CONTENTS

Preface xi
Acknowledgements xiii

1 Physical Basics of Spectroscopy 1

1.1 Photons: Carriers of Information and Energy 1

1.1.1 Photons: Carriers of Information 1

1.1.2 The Wave–Particle Duality 1

1.1.3 The Quantization of Electromagnetic Radiation 2

1.1.4 Photons: Carriers of Energy 2

1.1.5 Other Properties of Photons 2

1.2 The Electromagnetic Spectrum 2

1.2.1 The Usable Spectral Range for Amateurs 2

1.2.2 The Selection of the Spectral Range 2

1.2.3 Terminology of the Spectroscopic Wavebands 3

1.3 Wavelength and Energy 3

1.3.1 Preliminary Remarks 3

1.3.2 Units for Energy and Wavelength Applied in Spectroscopy 3

1.3.3 Planck’s Energy Equation 4

1.4 The Continuum and Blackbody Radiation 4

1.4.1 The Blackbody as a Physical Model for Stellar Radiation 4

1.4.2 Planck’s Radiation Law and Course of the Continuum Level 5

1.4.3 Wien’s Displacement Law 5

1.4.4 Effective Temperature $T_{\text{eff}}$ and the Stefan–Boltzmann Law 5

2 Electron Transitions and Formation of the Spectra 7

2.1 Simple Textbook Example: The Hydrogen Atom 7

2.2 Transition Types and Probabilities 8

2.2.1 Absorption 8

2.2.2 Emission 8

2.2.3 Ionization 8

2.2.4 Recombination 8

2.2.5 Electrons in the Free–Free Mode 9

2.3 Definitions and Notation 9

2.3.1 Ionization Stage versus Degree of Ionization 9

2.3.2 Astrophysical Notation for the Ionization Stage 9

2.4 The Hydrogen Spectral Series 9

2.4.1 The Photon Energy at the Wavelengths of the H-Balmer Series 9

2.4.2 The Photon Energy of Electron Transitions 10

2.4.3 Quantified Orbital Energy Level Diagram of the H-Balmer Series 10

2.4.4 The Lyman Limit of Hydrogen 10

2.4.5 The Balmer and Rydberg Equations 10

2.4.6 The Balmer, Paschen and Bracket Continua 11

2.5 Formation and Typology of Astronomical Spectra 11

2.5.1 Overview 11

2.5.2 The Three Basic Types of Spectra in the Context of the Sun 13

2.5.3 Molecular Absorption Band Spectrum 13

2.5.4 Molecular Absorption Band with Inversely Running Intensity Gradient 13

2.5.5 Composite or Integrated Spectrum 13

2.5.6 Reflectance Spectrum 14

3 Quantum Mechanical Aspects of Spectroscopy 15

3.1 Quantum Mechanical View of Transition Probabilities 15

3.2 The Energy Levels of Multi-Electron Atoms 16

3.2.1 The Quantum Numbers $n$, $l$, $m$, and $s$ and Parity Operator $P$ 16

3.2.2 Dipole Transitions, Laporte Rule and Forbidden Transitions 17

3.2.3 Grotrian Diagrams of Astrophysical Interest 18

3.2.4 Spectroscopic Notation: The Term Symbol 18

3.2.5 The Hyperfine Structure 19

3.3 The Schrödinger Equation 20

3.3.1 Preliminary Remarks 20

3.3.2 De Broglie’s Electron Wave Model 20

3.3.3 The Schrödinger Equation and Astronomical Spectroscopy 21

3.3.4 Time-independent and Time-dependent Forms 21

3.3.5 Hydrogen 22
4
Types and Function of Dispersive Elements

4.1 Physical Principle of Dispersion
  4.1.1 Preliminary Remarks
  4.1.2 Dispersion by Refraction
  4.1.3 Dispersion by Diffraction

4.2 The Dispersive Principle of Prism Spectrographs
  4.2.1 Specific Glass Types for Prism Spectrographs
  4.2.2 Minimum Angle of Deviation and Angular Dispersion
  4.2.3 Resolving Power: A Measure of Performance
  4.2.4 Practical Applications of Prisms Today

4.3 The Dispersive Principle of Grating Spectrographs
  4.3.1 The Grating Equation
  4.3.2 Manufacturing Process and Performance Parameters
  4.3.3 Angular Dispersion
  4.3.4 Grating Diffraction Efficiency

5
Types and Function of Spectrographs

5.1 Slitless Spectrographs with Transmission Grating
  5.1.1 Available Transmission Gratings

5.2 Slit Spectrographs with Reflection or Transmission Grating
  5.2.1 The Classical Concept
  5.2.2 The Littrow Design
  5.2.3 Configurations and Options for the Development of Slit Spectrographs
  5.2.4 Anamorphic Magnification
  5.2.5 Spectrograph Throughput and Etendue

