Galaxy Formation and Evolution

Houjun Mo  
Department of Astronomy, University of Massachusetts  
710 North Pleasant Str., Amherst, MA 01003-9305, USA

Frank van den Bosch  
Department of Physics & Astronomy, University of Utah  
115 South 1400 East, Salt Lake City, UT 84112-0830, USA

Simon White  
Max-Planck Institute for Astrophysics  
Karl-Schwarzschild Str. 1, D-85741 Garching, Germany
## Contents

### Preface

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>xiii</td>
</tr>
</tbody>
</table>

### 1 Introduction

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1 The Diversity of the Galaxy Population</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Basic Elements of Galaxy Formation</td>
<td>5</td>
</tr>
<tr>
<td>1.2.1 The Standard Model of Cosmology</td>
<td>6</td>
</tr>
<tr>
<td>1.2.2 Initial Conditions</td>
<td>6</td>
</tr>
<tr>
<td>1.2.3 Gravitational Instability and Structure Formation</td>
<td>7</td>
</tr>
<tr>
<td>1.2.4 Gas Cooling</td>
<td>8</td>
</tr>
<tr>
<td>1.2.5 Star Formation</td>
<td>8</td>
</tr>
<tr>
<td>1.2.6 Feedback Processes</td>
<td>10</td>
</tr>
<tr>
<td>1.2.7 Mergers</td>
<td>10</td>
</tr>
<tr>
<td>1.2.8 Dynamical Evolution</td>
<td>12</td>
</tr>
<tr>
<td>1.2.9 Chemical Evolution</td>
<td>12</td>
</tr>
<tr>
<td>1.2.10 Stellar Population Synthesis</td>
<td>13</td>
</tr>
<tr>
<td>1.2.11 The Intergalactic Medium</td>
<td>13</td>
</tr>
<tr>
<td>1.3 Time Scales</td>
<td>14</td>
</tr>
<tr>
<td>1.4 A Brief History of Galaxy Formation</td>
<td>15</td>
</tr>
<tr>
<td>1.4.1 Galaxies as Extragalactic Objects</td>
<td>15</td>
</tr>
<tr>
<td>1.4.2 Cosmology</td>
<td>16</td>
</tr>
<tr>
<td>1.4.3 Structure Formation</td>
<td>18</td>
</tr>
<tr>
<td>1.4.4 The Emergence of the Cold Dark Matter Paradigm</td>
<td>20</td>
</tr>
<tr>
<td>1.4.5 Galaxy Formation</td>
<td>22</td>
</tr>
</tbody>
</table>

### 2 Observational Facts

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Astronomical Observations</td>
<td>25</td>
</tr>
<tr>
<td>2.1.1 Fluxes and Magnitudes</td>
<td>26</td>
</tr>
<tr>
<td>2.1.2 Spectroscopy</td>
<td>29</td>
</tr>
<tr>
<td>2.1.3 Distance Measurements</td>
<td>32</td>
</tr>
<tr>
<td>2.2 Stars</td>
<td>34</td>
</tr>
<tr>
<td>2.3 Galaxies</td>
<td>38</td>
</tr>
<tr>
<td>2.3.1 The Classification of Galaxies</td>
<td>38</td>
</tr>
<tr>
<td>2.3.2 Elliptical Galaxies</td>
<td>42</td>
</tr>
<tr>
<td>2.3.3 Disk Galaxies</td>
<td>50</td>
</tr>
</tbody>
</table>
2.3.4 The Milky Way 56
2.3.5 Dwarf Galaxies 58
2.3.6 Nuclear Star Clusters 60
2.3.7 Starbursts 61
2.3.8 Active Galactic Nuclei 61

2.4 Statistical Properties of the Galaxy Population 62
  2.4.1 Luminosity Function 63
  2.4.2 Size Distribution 64
  2.4.3 Color Distribution 65
  2.4.4 The Mass-Metallicity Relation 66
  2.4.5 Environment Dependence 67

