

List of Contents

1. Introduction and Overview	1.1 Introduction	1
	1.2 Overview	4
	1.2.1 Our Milky Way as a Galaxy	4
	1.2.2 The World of Galaxies	7
	1.2.3 The Hubble Expansion of the Universe	8
	1.2.4 Active Galaxies and Starburst Galaxies	10
	1.2.5 Voids, Clusters of Galaxies, and Dark Matter	12
	1.2.6 World Models and the Thermal History of the Universe	14
	1.2.7 Structure Formation and Galaxy Evolution	17
	1.2.8 Cosmology as a Triumph of the Human Mind	17
	1.3 The Tools of Extragalactic Astronomy	18
	1.3.1 Radio Telescopes	19
	1.3.2 Infrared Telescopes	22
	1.3.3 Optical Telescopes	25
	1.3.4 UV Telescopes	30
	1.3.5 X-Ray Telescopes	31
	1.3.6 Gamma-Ray Telescopes	32
2. The Milky Way as a Galaxy	2.1 Galactic Coordinates	35
	2.2 Determination of Distances Within Our Galaxy	36
	2.2.1 Trigonometric Parallax	37
	2.2.2 Proper Motions	38
	2.2.3 Moving Cluster Parallax	38
	2.2.4 Photometric Distance; Extinction and Reddening	39
	2.2.5 Spectroscopic Distance	43
	2.2.6 Distances of Visual Binary Stars	43
	2.2.7 Distances of Pulsating Stars	43
	2.3 The Structure of the Galaxy	44
	2.3.1 The Galactic Disk: Distribution of Stars	46
	2.3.2 The Galactic Disk: Chemical Composition and Age	47
	2.3.3 The Galactic Disk: Dust and Gas	50
	2.3.4 Cosmic Rays	51
	2.3.5 The Galactic Bulge	54
	2.3.6 The Visible Halo	55
	2.3.7 The Distance to the Galactic Center	56
	2.4 Kinematics of the Galaxy	57
	2.4.1 Determination of the Velocity of the Sun	57
	2.4.2 The Rotation Curve of the Galaxy	59
	2.5 The Galactic Microlensing Effect: The Quest for Compact Dark Matter	64

2.5.1	The Gravitational Lensing Effect I	64
2.5.2	Galactic Microlensing Effect	69
2.5.3	Surveys and Results	72
2.5.4	Variations and Extensions	75
2.6	The Galactic Center	77
2.6.1	Where is the Galactic Center?	78
2.6.2	The Central Star Cluster	78
2.6.3	A Black Hole in the Center of the Milky Way	80
2.6.4	Flares from the Galactic Center	82
2.6.5	The Proper Motion of Sgr A*	83
2.6.6	Hypervelocity Stars in the Galaxy	84
3.	The World of Galaxies	
3.1	Classification	88
3.1.1	Morphological Classification: The Hubble Sequence	88
3.1.2	Other Types of Galaxies	89
3.2	Elliptical Galaxies	90
3.2.1	Classification	90
3.2.2	Brightness Profile	90
3.2.3	Composition of Elliptical Galaxies	92
3.2.4	Dynamics of Elliptical Galaxies	93
3.2.5	Indicators of a Complex Evolution	95
3.3	Spiral Galaxies	98
3.3.1	Trends in the Sequence of Spirals	98
3.3.2	Brightness Profile	98
3.3.3	Rotation Curves and Dark Matter	100
3.3.4	Stellar Populations and Gas Fraction	102
3.3.5	Spiral Structure	103
3.3.6	Corona in Spirals?	103
3.4	Scaling Relations	104
3.4.1	The Tully–Fisher Relation	104
3.4.2	The Faber–Jackson Relation	107
3.4.3	The Fundamental Plane	107
3.4.4	The D_n – σ Relation	108
3.5	Black Holes in the Centers of Galaxies	109
3.5.1	The Search for Supermassive Black Holes	109
3.5.2	Examples for SMBHs in Galaxies	110
3.5.3	Correlation Between SMBH Mass and Galaxy Properties	111
3.6	Extragalactic Distance Determination	114
3.6.1	Distance of the LMC	115
3.6.2	The Cepheid Distance	115
3.6.3	Secondary Distance Indicators	116
3.7	Luminosity Function of Galaxies	117
3.7.1	The Schechter Luminosity Function	118
3.7.2	The Bimodal Color Distribution of Galaxies	119

