

# CONTENTS

<i>Tables</i>	<i>page</i>	xii	Further Reading	20
<i>Preface</i>		xiii	Problems	21
<i>Color plates follow page</i>		xvi		
<b>1 Introduction</b>		1	<b>2 Dynamics</b>	24
1.1 A Brief History of the Planetary Sciences		2	2.1 The Two-Body Problem	25
1.2 Inventory of the Solar System		3	2.1.1 <i>Kepler's Laws of Planetary Motion</i>	26
1.2.1 <i>Giant Planets</i>		4	2.1.2 <i>Newton's Laws of Motion and Gravity</i>	27
1.2.2 <i>Terrestrial Planets</i>		5	2.1.3 <i>Reduction of the Two-Body Problem to the One-Body Problem</i>	27
1.2.3 <i>Minor Planets and Comets</i>		7	2.1.4* <i>Generalization of Kepler's Laws</i>	27
1.2.4 <i>Satellite and Ring Systems</i>		8	2.1.5 <i>Orbital Elements</i>	29
1.2.5 <i>Tabulations</i>		8	2.1.6 <i>Bound and Unbound Orbits</i>	30
1.2.6 <i>Heliosphere</i>		10	2.2 The Three-Body Problem	31
1.3 What is a Planet?		10	2.2.1 <i>Jacobi's Constant and Lagrangian Points</i>	31
1.4 Planetary Properties		11	2.2.2 <i>Horseshoe and Tadpole Orbits</i>	33
1.4.1 <i>Orbit</i>		11	2.2.3 <i>Hill Sphere</i>	34
1.4.2 <i>Mass</i>		12	2.3 Perturbations and Resonances	35
1.4.3 <i>Size</i>		13	2.3.1 <i>Resonant Forcing</i>	36
1.4.4 <i>Rotation</i>		14	2.3.2 <i>Mean Motion Resonances</i>	36
1.4.5 <i>Shape</i>		15	2.3.3 <i>Secular Resonances</i>	37
1.4.6 <i>Temperature</i>		16	2.3.4 <i>Resonances in the Asteroid Belt</i>	37
1.4.7 <i>Magnetic Field</i>		16		
1.4.8 <i>Surface Composition</i>		17		
1.4.9 <i>Surface Structure</i>		17		
1.4.10 <i>Atmosphere</i>		17		
1.4.11 <i>Interior</i>		18		
1.5 Formation of the Solar System		19		
Key Concepts		20		

2.3.5	<i>Regular and Chaotic Motion</i>	38	3.1.5	<i>Material Properties: Phase Changes</i>	69
2.4	Stability of the Solar System	40	3.2	Barometric Law and Hydrostatic Equilibrium	69
2.4.1	<i>Orbits of the Eight Planets</i>	40	3.3	Stellar Properties and Lifetimes	72
2.4.2	<i>Survival Lifetimes of Small Bodies</i>	43	3.3.1	<i>Virial Theorem</i>	72
2.5*	Dynamics of Spherical Bodies	43	3.3.2	<i>Luminosity</i>	72
2.5.1	<i>Moment of Inertia</i>	43	3.3.3	<i>Size</i>	74
2.5.2	<i>Gravitational Interactions</i>	45	3.3.4	<i>Sizes and Densities of Massive Planets</i>	75
2.6	Orbits about an Oblate Planet	46	3.4	Nucleosynthesis	77
2.6.1*	<i>Gravity Field</i>	46	3.4.1	<i>Primordial Nucleosynthesis</i>	78
2.6.2	<i>Precession of Particle Orbits</i>	47	3.4.2	<i>Stellar Nucleosynthesis</i>	80
2.6.3	<i>Torques on an Oblate Planet</i>	47	3.4.3	<i>Radioactive Decay</i>	83
2.7	Tides	48	Key Concepts		83
2.7.1	<i>The Tidal Force and Tidal Bulges</i>	50	Further Reading		84
2.7.2	<i>Tidal Torque</i>	51	Problems		84
2.7.3	<i>Tidal Heating</i>	53	<b>4 Solar Heating and Energy Transport</b>		86
2.8	Dissipative Forces and the Orbits of Small Bodies	53	4.1	Energy Balance and Temperature	87
2.8.1	<i>Radiation Pressure (Micrometer Grains)</i>	54	4.1.1	<i>Thermal (Blackbody) Radiation</i>	88
2.8.2	<i>Poynting–Robertson Drag (Small Macroscopic Particles)</i>	55	4.1.2	<i>Albedo</i>	90