2.5 Clusters and Groups of Galaxies 68
  2.5.1 Clusters of Galaxies 68
  2.5.2 Groups of Galaxies 72

2.6 Galaxies at High Redshifts 74
  2.6.1 Galaxy Counts 75
  2.6.2 Photometric Redshifts 75
  2.6.3 Galaxy Redshift Surveys at z ~ 1 77
  2.6.4 Lyman-Break Galaxies 78
  2.6.5 Lyα Emitters 79
  2.6.6 Sub-Millimeter Sources 80
  2.6.7 Extremely Red Objects and Distant Red Galaxies 80
  2.6.8 The Cosmic Star Formation History 82

2.7 Large-Scale Structure 82
  2.7.1 Two-Point Correlation Functions 83
  2.7.2 Probing the Matter Field via Weak Lensing 86

2.8 The Intergalactic Medium 86
  2.8.1 The Gunn-Peterson Test 87
  2.8.2 Quasar Absorption Line Systems 87

2.9 The Cosmic Microwave Background 91

2.10 The Homogeneous and Isotropic Universe 94
  2.10.1 The Determination of Cosmological Parameters 96
  2.10.2 The Mass and Energy Content of the Universe 97

3 Cosmological Background 101

3.1 The Cosmological Principle and the Robertson-Walker Metric 103
  3.1.1 The Cosmological Principle and its Consequences 103
  3.1.2 Robertson-Walker Metric 105
  3.1.3 Redshift 107
  3.1.4 Peculiar Velocities 108
  3.1.5 Thermodynamics and the Equation of State 109
  3.1.6 Angular-Diameter and Luminosity Distances 111

