

Contents

<i>Preface</i>	v
Part I. Observations Reveal Gravity	
1. Early Observations	3
1.1 Stars and Planets	3
1.2 Interpretations of the Observations	6
1.3 Sun, Moon and Earth	9
1.4 The Shapes of the Orbits	12
1.5 Kepler's Laws of Planetary Motion	15
1.6 Galileo's Law of Inertia: Newton's Laws of Motion	16
1.7 Newton's Law of Gravitation	18
1.8 A Passing Encounter without Capture	19
2. A Planet and a Sun: The Role of Gravity	22
2.1 Specification of an Elliptic Orbit	22
2.2 Equal Areas in Equal Times	24
2.3 Consequences of an Elliptical Path: The Inverse Square Force Law	25
2.4 The Semi-Major Axis and the Period of the Orbit: The 3 rd Law	28
2.5 Two Immediate Consequences	29
2.6 The Energy in an Elliptic Orbit	30
2.7 Specifying the Orbit from Observations	31
2.8 The Different Possible Orbits	32
3. Several Planets: The Centre of Mass	35
3.1 More Than One Planet	35
3.2 Jupiter, Mars and the Asteroids	38
3.3 The Centre of Mass: Two Masses	39
3.4 Transfer Orbits	42
3.5 Tidal Forces	45

3.6	The Roche Limit	48
4.	The General Structure of a Planet	51
4.1	Several Energies	51
4.2	Packing Atoms Together	54
4.3	The Mass–Radius Relation	57
4.4	Maximum Size and Mass	58
4.5	Defining a Planetary Body	59
4.6	Cosmic Bodies	61
4.7	Planets and Satellites: Planetary Bodies	63
5.	Fluid Flows and Magnetism	65
5.1	The Fluid State	65
5.2	The Importance of Time Scales	68
5.3	Specifying Fluid Behaviour	69
5.4	Isothermal Insulating Fluids	70
5.5	Thermal Insulating Fluid Flows	73
5.6	Natural Convection: Volcanic Activities	76
5.7	Boundary Conditions	77
5.8	Electrically Conducting Fluids	79
5.9	Application to Planetary Magnetic Fields	81

Part II. General Features of the Solar System

6.	The Larger Members of the Solar System	85
6.1	The Sun	85
6.2	The Planets	85
6.3	Satellites	90
6.4	Planetary Rings	93
6.5	Angular Momentum	95
6.6	Magnetism and Rotation	96
7.	Smaller Members: Asteroids, Comets and Meteorites	98
7.1	Asteroids	98
7.2	Comets and Meteor Showers	103
7.3	Meteorites	106
7.4	The Edgeworth–Kuiper Belt	106
7.5	The Oort Cloud	107
8.	The Material of the Solar System	110
8.1	The Solar/Cosmic Abundance of the Elements	110
8.2	The Formation of Molecules	111
8.3	The Compositions of Terrestrial Materials	113
8.4	The Moon	116
8.5	Venus	118
8.6	The Material of the Solar System	118

8.7	Material in Orbit	120
9.	Finding the Ages of Rocks: Geochronology	122
9.1	Atoms and Radioactive Decay	122
9.1.1	Some comments on atomic structure	122
9.1.2	Atomic transformations: Isotopes	123
9.1.3	Radioactive series	124
9.1.4	Single radioactive decay	125
9.1.5	A radioactive chain	126
9.2	Nuclear Reactions	126
9.3	An Elementary Method for Dating Rocks	128
9.4	The Closure Temperature	129
9.5	Selecting a Particular Decay Mode	129
9.5.1	The rubidium–strontium method	129
9.5.2	Other decay schemes	130
9.6	Dating Using Nuclear Reactors	132
10.	Surfaces and Interiors	135
10.1	The Surface Figure	135
10.1.1	The shape of a planet	136
10.1.2	Radar studies	138
10.2	The Interior	139
10.2.1	Density with depth	139
10.2.2	The isothermal bulk modulus: Seismology	141
10.2.3	Travel times	143
10.2.4	The quality factor, Q	144
10.2.5	Seismic tomography	145
10.2.6	Rotation included	145
10.3	The Near-Surface Interior Region	146
10.3.1	Surface waves	146
10.4	Free Body Oscillations	147
10.5	Empirical Equations of State	149
10.6	Fluid Bodies	150
11.	The Solid Earth	153
11.1	General Parameters	154
11.2	The Interior Seismic Structure	156
11.2.1	Seismic tomography	158
11.3	An Active Structure	159
11.3.1	Mantle material	160
11.3.2	Mid-ocean ridges and ocean trenches	160
11.4	Plates and Plate Tectonics	163
11.5	The Inner and Outer Cores	164
11.6	A Dynamic Earth	165
11.7	Comments on the Atmosphere	168

