This timely volume provides the first comprehensive review and synthesis of the current understanding of the origin, evolution, and effects of magnetic fields in the Sun and other cool stars. Magnetic activity results in a wealth of phenomena – including starspots, nonradiatively heated outer atmospheres, activity cycles, deceleration of rotation rates, and even, in close binaries, stellar cannibalism – all of which are covered clearly and authoritatively.

This book brings together for the first time recent results in solar studies, with their wealth of observational detail, and stellar studies, which allow the study of how activity evolves and depends on the mass, age, and chemical composition of stars. The result is an illuminating and comprehensive view of stellar magnetic activity. Observational data are interpreted by using the latest models in convective simulations, dynamo theory, outer-atmospheric heating, stellar winds, and angular momentum loss.

Researchers are provided with a state-of-the-art review of this exciting field, and the pedagogical style and introductory material make the book an ideal and welcome introduction for graduate students.

SOLAR AND STELLAR MAGNETIC ACTIVITY

Cambridge astrophysics series

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SOLAR AND STELLAR MAGNETIC ACTIVITY

C. J. SCHRIJVER
Stanford-Lockhead Institute for Space Research, Palo Alto

C. ZWAAN
Astronomical Institute, University of Utrecht

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Die Sonne tönt nach alter Weise
In Brudersphären Wettgesang,
Und ihre vorgeschriebene Reise
Vollendet sie mit Donnergang.

Ihr Anblick gibt den Engeln Stärke,
Wenn Keiner Sie ergründen mag.
Die unbegreiflich hohen Werke
Sind herrlich wie am ersten Tag.

Johann Wolfgang von Goethe

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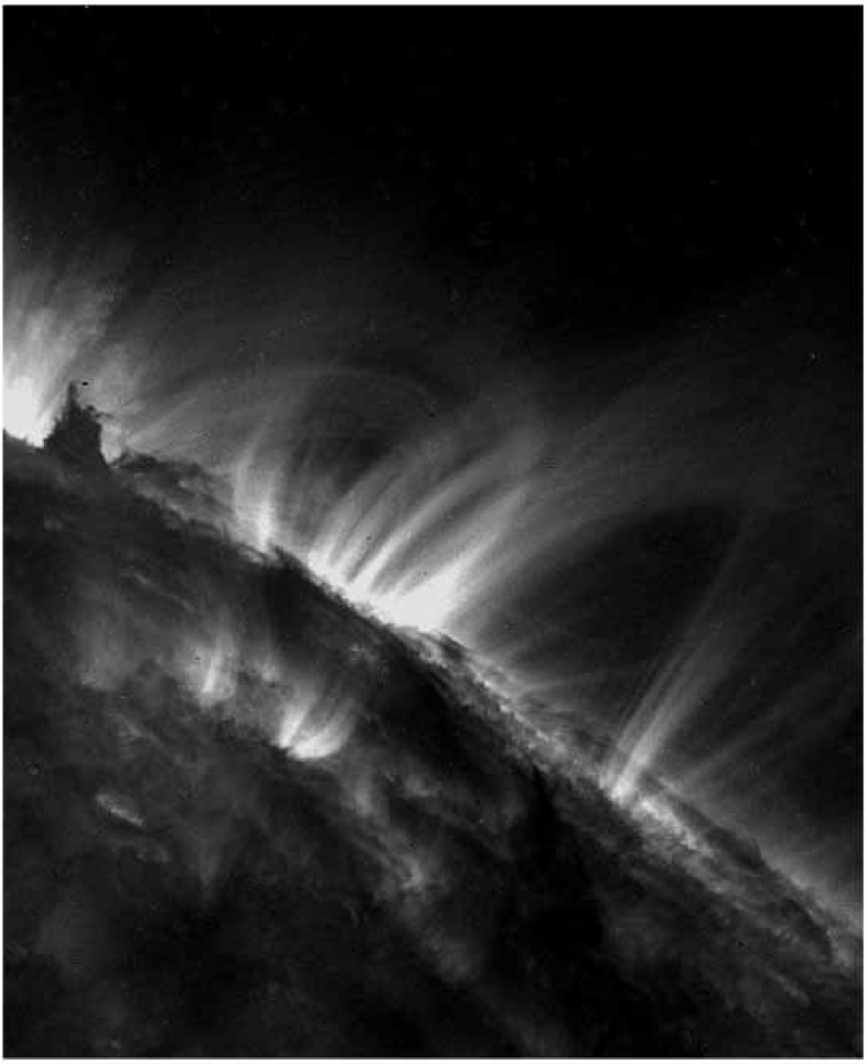

