Good Hope, Prague, and Tasmania (Kellner, 1959).

Moreover, although Humboldt obviously did not know about what is now called space weather, he extensively discussed the knowledge at the time about several corresponding phenomena, such as the Sun and sunspots, geomagnetism, and aurorae, in his famous, comprehensive work *Kosmos* (Schlegel, 2006). Humboldt provided a detailed historical account of the discovery of sunspots by Johann Fabricius, Galileo Galilei, and Christoph Scheiner. He describes that the sunspots recurred within only a limited belt of solar latitudes and are attributed to solar rotation. Humboldt noted an averaged recurrence of 25.5 days, but he also mentioned that sunspots exhibit a motion of their own. Even if it is not mentioned in *Kosmos*, Humboldt was aware of the work by Samuel Schwabe and his discovery of the 10-year solar cycle (private communication exists between the two savants; see Schlegel, 2006). Humboldt also noted in *Kosmos* observations with respect to auroras. He described these events, indicating that the sky becomes a “flickering sea of flames,” before it breaks up into “luminous immovable patches.” The most interesting scientific remark appears to be the link between the frequency of aurora occurrence and magnetic latitude.

Finally, in 1828, Humboldt arranged for frequent magnetic field observations to be carried out in an underground mine in Freiberg. He wanted to find out if the daily variations below ground were the same as above and whether the Sun has an influence on observations (Honigmann, 1984).

2.3. Scientific Collaboration and Networking

Apart from his direct scientific achievements, Alexander von Humboldt demonstrates the values of collaboration and networking. The worldwide international collaboration in the field of geomagnetism, still highly relevant today, was strongly stimulated by Humboldt (Kellner, 1959; Malin & Barraclough, 1991).

Around the time when Humboldt and Arago built their first geomagnetic observatory in Paris, they were visited by two Russian scientists from the University at Kazan. Adolph Theodore Kupffer and Ivan Michajlovi Simonov were highly interested in the Earth's magnetic field. Upon their return to Kazan, they built an

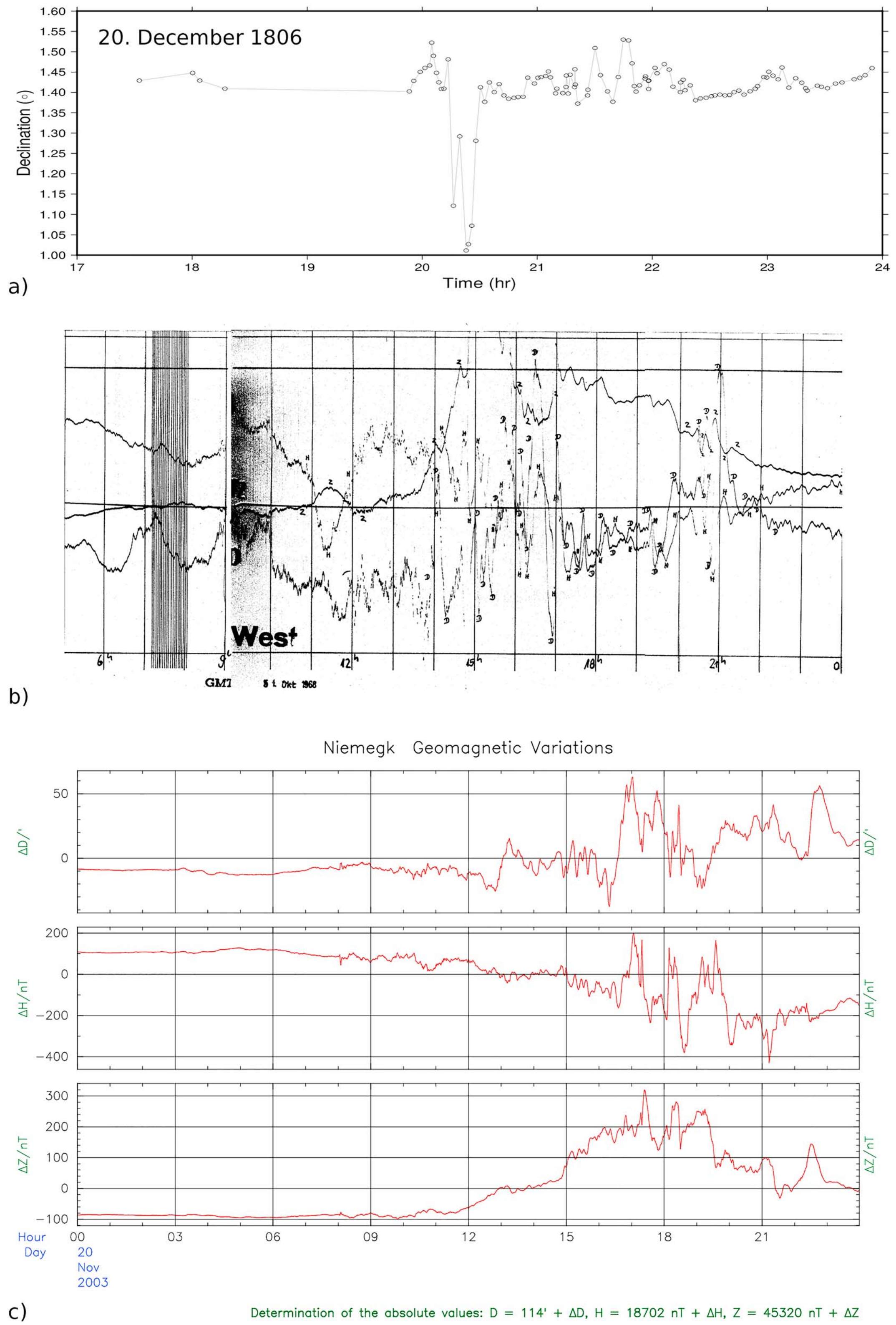

Figure 3. (a) Plot of Humboldt's published declination observations (circles) during an aurora in December 1806 in Berlin. (b) Scan of the photographic recording of a magnetic storm in October 1968 at the Niemegk geomagnetic observatory (~70 km southwest of Berlin). The variations of the three components declination (D), horizontal (H), and vertical (Z) intensity are recorded together and mix up during the strong storm variations. (c) Plot of the modern digital recording of a strong magnetic storm in November 2003 for the variations of the three components D, H, and Z.

observation pavilion and started observations in September 1825 with a comparable instruments as the ones used in Paris (Reich et al., 2016).

