The Analysis of Starlight

This is the story of the analysis of starlight by astronomical spectroscopy, spanning from Joseph Fraunhofer's discovery of spectral lines in the early nineteenth century through to around the year 2000. In addition to the key discoveries, it presents the culture and social history of stellar astrophysics by introducing the leading astronomers, and their struggles, triumphs and disagreements. Basic concepts in spectroscopy and spectral analysis are included, so both observational and theoretical aspects are described, in a nonmathematical framework. This new edition covers the final decades of the twentieth century, with its major advances in stellar astrophysics: the discovery of extrasolar planets, new classes of stars and the observation of the ultraviolet spectra of stars from satellites. The in-depth coverage of the subject makes it essential reading for graduate students working in stellar spectroscopy, as well as a major reference for professional and amateur astronomers and historians of science.

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The Analysis of Starlight: Two Centuries of Astronomical Spectroscopy

Second Edition

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Contents

Preface to the second edition

The first edition of this book was published more than a quarter century ago, and at the time of writing this it has long been out of print and is also out of date.

In 2007 I decided to up-date it with this second edition. The main purpose was to bring the story of stellar spectroscopy forwards from about 1970, the closing date for material in the first edition, to about 2000. A secondary aim was to correct a number of typographical and factual errors that had crept into the first edition. The first edition manuscript was mainly handwritten and typed by a secretary prior to submission in the days before computers were widespread for text formatting. On the other hand, this second edition was prepared using LaTeX which has (I hope) permitted a much lower error rate. I entered the entire manuscript at a keyboard myself, so I am solely responsible if any typographical errors remain.

Since 1970 there has been a huge advance in all fields of astronomy, especially in stellar astrophysics and spectroscopy. In fact, about as many papers on stellar spectroscopy have been published in the research literature in the last three decades of the twentieth century as in all the time before 1970. During these last few decades since the publication of the first edition, many discoveries were made using stellar spectroscopy, and there were also important instrumental advances in spectrograph design. The discoveries and advances included the first extrasolar planets, the discovery of extremely metal-poor stars, the discovery of failed stars called brown dwarfs and the extension of the spectral classification system (spectral types L and T) to account for their spectra, the analysis of stellar spectra with new techniques using departures from local thermodynamic equilibrium, the measurement of new precise oscillator strengths for many spectral lines, the discovery from UV spectroscopy of a coronal gas phase in the interstellar medium, the observation of the brightest naked eye supernova for nearly four centuries, an analysis of the chemical evolution of the Galaxy from measurements of element abundances in stars and of stellar ages, age measurements of stars from the abundances of radioactive elements uranium and thorium in their atmospheres, the discovery of amazing new stars with truly bizarre spectra (such as SS433 and FG Sagittae), and much more. In instrumentation there has been the introduction of electronic detectors such as the CCD, diode arrays and photon-counting devices, the introduction of the échelle grating to astronomical spectrographs, the first use of optical fibres to link telescopes to bench-mounted spectrographs, and the advent of ultraviolet spectroscopy from space (including the Hubble Space Telescope and its predecessors, such as the IUE satellite).

Given that about as many papers based on stellar spectroscopy were published from 1970 to 2000 as before 1970, one might suppose that the length of this second edition should have doubled. This is far from the case, and the choice of topics presented is highly selective (being my personal choice), and the discussion is much less comprehensive for the last few decades of the twentieth century. For example, the fact that nearly 50 000 refereed papers on peculiar A-type stars were published in the years 1971–2000 illustrates the necessity for being highly selective in the papers cited. In the first edition there were about 1600 references to original papers in the literature, whereas in this edition this number is well over 2200. Most of the increase is in the last four chapters of the book covering the developments of the late twentieth century.

I consider *The Analysis of Starlight* to be essential reading for any graduate student working in stellar spectroscopy, and no doubt many practising stellar astronomers will find some information here they may not be familiar with, but that they ought to know! In addition, amateur astronomers and historians of science may find this volume useful. The level of mathematical detail has deliberately been minimized to make the work more accessible to these latter readers. Some may read the book straight through for enjoyment, while others just use it as a reference book. The citation of more than 2200 original papers in the scientific literature and the referencing of nearly 9500 index citations in the four indexes should enhance the book's utility as a reference work.

I started the work of preparing this second edition in 2009, when I went to the Instituto de Astrofisica de Andalucía in Granada, Spain, where I spent five months from March of that year. I am grateful to Dr Alberto Castro-Tirado for hosting my visit. During my time in Spain I also visited the excellent astronomical library at the Observatorio

Real de la Armada in San Fernando near Cádiz. I am grateful to the librarian there, Dr Francisco González, for facilitating my visit.

I continued work on the second edition at the Institute of Astronomy in Cambridge, England, in 2011, during a two-month visit as a Visiting Scholar at Trinity College Cambridge. I am grateful to Lord Rees, then the Master of Trinity, for supporting my visit and to Professor Gerry Gilmore at the Institute of Astronomy for acting as a host. Mark Hurn, the institute's librarian, was especially helpful in introducing me to the library. I am grateful to the Erskine Fund of the University of Canterbury for support for my travels to Cambridge.

Apart from these two locations in Europe, I completed a large part of the work for the second edition at the University of Canterbury in Christchurch, in spite of the disruption of four major earthquakes during the time that this work was in progress.

Preface to the first edition, 1986

My main motivation for writing this book was an act of self-indulgence. As a hobby I enjoyed delving into the earlier literature of astronomical spectroscopy. As a practising observational astronomer, I found it especially refreshing to have a feel for the way the topic had developed, and to be able to glimpse at the lives of some of the early pioneers in stellar spectroscopy.

