An Introduction to Space Weather

Our space age technology enables global communication, navigation, and power distribution that have given rise to our "smart," interconnected, and spacefaring world. Much of the infrastructure modern society depends on, to live on Earth and to explore space, is susceptible to space weather storms originating from the Sun. The second edition of this introductory textbook is expanded to reflect our increased understanding from more than a dozen scientific missions over the past decade. Updates include discussions of the rapidly expanding commercial space sector, orbital debris and collision hazards, our understanding of solar–terrestrial connections to climate, and the renewed emphasis on human exploration of the Moon and Mars. The book provides new learning features to help students understand the science and solve meaningful problems, including some based on real-world data. Each chapter includes learning objectives and supplements that provide descriptions of the science, and learning strategies to help students and instructors alike.

Mark Moldwin is an Arthur F. Thurnau Professor of Climate and Space Sciences and Engineering at the University of Michigan, Ann Arbor. An award-winning teacher, his primary research interests are magnetospheric, ionospheric, and heliospheric plasma physics, and precollege space science education and outreach. He is a Past-President of the American Geophysical Union's Education Section, a former Editor-in-Chief of *Reviews of Geophysics*, and among his numerous honors he received the 2016 AGU's Waldo E. Smith Award for his "extraordinary service to geophysics."

"Professor Moldwin lays out the complex topic of space weather in a clear and comprehensive way, with a masterful educational touch that keeps the reader engaged in every chapter. The second edition of this foundational book comes at the perfect time, as the space economy is rapidly expanding and the topic of space weather becomes more pertinent than ever before."

Professor Jacob Bortnik, University of California, Los Angeles

"From solar explosions to their impact on society, this wonderful text uses understandable prose to introduce students with widely different backgrounds to the physics of the local universe and to how the ever-changing connections between Sun and Earth affect society. For the second edition, the diverse supplemental material – ranging from how science works to the foundations of physics – has been expanded, while a newly developed companion webpage leads to beautiful images, illustrative videos, and ready-to-use lecture slide sets."

Dr. Karel Schrijver, Lockheed Martin Advanced Technology Center

"A very fine introduction to the science and applications of the broad topic of solar–terrestrial physics (space weather) by Professor Moldwin, an eminent scholar who has personally contributed substantially to the field. In this substantially revised edition, the clever division of each chapter into descriptive and more quantitative portions will make this volume the preeminent academic introduction to the subject."

Professor Louis J. Lanzerotti, New Jersey Institute of Technology

"We have used the first edition of *An Introduction to Space Weather* for several years in Penn State's cross-listed 'Space Weather' course; it reaches our students well, regardless of their diverse backgrounds. This new edition brings welcome updates (including a brand new chapter on forecasting, educational and other supplementary content toward the end of each section, as well as a companion website) while remaining concise and affordable."

Professor Timothy Kane, The Pennsylvania State University

"I have used Professor Moldwin's book in Embry–Riddle's second-year undergraduate class 'Introduction to Space Weather'. Professor Moldwin's book has worked as a great and highly motivating introductory text for important space weather phenomena. It has been developed with pedagogy and student learning in mind. The book is well written, clear, and captivating. The freshmen students liked the conceptual nature of the text, so the content was easy to grasp with only some introductory physics/math background. I plan on continuing to use this book when teaching this class next time."

Professor Heidi Nykyri, Embry–Riddle Aeronautical University

An Introduction to Space Weather

SECOND EDITION

Mark Moldwin
University of Michigan,
Ann Arbor

CAMBRIDGE UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre,
New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment, a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/highereducation/isbn/9781108791717
DOI: 10.1017/9781108866538

First published 2008
Second edition 2023

Printed in the United Kingdom by TJ Books Limited, Padstow, Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-79171-7 Paperback

Additional resources for this publication at www.cambridge.org/moldwin2.

Contents

The color plate section is located between pages 52 and 53.

Preface

In the last few decades our technological civilization has become dependent on satellites for global communication, navigation, and commerce. We have also begun the long journey to explore the Moon, Mars, and our solar system.

This exploration has led to some amazing discoveries about our dynamic Sun and its interaction with Earth. We now know that the Sun is a variable star that expels high-energy particles and deadly radiation continuously out into space. This radiation can impact and destroy technological systems and is one of the major concerns for modern civilization and human space exploration.

In the 1990s, the commercial satellite industry boomed with direct satellite-to-home TV and radio markets and satellite communication options expanding. By the 2000s, the satellite industry was doing over $100 billion (US) per year of business with nearly a hundred new satellites launched each year. In 2020, global satellite revenue was over $370 billion. With the increasing number of commercial space businesses and the reliance that different markets started to have on space, society began to notice when something went wrong in space.

