

# CONTENTS

|  |         |  |  |
|--|---------|--|--|
| <i>Preface</i>   | page xi |  |  |
| <i>Acknowledgements</i>  | xiii    |  |  |
| <b>1</b>   |         |  |  |
| <b>Directory of Plates</b>   | 1       |  |  |
| <b>2</b>   |         |  |  |
| <b>Selection, Processing and Presentation of the Spectra</b>               | 7       |  |  |
| 2.1 Selection of Spectra   | 7       |  |  |
| 2.2 Recording and Resolution of the Spectra                                | 7       |  |  |
| 2.3 Processing of the Spectra  | 7       |  |  |
| 2.4 Calibration of the Wavelength  | 8       |  |  |
| 2.5 Display of the Intensity Scale and Normalization of the Profiles       | 8       |  |  |
| 2.6 Identification and Labeling of the Spectral Lines                      | 8       |  |  |
| 2.7 Presentation   | 9       |  |  |
| 2.8 Object Coordinates   | 9       |  |  |
| 2.9 Distances  | 9       |  |  |
| <b>3</b>   |         |  |  |
| <b>Terms, Definitions and Abbreviations</b>                                | 10      |  |  |
| 3.1 Designation and Parameters of the Stars                                | 10      |  |  |
| 3.2 Galactic Nebulae and Star Clusters                                     | 10      |  |  |
| 3.3 Extragalactic Objects  | 10      |  |  |
| 3.4 Labeling of the H-Balmer series  | 10      |  |  |
| 3.5 Labeling of Elements and Ions  | 10      |  |  |
| 3.6 Abbreviations, Symbols and Common Units                                | 10      |  |  |
| <b>4</b>   |         |  |  |
| <b>Overview and Characteristics of Stellar Spectral Classes</b>            | 13      |  |  |
| 4.1 Preliminary Remarks  | 13      |  |  |
| 4.2 The Fraunhofer Lines   | 13      |  |  |
| 4.3 Further Development Steps: The Five Secchi Classes                     | 14      |  |  |
| 4.4 “Early” and “Late” Spectral Types                                      | 15      |  |  |
| 4.5 Temperature Sequence of the Harvard Classification System              | 15      |  |  |
| 4.6 Rough Determination of the One-Dimensional Spectral Class              | 15      |  |  |
| 4.7 Flowcharts for Estimation of the Spectral Class                        | 16      |  |  |
| 4.8 Further Criteria for Estimation of the Spectral Class                  | 16      |  |  |
| 4.9 The Two-Dimensional MK (Morgan–Keenan) or Yerkes Classification System | 18      |  |  |
| 4.10 Effect of the Luminosity Class on the Line Width                      | 18      |  |  |
| 4.11 Suffixes, Prefixes and Special Classes                                | 19      |  |  |
| 4.12 Statistical Distribution of Spectral Types to the Main Sequence Stars | 20      |  |  |
| <b>5</b>   |         |  |  |
| <b>Spectral Class O</b>  | 23      |  |  |
| 5.1 Overview   | 23      |  |  |
| 5.2 Parameters of the Late to Early O-Class Stars                          | 24      |  |  |
| 5.3 Spectral Characteristics of the O Class                                | 24      |  |  |
| 5.4 General Remarks on the Classification of O Stars                       | 24      |  |  |
| 5.5 Comments on Observed Spectra   | 24      |  |  |
| <b>6</b>   |         |  |  |
| <b>Spectral Class B</b>  | 30      |  |  |
| 6.1 Overview   | 30      |  |  |
| 6.2 Parameters of the Late to Early B-Class Stars                          | 30      |  |  |
| 6.3 Spectral Characteristics of the B Class                                | 30      |  |  |
| 6.4 Comments on Observed Spectra   | 31      |  |  |
| <b>7</b>   |         |  |  |
| <b>Spectral Class A</b>  | 36      |  |  |
| 7.1 Overview   | 36      |  |  |
| 7.2 Parameters of the Late to Early A-Class Stars                          | 36      |  |  |
| 7.3 Spectral Characteristics of the A Class                                | 36      |  |  |
| 7.4 Comments on Observed Spectra   | 37      |  |  |

|  |    |   |    |
|--|----|---|----|
| <b>8</b>   |    | <b>14</b>   |    |
| <b>Spectral Class F</b>  | 42 | <b>Spectral Class S on the AGB</b>  | 72 |
| 8.1 Overview   | 42 | 14.1 Overview and Spectral Characteristics                                  | 72 |
| 8.2 Parameters of the Late to Early F-Class Stars              | 42 | 14.2 The Boeshaar–Keenan S-Classification System                            | 72 |