Humboldt had realized that simultaneous observations at widely distributed stations were necessary to understand the sources of daily and irregular magnetic field variations. In early 1829, regular declination observations in Berlin were synchronized with those in Paris and Freiberg (Kellner, 1959). Humboldt also wrote to Boussingault, a French traveler staying in South America, and thus obtained synchronized observations from Marmato (Colombia; Honigmann, 1984). In the same year, during his journey to Russia, he stimulated Kupffer, who had moved to St. Petersburg, to participate in the synchronized observations of his magnetic association (Honigmann, 1984).

Indeed, it was Humboldt's Russian journey that led to the first globally coordinated network of geomagnetic observatories. Due to its vast extent and strong differences of declination over its territory, Russia was ideally suited for geomagnetic research (Honigmann, 1984). This had already been considered more than a century before Humboldt's time, by Gottfried Wilhelm Leibniz, who aimed to show that there was only one line of zero declination and no more than two magnetic poles. In 1712 and again shortly before his death, Leibniz had written to the Tzar and suggested the establishment of locations for magnetic declination observations in several places across the country (Honigmann, 1984; Roussanova, 2011). Humboldt was aware of these suggestions that had never been realized but probably paved the ground for Humboldt's success: He used an invitation to the Russian Academy of Sciences to suggest the organization of coordinated magnetic declination, inclination, and intensity observations throughout the Russian empire, with standardized instruments (Honigmann, 1984). In addition to geomagnetic observatories in Kazan and St. Petersburg, only a year after this suggestion, observers had been trained and equipped with instruments in Moscow, Nikolayev, and Sitka (Alaska), Branaul and Nerchinsk (Siberia), and even Beijing (China; Kellner, 1959). Although the centralized collection of the observations in Berlin intended by Humboldt was not fully successful and Humboldt's association had declined by 1834, a few published synchronized observations from additional locations demonstrate Humboldt's vision of a global geomagnetic network. Alexander von Humboldt laid the foundation for international geomagnetic collaboration that is still alive and fruitful today.

Moreover, when talking about Alexander von Humboldt's influence on geomagnetism, one also has to mention his contemporary, Carl Friedrich Gauss. Gauss had been interested in the Earth's magnetic field since 1803. Humboldt first contacted Gauss in 1807, and a more or less frequent exchange of letters between them lasted nearly until Gauss' death in 1855 (Reich, 2011). The theoretician Gauss ideally complemented Humboldt's empirical approach. Humboldt was the first to carry out a large number of systematic relative magnetic intensity observations, and Gauss was the one to find a method to determine the absolute intensity in 1832 (Gauss, 1833). Gauss and Wilhelm Weber founded the "Göttinger Magnetischer Verein" (Göttingen magnetic association) in 1836, in the tradition of Humboldt's earlier magnetic association. Humboldt used his reputation and tried to interest the British Royal Society in the establishment of geomagnetic observatories for this new magnetic association. In a letter, he suggested magnetic stations in New Holland (now Australia), Ceylon (now Sri Lanka), Mauritius, the Cape of Good Hope (South Africa), St. Helena island, the east coast of South America, and Quebec (Canada; Kellner, 1959; Malin & Barraclough, 1991). The publication series "Resultate aus den Beobachtungen des magnetischen Vereins" (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. Last but not least, it was Gauss who developed the method that is still widely used in modeling and globally mapping the geomagnetic field: the spherical harmonic analysis (using Humboldt's observations among others; Gauss, 1839).

3. Geomagnetism Today: A Short Tour

Nowadays, many more details about the sources of the observed geomagnetic field and its variations are known, not least due to the fundamental works on electromagnetism by Andreé-Marie Ampère, Georg Simon Ohm, Michael Faraday, and James Clerk Maxwell in the nineteenth century, just to name a few. Additional applications of geomagnetic data beyond navigation and understanding the field generation mechanisms have been noticed, and new societal relevance has turned up. In this section we outline our

