

Contents

Preface	xi
Acknowledgements	xiii
Abbreviations	xv
List of figures	xvii
List of tables	xxiii
List of plates	xxv
1 The cosmos	1
1.1 The Solar System	1
1.1.1 The orbits of the planets	1
1.1.2 The Sun as a body	5
1.1.3 The planets as bodies	8
1.1.4 The large satellites	11
1.2 The origin of the Solar System.	13
1.2.1 The nebular theory	13
1.2.2 Pluto, comets, and satellites	16
1.2.3 The acquisition of volatile substances by the terrestrial planets	17
1.2.4 The origin of the heavy elements	17
1.3 Beyond the Solar System	18
1.3.1 The stars.	18
1.3.2 The Galaxy (and others)	20

vi Contents

1.4	Summary	22
1.5	Questions.	23
2	Life on Earth	25
2.1	The Earth	25
2.1.1	The Earth's interior.	25
2.1.2	The Earth's crust, lithosphere, and plate tectonics	26
2.1.3	Atmosphere, oceans, and biosphere	27
2.2	The chemicals of life	29
2.2.1	Proteins and nucleic acids.	29
2.2.2	Polysaccharides, lipids, and small molecules	32
2.3	The cell.	32
2.4	The fundamental processes of life.	34
2.4.1	Chemical energy	34
2.4.2	Energy for the cell	35
2.4.3	Protein synthesis.	38
2.4.4	Reproduction and evolution	40
2.5	Diversity of habitats	43
2.5.1	Non-extreme habitats.	43
2.5.2	Extreme habitats.	44
2.6	The tree of life	49
2.7	Summary.	50
2.8	Questions.	51
3	The evolution and origin of life on Earth	53
3.1	The process of evolution.	53
3.2	Life on Earth since the last common ancestor.	55
3.2.1	The major events and their timing	55
3.2.2	The causes of mass extinctions	61
3.2.3	The effect of the biosphere on the Earth's atmosphere	62
3.2.4	Radiometric dating	65
3.3	The origin of life on Earth	66
3.3.1	RNA world.	67
3.3.2	The origin of cells.	68
3.3.3	The role of minerals	68
3.3.4	Chirality in biomolecules	71
3.3.5	Where did life originate?	73
3.3.6	When did life originate?	74
3.3.7	Conclusions	74
3.4	Summary.	75
3.5	Questions.	76
4	Where to look for life elsewhere in the Solar System.	77
4.1	What sort of life are we searching for?	77
4.1.1	Potential habitats for carbon-liquid water life.	78

4.2	The habitable zone (HZ)	79
4.2.1	The HZ in the Solar System	82
4.2.2	Further considerations	85
4.3	Potential habitats beyond the HZ	86
4.3.1	Planetary interiors	86
4.3.2	Tidal heating	87
4.3.3	Tidally heated bodies	89
4.4	Titan	95
4.5	Summary	96
4.6	Questions	97
5	Life on Mars?	99
5.1	The planet Mars today	99
5.1.1	Mars in space	99
5.1.2	The martian interior	101
5.1.3	The martian atmosphere	102
5.1.4	The martian surface from space	104
5.1.5	Features that indicate the presence of liquid water	108
5.1.6	The martian surface from landers	112
5.2	Mars in the past	114
5.2.1	The three epochs of martian history	114
5.2.2	Atmospheric change on Mars	114
5.3	The search for life on Mars	116
5.3.1	Before the space age	116
5.3.2	The Viking Landers	118
5.3.3	Martian meteorites and fossils	120
5.3.4	Prospects for the future	122
5.4	Summary	123
5.5	Questions	124
6	Life on Europa?	127
6.1	Europa	127
6.2	Is there an ocean on Europa?	128
6.3	The potential of Europa as a habitat	133
6.3.1	Current knowledge	133
6.3.2	The future exploration of Europa	134
6.4	Summary	136
6.5	Questions	136
7	The fate of life in the Solar System.	137
7.1	The evolution of the Sun	139
7.1.1	The main sequence phase and the transition to the giant phase	139
7.1.2	The giant phase and after	140
7.2	The effect of solar evolution on Solar System habitability	143

