INTRODUCTION TO GEOMAGNETIC FIELDS

Introduction to Geomagnetic Fields is a textbook for advanced undergraduate and graduate students of geophysics. It explains the natural magnetic fields in and surrounding the Earth that arise from a variety of electric currents. Such electric currents exist within atomic structures, in the Earth's liquid outer core, in the ionized upper atmosphere, and in the Earth's space environment during solar–terrestrial disturbances (magnetic storms).

The author clearly presents these different components of the Earth's magnetic field with a minimum of mathematical complexity. Variations in the geomagnetic field over a range of time-scales are discussed, including reversals of the Earth's main dipolar field, disturbances of the magnetosphere caused by particles and fields radiating from the Sun, and daily changes caused by the tidal and wind motion of the ionosphere. Readers are also introduced to the techniques and instrumentation for measuring geomagnetic fields, and to the range of applications for which these measurements are used.

This second edition has been fully revised to include many of the most recent advances in this subject area. It has been designed as a textbook for use with semester courses in geomagnetism and includes student exercises at the end of each chapter. Special appendices review relevant mathematical techniques and direct the reader to various journals, books, organizations, and websites where the latest computer programs for geomagnetism may be downloaded. Solutions to the exercises can be found at http://www.cambridge.org/9780521822060.

WALLACE CAMPBELL graduated with a Ph.D. in Physics from the University of California, Los Angeles, in 1959. Following a year with the Geophysical Institute in the University of Alaska, he accepted a position for geomagnetic field studies with the National Bureau of Standards Laboratory in Boulder, Colorado, that subsequently became the Environmental Research Laboratory of NOAA. He remained there until 1973 when a federal reorganization transferred his group to the United States Geological Survey in Golden, Colorado, for studies in geomagnetic applications. He retired from the USGS in 1996 and since then has worked as a Guest Scientist with the Solar–Terrestrial Physics Division, National Geophysical Data Center of NOAA. Dr Campbell is the author of 128 geomagnetism publications. His research subjects include ionospheric currents, deep-Earth electrical conductivity, geomagnetic storms, geomagnetic pulsations, quiet-time field variations, and geomagnetic field applications. He is also the coeditor (and contributing author) of the textbook *Physics of Geomagnetic Phenomena* (1967) and the author of *Earth Magnetism: a Guided Tour Through Magnetic Fields* (2001).

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Second Edition

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Contents

Preface

This second edition of *Introduction to Geomagnetic Fields* has been redesigned as a classroom textbook for a semester course in geomagnetism. Student exercises have been added at the end of each chapter. Outdated figures and tables are replaced with more modern equivalents. Recent discoveries, field information, and references have been added along with special websites and computer programs. The basic structure of the original edition remains, providing a condensed and more readable coverage of geomagnetic topics than is afforded by existing textbooks.

My intention has been to focus upon the basic concepts and physical processes necessary for understanding the Earth's natural magnetic fields. When mathematical presentation is required, I have tried to remove the mystery of the scientists' special jargon and to emphasize the meanings of important equations, rather than obscure the relationships with complex formulas. Because some formulas are needed to appreciate geomagnetism, I have included, in an appendix, a succinct review of the required mathematical definitions and facts. For those readers who are approaching the subject of Earth magnetic fields for the very first time it may be helpful to start with the small layman's presentation, devoid of all mathematical equations, that I provided as *Earth Magnetism: A Guided Tour Through Magnetic Fields*, Academic Press, San Diego, 151 pp, 2001.

The student reader is expected to have a familiarity with the elementary scientific concepts identified by words of specific meaning, such as "force, velocity, energy, temperature, heat, charge, light waves, and fields of electric, magnetic, and gravitational nature". Excellent help is available if you are among those readers who have somehow missed receiving an explanation of these terms in your schooling. Albert Einstein and Leopold Infeld realized this need back in 1938 and wrote for you a small book, *The Evolution of Physics* (republished by Simon and Schuster, New York, 1961), which is as applicable today as it was over sixty years ago. That book uses remarkable simplicity of logic and language to reveal the fundamental concepts and terms now in use by physical scientists. In particular, with no mathematical formulas, their

first two chapters not only provide the necessary basics for the science novice but also can reawaken an appreciation of the physical world made dormant by a schooling overdose of isolated facts and mathematical gymnastics.