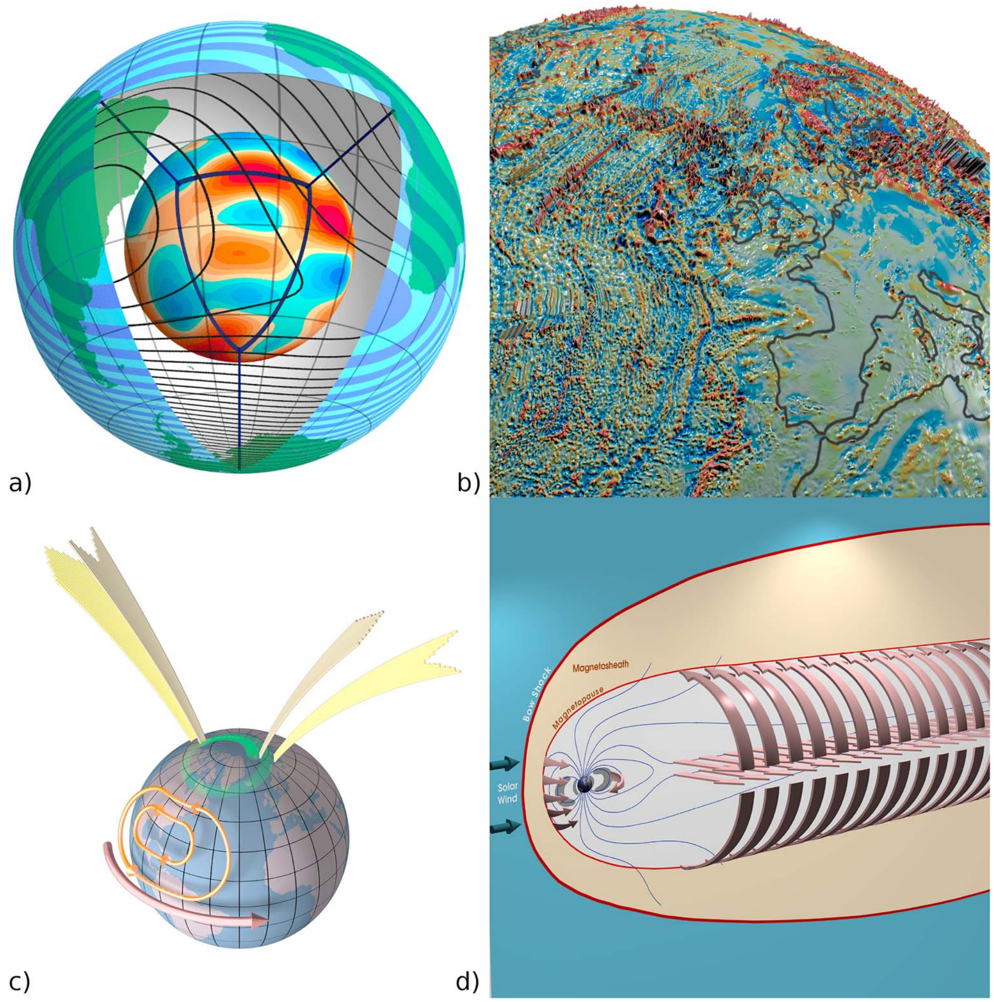

Figure 4. Sketches of various sources of the geomagnetic field. (a) Contour lines of the dominating core field intensity at Earth's surface and downward continued (radial field component) to the core-mantle boundary. The South Atlantic weak field anomaly is seen as a minimum in the intensity at the surface, caused by a large patch or reverse (blue) magnetic flux at the core-mantle boundary. (b) The lithospheric field caused by magnetized rocks and tectonic structures from the World Digital Magnetic Anomaly Map. In the Atlantic region (left side of panel), the striped normal and reverse magnetic field pattern is seen. (c) The ionospheric solar quiet (orange) and equatorial electrojet (red) currents, with field-aligned currents (yellow) linking high latitude ionospheric currents to the more distant magnetospheric current systems. (d) The magnetosphere shielding our planet against the solar wind, with Chapman-Ferraro currents on the dayside, tail current on the night side, and the ring current circling the Earth at a few Earth's radii distance (all in pink). Magnetic field lines are stylized in blue.

current understanding of the different magnetic field sources, internal and external to the Earth's surface, with their relevance and applications, and the state-of-the-art concerning geomagnetic field observation. We mainly refer to recent reviews rather than original works, in order to provide guidance for comprehensive further reading about the various aspects of geomagnetism.

3.1. Magnetic Field Sources

3.1.1. Earth's Internal Sources

Every magnetic field observation contains contribution from several different sources. The largest part, in general more than 90% of the magnetic field measured at Earth's surface, originates deep inside the Earth, generated by dynamo processes in the fluid outer core and changing slowly in time by what is known as "secular variation" (see, e.g., Jackson & Finlay, 2015). One of the methods that still used to describe the geomagnetic field variations is Gauss's spherical harmonic method to derive empirical models of the core field and its secular variation from ground and satellite observations. The distribution of the magnetic field components that was first studied systematically by Humboldt is well-known for the present and historical fields

(Figure 4a). Indeed, the maps from Humboldt's time agree well with modern findings using all available historical data (Mandea et al., 2010). Standard models such as the International Geomagnetic Reference Field (IGRF*; for items marked by *, a URL to a website with more information is listed in Appendix A) by the International Association of Geomagnetism and Aeronomy (IAGA*) (Macmillan & Finlay, 2011; Thébault et al., 2015) and its U.S.-British equivalent, the World Magnetic Model (WMM*), that mainly serve practical applications are frequently obtained in international collaborations and using freely available global geomagnetic data. Individual, specialized scientific models are developed by several groups (see Gillet et al., 2010; Hulot et al., 2015; Lesur et al., 2011). Under the assumption of an electrically insulating mantle, they can be downward continued to the core-mantle boundary and used to infer magnetic flux patterns and core dynamics (Figure 4a). Geomagnetic core field variations, including rapid so-called geomagnetic jerks (see Mandea et al., 2010), are used to study fluid motions and processes deep inside Earth's interior that are not accessible to direct observation (Aubert & Finlay, 2019). An improved understanding of the geodynamo processes that sustain our magnetic shield is obtained from discussions of kinematic concepts of magnetic frozen flux and diffusion, possible magnetohydrodynamic regimes and dynamics such as waves and oscillations in the outer core (see, e.g., Finlay et al., 2010; Jackson & Finlay, 2015). It has been shown that conservation of angular momentum links outer core dynamics to tiny changes in Earth's rotation rate (see, e.g., Holme, 2015; Mandea et al., 2010.

Since the middle of the 1990s, increasingly powerful computers enabled numerical simulation of the magnetohydrodynamic flow that generate the Earth's magnetic field. This flow is mainly driven by thermal and compositional convective circulation of the electrically conducting core fluid. Currently, several such geodynamo simulations successfully produce self-sustaining magnetic fields (see, e.g., Christensen & Wicht, 2015; Roberts, 2015). Although they operate in different regimes and it is not (yet) possible to set all fundamental control parameters to the values assumed for Earth, they show more and more characteristics similar to features found in data-based models and bring us closer to fully understanding the mechanisms generating the geomagnetic field. The past decade has seen increasing efforts to combine observations and theory in data assimilation approaches to predict the future geomagnetic core field evolution, using methodologies such as developed in meteorology for weather forecasting (see, e.g., Fournier et al., 2010; Hulot et al., 2015; Kuang & Tangborn, 2011). It is even becoming possible to simulate some of the core dynamics in large experiments that use liquid sodium as the electrically conducting material to generate magnetic fields (see, e.g., Cardin & Olson, 2015).

Understanding that igneous rocks and sediments often carry a remanent magnetization and that varying magnetic fields and electric currents induce secondary magnetic fields has found broad applications. The magnetic field signature of rocks and structures in the Earth's crust and upper mantle (the so-called lithospheric field) can be mapped (Figure 4b) and used to draw inferences about physical, chemical, or mineralogical properties of the subsurface (see, e.g., Purucker & Whaler, 2015; Thébault et al., 2010). These are interpreted, often in combination with results from other geophysical methods, in exploration and to answer geological or tectonic questions. Intense international collaboration (IAGA Working Group V-MOD*) led to the derivation of the first detailed global map of lithospheric field anomalies in 2007, the World Digital Magnetic Anomaly Map (WDMAM*; see, e.g., Purucker & Clark, 2011). An updated version has been released in 2015 (Lesur et al., 2016).

