

Cambridge University Press

978-0-521-85186-2 - The Observation and Analysis of Stellar Photospheres

David F. Gray

Frontmatter

[More information](#)

THE OBSERVATION AND ANALYSIS OF STELLAR PHOTOSPHERES

Most of what we know about stars is learned from studying the light from their photospheres. *The Observation and Analysis of Stellar Photospheres* describes the equipment, observational techniques, and analysis used in the investigation of stellar photospheres. This third edition builds on the success of the previous editions, improving the presentation, and revising topics and results to keep up-to-date with the latest research. Exercises have been added for each chapter.

The first half of the book develops the tools of analysis and the second half demonstrates how they can be applied. Topics covered include radiation transfer, models of stellar photospheres, spectroscopic equipment, how to observe stellar spectra, and techniques for measuring stellar temperatures, radii, surface gravities, chemical composition, velocity fields, and rotation rates. Up-to-date results for real stars are included. Useful data can be found throughout the text and in the appendices, and there are extensive references to the primary literature.

This textbook is for advanced undergraduate and graduate students studying stellar atmospheres or stellar physics. It presents introductory material from the basics and develops it to a professional level. It is ideal for use on university courses, and also includes a wealth of reference material useful to research scientists.

DAVID F. GRAY is Director of the Elginfield Observatory and Professor of Astronomy at the University of Western Ontario, London, Canada, where he has held positions since 1966. He has served on, organized and chaired advisory committees for organizations such as the International Astronomical Union, the Canadian Astronomical Society, and the Canada–France–Hawaii Telescope. He was president of Commission 36, on the Theory of Stellar Atmospheres between 1988 and 1991, and served on the observing-time allocation panel of the Hubble Space Telescope in 1996.

Professor Gray has published numerous papers in journals including *The Astrophysical Journal*, *Publications of the Astronomical Society of the Pacific*, *The Astronomical Journal*, *Nature*, and *Solar Physics*. He has written or contributed chapters to several books, and previous editions of this book have been used widely, including translations into Russian and Chinese. He has also edited three volumes of conference proceedings for the IAU. He is a member of the Canadian Astronomical Society, the International Astronomical Union, the Astronomical Society of the Pacific, Sigma Xi Honorary Society, and the American Astronomical Society.

Cambridge University Press
978-0-521-85186-2 - The Observation and Analysis of Stellar Photospheres
David F. Gray
Frontmatter
[More information](#)

THE OBSERVATION AND
ANALYSIS OF STELLAR
PHOTOSPHERES

DAVID F. GRAY

University of Western Ontario, London, Ontario, Canada



Cambridge University Press
978-0-521-85186-2 - The Observation and Analysis of Stellar Photospheres
David F. Gray
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo
Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK
Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521851862

© C. D.F. Gray 2005

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 2005

Printed in the United Kingdom at the University Press, Cambridge

A record for this publication is available from the British Library

Library of Congress in Publication data

ISBN-13 978-0-521-85186-2
ISBN-10 0-521-85186-6

Contents

<i>Preface to the first edition</i>	<i>page</i> xiii
<i>Preface to the second edition</i>	xv
<i>Preface to the third edition</i>	xvi
1 Background	1
What is a stellar atmosphere?	1
Spectral types	3
Magnitudes and color indices	7
The Hertzsprung–Russell diagram	10
The gas laws	10
The velocity distributions	12
Atomic excitation and ionization in thermodynamic equilibrium	13
Stellar catalogues, tables, and atlases	18
<i>References</i>	20
<i>Questions and exercises</i>	22
2 Fourier transforms	26
The definition	26
Some common transforms	29
Data sampling and data windows	34
Convolutions	36
Convolution with a δ -function	37
Convolutions of Gaussians and dispersion profiles	38
Resolution: our blurred data	39
Sampling and aliasing	40
Useful theorems	42
Numerical calculation of transforms	43

