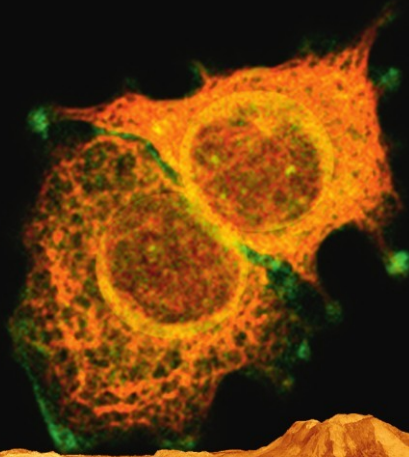


COSMIC BIOLOGY

**How Life Could Evolve
on Other Worlds**



LOUIS NEAL IRWIN and DIRK SCHULZE-MAKUCH

 Springer

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Cosmic Biology

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Contents



| | |
|---|-----|
| Preface | xv |
| List of illustrations | xix |
| 1 Rare Earths and Life Unseen | 1 |
| 1.1 How habitats come about | 3 |
| 1.1.1 Genesis: A scientific story of creation | 3 |
| 1.1.2 How solar systems and planets form | 5 |
| 1.1.3 Exoplanets | 7 |
| 1.2 The Rare Earth model | 9 |
| 1.3 The Life Unseen model | 10 |
| 1.4 Strategy for the study of cosmic biology | 11 |
| 1.5 Chapter summary | 13 |
| 1.6 References and further reading | 14 |
| 2 Life, Chemistry, Action! | 15 |
| 2.1 The challenge of defining “life” | 15 |
| 2.1.1 Life as a duality of process and entity | 16 |
| 2.1.2 Defining a living organism | 17 |
| 2.2 Matter gone wild: the special chemistry of life | 21 |
| 2.2.1 The elemental composition of living things | 22 |
| 2.2.2 Biomolecules | 25 |
| 2.2.3 Macromolecules | 29 |
| 2.3 The advantages of liquids for life | 32 |
| 2.3.1 General properties of liquids | 32 |
| 2.3.2 The special properties of water | 34 |
| 2.4 The need for and sources of energy for living systems | 36 |
| 2.4.1 Oxidation-reduction chemistry | 36 |
| 2.4.2 Thermal energy | 38 |
| 2.4.3 Kinetic energy | 39 |
| 2.4.4 Ionic diffusion | 39 |
| 2.4.5 Osmosis | 40 |
| 2.4.6 Other sources of energy | 41 |
| 2.5 Chapter Summary | 42 |
| 2.6 References and further reading | 43 |
| 3 Life’s Fundamentals | 45 |
| 3.1 Beginnings | 45 |

vi **Cosmic Biology**

| | | |
|----------|--|-----------|
| 3.1.1 | A nine-step program for the origin of life on Earth | 45 |
| 3.1.2 | Qualifications and limitations | 51 |
| 3.1.3 | Alternative origin scenarios | 52 |
| 3.2 | Organic evolution: the process of biological change through time | 54 |
| 3.2.1 | Selection | 55 |
| 3.2.2 | Chance | 58 |
| 3.2.3 | Heredity | 60 |
| 3.3 | Ecosystems: from populations to pyramids | 61 |
| 3.3.1 | Food webs | 61 |
| 3.3.2 | Trophic structures | 61 |
| 3.4 | Chapter summary | 64 |
| 3.5 | References and further reading | 66 |
| 4 | Fire and Water | 69 |
| 4.1 | Nature of Earth | 69 |
| 4.1.1 | Atmosphere | 70 |
| 4.1.2 | Building blocks | 70 |
| 4.1.3 | Energy | 70 |
| 4.1.4 | Temperature | 70 |
| 4.1.5 | Topography | 71 |
| 4.1.6 | Cycles | 72 |
| 4.1.7 | Conditions for life on Earth | 72 |
| 4.1.8 | Facts consistent with the existence of life on Earth | 73 |
| 4.1.9 | Possible assumptions about the nature of Earth's biosphere | 74 |
| 4.2 | A model for the history of life on Earth | 74 |
| 4.2.1 | Origin of life on Earth | 74 |
| 4.2.2 | Early stages of life on Earth | 75 |
| 4.2.3 | The dilemma of oxygen and the earliest forms of life | 76 |
| 4.2.4 | Transition to multicellularity | 76 |
| 4.2.5 | A brief descriptive history of life on Earth | 79 |
| 4.3 | A deduced biosphere for Earth | 89 |
| 4.3.1 | Trophic levels of life on Earth | 90 |
| 4.3.2 | Ecosystems on Earth | 94 |
| 4.3.3 | Biotic communities on Earth | 95 |
| 4.4 | Characteristics of biota on Earth | 96 |
| 4.4.1 | Metabolism | 96 |
| 4.4.2 | Reproduction | 97 |
| 4.4.3 | Motility | 98 |
| 4.4.4 | Sensory systems | 98 |
| 4.4.5 | Cognition | 99 |
| 4.4.6 | Technology | 100 |
| 4.5 | What alien observers could get wrong about life on Earth | 101 |
| 4.6 | Chapter Summary | 102 |
| 4.7 | References and further reading | 103 |