The remanent magnetization of igneous rocks, sediments, and also archeological artifacts that was acquired at the time of their formation (see section 3.2.3) is used in the field of paleomagnetism to study the Earth's magnetic field at times prior to direct observations. The amount of paleomagnetic and archeomagnetic data published over the last decades has enabled the construction of global geomagnetic field reconstructions spanning millennia (see, e.g., Constable & Korte, 2015; Donadini et al., 2010; Korte et al., 2019) and even 100 ka (Panovska et al., 2018). These models provide an increasingly good picture of the global field evolution on longer timescales with similar applications to investigate the geodynamo processes as present-day models. Moreover, they find interdisciplinary applications such as providing an estimate of geomagnetic shielding against galactic cosmic rays and solar wind. This is required, for example, in investigations of cosmogenic isotope production rates to study past solar activity or climate variations or in surface exposure studies (see, e.g., Constable & Korte, 2015). Moreover, good knowledge of paleomagnetic field variations can aid in dating sediments, volcanic rocks, or archeological artifacts for applications in, for example, climatology, volcanology, and archeology (see, e.g., Korte et al., 2019). On even longer timescales, local data records, or regional or/and global compilations, are realized. Thus, for instance, a reasonably good understanding of variations in Earth's dipole field strength over the past 2 Myr is acquired (see, e.g., Roberts et al., 2013), and some statistical properties of the time-averaged field over the past 2 to 5 Myr are determined. An interesting result is that even on very long timescales, the field does not seem to fully average to a simple dipole aligned with the Earth's rotation axis, which is an assumption known as the geocentric axial dipole hypothesis (see, e.g., Cromwell et al., 2018; Johnson & McFadden, 2015).

When Alexander von Humboldt made his magnetic field observations, he had no idea how extremely the geomagnetic field could change over geological times. From paleomagnetic records and striped patterns of normally and inverse magnetized ocean floor, we now know that the geomagnetic field has repeatedly reversed its polarity fully or partly, over millions of years. These drastic changes are known as magnetic reversals and excursions. Reversals are characterized by a full polarity change, where the field is stably dipole dominated but with opposite direction, before and after for an extended time (typically in the order of a few 100 Kyr). Excursions are defined by strong directional field variations where the poles seem to reach latitudes at least below 45° latitude and up to equatorial or fully reversed orientations but only for a short time (typically several centuries to very few millennia), before the field returns to its original polarity (see, e.g., Laj & Channell, 2015). However, the magnetic field is likely dominated by nondipole field contributions during excursions and the transitional phase of reversals (see, e.g., Amit et al., 2010). In that case, excursions might not always manifest globally at the Earth's surface. The last geomagnetic reversal occurred ∼780 ka ago, and at least seven excursions have occurred since then (Laj & Channell, 2015). The best documented is the Laschamp excursions, which happened ∼41 ka. The occurrence frequency of both reversals and excursions is highly irregular. The magnetic polarity timescale (see, e.g., Gee & Kent, 2015), that is, the record of time intervals of normal and reverse polarity with transition ages, is a powerful geochronological tool.

3.1.2. Sources External to Earth

It had already been realized in Humboldt's time that magnetic field observations were linked to effects external to the Earth, such as the diurnal variation that had to do with the time of day or the Sun's position, and the strong magnetic field variations going along with aurora occurrences in midlatitudes. Our current knowledge about a variety of electric current systems in the Earth's surroundings drastically improved over decades, with a notable progress in the era of magnetic satellite observations. The Earth is surrounded by the ionosphere, an ionized region of the upper atmosphere in a height of about 75 to 1,000 km. The electrical conductivity of the ionosphere is dependent on solar irradiation and particle precipitation. The regular daily geomagnetic variation, known as solar quiet variation, is caused by electric currents flowing on the sunlit side in the lower ionosphere and driven by an ionospheric dynamo (Figure 4c). The equatorial electrojet, a strong ionospheric current flowing eastward along the magnetic equator, may or may not be part of the solar quiet current system (see, e.g., Olsen & Stolle, 2017; Yamazaki & Maute, 2017). At high latitudes, ionospheric polar electrojets vary strongly with solar activity and field-aligned currents link near-Earth ionospheric to more distant magnetospheric current systems in the auroral regions (see, e.g., Olsen & Stolle, 2017). The frequently updated International Reference Ionosphere by the Committee on Space Research (COSPAR*) and the International Union of Radio Science (URSI*) is the standard for the parameter state of the ionosphere, derived by comprehensive international collaboration (e.g., Bilitza et al., 2017).

The magnetosphere is the whole region that is influenced by the Earth's core magnetic field (Figure 4d). Its principally dipolar shape is compressed to about 10 Earth's radii on the Sun-facing dayside under the pressure of the solar wind and stretched out to more than six times that distance on the far nightside, the so-called magnetotail. The boundary of the magnetosphere is called the magnetopause. The main magnetospheric current systems are the Chapman-Ferraro currents flowing on the dayside magnetopause, the tail current flowing north and south on the nightside magnetopause and closing in the equatorial plain in the tail, and the ring current flowing in a distance of a few Earth's radii in the equatorial plain (see, e.g., Ganushkina et al., 2018). Field-aligned currents link to the high latitude ionosphere both from the ring current and the magnetopause. The series of empirical Tsyganenko (2013) models describes various aspects of the distant Earth's magnetic field, that is, the magnetosphere and its dynamics.

All the ionospheric and magnetospheric current systems are highly dynamic and influenced strongly by solar wind variations (see, e.g., Ganushkina et al., 2018). Their investigation through their geomagnetic signatures in ground and space observations plays an important role in space weather research, the study of solar-terrestrial relations with their impacts on technology and human habitat (see, e.g., Koskinen et al., 2017).