vi	<i>Contents</i>	
	Noise transfer between domains	45
	Time-series analysis	47
	<i>References</i>	50
	<i>Questions and exercises</i>	50
3	Spectroscopic tools	52
	Spectrographs: some general relations	52
	Diffraction gratings	54
	The blazed reflection grating	61
	Wavelength of the true blaze	65
	Shadowing	67
	Grating ghosts	69
	Dispersion, slit magnification, and spectral resolution	72
	Echelle spectrographs	75
	Multi-object spectroscopy	78
	Spectra from interferometers	78
	Aspects of telescopes	83
	<i>References</i>	85
	<i>Questions and exercises</i>	87
4	Light detectors	89
	Quantum efficiency and spectral response	90
	Linearity	90
	Silicon-diode arrays	92
	Background and cosmic rays	95
	Noise in the measurements	96
	Choosing a detector to maximize s/n	97
	Dynamic range and well capacity	99
	Measuring the noise of a detector	100
	Spatial resolution	101
	Photomultiplier tubes	104
	The photographic plate	105
	<i>References</i>	106
	<i>Questions and exercises</i>	106
5	Radiation terms and definitions	107
	Specific intensity	107
	Flux	109
	The K integral and radiation pressure	111
	The absorption coefficient and optical depth	113

	<i>Contents</i>	vii
	The emission coefficient and the source function	113
	Pure isotropic scattering	114
	Pure absorption	115
	The Einstein coefficients	115
	<i>Questions and exercises</i>	117
6	The black body and its radiation	118
	Observed relations	119
	Planck’s radiation law	121
	Numerical values of black-body radiation	123
	The black body as a radiation standard	124
	<i>References</i>	125
	<i>Questions and exercises</i>	125
7	Radiative and convective energy transport	127
	The transfer equation and its formal solution	127
	The transfer equation for different geometries	129
	The flux integral	133
	The mean intensity and <i>K</i> integrals	134
	Exponential integrals	134
	Radiative equilibrium	136
	The grey case	139
	Convective transport	141
	Conditions for convective flow	143
	The mixing-length formulation	144
	<i>References</i>	145
	<i>Questions and exercises</i>	146
8	The continuous absorption coefficient	147
	The origins of continuous absorption	147
	The stimulated emission factor	148
	Neutral hydrogen	149
	The negative hydrogen ion	154
	Other hydrogen continuous absorbers	157
	Absorption by helium	158
	Electron scattering	160
	Other sources of continuous absorption	163
	Line opacity	165
	The total absorption coefficient	166
	<i>References</i>	167
	<i>Questions and exercises</i>	169

viii	<i>Contents</i>	
9	The model photosphere	170
	The equation of hydrostatic equilibrium	171
	The temperature distribution in the solar photosphere	174
	Temperature distributions in other stars	178
	The $P_g - P_e - T$ relation	181
	Completion of the model	185
	The geometrical depth	185
	Computation of the spectrum	186
	Properties of models: pressure relations	189
	The effects of chemical composition	193
	Changes with effective temperature	196
	Tabulations of model photospheres	197
	Reflection	198
	<i>References</i>	200
	<i>Questions and exercises</i>	202
10	The measurement of stellar continua	204
	Ultra-low-resolution spectrographs	205
	Observations using standard stars	206
	Absolute calibration of standard stars	207
	Photometric standard stars	213
	Observations of stellar continua	213
	Continua from photospheric models	215
	Line absorption	218
	Comparison of model to stellar continua	219
	Luminosity and bolometric flux	223
	<i>References</i>	227
	<i>Questions and exercises</i>	229
11	The line absorption coefficient	231
	The natural atomic absorption	232
	Damping constants for natural broadening	236
	Pressure broadening	238
	The impact approximation	240
	Theoretical evaluation of the collisional damping constant	242
	Numerical values for collisions with charged perturbers	244
	Numerical values for collisions with neutral perturbers	245
	Hydrogen line broadening	247
	Thermal broadening	253
	Microturbulence	254

	<i>Contents</i>	ix
	Combining absorption coefficients	255
	Hyperfine and isotopic splitting	259
	The mass absorption coefficient for lines	260
	Comments	261
	<i>References</i>	262
	<i>Questions and exercises</i>	264
12	The measurement of spectral lines	265
	The coude grating spectrograph	266
	The Bowen image slicer	270
	Fiber-optics slicers	270
	The Richardson image slicer	270
	Diffraction gratings for precise spectral-line work	273
	Spectrograph cameras	273
	The instrumental profile	274
	The restoration process	277
	Noise and its complications	278
	Fourier noise filters	280
	The discrete Fourier transform	283
	δ -function spectra	284
	Measurement of the instrumental profile	286
	Scattered light	287
	Measurement of scattered light	288
	Corrections for scattered light	290
	Continuum normalization	291
	Determination of the dispersion and the wavelength scale	292
	Line measurements with low resolution	293
	Measurement of line broadening and shape	295
	Measurement of asymmetry	297
	Measurement of line position	299
	<i>References</i>	300
	<i>Questions and exercises</i>	302
13	The behavior of spectral lines	304
	The line transfer equation	304
	The line source function	305
	The level populations	308
	Other formalisms for S_v	309
	Computation of a line profile in LTE	310
	Contribution functions and the depth of formation of spectral lines	313

