Contents

Prefaces

1 Introduction
1.1 The challenge
1.2 Discovery status
1.3 Outline of the treatment
1.3.1 Observational techniques
1.3.2 Host star properties and brown dwarfs
1.3.3 Theoretical considerations
1.4 Astronomical terms and units
1.5 Definition of a planet
1.6 On-line reference compilations

2 Radial velocities
2.1 Description of orbits
2.1.1 Orbits from radial velocity measurements
2.2 Measurement principles and accuracies
2.2.1 Introduction
2.2.2 Cross-correlation spectroscopy
2.2.3 Deriving radial velocities from Doppler shifts
2.2.4 Wavelength calibration
2.2.5 Exposure metering
2.2.6 Accuracy limits
2.2.7 Excluding other sources of periodicity
2.3 Instrument programmes
2.3.1 State-of-the-art in échelle spectroscopy
2.3.2 Externally dispersed interferometry
2.3.3 Future developments
2.4 Results to date
2.4.1 The first radial velocity exoplanets
2.4.2 The present radial velocity census
2.4.3 On-line compilations
2.4.4 Main sequence stars
2.4.5 Evolved stars
2.4.6 Other star categories
2.5 Properties of the radial velocity planets
2.5.1 Frequency of massive planets
2.5.2 Mass distribution
2.5.3 Orbits
2.5.4 Host star dependencies
2.6 Multiple planet systems
2.6.1 General considerations
2.6.2 Resonances
2.6.3 Long-term integration and system stability
2.6.4 Systems with three or more giant planets
2.6.5 Systems in mean motion resonance
2.6.6 Interacting doubles
2.6.7 Non-interacting doubles
2.6.8 Super-Earth systems
2.6.9 Stability of habitable zone systems

2.7 Planets around binary and multiple stars
2.7.1 Configurations and stability
2.7.2 Present inventory
2.7.3 Specific examples

3 Astrometry
3.1 Introduction
3.2 Astrometric accuracy from ground
3.3 Microarcsec astrometry
3.4 Astrophysical limits
3.4.1 Surface structure jitter
3.5 Multiple planets and mandalas
3.6 Modeling planetary systems
3.7 Astrometric measurements from ground
3.8 Astrometric measurements from space
3.8.1 Hipparcos
3.8.2 HST–Fine Guidance Sensor
3.9 Future observations from space

4 Timing
4.1 Pulsars
4.1.1 PSR B1257+12
4.1.2 PSR B1620–26
4.1.3 Other considerations
4.2 Pulsating stars
4.2.1 White dwarfs
4.2.2 Hot subdwarfs
4.3 Eclipsing binaries
4.3.1 Confirmed planets
4.3.2 Unconfirmed planets

