

Origins of Life in the Universe

Origins of Life in the Universe traces the evolution of the Cosmos from the Big Bang to the development of intelligent life on Earth. Conveying clear, concise science in an engaging narrative it maps the history of the Universe for introductory science and astrobiology courses for non-science majors.

What is the origin of the Universe? How do stars and planets form? How does life begin? How did intelligence arise? Are we alone in the Cosmos? Physics, chemistry, biology, astronomy, and geology are combined to answer some of the most fascinating questions in science and create a chronicle of events in which the swirling vapors in the primordial cloud of the Universe evolved over billions of years into conscious life. Coverage of the latest discoveries in astrobiology give a sense of the excitement of this fast-moving field.

ROBERT JASTROW, internationally acclaimed as an astronomer and popularizer of science, was the founder of the Goddard Institute for Space Studies, a US Government laboratory charged with carrying out research in astronomy and planetary science. He has authored several books that have made science accessible to a wider audience, and has been a frequent commentator on science news. His research spanned nuclear physics, planetary science, atmospheric physics, weather and climate prediction.

MICHAEL RAMPINO is an Associate Professor of earth science and biology at New York University, and a Research Associate at GISS in New York. His research spans many areas of the earth sciences, especially the inter-relationships between Earth's changing environments and the evolution of life. He is Series Co-Editor for the highly acclaimed *Encyclopedia of Earth Sciences* (Springer) and the Editor-in-Chief of the *Earth Science Encyclopedia On-Line*.

Cambridge University Press
978-0-521-53283-9 - Origins of Life in the Universe
Robert Jastrow and Michael Rampino
Frontmatter
[More information](#)



Origins of Life in the Universe

ROBERT JASTROW MICHAEL RAMPINO



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-53283-9 - Origins of Life in the Universe
Robert Jastrow and Michael Rampino
Frontmatter
[More information](#)

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi
Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521825764

© R. Jastrow and M. Rampino 2009

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2009

Printed in the United Kingdom at the University Press, Cambridge

A catalog record for this publication is available from the British Library

ISBN 978-0-521-82576-4 hardback
ISBN 978-0-521-53283-9 paperback

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Contents

Extended contents page vii
Foreword Robert Shapiro xv
Preface xvii

PART I The Universe

- 1 Our place in the Universe: The realm of the galaxies 3
- 2 A view of the origin of the Universe: Evidence for an explosive beginning 18
- 3 Life from the cosmic cauldron: Life history of a star; Creation of the chemical elements within stars 42

PART II The Solar System

- 4 Formation of the conditions for life: Planets and moons 73
- 5 Origins of a habitable planet: The Moon as a record of early Earth history 106
- 6 Prospects for life: Is Mars a habitable planet? 119
- 7 Venus – our sister planet: The evolution of a hostile world 144

PART III The Earth

- 8 Earth: Composition and structure of a habitable planet 163
- 9 The changing face of an active habitable planet: Explanation of Earth's surface features 196
- 10 Climate change and the evolution of life: Climate changes and Earth history 228

PART IV Origin and history of life on Earth

- 11 The origin and evolution of life: Life's beginnings and Darwin's theory of evolution 253
- 12 The early history of life on Earth: From single cells to complex organisms 285
- 13 The development of higher life forms: The age of the reptiles and dinosaurs 309

PART V Evolution of intelligent life

- 14 The mammals: The rise of intelligence 337
- 15 The evolution of higher intelligence: Growth of the brain 354
- 16 Are we alone in the Universe? Humankind's place in the cosmic community 369

