

CONTENTS

1.	Introduction	1
2.	Galaxy Formation: From Start to Finish	5
	<i>Andrew Benson</i>	
2.1	Historical Perspective	5
2.2	The Universe Before Galaxies	7
2.3	The Story So Far	9
	2.3.1 The end of the dark ages	9
	2.3.2 Population III and the first galaxies	13
	2.3.3 The reionization of the universe	15
	2.3.4 Establishing the Hubble sequence	17
	2.3.5 The rise of the supermassive black holes	25
2.4	What the Future Holds	32
	References	35
3.	The Reionization of Cosmic Hydrogen by the First Galaxies	41
	<i>Abraham Loeb</i>	
3.1	Introduction	42
	3.1.1 Observing our past	42
	3.1.2 The expanding Universe	46
3.2	Galaxy Formation	49
	3.2.1 Growth of linear perturbations	49
	3.2.2 Halo properties	53
	3.2.3 Formation of the first stars	56

3.2.4	Gamma-ray bursts: probing the first stars one star at a time	61
3.2.5	Supermassive black holes	63
3.2.6	The epoch of reionization	66
3.2.7	Post-reionization suppression of low-mass galaxies	71
3.3	Probing the Diffuse Intergalactic Hydrogen	73
3.3.1	Lyman-alpha absorption	73
3.3.2	21-cm absorption or emission	75
3.3.2.1	The spin temperature of the 21-cm transition of hydrogen	75
3.3.2.2	A handy tool for studying cosmic reionization	79
3.4	Epilog	86
	References	87
4.	Clusters of Galaxies	89
	<i>Elena Pierpaoli</i>	
4.1	What are Galaxy Clusters? Why are They Interesting? . .	89
4.2	Structure Formation	91
4.3	How do We Observe Clusters?	93
4.4	Clusters in Cosmology	97
4.5	Dark Matter or Modified Gravity?	105
4.6	Gas, Galaxies and Their Evolution	107
	References	109
5.	Reionizing the Universe with the First Sources of Light	111
	<i>Volker Bromm</i>	
5.1	The End of The Dark Ages	113
5.2	Formation of a Population III Star	115
5.3	Feedback in the Early Universe	120
5.4	Brief History of Reionization	124
5.5	Empirical Probes for Reionization	127

Contents

5.6	Explosions at Cosmic Dawn	129
5.7	The First Black Holes	132
5.8	Toward the First Galaxies	134
	References	136
6.	Mapping the Cosmic Dawn	139
	<i>Steven Furlanetto</i>	
6.1	A Brief History of Our Universe: From Soup to Galaxies	140
6.2	The Hidden Cosmic Dawn	143
6.3	The Solution: Flipping Spins	145
6.4	The Spin-Flip Transition as an Astronomical Tool	146
6.5	Foiled!: Early Cosmology with the Spin-Flip Transition	148
6.6	Spin-Flip Radiation Holds the Key to Observing the Cosmic Dawn	149
6.7	The Spin-Flip Background: The First Stars	153
6.8	The Spin-Flip Background: The First Black Holes	156
6.9	The Spin-Flip Background: The Epoch of Reionization	158
6.10	FM Radio Antennae as Cosmic Observatories	159
6.11	Piles and Tiles of Antennae: Mapping the Spin-Flip Background	161
6.12	Mountains to Scale: Challenges to Observing the Spin-Flip Background	164
6.13	Sound and Fury, Signifying Statistics	167
6.14	An Explosion of Telescopes	167
6.15	Dreams for the Future	169
6.16	An Unfinished Story	171
7.	Neutrino Masses from Cosmology	173
	<i>Ofer Lahav and Shaun Thomas</i>	
7.1	A Brief History of Cosmological Neutrinos and Hot Dark Matter	174
7.2	Insights from Particle Physics	175