3.2 Relativistic Cosmology 113
  3.2.1 Friedmann Equation 113
  3.2.2 The Densities at the Present Time 115
  3.2.3 Explicit Solutions of the Friedmann Equation 116
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.4</td>
<td>Horizons</td>
<td>119</td>
</tr>
<tr>
<td>3.2.5</td>
<td>The Age of the Universe</td>
<td>120</td>
</tr>
<tr>
<td>3.2.6</td>
<td>Cosmological Distances and Volumes</td>
<td>122</td>
</tr>
<tr>
<td>3.3</td>
<td>The Production and Survival of Particles</td>
<td>125</td>
</tr>
<tr>
<td>3.3.1</td>
<td>The Chronology of the Hot Big Bang</td>
<td>126</td>
</tr>
<tr>
<td>3.3.2</td>
<td>Particles in Thermal Equilibrium</td>
<td>128</td>
</tr>
<tr>
<td>3.3.3</td>
<td>Entropy</td>
<td>130</td>
</tr>
<tr>
<td>3.3.4</td>
<td>Distribution Functions of Decoupled Particle Species</td>
<td>132</td>
</tr>
<tr>
<td>3.3.5</td>
<td>The Freeze-Out of Stable Particles</td>
<td>133</td>
</tr>
<tr>
<td>3.3.6</td>
<td>Decaying Particles</td>
<td>139</td>
</tr>
<tr>
<td>3.4</td>
<td>Primordial Nucleosynthesis</td>
<td>140</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Initial Conditions</td>
<td>140</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Nuclear Reactions</td>
<td>141</td>
</tr>
<tr>
<td>3.4.3</td>
<td>Model Predictions</td>
<td>143</td>
</tr>
<tr>
<td>3.4.4</td>
<td>Observational Results</td>
<td>145</td>
</tr>
<tr>
<td>3.5</td>
<td>Recombination and Decoupling</td>
<td>146</td>
</tr>
<tr>
<td>3.5.1</td>
<td>Recombination</td>
<td>147</td>
</tr>
<tr>
<td>3.5.2</td>
<td>Decoupling and the Origin of the CMB</td>
<td>149</td>
</tr>
<tr>
<td>3.5.3</td>
<td>Compton Scattering</td>
<td>150</td>
</tr>
<tr>
<td>3.5.4</td>
<td>Energy Thermalization</td>
<td>151</td>
</tr>
<tr>
<td>3.6</td>
<td>Inflation</td>
<td>152</td>
</tr>
<tr>
<td>3.6.1</td>
<td>The Problems of the Standard Model</td>
<td>152</td>
</tr>
<tr>
<td>3.6.2</td>
<td>The Concept of Inflation</td>
<td>155</td>
</tr>
<tr>
<td>3.6.3</td>
<td>Realization of Inflation</td>
<td>157</td>
</tr>
<tr>
<td>3.6.4</td>
<td>Models of Inflation</td>
<td>159</td>
</tr>
<tr>
<td>4</td>
<td>Cosmological Perturbations</td>
<td>162</td>
</tr>
<tr>
<td>4.1</td>
<td>Newtonian Theory of Small Perturbations</td>
<td>162</td>
</tr>
<tr>
<td>4.1.1</td>
<td>Ideal Fluid</td>
<td>162</td>
</tr>
<tr>
<td>4.1.2</td>
<td>Isentropic and Isocurvature Initial Conditions</td>
<td>166</td>
</tr>
<tr>
<td>4.1.3</td>
<td>Gravitational Instability</td>
<td>166</td>
</tr>
<tr>
<td>4.1.4</td>
<td>Collisionless Gas</td>
<td>168</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Free–Streaming Damping</td>
<td>171</td>
</tr>
<tr>
<td>4.1.6</td>
<td>Specific Solutions</td>
<td>172</td>
</tr>
<tr>
<td>4.1.7</td>
<td>Higher Order Perturbation Theory</td>
<td>176</td>
</tr>
<tr>
<td>4.1.8</td>
<td>The Zel’dovich Approximation</td>
<td>177</td>
</tr>
<tr>
<td>4.2</td>
<td>Relativistic Theory of Small Perturbations</td>
<td>178</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Gauge Freedom</td>
<td>179</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Classification of Perturbations</td>
<td>181</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Specific Examples of Gauge Choices</td>
<td>183</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Basic Equations</td>
<td>185</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Coupling between Baryons and Radiation</td>
<td>189</td>
</tr>
<tr>
<td>4.2.6</td>
<td>Perturbation Evolution</td>
<td>191</td>
</tr>
<tr>
<td>4.3</td>
<td>Linear Transfer Functions</td>
<td>197</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Adiabatic Baryon Models</td>
<td>199</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Adiabatic Cold Dark Matter Models</td>
<td>200</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Adiabatic Hot Dark Matter Models</td>
<td>201</td>
</tr>
</tbody>
</table>
4.3.4 Isocurvature Cold Dark Matter Models 202
4.4 Statistical Properties 203
  4.4.1 General Discussion 203
  4.4.2 Gaussian Random Fields 204
  4.4.3 Simple Non–Gaussian Models 205
  4.4.4 Linear Perturbation Spectrum 206
4.5 The Origin of Cosmological Perturbations 209
  4.5.1 Perturbations from Inflation 209
  4.5.2 Perturbations from Topological Defects 213

5 Gravitational Collapse and Collisionless Dynamics 215
  5.1 Spherical Collapse Models 215
    5.1.1 Spherical Collapse in a $\Lambda = 0$ Universe 215
    5.1.2 Spherical Collapse in a Flat Universe with $\Lambda > 0$ 218
    5.1.3 Spherical Collapse with Shell Crossing 219
  5.2 Similarity Solutions for Spherical Collapse 220
    5.2.1 Models with Radial Orbits 220
    5.2.2 Models Including Non-Radial Orbits 224
  5.3 Collapse of Homogeneous Ellipsoids 227
  5.4 Collisionless Dynamics 230
    5.4.1 Timescales for Collisions 230
    5.4.2 Basic Dynamics 232
    5.4.3 The Jeans Equations 233
    5.4.4 The Virial Theorem 234
    5.4.5 Orbit Theory 236
    5.4.6 The Jeans Theorem 240
    5.4.7 Spherical Equilibrium Models 240
    5.4.8 Axisymmetric Equilibrium Models 245
    5.4.9 Triaxial Equilibrium Models 247
  5.5 Collisionless Relaxation 248
    5.5.1 Phase Mixing 249
    5.5.2 Chaotic Mixing 250
    5.5.3 Violent Relaxation 251
    5.5.4 Landau Damping 253
    5.5.5 The End-State of Relaxation 254
  5.6 Gravitational Collapse of the Cosmic Density Field 257
    5.6.1 Hierarchical Clustering 257
    5.6.2 Results from Numerical Simulations 258

