

Contents

| | |
|----------------|---|
| Preface | V |
| 1 | Introduction 1 |
| 1.1 | First Light and Reionization 1 |
| 1.2 | The Cosmological Framework 2 |
| 1.3 | Organization of this Book 2 |
| 1.4 | Key Observations in this Field 4 |
| Part 1 | Theory 5 |
| 2 | The First Stars 7 |
| 2.1 | Overview 7 |
| 2.1.1 | First Light 7 |
| 2.1.2 | Forming the First Stars 8 |
| 2.1.3 | The Legacy of the First Stars 9 |
| 2.2 | Before the First Stars 9 |
| 2.2.1 | Recombination and Residual Ionization Fraction 9 |
| 2.2.2 | The Formation of Molecular Hydrogen 13 |
| 2.2.3 | Cooling Functions 16 |
| 2.3 | Forming the First Stars 18 |
| 2.3.1 | Perturbations in the Early Universe 18 |
| 2.3.2 | Collapse of Perturbations in the Early Universe 21 |
| 2.3.3 | Cooling and the Jeans Instability 25 |
| 2.3.4 | Properties of the First Stars 31 |
| 2.3.5 | Remnants and Signatures of a Population III 34 |
| 2.4 | Primordial HII Regions 35 |
| 2.5 | What if Dark Matter is not Cold? 37 |
| 2.6 | Hints for Further Study 38 |
| 3 | The First Star Clusters and Galaxies 39 |
| 3.1 | Overview 39 |
| 3.2 | Subsequent Generations of Stars 39 |
| 3.2.1 | Second-Generation Population III Stars 40 |
| 3.2.2 | Population III Stars Forming in Self-Shielding Halos 41 |

| | | |
|----------|--|-----------|
| 3.2.3 | Late Population III Star Formation by Atomic-Hydrogen Cooling in Massive Halos | 48 |
| 3.2.4 | Termination of the First Stars Phase | 49 |
| 3.3 | Containing Gas in the Halos of Population III Stars | 49 |
| 3.3.1 | Ionization Heating and Gas Temperature | 49 |
| 3.3.2 | The Escape of Gas Heated by Ionization | 53 |
| 3.3.3 | The Escape of Gas Following a Supernova Explosion | 56 |
| 3.3.4 | Population II.5 | 58 |
| 3.4 | The First Star Clusters | 59 |
| 3.4.1 | Clusters of Population III Stars and of Metal-Poor Stars | 61 |
| 3.4.2 | The Origin of Globular Clusters | 62 |
| 3.5 | The First Galaxies | 63 |
| 3.6 | The First Active Galactic Nuclei | 64 |
| 3.6.1 | Population III Black Holes | 64 |
| 3.6.2 | Black-Hole Mergers | 65 |
| 3.6.3 | The Highest-Redshift QSOs | 66 |
| 3.6.4 | Direct Collapse to Black Holes | 67 |
| 3.7 | Low-Metallicity HII Regions | 67 |
| 3.8 | Numerical Techniques and Their Limitations | 68 |
| 3.8.1 | Collisionless Dynamics | 68 |
| 3.8.2 | Collisionless Dynamics: Particle-Mesh Codes | 70 |
| 3.8.3 | Collisionless Dynamics: Treecodes | 71 |
| 3.8.4 | Gas Dynamics | 71 |
| 3.8.5 | Gas Dynamics: Smooth Particle Hydrodynamics | 72 |
| 3.8.6 | Gas Dynamics: Eulerian Codes | 72 |
| 3.8.7 | Improving Resolution Through Mesh Refinement | 73 |
| 3.8.8 | Radiative Transfer | 73 |
| 3.9 | Hints for Further Study | 73 |
| 4 | Cosmic Reionization | 75 |
| 4.1 | Overview | 75 |
| 4.2 | The Properties of the Sources of Reionization | 76 |
| 4.2.1 | The Surface Brightness of Reionization Sources | 77 |
| 4.2.2 | Reionization in a Hydrogen-Only IGM | 79 |
| 4.2.3 | Reionization in a Hydrogen–Helium IGM | 80 |
| 4.2.4 | Results for a Homogeneous IGM | 81 |
| 4.2.5 | Mean Metallicity at Reionization | 83 |
| 4.3 | Adding Realism to the Calculations | 85 |
| 4.3.1 | Escape of Ionizing Photons | 85 |
| 4.3.2 | Clumpy IGM | 88 |
| 4.3.3 | Two-Parameter Models | 90 |
| 4.4 | Luminosity Function of Ionizing Sources | 90 |
| 4.4.1 | Detecting Lyman α from Ionizing Sources | 92 |
| 4.5 | Reionization by Population III Stars | 95 |
| 4.6 | How Is the Intergalactic Medium Enriched? | 96 |

- 4.7 Reheating of the Intergalactic Medium 97
- 4.8 Keeping the Intergalactic Medium Ionized 98
- 4.9 Hints for Further Study 100