3.2. Geomagnetic Field Observation and Data

3.2.1. Magnetic Ground and Near-Surface Observations

The need to measure and map the geomagnetic field globally is not only relevant for scientific purposes. The possibility to navigate by magnetic compass is still an important safety backup in air and sea travel, considering that satellite navigation (GPS*, GALILEO*, GLONASS*, BeiDou*, and QZSS*) might fail. Electronic maps as implemented in smartphones use the magnetic field and require declination information to point the user to geographic north. Modern directional drilling methods for oil and gas resources also depend on accurate declination information. Detailed knowledge of declination everywhere on Earth therefore remains essential and can only be achieved by a good global observational data coverage. Moreover, magnetic measurements have kept their relevance for empirical modeling and the investigation of the different field sources and for validation of numerical simulations and theories.

A global network of geomagnetic observatories in the tradition of Humboldt's one has been developed (Matzka et al., 2010; Rasson et al., 2011; Turner et al., 2015). Over 800 geomagnetic observatories have been operational since Humboldt's time, though some only for a short time. Currently, 177 observatories are reported as operational (Figure 2b). Humboldt's ideas for standardized global data, obtained with instruments adhering to the same quality standards and freely made available by publication, are still highly relevant. Therefore, the observatories now are coordinated by a Working Group (V-OBS*) of IAGA. They freely exchange and distribute their data through World Data Centers of the World Data System*, such as Boulder*, Edinburgh*, Kyoto*, and Moscow*. Many geomagnetic observatories (132 in 56 countries) moreover participate in INTERMAGNET*, the *Inte*rnational *R*eal-time *Mag*netic Observatory *Net*work established in August 1987 for the faster dissemination of the digital data that started to replace previous photographic magnetic variation recordings around that time (Figures 3b and 3c). The IAGA Working Groups and INTERMAGNET provide guidelines and define quality standards for geomagnetic field recordings, and they find agreements on formats for electronic data exchange. These international collaborative efforts to make global, homogeneous geomagnetic data freely available facilitate research and the derivation of global geomagnetic field models for scientific and practical purposes tremendously.

Geomagnetic observatories have not lost their relevance in the era of magnetic satellite missions (section 3.2.2). They provide pure time series in contrast to the mixed spatiotemporal records obtained from satellites. This and the fact that ground observatories and satellites deliver data from different altitudes, that is, distance from the field sources, make them an important complement to benefit in particular in separating the magnetic signals from different contributions. Moreover, geomagnetic observatories are the only source of high-quality geomagnetic field observations if gaps occur between fully operational, dedicated magnetic satellite missions, as happened from 2010 to 2013 (see section 3.2.2), and might be the case again when the current ESA Swarm mission ends. Although frequently some observatories are threatened by closure, either due to contamination with technical noise from growing surrounding infrastructure or funding issues, the persistent need has been realized by many institutes and countries, and several new observatories became operational in the last few years (Matzka et al., 2010; Rasson et al., 2011).

The observation practice at geomagnetic observatories has changed from tedious individual measurements in Humboldt's time, over continuous photographic recording from the middle of the nineteenth century to the 1980s or 1990s, to digital recording with sampling rates of 1 s and higher (Hrvoic & Newitt, 2011; Turner et al., 2015; Figure 3). Data precision and accuracy has increased accordingly (Reda et al., 2011). Magnetic field intensity can be automatically recorded with high accuracy by modern instruments that use atomic effects and are independent of outer influences such as temperature and humidity. Nevertheless, continuous vector field recordings still have to be calibrated manually, due to the required extremely high accuracy in absolute field orientation. These so-called absolute measurements of declination and inclination are carried out by means of a nonmagnetic theodolite equipped with a magnetic field sensor, to ensure highly precise orientation control (Hrvoic & Newitt, 2011; Jankowski & Sucksdorff, 1996; Matzka et al., 2010). Common and standardized data products from geomagnetic observatories are hourly, 1-min and increasingly also 1-s values of the full magnetic field vector (Reay et al., 2011).

Detailed ground magnetic field surveys on dense grids were first used to map the magnetic signature of crustal rocks and geological structures. Aeromagnetic or marine surveys, where a magnetometer is fixed to or towed by an aircraft, helicopter, or vessel were begun in the middle of the twentieth century and are now widely used to map the lithospheric field signature for exploration purposes and the study of geological and tectonic questions on local to regional scale (see, e.g., Hamoudi et al., 2011; Turner et al., 2015). Their application, often in combination with other geophysical methods, to detect natural resources required for infrastructure and industry or to assess natural hazards such as subduction zone earthquakes or volcanic eruptions, underlines the societal relevance of lithospheric magnetic field research.

3.2.2. Magnetic Satellite Missions

The era of low-Earth orbiting satellite missions that provide full vector magnetic field observations for geomagnetic research and mapping began with the U.S. satellite *Magsat*, that was in orbit for some 7 months in 1979/1980. However, it took nearly another 20 years until the next magnetic vector field satellite missions became operational. The Danish Ørsted (launched in 1999) and the German CHAMP (2000–2010) satellites provided a global data coverage that Humboldt would never have imagined (see, e.g., Olsen et al., 2010; Olsen & Kotsiaros, 2011). 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. These two highly successful missions both exceeded their initial nominal lifetimes of 14 months and 4 years, respectively, by far. Nevertheless, a gap occurred in monitoring the full vector field from space between September 2010 and November 2013. The CHAMP mission ended in 2010, after 58,277 orbits, because a very low orbit cannot be maintained arbitrarily long due to atmospheric drag that constantly slows down the satellite. The higher-orbit Ørsted is still in space, but only field intensity and no directional data have been available since 2005. At present, the ESA magnetic field satellite mission Swarm is delivering vector data from a constellation of three identical satellites (Figure 2c). The novel constellation approach with one satellite on a higher orbit (∼520 km) and two side by side on a lower orbit (∼400 km) offers new opportunities to combine data from different altitudes and study differences between simultaneous satellite observations at different locations—one might say that Humboldt's ideas for synchronous measurements have been carried into the satellite era. These new opportunities in particular aid the persistent challenge to separate the various magnetic field sources (see, e.g., Olsen et al., 2016).