| | | |
|----------|---|-----|
| 5 | Frozen Desert | 105 |
| 5.1 | Peeling through layers of Martian mystery | 105 |
| 5.2 | Overview of Martian planetary history | 111 |
| 5.3 | Reconstructing a plausible evolutionary history for putative life on Mars | 115 |
| 5.3.1 | Rise of the autotrophs | 116 |
| 5.3.2 | Phototrophic diversification | 116 |
| 5.3.3 | The heterotrophic succession | 118 |
| 5.3.4 | Colonial heterotrophs ensue | 118 |
| 5.3.5 | Offshoots of colonial life diversify | 119 |
| 5.3.6 | A succession of subterranean retreats | 119 |
| 5.3.7 | The sanctuary of caves | 120 |
| 5.3.8 | Living stones | 121 |
| 5.3.9 | Cryptobionts | 121 |
| 5.3.10 | Fossil remnants and life unseen | 121 |
| 5.4 | A putative Martian biosphere | 122 |
| 5.5 | Ecosystems on Mars | 124 |
| 5.6 | Biotic communities on Mars | 125 |
| 5.7 | Earth analogues of Martian habitats | 126 |
| 5.8 | Characteristics of life on Mars | 128 |
| 5.8.1 | Metabolism | 128 |
| 5.8.2 | Reproduction | 128 |
| 5.8.3 | Motility | 129 |
| 5.8.4 | Sensory systems | 130 |
| 5.8.5 | Cognition | 130 |
| 5.9 | What could be wrong with this picture? | 130 |
| 5.10 | Life may have been discovered on Mars already | 131 |
| 5.11 | Chapter summary | 133 |
| 5.12 | References and further reading | 134 |
| | | |
| 6 | Hell Fire and Brimstone | 137 |
| 6.1 | Nature of Venus | 137 |
| 6.1.1 | Atmosphere | 138 |
| 6.1.2 | Topography | 139 |
| 6.1.3 | Volcanism | 140 |
| 6.1.4 | Tectonic features | 142 |
| 6.2 | Planetary history of Venus | 143 |
| 6.3 | A possible evolutionary history for putative life on Venus | 145 |
| 6.3.1 | Life in the age of water on Venus | 145 |
| 6.3.2 | Life as Venus became hotter and the water evaporated | 147 |
| 6.3.3 | The possibility of life below the surface of Venus | 148 |
| 6.4 | The prospect of finding fossil evidence of life on Venus | 149 |
| 6.5 | Ecosystem possibilities for life on Venus | 149 |
| 6.6 | Characteristics of life on Venus | 150 |
| 6.7 | Possibilities for life on exoplanets like Venus | 150 |

viii **Cosmic Biology**

| | | |
|----------|--|-----|
| 6.8 | Chapter summary | 151 |
| 6.9 | References and further reading | 152 |
| 7 | Suspended Animation | 153 |
| 7.1 | Prospects for life in the clouds of Venus | 153 |
| 7.1.1 | Composition and characteristics of Venusian clouds | 154 |
| 7.1.2 | Properties conducive to life in the clouds of Venus | 155 |
| 7.1.3 | Challenges for life in the clouds of Venus | 157 |
| 7.1.4 | Possible trajectories for the evolution of life in the clouds of Venus | 157 |
| 7.1.5 | Ecosystem possibilities in the clouds of Venus | 160 |
| 7.2 | Prospects for life in the atmospheres of gas giant planets | 160 |
| 7.2.1 | Composition of the gas giants | 161 |
| 7.2.2 | Conceivable habitats for life on the gas giants | 164 |
| 7.2.3 | Assessing the plausibility of life in the atmosphere of the gas giants | 166 |
| 7.3 | Prospects for life in the atmospheres of exoplanets | 169 |
| 7.4 | Chapter summary | 170 |
| 7.5 | References and further reading | 172 |
| 8 | Deep and Dark | 173 |
| 8.1 | Nature of Europa | 173 |
| 8.2 | Planetary history of Jovian satellites | 176 |
| 8.3 | Conditions for life on Europa | 178 |
| 8.4 | Energy for life on Europa | 178 |
| 8.4.1 | Light | 178 |
| 8.4.2 | Radiation | 179 |
| 8.4.3 | Chemistry | 179 |
| 8.4.4 | Fluid in motion | 179 |
| 8.4.5 | Osmotic and ionic gradients | 180 |
| 8.4.6 | Heat | 180 |
| 8.4.7 | Other long-shot possibilities | 183 |
| 8.5 | Forms of life on Europa | 183 |
| 8.5.1 | Producers | 183 |
| 8.5.2 | Consumers | 185 |
| 8.6 | Possible evolutionary history for putative life on Europa | 186 |
| 8.7 | Ecosystems on Europa | 189 |
| 8.8 | Biotic communities on Europa | 193 |
| 8.8.1 | The near-surface community | 193 |
| 8.8.2 | The ice ceiling community | 193 |
| 8.8.3 | The benthic community | 193 |
| 8.8.4 | The pelagic community | 194 |
| 8.9 | Characteristics of European biota | 194 |
| 8.9.1 | Metabolism | 194 |
| 8.9.2 | Reproductive systems | 194 |

| | | |
|-----------|---|------------|
| 8.9.3 | Motility | 195 |
| 8.9.4 | Sensory systems | 195 |
| 8.9.5 | Cognition | 195 |
| 8.10 | Properties of Europa <i>not</i> conducive for life | 196 |
| 8.11 | Enceladus: variations on a theme | 196 |
| 8.12 | Significance of the potential for life on Europa or Enceladus | 198 |
| 8.13 | Chapter summary | 199 |
| 8.14 | References and further reading | 199 |
| 9 | Fire and Ice | 201 |
| 9.1 | Nature of Io | 201 |
| 9.1.1 | Geology | 202 |
| 9.1.2 | Thermal environment | 207 |
| 9.1.3 | Radiation environment | 209 |
| 9.2 | Planetary history of Io | 210 |
| 9.3 | Conditions for life on Io | 210 |
| 9.3.1 | Solvents for life on Io | 212 |
| 9.3.2 | Chemical building blocks for life on Io | 213 |
| 9.3.2 | Energy for life on Io | 214 |
| 9.4 | Origin of life on Io | 214 |
| 9.5 | Habitats for life on Io | 215 |
| 9.6 | A possible evolutionary history for life on Io | 216 |
| 9.7 | Ecosystem possibilities for life on Io | 218 |
| 9.8 | Characteristics of life on Io | 219 |
| 9.8.1 | Radiation resistance | 219 |
| 9.8.2 | Metabolism | 220 |
| 9.8.3 | Growth and reproduction | 220 |
| 9.8.4 | Motility | 220 |
| 9.8.5 | Sensory systems | 220 |
| 9.8.6 | Cognition | 221 |
| 9.9 | Chapter summary | 221 |
| 9.10 | References and further reading | 222 |
| 10 | Petrolakes | 225 |
| 10.1 | Nature of Titan | 226 |
| 10.1.1 | Atmosphere and climate | 226 |
| 10.1.2 | Topography | 228 |
| 10.1.3 | Interior | 231 |
| 10.2 | Planetary history of Titan | 232 |
| 10.3 | Conditions (good and bad) for life on Titan | 234 |
| 10.3.1 | Chemistry | 234 |
| 10.3.2 | Temperature | 237 |
| 10.3.3 | Habitats | 237 |
| 10.4 | A possible evolutionary history for putative life on Titan | 239 |
| 10.4.1 | An aqueous origin and evolution for life on Titan | 240 |

