

Contents

1	Introduction	1
	<i>Louise Harra and Keith Mason</i>	
1.1	A Brief History of Discovery	2
1.1.1	Exploration of the Solar System	3
1.1.2	The Sun and beyond	5
1.2	Observing from Space	9
2	Remote Sensing of the Earth's Climate System	13
	<i>Ian Mason</i>	
2.1	Remote Sensing of the Climate System	13
2.1.1	Remote sensing and Earth system science	13
2.1.2	The requirements for remote sensing of the climate system	15
2.2	Remote Sensing Methodology	19
2.2.1	Constraints due to observing from space	19
2.2.2	Measurement by remote sensing: basic concepts	25
2.2.3	Some surface factors affecting the remote sensing process	30
2.2.4	Some atmospheric factors affecting the remote sensing process	32
2.2.5	Some instrumental factors affecting the remote sensing process	35
2.3	Using Reflected Sunlight	42
2.3.1	Visible/infrared imaging systems	42
2.3.2	Global vegetation remote sensing	44
2.3.2.1	Surface effects	45
2.3.2.2	Instrumental effects	47

	2.3.2.3	Atmospheric effects	48
	2.3.2.4	Vegetation monitoring with MODIS	49
2.4		Using Thermal Emission	50
	2.4.1	Global sea surface temperature measurement	51
	2.4.2	The Along Track Scanning Radiometer (ATSR)	53
	2.4.2.1	Instrumental effects	54
	2.4.2.2	Surface effects	55
	2.4.2.3	Atmospheric effects	57
	2.4.2.4	SST monitoring with ATSR	61
2.5		Using Radar	61
	2.5.1	Radar altimetry	62
	2.5.1.1	Surface effects	65
	2.5.1.2	Atmospheric effects	68
	2.5.1.3	Instrumental effects	69
	2.5.1.4	Examples of ocean and ice monitoring by radar altimetry	70
3		Planetary Science	73
		<i>Andrew Coates</i>	
	3.1	Introduction	73
	3.2	The Solar System in the Last Four Millennia	74
	3.3	Origin of the Solar System	75
	3.3.1	Processes: collisions, accretion and volcanism	76
	3.4	Evolution of Atmospheres	81
	3.5	Terrestrial Planets	82
	3.6	Outer Planets	88
	3.7	Comets	91
	3.8	Asteroids	94
	3.9	Magnetospheres	95
	3.9.1	Magnetised planet interaction	97
	3.9.2	Comet–solar-wind interaction	100
	3.9.3	Effect of charged particles on surfaces	102
	3.10	Missions	102
	3.10.1	Planetary mission example — <i>Cassini–Huygens</i>	105
	3.11	Other Solar Systems	107
	3.12	Conclusion	109
4		Space Plasma Physics — A Primer	111
		<i>Christopher J. Owen</i>	
	4.1	What Is Space Plasma Physics?	111
	4.2	So What Is a Plasma?	111

4.3	The Realm of Plasma Physics	112
4.4	Ways to Understand Plasmas	113
4.4.1	Single particle dynamics — basic principles	114
4.4.2	Single particle dynamics — application	119
4.5	Space Plasma Applications	122
4.5.1	The frozen-in flux approximation	122
4.5.2	MHD plasma waves	123
4.5.3	The solar wind and IMF	125
4.5.4	Collisionless shocks and bow shocks	127
4.5.4.1	MHD shock jump relations	129
4.5.4.2	Shock structure	130
4.5.5	Shock acceleration	131
4.5.6	Magnetic reconnection — a recap	134
4.5.7	The terrestrial magnetosphere	136
4.5.7.1	A ‘closed’ model magnetosphere	136
4.5.7.2	The ‘open’ magnetosphere	139
4.5.7.3	Dynamics — flux transfer events (FTEs), storms and substorms	143
4.5.8	Solar wind interaction with other bodies	150
4.5.8.1	Other planetary magnetospheres	150
4.5.8.2	Solar-wind–ionosphere interaction	151
4.5.9	Insulator bodies (e.g. the Moon)	152
4.5.10	Comets	154
4.6	Concluding Remarks	155
5	Space Weather	157
	<i>Sarah Matthews</i>	
5.1	What Is Space Weather?	157
5.2	Solar Activity	158
5.3	The Solar Wind	159
5.4	Aurora	162
5.5	Auroral Substorms	164
5.6	Co-rotating Interaction Regions (CIRs)	165
5.7	Solar Flares	167
5.8	The Ionosphere	168
5.9	Solar Energetic Particle Events (SEPs)	169
5.10	Other Sources of Energetic Particles	172
5.11	Coronal Mass Ejections and Geomagnetic Storms	173
5.12	Halo CMEs	176
5.13	Interplanetary CMEs (ICMEs) and Magnetic Clouds	178