5.3 Commercial Slit Spectrographs for Amateur Applications
  5.3.1 ALPY, Shelyak Instruments
  5.3.2 DADOS, Baader Planetarium
  5.3.3 Lhires III, Shelyak Instruments
  5.3.4 LISA, Shelyak Instruments
  5.3.5 Minispec, Astro Spectroscopy Instruments
  5.3.6 Spectra L200, JTW Astronomy
  5.3.7 Starlight Xpress SX, Starlight Xpress

5.4 Echelle Spectrograph
  5.4.1 Overview
  5.4.2 Basic Designs of Echelle Spectrographs

5.5 Commercial Echelle Spectrographs for Amateur Applications
  5.5.1 BACHES Spectrograph, Baader Planetarium
  5.5.2 eShel, Shelyak Instruments
  5.5.3 SQUES, Eagle optics

5.6 Czerny–Turner Spectrograph
  5.6.1 Overview
  5.6.2 Application of Czerny–Turner Spectrographs for Amateurs

6
Recording of the Spectra

6.1 Visual Observation of Spectra
  6.1.1 Scotopic or Nighttime Vision
  6.1.2 Photopic or Daytime Vision

6.2 Recording of Spectra with Electronic Image Sensors
  6.3 The Recording System: Telescope, Spectrograph and Camera
  6.3.1 Preliminary Remarks
  6.3.2 Limiting Magnitude of the System
  6.3.3 Exposure Times for Grating Spectrographs
  6.3.4 Pixel Size and Sampling with Slit Spectroscopy
  6.3.5 Determination of the Sampling by a Recorded Slit Image
  6.3.6 Analytical Determination of the Sampling
  6.3.7 Interference Fringes and Reflection Ghosts

6.4 Recording of Echelle Spectra
  6.4.1 Preliminary Remarks
  6.4.2 Special Features of Echelle Spectra
  6.4.3 The Orientation of the Spectral Image
  6.4.4 Focusing of the Spectral Image
  6.4.5 Exposure Times for Echelle Spectrographs

6.5 Influences of Mount and Guiding
  6.5.1 Mechanical and Structural Problems with Small Mounts
  6.5.2 The Option of Fiber Coupling
  6.5.3 Impact of the Spectrograph Load to Small Mounts
  6.5.4 Positioning of Faint Objects on the Slit
  6.5.5 Specific Requirements to the Guiding Quality

6.6 Recording of the Spectra
  6.6.1 Load Distribution and Autoguiding Process with Small Mounts
  6.6.2 Autoguiding: Interaction of Hardware and Software Components
  6.6.3 Spectroscopic Aspects of the Guide Star
  6.6.4 Recording of Close Binary Star Components

7
Processing of Recorded Spectra

7.1 Available Software for Data Reduction
  7.1.1 Software Packages for the Amateur
  7.1.2 Professional Software Packages
  7.1.3 Spectroscopy @ Cyberspace: The Virtual Observatory
7.2 From the Recorded Spectrum to the Calibrated Intensity Profile 63
7.2.1 Preliminary Remarks 63
7.3 Removal of Light Pollution and Airglow 63
7.3.1 Objects of Point-shaped Appearance 63
7.3.2 Objects Appearing as 2D 63
7.4 Removal of Remaining Hot Pixels and Cosmics 63
7.5 Dark-frames and Flat-fielding 65
7.5.1 Dark-frames 65
7.5.2 Flat-fields 65
7.6 Processing of Echelle Spectra 65
7.6.1 The Processing of an Entire Echelle Spectrum 65
7.6.2 The Processing of Individual Orders 66
7.6.3 Subtraction of the Sky Background and Light Pollution 66

8 Calibration of the Spectra 67
8.1 Calibration of the Wavelength 67
8.1.1 Preliminary Remarks 67
8.1.2 Relative Calibration Based on Known Lines 67
8.1.3 Absolute Calibration with Light Sources 67
8.1.4 Absolute Calibration by Unshifted Wavelengths of Atmospheric H₂O Lines 67
8.1.5 Linear and Nonlinear Calibration 67
8.1.6 Practical Aspects to Minimize Sources of Errors 69
8.1.7 Heliocentric and Geocentric Corrections 69
8.1.8 The Selection of the Calibration Light Source 69
8.1.9 The Feeding of the Calibration Light 69
8.2 Calibration of the Spectral Flux Density (Intensity) 70
8.2.1 Preliminary Remarks 70
8.2.2 Selective Attenuation of the Continuum Intensity 70
8.2.3 Proportional Attenuation of the Spectral Lines 71
8.2.4 Information Content of the Pseudo-Continuum 71
8.2.5 Proportional Procedures for the Relative Flux Calibration 72
8.2.6 Rectification of the Continuum Intensity 72
8.2.7 Relative Flux Calibration by a Synthetic Continuum 73
8.2.8 Relative Flux Calibration by Recorded Standard Stars 74
8.2.9 Absolute Flux Calibration 74
8.2.10 Tasks and Required Calibration Procedures 75