3.2.3. Paleomagnetic and Archeomagnetic Data

The processes how rocks and minerals obtained a remanent magnetization in the past are studied by the field of rock magnetism. It is now generally understood how igneous rocks, but also burnt archeological artifacts, acquired a thermoremanent magnetization when they cooled down below the Curie temperature (see, e.g., Dunlop & Özdemir, 2015). The exact process how sediments acquire a detrital remanent magnetization is less well understood so far (see, e.g., Roberts et al., 2013; Tauxe & Yamazaki, 2015). Nevertheless, drill cores from lake and ocean bottoms or exposed sediment sequences also provide a wealth of information about the geomagnetic field before the time of direct observations, the palaeomagnetic field. A suite of laboratory experiments have been developed over the past decades to retrieve direction and intensity of the paleomagnetic field from igneous rocks, sediments, and archeological artifacts (see, e.g., Tauxe & Yamazaki, 2015; Turner et al., 2015). Declination and inclination can be obtained from samples when their orientation at the time of formation or burning is known. Obtaining information about past field strength is more challenging, and only igneous rocks and archeological artifacts can provide absolute paleointensity values from demagnetisation experiments. Sediments only act as recorders of relative intensity variations (see, e.g., Tauxe & Yamazaki, 2015). Paleomagnetic data do not only serve to investigate geomagentic field evolution and generation mechanism on longer timescales than direct observations, but they also provide valuable information to study the Earth's thermal and geological history, in particular including the reconstruction of the movement of the tectonic plates and continents. Humboldt would have been delighted to see that, just as his field observations, paleomagnetic data have been globally compiled and made available to the scientific community since the 1990s. First database efforts have been merged into currently maintained versions, which include a wealth of relevant metadata. They are

- the comprehensive Magnetics Information Consortium (MagIC*) archive and database, which accommodates all kinds of paleomagnetic and rock magnetic results down to experimental level and on all age scales (Tauxe et al., 2016);
- the PINT* paleointensity database, which aims at compiling all published palaeointensity data >50 ka (Biggin et al., 2009);
- the PALEOMAGIA* database of Precambrian paleomagnetic data (Veikkolainen et al., 2017);

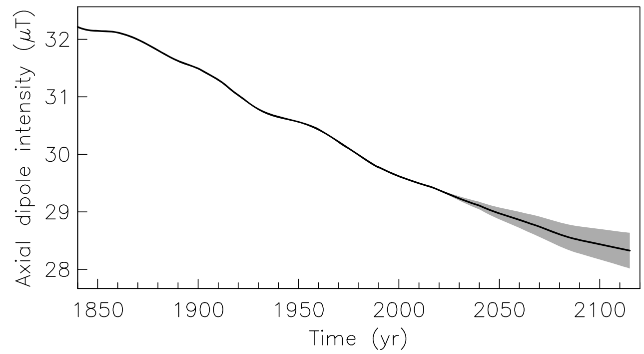

Figure 5. Axial dipole intensity decay determined by global models from the first absolute intensity determinations with Gauss' method in 1840 to modern satellite data, with 100-year forecast (2015–2115) using data assimilation (Aubert, 2015).

- the latest version of the GEOMAGIA50* database includes archeomagnetic, volcanic, and sediment data of the past 50 Kyr (Brown, Donadini, Korte, et al., 2015; Brown, Donadini, Frank, et al., 2015); and
- the HISTMAG* database, which combines archeomagnetic and volcanic data with historical observations from the past 500 years (Arneitz et al., 2017).

4. Geomagnetism Tomorrow: New Challenges

Despite the significant progress in our understanding of all aspects of the geomagnetic field since Humboldt's time, several open questions and challenges remain. An overarching challenge regarding the full understanding of all geomagnetic field contributions remains the source separation in observational data, as each magnetic field measurement is the sum of various signals from all field contributions.

4.1. Full Understanding and Forecasting of the Geomagnetic Core Field

The geomagnetic core field is the planetary protective shield against solar wind and cosmic radiation. However, we still lack a full understanding of the geodynamo processes that maintain the field. Together with its chaotic nature, this hampers our ability to forecast the future field evolution. On the empirical side, a more complete understanding is needed of the full global characteristics of long-term (>100 ka) geomagnetic field changes, including in particular the extreme variations during excursions and reversals (Brown et al., 2018; Laj & Channell, 2015; Roberts, 2008). At the other end of the spectrum, the dynamical sources of the fastest secular variations (such as geomagnetic jerks and rapid fluctuations), the role of diffusion or influences from the weakly conducting mantle remain to be fully understood (Holme, 2015; Jackson & Finlay, 2015). Archeomagnetic results indicating very rapid field intensity variations of high amplitude have raised the question if the geomagnetic field can vary significantly faster than seen in the present and historical field and in a way incompatible with our present understanding of the dynamic core processes (Livermore et al., 2014; Shaar et al., 2011). A better theoretical understanding of the force balances in the geodynamo and validation of Earth's parameter scaling laws is required to understand if numerical simulations correctly represent the processes deep inside the Earth (Christensen & Wicht, 2015; Wicht & Sanchez, 2019). As computing power keeps increasing, dynamo simulations can be driven to more extreme parameter regimes. The influences of boundary conditions (e.g., heat flow) and coupling between outer core and inner core and lower mantle, respectively, on the geodynamo processes have yet to be fully understood. The controversial discussions whether stably stratified layers exist at the top and/or bottom of the outer core (Christensen & Wicht, 2015) need also to find an answer.

Assimilating data into numerical simulations is required to combine observations with the physics of a process to obtain meaningful forecasts. What has been used over several decades in meteorology for weather forecast is still in its early stages in geomagnetism and can be expected to bring a significant advance to geomagnetic field forecasting in the future (Hulot et al., 2015; Wicht & Sanchez, 2019). This year, one of the main geomagnetic field reference models, the WMM, had to be updated ahead of schedule. The rapid declination change in high northern latitudes together with the recent acceleration of the northern magnetic pole was not described sufficiently well by a simple extrapolation (Chulliat et al., 2018; Witze, 2019). Further scientific and societal relevant questions aimed to be answered by forecasting the chaotic secular variation in the dynamic outer core are the following: How much longer will the presently observed decay of the dominating dipole field contribution continue (Figure 5)? Will the decrease eventually directly lead to an excursion or reversal of the field and can we define a trigger for such dramatic field changes? Even if the dipole field will recover, how weak will the minimum regional field intensity get, for example, in the area of the South Atlantic Anomaly? The latter question is of high relevance to assess space weather hazards on our modern technology and habitat.