5.14	Magnetic Storms and Substorms	181
5.15	Very Intense Storms	183
5.16	The Future	184
6	The Physics of the Sun	187
	<i>Louise Harra</i>	
6.1	Why Do We Study the Sun?	187
6.2	The Structure of the Solar Interior	188
6.3	The Energy Source of the Sun	189
6.4	The Neutrino Problem	190
	6.4.1 Possible explanations	192
	6.4.2 New experiments	192
6.5	Helioseismology	193
6.6	Creation of the Sun's Magnetic Field	196
6.7	The Photosphere	198
	6.7.1 The photospheric magnetic field	201
6.8	The Chromosphere	202
6.9	The Corona	208
	6.9.1 Coronal heating	209
	6.9.1.1 Wave models	210
	6.9.1.2 Microflare and nanoflare heating	211
6.10	Solar Flares	213
	6.10.1 Coronal mass ejections	217
6.11	Solar Wind	218
6.12	Where to Next?	220
7	X-Ray Astronomy	223
	<i>Keith Mason</i>	
7.1	Astronomy from Space	223
7.2	The Origins of X-Ray Astronomy	224
7.3	Binary X-Ray Sources — The Power of Accretion	227
	7.3.1 Thin accretion discs	230
	7.3.2 Real life	232
	7.3.3 The X-ray binary zoo	233
	7.3.4 High-mass X-ray binaries	233
	7.3.5 Low-mass X-ray binaries	234
	7.3.6 Cataclysmic variables	236
	7.3.7 Black hole or neutron star?	238
	7.3.8 . . . or white dwarf?	239
7.4	Supernova Remnants	239
7.5	Clusters of Galaxies	241

7.6	Active Galactic Nuclei	243
7.6.1	X-ray emission from AGNs	245
7.6.2	Quasar evolution	248
8	Using Quantum Physics and Spectroscopy to Probe the Physical Universe	251
	<i>Louise Harra and Keith Mason</i>	
8.1	Introduction	251
8.2	Quantum Theory of an Atom	251
8.2.1	Blackbody radiation	252
8.2.2	Is light made up of waves or particles?	252
8.2.3	The photoelectric effect	253
8.2.4	Heisenberg’s uncertainty principle	253
8.2.5	Bohr’s atom	254
8.2.6	Visualising a real atom	255
8.3	Rules of the Atom	258
8.4	Spectroscopy — The Basic Processes	259
8.4.1	Thermal processes	259
8.4.1.1	Blackbody radiation	259
8.4.1.2	Discrete line emission	260
8.4.1.3	Radiative recombination continuum	261
8.4.1.4	Dielectronic recombination	261
8.4.1.5	Thermal Bremsstrahlung	262
8.4.1.6	Two-photon continuum	262
8.4.2	Non-thermal processes	263
8.4.2.1	Cyclotron radiation	263
8.4.2.2	Synchrotron radiation	263
8.4.2.3	Inverse Compton radiation	264
8.5	Environmental Influences on Spectra	264
8.5.1	Broadening of spectral lines	264
8.5.1.1	Natural width	264
8.5.1.2	Collisional broadening	265
8.5.1.3	Doppler broadening	265
8.5.1.4	Zeeman effect	266
8.5.2	Dynamical effects	266
8.5.3	Photoelectric absorption	266
8.5.4	Electron scattering	267
8.5.5	Pair production	267
8.6	Spectroscopy in Action	268
8.6.1	How dense is it?	268
8.6.2	How hot is it?	271
8.6.3	How fast is it?	271