7.2.1	Planetary orbits	143
7.2.2	The habitable zone (HZ)	143
7.3	Summary	146
7.4	Questions.	147
8	Potential habitats beyond the Solar System	149
8.1	The variety of stars	150
8.1.1	The Hertzsprung-Russell (H-R) diagram	150
8.1.2	Stellar populations	154
8.2	Suitable stars for life	155
8.2.1	Main sequence lifetime and life detectable from afar	156
8.2.2	Metallicity and other considerations	156
8.2.3	Main sequence M stars (M dwarfs)	157
8.3	The galactic HZ	161
8.4	Summary	162
8.5	Questions.	163
9	Searching for planets: direct methods	165
9.1	The challenge of direct detection	165
9.2	Coronagraphy.	168
9.2.1	Signal-to-noise ratio (<i>snr</i>) in a telescope image	169
9.2.2	The effect of one type of coronagraph	170
9.3	Atmospheric effects and their reduction	171
9.3.1	Atmospheric ‘seeing’ and its effects.	173
9.3.2	Adaptive optics	173
9.4	Large optical telescopes	175
9.4.1	Ground-based telescopes.	175
9.4.2	Telescopes in space	176
9.5	Interferometers	177
9.5.1	The basic principle of interferometry.	177
9.5.2	Imaging interferometers	180
9.6	Summary	183
9.7	Questions.	184
10	Searching for planets: indirect methods	185
10.1	Detecting a planet through the motion of its star	185
10.1.1	The effect of a planet on its star’s motion	185
10.1.2	Astrometry: principles	186
10.1.3	Astrometry: practice	190
10.1.4	Doppler spectroscopy: principles	194
10.1.5	Doppler spectroscopy: practice.	200
10.2	Transit photometry	203
10.3	Gravitational microlensing.	205

10.4	Observations of circumstellar discs and rings	208
10.5	Summary	209
10.6	Questions.	209
11	Exoplanetary systems	211
11.1	The discovery of exoplanetary systems.	211
11.2	The known (non-pulsar) exoplanetary systems.	214
11.2.1	The stars that host the known exoplanetary systems . . .	214
11.2.2	Exoplanet masses	216
11.2.3	Exoplanet composition.	217
11.2.4	Exoplanet orbits	219
11.3	Migration of giant exoplanets and its consequences	221
11.3.1	Migration mechanisms and consequences for giants	221
11.3.2	Giant planet migration and the formation of Earth-mass planets in HZs	225
11.3.3	Earth-mass planets in HZs	226
11.4	The undiscovered exoplanets	228
11.4.1	The known exoplanetary systems – a summary.	228
11.4.2	What planets await discovery and when might we discover them?	229
11.4.3	A note on evidence from circumstellar discs.	232
11.5	Stars, planets, and life forms	233
11.6	Summary	233
11.7	Questions.	234
12	How to find life on exoplanets	237
12.1	Planets with habitable surfaces.	238
12.2	Detecting biospheres from a distance.	239
12.2.1	Is there life on Earth?	239
12.2.2	The infrared spectrum of the Earth	243
12.2.3	The infrared spectrum of Mars	247
12.2.4	The infrared spectra of exoplanets	247
12.2.5	Exoplanet spectra at visible and near-infrared wavelengths	249
12.2.6	Interstellar probes	252
12.3	Summary	254
12.4	Questions.	254
13	Extraterrestrial intelligence	257
13.1	The number of technological intelligences in the Galaxy	257
13.2	Searching for ETI	259
13.3	Microwave and optical searches	261
13.3.1	Microwave searches.	261
13.3.2	What a microwave signal from ETI might be like	264
13.3.3	The outcome of microwave searches and their future. . . .	267
13.3.4	Searches at optical wavelengths (OSETI).	268

x **Contents**

13.4	Spacecraft and other artefacts from ETI	270
13.4.1	Interstellar travel	270
13.4.2	Galactic exploration	272
13.5	Technological modifications by ETI of their cosmic environment	273
13.6	The Fermi paradox	274
13.7	Communicating with extraterrestrial intelligence (CETI)	275
13.8	Summary	278
13.9	Questions.	279
Glossary	281
Answers to questions	287
Resources	303
Index	309