

## Table of Contents

<b>1</b>	<b>Astrobiology: From the Origin of Life on Earth to Life in the Universe</b>
	<i>André Brack</i>
1.1	General Aspects of Astrobiology 1
1.1.1	Historical Milestones 1
1.1.2	Searching for Emerging Life 3
1.1.3	The Role of Water 4
1.1.4	The Physicochemical Features of Carbon-based Life 4
1.1.5	Clays as Possible Primitive Robots 6
1.2	Reconstructing Life in a Test Tube 7
1.2.1	The Quest for Organic Molecules 7
1.2.1.1	Terrestrial Production 7
1.2.1.2	Delivery of Extraterrestrial Organic Molecules 8
1.2.2	Space Experiments 10
1.2.3	Attempts to Recreate Life in a Test Tube 11
1.2.4	A Primitive Life Simpler than a Cell? 13
1.3	The Search for Traces of Primitive Life 14
1.3.1	Microfossils 14
1.3.2	Oldest Sedimentary Rocks 15
1.4	The Search for Life in the Solar System 15
1.4.1	Planet Mars and the SNC Meteorites 15
1.4.2	Jupiter's Moon Europa 17
1.4.3	Saturn's Moon Titan 18
1.5	The Search for Life Beyond the Solar System 19
1.5.1	The Search for Rocky Earthlike Exoplanets 19
1.5.2	Detecting Extrasolar Life 20
1.6	Conclusions 20
1.7	Further Reading 21
1.7.1	Books and Articles in Books 21
1.7.2	Articles in Journals 21
1.7.3	Web Sites 22

<b>2</b>	<b>From the Big Bang to the Molecules of Life</b>
	<i>Harry J. Lehto</i>
2.1	Building Blocks of Life 23
2.2	Big Bang: Formation of H and He 25
2.3	First Stars: Formation of Small Amounts of C, O, N, S and P and Other Heavy Elements 28
2.4	Normal Modern Stars, Bulk Formation of C, O, N, S, P and Other Heavy Elements 29
2.5	The First Molecules (CO and H <sub>2</sub> O) 35
2.6	Interstellar Matter 35
2.6.1	Interstellar Clouds 37
2.6.2	Interstellar Grains 39
2.6.2.1	Formation 39
2.6.2.2	Observed Properties 40
2.6.3	Ices 41
2.6.4	Molecules in the Gas Phase 42
2.6.4.1	Observed Properties 42
2.6.4.2	Formation of H <sub>2</sub> 43
2.6.4.3	Formation of CO and H <sub>2</sub> O 44
2.7	Generation of Stars: Formation of the Sun and Planets 44
2.7.1	Accretion Disk of the Sun 44
2.7.2	Formation of the Earth 46
2.7.3	Early Rain of Meteorites, Comets, Asteroids, and Prebiotic Molecules 47
2.7.4	D/H Ratio and Oceans 49
2.8	Further Reading 51
2.8.1	Books or Articles in Books 51
2.8.2	Articles in Journals 51
2.8.3	Web Sites 53
2.9	Questions for Students 53
<b>3</b>	<b>Basic Prebiotic Chemistry</b>
	<i>Hervé Cottin</i>
3.1	Key Molecules of Life 55
3.1.1	Dismantling the Robots 56
3.1.2	Proteins and Amino Acids 58
3.1.3	DNA, RNA, and Their Building Blocks 60
3.1.4	First “Prebiotic Robot” 63
3.2	Historical Milestones 63
3.3	Sources of Prebiotic Organic Molecules 69
3.3.1	Endogenous Sources of Organic Molecules 69
3.3.1.1	Atmospheric Syntheses 69
3.3.1.2	Hydrothermal Vents 70
3.3.2	Exogenous Delivery of Organic Molecules 71
3.3.2.1	Comets 71
3.3.2.2	Meteorites 73

3.3.2.3	Micrometeorites	74
3.3.3	Relative Contribution of the Different Sources	74
3.4	From Simple to Slightly More Complex Compounds	75
3.4.1	Synthesis of Amino Acids	75
3.4.2	Synthesis of Purine and Pyrimidine Bases	76
3.4.3	Synthesis of Sugars	78
3.4.4	Synthesis of Polymers	80
3.5	Conclusions	81
3.6	Further Reading	82
3.6.1	Books or Articles in Books	82
3.6.2	Articles in Journals	82
3.7	Questions for Students	83
3.7.1	Basic-level Questions	83
3.7.2	Advanced-level Questions	83