	3.8 Galaxies as Gravitational Lenses	121
	3.8.1 The Gravitational Lensing Effect – Part II	121
	3.8.2 Simple Models	123
	3.8.3 Examples for Gravitational Lenses	125
	3.8.4 Applications of the Lens Effect	130
	3.9 Population Synthesis	132
	3.9.1 Model Assumptions	132
	3.9.2 Evolutionary Tracks in the HRD; Integrated Spectrum	133
	3.9.3 Color Evolution	135
	3.9.4 Star Formation History and Galaxy Colors	136
	3.9.5 Metallicity, Dust, and HII Regions	136
	3.9.6 Summary	136
	3.9.7 The Spectra of Galaxies	137
	3.10 Chemical Evolution of Galaxies	138
4. Cosmology I: Homogeneous Isotropic World Models	4.1 Introduction and Fundamental Observations	141
	4.1.1 Fundamental Cosmological Observations	142
	4.1.2 Simple Conclusions	142
	4.2 An Expanding Universe	145
	4.2.1 Newtonian Cosmology	146
	4.2.2 Kinematics of the Universe	146
	4.2.3 Dynamics of the Expansion	147
	4.2.4 Modifications due to General Relativity	148
	4.2.5 The Components of Matter in the Universe	149
	4.2.6 “Derivation” of the Expansion Equation	150
	4.2.7 Discussion of the Expansion Equations	150
	4.3 Consequences of the Friedmann Expansion	152
	4.3.1 The Necessity of a Big Bang	152
	4.3.2 Redshift	155
	4.3.3 Distances in Cosmology	157
	4.3.4 Special Case: The Einstein–de Sitter Model	159
	4.3.5 Summary	160
	4.4 Thermal History of the Universe	160
	4.4.1 Expansion in the Radiation-Dominated Phase	161
	4.4.2 Decoupling of Neutrinos	161
	4.4.3 Pair Annihilation	162
	4.4.4 Primordial Nucleosynthesis	163
	4.4.5 Recombination	166
	4.4.6 Summary	169
	4.5 Achievements and Problems of the Standard Model	169
	4.5.1 Achievements	169
	4.5.2 Problems of the Standard Model	170
	4.5.3 Extension of the Standard Model: Inflation	173

5. Active Galactic Nuclei	5.1 Introduction	177
	5.1.1 Brief History of AGNs	177
	5.1.2 Fundamental Properties of Quasars	178
	5.1.3 Quasars as Radio Sources: Synchrotron Radiation	178
	5.1.4 Broad Emission Lines	181
	5.2 AGN Zoology	182
	5.2.1 Quasi-Stellar Objects	183
	5.2.2 Seyfert Galaxies	183
	5.2.3 Radio Galaxies	183
	5.2.4 Optically Violently Variables	184
	5.2.5 BL Lac Objects	185
	5.3 The Central Engine: A Black Hole	185
	5.3.1 Why a Black Hole?	186
	5.3.2 Accretion	186
	5.3.3 Superluminal Motion	188
	5.3.4 Further Arguments for SMBHs	191
	5.3.5 A First Mass Estimate for the SMBH: The Eddington Luminosity	193
	5.4 Components of an AGN	195
	5.4.1 The IR, Optical, and UV Continuum	195
	5.4.2 The Broad Emission Lines	196
	5.4.3 Narrow Emission Lines	201
	5.4.4 X-Ray Emission	201
	5.4.5 The Host Galaxy	202
	5.4.6 The Black Hole Mass in AGNs	204
	5.5 Family Relations of AGNs	207
	5.5.1 Unified Models	207
	5.5.2 Beaming	210
	5.5.3 Beaming on Large Scales	211
	5.5.4 Jets at Higher Frequencies	212
	5.6 AGNs and Cosmology	215
	5.6.1 The K-Correction	215
	5.6.2 The Luminosity Function of Quasars	216
	5.6.3 Quasar Absorption Lines	219
6. Clusters and Groups of Galaxies	6.1 The Local Group	224
	6.1.1 Phenomenology	224
	6.1.2 Mass Estimate	225
	6.1.3 Other Components of the Local Group	227
	6.2 Galaxies in Clusters and Groups	228
	6.2.1 The Abell Catalog	228
	6.2.2 Luminosity Function of Cluster Galaxies	230
	6.2.3 Morphological Classification of Clusters	231

	6.2.4	Spatial Distribution of Galaxies	231
	6.2.5	Dynamical Mass of Clusters	233
	6.2.6	Additional Remarks on Cluster Dynamics	234
	6.2.7	Intergalactic Stars in Clusters of Galaxies	236
	6.2.8	Galaxy Groups	237
	6.2.9	The Morphology–Density Relation	239
	6.3	X-Ray Radiation from Clusters of Galaxies	242
	6.3.1	General Properties of the X-Ray Radiation	242
	6.3.2	Models of the X-Ray Emission	246
	6.3.3	Cooling Flows	248
	6.3.4	The Sunyaev–Zeldovich Effect	252
	6.3.5	X-Ray Catalogs of Clusters	255
	6.4	Scaling Relations for Clusters of Galaxies	256
	6.4.1	Mass–Temperature Relation	256
	6.4.2	Mass–Velocity Dispersion Relation	257
	6.4.3	Mass–Luminosity Relation	258
	6.4.4	Near-Infrared Luminosity as Mass Indicator	259
	6.5	Clusters of Galaxies as Gravitational Lenses	260
	6.5.1	Luminous Arcs	260
	6.5.2	The Weak Gravitational Lens Effect	264
	6.6	Evolutionary Effects	270
7. Cosmology II: Inhomogeneities in the Universe	7.1	Introduction	277
	7.2	Gravitational Instability	278
	7.2.1	Overview	278
	7.2.2	Linear Perturbation Theory	279
	7.3	Description of Density Fluctuations	282
	7.3.1	Correlation Functions	283
	7.3.2	The Power Spectrum	284
	7.4	Evolution of Density Fluctuations	285
	7.4.1	The Initial Power Spectrum	285
	7.4.2	Growth of Density Perturbations	286
	7.5	Non-Linear Structure Evolution	289
	7.5.1	Model of Spherical Collapse	289
	7.5.2	Number Density of Dark Matter Halos	291
	7.5.3	Numerical Simulations of Structure Formation	293
	7.5.4	Profile of Dark Matter Halos	298
	7.5.5	The Substructure Problem	302
	7.6	Peculiar Velocities	306
	7.7	Origin of the Density Fluctuations	307