8.6.4	How turbulent is it?	275
8.6.5	What is it made of?	275
8.6.6	Does it have a strong magnetic field?	278
8.7	Conclusions	278
9	An Introduction to Magnetohydrodynamics	279
	<i>Lidia van Driel-Gesztelyi</i>	
9.1	Introduction	279
9.1.1	Vector combinations	280
9.1.2	Vector operators	280
9.2	Conservation Principles	280
9.2.1	Mass conservation (mass continuity equation)	280
9.2.2	Momentum conservation (motion equation)	281
9.2.3	Internal energy conservation (energy or heat equation)	281
9.3	Maxwell's Equations and Ohm's Law	282
9.3.1	Poisson's equation, or Gauss's law for \mathbf{E}	282
9.3.2	Faraday's law	282
9.3.3	Ampère's law	282
9.3.4	Gauss's law for \mathbf{B}	282
9.3.5	Ohm's law	283
9.3.6	Maxwell's equations in MHD	283
9.4	The MHD Induction Equation	283
9.4.1	The magnetic Reynolds number	285
9.4.2	An example: interaction between convective flows and magnetic fields	287
9.5	Examining the Momentum Equation	288
9.5.1	Alfvén speed	288
9.5.2	Pressure scale height	288
9.5.3	Pressure force and magnetic tension force	288
9.5.4	Plasma- β parameter	289
9.5.5	Force-free magnetic field conditions	289
9.5.6	Magnetostatic equilibrium	290
9.5.7	Magnetic buoyancy	291
9.6	Magnetic Reconnection	292
9.6.1	Current sheet	292
9.6.2	Force balance in current sheets	292
9.6.3	Kelvin–Helmholz instability in a simple current sheet	293
9.6.4	Tearing mode instability	293
9.6.5	The Sweet–Parker reconnection model	293
9.6.6	Conditions for fast reconnection	294
9.6.7	The Petschek reconnection model	294

9.6.8	A key issue: the rate of reconnection	295
9.6.9	An application: reconnection in solar flares	297
9.6.10	The first observation of the reconnection inflow and outflow	299
9.6.11	Reconnection in astrophysical phenomena	300
9.7	Magnetic Helicity	300
9.8	Waves	301
9.8.1	Acoustic waves	303
9.8.2	Alfvén waves or magnetohydrodynamic waves	304
9.8.3	Alfvén waves	305
9.8.4	Compressional Alfvén waves	305
9.8.5	Magnetoacoustic waves	306
9.8.6	Internal gravity waves	306
9.8.7	Inertial waves	307
9.9	The Future	308
10	‘Minimal’ Relativity	309
	<i>Kinwah Wu</i>	
10.1	Prelude	309
10.2	Some Mathematics	310
10.2.1	Algebra	310
10.2.2	Geometry	310
10.2.3	Co-ordinate transformation	311
10.3	From Classical Physics to Relativity	312
10.3.1	Maxwell equations	312
10.3.2	Newton’s second law of motion	314
10.3.3	Rotating-bucket experiment	314
10.3.4	Newton’s law of gravity	315
10.3.5	Galileo’s experiment and the principle of equivalence	316
10.3.6	Some thoughts	318
10.3.6.1	Newton’s third law of motion	318
10.3.6.2	Negative masses?	318
10.4	Geometrical Aspect	320
10.4.1	Metrics	320
10.4.2	Extremum	321
10.4.3	Geodesics and world lines	322
10.4.4	Equation of motion	324
10.4.5	Curved space–time	324
10.4.6	Einstein’s field equation	325
10.5	Astrophysical Examples	326
10.5.1	Schwarzschild metric and non-rotating black holes	326
10.5.2	Kerr metric and rotating black holes	327

