Geomagnetism, Aeronomy and Space Weather

On the centenary of the International Union of Geodesy and Geophysics, this book reviews the state-of-the-art research in geomagnetism, aeronomy and space weather. Written by eminent researchers from these fields, it summarises the advances in research over the past one hundred years and looks ahead to current and emerging studies on Earth's magnetic field. It provides a comprehensive overview of the generation of Earth's magnetic field, its history and its response to external forces. Starting at the centre of the Earth, the reader is taken on a journey from the interior core and mantle through the upper atmosphere and magnetosphere before reaching the Sun's atmosphere and corona. The applications of this research are also discussed, particularly the societal impact of solar activity on critical infrastructures in our increasingly technologically dependent society. This book is a valuable resource and reference for academic researchers and students in geomagnetism and aeronomy.

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The International Union of Geodesy and Geophysics (IUGG) promotes and co-ordinates international scientific studies of Earth (physical, chemical, and mathematical) and its environment in space, aiming to apply this knowledge to societal needs such as mineral resources, mitigation of natural hazards, and environmental preservation. The series is co-published by the IUGG and Cambridge University Press, providing researchers and graduate students with authoritative insights into major scientific developments and state-of-the-art research.

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M. Mandea, M. Korte, A. Yau, and E. Petrovský, *Geomagnetism, Aeronomy and Space Weather: A Journey from the Earth's Core to the Sun*

Geomagnetism, Aeronomy and Space Weather

A Journey from the Earth's Core to the Sun

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Preface

The geomagnetic field is generated deep inside the Earth, yet it surrounds our planet in the form of the magnetosphere reaching far into space. As such, it plays an important role in shielding the human habitat against harmful influences from the solar wind and cosmic radiation. Earth's magnetic field signatures and their changes in space and time provide important information on our planet's deep interior dynamics, lithospheric structures and tectonics and the state of Sun–Earth interactions and space weather conditions.

The Earth's core and mantle dynamics are driven by heat flow from the centre to the surface of the Earth. The outer core dynamics, which generate the magnetic field by geodynamo processes, and the coupling between the core and the mantle influence Earth's rotation rate and are linked to mantle dynamics that are responsible for tectonic processes.

The (electro)magnetic signatures of lithospheric rocks and geological formations are interpreted, often in conjunction with other geophysical observables (e.g. gravity and seismics), for the exploration of natural resources, for natural hazard assessment in seismically or volcanic active regions and for understanding geological processes such as plate tectonics or ancient meteor impact craters. The palaeomagnetic signals preserved in volcanic rocks and sediments over geological times not only provide information about past geodynamo action and magnetic field configuration but also find applications in dating and studies of past climatic changes.

Strongly increased solar activity during solar storms can adversely affect critical technological infrastructures, from power grids and rail networks to aviation, telecommunications and satellite navigation, when the prevailing interplanetary conditions lead to the development of geomagnetic storms. The sensitivity of these modern technologies to severe space weather phenomena enhances our vulnerability to their adverse impacts, as society becomes increasingly technology dependent. In order to advance our capability to forecast space weather and mitigate such impacts, an improved and deeper understanding of the geomagnetic field is essential, including its variations on all spatial and temporal scales and its connection to the dynamics of the magnetosphere and solar–terrestrial interactions.

The increased interest in studying the Earth's magnetic field is underlined by the Swarm satellite mission launched by the European Space Agency in 2013. This constellation of three low-Earth-orbiting satellites offers an unprecedented opportunity to achieve an improved separation between the internal and external magnetic field sources, a detailed mapping of the large-scale lithospheric magnetic field and multipoint monitoring of magnetic disturbances and related aeronomic processes for space weather applications.