x **Cosmic Biology**

| | | |
|-----------|---|------------|
| 10.4.2 | A hydrocarbon habitat for the origin and evolution of life on Titan | 241 |
| 10.5 | Ecosystem possibilities for life on Titan | 245 |
| 10.6 | Characteristics of life on Titan | 245 |
| 10.6.1 | Metabolism | 245 |
| 10.6.2 | Growth and reproduction | 246 |
| 10.6.3 | Motility | 247 |
| 10.6.4 | Sensory systems | 247 |
| 10.6.5 | Cognition | 248 |
| 10.7 | Note of caution | 248 |
| 10.8 | Chapter summary | 249 |
| 10.9 | References and further reading | 250 |
| 11 | Exotic Cocktails | 253 |
| 11.1 | Nature of dwarf planets | 254 |
| 11.2 | Outline of the history of dwarf planets like Pluto and Triton | 255 |
| 11.3 | Nature of Pluto and Charon | 256 |
| 11.4 | Nature of Triton | 258 |
| 11.4.1 | Composition and chemistry | 258 |
| 11.4.2 | Atmosphere | 259 |
| 11.4.3 | Topography | 259 |
| 11.4.4 | Geological activity | 262 |
| 11.5 | Conditions conducive for life on Triton and Pluto | 262 |
| 11.5.1 | Energy for life on Triton | 262 |
| 11.5.2 | Building blocks for life on Triton | 264 |
| 11.5.3 | Solvents for life on Triton | 265 |
| 11.5.4 | Habitats for life on Triton | 266 |
| 11.6 | Scenarios for the possible evolution of life on Triton | 266 |
| 11.7 | Chapter summary | 269 |
| 11.8 | References and further reading | 270 |
| 12 | Biocomplexity in the Cosmos | 273 |
| 12.1 | Evolution of size, complexity, and biodiversity | 273 |
| 12.1.1 | Energy | 274 |
| 12.1.2 | Temperature | 274 |
| 12.1.3 | Mobility | 275 |
| 12.1.4 | Time | 275 |
| 12.1.5 | Habitat fractionation | 276 |
| 12.1.6 | Planetary history | 276 |
| 12.2 | Evolution of intelligence and technology | 277 |
| 12.2.1 | What is intelligence | 278 |
| 12.2.2 | Under what circumstances does intelligence arise? | 281 |
| 12.2.3 | Under what circumstances has meta-intelligence arisen? | 283 |
| 12.2.4 | Why has intelligence arisen so rarely on Earth? | 283 |
| 12.3 | Emergence of technology | 285 |

| | | |
|-----------|--|-----|
| 12.3.1 | Under what circumstances does technology arise? | 285 |
| 12.3.2 | Why has technology arisen more rarely than intelligence? | 287 |
| 12.4 | Where are they? Dealing with the Fermi Paradox | 289 |
| 12.4.1 | The improbability of discovery | 289 |
| 12.4.2 | The disincentive for contact | 290 |
| 12.4.3 | The possibility of past or present visitations | 291 |
| 12.4.4 | The possibility that technology is self-limiting | 291 |
| 12.4.5 | Argument by analogy: the discovery and fate of the Hawaiian Islands | 292 |
| 12.5 | Chapter summary | 293 |
| 12.6 | References and further reading | 293 |
| 13 | Anticipating the Future | 295 |
| 13.1 | Three prospects for any form of life | 295 |
| 13.1.1 | Plateau | 295 |
| 13.1.2 | Extinction | 297 |
| 13.1.3 | Transition | 297 |
| 13.2 | Thoughts on the relative frequency of different forms of life | 299 |
| 13.2.1 | Biodiversity in the Solar System under the familiar scenario | 299 |
| 13.2.2 | Biodiversity in the Solar System under the exotic scenario | 300 |
| 13.2.3 | Biodiversity in the cosmos under the familiar scenario | 300 |
| 13.2.4 | Biodiversity in the cosmos under the exotic scenario | 301 |
| 13.2.5 | Revisiting the Rare Earth Hypothesis | 301 |
| 13.3 | The fate and future of life on Earth | 302 |
| 13.3.1 | Fate of human life | 303 |
| 13.3.2 | Fate of insects | 305 |
| 13.3.3 | Fate of everything else | 306 |
| 13.3.4 | Summary of the fate of life on Earth | 307 |
| 13.4 | The fate and future of life on other worlds | 307 |
| 13.5 | Chapter summary | 307 |
| 13.6 | References and further reading | 309 |
| | Glossary | 311 |
| | Index | 327 |

This book is dedicated to the people of the former Soviet Union, who opened the space age on 4 October 1957, to the people of the United States who first sent humans to another world on 20 July 1969, to the thousands of scientists and engineers of all nations whose hearts have been broken by the countless failed missions that inevitably occurred on the way to the spectacular successes of Luna, Venera, numerous Mars orbiters and rovers, Pioneer, Mariner, Viking, Magellan, and Hubble; and especially to the visionary government leaders, scholars, and technicians who funded, built, and sent forth the Voyager, Galileo, and Cassini-Huygens spacecraft to give us the incredible views we have of the other worlds in our cosmic neighborhood that may well hold our nearest neighboring forms of alien life.

Preface



This is a work of both science *and* imagination.

Science uses logic and demonstrable facts to reveal the nature of the material world. Imagination leads the search for facts in new directions, and stretches the limits of logical inference in creative ways. Both are needed to uncover the mysteries of the natural world.

Life is a dynamic manifestation of the material world – complex, incredibly variable, and constantly changing – but material nonetheless, and therefore subject to scientific study just as much as the stars that burn and the atoms that make them up. We strongly suspect that life extends as far as the stars do into the vastness of the cosmos. Unlike the stars that we can see with certainty, though, life lies hidden from view, of unknown extent, with properties that can be reasonably surmised but not yet confirmed on even our nearest planetary neighbor. Our science will reveal the nature of that life in due time. But where to look, what to expect, and how to interpret what we find, for now lies in the province of our imaginations.