My hobby began in 1974 when I was at the Observatoire de Paris-Meudon on a fellowship. I frequently browsed in the excellent library there, and one day I began reading the collected papers of the eminent English astronomer Sir William Huggins, one of the founders of stellar spectroscopy. Huggins' lucid and eloquent papers and his many remarkable achievements provided the inspiration from which my interest developed further, to form the basis for this book.

However, I had little time to pursue these interests very intensively until 1981, when an opportunity arose that allowed me to spend a year in Germany with the support of the Alexander von Humboldt Foundation, while on sabbatical from the University of Canterbury. I went to the Landessternwarte (State Observatory) in Heidelberg and resolved to spend most of my time there researching and writing a book on the development of stellar spectroscopy.

This book is not primarily intended for the science historian, nor is it a popular book for the layman, although I hope that readers in both these categories may find material here which is useful or interesting. Instead I have aimed at writing for the practising astronomer what is essentially an interpreted guide to the literature covering the development of observational stellar spectroscopy. For this reason I have placed a lot of emphasis on providing a good list of references to the original material. The primary sources are the papers in journals and observatory publications. I have generally avoided citing secondary references (with a few exceptions), such as modern commentaries by science historians.

A typical review paper in astronomy or any scientific discipline might devote an introductory paragraph to a brief historical summary, covering the subject over the past half century or so. The next several dozen pages might then discuss what has been achieved in the last five or at most ten years. This format is fine, and the review paper has an important role to play in today's world with its phenomenal growth in recent scientific literature. What I view less kindly is when that brief historical introduction is inaccurate and improperly researched. I know of several by distinguished authors with erroneous facts in the historical introductions; I trust that the readers of this book will not perpetuate such mistakes.

The method I have adopted here is just the reverse of the modern review article. For each topic I have deliberately emphasized the earlier references, so as to give precedence to whoever first entered a new field or established a new fact. On the other hand, for the more recent work up to 1965, I have generally been progressively briefer and more selective in the choice of material cited. I warn all readers that this is not a textbook of modern astrophysics; between 1965 and 1970 the treatment is not comprehensive, and developments after 1970 are not covered here at all.

I found the Landessternwarte library in Heidelberg an excellent place to work on the manuscript of this book. For historical purposes it houses a collection of outstanding importance; in addition it is one of the least regulated libraries I have ever come across – no fixed library hours, no full-time librarian and no limits to loans either in time or in quantity of books. I spent a year in this paradise researching and writing about two-thirds of this manuscript. The remainder was written at the University of Canterbury in Christchurch between 1982 and 1985. In addition to the libraries at the Landessternwarte and the University of Canterbury, I referred to material in the libraries at the University of Heidelberg, the Physikalische Institute, Heidelberg, the Göttingen Observatory, the Observatoire de Paris and the Observatoire de Meudon, the Carter Observatory, Wellington, New Zealand, and the Niels Bohr Library at the American Institute of Physics in New York City. I am grateful to all these places for their kind assistance and for permission to use their excellent resources.

The scope of this book in the period it covers is discussed in Section 1.1. The main emphasis is the century and a half from Fraunhofer's first observations of solar and stellar spectra to about 1965. The subject matter is observational stellar spectroscopy. Occasionally I have treated theoretical topics (for example, model atmosphere theory) if

these seemed indispensable to the discussion of the observations and their immediate interpretation. The development of solar physics has been covered only where this was essential for an understanding of stellar physics. Therefore some of the early nineteenth-century work in solar spectroscopy is dealt with. On the other hand, later work of real importance in solar spectroscopy for the Sun, such as Samuel Pierpont Langley's infrared bolometry of sunlight, I have omitted altogether, as this work did not immediately lead to corresponding advances in stellar research.[1] Similarly I have included some mention of the spectroscopy of gaseous nebulae, because it was generally supposed in the early days of spectral classification that nebular spectra could be incorporated into the classification of stellar spectra as part of a continuous sequence. The spectra of external galaxies I consider to comprise another topic of equal importance to stellar spectra, but whose historical development is best segregated from that of individual stars. It is not treated here at all.

A textbook in modern astronomy should only use S.I. (Système International) units, though regrettably not all do. However, I found adherence to this rule inconvenient here. For example, many quoted passages refer to line wavelengths in Angstrom units and not nanometres. I have therefore adopted the Angstrom unit as the unit of wavelength. American and British astronomers until recently have almost invariably referred to the apertures of their telescopes in inches, so much so that appellations such as the Mt Wilson '100-inch telescope' have become familiar names rather than mere measures of a telescope's dimension. In view of this it seemed pedantic to change all the old and familiar references to telescopes in inches into metric units. I have therefore compromised and employed both imperial and metric units for telescopes in this book, whichever was the appropriate choice in each instance.

I have included numerous quotations from original works; for those that appeared originally in French or German, the translations are my own. I have included the dates of astronomers referred to in the text in many cases. Where a name is not followed by dates, this is because the dates appeared earlier in the book, or because it is only a passing reference to that individual, or (in a few cases) because I was unable to ascertain the dates after a brief search.

[1] The development of solar spectroscopy is covered in my book *Astronomical spectrographs and their history*, published by Cambridge University Press in 2009.

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My acknowledgement and thanks to all those who gave advice or made figures available for the first edition automatically continue for the second edition, as most of the earlier content reappears here.

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