## THE OBSERVATION AND ANALYSIS OF STELLAR PHOTOSPHERES

## DAVID F. GRAY

University of Western Ontario, London, Ontario, Canada



## Contents

.

	Preface to the first edition	<i>page</i> xiii
	Preface to the second edition	XV
	Preface to the third edition	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
	References	20
	Questions and exercises	22
2	Fourier transforms	26
	The definition	26
	Some common transforms	29
	Data sampling and data windows	34
	Convolutions	36
	Convolution with a $\delta$ -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

Contents

	Noise transfer between domains	45
	Time-series analysis	47
	References	50
	Questions and exercises	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
	References	85
	Questions and exercises	87
4	Light detectors	89
	Quantum efficiency and spectral response	90
	Linearity	90
	Silicon-diode arrays	92
	•	
	Dackground and cosinic rays	95
	Background and cosmic rays Noise in the measurements	95 96
	Noise in the measurements	
	Noise in the measurements Choosing a detector to maximize $s/n$	96
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity	96 97
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector	96 97 99
	Noise in the measurements Choosing a detector to maximize $s/n$ Dynamic range and well capacity Measuring the noise of a detector Spatial resolution	96 97 99 100 101
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes	96 97 99 100 101 104
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate	96 97 99 100 101 104 105
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes	96 97 99 100 101 104
	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate <i>References</i>	96 97 99 100 101 104 105 106
5	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate <i>References</i>	96 97 99 100 101 104 105 106
5	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate <i>References</i> <i>Questions and exercises</i>	96 97 99 100 101 104 105 106 106
5	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate <i>References</i> <i>Questions and exercises</i> <b>Radiation terms and definitions</b>	96 97 99 100 101 104 105 106 106 106
5	Noise in the measurements Choosing a detector to maximize <i>s/n</i> Dynamic range and well capacity Measuring the noise of a detector Spatial resolution Photomultiplier tubes The photographic plate <i>References</i> <i>Questions and exercises</i> <b>Radiation terms and definitions</b> Specific intensity	96 97 99 100 101 104 105 106 106

vi

	Contents	vii
	The emission coefficient and the source function	113
	Pure isotropic scattering	114
	Pure absorption	115
	The Einstein coefficients	115
	Questions and exercises	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
	References	125
	Questions and exercises	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 K 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
	References	145
	Questions and exercises	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
	References	167
	Questions and exercises	169

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
	References		200
	Questions and exercises		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	ì	223
	References		227
	Questions and exercises		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

viii

	Contents	ix
	Combining absorption coefficients	255
	Hyperfine and isotopic splitting	259
	The mass absorption coefficient for lines	260
	Comments	261 -
	References	262
	Questions and exercises	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
	References	300
	Questions and exercises	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

Co	nt	er	its

	The behavior of line strength		314
	The temperature dependence		315
	The pressure dependence		320
	The abundance dependence	- ·	- 326
	Comment		330
	References		335
	Questions and exercises		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
1	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
	References	Ϋ́,	360
	Questions and exercises	l.	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
	References		380
	Questions and exercises		382

х

.

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
	References	415
	Questions and exercises	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

	Modeling line bisectors		451
	References		454
	Questions and exercises		456
1	8 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
	References		499
	Questions and exercises		504
A	Appendix A. A table of useful constants		505
A	Appendix B. Physical parameters of stars		506
A	Appendix C. A fast Fourier transform Fortran program		509
A	Appendix D. Atomic data	,	511
A	Appendix E. The strongest lines in the solar spectrum		521
A	Appendix F. Computation of random errors		522
I	ndex	۰.	525

ν

xii