x	<i>Contents</i>	
	The behavior of line strength	314
	The temperature dependence	315
	The pressure dependence	320
	The abundance dependence	326
	Comment	330
	<i>References</i>	335
	<i>Questions and exercises</i>	336
14	The measurement of stellar radii and temperatures	338
	Interferometers	339
	Lunar occultations	340
	Eclipsing binaries	342
	Radii from bolometric flux	343
	Photometric radii: a simpler method	344
	The surface-brightness method	346
	Inferred radii: the radius calibration	348
	Measured effective temperatures	350
	Stellar temperatures from model photospheres	351
	Inferred temperatures: the temperature calibration	352
	“Generalized” temperatures	354
	The Paschen continuum	354
	Color indices: synthetic colors	355
	The Balmer jump	356
	Hydrogen lines	356
	Metal lines as temperature indicators	357
	<i>References</i>	360
	<i>Questions and exercises</i>	363
15	The measurement of photospheric pressure	365
	The continuum as a pressure indicator	366
	The hydrogen lines	367
	Other strong lines	369
	The weak lines	371
	The gravity–temperature diagram	372
	Empirical indicators of gravity	374
	The helium abundance	376
	Binaries for calibration	377
	Inferred surface gravity	377
	<i>References</i>	380
	<i>Questions and exercises</i>	382

	<i>Contents</i>	xi
16	Chemical analysis	384
	What can be determined	385
	Direct computational analysis	386
	Curves of growth for analytical models: an historical note	387
	Scaling relations	387
	Temperature effects	391
	Surface gravity effects	391
	Saturation: the flat part of the curve of growth	393
	A reference curve of growth	396
	Derivation of abundances	397
	Differential analysis	399
	The synthesis method	400
	Abundance indices	402
	The solar chemical composition	403
	Stellar abundances: summaries	406
	Galactic variations	407
	Evolutionary changes: lithium	409
	Evolutionary changes: carbon	412
	Chemically peculiar stars	413
	Comments	415
	<i>References</i>	415
	<i>Questions and exercises</i>	421
17	Velocity fields in stellar photospheres	423
	Examples of velocity broadening	424
	Solar velocity fields	426
	Modeling the motions	428
	From velocity to spectrum	429
	Microturbulence in line computations	430
	Macroturbulence in line computations	431
	(Fictitious) isotropic macroturbulence	432
	Radial–tangential anisotropic macroturbulence	433
	Including rotation	434
	Disk integration mechanics	437
	Fourier analysis for turbulence	439
	Some results from line broadening	442
	Line asymmetries	443
	The stellar case: cool stars	447
	The stellar case: hot stars	449
	The granulation boundary	450

xii	<i>Contents</i>	
	Modeling line bisectors	451
	<i>References</i>	454
	<i>Questions and exercises</i>	456
18	Stellar rotation	458
	The Doppler-shift distribution	460
	The rotation profile	461
	Profile fitting for $v \sin i$	467
	Profile width as a measure of $v \sin i$	470
	Fourier analysis for large $v \sin i$	471
	Transform width as a measure of $v \sin i$	475
	Fourier analysis for moderate to small rotation	475
	Additional aspects of spectroscopic rotation analysis	477
	Statistical corrections for axial projection	482
	Rotational modulation	483
	Rotation of dwarfs	485
	Rotation of evolved stars	488
	Rotation and magnetic activity	490
	Rapid rotators	492
	Rotation of binary stars	495
	Rotational mapping	496
	<i>References</i>	499
	<i>Questions and exercises</i>	504
	Appendix A. A table of useful constants	505
	Appendix B. Physical parameters of stars	506
	Appendix C. A fast Fourier transform Fortran program	509
	Appendix D. Atomic data	511
	Appendix E. The strongest lines in the solar spectrum	521
	Appendix F. Computation of random errors	522
	<i>Index</i>	525

Preface to the first edition

The remarkable nature of stars is transmitted to us by the light they send. The light escapes from the outer layers of the star – called, by definition, the atmosphere. The complete atmosphere of a star can be viewed comprehensively as a transition from the stellar interior to the interstellar medium. And yet almost the whole visible stellar spectrum comes from a relatively thin part called the photosphere. Obviously we cannot disconnect the photosphere from the adjacent portions of the atmosphere, but in actual fact it is the only region we can study extensively for most stars. It is for this reason that the photosphere has taken its place as the central theme of this book.