#### 4 From Molecular Evolution to Cellular Life

*Kirsi Lehto*

4.1	History of Life at Its Beginnings	85
4.2	Life as It Is Known	88
4.2.1	The Phylogenetic Tree of Life	88
4.2.2	Life is Cellular, Happens in Liquid Water, and Is Based on Genetic Information	88
4.2.2.1	Genetic Information	92
4.2.2.2	The Genetic Code and Its Expression	94
4.3	Last Universal Common Ancestor (LUCA)	96
4.3.1	Containment in a Cell Membrane	97
4.3.2	Genes and Their Expression	99
4.3.3	Hypothetical Structure of the LUCA Genome	103
4.4	"Life" in the RNA–Protein World: Issues and Possible Solutions	105
4.4.1	Evolutionary Solutions	106
4.4.2	Solutions Found in the Viral World	107
4.5	"Life" Before the Appearance of the Progenote	108
4.5.1	The Breakthrough Organism and the RNA–Protein World	108
4.5.2	Primitive Translation Machinery	108
4.5.3	Origin of Ribosomes	109
4.6	The RNA World	111
4.6.1	Origin of the RNA World	113
4.6.1.1	Prebiotic Assembly of Polymers	113
4.6.1.2	The Building Blocks of the RNA World	114
4.6.1.3	Where Could the RNA World Exist and Function?	115
4.7	Beginning of Life	117
4.8	Further Reading	118
4.8.1	Books	118
4.8.2	Articles in Journals	118
4.9	Questions for Students	120

**5 Extremophiles, the Physicochemical Limits of Life (Growth and Survival)***Helga Stan-Lotter*

- 5.1 A Brief History of Life on Earth 121
- 5.1.1 Early Earth and Microfossils 121
- 5.1.2 Prokaryotes, Eukaryotes, and the Tree of Life 123
- 5.1.3 Some Characteristics of Bacteria and Archaea 126
  - 5.1.3.1 Cell Walls, Envelopes, and Shape 126
  - 5.1.3.2 Lipids and Membranes 127
- 5.2 Extremophiles and Extreme Environments 127
  - 5.2.1 Growth versus Survival 129
  - 5.2.2 The Search for Life on Mars: The *Viking* Mission 130
  - 5.2.3 Temperature Ranges for Microorganisms 132
  - 5.2.4 High-temperature Environments 133
    - 5.2.4.1 Geography and Isolates 133
    - 5.2.4.2 Molecular Properties of Hyperthermophiles 136
    - 5.2.4.3 Early Evolution and Hyperthermophiles 137
    - 5.2.4.4 Applications 138
  - 5.2.5 Low-temperature Environments 138
    - 5.2.5.1 Geography and Isolates 138
    - 5.2.5.2 Molecular Adaptations 139
  - 5.2.6 Barophiles or Piezophiles 140
  - 5.2.7 High-salt Environments 140
  - 5.2.7.1 Hypersaline Environments and Isolates 140
  - 5.2.7.2 Viable Haloarchaea from Rock Salt 141
  - 5.2.7.3 Molecular Mechanisms 142
  - 5.2.7.4 Extraterrestrial Halite 143
  - 5.2.8 Subterranean Environments 144
  - 5.2.9 Radiation 145
- 5.3 Microbial Survival of Extreme Conditions 146
- 5.4 Conclusions 148
- 5.5 Further Reading 149
  - 5.5.1 Books or Articles in Books 149
  - 5.5.2 Articles in Journals 149
  - 5.5.3 Web Sites 150
- 5.6 Questions for Students 150

**6 Habitability***Charles S. Cockell*

- 6.1 A Brief History of the Assessment of Habitability 151
- 6.2 What Determines Habitability? 154
- 6.3 Uninhabited Habitable Worlds 156
- 6.4 Factors Determining Habitability 156
  - 6.4.1 Habitability and Temperature 156
  - 6.4.2 Habitability and Energy 160
  - 6.4.3 Other Factors that Determine Habitability 164

6.5	A Postulate for Habitability	165
6.5.1	Assumptions about the Habitat	167
6.5.2	Assumptions on Life	167
6.5.3	Attempt to Formulate a Habitability Postulate	167
6.6	Some Test Cases for Habitability	169
6.6.1	Test Case One: Life on Venus	169
6.6.2	Test Case Two: Life on the Early Earth	171
6.6.3	Résumé of the Two Test Cases	173
6.7	Conclusions	173
6.8	Further Reading	174
6.8.1	Books and Articles in Books	174
6.8.2	Articles in Journals	174
6.9	Questions for Students	176

## 7 **Astrodynamics and Technological Aspects of Astrobiology Missions in Our Solar System**

*Stefanos Fasoulas and Tino Schmiel*

7.1	Introduction	179
7.2	The Rocket Equation	180
7.2.1	Single-staged Rockets	180
7.2.2	Multiple-staged Rockets	183
7.3	Orbital Mechanics and Astrodynamics	184
7.3.1	Some Historical Notes	184
7.3.2	The Energy Conservation Equation	187
7.3.3	Some Typical Velocities	188
7.4	Orbital Maneuvers	190
7.4.1	High-thrust Maneuvers	190
7.4.2	Low-thrust Maneuvers	192
7.4.3	Gravity-assist Maneuvers	193
7.5	Example: Missions to Mars	195
7.6	Further Reading	200
7.7	Questions for Students	200