Galaxy IV was an operating and profitable communications satellite until May 19, 1998, when, after experiencing weeks of intense radiation generated by the Sun and the Sun's interaction with the Earth's space environment, it failed. Galaxy IV carried the signals of over 90% of North America's pagers (early wireless communication devices) and several major broadcast networks including the US National Public Radio (NPR) and CBS. Without the $200 million satellite, millions of pager messages and NPR radio and CBS television programs never made it to their intended audience. Radio and TV producers were left scrambling to fill dead-air time, and medical doctors and business people found themselves out of contact with their hospitals and clients. Galaxy IV in all likelihood was a victim of a space weather storm.

Though the cause of failure is not yet known, SiriusXM's geosynchronous SXM-7 satellite failed while on-orbit in early 2021 just six weeks after successful launch, becoming a $225 million "total loss." Even if the cause of failure was not space weather related, the "dead"

satellite needed to put into a graveyard orbit, otherwise it would have been a space weather hazard for other geosynchronous spacecraft due to potential collisions. The launch of more and more satellites increases the number of orbiting objects, which increases the number of operational spacecraft, derelict spacecraft, and orbital debris that become space weather collision hazards.

Space storms can not only damage or destroy orbiting satellites, but also injure or kill astronauts, degrade or blackout certain radio and navigation communications, and cause regional power failures by destroying critical components of electrical power grids. With the continued growth of the satellite communications industry, the advent of space tourism, and our growing dependence on wireless communication and instant access to global information, we are becoming more and more susceptible to problems caused by space weather.

This textbook aims to introduce the reader to the field of space weather in both a descriptive and quantitative approach. The mathematical sophistication of the reader is assumed to be at the level of high school algebra. Since science is not just a collection of facts, but a process or way of understanding our natural world, the book attempts to answer the question "How do we know that?" by including discussions on the historical development of different concepts.

The first edition of this book was derived from the notes for three undergraduate courses at UCLA – the first a freshman seminar, the second an Honors Collegium course, and the third a general education course for non-science majors entitled "The Perils of Space: An Introduction to Space Weather," first taught in Fall 2004. The second edition of this book benefits from SPACE103 Introduction to Space Weather, first taught at the University of Michigan in 2014.

Each chapter is divided into two separate parts: the main text describing space weather topics, and supplements describing important physical concepts behind each topic. In this second edition, the supplements also include discussions on learning theory and study skills that are aimed to help students develop their conceptual understanding. End-of-chapter problems allow students to test their understanding and delve deeper into aspects of the chapter. A list of key concepts is given for each chapter, and the concepts are in bold at their first occurrence in the main body of the text. Finally, learning objectives follow the list of key concepts at the beginning of each chapter, describing what the reader should be able to *do* after reading the chapter. Additional learning objectives at the start of the supplements to each chapter describe what students should be able to do after reading the supplements. Students wishing to understand space weather should conceptually know the key concepts and be able to use that information to analyze,

synthesize, and evaluate a variety of space weather problems and questions. Key concepts are indicated by bold in the index. The second edition now also includes a glossary of important terms and key concepts to provide understanding of overarching processes, regions, events, and the connections between them.

A new aspect of the second edition are the online resources available at www.cambridge.org/moldwin2 that provide access to data of the Sun, solar wind, the Earth's magnetosphere, and upper atmosphere that can be used to practice applying space weather concepts to actual observations. (For example: Can you identify a coronal mass ejection [CME] in solar coronagraph images and its signatures in the solar wind? With that identification, can you estimate the arrival time of the disturbances at Earth, and what will that look like in different regions of the Earth's space environment?) The online resources also include a variety of lecture slides, images, and videos that help visualize the key regions, processes, and events outlined in the text.

Acknowledgments

Students in the "Introduction to Space Weather" courses at the University of Michigan inspired and helped in the writing of the second edition of this textbook. Several colleagues who have adopted the text at their university have provided ideas, suggestions, and support, and I owe them thanks and gratitude for helping to spread awareness of space weather more broadly. Much of the revision of the textbook took place during a sabbatical supported by the US–Norway Fulbright Arctic Chair visit to the University of Bergen's Birkeland Center for Space Science. My hosts (Professor Michael Hesse, Dr. Therese Moretto Jorgensen, Professor Nikolai Østgaard, and Kavitha Østgaard) provided office space and resources, and welcomed me into their research groups, for which I am very grateful. I also would like to thank my University of Michigan colleagues and my Magnetometer Lab science, engineering, and art students for their support and motivation during the years of writing this revised edition of the book.