The International Association of Geomagnetism and Aeronomy (IAGA), one of the eight associations of the International Union of Geodesy and Geophysics (IUGG), brings together scientists from all over the globe working on all aspects of the Earth's magnetic field, the magnetosphere, aeronomy and space weather. Within the Special Publication Series on the one-hundredth anniversary of the IUGG, expert authors from the IAGA community present here reviews of the state of the art and recent progress in the fields of geomagnetism, aeronomy and space weather. This book provides a comprehensive overview of the current knowledge of the Earth's magnetic field; its history, generation and present state; and the way it responds to external – in particular, solar – forces. The book also highlights applications and societal implications of these results. It is structured as follows.

In the first part, the relevance of different aspects of geomagnetic and aeronomy studies is introduced, and the role of IAGA is described. This broad introduction shows the wide range, complexity and heterogeneity of IAGA-related studies, which are not limited to the topics detailed further in this volume. It begins with some historical notes and a general overview of the objectives of geomagnetic and aeronomy studies (Chapter 1). Chapter 2 starts with brief descriptions of how Earth's internal structure can be depicted using electromagnetic induction caused by geomagnetic field variations of external origin and how rocks carrying a magnetic record may help in assessing and untangling Earth's tectonic history, in dating past events and in reconstructing the environment in different geological epochs. This is followed by overviews of applications of studies of geomagnetic field variations, from very slow to rapid and from both the internal geodynamo and the external sources in magnetosphere and ionosphere. Brief reviews of the relationship of magnetosphere and ionosphere with solar variability, which is an important component of space weather, and of hazards associated with space weather are also included in this chapter. Finally, the effects of the geomagnetic field, and in particular, of its changes, on the biosphere are introduced. In the last part of the introduction (Chapter 3), the scientific landscape before IAGA and major achievements obtained either with direct IAGA involvement or representing the most important benchmarks in geomagnetic and aeronomy studies are briefly summarised.

Information on the different sources contributing to the measurable geomagnetic field and on the methods, platforms and instruments used to observe and monitor the field is given in Part II. This part starts with an overview of the geomagnetic field sources from Earth's core to the Sun, in particular focusing on individual current systems interacting in the magnetosphere (Chapter 4). This is followed by a chapter (Chapter 5) on what paleomagnetic data obtained by laboratory experiments from ancient rocks and sediments can tell us about the operation of the outer core geodynamo throughout Earth's history. Chapter 6 describes modern geomagnetic, electromagnetic and magnetotelluric observations at the Earth's surface and gives a comprehensive overview of the available ground-based data providing information for several aspects and applications of geomagnetic field variations. It includes a special discussion on solar cycle responses in geomagnetic records. Chapter 7 discusses data from low-Earth-orbiting satellites and, in particular, their application in data-based modelling of the geomagnetic field. Part II is completed by a chapter (Chapter 8) that provides an exhaustive overview of recent space missions to investigate the solar wind and the terrestrial space environment and magnetosphere.

The different aspects of spatial and temporal geomagnetic field variations and relevant inferences for other scientific fields and society are the topics of Part III. Going from the deep Earth interior out to the magnetosphere, the part starts with an overview of observational constraints on core field variations and their interpretation in terms of outer core fluid dynamics (Chapter 9). A chapter (Chapter 10) on the lithospheric magnetic field signatures in particular focuses on the international efforts to compile the global World Digital Magnetic Anomaly Map and discusses recent advances in interpreting the structures in terms of magnetisation of the Earth's crust. Chapter 11 deals with energy coupling between different regions in the magnetosphere–ionosphere–thermosphere system. Various processes dominating in different geographical regions from equatorial to auroral zones and polar caps and models thereof are discussed, considering both magnetically quiet and solar storm conditions. The next chapter (Chapter 12) provides an overview of recent developments in energy transport from the solar wind into the Earth's magnetosphere and the role of the boundary layer. It describes how charged particles contained in the magnetospheric ring current and Van Allen radiation belts give rise to boundary regions and waves on magnetospheric scale from ultra-low-frequency up to upper-hybrid waves and continuum radiation. The plasmasphere and plasmapause as its associated boundary are also considered in this chapter. The last chapter in this part (Chapter 13) provides a broad overview of temporal geomagnetic variations ranging from reversals of the internal field to rapid variations in the magnetospheric environment.