## 8 **Astrobiology of the Terrestrial Planets, with Emphasis on Mars**

*Monica M. Grady*

8.1	The Solar System	203
8.2	Terrestrial Planets	206
8.2.1	Mercury	206
8.2.2	Venus	207
8.2.3	Earth	208
8.2.4	Mars	208
8.2.4.1	Observing Mars	208
8.2.4.2	Evidence for Water	210
8.2.4.3	Evidence of Heat	213
8.2.5	Meteorites from Mars	213

8.2.5.1	Why from Mars?	213
8.2.5.2	What can we Learn About Mars from Martian Meteorites?	216
8.2.5.3	Microfossils in a Martian Meteorite?	218
8.2.6	Can We Detect Signatures of Life on Mars?	219
8.2.7	Conclusions: Life Beyond Earth?	220
8.3	Further Reading	220
8.3.1	Concerning Planetary Formation and Chronology	220
8.3.2	Concerning Recent Results from Mars	221
8.3.3	Concerning Terrestrial and Martian Microfossils	221
8.3.4	Concerning Meteorites from Mars	221
8.4	Questions for Students	222

## 9 Astrobiology of Saturn's Moon Titan

*François Raulin*

9.1	Extraterrestrial Bodies of Astrobiological Interest	223
9.2	Some Historical Milestones in the Exploration of Titan	225
9.3	General Properties, Formation and Internal Structure of Titan	226
9.3.1	Main Properties	226
9.3.2	Models of Formation and Internal Structure	227
9.4	Atmosphere and Surface of Titan	229
9.4.1	Theoretical Modeling of Titan's Atmosphere	229
9.4.2	Experimental Approach	233
9.4.3	Observational Approach	236
9.5	Astrobiological Aspects of Titan	241
9.5.1	Analogies with Planet Earth	241
9.5.2	Organic Chemistry	242
9.5.3	Life on Titan?	246
9.6	Outlook: Astrobiology and Future Exploration of Titan	247
9.7	Further Reading	249
9.7.1	Books and Articles in Books	249
9.7.2	Articles in Journals	250
9.7.3	Web Sites	250
9.8	Questions for Students	251

## 10 Jupiter's Moon Europa: Geology and Habitability

*Christophe Sotin and Daniel Prieur*

10.1	A Short Survey of the Past Exploration of Europa	253
10.2	Geology of the Moon Europa	255
10.2.1	Surface Features	255
10.2.2	Composition of the Surface	257
10.3	Internal Structure of the Moon Europa	258
10.4	Models of Evolution of the Moon Europa	260
10.5	Astrobiological Considerations about Possibilities for Life on the Moon Europa	263
10.6	Summary and Conclusions	267

10.7	Outlook and Plans for Future Missions	268
10.8	Further Reading	269
10.8.1	Books and Articles in Books	269
10.8.2	Articles in Journals	270
10.8.3	Web Sites	271
10.9	Questions for Students	271
<b>11</b>	<b>Astrobiology Experiments in Low Earth Orbit: Facilities, Instrumentation, and Results</b>	
	<i>Pietro Baglioni, Massimo Sabbatini, and Gerda Horneck</i>	
11.1	Low Earth Orbit Environment, a Test Bed for Astrobiology	273
11.1.1	Cosmic Radiation Field in LEO	275
11.1.1.1	Galactic Cosmic Radiation	276
11.1.1.2	Solar Cosmic Radiation	277
11.1.1.3	Radiation Belts	278
11.1.2	Solar Extraterrestrial UV Radiation	279
11.1.3	Space Vacuum	280
11.1.4	Temperature Extremes	280
11.1.5	Microgravity	281
11.2	Astrobiology Questions Tackled by Experiments in Earth Orbit	281
11.3	Exposure Facilities for Astrobiology Experiments	282
11.3.1	BIOPAN	283
11.3.1.1	Technical Characteristics of BIOPAN	283
11.3.1.2	Experiment Hardware Accommodated within BIOPAN	285
11.3.1.3	Operational Aspects of BIOPAN	288
11.3.1.4	Orbital Characteristics of a BIOPAN Mission	291
11.3.1.5	Environment of BIOPAN Experiments	292
11.3.2	STONE	293
11.3.3	EXPOSE	295
11.3.3.1	EXPOSE Facility	295
11.3.3.2	EXPOSE Experiments	297
11.3.3.3	EXPOSE Experiment Hardware	299
11.3.3.4	EXPOSE-R and EXPOSE-E	301
11.3.3.5	Process of Experiment Proposal, Acceptance, Preparation, and Validation	302
11.4	Results from Astrobiology Experiments in Earth Orbit	303
11.4.1	Relevance of Extraterrestrial Organic Molecules for the Emergence of Life	304
11.4.2	Role of Solar UV Radiation in Evolutionary Processes Related to Life	306
11.4.2.1	Efficiency of the Stratospheric Ozone Layer to Protect Our Biosphere	306
11.4.3	Chances and Limits of Life Being Transported from One Body of Our Solar System to Another or Beyond	307
11.4.3.1	Effects of Space Vacuum	309