So this is a book grounded in science but driven by imagination to predict the form that life *may have taken* on other worlds. It hasn't been easy to put a narrative together that genuinely attempts to stay well within the boundaries of scientific constraint, while at the same time stretching as far as we dare the limits of what ought to be possible. As scientists addicted to the comfort of known facts, we have had to grit our teeth with every use of the subjunctive case: *might be* instead of *is*, *may have been* instead of *was*, *could* instead of *did*, *ought* instead of *can*, *possibly* or *probably* instead of *certainly*, and so forth. But once we committed to writing a book about what we fully believe but of which we as yet have no certain knowledge, we had no choice. We have given the reader fair warning in the subtitle that this is ultimately a work of speculation, then we have forged ahead.

We wrote our first book, *Life in the Universe: Expectations and Constraints*, with the conviction that exobiology (morphing into NASA's astrobiology) needed a firm base of factual information, grounded in the physical sciences, with more than a token treatment of biology. We deliberately wrote a technical treatise, leaving to others the task of conveying a more accessible account for the general reader of life as it could exist in the rest of the universe. We made some pretty clear-cut predictions about the possibilities for life on other specific worlds, based on a logical extension of facts and principles. But we kept our predictions couched in technical language, and limited them simply to the existence of life, *per se*, without elaboration.

Encouraged by the success of *Life in the Universe*, we have decided that those predictions deserve full-blown elaboration, in a manner accessible to a reader without a higher education in science. Since everyone interested in the subject has a basic knowledge of our Solar System, we thought a case-history approach might be the best way to write an engaging narrative. This being a book of applied science, a certain amount of science can't be avoided. We have tried to provide this as painlessly as possible in the first three chapters – defining life precisely, reviewing the relevant essentials of chemistry and physics, and outlining the principles of evolutionary biology and ecology that most books on astrobiology avoid. Amateur and professional scientists alike can skip directly to chapter 4 without missing the basic message, though occasional reference back to the underlying principles and assumptions may prove helpful on occasion.

In chapter 4, we consider life on our home planet of Earth, not as we know it to be, but as an intelligent observer on another world could deduce it. We placed our hypothetical observer in the nearest solar system that we think could host a level of technology comparable to ours. By comparing what our alien scientists might infer about Earth, and why they would do so, we hope to illustrate *our* strategy for imagining how life could unfold on other worlds. Our exercise, beginning in chapter 5, takes a travelogue approach through our own Solar System, visiting first Mars, the planet with a climate and environment least different from Earth's, then Venus, as the other planet with Mars that resembled Earth most in its early history. We then consider the possibility of life in the unconventional habitats of the atmospheres of Venus and the gas giant planets. From there, we look at two exotic worlds circling Jupiter, Io and Europa (with a brief glance at Saturn's Enceladus). From there, our attention turns to the only other world besides Earth to host a nitrogen-rich atmosphere and abundance of organic chemicals – Saturn's giant moon, Titan – a featured attraction for every astrobiologist. But Neptune's captured satellite, Triton, and the biplanetary dwarfs, Pluto and Charon, may hold very different forms of life that we can't afford to disregard, so they will be our final destinations in the Solar System. Along the way, we'll look briefly at exoplanets and their capacity for hosting some forms of life. By the time we reach the outer reaches of our own Solar System, we will have concluded that we are very likely the only technologically-competent species in our region of the universe. We will therefore devote chapter 12 to an examination of why that might be, and what it says about the chances of our finding similar beings elsewhere (or of them finding us). Finally, we will conclude with a discussion in chapter 13 of the ultimate fate of life, on Earth in particular, but wherever it may arise in the universe.

Affirming the widely-held assumption that scientific truth holds true throughout the universe, our logical inferences are based on application of physicochemical principles on other worlds just as they apply on Earth. We likewise have no reason to doubt that the principles of evolutionary biology and ecology are just as universal. Therefore, they too have been applied without regard to the specific world on which we assume they operate.

On the other hand, we have made a few concessions to the uncertainty of our subject matter. Several terms, like *species* and all other taxonomic units, and specific subcellular structures or organ systems which have a specific reality for living organisms on Earth, cannot be assumed for life on other worlds, and therefore have been avoided. Even the broadest categories, like *plant* and *animal*, are usually replaced with *plant-like* or *animal-like*. For the same reason, while we are tempted to assume that cellular dimensions and structures obey some fairly universal constraints, we have felt uncomfortable assuming anything about higher-level cellular organization in alien biospheres, and so avoid referring to “multi-cellular” organisms except when speaking of known examples on Earth. We hope that any reader who finds this form of dissimulation annoying will grant us the freedom to be imprecise, for the sake of avoiding the implication of knowing what we do not.

We are honored to offer this work in the year of the 400th anniversary of Galileo’s discovery of the four Jovian satellites. Two of them, Io and Europa, are featured chapters in this book – worlds on which life could exist today. Or it may not. We simply hope that, in setting forth the possibilities, we have imagined today what the science of tomorrow will be able to confirm or refute.

Louis Irwin thanks his wife, Carol, for her constant support and encouragement. Dirk Schulze-Makuch thanks his wife and kids for their continuous patience. Both of us acknowledge with deep appreciation our many colleagues for their insights and valuable discussions with us over the years.

Louis Neal Irwin and Dirk Schulze-Makuch
El Paso and Pullman
April, 2010

Illustrations



| | | |
|------|--|----|
| 1.1 | Conceptual scheme for the “Big Bang” formation of the Universe | 4 |
| 1.2 | Star formation | 5 |
| 1.3 | Exoplanet orbiting a red dwarf | 6 |
| 1.4 | Planetary formation | 8 |
| 2.1 | Entropy and organization from the atomic to organismic level | 19 |
| 2.2 | Schematic representation of the major chemical components of living systems | 22 |
| 2.3 | Schematic representation of molecules formed by the overlap of the outermost electrons from contiguous atoms | 24 |
| 2.4 | Polarity | 25 |
| 2.5 | Major categories of biomolecules | 28 |
| 2.6 | Proteins | 30 |
| 2.7 | Nucleic acids | 31 |
| 2.8 | Chemistry in a polar solvent | 35 |
| 2.9 | Adenosine Triphosphate (ATP) | 37 |
| 3.1 | NitroGlycoPeptides (NGPs) | 46 |
| 3.2 | Formation of protopolymers | 47 |
| 3.3 | Prebiotic evolution | 48 |
| 3.4 | Protometabolism | 49 |
| 3.5 | Protoreplication | 50 |
| 3.6 | Natural selection under different types of selective pressure | 57 |
| 3.7 | Food web in a marine ecosystem | 62 |
| 3.8 | Energy flow and trophic structure of an idealized marine ecosystem | 63 |
| 4.1 | Third rocky planet from the Sun | 71 |
| 4.2 | Ancestral forms of life on Earth | 75 |
| 4.3 | Multicellularity | 77 |
| 4.4 | Ancestral sea floor | 78 |
| 4.5 | Cyclic production and consumption of glucose ($C_6H_{12}O_6$), O_2 , CO_2 , and H_2O | 80 |
| 4.6 | Descendents of the Cambrian Explosion | 82 |
| 4.7 | A succession of large animals have dominated the food chain in the oceans at different times | 83 |
| 4.8 | Early evolution of plants on land | 84 |
| 4.9 | Life covers the land | 85 |
| 4.10 | Major innovations during the Mesozoic | 86 |