2.8.3	<i>Yarkovsky Effect (1–10<sup>4</sup>-Meter Objects)</i>	56	4.1.3	<i>Temperature</i>	91
2.8.4	<i>Corpuscular Drag (Submicrometer Dust)</i>	56	4.2	Energy Transport	92
2.8.5	<i>Gas Drag</i>	56	4.3	Conduction	93
2.9	Orbits about a Mass-Losing Star	58	4.4	Convection	94
Key Concepts		58	4.4.1	<i>Adiabatic Gradient</i>	94
Further Reading		59	4.5	Radiation	95
Problems		60	4.5.1	<i>Photons and Energy Levels in Atoms</i>	96
<b>3 Physics and Astrophysics</b>		65	4.5.2	<i>Spectroscopy</i>	98
3.1	Thermodynamics	66	4.5.3	<i>Radiative Energy Transport</i>	101
3.1.1	<i>Laws of Thermodynamics</i>	66	4.5.4	<i>Radiative Equilibrium</i>	103
3.1.2	<i>Enthalpy</i>	67	4.6	Greenhouse Effect	103
3.1.3	<i>Entropy</i>	68	4.6.1	<i>Quantitative Results</i>	104
3.1.4	<i>Gibbs Free Energy</i>	68	4.6.2*	<i>Derivations</i>	105
			Key Concepts		107
			Further Reading		107
			Problems		108

<b>5 Planetary Atmospheres</b>	111	6.2.2 <i>Shape and Gravity Field</i>	153
5.1 Thermal Structure	112	6.2.3 <i>Internal Heat: Sources, Losses and Transport</i>	155
5.1.1 <i>Sources and Transport of Energy</i>	115	6.3 Surface Morphology	157
5.1.2 <i>Observed Thermal Profiles</i>	116	6.3.1 <i>Tectonics</i>	157
5.2 Atmospheric Composition	117	6.3.2 <i>Volcanism</i>	161
5.3 Clouds	120	6.3.3 <i>Atmospheric Effects on Landscape</i>	165
5.4 Meteorology	121	6.4 Impact Cratering	169
5.4.1 <i>Coriolis Effect</i>	122	6.4.1 <i>Crater Morphology</i>	170
5.4.2 <i>Winds Forced by Solar Heating</i>	123	6.4.2 <i>Crater Formation</i>	172
5.5 Photochemistry	125	6.4.3 <i>Impact Modification by Atmospheres</i>	179
5.5.1 <i>Photolysis and Recombination</i>	125	6.4.4 <i>Spatial Density of Craters</i>	180
5.5.2 <i>Photoionization: Ionospheres</i>	127	6.4.5 <i>Impacts on Earth</i>	183
5.6 Molecular and Eddy Diffusion	128	Key Concepts	184
5.6.1 <i>Eddy Diffusion</i>	128	Further Reading	185
5.6.2 <i>Molecular Diffusion</i>	128	Problems	186
5.7 Atmospheric Escape	129	<b>7 Sun, Solar Wind and Magnetic Fields</b>	189
5.7.1 <i>Thermal (Jeans) Escape</i>	129	7.1 The Sun	190
5.7.2 <i>Nonthermal Escape</i>	130	7.2 The Interplanetary Medium	193
5.7.3 <i>Hydrodynamic Escape and Impact Erosion</i>	130	7.2.1 <i>Solar Wind</i>	193
5.8 History of Secondary Atmospheres	131	7.2.2 <i>The Parker Model</i>	194
5.8.1 <i>Formation</i>	131	7.2.3 <i>Space Weather</i>	197
5.8.2 <i>Climate Evolution</i>	132	7.2.4 <i>Solar Wind–Planet Interactions</i>	198
5.8.3 <i>Summary of Secondary Atmospheres</i>	138	7.3 Planetary Magnetospheres	199
Key Concepts	138	7.3.1 <i>Earth's Magnetosphere</i>	200
Further Reading	139	7.3.2 <i>Aurora</i>	201
Problems	139	7.3.3 <i>Magnetospheric Plasmas</i>	202
		7.3.4 <i>Radio Emissions</i>	205
<b>6 Surfaces and Interiors</b>	143	7.4 Generation of Magnetic Fields	205
6.1 Mineralogy and Petrology	144	7.4.1 <i>Variability of Earth's Magnetic Field</i>	205