To be called a proper "Introduction to Geomagnetic Fields" my book must contain the particular subjects that I have grouped into five chapters as follows. In Chapter 1 we explore the Earth's main field, consider its dipole representation, examine the vast extension of the fields into space, decipher the modeling methods of compact field representation, locate the many magnetic poles, and discuss paleomagnetic field reversals due to the source currents in the deep liquid core of the Earth. In Chapter 2 we find the reasons for quiet-time regular daily and seasonal field variations arising as electric currents in our Earth's upper atmosphere. We separate out the secondary currents that are induced to flow in the Earth itself – but find application in determining Earth conductivity profiles. In Chapter 3 we consider the major disturbances to the ordered particle and field configuration about the Earth. These geomagnetic storms have their origin in solar outbursts and act as monitors of changes in our space environment. In Chapter 4 we discover how magnetic field sensors (magnetometers) function, discuss some observation techniques, and look at measurement methods on the ground and in space. Finally, in Chapter 5 we consider the many useful applications of our knowledge of the main geomagnetic field and its temporal changes.

The book also contains three appendices. Appendix A is a review of mathematical concepts that the reader will encounter. Appendix B provides a guide to the major international organizations, a geomagnetism bibliography, and the useful source and website addresses for geomagnetic information. Appendix C gives the description of free special computer programs that are designed to help the beginning student in geomagnetism.

I have included more than the typical amount of text illustrations. They have been carefully selected to clarify concepts for the reader, rather than to burden him with a tedious overabundance of data reproductions. A great number of significant website addresses have been included. Although I have tried to guide the reader to known non-volatile websites, neither I nor the publisher can be held responsible if a site listed in this book is modified or disappears. The book index has been limited to those special words that I have considered to be of particular importance for an introduction to geomagnetic fields; don't expect to find place names, etc. This is a beginning textbook about geomagnetism; for full details on each of the chapter topics please borrow, from your library, the excellent reference books listed in Appendix B.

For the interpretation of phenomena, I have tried to stay with the current scientific consensus. However, in the future, many aspects of geomagnetism that are still being explored will undoubtedly change some of my viewpoints. Perhaps you can be the one to make such a contribution.

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Acknowledgments

This small book had its origin, organization, and testing in my tutorial lectures at US Geological Survey; the Space Environment Laboratory of the National Oceanic and Atmospheric Administration; the World Data Center of the National Geophysical Data Center; the Australian Geological Survey Organisation (now Geoscience Australia); the Australian IPS Radio and Space Services; the Colorado School of Mines; the University of Colorado; the Academy of Sciences, Beijing; and the University of Cairo, Egypt.

I give special thanks for the guidance provided by researchers whose works are listed in the Bibliography and Reference sections, all of whom have made important contributions to the study of geomagnetic fields. In addition I have relied heavily on my personal scientific publications; the unreferenced figures are my own.

I appreciate the help of many scientists, teachers, special friends, and excellent technical reviewers who provided suggestions and material for improving various sections of the book. In particular, for assistance in preparing this second revision, I give special thanks to J. Quinn and D. Herzog (both at the US Geological Survey, Golden, USA), S. McLean, H. Coffey, E. Kihn, and B. Poppe (all at the National Oceanic and Atmospheric Administration, Boulder, USA), C. Barton, P. McFadden, and P. Milligan (all at Geophysics Australia, Canberra, Australia), D. Cole (at IPS Radio and Space Services, Sydney, Australia), D. Boteler (at the Geological Survey of Canada), G. Rostoker (at the University of Alberta, Canada), M. Barreto (at Observatorio Nacional, Rio de Janeiro, Brazil) and A. Adam (at the Geodetic and Geophysical Research Institute, Sopron, Hungary). I also thank my wife Beth, who assisted in editing the manuscript and endured my many hours spent at the computer.

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