11.4.3.2	Effects of Extraterrestrial Solar UV Radiation	310
11.4.3.3	Effects of Galactic Cosmic Radiation	311
11.4.3.4	Combined Effects of All Parameters of Space	313
11.4.3.5	Time Scales of Interplanetary Transport of Life	313
11.4.4	Radiation Dosimetry in Space	314
11.5	Future Development and Applications of Exposure Experiments	316
11.6	Further Reading	317
11.6.1	Books and Articles in Books	317
11.6.2	Articles in Journals	318
11.6.3	ESA Online Archives	319
11.7	Questions for Students	319

## 12 Putting Together an Exobiology Mission: The *ExoMars* Example

*Jorge L. Vago and Gerhard Kminek*

12.1	Background of the <i>ExoMars</i> Mission	321
12.1.1	Searching for Life on Mars	321
12.1.2	Exobiology Research at ESA	322
12.1.2.1	The ESA Exobiology Science Team Study	324
12.1.2.2	The 1999 Exobiology Announcement of Opportunity	325
12.1.3	The AURORA and the ELIPS Program of ESA	326
12.1.3.1	The 2003 Pasteur Call for Ideas	326
12.1.3.2	Approval of the <i>ExoMars</i> Mission	328
12.2	<i>ExoMars</i> Science Objectives	328
12.2.1	Searching for Signs of Life	328
12.2.1.1	Extinct Life	328
12.2.1.2	Extant Life	332
12.2.1.3	Search for Life: Conclusions	334
12.2.2	Hazards for Human Operations on Mars	334
12.2.3	Geophysics Measurements	335
12.3	<i>ExoMars</i> Science Strategy	335
12.4	<i>ExoMars</i> Mission Description	337
12.4.1	The <i>ExoMars</i> Rover	339
12.5	Outlook and Conclusions	345
12.6	Further Reading	346
12.6.1	Books and Articles in Books	346
12.6.2	Articles in Journals	346
12.7	Questions for Students	351

## 13 Astrobiology Exploratory Missions and Planetary Protection Requirements

*Gerda Horneck, André Debus, Peter Mani, and J. Andrew Spry*

13.1	Rationale and History of Planetary Protection	353
13.2	Current Planetary Protection Guidelines	355
13.2.1	Category I Missions	357
13.2.2	Category II Missions	357
13.2.3	Category III Missions	359

13.2.4	Category IV Missions	359
13.2.5	Category V Missions	360
13.2.6	Future Development of Planetary Protection Guidelines	361
13.3	Implementation of Planetary Protection Guidelines	362
13.3.1	Bioload Measurements	363
13.3.2	Bioburden Reduction	367
13.3.2.1	Surface Wiping with Biocleaning Agents	371
13.3.2.2	Gamma Radiation Sterilization	371
13.3.2.3	Dry-heat Sterilization	372
13.3.2.4	Hydrogen Peroxide Vapor/Gas Plasma Sterilization	372
13.3.3	Prevention of Recontamination	373
13.4	Astrobiology Exploratory Missions of Concern to Planetary Protection	374
13.4.1	Missions to the Moon	374
13.4.2	Missions to Mars	376
13.4.2.1	Orbiters or Flyby Missions to Mars	376
13.4.2.2	Landers or Rovers with <i>in Situ</i> Measurements	378
13.4.2.3	Landers or Rovers with Martian Samples Returned to the Earth	383
13.4.2.4	Human Missions to Mars	387
13.4.3	Missions to Venus	388
13.4.4	Missions to the Moons of the Giant Planets	389
13.4.5	Missions to Asteroids or Comets	390
13.5	Outlook: Future Tasks of Planetary Protection	392
13.6	Further Reading	394
13.6.1	Concerning COSPAR Planetary Protection Guidelines	395
13.6.2	Concerning Handbooks and Standards on Planetary Protection	395
13.6.3	Concerning Biolod of Spacecraft	395
13.6.4	Concerning Lunar Missions	396
13.6.5	Concerning Missions to Terrestrial Planets	396
13.6.6	Concerning Missions to Jupiter's Moon Europa	397
13.7	Questions for students	397

**Index** 399