| 8.3 Spectral Characteristics of the F Class                    | 42 | 14.3 “Intrinsic” and “Extrinsic” or “Symbiotic”<br>S Stars                  | 72 |
| 8.4 Comments on Observed Spectra                               | 42 | 14.4 Hints for the Observation of S-Class Stars                             | 73 |
| <b>9</b>   |    | 14.5 Comments on Observed Spectra   | 73 |
| <b>Spectral Class G</b>  | 46 | <b>15</b>   |    |
| 9.1 Overview   | 46 | <b>Carbon Stars on the AGB</b>  | 78 |
| 9.2 Parameters of the Late to Early G-Class Stars              | 46 | 15.1 Overview and Spectral Characteristics                                  | 78 |
| 9.3 Spectral Characteristics of the G Class                    | 46 | 15.2 Competing Classification Systems                                       | 78 |
| 9.4 Comments on Observed Spectra                               | 47 | 15.3 The Morgan–Keenan (MK) C-System  | 79 |
| <b>10</b>  |    | 15.4 The Revised Keenan 1993 System   | 79 |
| <b>Spectral Class K</b>  | 53 | 15.5 Connection of the Subclasses to the Evolution<br>of Carbon Stars       | 80 |
| 10.1 Overview  | 53 | 15.6 Merrill–Sanford Bands (MS)   | 80 |
| 10.2 Parameters of the Late to Early K-Class Stars             | 53 | 15.7 Comments on Observed Spectra   | 80 |
| 10.3 Spectral Characteristics of the K Class                   | 54 | <b>16</b>   |    |
| 10.4 Comments on Observed Spectra                              | 55 | <b>Post-AGB Stars and White Dwarfs</b>                                      | 85 |
| <b>11</b>  |    | 16.1 Position of Post-AGB Stars in Stellar<br>Evolution                     | 85 |
| <b>Spectral Class M</b>  | 61 | 16.2 Post-AGB Stars   | 85 |
| 11.1 Overview  | 61 | 16.3 Spectral Features of Post-AGB Stars                                    | 85 |
| 11.2 Parameters of the Late to Early M-Class Stars             | 61 | 16.4 White Dwarfs   | 85 |
| 11.3 Spectral Characteristics of the M Class                   | 62 | 16.5 Spectral Characteristics and Special Features<br>of White Dwarfs       | 86 |
| 11.4 Comments on Observed Spectra                              | 62 | 16.6 Classification System by McCook and Sion                               | 86 |
| <b>12</b>  |    | 16.7 Comments on Observed Spectra   | 86 |
| <b>Spectral Sequence on the AGB</b>                            | 67 | <b>17</b>   |    |
| 12.1 Evolution of Stars in the Post-Main<br>Sequence Stage     | 67 | <b>Wolf–Rayet Stars</b>   | 89 |
| 12.2 The Spectral Sequence of the Mira Variables<br>on the AGB | 67 | 17.1 Overview   | 89 |
| <b>13</b>  |    | 17.2 Spectral Characteristics and Classification                            | 89 |
| <b>M(e) Stars on the AGB</b>                                   | 69 | 17.3 Classification System for WR Stars in the Optical<br>Spectral Range    | 90 |
| 13.1 Overview  | 69 | 17.4 The WR Phase in Stellar Evolution                                      | 91 |
| 13.2 Spectral Characteristics of the M(e) Stars<br>on the AGB  | 69 | 17.5 Analogies and Differences to the Central Stars<br>of Planetary Nebulae | 91 |
| 13.3 Comments on Observed Spectra                              | 70 | 17.6 Comments on Observed Spectra of the WR<br>Classes WN, WC and WO        | 91 |

|   |     |  |     |
|---|-----|--|-----|
| <b>18</b>                                       |     | <b>23</b>  |     |
| <b>LBV Stars</b>                                | 96  | <b>Spectroscopic Binaries</b>                                      | 123 |
| 18.1 Overview                                   | 96  | 23.1 Short Introduction and Overview                               | 123 |
| 18.2 Spectral Characteristics of LBV Stars      | 96  | 23.2 Impact on the Spectral Features                               | 123 |
| 18.3 Comments on Observed Spectra               | 97  | 23.3 SB1 and SB2 Systems   | 125 |
|   |     | 23.4 Comments on Observed Spectra                                  | 125 |
| <b>19</b>                                       |     | <b>24</b>  |     |
| <b>Be Stars</b>                                 | 100 | <b>Novae</b>   | 132 |