xx **Cosmic Biology**

| | | |
|------|--|-----|
| 4.11 | Evolution of birds | 87 |
| 4.12 | Evolution of mammals | 89 |
| 4.13 | Ecological structure for the biosphere on Earth | 90 |
| 5.1 | Surface of Mars | 106 |
| 5.2 | Channels on the surface of Mars | 107 |
| 5.3 | Elevations on Mars | 109 |
| 5.4 | Small-scale volcanism and erosion in the equatorial highlands | 110 |
| 5.5 | Valley drainage networks in the southern highlands of Mars | 111 |
| 5.6 | Argument for a surface ocean northwest of Olympus Mons, by terrestrial analogy | 113 |
| 5.7 | Effect of obliquity on humidity and ice distribution | 114 |
| 5.8 | Schematic timeline of geological history on Mars, with comparison to Earth | 115 |
| 5.9 | Scenario for the evolution of life on Mars through time in different environments | 117 |
| 5.10 | Trophic structure of Martian ecosystem | 124 |
| 5.11 | Putative fossil microbe from Mars | 132 |
| 6.1 | Venus | 138 |
| 6.2 | Atmospheric structure and its consequences on Venus | 139 |
| 6.3 | Topography of Venus | 140 |
| 6.4 | Channels on Venus | 141 |
| 6.5 | Venusian landforms | 142 |
| 6.6 | Scenario for the evolution of life through stages of environmental change on Venus | 146 |
| 7.1 | Schematic structure of the Venusian atmosphere | 154 |
| 7.2 | Scenario for the evolution of life in the clouds through stages of environmental change on Venus | 158 |
| 7.3 | Internal structure of gas giant planets | 162 |
| 7.4 | Cloud patterns on Jupiter and Saturn | 163 |
| 7.5 | Cloud patterns on Uranus and Neptune | 165 |
| 7.6 | Comparison of size and position of planets in the Gliese 581 system with those in our Solar System | 169 |
| 8.1 | Europa, surface and interior | 174 |
| 8.2 | Surface features of Europa | 175 |
| 8.3 | The moons of Jupiter | 177 |
| 8.4 | Osmotic energy sources possible in the ocean of Europa | 181 |
| 8.5 | Thermal energy sources possible in the ocean of Europa | 182 |
| 8.6 | Scenario for the evolution of life on Europa | 188 |
| 8.7 | Hypothetical European ecosystem based on chemical energy | 190 |
| 8.8 | Hypothetical European ecosystem based on energy from osmotic or ionic gradients | 191 |
| 8.9 | Enceladus | 197 |

| | | |
|-------|--|-----|
| 9.1 | Io | 202 |
| 9.2 | Jupiter and its satellites | 204 |
| 9.3 | Eruptions, calderas and sapping on Io | 205 |
| 9.4 | Geological complexity of Io | 206 |
| 9.5 | Surface of Io at close range | 207 |
| 9.6 | Mountains on Io | 208 |
| 9.7 | Amirani lava field | 208 |
| 9.8 | Hot spots on Io | 209 |
| 9.9 | Gradient variations in microbial life | 211 |
| 9.10 | Surface and subsurface microbial gradients | 212 |
| 9.11 | Possible evolutionary trajectory for life on Io | 217 |
| 10.1 | Saturn and satellites | 226 |
| 10.2 | Atmosphere of Titan | 227 |
| 10.3 | Titan's surface | 228 |
| 10.4 | Upland channels and seas on Titan | 229 |
| 10.5 | Northern lakes on Titan | 229 |
| 10.6 | Topography of Titan | 230 |
| 10.7 | Internal structure of Titan | 232 |
| 10.8 | Theoretical pathway for creation of information-containing polymer | 236 |
| 10.9 | Two possible biospheres on Titan | 238 |
| 10.10 | Stormy weather on Titan | 239 |
| 10.11 | Possible evolutionary trajectory for life on Titan | 241 |
| 10.12 | Hydrocarbon-degrading microbe | 243 |
| 11.1 | Pluto and Charon | 257 |
| 11.2 | Triton's orbit and orientation | 259 |
| 11.3 | Triton | 260 |
| 11.4 | Surface features of Triton | 261 |
| 11.5 | Volcanic Plains of Triton | 263 |
| 11.6 | Similarity of silanes and hydrocarbons | 265 |
| 11.7 | Possible trajectory for the putative evolution of life on Triton | 267 |
| 12.1 | Biodiversity in a coral reef | 277 |
| 12.2 | Intelligent species | 279 |
| 12.3 | Intelligence as maladaptive | 285 |
| 12.4 | Path to technology | 286 |
| 12.5 | Technology as an amplification of intelligence | 288 |
| 13.1 | Generalized evolutionary trajectories | 296 |
| 13.2 | Plateau, extinction, and transition | 298 |

1

Rare Earths and Life Unseen

A strategy for cosmic biology

Speculation that alien life might be found on other worlds can be traced to ancient times. Copernicus, Kepler, and Galileo fed those thoughts by showing that the Earth is not the center of the universe. Once it was understood that our planet is just one of several rotating around a solar center, thoughts of other solar systems naturally arose. By 1584, Giordano Bruno was asserting that there must be "... countless suns, and countless earths all rotating around their suns." The next conceptual step – that on some of those "countless earths" there might be life – was easy to take.