10.5.3	How black is a black hole?	328
10.5.4	Least-action principle	329
10.5.5	Conservation laws and equations of motion	330
11	Cosmology	333
	<i>Mat Page</i>	
11.1	Introduction	333
11.2	A Brief History of Cosmology	333
11.3	Axioms, Principles and Limitations	334
11.4	A Brief History of the Universe	335
11.5	The Geometry and Fate of the Universe	336
11.6	Age and Distance Scales	336
11.7	What Does the Universe Contain?	337
11.8	Key Cosmological Probes	338
11.9	Formation of Structure	339
11.9.1	The complexity of galaxy formation	339
11.9.2	The history of star formation	340
11.10	Cosmic Background Radiation	340
11.11	Observations of Evolution	342
11.11.1	Clusters of galaxies	342
11.11.2	Galaxies	342
11.11.3	Active galactic nuclei and quasars	344
11.12	Black Holes and Stars	344
11.13	Prospects	345
12	Topics in Practical Statistics	347
	<i>Mark Cropper</i>	
12.1	Introduction	347
12.2	Probability Distributions	347
12.2.1	Central value: means, medians and modes	347
12.2.2	Width: standard deviations, variances, standard errors	349
12.2.3	Important theoretical probability distributions	350
12.2.3.1	Binomial	350
12.2.3.2	Poisson	350
12.2.3.3	Gaussian	352
12.3	Populations	352
12.4	Fitting Data	354
12.4.1	Overview	354
12.4.2	The chi-squared fit	355

12.4.3	The appropriateness of the fit	356
12.4.4	Confidence intervals and error calculation	357
12.5	Error Propagation	361
13	Instrumentation for Photon Detection in Space	365
	<i>J.L. Culhane</i>	
13.1	Introduction	365
13.2	The Electromagnetic Spectrum	367
13.3	Photons in Space	369
13.3.1	Radio	369
13.3.2	Sub-mm/IR	371
13.3.3	Visible	374
13.3.4	X-ray	377
13.3.5	Gamma-ray	382
13.4	Photon Detection	385
13.4.1	Low energy photons — radio, sub-mm, IR, visible	385
13.4.1.1	Hetrodyne receivers	385
13.4.1.2	Bolometers	387
13.4.1.3	Charge-coupled devices (CCDs)	390
13.4.2	Higher energy photons — EUV and X-ray	393
13.4.2.1	X-ray and EUV application of CCDs	394
13.4.2.2	Cryogenic detectors for non-dispersive X-ray and optical spectroscopy	396
13.4.2.3	Cryogenic techniques	404
13.5	Imaging and Spectroscopy	410
13.5.1	Imaging at longer wavelengths	410
13.5.2	Grazing incidence systems and multilayers	417
13.5.3	Spectroscopy	423
13.5.3.1	Dispersive spectroscopy	424
13.5.3.2	Non-dispersive spectroscopy	437
13.6	Summary and Conclusions	438
14	Space Engineering	443
	<i>Alan Smith</i>	
14.1	Introduction	443
14.2	The Engineering Challenges of Space	443
14.3	Spacecraft Design	446
14.4	The Systems Engineering Process	449
14.5	Requirements Capture	451
14.6	Architectural Design, Integration and Test, and Sub-system Development	452

14.7	Project Management	456
14.8	Underpinning Instrument Development	457
	<i>Bibliography</i>	459
	<i>Glossary</i>	469
	<i>Index</i>	493
	<i>Colour Plates</i>	505