6.1.1 <i>Minerals</i>	144	7.4.2 <i>Magnetic Dynamo Theory</i>	206
6.1.2 <i>Rocks</i>	145	Key Concepts	206
6.1.3 <i>Material under High Temperature and Pressure</i>	149	Further Reading	207
6.1.4 <i>Cooling of a Magma</i>	151	Problems	207
6.2 Planetary Interiors	152	<b>8 Giant Planets</b>	208
6.2.1 <i>Interior Structure of the Earth</i>	152	8.1 Jupiter	209

8.1.1	<i>Atmosphere</i>	209	<b>10 Planetary Satellites</b>	260	
8.1.2	<i>Impacts on Jupiter</i>	213	10.1	Moons of Mars: Phobos and Deimos	261
8.1.3	<i>Interior Structure</i>	216	10.2	Satellites of Jupiter	262
8.1.4	<i>Magnetic Field</i>	216	10.2.1	<i>Io</i>	262
8.2	Saturn	218	10.2.2	<i>Europa</i>	265
8.2.1	<i>Atmosphere</i>	218	10.2.3	<i>Ganymede and Callisto</i>	269
8.2.2	<i>Interior Structure</i>	220	10.2.4	<i>Jupiter's Small Moons</i>	271
8.2.3	<i>Magnetic Field</i>	220	10.3	Satellites of Saturn	272
8.3	Uranus and Neptune	221	10.3.1	<i>Titan</i>	272
8.3.1	<i>Atmospheres</i>	221	10.3.2	<i>Midsized Saturnian Moons</i>	274
8.3.2	<i>Interiors</i>	222	10.3.3	<i>Enceladus</i>	275
8.3.3	<i>Magnetic Fields</i>	224	10.3.4	<i>Small Regular Satellites of Saturn</i>	277
Key Concepts		225	10.3.5	<i>Saturn's Irregular Moons</i>	277
Further Reading		226	10.4	Satellites of Uranus	278
Problems		226	10.5	Satellites of Neptune	280
<b>9 Terrestrial Planets and the Moon</b>		228	Key Concepts		283
9.1	The Moon	230	Further Reading		283
9.1.1	<i>Surface</i>	230	Problems		284
9.1.2	<i>Atmosphere</i>	232	<b>11 Meteorites</b>		286
9.1.3	<i>Interior</i>	232	11.1	Classification	288
9.1.4	<i>Magnetic Field</i>	233	11.2	Source Regions	291
9.2	Mercury	233	11.3	Fall Phenomena	294
9.2.1	<i>Surface</i>	233	11.4	Chemical and Isotopic Fractionation	297
9.2.2	<i>Atmosphere</i>	238	11.4.1	<i>Chemical Separation</i>	298
9.2.3	<i>Interior</i>	238	11.4.2	<i>Isotopic Fractionation</i>	298
9.2.4	<i>Magnetic Field</i>	238	11.5	Main Components of Chondrites	299
9.3	Venus	240	11.6	Radiometric Dating	300
9.3.1	<i>Surface</i>	240	11.6.1	<i>Decay Rates</i>	300
9.3.2	<i>Atmosphere</i>	243	11.6.2	<i>Dating Rocks</i>	302
9.3.3	<i>Interior</i>	244	11.6.3	<i>Extinct-Nuclide Dating</i>	302
9.4	Mars	244	11.6.4	<i>Cosmic-Ray Exposure Ages</i>	303
9.4.1	<i>Global Appearance</i>	245	11.7	Meteorite Clues to Planet Formation	303
9.4.2	<i>Interior</i>	245	11.7.1	<i>Meteorites from Differentiated Bodies</i>	304
9.4.3	<i>Atmosphere</i>	246	11.7.2	<i>Primitive Meteorites</i>	305
9.4.4	<i>Frost, Ice and Glaciers</i>	249	11.7.3	<i>Presolar Grains</i>	306
9.4.5	<i>Water on Mars</i>	250	Key Concepts		307
9.4.6	<i>Geology at Rover Sites</i>	252	Further Reading		307
9.4.7	<i>Magnetic Field</i>	255	Problems		308
Key Concepts		257			
Further Reading		257			
Problems		258			

<b>12 Minor Planets and Comets</b>	<b>311</b>	<b>13 Planetary Rings</b>	<b>350</b>
12.1 Nomenclature	312	13.1 Tidal Forces and Roche's Limit	353
12.2 Orbits	313	13.2 Flattening and Spreading of Rings	356
12.2.1 Asteroids	314	13.3 Observations	357
