

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

ULTRAVIOLET AND X-RAY SPECTROSCOPY OF THE SOLAR ATMOSPHERE

The solar atmosphere above the photosphere, the Sun's surface layers, is heated up to megakelvin temperatures and raised to a high level of dynamic activity through processes involving a pervading magnetic field. This book is concerned with one of the most important means of understanding the solar atmosphere, its ultraviolet and soft X-ray emission. The ultraviolet and X-ray spectra of the Sun's atmosphere provide valuable information about its nature – the heat and density of its various parts, its dynamics, and its chemical composition.

After a brief introduction, the book describes the principles governing spectral line and continuous emission, together with how spectral studies lead to deductions about physical properties. Spacecraft instrumentation from *Skylab*, the *P78-1* mission *SolarMax*, *Yohkoh*, *SOHO*, *TRACE*, and *Hinode* are described. With introductions to atomic physics and the diagnostic techniques used by solar spectroscopists, a list of emission lines in the ultraviolet and soft X-ray region, and a glossary of terms, this book is an ideal reference for graduate students and researchers in astrophysics and solar physics.

KENNETH J. H. PHILLIPS is a Research Fellow in the Department of Space and Climate Physics at the Mullard Space Science Laboratory, University College London. Prior to this he was a Senior Research Associate at the NASA Goddard Space Flight Center, and was involved in various spacecraft projects at the Rutherford Appleton Laboratory.

URI FELDMAN is employed by Artep Inc. a company specialising in Space Science and Plasma Physics research. In 1969 he was appointed as first director of the Wise Astronomical Observatory, Tel-Aviv University, responsible for its construction and operation. Between 1972 and his retirement from the Naval Research Laboratory, Washington, in 2001, he was involved with *Skylab*, *P78-1*, *Yohkoh* and *SOHO* space missions. In 1989 he was awarded the NRL E. O. Hulburt Annual Science and Engineering Award.

ENRICO LANDI received his Physics degree and Astrophysics Ph.D. Degree at the University of Florence, Italy, and has worked at the University of Florence, the Max-Planck Institut Für Aeronomie, Germany, and the Naval Research Laboratory, Washington, USA, where he is currently working. His interests cover X-ray, EUV and UV spectroscopy, atomic physics and solar physics.

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

Cambridge Astrophysics Series

Series editors

Andrew King, Douglas Lin, Stephen Maran, Jim Pringle,

Martin Ward and Robert Kennicutt

Titles available in the series

7. Spectroscopy of Astrophysical Plasmas
edited by A. Dalgarno, D. Layzer
10. Quasar Astronomy
by Daniel W. Weedman
18. Plasma Loops in the Solar Corona
by R. J. Bray, L. E. Cram, C. Durrant, R. E. Loughhead
19. Beams and Jets in Astrophysics
edited by P. A. Hughes
22. Gamma-ray Astronomy 2nd Edition
by P. V. Ramana Murthy, A. W. Wolfendale
24. Solar and Stellar Activity Cycles
by Peter R. Wilson
25. 3k: The Cosmic Microwave Background Radiation
by R. B. Patridge
26. X-ray Binaries
by Walter H. G. Lewin, Jan van Paradijs, Edward P. J. van den Heuvel
27. RR Lyrae Stars
by Horace A. Smith
28. Cataclysmic Variable Stars
by Brian Warner
29. The Magellanic Clouds
by Bengt E. Westerlund
32. Accretion Processes in Star Formation
by Lee Hartmann
33. The Origin and Evolution of Planetary Nebulae
by Sun Kwok
35. The Galaxies of the Local Group
by Sidney van den Bergh
36. Stellar Rotation
by Jean-Louis Tassoul
37. Extreme Ultraviolet Astronomy
by Martin A. Barstow, Jay B. Holberg
38. Pulsar Astronomy 3rd Edition
by Andrew G. Lyne, Francis Graham-Smith
39. Compact Stellar X-ray Sources
edited by Walter H. G. Lewin, Michiel van der Klis
40. Evolutionary Processes in Binary and Multiple Stars
by Peter Eggleton
41. The Physics of the Cosmic Microwave Background
by Pavel D. Naselsky, Dmitry I. Novikov, Igor D. Novikov
42. Molecular Collisions in the Interstellar Medium 2nd Edition
by David Flower
43. Classical Novae 2nd Edition
edited by M. F. Bode, A. Evans
44. Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere
by Kenneth J. H. Phillips, Uri Feldman, Enrico Landi