6 Probing the Cosmic Density Field 262
  6.1 Large-Scale Mass Distribution 263
    6.1.1 Correlation Functions 263
    6.1.2 Particle Sampling and Bias 264
    6.1.3 Mass Moments 266
  6.2 Large-Scale Velocity Field 270
Contents

6.2.1 Bulk Motions and Velocity Correlation Functions 270
6.2.2 Mass Density Reconstruction from the Velocity Field 271

6.3 Clustering in Real Space and Redshift Space 273
6.3.1 Redshift Distortions 273
6.3.2 Real-Space Correlation Functions 276

6.4 Clustering Evolution 278
6.4.1 Dynamics of Statistics 279
6.4.2 Self-Similar Gravitational Clustering 280
6.4.3 Development of Non-Gaussian Features 282

6.5 Galaxy Clustering 283
6.5.1 Correlation Analyses 284
6.5.2 Power Spectrum Analysis 288
6.5.3 Angular Correlation Function and Power Spectrum 290

6.6 Gravitational Lensing 292
6.6.1 Basic Equations 293
6.6.2 Lensing by a Point Mass 295
6.6.3 Lensing by an Extended Object 297
6.6.4 Cosmic Shear 300

6.7 Fluctuations in the Cosmic Microwave Background 303
6.7.1 Observational Quantities 303
6.7.2 Theoretical Expectations of Temperature Anisotropy 304
6.7.3 Thomson Scattering and Polarization of the Microwave Background 311
6.7.4 Interaction between CMB Photons and Matter 314
6.7.5 Constraints on Cosmological Parameters 317

7 Formation and Structure of Dark Matter Halos 319

7.1 Density Peaks 321
7.1.1 Peak Number Density 321
7.1.2 Spatial Modulation of the Peak Number Density 323
7.1.3 Correlation Function 324
7.1.4 Shapes of Density Peaks 325

7.2 Halo Mass Function 326
7.2.1 Press-Schechter Formalism 326
7.2.2 Excursion Set Derivation of the Press-Schechter Formula 328
7.2.3 Spherical versus Ellipsoidal Dynamics 331
7.2.4 Tests of the Press-Schechter Formalism 333
7.2.5 Number Density of Galaxy Clusters 334

7.3 Progenitor Distributions and Merger Trees 336
7.3.1 Progenitors of Dark Matter Halos 336
7.3.2 Halo Merger Trees 336
7.3.3 Main Progenitor Histories 339
7.3.4 Halo Assembly and Formation Times 340
7.3.5 Halo Merger Rates 342
7.3.6 Halo Survival Times 343

7.4 Spatial Clustering and Bias 345
7.4.1 Linear Bias and Correlation Function 345
7.4.2 Assembly Bias 348
7.4.3 Non-Linear and Stochastic Bias 348

7.5 Internal Structure of Dark Matter Halos 351
7.5.1 Halo Density Profiles 351
7.5.2 Halo Shapes 354
7.5.3 Halo Substructure 355
7.5.4 Angular Momentum 358

7.6 The Halo Model of Dark Matter Clustering 362

8 Formation and Evolution of Gaseous Halos 366

8.1 Basic Fluid Dynamics and Radiative Processes 366
8.1.1 Basic Equations 366
8.1.2 Compton Cooling 367
8.1.3 Radiative Cooling 367
8.1.4 Photoionization Heating 369

8.2 Hydrostatic Equilibrium 371
8.2.1 Gas Density Profile 371
8.2.2 Convective Instability 373
8.2.3 Virial Theorem Applied to a Gaseous Halo 374

8.3 The Formation of Hot Gaseous Halos 376
8.3.1 Accretion Shocks 376
8.3.2 Self–Similar Collapse of Collisional Gas 379
8.3.3 The Impact of a Collisionless Component 382
8.3.4 More General Models of Spherical Collapse 384