By the 19th Century, the possibility of alien civilizations on Earth's nearest sibling planets, Venus and Mars, was taken seriously in the educated world. Spurred by the human propensity for both fear and wonder, ideas ranged from a war-like race of Martians bent on conquering Earth, to the prospect of a peaceful paradise flourishing beneath the clouds of Venus. Percival Lowell, an American astronomer, fueled speculation of intelligent life on Mars by claiming to see long canals, built perhaps to transport water from the poles to drying equatorial regions. This inspired science fiction writers to imagine a technologically advanced but dying, warring world, especially in the work of Edgar Rice Burroughs in the early 20th century. Speculations about life on Venus were generally more benign. A dense cloud cover enshrouded the planet in mystery, giving free reign to romantic images of a verdant biosphere. From Ray Bradbury's short stories depicting incessant rainfall, to Robert Heinlein's vision of a Carboniferous swamp, the Venus of science fiction most often was seen as a warm, dripping-wet, water world, capable perhaps of supporting a prolific alien flora and fauna.

As the space age dawned, reality set in. Robotic probes to our nearest neighbors doused all thoughts of technological civilizations or even widespread but unintelligent forms of life, as cameras landing on the surface of both Mars and Venus saw no evidence of either. In 1969, humans first set foot on the Moon, finding it as sterile on site as it appeared through the telescope. Since Mercury resembles the Moon in both topology and torrid fluctuations between extreme heat and cold, life seems equally improbable on that planet. As scientific data on the nature of the gas giants and their satellites accumulated, it became clear that Earth-like conditions were not to be found on any other world in our Solar System – that our planet, at least within a radius of four light years (the distance to our nearest star), is not only rare but unique.

2 Cosmic Biology

Against this revelation, admittedly discouraging for those who dream of finding sister systems of life beyond Earth, came the counterbalancing realization of just how vast the universe truly is. Maybe, except for Earth, *our* Solar System isn't all that inviting for life, but there must be solar systems galore in a universe that measures over 13 billion light years across. With evidence accumulating over the past decade that planets orbit other suns in our Galaxy, the assumption that solar systems pervade the universe seems reasonable. Even if Earth-like planets are rare, given enough solar systems, planets as inviting for life as Earth must exist elsewhere. Since we know that life exists on Earth, we're most likely to find it and recognize it on other worlds that resemble Earth. This is the logic of the search for Earth-like planets in other systems, and the terracentric search for life on those worlds. It fuels the drive to "follow the water." It forms the basis for seeking planets where liquid water and protective atmospheres exist, preferably on medium-sized, rocky planets with stable near-circular orbits with diurnal and seasonal cycles that are not too extreme. It supports the concept of the "stellar habitable zone," which presumes that life is restricted to those planets at just the right distance from their central star for Earth-like conditions to exist. It fits perfectly with the search for life in our own image.

The alternative logic is one that starts from a different premise – that life on Earth is not representative necessarily of life elsewhere, and that therefore the conditions that led to and sustain life on Earth need not be viewed as limitations [1,2]. A nuanced version of this alternative is that, in fact, the life we see around us as humans is not even typical of the vast majority of biomass on Earth; that the unseen microbial world beneath our feet, in our oceans, and to a considerable depth within the crust of our planet is the rule for life on most worlds, including our own, with the larger organisms that catch our eye simply being the exceptions that command our attention.

Peter Ward and Donald Brownlee, a paleontologist and astronomer respectively, at the University of Washington tried to merge these disparate models into a unified hypothesis in their influential book, *Rare Earth: Why Complex Life Is Uncommon in the Universe* [3]. They defined their Rare Earth Hypothesis as, "the paradox that life may be nearly everywhere but complex life almost nowhere." They argued that complex life is likely to arise only under conditions (implicitly, Earth-like conditions) that come about through a very special combination of circumstances. Since that combination on statistical grounds is likely to occur very rarely, complex life itself must be a rarity. Microscopic (by inference, "non-complex") life, on the other hand, is known to be highly adaptable to the most extreme environments. Since extreme environments, by terracentric standards, are common, then microscopic forms of "simple" life may well be common throughout the universe.

In the sections that follow, we review these two major points of view, then offer our own strategy for a systematic study of cosmic biology. But first, since history matters for the way things are today, we need to understand how all the potential habitats for alien life, from rare earths, to snowball planets, to gas

giants, came into being. We will therefore start by providing a brief overview of the history of the universe and our Solar System.

1.1 How habitats come about

An assumption we make is that life cannot exist in the midst of an actively burning star, because the chemical reactions that make up living processes cannot proceed stably at the temperatures present in them. Therefore, cosmic biology is really planetary biology (meaning planets, planetoids, and their satellites). So we begin by considering where planets come from.

Science has not always assumed that the universe had a finite beginning. The visionary cosmologist, Fred Hoyle, long championed the idea that mass and energy are products of a steady, continuous, and endless process of generation throughout space. But increasingly scientists have come to the mind-bending view that the universe did indeed begin at a singular point in both time and space. The evidence for this is that the universe is expanding now, that the oldest objects in the universe are at its furthest reaches, and that remnants of the violent birth of the universe – what Fred Hoyle facetiously called the “Big Bang” – still lurk in the form of a background of electromagnetic radiation that would be predicted to be left over from such an event.

1.1.1 Genesis: A scientific story of creation

No myth or metaphor from any of the world’s religions can match the audacity and incredibility of the currently favored scientific explanation for the origin of the universe. Until evidence to the contrary comes along, though, most scientists give grudging credence to the “Big Bang” theory, which envisions the emergence of all the matter and energy of the universe according to the following model [4].

Space and time did not exist before the universe was born. Our universe came into being about 13.7 billion years ago, when something emerged from nothing with such violence and rapidity that matter and energy were indistinguishable.

In the first microsecond of its existence, the universe expanded from a singular point to a volume of space 100 billion kilometers across at a temperature of 10 trillion °C. This explosive expansion of space enabled matter in the form of subatomic quarks to differentiate from pure energy and coalesce into baryons (protons and neutrons).

By the end of the first second of the universe, neutrons started changing into protons by emitting more electrons. Once the ratio of protons to neutrons reached about seven to one, they started combining into combinations of (mostly) two protons and two neutrons, the nuclei for future helium atoms. Nearly all the free neutrons were soaked up by this process within a couple of minutes, leaving a huge excess of free protons to form the nuclei for hydrogen atoms.