7.3	Background to Cosmology	178
7.4	The Physics of Cosmological Neutrinos	181
7.5	Observational Methods	184
7.5.1	The cosmic microwave background	184
7.5.2	Galaxy clustering	185
7.5.3	Weak gravitational lensing	186
7.5.4	The Lyman-alpha forest	187
7.6	Observational Limits as of 2010	187
	References	191
8.	Measuring the Expansion Rate of the Universe	193
	<i>Laura Ferrarese</i>	
8.1	Introduction	193
8.2	Twinkle Twinkle Little Star: Cepheid Variables	199
8.2.1	A brief historical overview	201
8.2.2	The theoretical perspective	203
8.2.3	The Leavitt law	206
8.2.4	An independent check	208
8.2.5	Hubble (the telescope) observes Cepheids	209
8.3	The Aborted Explosion of Stars: The Tip of the Red Giant Branch	210
8.4	Bumpy Galaxies: The Surface Brightness Fluctuation Method	214
8.5	The Orderly Nature of Early Type Galaxies: The Fundamental Plane	217
8.6	The (Not Quite As) Orderly Nature of Spiral Galaxies: The Tully–Fisher Relation	220
8.7	Stellar Explosions: Type Ia Supernovae	224
8.8	Further Reflections and Future Directions	229
8.8.1	Eighty years of Hubble constants	229
8.8.2	The age of the Universe	232
8.8.3	Room for improvement	236
	References	237

9. Particles as Dark Matter	241
<i>Dan Hooper</i>	
9.1 The Evidence for Dark Matter	241
9.2 The Production of Dark Matter in the Early Universe	244
9.2.1 Case example — the thermal abundance of a light or heavy neutrino	247
9.3 Beyond the Standard Model Candidates for Dark Matter	248
9.3.1 Supersymmetry	249
9.3.2 Kaluza–Klein dark matter in models with universal extra dimensions	251
9.3.3 A note on other possibilities for TeV-scale dark matter	254
9.4 Direct Detection	254
9.4.1 Direct detection of neutralino dark matter	256
9.4.2 Direct detection of Kaluza–Klein dark matter	257
9.4.3 Some model-independent comments regarding direct detection	258
9.5 Indirect Detection	259
9.6 Dark Matter at Particle Colliders	264
9.7 Conclusions	265
References	265
10. Detection of WIMP Dark Matter	269
<i>Sunil Golwala and Dan McKinsey</i>	
10.1 Introduction	269
10.2 Direct Detection of WIMPs via WIMP–Nucleon Elastic Scattering	269
10.3 Inelastic Scattering	274
10.4 Background Sources	274
10.5 Backgrounds and WIMP Sensitivity	279

10.6	Direct Detection Techniques	283
10.6.1	Detectors without nuclear-recoil discrimination . . .	283
10.6.1.1	Germanium spectrometers	284
10.6.1.2	Scintillation-mediated detectors	285
10.6.2	Detectors with nuclear-recoil discrimination	289
10.6.2.1	Metastable or threshold detectors	289
10.6.2.2	Sub-Kelvin detectors	293
10.6.2.3	Liquid noble detectors	302
10.6.2.4	Two-phase detectors	308
10.6.2.5	Single-phase argon detectors	313
10.6.3	Direction-sensitive detectors	316
	References	318
11.	The Accelerating Universe	321
	<i>Dragan Huterer</i>	
11.1	Introduction and History: Evidence for the Missing Component	321
11.2	Type Ia Supernovae and Cosmology	322
11.3	Parametrizations of Dark Energy	331
11.4	Other Probes of Dark Energy	337
11.5	The Accelerating Universe: Summary	347
	References	349
12.	Frontiers of Dark Energy	355
	<i>Eric V. Linder</i>	
12.1	Introduction to Dark Energy	355
12.2	The Dynamics of Nothing	356
12.3	Knowing Nothing	364
12.4	The Frontiers of Nothing	370
12.5	Conclusions	375
	References	376

Contents

13. The First Supermassive Black Holes in the Universe	379
<i>Xiaohui Fan</i>	
13.1 Supermassive Black Holes and Galaxy Formation	380
13.2 Observations of the Most Distant Quasars	386
13.3 Growing the First Supermassive Black Holes in the Universe	395
13.4 Future Prospects	399
References	404
Index	407