Image taken with *TRACE* in its 171-Å passband on 26 July 1998, at 15:50:23 UT of Active Region 8,272 at the southwest limb, rotated over −90°. High-arching loops are filled with plasma at ∼1 MK up to the top. Most of the material is concentrated near the lower ends under the influence of gravity. Hotter 3–5 MK loops, at which the bulk of the radiative losses from the corona occur, do not show up at this wavelength. Their existence can be inferred from the emission from the top of the conductively heated transition region, however, where the temperature transits the 1-MK range, as seen in the low-lying bright patches of "moss." A filament-prominence configuration causes extinction of the extreme-ultraviolet radiation.

Preface

This book is the first comprehensive review and synthesis of our understanding of the origin, evolution, and effects of magnetic fields in stars that, like the Sun, have convective envelopes immediately below their photospheres. The resulting magnetic activity includes a variety of phenomena that include starspots, nonradiatively heated outer atmospheres, activity cycles, the deceleration of rotation rates, and – in close binaries – even stellar cannibalism. Our aim is to relate the magnetohydrodynamic processes in the various domains of stellar atmospheres to processes in the interior. We do so by exploiting the complementarity of solar studies, with their wealth of observational detail, and stellar studies, which allow us to study the evolutionary history of activity and the dependence of activity on fundamental parameters such as stellar mass, age, and chemical composition. We focus on observational studies and their immediate interpretation, in which results from theoretical studies and numerical simulations are included. We do not dwell on instrumentation and details in the data analysis, although we do try to bring out the scope and limitations of key observational methods.

This book is intended for astrophysicists who are seeking an introduction to the physics of magnetic activity of the Sun and of other cool stars, and for students at the graduate level. The topics include a variety of specialties, such as radiative transfer, convective simulations, dynamo theory, outer-atmospheric heating, stellar winds, and angular momentum loss, which are all discussed in the context of observational data on the Sun and on cool stars throughout the cool part of the Hertzsprung–Russell diagram. Although we do assume a graduate level of knowledge of physics, we do not expect specialized knowledge of either solar physics or of stellar physics. Basic notions of astrophysical terms and processes are introduced, ranging from the elementary fundamentals of radiative transfer and of magnetohydrodynamics to stellar evolution theory and dynamo theory.

The study of the magnetic activity of stars remains inspired by the phenomena of solar magnetic activity. Consequently, we begin in Chapter 1 with a brief introduction of the main observational features of the Sun. The solar terminology is used throughout this book, as it is in stellar astrophysics in general.

Chapter 2 summarizes the internal and atmospheric structure of stars with convective envelopes, as if magnetic fields were absent. It also summarizes standard stellar terminology and aspects of stellar evolution as far as needed in the context of this monograph.

The Sun forms the paradigm, touchstone, and source of inspiration for much of stellar astrophysics, particularly in the field of stellar magnetic activity. Thus, having introduced the basics of nonmagnetic solar and stellar "classical" astrophysics in the first two chapters, we discuss solar properties in Chapters 3–8. This monograph is based on the premise that the phenomena of magnetic activity and outer-atmospheric heating are governed by processes in the convective envelope below the atmosphere and its interface with the atmosphere. Consequently, in the discussion of solar phenomena, much attention is given to the deepest part of the atmosphere, the photosphere, where the magnetic structure dominating the outer atmosphere is rooted. There we see the emergence of magnetic flux, its transport across the photospheric surface, and its ultimate removal from the atmosphere. We concentrate on the systematic patterns in the dynamics of magnetic structure, at the expense of very local phenomena (such as the dynamics in sunspot penumbrae) or transient phenomena (such as solar flares), however fascinating these are. Page limitations do not permit a discussion of heliospheric physics and solar–terrestrial relationships.

Chapter 3 discusses the solar rotation and large-scale flows in the Sun. Chapters 4–8 cover solar magnetic structure and activity. Chapter 4 deals with fundamental aspects of magnetic structure in the solar envelope, which forms the foundation for our studies of fields in stellar envelopes in general. Chapter 5 discusses time-dependent configurations in magnetic structure, namely the active regions and the magnetic networks. Chapter 6 addresses the global properties of the solar magnetic field, and Chapter 7 deals with the solar dynamo and starts the discussion of dynamos in other stars. Chapter 8 discusses the solar outer atmosphere.

