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 Aereonomie, 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.

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KENNETH J. H. PHILLIPS
Mullard Space Science Laboratory

URI FELDMAN
Artep Inc.

ENRICO LANDI
US Naval Research Laboratory

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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,

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.