Part 2 Observational Techniques and their Results 101

5 Studying the Epoch of Reionization of Hydrogen 103

- 5.1 Overview 103
- 5.2 Gunn–Peterson Troughs in Redshift 6 QSOs 104
 - 5.2.1 A Simple Gunn–Peterson Test 104
 - 5.2.2 The Gunn–Peterson Trough 106
 - 5.2.3 Lyman Series Lines 108
 - 5.2.4 Metal Lines 109
 - 5.2.5 HII Region Size Test 109
 - 5.2.6 Dark Gaps 110
 - 5.2.7 An Assessment of the Indication from QSOs Spectra 110
- 5.3 Lyman α Sources as Diagnostics of Reionization 111
 - 5.3.1 Effect of a Finite Lyman α Line Width 111
 - 5.3.2 Intrinsic Properties of Lyman α Emitters 111
 - 5.3.3 Effect of a Local Ionized Bubble 114
 - 5.3.4 A Realistic Lyman α Escape Model 115
 - 5.3.5 Perspectives on Studying Reionization with Lyman α Sources 117
 - 5.3.6 Faint Lyman α Halos 119
- 5.4 Neutral-Hydrogen Searches 121
 - 5.4.1 Other Applications of High- z 21-cm Observations 124
- 5.5 Compton Optical Depth 126
- 5.6 Lyman α Signature in the Diffuse Near-IR Background 127
- 5.7 Hints for Further Study 128

6 The First Galaxies and Quasars 129

- 6.1 Overview 129
- 6.2 The Lyman-Break Technique 129
 - 6.2.1 The Lyman Break as a Function of Redshift 130
 - 6.2.2 Synthetic Stellar Population Models 131
 - 6.2.3 Redshift 6 Dropout Galaxies 132
 - 6.2.4 Lyman-Break Galaxies at Redshift Greater than 6 133
- 6.3 The Lyman α Excess Technique 135
- 6.4 The Balmer-Jump Technique 136
 - 6.4.1 An Old Galaxy at Low or High Redshift? 137
- 6.5 Photometric Redshifts 139
- 6.6 Samples of High-Redshift Galaxies 141
 - 6.6.1 Lyman-Break Galaxies at $z = 6$ 141
 - 6.6.2 Lyman-Break Galaxies at $z > 7$ 143
 - 6.6.3 Lyman α Emitters 144
 - 6.6.4 High-Redshift QSOs 146
- 6.7 Fluctuations 147

| | | |
|----------|--|------------|
| 6.8 | Direct Detection of the First Stars | 148 |
| 6.9 | Hints for Further Study | 149 |
| 7 | Deep Imaging and Spectroscopy Surveys | 151 |
| 7.1 | Overview | 151 |
| 7.2 | Field Choice for a Deep Imaging Survey | 151 |
| 7.3 | Observing Techniques for Deep Imaging Surveys | 154 |
| 7.3.1 | General Considerations | 154 |
| 7.3.2 | Dithering | 154 |
| 7.3.3 | Super Bias and Super Dark | 155 |
| 7.3.4 | Flat Fielding | 156 |
| 7.3.5 | Image Combination | 157 |
| 7.4 | Self-Calibration | 160 |
| 7.5 | Catalogs | 161 |
| 7.5.1 | Layout of an Automated Photometry Algorithm | 162 |
| 7.5.2 | SExtractor Photometry Tips | 163 |
| 7.5.3 | Simulations | 164 |
| 7.6 | Cosmic Variance | 166 |
| 7.7 | The Gravitational Telescope | 166 |
| 7.8 | Deep Spectroscopy | 169 |
| 7.8.1 | Spectroscopic Analysis Techniques | 169 |
| 7.8.2 | Slit Spectroscopy of Faint Targets | 170 |
| 7.8.3 | Slitless Spectroscopy | 171 |
| 7.9 | Hints for Further Study | 171 |
| 8 | The Reionization of Helium | 173 |
| 8.1 | Overview | 173 |
| 8.2 | Gunn–Peterson Troughs in QSOs | 173 |
| 8.3 | Constraints from the Temperature of the IGM | 175 |
| 8.4 | Change in Metal-Line Ratios | 176 |
| 8.5 | Change in HI Lyman α Forest | 177 |
| 8.6 | Reionizing Hydrogen First and Helium Later | 177 |
| 8.7 | A Limit on the Escape Fraction from Galaxies at $z \simeq 3$ | 178 |
| 9 | Future Instrumentation | 181 |
| 9.1 | Overview | 181 |
| 9.2 | The James Webb Space Telescope | 181 |
| 9.2.1 | Historical Remarks | 182 |
| 9.2.2 | The JWST Science Requirements Document | 183 |
| 9.2.3 | Overview of JWST Instrumentation | 184 |
| 9.3 | Other Space-Based Instrumentation | 185 |
| 9.3.1 | The Wide-Field Planetary Camera 3 | 185 |
| 9.3.2 | The Cosmic Origins Spectrograph | 186 |
| 9.3.3 | A Possible Future Large Telescope in Space | 186 |
| 9.4 | Large Ground-Based Telescopes | 189 |
| 9.4.1 | Ground vs. Space Comparison | 189 |

| | | |
|--------------|--|-----|
| 9.4.2 | Multiobject Spectroscopy | 191 |
| 9.4.3 | Very High Resolution Imaging | 191 |
| 9.5 | Observing 21-cm Radiation at High Redshift | 191 |
| 9.5.1 | Murchison Wide-Field Array | 192 |
| 9.5.2 | Low-Frequency Array | 192 |
| 9.5.3 | Square-Kilometer Array | 193 |
| 9.5.4 | A Radiotelescope on the Far Side of the Moon | 194 |
| 9.6 | Atacama Large Millimeter Array | 194 |
| 9.7 | Large Field of View Imaging | 194 |
| 9.7.1 | Large Synoptic Survey Telescope | 195 |
| 9.7.2 | Large Field of View Imaging from Space | 195 |
| 9.8 | Planck | 195 |
| A | Overview of Physical Concepts | 197 |
| A.1 | Cosmological Quantities | 197 |
| A.2 | Saha Equation | 198 |
| A.3 | Polytropic Stars | 200 |
| A.4 | Jeans Instability for a Two-Fluid System | 201 |
| Index | | 213 |