The highly societally relevant topic of space weather is discussed in detail in Part IV, which consists of three chapters. Chapter 14 discusses the underlying physical processes of weather in the near-Earth space, in terms of the complex system of Sun–Earth interaction processes. Such processes span a wide range of temporal scales, from thousands of years for the hydrological ocean cycles driven by the total solar radiation to scales of minutes and below for particle acceleration in magnetic reconnection. This chapter briefly describes the important component processes, including solar disturbances such as solar flares and coronal mass ejection, and the connection between magnetic storms and magnetic field depressions at the magnetic equator. Chapter 15 discusses the effects of space weather in the ionosphere and thermosphere and at the Earth's surface, respectively, in the context of the three-way coupling between the magnetosphere, ionosphere and thermosphere. This chapter describes the dynamics of the ionosphere during magnetic storms and sub-storms, especially the role of Alfvén waves and field-aligned currents therein, and the resulting magnetic field perturbations. The chapter also outlines the response of the thermosphere to geomagnetic storms and sub-storms in terms of its heating, expansion and composition changes at high and middle latitudes and the surface-level response in terms of geomagnetically induced currents (GIC) and other geomagnetic and geoelectric disturbances. Chapter 16 explains the various potential impact of space weather on our increasingly technology-dependent society, including the adverse effects of GIC, the disruption of satellite communications and navigation and risks of radiation damage both in space and in aviation.

The book concludes in Part V with a brief overview of the magnetic fields of other bodies in the solar system and an outlook on future challenges in geomagnetism and aeronomy research. Firstly, Chapter 17 presents the results of recent studies on the mechanism of dynamo generation and the magnetic field evolution of planetesimals and exoplanets. The general physics of thermal and chemical dynamos are described. Important new scientific results are underlined, including the thermal and magnetic field evolution of Mercury, Mars, the Moon and Ganymede as well as of planetesimals and rocky exoplanets. Chapter 18 describes the physical processes that contribute to the variability of the solar wind flow that expands from its atmospheric and coronal sources to fill (and propagate through) the whole interplanetary medium. A concise view of the different types of phenomena capable of driving space weather events is given, from those intrinsic to the background solar wind flow itself to the impulsive perturbations related to solar activity. The final chapter (Chapter 19) discusses the problems of the geomagnetic field predictability and the techniques applied for forecasting. From the variety of geomagnetic parameters, two representative variables have been chosen for detailed analysis. One is the magnetic signal of gravitational tidal phenomena, which generate relatively weak but periodic magnetic perturbations. Another variable is the secular variation of the main geomagnetic field, which

depends on the evolution of geodynamo and changes slowly but chaotically. Thus the first parameter may be related to short-term geomagnetic prediction, while the second one is suitable for long-term prediction.

This volume represents a compilation of different points of view presented by different authors. Thus some of the chapters partly overlap with others, attesting to the complexity and variability of geomagnetism and aeronomy studies.

We thank all the authors for their dedicated efforts to make this book a true community product. We also wish to express our thanks to our associate editors from the IAGA executive committee, who compiled the five parts of the book: Inez Batista, Archana Bhattacharyya, Brian Fraser, Pieter Kotze, Renata Lukianova and Alan Thomson. We are grateful to the following reviewers, who helped ensure the high quality of the individual chapters: Livia Ribeiro Alves, David Boteler, Nicolas Gillet, Andrew Jackson, Larry Kepko, Jan Lastovicka, Vincent Lesur, Stefan Lotz, Robert Lysak, Frederik Menk, Katia Pinheiro, Rui Pinto, Dhananjay Ravat, Craig Rodger, Angelo de Santis, James Slavin, Sabine Stanley and Du Toit Strauss. Last, but not least, we thank VR2Planets and especially the founder of this start-up company, Francois Civet, for preparing the cover figure. The representation of the geomagnetic field is based on a model from satellite and observatory data.