4.2. Lithospheric Field

The lithospheric geomagnetic field holds a wealth of information that can be used for applications such as exploration or complementing other geophysical methods in natural hazard assessment. Two main challenges regarding the lithospheric magnetic field remain. The first is to resolve several interpretational ambiguities by improved mathematical methods. This includes in particular the separation of remanent and induced magnetizations (Purucker & Whaler, 2015). The second challenge is to close the spectral gap in cross-regional lithospheric anomaly maps (Thébault & Vervelidou, 2015). When such maps are obtained from magnetic satellite data in combination with several individual regional aeromagnetic or marine surveys, any anomalies with length scales between approximately 200 and 450 km are in general not well represented. Due to the observation altitudes above ground, the necessary information to solve these correctly is neither contained in the long-wavelength satellite data nor in the short-wavelength aeromagnetic data. Less ambiguous interpretations and improved mapping of medium-scale lithospheric magnetic anomalies will increase the efficiency and accuracy of results, needed for applications such as exploration and contributions to seismic or volcanic hazard assessment.

4.3. Ionospheric and Magnetospheric Magnetic Fields

The geomagnetic field plays a crucial role for space weather inside the magnetosphere, that is, the conditions in the near-Earth's space determined by solar-terrestrial interactions (Koskinen et al., 2017; Mandea & Purucker, 2018). Harmful consequences for important technologies can occur when solar storms hit the Earth under conditions that enable large amounts of highly energetic particles to enter into the magnetosphere and lead to strong geomagnetic storms. Many details of the ionospheric and magnetospheric electrical current systems that govern the highly variable space weather conditions remain incompletely understood (Ganushkina et al., 2018). Several indices obtained from geomagnetic observatory data (see IAGA Working Group V-DAT* and the International Service of Geomagnetic Indices, ISGI*) provide estimates of individual aspects of ionospheric and magnetospheric geomagnetic activity and underlying electrical current systems (Menvielle et al., 2011). However, the traditional indices do not optimally describe the phenomena that they were originally developed for (Lühr et al., 2017). Improved indices that characterize the various electrical current systems are being developed and remain one of the challenges in the geomagnetic aspects of space weather research. Producing relevant indices from real-time data and forecasting these indices, for example, using data assimilation techniques, is required in the context of forecasting and implementing early warning systems for geomagnetic storms. Just as in meteorology, short-term weather variations are linked to long-term climate changes, it is also relevant to understand space climate changes resulting from long-term solar variability trends but also geomagnetic core field changes (Mandea & Purucker, 2018). Influences of a weaker (or stronger) geomagnetic core field and of changes to the magnetosphere caused by geomagnetic excursions and reversals need to be understood to assess potential future space weather hazard changes (Vogt et al., 2007; Zossi et al., 2019).

4.4. Observational Challenges

Many aspects of addressing the above-listed challenges depend on high-quality geomagnetic field observations and paleomagnetic data. Producing these data with the best possible global coverage contains challenges of its own. The current ESA Swarm constellation mission will hopefully collect data for at least one solar cycle, that is, around 2024. However, satellite missions are finite. A crucial need for new dedicated low-Earth orbiting magnetic field satellite missions exists. They can be imagined as a constellation of nanosatellites to continously monitor the field with a global coverage required for a clear separation of contributions from different sources, for, for example, studies of the rapid core field variations, highly accurate lithospheric field mapping, and the investigation of space weather processes. The global network of geomagnetic observatories still plays an important role in geomagnetism research and certainly not only when low-Earth orbiting satellite observations are lacking. The very uneven global distribution of geomagnetic observatories poses a challenge for several applications. Improving the observatory data coverage over oceans and remote regions requires progress toward fully automated (Korte et al., 2013; Rasson et al., 2011) and sea-floor observatories (Rasson et al., 2011). Moreover, recent efforts toward near real-time definitive data (Clarke et al., 2013; Mandic & Korte, 2017; Peltier & Chulliat, 2010) and high cadence (1 s) data (Brunke et al., 2017; Reay et al., 2011

To understand the long-term past geomagnetic field evolution, with relevance to predicting long-term future changes, several challenges for paleomagnetic data have to be overcome. The most basic is the need for more archeomagnetic and paleomagnetic data to provide the global and temporal coverage required to obtain the full global picture of the geomagnetic field over its long geological history. Moreover, an improved understanding of the mechanism of magnetization acquirement in sediments and more reliable methods to distinguish between the desired paleointensity signal and environmental influences in measurements of sediment magnetization (Tauxe & Yamazaki, 2015) are important to better constrain our knowledge about magnetic dipole moment variations. An additional challenge regarding paleomagnetic and archeomagnetic data is the exact, independent dating by radiometric or other methods (e.g., Korte et al., 2019).

5. Summary

On the occasion of the centennial of the American Geophysical Union and the 250th anniversary of Alexander von Humboldt, one of the great polymaths of the nineteenth century, we reviewed the scientific study of the Earth's magnetic field from its early times to current challenges. Alexander von Humboldt played a significant role in a period that represents the roots of modern geomagnetism, the study of all aspects of our planet's magnetic field. Humboldt observed and described several individual phenomena in his geomagnetic field observations, from magnetized rocks to fast magnetic variations related to the Sun and the occurrence of aurora. One of his main achievements was to show that the magnetic field intensity increases from the equator to the poles. His empirical approach was fruitfully complemented by his contemporary Carl Friedrich Gauss, who developed methods to determine the field intensity in absolute units and model the global field based on observation data. Humboldt's lasting legacy has been the organization of a worldwide scientific cooperation in the gathering of geophysical, in particular geomagnetic data.