9 Analysis of the Spectra 76
9.1 Measurement of Spectral Lines 76
9.1.1 Measurement of the Wavelength in a Spectral Profile 76
9.1.2 Intensity Measurement in a Spectral Profile 76
9.1.3 Peak Intensity I₀ and Energy Flux F of a Spectral Line 76
9.1.4 Peak Intensity and Energy Flux of an Absorption Line 76
9.1.5 Peak Intensity and Energy Flux of an Emission Line 77
9.1.6 Energy Flux of the Continuum 77
9.1.7 Suppression of Emission and Absorption Lines 77
9.1.8 The Continuum-Related Peak Intensity P 78
9.1.9 The Continuum-Related Energy Flux: Equivalent Width EW 78
9.1.10 Normalized Equivalent Width W₅ 79
9.1.11 Full Width at Half Maximum Height (FWHM) 79
9.1.12 Half Width at Half Depth (HWHD or HWHM) 79
9.1.13 Full Width at Zero Intensity (FWZI) 79
9.1.14 Half Width at Zero Intensity (HWZI) 80
9.1.15 Measurement of Asymmetry 80
9.1.16 Influence of the Spectrograph Resolution on the FWHM and EW Values 80
9.1.17 Additional Measurement Options 81
9.2 Shape and Intensity of Spectral Lines 81
9.2.1 The Shape of Absorption Lines 81
9.2.2 The Shape of Emission Lines 81
9.2.3 The Information Content of the Line Shape 81
9.2.4 Blends 81
9.3 Identification of Spectral Lines 82
9.3.1 Task and Requirements 82
9.3.2 Practical Problems and Strategies for Solving Them 82
9.3.3 Tools for the Identification of Spectral Lines 82
9.4 Temperature Related Appearance of Elements and Molecules in the Spectra 83

10 Temperature and Luminosity 85
10.1 Information Content of the Spectral Classification 85
10.1.1 The Hertzsprung–Russell Diagram 85
10.1.2 Information Content 85
10.1.3 Spectral Class, Stellar Mass and Life Expectancy 85
10.1.4 The Evolution of the Sun in the HRD 86
10.1.5 The Evolution of Massive Stars 87
10.2 Measurement of the Stellar Effective Temperature Tₑff 87
10.2.1 Introduction 87
10.2.2 Temperature Estimation by the Spectral Class 87
10.2.3 Temperature Estimation by Applying Wien’s Displacement Law 88
10.2.4 Temperature Determination Based on Individual Lines 89
10.2.5 The “Balmer Thermometer” 89
10.3 Spectroscopic Distance Measurement