5 Microlensing
5.1 Introduction
5.2 Description
5.3 Caustics and critical curves
5.4 Other light curve effects
5.5 Microlens parallax and lens mass
5.6 Astrometric microlensing
5.7 Other configurations
5.8 Microlensing observations in practice
5.9 Exoplanet results
5.9.1 Individual objects
5.9.2 Statistical results
5.10 Summary of limitations and strengths
5.11 Future developments
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>6.1</td>
<td>Introduction</td>
<td>103</td>
</tr>
<tr>
<td></td>
<td>6.2</td>
<td>Transit searches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.2.1</td>
<td>Large-field searches from the ground</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>6.2.2</td>
<td>Other searches from the ground</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>6.2.3</td>
<td>Searches in open and globular clusters</td>
<td>108</td>
</tr>
<tr>
<td></td>
<td>6.2.4</td>
<td>Future searches from the ground</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>6.2.5</td>
<td>Searches from space</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>6.2.6</td>
<td>Follow-up observations from space</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td>6.2.7</td>
<td>Future observations from space</td>
<td>112</td>
</tr>
<tr>
<td></td>
<td>6.2.8</td>
<td>Searches around specific stellar types</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>Noise limits</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>6.4</td>
<td>Transit light curves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.4.1</td>
<td>Observables</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>6.4.2</td>
<td>Theoretical light curves</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>6.4.3</td>
<td>Circular orbits</td>
<td>119</td>
</tr>
<tr>
<td></td>
<td>6.4.4</td>
<td>Eccentric orbits</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>6.4.5</td>
<td>Physical quantities</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>6.4.6</td>
<td>Interferometric observations</td>
<td>123</td>
</tr>
<tr>
<td></td>
<td>6.4.7</td>
<td>Reflected light</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>6.4.8</td>
<td>Doppler variability</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>6.4.9</td>
<td>Polarisation</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>6.4.10</td>
<td>Secondary eclipse</td>
<td>126</td>
</tr>
<tr>
<td></td>
<td>6.4.11</td>
<td>Rossiter–McLaughlin effect</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>6.4.12</td>
<td>Higher-order photometric effects</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>6.4.13</td>
<td>Higher-order timing effects</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>6.4.14</td>
<td>Higher-order spectroscopic effects</td>
<td>136</td>
</tr>
<tr>
<td></td>
<td>6.5</td>
<td>Transmission and emission spectroscopy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.5.1</td>
<td>Background</td>
<td>137</td>
</tr>
<tr>
<td></td>
<td>6.5.2</td>
<td>Observations</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>6.6</td>
<td>Properties of transiting planets</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.6.1</td>
<td>Mass–radius relation</td>
<td>143</td>
</tr>
<tr>
<td></td>
<td>6.6.2</td>
<td>Observed correlations</td>
<td>146</td>
</tr>
<tr>
<td>7</td>
<td>7.1</td>
<td>Introduction</td>
<td>149</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>Techniques</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>7.2.1</td>
<td>Active optics</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>7.2.2</td>
<td>Adaptive optics</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>7.2.3</td>
<td>Coronagraphic masks</td>
<td>152</td>
</tr>
<tr>
<td></td>
<td>7.2.4</td>
<td>Speckle noise</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>7.3</td>
<td>Ground-based imaging instruments</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>7.3.1</td>
<td>Extreme adaptive optics instruments</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>7.3.2</td>
<td>Extremely large telescopes</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>7.3.3</td>
<td>Imaging from the Antarctic</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>7.3.4</td>
<td>Ground-based interferometry</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>7.4</td>
<td>Space-based imaging</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>7.4.1</td>
<td>Existing telescopes</td>
<td>162</td>
</tr>
<tr>
<td></td>
<td>7.4.2</td>
<td>Space interferometry</td>
<td>163</td>
</tr>
<tr>
<td></td>
<td>7.4.3</td>
<td>The future: resolved imaging</td>
<td>167</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>Imaging results</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>7.5.1</td>
<td>Searches around nearby stars</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>7.5.2</td>
<td>Searches around exoplanet host stars</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>7.5.3</td>
<td>Searches in systems with debris disks</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td>7.5.4</td>
<td>Searches around white dwarfs</td>
<td>172</td>
</tr>
</tbody>
</table>
# Table of Contents

## Chapter 7

7.6 Observations at radio wavelengths 173
  7.6.1 Astrometry 173
  7.6.2 Direct imaging 173
7.7 Observations at mm/sub-mm wavelength 177
7.8 Miscellaneous signatures 177
  7.8.1 Planetary and proto-planet collisions 177
  7.8.2 Collisional debris 178
  7.8.3 Accretion onto the central star 178
  7.8.4 Gravitational wave modulation 179

## Chapter 8

8 Host stars 181
  8.1 Knowledge from astrometry 181
    8.1.1 Hipparcos distances and proper motions 181
    8.1.2 Nearby star census 181
    8.1.3 Galactic coordinates 183
  8.2 Photometry and spectroscopy 184
  8.3 Evolutionary models 186
  8.4 Element abundances 188
    8.4.1 Metallicity 188
    8.4.2 Possible biases 191
    8.4.3 Origin of the metallicity difference 191
    8.4.4 Refractory and volatile elements 194
    8.4.5 The r- and s-process elements 198
    8.4.6 The alpha elements 198
    8.4.7 Lithium 199
    8.4.8 Beryllium 201
  8.5 Asteroseismology 201
    8.5.1 Principles 201
    8.5.2 Application to exoplanet host stars 203
  8.6 Activity and X-ray emission 205
    8.6.1 Magnetic and chromospheric activity 205
    8.6.2 X-ray emission 206
  8.7 Stellar multiplicity 206