Several books have appeared during the last decade dealing with the *theory* of stellar atmospheres. These works are for the most part excellent. It is to the material largely omitted by these books that the present treatise is directed. My students and I have felt for some time the need of a book that presents the basics of the field through the eyes of an observer and analyzer of stellar atmospheres.

An introduction to a subject, in my opinion, should be presented in a way that can be understood by a reader who has not studied the topic before. It follows that the material should be presented in as simple and straightforward a manner as possible. The Fourier transform (as covered in Chapter 2) is a unifying theme helping to accomplish this aim. Transforms lead naturally into the material on data collection, optical instruments, the instrumental profile, line absorption coefficients, velocity fields, and spectral line analysis. In addition, I have selected and developed topics that I consider to be important to those of us who look at stars and attempt to understand what we see. At the same time, I have tried to present the material in the least complicated manner. The word “complicated” is affixed to things that are difficult to understand. Complicated things consequently are often unsuitable topics for the novice. We should seek not the most general case conceivable, but the least complicated case that is serviceable (a version of the principle of minimum assumption).

Cambridge University Press

978-0-521-85186-2 - The Observation and Analysis of Stellar Photospheres

David F. Gray

Frontmatter

[More information](#)

xiv

Preface

The development of each of the main topics starts at an elementary level, proceeds with a discussion of the topic, and ends by pointing the direction to the more advanced literature. It should be easy to expand from this book into the areas holding an attraction for you. Realizing that astrophysics is a very dynamic field, I have documented (or otherwise made clear) the source of the material used in examples. When no source is indicated, the material is from observations or calculations of my own. The references in general have been selected because they are good illustrations of the material being discussed or because they have a basic lasting approach to the subject. I have also biased the referencing toward good starting points in the literature and toward review articles and journals to which the student is likely to have access. The references are listed at the end of each chapter and ordered according to the author's name and date of publication.

The first two chapters contain preparatory material. The main theme starts in Chapter 3 with a discussion of spectroscopic tools. Generally the continuous spectrum topics are developed first, followed by the somewhat more involved subject of the line spectrum. From Chapter 14 (Chemical analysis) through to Chapter 18, the material is oriented completely toward analysis and deduction. These later chapters are closely interlinked with the preceding chapters.

The book is suitable as a text for a one-year course and as a reference to the more advanced reader.

Preface to the second edition

Wonderful growth has occurred in our understanding of stellar photospheres during the 15 years since the appearance of the first edition of “Photospheres.” I have managed to retain the same chapter names and the general plan of the first edition, and many of the equation numbers are also the same. But a significant portion of the material is new or revised. A revolution in light detectors has given us hundreds of times greater efficiency in measuring stellar spectra; Chapter 4 on detectors has been re-done. The astronomical literature is burgeoning with new results on the structure of photospheres, chemical abundances, radius measurements, stellar rotation, and photospheric velocity fields. Many of these results have been incorporated in this second edition, of course. At the same time, I stayed with my original purpose of making this volume an introduction to the subject. Unhappily, this means leaving out numerous exciting topics. My book *Lectures* (Gray 1988) takes up some of these, and it is recommended as a second installment, after the material in “Photospheres” has been mastered.

More than ever, the reader should keep in mind the fundamental nature of the stellar photosphere: of interest in its own right, with marvelous and intriguing physics, yet the link between the interior and chromospheres, coronae, and interstellar surroundings, and the source of most of our basic information about stars and stellar systems.

Once again, I thank my students and colleagues for their help and patience.

Reference

Gray, D.F. 1988. *Lectures on Spectral-Line Analysis: F, G, and K Stars* (Arva, Ontario: The Publisher).

Preface to the third edition

Studies of stars continue to flourish. More detailed and sophisticated observations continue to be made, analysis tools are honed, understanding grows for more complex situations. The beauty of the stars is integrated more fully into our lives. I hope you enjoy the many revisions incorporated in this third edition of *Photospheres*: new figures, more complete data sets, re-organization of some of the material, a cleaner presentation of several topics, and some exercises and questions to help you probe the material.

I extend my thanks to J. Power for proofreading and to the many others who have guided my thoughts, given me corrections and suggestions, and contributed their efforts to knowing the stars.