12.2.2 Trans-Neptunian Objects, Centaurs	316	13.3.1 Jupiter's Rings	357
12.2.3 Oort Cloud	318	13.3.2 Saturn's Rings	358
12.2.4 Nongravitational Forces	319	13.3.3 Uranus's Rings	366
12.3 Size Distribution and Collisions	320	13.3.4 Neptune's Rings	368
12.3.1 Size Distribution	320	13.4 Ring–Moon Interactions	369
12.3.2 Collisions and Families	321	13.4.1 Resonances	369
12.3.3 Collisions and Rubble Piles	322	13.4.2 Spiral Waves	370
12.3.4 Binary and Multiple Systems	323	13.4.3 Shepherding	372
12.3.5 Comet-Splitting Events	324	13.5 Origins of Planetary Rings	374
12.3.6 Mass and Density	325	Key Concepts	375
12.3.7 Rotation	326	Further Reading	376
12.3.8 Interplanetary Dust	327	Problems	376
12.4 Bulk Composition and Taxonomy	327	<b>14 Extrasolar Planets</b>	<b>380</b>
12.4.1 Asteroid Taxonomy	328	14.1 Detecting Extrasolar Planets	381
12.4.2 Taxometric Spatial Distribution	329	14.1.1 Timing Pulsars and Pulsating Stars	382
12.4.3 Trans-Neptunian Object Spectra	330	14.1.2 Radial Velocity	382
12.5 Individual Minor Planets	330	14.1.3 Astrometry	383
12.5.1 Near-Earth Asteroids	330	14.1.4 Transit Photometry	385
12.5.2 Main Belt Asteroids	332	14.1.5 Transit Timing Variations	386
12.5.3 Trans-Neptunian Objects	335	14.1.6 Microlensing	387
12.6 Shape and Structure of Comet Nuclei	336	14.1.7 Imaging	388
12.7 Comas and Tails of Comets	337	14.1.8 Other Techniques	389
12.7.1 Brightness	339	14.1.9 Planets in Multiple Star Systems	390
12.7.2 Ultimate Fate of Coma Gas	340	14.1.10 Exoplanet Characterization	390
12.7.3 Dust Entrainment	340	14.2 Exoplanet Nomenclature	392
12.7.4 Morphology and Composition of Dust Tails	341	14.3 Observations of Extrasolar Planets	392
12.7.5 Ion Tails	343	14.3.1 Pulsar Planets	392
12.7.6 Comet Composition	344	14.3.2 Radial Velocity Detections	394
12.8 Temporal Evolution of the Population of Asteroids and Comets	345	14.3.3 Transiting Planets	395
Key Concepts	346	14.3.4 Rossiter–McLaughlin Effect	399
Further Reading	346	14.3.5 NASA's Kepler Mission	400
Problems	347	14.3.6 Small Nearby Exoplanets	403
		14.3.7 Planets Orbiting Pulsating Stars	404
		14.3.8 Microlensing Detections	404

14.3.9	<i>Images and Spectra of Exoplanets</i>	405	15.5.3	<i>Accumulation (and Loss) of Atmospheric Volatiles</i>	445
14.3.10	<i>Planets in Multiple Star Systems</i>	407	15.6	Formation of the Giant Planets	446
14.4	Mass–Radius Relationship	407	15.7	Planetary Migration	449
14.4.1	<i>Theory</i>	408	15.7.1	<i>Torques from Protoplanetary Disks</i>	449
14.4.2	<i>Observations</i>	409	15.7.2	<i>Scattering of Planetesimals</i>	449
14.5	Exoplanet Demographics	409	15.8	Small Bodies Orbiting the Sun	450
14.5.1	<i>Radial Velocity Surveys</i>	411	15.8.1	<i>Asteroid Belt</i>	450
14.5.2	<i>Kepler Planet Candidates</i>	413	15.8.2	<i>Comet Reservoirs</i>	451
14.5.3	<i>Microlensing and Imaging</i>	416	15.9	Planetary Rotation	452
14.6	Conclusions	416	15.10	Satellites of Planets and of Minor Planets	452