12.	The Planets: Mercury and Mars	173
12.1	Rotation and Temperature	173
12.2	Surface Details	174
12.3	Internal Structure of Mercury	178
12.4	The Mercury Atmosphere	178
12.5	The General Topology of Mars	181
12.6	Martian Geology	182
12.7	Thermal Mars	185
12.8	The Internal Structure of Mars	186
12.9	The Atmosphere of Mars	188
12.10	A Tentative History of Mars	189
13.	Planet Venus	192
13.1	First Views of the Surface	193
13.2	Surface Details	195
13.3	The Venus Interior	199
13.4	Venus Atmosphere	200
13.4.1	Composition	200
13.4.2	Temperature profile	200
13.4.3	Structure	201
14.	The Planets: Jupiter and Saturn	204
14.1	Surface Features	206
14.2	The Heat Budgets	209
14.3	Visible Surface Compositions	210
14.4	General Comments on Internal Conditions	211
14.5	Detailed Model Interiors	213
14.5.1	Jupiter model interior	213
14.5.2	Saturn model interior	214
14.6	Comment on Interior Heat Flow	214
14.7	Intrinsic Magnetic Fields	215
15.	The Planets: Uranus and Neptune	219
15.1	Surface Features	221
15.2	Heat Budgets	222
15.3	Visible Surface Compositions	224
15.4	Internal Structure and Conditions	224
15.5	Comment on Interior Heat Flow	225
15.6	Intrinsic Magnetism	226
16.	Satellites of the Solar System	228
16.1	The Moon	228
16.1.1	Some historical background	228
16.1.2	Bulk properties	230
16.1.3	Surface composition: The lava flows	231
16.1.4	Surface composition: The highland rocks	232
16.1.5	Surface composition: The lunar “soil”	233

16.1.6	The interior	233
16.1.7	Lunar magnetism	236
16.1.8	Transient lunar events	236
16.2	The Satellites of Mars	236
16.3	The Larger Satellites	238
16.3.1	Io	240
16.3.2	Europa	243
16.3.3	Ganymede and Callisto	245
16.3.4	Titan	247
16.3.5	Triton	251
16.4	The Smaller Satellites	251
16.5	Internal Conditions: Internal Differentiation	251

Part III. Magnetism within the Solar System

17.	Intrinsic Magnetism of the Earth	257
17.1	The Magnetic Poles	257
17.2	The Magnetic Elements	259
17.3	Separation into a Dipole and Non-dipole Fields	261
17.4	Short Time Variations: The Secular Variation	265
17.5	Long Time Variations: Magnetic Field Reversals	265
17.6	The Geomagnetic Poles have Moved: Continental Drift	268
17.7	Creation of Ocean Floor	271
18.	The Earth's External Magnetism	273
18.1	The Effects of the Solar Emissions	273
18.2	The Interplanetary Magnetic Field	277
18.3	The Polar Aurorae	278
18.4	Magnetic Storms and Transient Disturbances	279
18.5	The Special Effect of the Moon	280
18.6	van Allen Radiation Belts	281
19.	The Magnetism of the Other Planets	284
19.1	The Intrinsic Magnetic Fields	284
19.2	The Magnetospheres	286
19.3	Other Examples for Planetary Bodies	292
19.4	Motion through the Interstellar Medium	294
19.5	Companions to Other Stars	294