Chapters 9 and 11–14 deal with magnetic activity in stars and binary systems. This set of chapters is self-contained, although there are many references to the chapters on solar activity. Chapter 9 discusses observational magnetic-field parameters and various radiative activity diagnostics, and their relationships; stellar and solar data are compared. Chapter 11 relates magnetic activity with other stellar properties. Chapter 12 reviews spatial and temporal patterns in the magnetic structure on stars and Chapter 13 discusses the dependence of magnetic activity on stellar age through the evolution of the stellar rotation rate. Chapter 14 addresses the magnetic activity of components in binary systems with tidal interaction, and effects of magnetic activity on the evolution of such interacting binaries.

Two integrating chapters, 10 and 15, are dedicated to the two great problems in magnetic activity that still require concerted observational and theoretical studies of the Sun and the stars: the heating of stellar outer atmospheres, and the dynamo action in stars with convective envelopes.

We use Gaussian cgs units because these are (still) commonly used in astrophysics. Relevant conversions between cgs and SI units are given in Appendix I.

We limited the number of references in order not to overwhelm the reader seeking an introduction to the field. Consequently, we tried to restrict ourselves to both historical, pioneering papers and recent reviews. In some domains this is not yet possible, so there we refer to sets of recent research papers.

We would appreciate your comments on and corrections for this text, which we intend to collect and eventually post on a web site. Domain and computer names are, however, notoriously unstable. Hence, instead of listing such a URL here, we ask that you send e-mail to kschrijver at solar.stanford.edu with either your remarks or a request to let you know where corrections, notes, and additions will be posted.

In the process of selecting, describing, and integrating the data and notions presented in this book, we have greatly profited from lively interactions with many colleagues by reading, correspondence, and discussions, from our student years, through collaboration with then-Ph.D. students in Utrecht, until the present day. It is impossible to do justice to these experiences here. We can explicitly thank the colleagues who critically commented on specific chapters: V. Gaizauskas (Chapters 1, 3, 5, 6, and 8), H. C. Spruit (Chapters 2 and 4), R. J. Rutten (Chapter 2), F. Moreno-Insertis (Chapters 4 and 5), J. W. Harvey (Chapter 5), A. M. Title (Chapters 5 and 6), N. R. Sheeley (Chapters 5 and 6), P. Hoyng (Chapters 7 and 15), B. R. Durney (Chapters 7 and 15), G. H. J. van den Oord (Chapters 8 and 9), P. Charbonneau (Chapters 8 and 13), J. L. Linsky (Chapter 9), R. B. Noyes (Chapter 11), R. G. M. Rutten (Chapter 11), A. A. van Ballegooijen (Chapter 10), K. G. Strassmeier (Chapter 12), and F. Verbunt (Chapters 2 and 14). These reviewers have provided many comments and asked thought-provoking questions, which have greatly helped to improve the text. We also thank L. Strous and R. Nightingale for their help in proof reading the manuscript. It should be clear, however, that any remaining errors and omissions are the responsibility of the authors.

The origin of the figures is acknowledged in the captions; special thanks are given to T. E. Berger, L. Golub and K. L. Harvey for their efforts in providing some key figures. C. Zwaan thanks E. Landré and S. J. Hogeveen for their help with figure production and with LaTeX problems.

Kees Zwaan died of cancer on 16 June 1999, shortly after the manuscript of this book had been finalized. Despite his illness in the final year of writing this book, he continued to work on this topic that was so dear to him. Kees' research initially focused on the Sun, but he reached out towards the stars already in 1977. During the past two decades he investigated solar as well as stellar magnetic activity, by exploiting the complementarity of the two fields. His interests ranged from sunspot models to stellar dynamos, and from intrinsically weak magnetic fields in the solar photosphere to the merging of binary systems caused by magnetic braking. His very careful observations, analyses, solar studies, and extrapolations of solar phenomena to stars have greatly advanced our understanding of the sun and of other cool stars: he was directly involved in the development of the flux-tube model for the solar magnetic field, he stimulated discussions of flux storage and emergence in a boundary-layer dynamo, lead the study of sunspot nests, and stimulated the study of stellar chromospheric activity. And Kees always loved to teach. That was one of the main reasons for him to undertake the writing of this book.

Kees Zwaan (24 July 1928–16 June 1999)