Key Concepts		421	15.10.1	<i>Giant Planet Satellites</i>	452
Further Reading		421	15.10.2	<i>Formation of the Moon</i>	453
Problems		422	15.10.3	<i>Satellites of Small Bodies</i>	455
<b>15 Planet Formation</b>		425	15.11	Exoplanet Formation Models	455
15.1	Solar System Constraints	426	15.12	Confronting Theory with Observations	456
15.2	Star Formation: A Brief Overview	429	15.12.1	<i>Solar System's Dynamical State</i>	456
15.2.1	<i>Molecular Cloud Cores</i>	429	15.12.2	<i>Composition of Planetary Bodies</i>	457
15.2.2	<i>Collapse of Molecular Cloud Cores</i>	430	15.12.3	<i>Extrasolar Planets</i>	458
15.2.3	<i>Young Stars and Circumstellar Disks</i>	431	15.12.4	<i>Successes, Shortcomings and Predictions</i>	458
15.3	Evolution of the Protoplanetary Disk	432	Key Concepts		458
15.3.1	<i>Infall Stage</i>	432	Further Reading		459
15.3.2	<i>Disk Dynamical Evolution</i>	434	Problems		460
15.3.3	<i>Chemistry in the Disk</i>	435	<b>16 Planets and Life</b>		464
15.3.4	<i>Clearing Stage</i>	437	16.1	Drake Equation	465
15.4	Growth of Solid Bodies	437	16.2	What Is Life?	466
15.4.1	<i>Planetesimal Formation</i>	437	16.3	Biological Thermodynamics	468
15.4.2	<i>From Planetesimals to Planetary Embryos</i>	438	16.4	Why Carbon and Water?	470
15.5	Formation of the Terrestrial Planets	442	16.5	Circumstellar Habitable Zones	471
15.5.1	<i>Dynamics of the Final Stages of Planetary Accumulation</i>	442	16.6	Planetary Requirements for Life	474
15.5.2	<i>Accretional Heating and Planetary Differentiation</i>	442	16.6.1	<i>Biogeochemical Cycles</i>	475
			16.6.2	<i>Gravitational and Magnetic Fields</i>	477

16.6.3	<i>Can Moonless Planets Host Life?</i>	477	16.11	Mass Extinctions	497
16.6.4	<i>Giant Planets and Life</i>	478	16.12	Panspermia	498
16.7	Impacts and Other Natural Disasters	479	16.13	Detecting Extraterrestrial Life	500
16.7.1	<i>K–T Event</i>	480	16.13.1	<i>Signs of (Past) Life on Mars?</i>	501
16.7.2	<i>Frequency of Impacts</i>	482	16.13.2	<i>Search for Extra terrestrial Intelligence</i>	503
16.7.3	<i>Volcanos and Earthquakes</i>	483	16.14	Are We Alone?	504
16.8	How Life Affects Planets	484		Key Concepts	505
16.9	Origin of Life	485		Further Reading	506
16.9.1	<i>Synthesis of Organic Molecules</i>	486		Problems	508
16.9.2	<i>The Phylogenetic Tree and Last Universal Common Ancestor</i>	487	Appendix A:	<i>Symbols Used</i>	513
16.9.3	<i>Young Earth and Early Life</i>	490	Appendix B:	<i>Acronyms Used</i>	517
16.10	Darwinian Evolution	491	Appendix C:	<i>Units and Constants</i>	519
16.10.1	<i>Sex, Gene Pools, and Inheritance</i>	493	Appendix D:	<i>Periodic Table of Elements</i>	522
16.10.2	<i>Development of Complex Life</i>	494	Appendix E:	<i>Solar System Tables</i>	523
16.10.3	<i>Intelligence and Technology</i>	496	Appendix F:	<i>Interplanetary Spacecraft</i>	534
			Appendix G:	<i>Recent Advances in Solar System Studies</i>	540
			References		574
			Index		582