It took 200,000 years or more for the universe to cool to 2700 °C, a temperature at which the protons and neutron-proton aggregates could start

4 Cosmic Biology

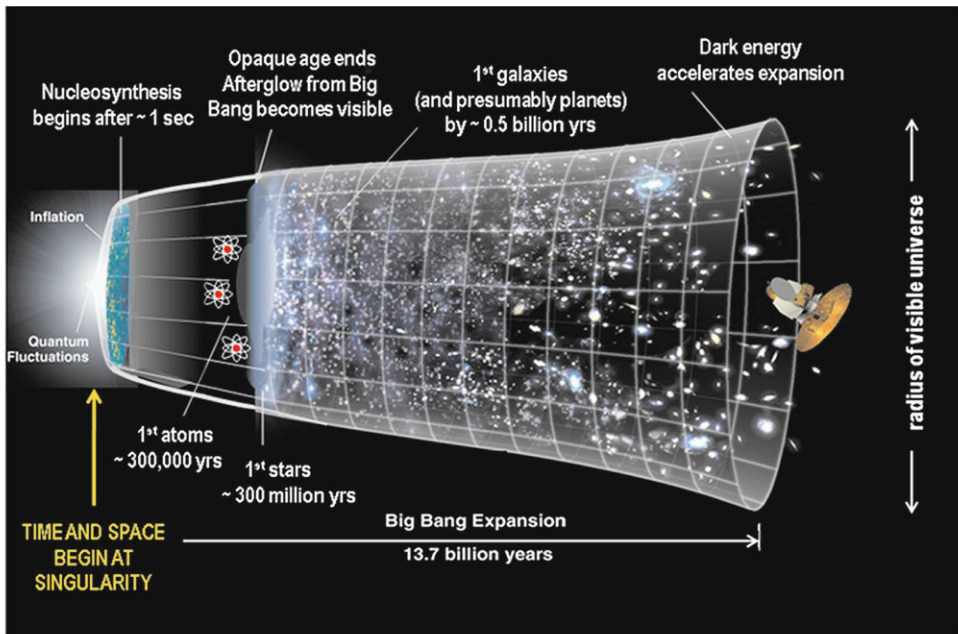


Figure 1.1 Conceptual scheme for the “Big Bang” formation of the Universe.

According to this model, all matter and energy in the universe had a singular point of origin in space and time. With expansion, energy and matter differentiated, and matter in time coalesced into galaxies consisting of stars, planets, and related objects (Modified from art by NASA/WMAP Science Team).

capturing the free flying electrons to form the first atoms of hydrogen and helium. As the dense fog of electrons condensed into newly formed atoms, the opaqueness cleared and photons could stream without interruption across the vastness of space, which now filled a volume of a hundred million light years.

By 300 million years into its life span, the universe was filled almost but not quite uniformly with mostly hydrogen, a little bit of helium, a tiny amount of lithium (the three smallest atoms), a lot of energy, and a whole lot of “dark matter” whose nature is still not understood today. Another fundamental force of nature, gravity, now worked on those discontinuities in the density of the “normal matter” in the universe. Clouds of hydrogen and helium began to collapse in regions where the gases were slightly more concentrated. When the clouds became massive enough, gravity sucked the atoms into a ball that gradually became compressed enough to force atoms of hydrogen to fuse together, forming helium and emitting energy as light and other forms of electromagnetic and particle energy. The first stars were born.

The stars of the early universe were massive by comparison with the average size of stars today. This meant more gravity, which meant a faster fusion at their cores. When all the hydrogen at the center of a star was consumed, the helium atoms started fusing into heavier elements like carbon, nitrogen, and oxygen.

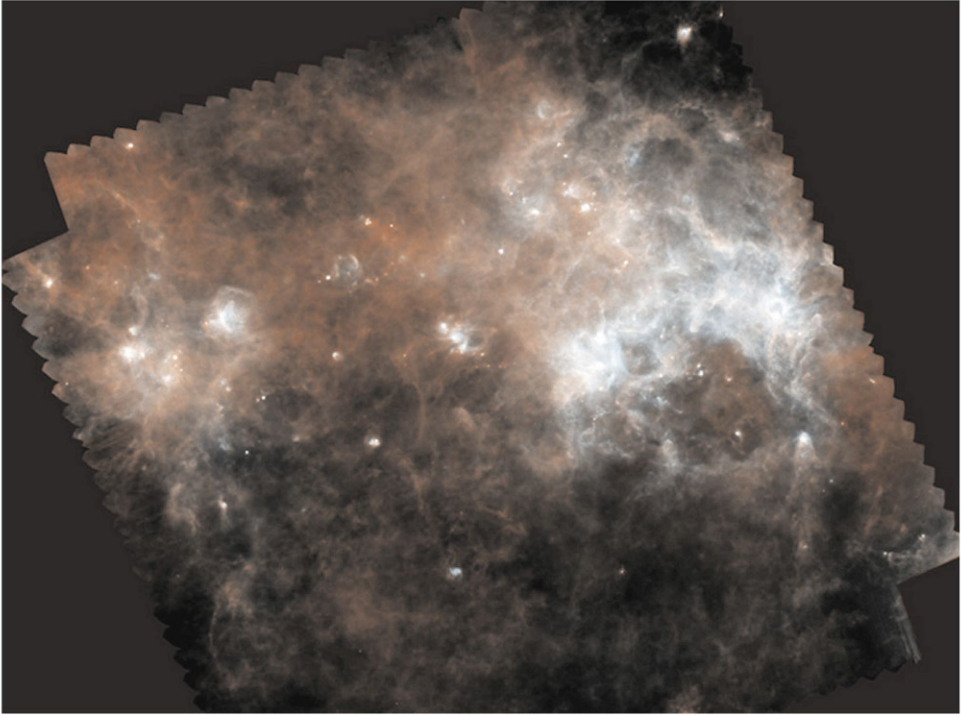


Figure 1.2 Star formation. Cool, dark clouds of gas and dust are just starting to condense in this region of our Milky Way Galaxy. There is a surprising amount of turmoil: the interstellar material is condensing into continuous and interconnected filaments glowing from the light emitted by new-born stars at various stages of development. The image was acquired by Herschel's spectral and photometric imaging receiver. Herschel is a European Space Agency mission with important participation from NASA (ESA/NASA/JPL-Caltech).