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

ULTRAVIOLET AND X-RAY SPECTROSCOPY OF THE SOLAR ATMOSPHERE

KENNETH J. H. PHILLIPS

Mullard Space Science Laboratory

URI FELDMAN

Artep Inc.

ENRICO LANDI

US Naval Research Laboratory



Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press

The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org

Information on this title: www.cambridge.org/9780521841603

© K. J. H. Phillips, U. Feldman and E. Landi 2008

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2008

Printed in the United Kingdom at the University Press, Cambridge

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

Library of Congress Cataloging-in-Publication Data

Phillips, Kenneth J. H.

Ultraviolet and x-ray spectroscopy of the solar atmosphere / Kenneth J. H. Phillips, Uri Feldman, Enrico Landi.

p. cm. — (Cambridge astrophysics series)

Includes bibliographical references and index.

ISBN 978-0-521-84160-3

1. Spectrum, Solar. 2. Ultraviolet spectroscopy. 3. X-ray spectroscopy.

I. Feldman, U. II. Landi, Enrico. III. Title.

QC455.P55 2008

523.7—dc22

2008008434

ISBN 978-0-521-84160-3 hardback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

Contents

	<i>Preface</i>	<i>page ix</i>
1	The solar atmosphere	1
1.1	Introduction	1
1.2	Chromosphere, transition region, and corona	2
1.3	The ultraviolet and X-ray spectrum of the solar atmosphere	4
1.4	Structure of the solar atmosphere	9
1.5	Dynamics of the solar atmosphere	14
1.6	The active Sun	16
1.7	Physical conditions and energy balance	20
1.8	Ionization and excitation conditions	24
1.9	Chemical composition	27
1.10	Solar-type stars	27
2	Fundamentals of solar radiation	31
2.1	Wavelength ranges	31
2.2	Specific intensity and flux	32
2.3	Radiative transfer and the source function	34
2.4	Radiation from the solar atmosphere	35
2.5	Radiant intensity and flux	40
3	Fundamentals of atomic physics	44
3.1	Introduction	44
3.2	The one-electron atom: Bohr's theory	44
3.3	The one-electron atom: quantum theory	48
3.4	The multi-electron atom: quantum theory	52
3.5	Isoelectronic sequences	61
3.6	Interaction between atoms and electromagnetic fields	63
3.7	Atomic codes	72
4	Mechanisms of formation of the solar spectrum	73
4.1	Introduction	73
4.2	Collisional excitation and de-excitation of atomic levels	73

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

vi	Contents	
4.3	Level populations	78
4.4	Ionization and recombination	83
4.5	Ion populations and ionization equilibrium	91
4.6	Line radiation	93
4.7	Continuum radiation	96
4.8	Spectral line profiles	106
4.9	Other excitation mechanisms of spectral lines	109
5	Plasma diagnostic techniques	119
5.1	Introduction	119
5.2	Electron density diagnostics	119
5.3	Electron temperature diagnostics	131
5.4	Ion temperature diagnostics	139
5.5	Emission measure diagnostics	142
5.6	Differential emission measure diagnostics	144
5.7	Element abundance diagnostics	150
5.8	Ion abundances	155
5.9	Plasma dynamics diagnostics	155
5.10	Magnetic field diagnostics	161
5.11	Spectral codes for solar corona research	162
6	Ultraviolet and X-ray emission lines	164
6.1	Introduction	164
6.2	The 1–7 Å range	165
6.3	The 7–23 Å range	166
6.4	The 23–170 Å range	169
6.5	The 170–630 Å range	169
6.6	The 630–2000 Å range (off-limb spectrum)	178
6.7	The 630–2000 Å range (disk spectrum)	180
7	Spectrometers and imagers for observing the solar ultraviolet and X-ray spectrum	184
7.1	Introduction	184
7.2	Transmittance properties of materials	185
7.3	Reflectance of VUV, EUV, and X-ray radiation from materials	186
7.4	Ultraviolet spectrometers	188
7.5	X-ray spectrometers	195
7.6	Imaging instruments	200
7.7	Instrument calibration	204
7.8	Summary of spacecraft instruments	209
8	Quiet Sun and coronal holes	210
8.1	Introduction	210
8.2	Quiet Sun corona and coronal holes: structure	211
8.3	Quiet Sun corona and coronal holes: plasma properties	214