8.4 Radiative Cooling in Gaseous Halos 385
8.4.1 Radiative Cooling Time Scales for Uniform Clouds 385
8.4.2 Evolution of the Cooling Radius 387
8.4.3 Self-Similar Cooling Waves 388
8.4.4 Spherical Collapse with Cooling 390

8.5 Thermal and Hydrodynamical Instabilities of Cooling Gas 393
8.5.1 Thermal Instability 393
8.5.2 Hydrodynamical Instabilities 396
8.5.3 Heat Conduction 397

8.6 Evolution of Gaseous Halos with Energy Sources 398
8.6.1 Blast Waves 399
8.6.2 Winds and Wind–Driven Bubbles 404
8.6.3 Supernova Feedback and Galaxy Formation 406

8.7 Results from Numerical Simulations 408
8.7.1 Three-Dimensional Collapse without Radiative Cooling 408
8.7.2 Three-Dimensional Collapse with Radiative Cooling 409

8.8 Observational Tests 410
8.8.1 X-ray Clusters and Groups 410
8.8.2 Gaseous Halos around Elliptical Galaxies 414
8.8.3 Gaseous Halos around Spiral Galaxies 416
## 9 Star Formation in Galaxies

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Giant Molecular Clouds: the Sites of Star Formation</td>
<td>418</td>
</tr>
<tr>
<td>9.1.1 Observed Properties</td>
<td>418</td>
</tr>
<tr>
<td>9.1.2 Dynamical State</td>
<td>419</td>
</tr>
<tr>
<td>9.2 The Formation of Giant Molecular Clouds</td>
<td>421</td>
</tr>
<tr>
<td>9.2.1 The Formation of Molecular Hydrogen</td>
<td>421</td>
</tr>
<tr>
<td>9.2.2 Cloud Formation</td>
<td>422</td>
</tr>
<tr>
<td>9.3 What Controls the Star Formation Efficiency</td>
<td>425</td>
</tr>
<tr>
<td>9.3.1 Magnetic Fields</td>
<td>425</td>
</tr>
<tr>
<td>9.3.2 Supersonic Turbulence</td>
<td>426</td>
</tr>
<tr>
<td>9.3.3 Self-Regulation</td>
<td>428</td>
</tr>
<tr>
<td>9.4 The Formation of Individual Stars</td>
<td>429</td>
</tr>
<tr>
<td>9.4.1 The Formation of Low-Mass Stars</td>
<td>429</td>
</tr>
<tr>
<td>9.4.2 The Formation of Massive Stars</td>
<td>432</td>
</tr>
<tr>
<td>9.5 Empirical Star Formation Laws</td>
<td>433</td>
</tr>
<tr>
<td>9.5.1 The Kennicutt-Schmidt law</td>
<td>434</td>
</tr>
<tr>
<td>9.5.2 Local Star Formation Laws</td>
<td>436</td>
</tr>
<tr>
<td>9.5.3 Star Formation Thresholds</td>
<td>438</td>
</tr>
<tr>
<td>9.6 The Initial Mass Function</td>
<td>440</td>
</tr>
<tr>
<td>9.6.1 Observational Constraints</td>
<td>441</td>
</tr>
<tr>
<td>9.6.2 Theoretical Models</td>
<td>443</td>
</tr>
<tr>
<td>9.7 The Formation of Population III Stars</td>
<td>446</td>
</tr>
</tbody>
</table>