## Chapter 9

9 Brown dwarfs and free-floating planets 209
  9.1 Brown dwarfs 209
    9.1.1 The role of fusion 209
    9.1.2 Detection 209
    9.1.3 Luminosity and age 211
    9.1.4 Classification 212
    9.1.5 Recognising brown dwarfs 212
    9.1.6 Other properties 213
    9.1.7 Formation 214
  9.2 Free-floating objects of planetary mass 215

## Chapter 10

10 Formation and evolution 217
  10.1 Overview 217
  10.2 Star formation 217
  10.3 Disk formation 218
    10.3.1 Initial collapse 218
    10.3.2 Young stellar objects 219
    10.3.3 Protoplanetary disks 220
    10.3.4 Debris disks 222
  10.4 Terrestrial planet formation 224
    10.4.1 The context 224
10.4.2 Stages in the formation of terrestrial planets 225
10.5 Size, shape, and internal structure 230
10.6 Giant planet formation 231
10.6.1 Formation by core accretion 231
10.6.2 Formation by gravitational disk instability 235
10.7 Formation of planetary satellites 237
10.8 Orbital migration 237
10.8.1 Evidence for migration 237
10.8.2 Gas disk migration 238
10.8.3 Planetesimal disk migration 243
10.8.4 Planet–planet scattering 243
10.9 Tidal effects 244
10.9.1 Tidal evolution of close-in planets 244
10.9.2 Orbital evolution 245
10.9.3 Spin-up of host stars 248
10.9.4 Tidal heating 249
10.9.5 Tidal heating and habitability 250
10.10 Population synthesis 251

11 Interiors and atmospheres 255
11.1 Introduction 255
11.2 Planetary constituents 255
11.2.1 Gas, rock, and ice 255
11.2.2 Chemical composition and condensation 257
11.3 Models of giant planet interiors 260
11.3.1 Equations of state 261
11.3.2 Hydrogen and water 261
11.3.3 Structural models 263
11.4 Predictions of interior models 265
11.4.1 Dependence on composition 265
11.4.2 H/He dominated gas giants 266
11.5 Super-Earths 267
11.5.1 General models 267
11.5.2 Ocean planets 269
11.6 Diagnostics from rotation 270
11.7 Atmospheres of gas giants 271
11.8 Atmospheres of terrestrial planets 278
11.8.1 Atmospheric formation 278
11.8.2 Atmospheric erosion 279
11.8.3 Atmospheres of ejected planets 281
11.9 Habitability 282
11.9.1 The habitable zone 283
11.9.2 Exoplanets in the habitable zone 286
11.9.3 Spectroscopic indicators of life 287
11.9.4 SETI 290

12 The solar system 293
12.1 Birth in clusters 293
12.2 The solar system giants 293
12.3 Minor bodies in the solar system 295
12.4 Solar nebula abundances 295
12.5 Constraints on formation 296
12.6 Orbit considerations 299
12.7 Planetesimal migration in the solar system 302
12.8 Atmosphere of the Earth 305
<table>
<thead>
<tr>
<th>Appendix</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>Numerical quantities</td>
<td>309</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Notation</td>
<td>313</td>
</tr>
<tr>
<td>Appendix C</td>
<td>Radial velocity planets</td>
<td>317</td>
</tr>
<tr>
<td>Appendix D</td>
<td>Transiting planets</td>
<td>325</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>329</td>
</tr>
<tr>
<td>Subject Index</td>
<td></td>
<td>403</td>
</tr>
</tbody>
</table>