| 19.1 Overview                                   | 100 | 24.1 The Phenomenon of Nova Outbursts                              | 132 |
| 19.2 Spectral Characteristics of Be Stars       | 100 | 24.2 Classical and Recurrent Novae                                 | 133 |
| 19.3 A Textbook Example: $\delta$ Scorpii       | 101 | 24.3 Dwarf Novae   | 133 |
| 19.4 Classification System for Be Stars         | 101 | 24.4 Symbiotic Stars   | 133 |
| 19.5 Comments on Observed Spectra               | 101 | 24.5 Nova-like Outbursts in LBV Stars                              | 134 |
|   |     | 24.6 Evolution of the Outbursts with Classical Novae               | 134 |
| <b>20</b>                                       |     | 24.7 Spectral Characteristics after Maximum Light                  | 134 |
| <b>Be Shell Stars</b>                           | 105 | 24.8 Evolution from the Permitted to the<br>Nebular Phase          | 134 |
| 20.1 Overview                                   | 105 | 24.9 The Spectroscopic Tololo Classification System                | 135 |
| 20.2 Spectral Characteristics of Be-Shell Stars | 105 | 24.10 Comments on Observed Spectra                                 | 135 |
| 20.3 Comments on Observed Spectra               | 105 |  |     |
| <b>21</b>                                       |     | <b>25</b>  |     |
| <b>Pre-Main Sequence Protostars</b>             | 108 | <b>Supernovae</b>  | 142 |
| 21.1 Overview                                   | 108 | 25.1 The Phenomenon of Supernova Explosions                        | 142 |
| 21.2 Herbig Ae/Be and T Tauri Stars             | 108 | 25.2 Designation of Supernovae                                     | 142 |
| 21.3 Spectral Characteristics of PMS Stars      | 109 | 25.3 Classification of SN Types                                    | 142 |
| 21.4 The FU Orionis Phenomenon                  | 109 | 25.4 SN Type I   | 143 |
| 21.5 Comments on Observed Spectra               | 109 | 25.5 SN Type II  | 143 |
|   |     | 25.6 Explosion Scenario: Core Collapse                             | 143 |
| <b>22</b>                                       |     | 25.7 Explosion Scenario: Thermonuclear Carbon<br>Fusion            | 144 |
| <b>Chemically Peculiar (CP) Stars</b>           | 115 | 25.8 SN Type Ia: An Important Cosmological<br>Standard Candle      | 144 |
| 22.1 Overview                                   | 115 | 25.9 Diagram for the Spectral Determination of the<br>SN Type      | 144 |
| 22.2 Classification of the CP Stars             | 115 | 25.10 SN Type Ia: Spectral Features in the<br>Optical Range        | 145 |
| 22.3 $\lambda$ Bootis Class                     | 115 | 25.11 SN Type II: Spectral Features in the<br>Optical Range        | 146 |
| 22.4 Am–Fm Class                                | 116 | 25.12 SN Type Ib and Ic: Spectral Features in the<br>Optical Range | 146 |
| 22.5 Ap–Bp Class                                | 116 |  |     |
| 22.6 Mercury–Manganese Class                    | 116 |  |     |
| 22.7 Helium-weak Stars                          | 117 |  |     |
| 22.8 Helium-rich Stars                          | 117 |  |     |
| 22.9 Subdwarf Luminosity Class VI               | 117 |  |     |
| 22.10 Comments on Observed Spectra              | 117 |  |     |

|   |  |     |  |
|---|--|-----|--|
| <b>26</b>   |  |     |  |
| <b>Extragalactic Objects</b>  |  | 149 |  |
| 26.1 Introduction   |  | 149 |  |
| 26.2 Morphological Classification of Galaxies                             |  | 149 |  |
| 26.3 Spectroscopic Classification of Galaxies                             |  | 150 |  |
| 26.4 Rough Scheme for Spectroscopic Classification of Galaxies            |  | 150 |  |
| 26.5 Absorption Line Galaxies   |  | 150 |  |
| 26.6 LINER Galaxies   |  | 150 |  |
| 26.7 Starburst Galaxies   |  | 152 |  |
| 26.8 The Phenomenon of Active Galactic Nuclei (AGN)                       |  | 153 |  |
| 26.9 Seyfert Galaxies   |  | 153 |  |
| 26.10 The Quasar Phenomenon   |  | 154 |  |
| 26.11 Blazars and BL Lacertae Objects (BL Lacs)                           |  | 156 |  |
| <b>27</b>   |  |     |  |
| <b>Star Clusters</b>  |  | 165 |  |
| 27.1 Short Introduction and Overview                                      |  | 165 |  |