Epilog 382

Appendix A History of the Earth 384

Appendix B Periodic table of the elements 386

Index 387

Extended contents

Foreward page xv

Preface xvii

PART I The Universe

- 1 **Our place in the Universe: The realm of the galaxies** 3
 - 1.1 The Sun and planets 4
 - 1.2 The Sun's nearest neighbors 5
 - 1.3 Our Galaxy 6
 - 1.4 Neighboring galaxies 11
 - 1.5 Clusters of galaxies 12
 - 1.6 The observable Universe 13
 - 1.7 The composition of the Universe 14
 - 1.8 The basic forces of nature 15
 - 1.9 Summary 17
 - Questions 17
- 2 **A view of the origin of the Universe: Evidence for an explosive beginning** 18
 - 2.1 Evidence for the explosive origin of the Universe 19
 - 2.1.1 *How the speeds of galaxies are measured: The Doppler shift* 20
 - 2.2 The law of the expanding Universe 24
 - 2.2.1 *Hubble's Law* 26
 - 2.2.2 *Is Earth at the center of the expanding Universe?* 28
 - 2.3 The age of the Universe 28
 - 2.4 The primordial fireball: Proof of the cosmic explosion 30
 - 2.5 Conditions in the evolving Universe 32
 - 2.6 The horizon problem 34
 - 2.7 The flat Universe problem 34
 - 2.8 The inflationary Universe 38
 - 2.9 Dark energy and an accelerating Universe 40
 - 2.10 Summary 41
 - Questions 41

- 3 **Life from the cosmic cauldron: Life history of a star; Creation of the chemical elements within stars** 42
- 3.1 Birth of a star 43
 - 3.2 Stellar evolution 47
 - 3.3 White dwarfs and supernovas 50
 - 3.4 Abundances of the elements in the Universe and the life cycle of stars 54
 - 3.5 Neutron stars and black holes 56
 - 3.6 Pulsars 58
 - 3.7 Black holes 61
 - 3.8 Quasars and giant black holes 64
 - 3.9 Summary 70
 - Questions 70

PART II The Solar System

- 4 **Formation of the conditions for life: Planets and moons** 73
- 4.1 The origin of the Sun and planets 74
 - 4.1.1 *The Sun's flare-up* 75
 - 4.1.2 *Accretion: Planetesimals into planets* 76
 - 4.2 Other solar systems 76
 - 4.3 A tour of the terrestrial planets 79
 - 4.3.1 *Mercury* 79
 - 4.3.2 *Venus* 80
 - 4.3.3 *The Earth–Moon system* 82
 - 4.3.4 *Mars* 82
 - 4.4 A tour of the outer planets 83
 - 4.4.1 *Jupiter* 83
 - 4.4.2 *The Galilean satellites* 85
 - 4.4.3 *Saturn* 91
 - 4.4.4 *The moons of Saturn* 93
 - 4.4.5 *The rings of Saturn* 94
 - 4.4.6 *Uranus and Neptune* 95
 - 4.4.7 *Pluto* 96
 - 4.5 Minor bodies of the Solar System 98
 - 4.5.1 *Asteroids* 98
 - 4.5.2 *Meteorites* 99
 - 4.5.3 *Comets* 101
 - 4.6 Summary 104
 - Questions 105
- 5 **Origins of a habitable planet: The Moon as a record of early Earth history** 106
- 5.1 The Moon as a Rosetta Stone 107
 - 5.2 The surface of the Moon 108

- 5.3 The Apollo findings 112
 - 5.3.1 *Ages of the lunar rocks* 113
 - 5.3.2 *Evidence for internal melting* 115
- 5.4 The origin of the Moon 115
- 5.5 Summary 118
 - Questions 118
- 6 Prospects for life: Is Mars a habitable planet? 119**
 - 6.1 Mars 120
 - 6.1.1 *Geology of Mars* 121
 - 6.1.2 *Evidence for geological activity* 123
 - 6.1.3 *Evidence for an early abundance of water* 128
 - 6.2 Prospects for life on Mars 133
 - 6.2.1 *The search for Martian life* 134
 - 6.2.2 *Pathfinder mission to Mars* 138
 - 6.2.3 *The Mars exploration rovers* 138
 - 6.2.4 *Ancient life in a Martian meteorite?* 139
 - 6.2.5 *The significance of the search for Martian life* 141
 - 6.3 Summary 142
 - Questions 143
- 7 Venus – our sister planet: The evolution of a hostile world 144**
 - 7.1 Venus 145
 - 7.2 Surface conditions 147
 - 7.3 The Venus atmosphere 150
 - 7.3.1 *The greenhouse effect* 151
 - 7.3.2 *Removal of carbon dioxide from Earth's atmosphere* 154
 - 7.3.3 *The runaway greenhouse effect* 155
 - 7.3.4 *Why oxygen is present in Earth's atmosphere but not on Venus* 156
 - 7.3.5 *Why Venus has less water than Earth* 157
 - 7.4 Conditions for life: The habitable zone around a star 158
 - 7.5 Summary 160
 - Questions 160