The Earth's magnetic field has long played an important role for navigation by means of the magnetic compass. However, as our knowledge in geomagnetism has grown over the centuries and technology developed, several additional applications and a wider relevance have turned up. In particular, this includes the magnetic field's shielding of our habitat against potentially harmful space weather conditions. Contributions to the observed magnetic field come from magnetohydrodynamic processes in Earth's outer, fluid core, magnetized rocks in Earth's crust and uppermost mantle and from electrical current systems at several distances within the ionosphere and magnetosphere around Earth. Consequently, modern geomagnetic field research has many aspects with regard to process understanding and societal relevance.

Detailed, continuous mapping of the core field and its change, the secular variation, remain a requirement for navigational purposes. Moreover, global empirical field models and numerical simulations based on physical theory are both important ingredients to study the dynamic processes in the Earth's core and validate theories about the mechanisms and influences from the Earth's mantle or inner core on the geodynamo process generating the field. The direct field observations since Humboldt's time are only a small part of the full spectrum of core field variations. Over geological times, these include lasting magnetic field polarity reversals and brief episodes of extreme field deviations from its normal dipole dominance, so-called excursions. A full global understanding of the whole spectrum of magnetic field dynamics and the ability to forecast future core field changes remain important challenges with regard to the magnetic shield. They are tackled by ongoing paleomagnetic data production from rocks and sediments and promising first efforts to combine observations and theory by data assimilation, respectively. Continued, dense global monitoring of the geomagnetic field from ground observatories and satellite missions remains an important ingredient to exact magnetic source separation and short-term to midterm forecasts. At the same time, free data exchange and international collaboration in the Humboldt's spirit are prerequisites to understand a global phenomenon such as the Earth's magnetic field.

Regarding the crustal geomagnetic field, challenges consist in deriving less ambiguous interpretation methods to further improve the utility of magnetic anomaly mapping for exploration or answering geological and tectonic questions, which may, for example, be related to the assessment of seismic or volcanic hazards. Further study of ionospheric and magnetospheric current systems based on both low-Earth orbiting and more distant satellite missions combined with advanced analyses and data assimilation techniques is highly relevant for future space weather predictions to mitigate adverse effects from strong solar activity.

To conclude, let us note that throughout his life, Alexander von Humboldt has emphasized the virtues of factual research and highlighted the advantages derived from meticulous scientific work. At the age of 26, on 24 January 1796, he wrote to Genevan naturalist Marc-Auguste Pictet: “Les théories, enfants de l'opinion, sont variables comme elle. Ce sont les météores du monde moral, rarement bienfaisants, et plus souvent nuisibles aux progrès intellectuels de l'humanité.” (Leitner & Knobloch, 2009), stating that theories are as variable as opinions and that they are often hindering intellectual progress if they are not properly validated. There are many occurrences of this creed in all of Alexander von Humboldt's writings over the years. At the end of his life, nearly 60 years after the letter, we have just quoted, when it comes to highlighting his principal works, Humboldt writes to his publisher Georg von Cotta: “Der wichtigsten und eigentümlichsten Arbeiten von mir gibt es nur drei: die Geographie der Pflanzen und das damit verbundene Naturgemälde der Tropenwelt; die Theorie der isothermen Linien und die Beobachtungen über den Geomagnetismus, welche die über den ganzen Planeten auf meine Veranlassung verbreiteten magnetischen Stationen zur Folge gehabt haben.” (Leitner & Knobloch, 2009), stating that his three main achievements are the geography of plants, the theory of isothermal lines, and his geomagnetic observations that lead to the global distribution of magnetic observatories on his initiative. Alexander von Humboldt indicated himself, with elegance, how important measuring and understanding the geomagnetic field is. His work also continuously reminds us that as we are making progress in understanding more and more details, we also have to come back to a holistic view and understand systemic, interdisciplinary links between individual aspects of natural phenomena.

Appendix A: Electronic Resources and References

This appendix contains the URLs of websites where more information about several entities briefly mentioned in the text can be found, sorted here in alphabetical order within three categories.

1. Scientific associations, commissions, and data repositories

- Committee on Space Research, COSPAR (http://www.isprs.org/society/cospar.aspx)
- GEOMAGIA50 database (http://geomagia.gfz-potsdam.de/index.php)
- HISTMAG database (http://www.conrad-observatory.at/zamg/index.php/data-en/histmag-database)
- INTERMAGNET (http://www.intermagnet.org)
- International Association of Geomagnetism and Aeronomy, IAGA (http://www.iaga-aiga.org)
- IAGA Working Group V-DAT (https://www.ngdc.noaa.gov/IAGA/vdat/)
- IAGA Working Group V-MOD (https://www.ngdc.noaa.gov/IAGA/vmod/index.html)
- IAGA Working Group V-OBS (https://www.bgs.ac.uk/iaga/vobs/home.html)
- International Service of Geomagnetic Indices, ISGI (http://isgi.unistra.fr/)
- International Union of Radio Science, URSI (http://www.ursi.org/homepage.php)
- MagIC database (https://www.earthref.org/MagIC)
- PALEOMAGIA database (https://h175.it.helsinki.fi/database/)
- PINT database (http://earth.liv.ac.uk/pint/)
- World Data System, WDS (https://www.icsu-wds.org/)
- WDC Boulder (https://www.ukssdc.ac.uk/wdcc1/wdca/wdc/usa/solar.html)
- WDC Edinburgh (http://www.wdc.bgs.ac.uk/)
- WDC Kyoto (http://wdc.kugi.kyoto-u.ac.jp/)
- WDC Moscow (http://www.wdcb.ru/stp/index.en.html)

1. Geomagnetic field models

- International Geomagnetic Refernce Field, IGRF (https://www.ngdc.noaa.gov/IAGA/vmod/igrf.html)
- World Digital Magnetic Anomaly Map, WDMAM (http://www.wdmam.org/)
- World Magnetic Model, WMM (https://www.ngdc.noaa.gov/geomag/WMM/; http://www.geomag.bgs.ac.uk/research/modelling/WorldMagneticModel.html)

1. Satellite navigation systems

- BeiDou (http://en.beidou.gov.cn/)
- GALILEO (https://www.esa.int/Our_Activities/Navigation/Galileo/What_is_Galileo)

- GLONASS (https://www.glonass-iac.ru/en/)
- GPS (https://www.gps.gov/)
- QZSS (http://qzss.go.jp/en/)

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