Part IV. Stars as a Continuing Source of Energy

20.	Evolution of Stars	299
20.1	Observations and Measurements	299
20.2	Galaxies and Stars	301
20.3	The Life Expectancy of a Star	302
20.4	The Hertzsprung–Russell Diagram	304

21.	The Constitution of Stars	312
21.1	A Family of Similar Stars: The Assumptions	312
21.2	Specifying the Family of Stars	314
21.3	Some Immediate Conclusions	315
21.4	The Luminosity: The Mass–Radius Relation	316
21.5	The Mass and Luminosity Relation	317
21.6	The Central Temperature	317
21.7	The Life Expectancy: Dependence on the Mass	318
21.8	The State of Dense Matter	318
21.8.1	Non-relativistic case	320
21.8.2	Relativistic case	321
22.	Stellar Energy Source	324
22.1	Isotopes	324
22.2	The Binding Energy: Fusion and Fission	325
22.3	Energy from Fusion	327
22.4	The Hydrogen–Helium Process	328
22.4.1	The proton–proton chain	328
22.4.2	The carbon–nitrogen cycle	329
22.5	Reactions at Higher Temperatures	330
22.6	The Escape of Radiation from a Star	331
22.7	Synthesizing the Heavier Elements: <i>r</i> - and <i>s</i> - processes	332
23.	The Sun and Its Interior	335
23.1	Internal Conditions	336
23.2	The Surface: The Photosphere	339
23.3	Solar Rotation	345
24.	Solar Emissions of Particles: The Solar Wind	348
24.1	Above the Surface: The Chromosphere and Corona	349
24.2	Magnetism	353
24.3	The Solar Wind	355
24.4	Present and Future Variability	357

Part V. Exoplanets

25.	A Planetary System from Afar: The Solar System	361
25.1	Observing the Motion of the Central Star	361
25.2	The Case of a Transit	366
25.3	Polarimetry	368
25.4	Nulling Interferometry	368
25.5	Astrometry	369
25.6	Direct Imaging — White Dwarf Stars	369
25.7	Conclusion	369

26.	Observed Exo-Planet Systems	371
26.1	Pulser Systems	371
26.2	A Companion to a Solar-Type Star	372
26.3	Stellar Transits	373
26.4	A Survey of the Measurements	374
26.5	Multiple Companion Systems	377
26.6	Small Eccentricities	378
26.7	Systems with a Large Semi-Major Axis	378
26.8	Small Eccentricity and Larger Semi-major Axis	380
27.	Assessing the Observational Data	381
27.1	Firm Characteristics	381
27.2	More Massive Companions	382
27.3	A Special Case: Transit Systems	383
27.4	Small Semi-Major Axes: Rôle of Eccentricity	384
27.5	The Future?	385
Part VI. Exo-Biology		
28.	Life on Earth	389
28.1	Early Life	389
28.2	The Characteristics of Early Life	391
28.3	Oxygen in the Atmosphere	393
28.4	The Evolutionary Sequence	394
28.5	The Movement of Continents	396
28.6	Life on the Atlantic mid-Ocean Ridge	397
28.7	Changes of Climate	398
28.8	Some Final Comments	399
29.	What Makes a Planet Habitable?	402
29.1	An Overall Requirement	402
29.2	Atomic Constraints: Binding Energies	403
29.3	Stellar Radiation	405
29.4	Heat from the Central Star	405
29.5	The Role of an Atmosphere: Planetary Mass	406
29.6	The Role of Water	408
29.7	Surface Features: Body Size and Scaling	409
30.	An Anthropoc Universe?	412
30.1	Describing the Physical World	412
30.2	Consequences of the Strength of the Forces of Nature	414
30.3	The Beginnings	415
30.4	The Size of Our Universe	418
30.5	Model Universes: Anthropic Principles	419
30.6	Information and the Universe	421
30.7	Extra-terrestrial Visitations	422

<i>Epilogue</i>	425
<i>Some Historic Events in the Space Probe Exploration of the Solar System</i>	431
<i>Some Useful References</i>	433
<i>Glossary</i>	435
<i>Problems and Solutions</i>	475
<i>Index</i>	485