

Contents

Foreword *xi*

Acknowledgments *xiii*

The Emergence of 3D Spectroscopy in Astronomy *1*

Scientific Rationale *1*

3D History *4*

3D Technology *9*

Part I 3D Instrumentation *11*

1	The Spectroscopic Toolbox	<i>13</i>
1.1	Introduction	<i>13</i>
1.1.1	Geometrical Optics #101	<i>13</i>
1.1.2	Etendue Conservation	<i>15</i>
1.2	Basic Spectroscopic Principles	<i>18</i>
1.2.1	The Spectroscopic Case	<i>18</i>
1.3	Scanning Filters	<i>20</i>
1.3.1	Introduction	<i>20</i>
1.3.2	Interference Filters	<i>22</i>
1.3.3	Fabry–Pérot Filter	<i>24</i>
1.4	Dispersers	<i>25</i>
1.4.1	Prisms	<i>25</i>
1.4.2	Grating Principle	<i>27</i>
1.4.3	The Grating Spectrograph	<i>28</i>
1.4.4	Grating Species	<i>29</i>
1.4.5	Grating Etendue	<i>30</i>
1.4.6	Conclusion	<i>31</i>
1.5	2D Detectors	<i>31</i>
1.5.1	Introduction	<i>31</i>
1.5.2	The Photographic Plate	<i>32</i>
1.5.3	2D Optical Detectors	<i>32</i>
1.5.4	2D Infrared Arrays	<i>35</i>
1.5.5	Conclusion	<i>35</i>

1.6	Optics and Coatings	36
1.6.1	Introduction to Optics	36
1.6.2	Optical Computation	37
1.6.3	Optical Fabrication	40
1.6.4	Anti-Reflection Coatings	42
1.6.5	High Reflectivity Coatings	43
1.6.6	Conclusions	44
1.7	Mechanics, Cryogenics and Electronics	45
1.7.1	Mechanical Design	45
1.7.2	Alignments	48
1.7.3	Cryogenics	48
1.7.4	Electronics and Control System	49
1.8	Management, Timeline, and Cost	50
1.9	Conclusion	52
2	Multiobject Spectroscopy	61
2.1	Introduction	61
2.1.1	MOS History: The Pioneers	61
2.1.2	MOS History: The Digital Age	62
2.1.3	MOS Flavors	62
2.2	Slitless Based Multi-Object Spectroscopy	62
2.2.1	Slitless Spectroscopy Concept	62
2.2.2	Slitless Spectroscopic Systems	64
2.3	Multislit-Based Multiobject Spectroscopy	64
2.3.1	Multislit Concept	64
2.3.2	Multislit Holders	66
2.3.3	Multislit Systems	69
2.3.4	Multislit Instruments	70
2.4	Fiber-Based Multiobject Spectroscopy	70
2.4.1	Multifiber Concept	70
2.4.2	Positioning Systems	71
2.4.3	Fiber-Based Spectrograph	75
2.4.4	Fiber Systems Performance	75
2.4.5	Present Multifiber Facilities	76
2.4.6	Conclusion	77
3	Scanning Imaging Spectroscopy	81
3.1	Introduction	81
3.2	Scanning Long-Slit Spectroscopy	81
3.2.1	The Scanning Long-Slit Spectroscopy Concept	81
3.2.2	Astronomical Use	82
3.3	Scanning Fabry–Pérot Spectroscopy	83
3.3.1	Introduction	83
3.3.2	Fixed Fabry–Pérot Concept	83
3.3.3	Scanning Fabry–Pérot	85
3.4	Scanning Fourier Transform Spectroscopy	88
3.4.1	Fourier Transform Spectrometer	88

3.4.2	Fourier Transform Spectrograph	90
3.5	Conclusion: Comparing the Different Scanning Flavors	91
4	Integral Field Spectroscopy	95
4.1	Introduction	95
4.2	Lenslet-Based Integral Field Spectrometer	95
4.3	Fiber-Based Integral Field Spectrometer	102
4.3.1	The Fiber-Based IFS Concept	102
4.3.2	The Fiber-Based IFS Development	103
4.3.3	Conclusion	103
4.4	Slicer-Based Integral Field Spectrograph	104
4.4.1	Introduction	104
4.4.2	Integral Field Spectroscopy from Space	107
4.5	Conclusion: Comparing the Different IFS Flavors	108
5	Recent Trends in Integral Field Spectroscopy	115
5.1	Introduction	115
5.2	High-Contrast Integral Field Spectrometer	115
5.2.1	Exoplanet Detection	115
5.2.2	High-Contrast Integral Field Spectrometer	116
5.3	Wide-Field Integral Field Spectroscopy	117
5.3.1	The Rationale for Wide-Field Integral Field Spectroscopy	117
5.3.2	Current Wide-Field Projects	117
5.3.3	Wide-Field Systems 3D Format	119
5.4	An Example: Autopsy of the MUSE Wide-Field Instrument	120
5.4.1	MUSE Concept	120
5.4.2	MUSE Approach	120
5.4.3	MUSE Conclusions	122
5.4.4	Validity of the Multi-instrument Approach	123
5.5	Deployable Multiobject Integral Field Spectroscopy	123
5.5.1	Concept	123
5.5.2	The First Deployable Integral Field Units System	124
5.5.3	Near Infra-Red Deployable Integral Field Units	124
5.5.4	Deployable Multi-Integral Field Systems: Conclusion	126
6	Comparing the Various 3D Techniques	129
6.1	Introduction	129
6.2	3D Spectroscopy Grasp Invariant Principle	129
6.3	3-D Techniques Practical Differences	130
6.3.1	Packing Efficiency	130
6.3.2	Observational Efficiency	131
6.4	A Tentative Rating	133
7	Future Trends in 3D Spectroscopy	137
7.1	3D Instrumentation for the ELTs	137
7.2	Photonics-Based Spectrograph	138