## 10 Stellar Populations and Chemical Evolution

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.1 The Basic Concepts of Stellar Evolution</td>
<td>449</td>
</tr>
<tr>
<td>10.1.1 Basic Equations of Stellar Structure</td>
<td>450</td>
</tr>
<tr>
<td>10.1.2 Stellar Structure Evolution</td>
<td>453</td>
</tr>
<tr>
<td>10.1.3 Equation of State, Opacity, and Energy Production</td>
<td>453</td>
</tr>
<tr>
<td>10.1.4 Scaling Relations</td>
<td>460</td>
</tr>
<tr>
<td>10.1.5 Main Sequence Lifetimes</td>
<td>462</td>
</tr>
<tr>
<td>10.2 Stellar Evolutionary Tracks</td>
<td>463</td>
</tr>
<tr>
<td>10.2.1 Pre-Main-Sequence Evolution</td>
<td>463</td>
</tr>
<tr>
<td>10.2.2 Post-Main-Sequence Evolution</td>
<td>464</td>
</tr>
<tr>
<td>10.2.3 Supernova Progenitors and Rates</td>
<td>468</td>
</tr>
<tr>
<td>10.3 Stellar Population Synthesis</td>
<td>470</td>
</tr>
<tr>
<td>10.3.1 Stellar Spectra</td>
<td>470</td>
</tr>
<tr>
<td>10.3.2 Spectral Synthesis</td>
<td>471</td>
</tr>
<tr>
<td>10.3.3 Passive Evolution</td>
<td>472</td>
</tr>
<tr>
<td>10.3.4 Spectral Features</td>
<td>474</td>
</tr>
<tr>
<td>10.3.5 Age-Metallicity Degeneracy</td>
<td>475</td>
</tr>
<tr>
<td>10.3.6 K- and E-Corrections</td>
<td>475</td>
</tr>
<tr>
<td>10.3.7 Emission and Absorption by the Interstellar Medium</td>
<td>476</td>
</tr>
<tr>
<td>10.3.8 Star Formation Diagnostics</td>
<td>482</td>
</tr>
<tr>
<td>10.3.9 Estimating Stellar Masses and Star Formation Histories of Galaxies</td>
<td>485</td>
</tr>
<tr>
<td>10.4 Chemical Evolution of Galaxies</td>
<td>486</td>
</tr>
</tbody>
</table>
10.4.1 Stellar Chemical Production 486
10.4.2 The Closed-Box Model 488
10.4.3 Models with Inflow and Outflow 490
10.4.4 Abundance Ratios 491

10.5 Stellar Energetic Feedback 492
10.5.1 Mass-Loaded Kinetic Energy from Stars 493
10.5.2 Gas Dynamics Including Stellar Feedback 494

11 Disk Galaxies 495

11.1 Mass Components and Angular Momentum 495
11.1.1 Disk Models 496
11.1.2 Rotation Curves 498
11.1.3 Adiabatic Contraction 501
11.1.4 Disk Angular Momentum 502
11.1.5 Orbits in Disk Galaxies 503

11.2 The Formation of Disk Galaxies 505
11.2.1 General Discussion 505
11.2.2 Non-Self-Gravitating Disks in Isothermal Spheres 505
11.2.3 Self-Gravitating Disks in Halos with Realistic Profiles 507
11.2.4 Including a Bulge Component 509
11.2.5 Disk Assembly 510
11.2.6 Numerical Simulations of Disk Formation 511

11.3 The Origin of Disk Galaxy Scaling Relations 512

11.4 The Origin of Exponential Disks 515
11.4.1 Disks from Relic Angular Momentum Distribution 515
11.4.2 Viscous Disks 517
11.4.3 The Vertical Structure of Disk Galaxies 518

11.5 Disk Instabilities 521
11.5.1 Basic Equations 521
11.5.2 Local Instability 523
11.5.3 Global Instability 525
11.5.4 Secular Evolution 528

11.6 The Formation of Spiral Arms 531

11.7 Stellar Population Properties 534
11.7.1 Global Trends 535
11.7.2 Color Gradients 537

11.8 Chemical Evolution of Disk Galaxies 538
11.8.1 The Solar Neighborhood 538
11.8.2 Global Relations 540

12 Galaxy Interactions and Transformations 544

12.1 High-Speed Encounters 545

12.2 Tidal Stripping 548
12.2.1 Tidal Radius 548
12.2.2 Tidal Streams and Tails 550
12.3 Dynamical Friction 553
  12.3.1 Orbital Decay 556
  12.3.2 The Validity of Chandrasekhar's Formula 559

12.4 Galaxy Merging 561
  12.4.1 Criterion for Mergers 561
  12.4.2 Merger Demographics 563
  12.4.3 The Connection between Mergers, Starbursts and AGN 565
  12.4.4 Minor Mergers and Disk Heating 565