With heavier elements raising the density of their cores, the crushing gravity of the biggest stars caused the collapse of atoms down to their positively charged nuclei, which repulsed one another with such explosive force that the star blew apart. This first generation of stars thus spewed the heavier elements it had made into space, giving rise to metallic particles of dust as well as free-floating lighter elements to join the hydrogen and helium gas already in abundance. These clouds of dust and gas would eventually collapse into the next, more chemically enriched generation of stars and the cycle would repeat itself. In this way, the heavier elements that would give rise in time to all the worlds and all the living things in the universe were created.

1.1.2 How solar systems and planets form

The laws of angular momentum dictate that as matter collapses on itself, it must begin to spin. In many if not most cases, as the dust and gas fell into the

6 Cosmic Biology

compacted gravity well of a protostellar mass, some of the matter would be kept by centrifugal force from falling into the central star. The matter spinning at the periphery would flatten into a disk, resulting in a spherical ball at the center with a smattering of material spinning around the central mass in a flat plane.

Thus compressed into a flattened space, dust particles, water, and other molecules that had formed in the interstellar void would collide with increasing frequency, often sticking together at the frigid temperatures that prevailed some distance from their growing sun at the center of their orbital trajectories. Discontinuities again played a role, with slightly heavier grains growing more massive slightly faster than those around them. The trend would continue for millions of years, leading to boulder-sized aggregates that coalesced into larger boulders, until masses of rock and ice called *planetesimals* had grown to several kilometers in diameter.

Planetesimals are large enough to generate gravitational attraction. The larger ones would pull in the smaller ones in a runaway process of accretion. At this point, the process would accelerate toward survival of a small number of planetesimals evolving toward *protoplanets* in a relatively short time. The larger the protoplanets became, the more fragments from the formative protostellar disk they would pull in.

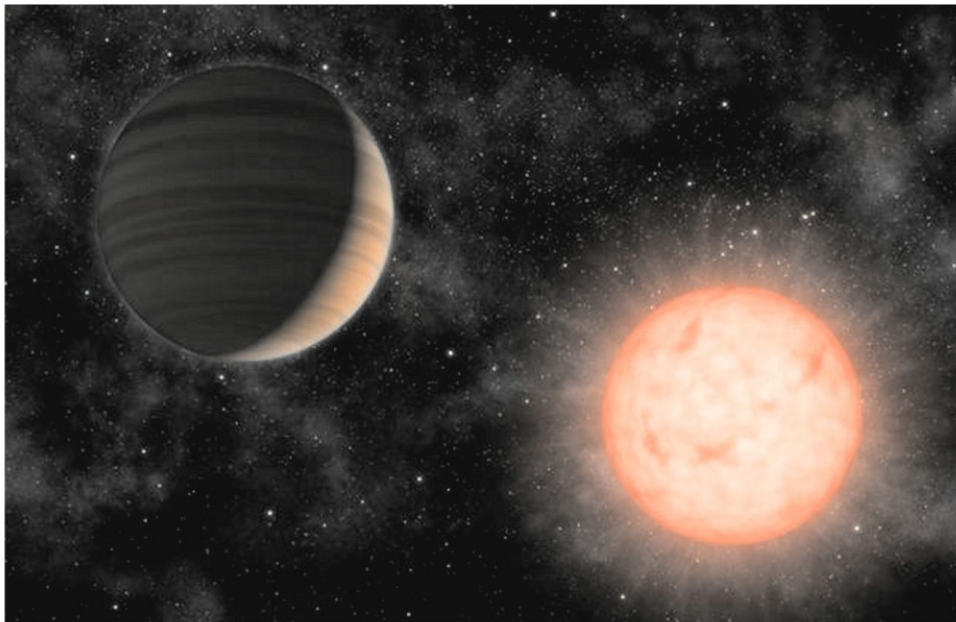


Figure 1.3 Exoplanet orbiting a red dwarf. This is an artist's conception of the smallest star known to host a planetary system. The dim red star, a red dwarf about the size of Jupiter named VB 10, is orbited by a planet of approximately the same size, about 20 light years away in the constellation Aquila (NASA/JPL-Caltech).

The newborn planets that were large enough became bombarded with so much matter and energy that their interiors melted, allowing the heaviest elements like iron and nickel to sink to the center. An outer crust of lighter metallic compounds like silicates formed a solid surface that underwent a high level of bombardment for millions of years more. This delivered both matter and energy to the growing planet's surface, while radioactive decay of the heavier elements in its interior generated heat from inside out.

Like the protostellar disk, the planetesimals that had collapsed to form the protoplanets were set spinning themselves, sometimes generating satellites that rotated around their central planet, as the planets rotated around their central star. As planets formed, they scooped up gases like hydrogen and nitrogen. The planet's size and temperature (depending on its distance from the central sun) dictated whether these light gases would evaporate back into space, be held as gases in an atmosphere, or be pulled with enough gravitational pressure to form a liquid shell around the planet's rocky core. The latter became characteristically massive "gas giants."

Our own Solar System was born about 4.6 billion years ago. The protostellar disk that gave rise to our local part of the universe generated a somewhat larger than average sun encircled by four rocky planets (Mercury, Venus, Earth, and Mars), four gas giants (Jupiter, Saturn, Uranus, and Neptune), and an assortment of smaller bodies including at least one binary dwarf planetary system (Pluto and Charon). All but the innermost two of our Solar System's planets have satellites of their own. The two largest giants, Jupiter and Saturn, also have the largest number of satellites, while the smaller inner planets have none (Mercury and Venus) to one (Earth) to two (Mars), perhaps because their parent planets had less starting material to begin with, or because keeping satellites in stable orbit that close to the immense gravitational pull of the Sun is more difficult.

Hundreds of other solar systems are now known to exist, and protostellar clouds can be seen in various stages of formation both near and far, suggesting a universe filled with recurrent and ongoing acts of creation.

1.1.3 Exoplanets

The first planets beyond our own Solar System were not discovered until 1992. Prior to that, we had no reason to doubt that the logic of our own system – smaller rocky planets and light atmospheres near the sun, with gas giants hosting dense atmospheres further out – was a general rule for the structure of solar systems everywhere. That assumption was dispelled with the discovery of gas giants larger than Jupiter orbiting their central stars much closer than the Earth orbits our Sun. Planets the size of our own rocky members, being much harder to detect, are just now being discovered, but enough have been found to suggest a far greater diversity of organizational structures for other solar systems, than our own "logical" planetary arrangement, or the rapidly revolving giant planets first found near their central suns, would suggest. This includes, for example, many