THE SOLAR CORONA
SECOND EDITION

Intended for graduate students and astronomers seeking an introduction to coronal physics, this textbook strikes a balance between the observational and theoretical aspects of the subject. This Second Edition takes into account the major observational and theoretical developments of recent years to provide an up-to-date treatment of our understanding of the solar corona.

After reviewing the latest observations of the solar corona, the authors explain how studies have advanced and shaped our understanding of coronal physics. The textbook introduces a wide variety of exciting physics, including dynamo theory and magnetohydrodynamics, and shows how the transient effects of the solar cycle affect space weather. Each subject area is introduced using basic physics, and refers readers to fundamental papers on the topic, key new studies in each area, and extensive discussions in recent review articles.

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Second Edition

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Preface to the First Edition

It has been three decades since a textbook devoted solely to the subject of the solar corona has been written. Since that time, both ground-based and spaceborne techniques have advanced enormously and the field has been changed dramatically. Some of the recent advances have been described in chapters appearing in more general books on the subject of solar studies, but no major review of coronal physics *per se* has appeared. It would appear, therefore, that the time is right for an updated treatment of the subject.

This book is intended for astronomers seeking an introductory level discussion of coronal physics, and also for students at the advanced undergraduate or beginning graduate level. Our presentation is by no means exhaustive, in that each of the ten chapters of this book could easily be the subject of an entire volume: publishers do, in fact, put page limits on manuscripts. Our goal, in each of the subject areas, has been to provide an introduction to the modern discussion at a level which will allow the interested reader to understand something of the subject[a] and to pursue the subject further, using the references and citations provided in each chapter. Thus, one should not expect to find in this book "everything you wanted to know about the corona." Rather, we give the reader a beginner's level introduction and also provide a treatment of some more advanced topics for reference purposes. This book might therefore have been entitled *Introduction to the Physics of the Solar Corona*.

The general plan of the book is to begin with a description of the solar corona in broad, simple terms and then to place the corona within a historical context and within the more general context of stellar coronae (Ch. 1). The history of scientific research on the corona divides naturally into the pre- and post-1940 periods, at which time the corona went from being a major puzzle for astrophysics to being one of its great success stories. A brief history of coronal studies leading up to the breakthrough in the 1940s is provided in Ch. 2.

A major feature of the book is the extensive discussion of the new observations and their role in determining our present understanding of coronal physics. To

[a] In this regard we attempt to follow the dictum expressed by V.F. Weisskopf: "Rather than trying to cover a subject, try to uncover a part of the subject."

this end, Chs. 3–8 discuss the basics of observational methods for the corona and of the main observational features. Chapter 3 is an extensive discussion of spectroscopy and of the spectroscopic techniques used in coronal studies. Chapter 4 provides an introduction to dynamo theory, with a summary of the relevant observational aspects of the solar cycle. Magnetic fields are central to the existence of the corona and the dual subjects of magnetic field production in the Sun and the effects of these fields when they reach the solar surface are discussed in some detail.

Both ground-based and spaceborne methods are used and the ways in which they complement each other are explored in Chs. 5, 6 and 8. Chapter 5 presents a discussion of ground-based observations of the Sun, particularly from eclipses and with radio techniques. Observations from space tend to be defined by the success of particular instruments or observatories and our organization in Chs. 6 and 8 generally follows the historical sequence of breakthrough space missions.

A more detailed discussion of coronal physics, with particular emphasis on theory and its interaction with experiment, follows in Chs. 7 and 9, which discuss the "normal" and flare-related coronal emission, respectively. The text concludes with a brief overview of solar–terrestrial studies in Ch. 10. In our discussion, we choose to emphasize the direct transient effects of solar variability on the local environment, which is broadly labelled "solar–terrestrial physics," and which has more recently been receiving attention under the name of "space weather."

The discussion of each topic is written for students who are unfamiliar with the subject, and we generally bring the reader up to the level expected of a graduate student who seeks a broad familiarity with the material. The book is therefore suitable for use in either an undergraduate or a graduate-level course. As a guide to those who wish to include this subject in a course, *we have marked the more technical discussions with an asterisk* (*). These sections, generally at the end of a chapter, may be omitted in an introductory study.

On the whole, we will use cgs units throughout most of this text. However, in some of the sub-fields of coronal studies mks units are in widespread use. Rather than add to the confusion by attempting to alter the conventional practices, and to aid the reader in referring to published articles, we will remain consistent with common usage. In all cases, the units being used will be indicated in the text.