12.5 Transformation of Galaxies in Clusters 568
  12.5.1 Galaxy Harassment 569
  12.5.2 Galactic Cannibalism 570
  12.5.3 Ram-Pressure Stripping 571
  12.5.4 Strangulation 572

13 Elliptical Galaxies 574

13.1 Structure and Dynamics 574
  13.1.1 Observables 575
  13.1.2 Photometric Properties 576
  13.1.3 Kinematic Properties 577
  13.1.4 Dynamical Modeling 579
  13.1.5 Evidence for Dark Halos 581
  13.1.6 Evidence for Supermassive Black Holes 582
  13.1.7 Shapes 584

13.2 The Formation of Elliptical Galaxies 587
  13.2.1 The Monolithic Collapse Scenario 588
  13.2.2 The Merger Scenario 590
  13.2.3 Hierarchical Merging and the Elliptical Population 593

13.3 Observational Tests and Constraints 594
  13.3.1 Evolution of the Number Density of Ellipticals 594
  13.3.2 The Sizes of Elliptical Galaxies 595
  13.3.3 Phase-Space Density Constraints 598
  13.3.4 The Specific Frequency of Globular Clusters 599
  13.3.5 Merging Signatures 600
  13.3.6 Merger Rates 601

13.4 The Fundamental Plane of Elliptical Galaxies 602
  13.4.1 The Fundamental Plane in the Merger Scenario 604
  13.4.2 Projections and Rotations of the Fundamental Plane 604

13.5 Stellar Population Properties 606
  13.5.1 Archaeological Records 606
  13.5.2 Evolutionary Probes 609
  13.5.3 Color and Metallicity Gradients 610
  13.5.4 Implications for the Formation of Elliptical Galaxies 610

13.6 Bulges, Dwarf Ellipticals and Dwarf Spheroidals 613
  13.6.1 The Formation of Galactic Bulges 614
  13.6.2 The Formation of Dwarf Ellipticals 616
# 14 Active Galaxies

14.1 The Population of Active Galactic Nuclei 619
14.2 The Supermassive Black Hole Paradigm 623
  14.2.1 The Central Engine 623
  14.2.2 Accretion Disks 625
  14.2.3 Continuum Emission 626
  14.2.4 Emission Lines 631
  14.2.5 Jets, Superluminal Motion and Beaming 634
  14.2.6 Emission-Line Regions and Obscuring Torus 637
  14.2.7 The Idea of Unification 638
  14.2.8 Observational Tests for Supermassive Black Holes 639
14.3 The Formation and Evolution of AGN 640
  14.3.1 The Growth of Supermassive Black Holes and the Fueling of AGN 640
  14.3.2 AGN Demographics 644
  14.3.3 Outstanding Questions 648
14.4 AGN and Galaxy Formation 649
  14.4.1 Radiative Feedback 650
  14.4.2 Mechanical Feedback 651

# 15 Statistical Properties of the Galaxy Population

15.1 Preamble 652
15.2 Galaxy Luminosities and Stellar Masses 654
  15.2.1 Galaxy Luminosity Functions 654
  15.2.2 Galaxy Counts 658
  15.2.3 Extragalactic Background Light 660
15.3 Linking Halo Mass to Galaxy Luminosity 663
  15.3.1 Simple Considerations 663
  15.3.2 The Luminosity Function of Central Galaxies 665
  15.3.3 The Luminosity Function of Satellite Galaxies 666
  15.3.4 Satellite Fractions 668
  15.3.5 Discussion 669
15.4 Linking Halo Mass to Star Formation History 670
  15.4.1 The Color Distribution of Galaxies 670
  15.4.2 Origin of the Cosmic Star Formation History 673
15.5 Environmental Dependence 674
  15.5.1 Effects within Dark Matter Halos 675
  15.5.2 Effects on Large Scales 677
15.6 Spatial Clustering and Galaxy Bias 679
  15.6.1 Application to High-Redshift Galaxies 683
15.7 Putting it All Together 684
  15.7.1 Semi-Analytical Models 684
  15.7.2 Hydrodynamical Simulations 686
## 16 The Intergalactic Medium