| 27.2 Open Clusters (OCL)  |  | 165 |  |
| 27.3 Globular Clusters (GCL)  |  | 165 |  |
| 27.4 Spectroscopic Analysis of Star Clusters                              |  | 166 |  |
| 27.5 Spectroscopic Age Estimation of Star Clusters by Amateurs            |  | 166 |  |
| 27.6 The Pleiades (M45): Analysis by Individual Spectra                   |  | 167 |  |
| 27.7 Age Estimation of M45  |  | 168 |  |
| 27.8 Globular Clusters: Analysis by Integrated Spectra                    |  | 168 |  |
| 27.9 Age Estimation of M3, M5 and M13                                     |  | 169 |  |
| <b>28</b>   |  |     |  |
| <b>Emission Nebulae</b>   |  | 173 |  |
| 28.1 Overview and Short Introduction                                      |  | 173 |  |
| 28.2 H II Regions   |  | 173 |  |
| 28.3 Planetary Nebulae  |  | 173 |  |
| 28.4 Protoplanetary Nebulae   |  | 174 |  |
| 28.5 Supernova Remnants   |  | 174 |  |
| 28.6 Wolf–Rayet Nebulae   |  | 175 |  |
| 28.7 Common Spectral Characteristics of Emission Nebulae                  |  | 175 |  |
| 28.8 Plasma Diagnostics and Excitation Class E                            |  | 176 |  |
| 28.9 Practical Aspects of the Determination of the E Class                |  | 176 |  |
| 28.10 Practical Aspects of the Recording of Planetary Nebula              |  | 177 |  |
| 28.11 The Excitation Class as an Indicator for Plasma Diagnostics         |  | 177 |  |
| 28.12 Emission Lines Identified in the Spectra of Nebulae                 |  | 178 |  |
| 28.13 Comments on Observed Spectra  |  | 178 |  |
| 28.14 Distinguishing Characteristics in the Spectra of Emission Nebulae   |  | 183 |  |
| <b>29</b>   |  |     |  |
| <b>Reflectance Spectra of Solar System Bodies</b>                         |  | 197 |  |
| 29.1 Overview   |  | 197 |  |
| 29.2 Comments on Observed Spectra   |  | 197 |  |
| 29.3 Reflectance Spectrum of a Total Lunar Eclipse                        |  | 198 |  |
| <b>30</b>   |  |     |  |
| <b>Telluric Molecular Absorption</b>                                      |  | 204 |  |
| 30.1 The Most Significant Molecular Absorptions by the Earth's Atmosphere |  | 204 |  |
| 30.2 Telluric H <sub>2</sub> O Absorptions around the H $\alpha$ line     |  | 204 |  |
| 30.3 Telluric O <sub>2</sub> Absorptions within Fraunhofer A and B Bands  |  | 205 |  |
| <b>31</b>   |  |     |  |
| <b>The Night Sky Spectrum</b>   |  | 209 |  |
| 31.1 Introduction   |  | 209 |  |
| 31.2 Effects on the Spectrum  |  | 209 |  |
| <b>32</b>   |  |     |  |
| <b>The Mesospheric Sodium Layer</b>                                       |  | 211 |  |
| 32.1 Overview   |  | 211 |  |
| 32.2 Spectroscopic Detection of the Sodium Layer                          |  | 211 |  |
| <b>33</b>   |  |     |  |
| <b>Terrestrial and Calibration Light Sources</b>                          |  | 213 |  |
| 33.1 Spectra of Common Gas Discharge Lamps                                |  | 213 |  |
| 33.2 Spectra of Glow Starters Modified as Calibration Light Sources       |  | 214 |  |
| 33.3 Calibration and Processing of an Entire Echelle Spectrum             |  | 215 |  |
| 33.4 Spectra of Hydrocarbon Flames  |  | 215 |  |
| 33.5 Terrestrial Lightning Discharges                                     |  | 215 |  |

|   |     |   |     |
|---|-----|---|-----|
| Appendix A: Spectral Classes and $v \sin i$ Values of<br>Bright Stars | 243 | Appendix H: Distant AGN and Quasars<br>Brighter than $m_v \approx 16$ | 259 |
| Appendix B: The 88 IAU Constellations                                 | 247 | Appendix J: Excerpts from Historical Spectral Atlases                 | 262 |
| Appendix C: Spectral Classes and B–V Color Index                      | 249 | Appendix K: Instruments   | 265 |
| Appendix D: Spectral Classes and Effective Temperatures               | 251 | Bibliography  | 266 |
| Appendix E: Excitation Classes of Bright Planetary Nebulae            | 253 | Subject Index   | 275 |
| Appendix F: Ionization Energies of Important Elements                 | 255 | Stellar Index   | 278 |
| Appendix G: Spectroscopic Measures and Units                          | 257 | Object Index: Deep Sky and Solar System                               | 279 |