7.2.1	OH Suppression Filter	138
7.2.2	Photonics Dispersers	141
7.2.3	Photonics Fourier Transform Spectrometer	141
7.2.4	Analysis	142
7.3	Quest for the Grail: Toward 3D Detectors?	144
7.3.1	Introduction	144
7.3.2	Photon-Counting 3D Detectors	144
7.3.3	Integrating 3D Detector	145
7.4	Conclusion	146
7.5	For Further Reading	146

Part II Using 3D Spectroscopy 151

8	Data Properties	153
8.1	Introduction	153
8.2	Data Sampling and Resolution	153
8.2.1	Spatial Sampling and Resolution	154
8.2.2	Spectral Sampling and Resolution	155
8.3	Noise Properties	158
9	Impact of Atmosphere	167
9.1	Introduction	167
9.2	Basic Seeing Principles	168
9.2.1	What is Astronomical Seeing?	168
9.2.2	Seeing Properties	170
9.3	Seeing-Limited Observations	172
9.3.1	Seeing Impact on 3D Instruments	172
9.4	Adaptive Optics Corrected Observations	173
9.4.1	The Need for Overcoming Atmospheric Turbulence	173
9.4.2	Adaptive Optics Correction Principle	173
9.4.3	Adaptive Optics Components	176
9.4.4	Adaptive Optics: The Optical Domain Curse	178
9.4.5	Addressing the Lack of Reference Stars	179
9.4.6	Addressing the Small Field Limitation	182
9.4.7	Large Field Partial AO Correction	183
9.4.8	AO-Based Scanning Interferometers	184
9.4.9	AO-Based Slit Spectrographs	185
9.4.10	AO-Based Integral Field Spectrographs	185
9.4.11	AO-Based Near-IR Multiobject Integral Field Spectrographs	187
9.4.12	Deriving AO-Corrected Point-Spread Functions	188
9.4.13	Conclusion	188
9.4.14	For Further Reading	189
9.5	Other Atmosphere Impacts	189
9.5.1	Atmospheric Extinction	189
9.5.2	Atmospheric Refraction	189

9.5.3	Night Sky Emission	191
9.6	Space-Based Observations	192
9.6.1	The Case for Space-Based Observations	192
9.6.2	Why all Telescopes are not Space Telescopes	193
9.7	Conclusion	194
10	Data Gathering	199
10.1	Introduction	199
10.2	Planning Observations	199
10.3	Estimating Observing Time	200
10.4	Observing Strategy	204
10.5	At the Telescope	206
10.6	Conclusion	209
11	Data Reduction	213
11.1	Introduction	213
11.2	Basics	214
11.3	Specific Cases	216
11.3.1	Slitless Multiobject Spectrograph	216
11.3.2	Scanning Fabry–Pérot Spectrograph	216
11.3.3	Scanning Fourier Transform Spectrograph	217
11.3.4	Getting Noise Variance Estimation	217
11.3.5	Minimizing Systematics	218
11.4	Data Reduction Example: The MUSE Scheme	219
11.4.1	Detector Calibration	221
11.4.2	Flat-Field Calibrations and Trace Mask	222
11.4.3	Wavelength Calibrations	224
11.4.4	Geometrical Calibration	225
11.4.5	Basic Science Extraction and Pixel Tables	226
11.4.6	Differential Atmospheric Correction	226
11.4.7	Sky Subtraction	228
11.4.8	Spectrophotometric and Astrometric Calibrations	229
11.4.9	Data-Cube Creation	232
11.4.10	Data Quality	233
11.5	Conclusion	236
12	Data Analysis	237
12.1	Introduction	237
12.2	Handling Data Cubes	237
12.2.1	The Spectral View	238
12.2.2	The Spatial View	239
12.2.3	The 3D View	239
12.3	Viewing Data Cubes	240
12.4	Conclusion	241
12.5	Further Reading	243

13	Conclusions	245
13.1	Conclusions	245
13.2	General-Use Instruments	245
13.3	Team-Use Instruments	250
13.4	The Bumpy Road to Success	251

References	253
-------------------	------------

Index	269
--------------	------------