### 16.1 The Ionization State of the Intergalactic Medium
- 16.1.1 Physical Conditions after Recombination
- 16.1.2 The Mean Optical Depth of the IGM
- 16.1.3 The Gunn-Peterson Test
- 16.1.4 Constraints from the Cosmic Microwave Background

### 16.2 Ionizing Sources
- 16.2.1 Photoionization versus Collisional Ionization
- 16.2.2 Emissivity from Quasars and Young Galaxies
- 16.2.3 Attenuation by Intervening Absorbers
- 16.2.4 Observational Constraints on the UV Background

### 16.3 The Evolution of the Intergalactic Medium
- 16.3.1 Thermal Evolution
- 16.3.2 Ionization Evolution
- 16.3.3 The Epoch of Reionization
- 16.3.4 Probing Reionization with 21-cm Emission and Absorption

### 16.4 General Properties of Absorption Lines
- 16.4.1 Distribution Function
- 16.4.2 Thermal Broadening
- 16.4.3 Natural Broadening and Voigt Profiles
- 16.4.4 Equivalent Width and Column Density
- 16.4.5 Common QSO Absorption Line Systems
- 16.4.6 Photoionization Models

### 16.5 The Lyman $\alpha$ Forest
- 16.5.1 Redshift Evolution
- 16.5.2 Column Density Distribution
- 16.5.3 Doppler Parameter
- 16.5.4 Sizes of Absorbers
- 16.5.5 Metallicity
- 16.5.6 Clustering
- 16.5.7 Lyman $\alpha$ Forests at Low Redshift
- 16.5.8 The Helium Lyman $\alpha$ Forest

### 16.6 Models of the Lyman $\alpha$ Forest
- 16.6.1 Early Models
- 16.6.2 Lyman $\alpha$ Forest in Hierarchical Models
- 16.6.3 Lyman $\alpha$ Forest in Hydrodynamical Simulations

### 16.7 Lyman-Limit Systems

### 16.8 Damped Lyman $\alpha$ Systems
- 16.8.1 Column Density Distribution
- 16.8.2 Redshift Evolution
- 16.8.3 Metallicities
- 16.8.4 Kinematics

### 16.9 Metal Absorption Line Systems
- 16.9.1 MgII Systems
- 16.9.2 CIV and OVI Systems
## Contents

<table>
<thead>
<tr>
<th>A1</th>
<th>Basics of General Relativity</th>
<th>741</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1</td>
<td>Spacetime Geometry</td>
<td>741</td>
</tr>
<tr>
<td>A1.2</td>
<td>The Equivalence Principle</td>
<td>743</td>
</tr>
<tr>
<td>A1.3</td>
<td>Geodesic Equations</td>
<td>744</td>
</tr>
<tr>
<td>A1.4</td>
<td>Energy-Momentum Tensor</td>
<td>746</td>
</tr>
<tr>
<td>A1.5</td>
<td>Newtonian Limit</td>
<td>747</td>
</tr>
<tr>
<td>A1.6</td>
<td>Einstein’s Field Equation</td>
<td>747</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A2</th>
<th>Gas and Radiative Processes</th>
<th>748</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2.1</td>
<td>Ideal Gas</td>
<td>748</td>
</tr>
<tr>
<td>A2.2</td>
<td>Basic Equations</td>
<td>749</td>
</tr>
<tr>
<td>A2.3</td>
<td>Radiative Processes</td>
<td>751</td>
</tr>
<tr>
<td>A2.4</td>
<td>Radiative Cooling</td>
<td>760</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>A3</th>
<th>Numerical Simulations</th>
<th>764</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3.1</td>
<td>N-Body Simulations</td>
<td>764</td>
</tr>
<tr>
<td>A3.2</td>
<td>Hydrodynamical Simulations</td>
<td>770</td>
</tr>
</tbody>
</table>

| A4   | Frequently Used Abbreviations | 775 |

| A5   | Useful Numbers               | 776 |

Bibliography  
Index  

806