Contents

Preface *page* ix

1 Observations of planetary systems **1**

1.1 Solar System planets 2

1.1.1 The minimum mass Solar Nebula 4

1.2 Minor bodies in the Solar System 6

1.3 Radioactive dating of the Solar System 8

1.4 The snowline in the Solar Nebula 12

1.5 Chondritic meteorites 13

1.6 Extrasolar planetary systems 14

1.6.1 Direct imaging 15

1.6.2 Radial velocity searches 17

1.6.3 Astrometry 23

1.6.4 Transits 24

1.6.5 Gravitational microlensing 27

1.7 Properties of extrasolar planets 29

1.8 Further reading 33

2 Protoplanetary disk structure **34**

2.1 Disks in the context of star formation 34

2.1.1 Classification of Young Stellar Objects 36

2.2 Vertical structure 38

2.3 Radial force balance 41

2.4 Radial temperature profile of passive disks 42

2.4.1 Razor-thin disks 43

2.4.2 Flared disks 45

2.4.3 Radiative equilibrium disks 47

2.4.4 The Chiang–Goldreich model 50

2.4.5 Spectral energy distributions 50

2.5 Opacity 52
2.5.1 Opacity in the optically thin outer disk 54
2.5.2 Analytic opacities 55
2.6 The condensation sequence 56
2.7 Ionization state of protoplanetary disks 58
2.7.1 Thermal ionization 59
2.7.2 Nonthermal ionization 60
2.8 Further reading 64
3 Protoplanetary disk evolution 65
3.1 Observations of disk evolution 65
3.2 Surface density evolution of a thin disk 68
3.2.1 The viscous time scale 69
3.2.2 Solutions to the disk evolution equation 70
3.2.3 Temperature profile of accreting disks 74
3.3 Vertical structure of protoplanetary disks 76
3.3.1 The central temperature of accreting disks 77
3.3.2 Shakura–Sunyaev α prescription 78
3.3.3 Vertically averaged solutions 80
3.4 Angular momentum transport mechanisms 82
3.4.1 The Rayleigh criterion 82
3.4.2 The magnetorotational instability 82
3.4.3 Disk winds and magnetic braking 87
3.4.4 Hydrodynamic turbulence 90
3.5 Effects of partial ionization on disk evolution 95
3.5.1 Layered disks 97
3.6 Disk dispersal 101
3.6.1 Photoevaporation 101
3.6.2 Viscous evolution with photoevaporation 103
3.7 Magnetospheric accretion 105
3.8 Further reading 108
4 Planetesimal formation 109
4.1 Aerodynamic drag on solid particles 110
4.1.1 Epstein drag 110
4.1.2 Stokes drag 111
4.2 Dust settling 112
4.2.1 Single particle settling with coagulation 113
4.2.2 Settling in the presence of turbulence 116
4.3 Radial drift of solid particles 118
4.3.1 Radial drift with coagulation 121
4.3.2 Particle concentration at pressure maxima 122

4.3.3 Turbulent radial diffusion 123
4.4 Diffusion of large particles 125
4.5 Planetesimal formation via coagulation 128
4.5.1 Coagulation equation 131
4.5.2 Sticking efficiencies 132
4.6 Goldreich–Ward mechanism 134
4.6.1 Gravitational stability of a particle layer 134
4.6.2 Application to planetesimal formation 140
4.6.3 Self-excited turbulence 142
4.7 Routes to planetesimal formation 144
4.8 Further reading 145
5 Terrestrial planet formation 146
5.1 Physics of collisions 147
5.1.1 Gravitational focusing 147
5.1.2 Shear versus dispersion dominated encounters 148
5.1.3 Accretion versus disruption 152
5.2 Statistical models of planetary growth 156
5.2.1 Approximate treatment 157
5.2.2 Shear and dispersion dominated limits 159
5.2.3 Isolation mass 164
5.3 Velocity dispersion 165
5.3.1 Viscous stirring 166
5.3.2 Dynamical friction 169
5.3.3 Gas drag 169
5.4 Analytic formulae for planetary growth 171
5.5 Collisional damping and turbulent excitation 176
5.6 Coagulation equation 178
5.7 Final assembly 182
5.8 Further reading 184
6 Giant planet formation 185
6.1 Core accretion 186
6.1.1 Core/envelope structure 191
6.1.2 Critical core mass 195
6.1.3 Growth of giant planets 198
6.2 Disk instability 203
6.2.1 Fragmentation conditions 204
6.2.2 Disk cooling time scale 206
6.3 Comparison with observations 210
6.4 Further reading 217

7 Early evolution of planetary systems **218**
7.1 Migration in gaseous disks 219
7.1.1 Resonant torques 222
7.1.2 Type 1 migration 226
7.1.3 Type 2 migration 229
7.1.4 Applications 234
7.2 Resonant evolution 238
7.2.1 Resonant capture 241
7.2.2 Kozai resonance 244
7.3 Migration in planetesimal disks 247
7.3.1 Application to the outer Solar System 251
7.3.2 The Nice Model 252
7.3.3 Application to extrasolar planetary systems 253
7.4 Planetary system stability 253
7.4.1 Hill stability 255
7.4.2 Planet–planet scattering 259
7.5 Further reading 262
Appendix 1 Physical and astronomical constants 263
Appendix 2 N-body methods 264
References 273
Index 281