Websites

With the advent of high-speed data transfer systems, there are now several sites on the Internet and World Wide Web which contain information, images, solar reports, and other data of interest to readers of this book. Some of the sites (updated for this 2nd edition) are:

- The American Astronomical Society:
  www.aas.org/
- The Solar Data Analysis Center at Goddard Space Flight Center:
  umbra.gsfc.nasa.gov/sdac.html

- The National Solar Observatory:
  www.nso.edu/
- The Space Weather Prediction Center:
  www.swpc.noaa.gov/
- NASA Marshall Space Flight Center Solar Physics Branch:
  solarscience.msfc.nasa.gov/
- "The Exploration of the Earth's Magnetosphere":
  iki.rssi.ru/mirrors/stern/Education/Intro.html
- The Ulysses Mission Home Page:
  ulysses.jpl.nasa.gov/
- Home Page of the CfA Solar & Stellar X-ray Group:
  hea-www.harvard.edu/SSXG/
- SoHO Observatory Home Page:
  sohowww.nascom.nasa.gov/
- Sunspot Number and Butterfly Diagram:
  solarscience.msfc.nasa.gov/SunspotCycle.shtml
- GONG (Global Oscillations Network Group):
  gong.nso.edu
- The 8 Planets – background information, photos and mirror sites:
  www.nineplanets.org
- NASA Heliophysics Division:
  sec.gsfc.nasa.gov
- NASA Solar Missions:
  nasascience.nasa.gov/heliophysics/mission_list
- International Astronomical Union Working Group on Eclipses:
  www.eclipses.info
- National Geophysical Data Center Solar Data Services:
  www.ngdc.noaa.gov/stp/SOLAR/solar.html
- Solar Influences Data Analysis Center:
  sidc.oma.be
- Daily Solar Activity Monitor:
  www.solarmonitor.org
- Space Weather:
  www.spaceweather.com
- As long as the technology is viable, we will keep an updated list of solar links, and other updates relevant to this book, at:
  www.williams.edu/astronomy/corona

Preface to the Second Edition

In the decade since the first edition of this book appeared coronal physics has undergone remarkable growth. A convergence of three major trends is responsible. First, there has been an increasing realization that the activity of the Sun produces serious consequences in the near-Earth environment. This subject, generically named "space weather," was known a decade ago but has taken on growing importance in recent years, leading to increased attention being focussed on the study of the origins of these disturbances at the Sun. Second, several space-borne experiments have been launched that have provided ground-breaking new observations, and a new generation of improved ground-based instrumentation has been developed, with unprecedented capabilities. Third, remarkable progress has been made in our theoretical understanding of the dynamics of hot magnetized plasmas and their properties, in particular via the analysis of the magnetic topology, and by computer modelling of coronal dynamics in 3-D.

It is a familiar story in science that progress depends on a balance between theory and observation working together dialectically, but coronal physics has been exceptionally fertile in this regard in recent years. In this edition we have updated all the chapters to take into account the most significant aspects of this recent progress. The discussion of ground-based methods has been updated to discuss some of the new techniques that have been developed and what they are producing. The discussion of coronal activity outside of flares has been augmented to include theoretical developments and the results from the above-mentioned space instrumentation. Related to this augmentation, but treated separately, the discussion of solar flares has been substantially updated and revised, and the chapters discussing the solar wind, flares and coronal mass ejections have been reorganized as Ch. Ch. 10. Discussions of the interconnected subjects of coronal mass ejections and near-Earth space weather effects have been expanded, as has the discussion of the solar wind (Ch. 9).

Perhaps the most significant change in solar studies during the past decade is in the theoretical framework used for understanding the dynamics of hot magnetized plasmas. The present view is that the coronal volume is divided into magnetic field regions which are active at the boundaries and at regions

of singularity (separatrices, spines, fans) that divide the space into volumes of field having different topological connectivities. For the observer, this new view means that it may be the skeletal structure of the field – which at present is not directly observable – that matters most in explaining coronal activity. We have included an introductory discussion to this topic, suitable for the beginning student.

The main aim of this book continues to be its use as an introduction to the field, providing enough depth and balance between observational and theoretical aspects to uncover a bit of the subject and thereby to allow the reader to enter the discussion without being overwhelmed by details. We have attempted to focus on the basic physics of each subject and to provide the reader with references to some of the fundamental papers in the given area. We also continue to provide references to some of the main new studies in each area and to more extensive discussions in recent review articles. For readers who wish to pursue the subject further, there are several recent books that are perhaps not for beginners but offer a more technical, in-depth discussion of these subjects: *Magnetic Reconnection* by Priest and Forbes and *Physics of the Solar Corona* by Aschwanden are most directly related to the topics herein discussed. For beginners, Ken Lang's *The Sun from Space*, 2nd edn., 2009, and *Sun, Earth and Sky*, 2nd edn., 2006, are useful as a basic introductory guide to the study of the solar atmosphere, as is our own *Nearest Star*. For a general overview of solar studies, *The Sun*, 2nd edn., by Michael Stix is an excellent overall introduction to solar physics.

In this edition we use both footnotes and endnotes. The former are used primarily for short comments that do not overly interrupt the flow of the discussion, and they are indicated by lower-case alphabetic characters. The endnotes are used mainly for longer or more technical discussions, and are identified using Arabic numerals.

Special thanks

We thank the many readers – too numerous to name individually – who sent us comments, criticisms and corrections, many of which have been incorporated in this edition. Several of the chapters, having undergone extensive revision, have been reread by experts in those subjects. We also have included many new figures and illustrations and we thank the individuals and organizations that provided them. We thank especially (in alphabetical order) Gemma Attrill, Ed DeLuca, Alec Engell, Fred Espenak, Terry Forbes, Dale Gary, Paolo Grigis, David Hathaway, Hugh Hudson, Jim Klimchuk, Niina Lehtinen, Silja Pohjolainen, Steve Saar, Joan Schmelz, Dan Seaton, Yingna Su and Andrei Zhukov.

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