PART III The Earth

- 8 Earth: Composition and structure of a habitable planet 163**
 - 8.1 Composition of Earth 164
 - 8.2 The chemical bond 165
 - 8.2.1 *Laws of the chemical bond* 165
 - 8.2.2 *Examples of chemically inactive and active elements* 167

- 8.2.3 *The common Earth elements and their electron configurations* 169
- 8.2.4 *Compounds of silicon and oxygen: The silicate minerals* 170
- 8.3 Rocks 175
- 8.4 Melting of Earth 177
 - 8.4.1 *Properties of radioactive substances* 177
 - 8.4.2 *How radioactivity is used to determine the “age” of a rock* 178
 - 8.4.3 *Dating a rock by its lead/uranium ratio* 179
- 8.5 Differentiation of Earth 180
- 8.6 Earthquakes and Earth’s interior 183
- 8.7 The floating crust: Isostasy 187
 - 8.7.1 *Creep* 189
- 8.8 Convection currents in Earth’s interior 190
- 8.9 Earth’s lithosphere 192
- 8.10 Summary 194
 - Questions 195
- 9 **The changing face of an active habitable planet: Explanation of Earth’s surface features** 196
 - 9.1 Continents and ocean basins 197
 - 9.2 Evidence for continental drift and plate tectonics 198
 - 9.2.1 *Match of fossil flora and fauna* 199
 - 9.2.2 *Match of rock units* 200
 - 9.2.3 *Evidence from the ocean floor: The Mid-Ocean Ridge* 201
 - 9.2.4 *Evidence from Earth’s magnetism* 203
 - 9.2.5 *Magnetic stripes on the ocean floor* 204
 - 9.2.6 *Age of ocean-floor rocks* 208
 - 9.2.7 *Direct measurements of plate motions* 208
 - 9.3 Boundaries of Earth’s plates 210
 - 9.4 Types of plate boundaries 211
 - 9.4.1 *Separating or diverging plates* 211
 - 9.4.2 *The opening of a new sea* 212
 - 9.4.3 *Colliding plates: Ocean against ocean* 213
 - 9.4.4 *Colliding plates: Ocean against continent* 214
 - 9.4.5 *Colliding plates: Continent against continent* 217
 - 9.4.6 *Sliding plate boundary* 219
 - 9.4.7 *The Hawaiian Islands and hotspots in Earth’s mantle* 220
 - 9.5 History of the super-continent Pangaea 224
 - 9.6 Summary 226
 - Questions 227

- 10 **Climate change and the evolution of life: Climate changes and Earth history** 228
- 10.1 Timescales of climate change 229
 - 10.2 Climate change over hundreds of millions of years 230
 - 10.2.1 *Plate tectonics and continental drift: A cause of major ice ages* 230
 - 10.3 Snowball Earth 234
 - 10.4 Episodes of climate change lasting tens to hundreds of thousands of years 235
 - 10.5 Short-term climate change: The last 10 000 years 242
 - 10.5.1 *The Medieval Warm Period* 243
 - 10.5.2 *The Little Ice Age* 244
 - 10.6 Causes of short-term climate change 245
 - 10.6.1 *Volcanic eruptions and climate* 245
 - 10.6.2 *Climate and the Sun's brightness* 246
 - 10.6.3 *Carbon dioxide and climate: The human factor* 248
 - 10.7 Summary 249
 Questions 250
- PART IV Origin and history of life on Earth**
- 11 **The origin and evolution of life: Life's beginnings and Darwin's theory of evolution** 253
- 11.1 What is life? 254
 - 11.2 The basic building blocks of life 255
 - 11.3 Proteins 257
 - 11.4 DNA 259
 - 11.4.1 *DNA replication* 263
 - 11.4.2 *Genes and chromosomes* 265
 - 11.5 The origin of life 267
 - 11.5.1 *The Miller–Urey experiment* 267
 - 11.6 The virus 270
 - 11.7 Evolution 274
 - 11.8 Darwin's discovery 275
 - 11.9 Natural selection 278
 - 11.10 DNA, mutations, and evolution 280
 - 11.11 Summary 283
 Questions 283
- 12 **The early history of life on Earth: From single cells to complex organisms** 285
- 12.1 The cell 286
 - 12.2 Photosynthesis 289
 - 12.2.1 *The growth of atmospheric oxygen* 290