8. Cosmology III: The Cosmological Parameters	8.1 Redshift Surveys of Galaxies	309
	8.1.1 Introduction	309
	8.1.2 Redshift Surveys	310
	8.1.3 Determination of the Power Spectrum	313
	8.1.4 Effect of Peculiar Velocities	316
	8.1.5 Angular Correlations of Galaxies	318
	8.1.6 Cosmic Peculiar Velocities	319
	8.2 Cosmological Parameters from Clusters of Galaxies	321
	8.2.1 Number Density	322
	8.2.2 Mass-to-Light Ratio	322
	8.2.3 Baryon Content	323
	8.2.4 The LSS of Clusters of Galaxies	323
	8.3 High-Redshift Supernovae and the Cosmological Constant	324
	8.3.1 Are SN Ia Standard Candles?	324
	8.3.2 Observing SNe Ia at High Redshifts	325
	8.3.3 Results	326
	8.3.4 Discussion	328
	8.4 Cosmic Shear	329
	8.5 Origin of the Lyman-α Forest	331
	8.5.1 The Homogeneous Intergalactic Medium	331
	8.5.2 Phenomenology of the Lyman- α Forest	332
	8.5.3 Models of the Lyman- α Forest	333
	8.5.4 The Ly α Forest as Cosmological Tool	335
	8.6 Angular Fluctuations of the Cosmic Microwave Background	336
	8.6.1 Origin of the Anisotropy: Overview	336
	8.6.2 Description of the Cosmic Microwave Background Anisotropy	338
	8.6.3 The Fluctuation Spectrum	339
	8.6.4 Observations of the Cosmic Microwave Background Anisotropy	341
	8.6.5 WMAP: Precision Measurements of the Cosmic Microwave Background Anisotropy	345
	8.7 Cosmological Parameters	349
	8.7.1 Cosmological Parameters with WMAP	349
	8.7.2 Cosmic Harmony	352
9. The Universe at High Redshift	9.1 Galaxies at High Redshift	356
	9.1.1 Lyman-Break Galaxies (LBGs)	356
	9.1.2 Photometric Redshift	362
	9.1.3 Hubble Deep Field(s)	364
	9.1.4 Natural Telescopes	367

9.2	New Types of Galaxies	369
9.2.1	Starburst Galaxies	369
9.2.2	Extremely Red Objects (EROs)	371
9.2.3	Submillimeter Sources: A View Through Thick Dust	374
9.2.4	Damped Lyman-Alpha Systems	377
9.2.5	Lyman-Alpha Blobs	378
9.3	Background Radiation at Smaller Wavelengths	379
9.3.1	The IR Background	380
9.3.2	The X-Ray Background	380
9.4	Reionization of the Universe	382
9.4.1	The First Stars	383
9.4.2	The Reionization Process	385
9.5	The Cosmic Star-Formation History	387
9.5.1	Indicators of Star Formation	387
9.5.2	Redshift Dependence of the Star Formation: The Madau Diagram	389
9.6	Galaxy Formation and Evolution	390
9.6.1	Expectations from Structure Formation	391
9.6.2	Formation of Elliptical Galaxies	392
9.6.3	Semi-Analytic Models	395
9.6.4	Cosmic Downsizing	400
9.7	Gamma-Ray Bursts	402
10.	Outlook	407
Appendix		
A.	The Electromagnetic Radiation Field	
A.1	Parameters of the Radiation Field	417
A.2	Radiative Transfer	417
A.3	Blackbody Radiation	418
A.4	The Magnitude Scale	420
A.4.1	Apparent Magnitude	420
A.4.2	Filters and Colors	420
A.4.3	Absolute Magnitude	422
A.4.4	Bolometric Parameters	422
B.	Properties of Stars	
B.1	The Parameters of Stars	425
B.2	Spectral Class, Luminosity Class, and the Hertzsprung–Russell Diagram	425
B.3	Structure and Evolution of Stars	427
C.	Units and Constants	431

D. Recommended Literature	D.1 General Textbooks	433
	D.2 More Specific Literature	433
	D.3 Review Articles, Current Literature, and Journals	434
E. Acronyms Used		437
F. Figure Credits		441
Subject Index		453