10.3.1 Options for Spectroscopic Distance Measurement

10.3.2 Term and Principle of Spectroscopic Parallax

10.3.3 Spectral Class and Absolute Magnitude

10.3.4 Wilson–Bappu Effect

10.3.5 Absolute Visual Magnitude Indicator by Millward–Walker

10.3.6 Distance Modulus and Estimation of the Distance

11 Expansion and Contraction

11.1 Radial Velocity and Expansion of the Spacetime Lattice

11.1.1 The Radial Velocity

11.1.2 The Classical Doppler Effect

11.1.3 The Spectroscopic Doppler Equation

11.1.4 The z-Value: A Fundamental Measure of Modern Cosmology

11.1.5 The Relativistic Doppler Equation

11.1.6 Measurement of the Doppler Shift and Determination of Radial Velocity

11.1.7 Radial Velocities of Nearby Stars

11.1.8 Relative Doppler Shift within a Spectral Profile

11.1.9 Radial Velocity of Galaxies

11.1.10 The Expansion of the Spacetime Lattice

11.1.11 The Apparent Dilemma at z > 1

11.1.12 The z-Value: Considered as a Measure for the Past

11.1.13 Messier Galaxies: Radial Velocity and Cosmological Spacetime Expansion

11.1.14 The Redshift of Quasar 3C273

11.1.15 The Gravitational Redshift or Einstein Shift

11.1.16 Age Estimation of the Universe

11.2 Measurement of Expansion and Contraction

11.2.1 P Cygni Profiles

11.2.2 Inverse P Cygni Profiles

11.2.3 Broadening of the Emission Lines

11.2.4 Splitting of the Emission Lines

12 Rotation and Orbital Elements

12.1 Measurement of Rotational Velocity

12.1.1 Terms and Definitions

12.1.2 The Rotational Velocity of Apparent 3D Objects

12.1.3 The Rotational Velocity of Large Planets

12.1.4 The Rotational Velocity of Galaxies

12.1.5 Example of a Light Reflecting Object

12.1.6 Example of a Self-Luminous Celestial Body

12.1.7 The Rotational Velocity of Stars

12.1.8 Empirical Equations for v sin i in Function of FWHM

12.1.9 Calibration Equations by F. Fekel

12.1.10 Suitable Metal Lines for the FWHM Measurement

12.1.11 Rotational Velocity of Circumstellar Disks around Be Stars

12.1.12 Empirical Equations for the Rotational Velocity of the Disk

12.1.13 Distribution of the Rotational Velocity within the Disk

12.1.14 Analysis of Double Peak Profiles

12.1.15 The Outer Disk Radius Rs

12.2 Measurement of Rotational Velocity

12.2.1 Introduction

12.2.2 Terms and Definitions

12.2.3 Some Basics of Celestial Mechanics

12.2.4 Spatial Orientation of the Orbit Plane

12.2.5 Analysis of the Doppler Shift Δv in SB2 Systems

12.2.6 The Calculation of the Individual Velocities of M1 and M2

12.2.7 The Estimation of Some Orbital Parameters in SB2 Systems

13 Gravity, Magnetic Fields and Element Abundance

13.1 Measurement of the Surface Gravity

13.1.1 Overview

13.1.2 Method Based on the Wilson–Bappu Effect

13.1.3 Further Surface Gravity Indicators

13.2 Measurement of Stellar Magnetic Fields

13.2.1 Overview

13.2.2 The Zeeman Effect

13.2.3 Spectral Lines with Strong Landé Factors

13.2.4 Possible Applications for Amateurs

13.3 Abundance of Elements

13.3.1 Astrophysical Definition of Element Abundance

13.3.2 Astrophysical Definition of Metallicity Z (Metal Abundance)

13.3.3 Quantitative Determination of the Abundance

13.3.4 Relative Abundance of Stars of Similar Spectral Class

14 Analysis of Emission Nebulae

14.1 The Balmer Decrement

14.1.1 Introduction
14.1.2 Definition of the Balmer Decrement 120
14.1.3 Theoretical Balmer Decrement for Emission Nebulae 120
14.1.4 Balmer Decrement at Stellar and other Astronomical Objects 121
14.1.5 Applications of the Balmer Decrement in the Amateur Sector 121
14.1.6 Measurement of the Balmer Decrement by Amateurs 122
14.1.7 Spectroscopic Estimation of Interstellar Extinction 122
14.1.8 Extinction Correction by the Measured Balmer Decrement 122
14.1.9 Balmer Decrement and Color Excess 122

14.2 Plasma Diagnostics for Emission Nebulae 123
14.2.1 Preliminary Remarks 123
14.2.2 The Photoionization in Emission Nebulae 123
14.2.3 Kinetic Energy and Maxwellian Velocity Distribution of Electrons 123
14.2.4 Significant Processes within Ionized Nebular Plasmas 123
14.2.5 Recombination Process (Case A) 123
14.2.6 Line Emission by Electron Transitions (Case B) 124
14.2.7 Line Emission by Collision Excitation (Case C) 124
14.2.8 Line Emission by Direct Absorption (Case D) 124
14.2.9 Line Emission by Forbidden Transitions 125
14.2.10 Scheme of the Fluorescence Processes in Emission Nebulae 126
14.2.11 Cooling Mechanism by Forbidden Transitions 127
14.2.12 Influences of $T_e$, $N_e$ and Transition Probability $A$ on the Cooling Mechanism 127
14.2.13 Estimation of $T_e$ and $N_e$ by the O III and N II Methods 128
14.2.14 Estimation of the Electron Density by the S II and O II Ratio 129

15 Amateurs and Astronomical Science 130
15.1 Participation in Astronomical Research 130
15.1.1 Astronomical Spectroscopy and the Pro-Am Culture 130
15.1.2 The Structure of a Pro-Am Collaboration 131
15.2 Observation Campaigns for Amateurs 132
15.3 Contributions by Amateurs 133
15.3.1 Short-term Campaign (Months) 133
15.3.2 Long-term Campaign (Years) 133

Appendix A Abbreviations, Acronyms and Common Units 134
Appendix B Absolute Magnitudes of Main Sequence Stars 137
Appendix C The Solar Echelle Spectrum: An Aid to Orientation 139
Appendix D Flip Mirror and Calibration Light Source 142
References and Further Reading 143
Index 148