- 12.3 Major steps in the early evolution of life 292
 - 12.3.1 *The Tree of Life* 292
 - 12.3.2 *The first cells with nuclei* 293
 - 12.3.3 *Utilization of oxygen* 296
 - 12.3.4 *The origins of sex* 297
 - 12.3.5 *Multi-celled organisms* 298
- 12.4 The Cambrian explosion: The appearance of hard-bodied organisms 300
- 12.5 The fishes 302
- 12.6 Invasion of the land 304
- 12.7 Summary 308
 - Questions 308
- 13 The development of higher life forms: The age of the reptiles and dinosaurs 309**
 - 13.1 Evolution of the reptile 310
 - 13.2 The mammal-like reptiles 313
 - 13.3 The mammals 315
 - 13.4 The dinosaurs 320
 - 13.5 Why were the dinosaurs successful? 324
 - 13.6 The End Cretaceous extinction 326
 - 13.7 The Alvarez Hypothesis 326
 - 13.8 Mass extinctions in Earth history 330
 - 13.9 Catastrophism 332
 - 13.10 Summary 333
 - Questions 334
- PART V Evolution of intelligent life**
- 14 The mammals: The rise of intelligence 337**
 - 14.1 Evolutionary radiation of the mammals 338
 - 14.2 Success of the mammals 341
 - 14.3 The evolution of mammal intelligence 342
 - 14.4 The tree dwellers 346
 - 14.5 The evolution of monkeys and apes 349
 - 14.6 Summary 352
 - Questions 353
- 15 The evolution of higher intelligence: Growth of the brain 354**
 - 15.1 Evolution of bipedalism 355
 - 15.2 The toolmakers 358
 - 15.2.1 *Explosive growth of the brain* 362
 - 15.2.2 *Why did the brain grow rapidly?* 363
 - 15.3 Summary 368
 - Questions 368

- 16 Are we alone in the Universe? Humankind's place
in the cosmic community 369
- 16.1 Habitable planets 370
 - 16.2 Are we alone? 371
 - 16.2.1 *What if life is common but intelligent life is rare?* 371
 - 16.3 Humankind's place in the cosmic community 373
 - 16.3.1 *Intelligent life in the Universe* 374
 - 16.4 The search for extraterrestrial intelligence 376
 - 16.4.1 *The Drake Equation* 376
 - 16.4.2 *The Fermi Paradox* 379
 - 16.4.3 *Search strategies* 379
 - 16.4.4 *Transmitting signs of intelligence on Earth* 380
 - 16.5 Summary 381
 - Questions 381
- Epilog* 382
- Appendix A History of the Earth* 384
- Appendix B Periodic table of the elements* 386
- Index* 387

Foreword

For most of us, our daily lives are carried out within a space of a few miles – our lifetimes measured in a few tens of years. Science enters our lives as a supplier of ever-newer conveniences for living and of modern medical treatment if we become ill. A non-scientist might choose to take these things for granted, and get on with his or her life. Why then devote time and energy to the study of science, and in particular to astrobiology and the history of the Universe?

The answer is that astrobiology will introduce you to new visions of the Universe that are grand and inspiring. Beyond Earth, lies an endless parade of glittering stars and galaxies. Among them are worlds, some like our own, others strangely different, which may also harbor life, even intelligent life. A person who is unaware of these prospects would be similar to someone who attended a concert wearing earplugs, or who traveled to a land rich in beauty and history, but stayed entirely in their hotel room.

For those who wish to take their minds on a more adventurous journey, this text will provide an admirable guide. I have known Bob Jastrow and Mike Rampino for years and admired the breadth of their interests, which range from the birth of stars to the extinction of the dinosaurs. I commend you into their expert care, and trust that you will have a magnificent trip.