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)

<i>Contents</i>		vii
8.4	Quiet Sun transition region	219
8.5	Non-thermal broadening of ultraviolet emission lines	221
8.6	Quiet Sun dynamic phenomena	224
8.7	Coronal waves and oscillations	228
9	Active regions	231
9.1	Introduction	231
9.2	Structure of active regions	231
9.3	Active region loops	239
9.4	Active region densities	245
9.5	Active region transient phenomena	247
10	Solar flares	251
10.1	Introduction	251
10.2	X-ray flare spectra	251
10.3	Ultraviolet flare spectra	256
10.4	Flare temperatures and emission measures	258
10.5	Flare densities	264
10.6	Flare morphology	268
10.7	Mass motions in flares	270
10.8	Non-thermal electrons	273
10.9	X-ray fluorescence lines in flares	273
10.10	Ionization equilibrium in flares	275
10.11	<i>GOES</i> observations of flares	277
11	Element abundances	282
11.1	Introduction	282
11.2	Solar wind abundances	285
11.3	Abundances in quiet Sun and coronal hole regions	287
11.4	FIP bias in distinct solar structures	290
11.5	FIP bias rate of change in the solar atmosphere	291
11.6	Is the FIP bias magnitude FIP dependent?	292
11.7	Number of free electrons in the photosphere	294
11.8	Summary	296
	<i>Appendix 1 Units</i>	297
	<i>Appendix 2 Line lists</i>	298
	<i>Glossary</i>	328
	<i>Further reading</i>	336
	<i>References</i>	337
	<i>Index</i>	346

Preface

Even those not engaged in solar physics will have noticed a huge increase in space observations of the solar atmosphere over the past few years. The last ten years especially have seen several notable space missions launched by NASA, the European Space Agency (ESA), the Japanese and Russian space agencies, and several other organizations, among which have been the *Yohkoh* and *RHESSI* X-ray spacecraft, *SOHO*, *TRACE*, and *CORONAS-F* which have on board high-resolution instruments working in the extreme ultraviolet spectrum, and most recently the *Hinode* and *STEREO* missions, both launched in late 2006, all of which are making spectacular observations in the visible, ultraviolet, and soft X-ray regions. Major contributions to our knowledge have also been made by rocket-borne instruments such as *SERTS* and *EUNIS*, working in the extreme ultraviolet.

The increase in our understanding of the solar atmosphere giving rise to this emission has been enormous as a direct result of studying the data from these instruments. We have built on the knowledge gained from previous large solar missions such as the *Skylab* mission and *Solar Maximum Mission* to develop models for the solar atmosphere and for phenomena such as flares and coronal mass ejections. However, to the dismay of some but the excitement of most, we are now presented with a picture of the solar atmosphere that is far more dynamic and complex than we ever expected from early spacecraft or ground-based telescopes. Consequently, it has really been the case that as fast as we solve some problems, others are created that will obviously need great ingenuity in finding satisfactory physical explanations. A case in point is the ever-elusive coronal heating problem, one that has been with us ever since the megakelvin temperatures of the solar corona were discovered, from optical spectroscopy, in the 1940s.

Much of our knowledge has come from studying images of phenomena, monochromatic or in broad-band ranges. But quantitative work, just as with studies of stars, begins with spectroscopic studies. Ultraviolet and X-ray spectra give us information about temperatures, densities, flow velocities, filling factors (indicating to what extent features are being spatially resolved), thermal structure, element abundances, ionization state of solar plasmas in the outer parts of the solar atmosphere: the chromosphere, the corona and the enigmatic transition region. They also allow insight into all phenomena in the solar atmosphere, e.g. flares, jets, and prominences.

Though there have been review articles and portions of textbooks devoted to solar spectroscopy in the ultraviolet and X-ray regions, no monograph has yet been written that specifically addresses this aspect. This book is meant to fill this gap in the literature. First,

Cambridge University Press

978-0-521-84160-3 - Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere

Kenneth J. H. Phillips, Uri Feldman and Enrico Landi

Frontmatter

[More information](#)x *Preface*

we review basic concepts in studies of the solar atmosphere, with descriptions of the properties of the various parts of the solar atmosphere and phenomena (Chapter 1). Then basic concepts in radiation from the solar atmosphere, from the photosphere outwards, are given, with applications specific to ultraviolet and X-ray spectroscopy (Chapter 2). Basic atomic theory, needed in understanding spectral line and continuum formation and interpretation, is given in Chapter 3, with descriptions of how lines and continua are formed (Chapter 4). We expect these two chapters to be most useful for students, postgraduates and others who wish to have a detailed understanding of atomic physics and how it relates to spectroscopy. How narrow-band images and spectral line ratios particularly are used in ‘diagnosing’ parts of the solar atmosphere, i.e. finding densities, temperatures, and other parameters, is dealt with in Chapter 5, including specific examples of lines that are suitable for diagnostic purposes (Chapter 6). A description of current and recent instrumentation is given in Chapter 7. Later chapters (8, 9, 10) review recent literature giving applications of spectroscopic techniques in the ultraviolet and X-ray bands to the quiet and active Sun and the particular case of solar flares. As the literature is now so extensive, this review has necessarily been subjective and has quite likely omitted work that others will consider important. We apologize to any who feel that their work is not justly treated in these chapters. This book was prepared as the first results from *Hinode* and *STEREO* were first being made available and we have made an attempt to include some of them here, but unfortunately not much more than a brief mention.

One of the most significant findings using ultraviolet and X-ray spectroscopy in recent years has been the discovery of departures of element abundances in the solar atmosphere from those in the solar photosphere, with a clear link to the first ionization potential (FIP) of these elements. This result first became clear in the study of solar wind and solar energetic particles, but spectroscopically determined abundances showed that this was also true for the solar corona and maybe other parts of the solar atmosphere. A more personal view on this topic is given in Chapter 11, with additional evidence that is not yet in the published literature.

Notes on units (following the still current usage in solar physics, we use the c.g.s. system), lists of emission lines in the solar ultraviolet and soft X-ray spectrum, and a glossary are also given.

We are grateful to the many colleagues who have helped us in the task of writing this book. We thank those who have allowed us to use figures and other results from their published works; their names are acknowledged in figure captions. Data from many spacecraft missions are freely available from web-based sources, and we have taken advantage of obtaining images and spectra accordingly. We particularly acknowledge teams of scientists who have made these data sources available to us and to the solar community generally. We are also indebted to colleagues who offered their time to read portions of the book manuscript, and who have helped enormously by making very helpful suggestions or correcting our misconceptions. They are: A. K. Bhatia, J. L. Culhane, J. M. Laming, M. Landini, J. C. Raymond. Acknowledgement is made to colleagues who have worked on the CHIANTI database and software package, which is a collaborative project involving the US Naval Research Laboratory, Rutherford Appleton Laboratory, Mullard Space Science Laboratory, the Universities of Florence (Italy) and Cambridge (UK), and George Mason University (USA). We are grateful to our institutes, Mullard Space Science Laboratory (University College London) and Naval Research Laboratory (the US Department of the Navy) for their support during the writing of this book.