Robert Shapiro
Professor Emeritus of Chemistry, New York University

Preface

Origins of Life in the Universe deals with the developing field of astrobiology – the study of the scientific disciplines bearing on the emergence of life and intelligence in the Cosmos. It combines material from the traditional disciplines of physics, chemistry, biology, astronomy, and geology to create a chronicle of events in which swirling vapors in the primordial Universe evolved over billions of years into conscious life on Earth.

The book is written to support an introductory science course aimed specifically at non-science students. In it, the basic facts and concepts of the major scientific disciplines are taught as a connected narrative – the story of the evolving Universe from the Big Bang to the appearance of intelligent life. In this book, facts and concepts in separate disciplines are taken up in a natural sequence as needed to advance the narrative. The book addresses some of the most fascinating and fundamental questions in science: What is the origin of the Universe? How do stars and planets form? How does life begin? How did intelligence arise? Are we alone in the Cosmos?

According to the scientific evidence, the story began approximately 14 billion years ago, when the Universe expanded in the aftermath of the cosmic explosion known to astronomers as the Big Bang. In a material sense, the seed of everything that has happened in the last 14 billion years can be traced back to the moment of the Big Bang; every star, planet, and living creature in the Universe came into being as a result of events set in motion at that moment.

What was the cause of the cosmic explosion? What was the Universe like before the explosion occurred? Did the Universe even exist before that moment? These questions are at the forefront of astrophysical research. The answers

remain among the greatest of scientific mysteries. In contrast, the collective labors of scientists in the modern era have yielded a detailed account of the events that followed the cosmic explosion. The Universe expanded rapidly outward from a hot, dense state, cooling as it expanded. Initially there were no galaxies, stars, or planets. But after about a billion years, the expanding cloud of matter and energy had cooled sufficiently to permit the formation of condensed knots of matter held together by gravity. These were the first galaxies and stars.

Another 8 or 9 billion years went by, and then, some 4.5 billion years ago, the Sun and its planets, including Earth, appeared as inconspicuous condensations in an undistinguished spiral galaxy – one among billions of galaxies, each containing hundreds of billions of stars.

At some point in the first billion years after Earth formed, life appeared in the waters covering its surface. We know this from the fossil record. How was that life created out of inanimate matter? A number of plausible theories exist, but we still cannot say which, if any, of these ideas is correct.

Once across the threshold of life, the scientist picks up the trail again. The remains of simple, bacteria-like organisms appear first in the record of the rocks about 3.5 billion years ago; traces of soft-bodied many-celled organisms are preserved in rocks about 600 million years old. A little later, about 540 million years ago, the remains of the first marine animals with hard shells and skeletons appear in the record. From this point on, the record of the history of life is fairly complete, until finally the remains of the first creature with a human level of intelligence are found in rocks about one hundred and fifty thousand years old.

All the larger trends in this history are clearly exhibited in the fossil record. This is particularly true of human ancestors, of whom essentially nothing was known when Charles Darwin first developed his theory of evolution by natural selection. Discoveries in recent years have filled in much of the missing record of human origins. Some gaps exist, but new finds are made nearly every year.

As scientists, we have both been involved in research in fields related to astrobiology. Jastrow, as director of NASA's

Goddard Institute for Space Studies and The Mount Wilson Observatory, directed cutting-edge research in astronomy, planetary science, and geology, and was the first chairman of NASA's Lunar Exploration Committee. Rampino has done geological fieldwork on six continents investigating volcanic activity, the record of climatic change, and role of catastrophic events in the history of life.

We hope that this book and the story it tells will convey to students the excitement and sense of wonder that we feel when we contemplate our long cosmic history. Our combined experience, based on teaching introductory college science courses over a period of 25 years, indicates that this chronological narrative of the evolution of the Cosmos strongly appeals to students with a wide variety of backgrounds and interests.

During this time, we have also developed supporting materials, including end-of-chapter questions with answers, and additional questions at www.cambridge.org/jastrow.

Many colleagues helped us with the preparation of this volume. We are particularly indebted to several people who were kind enough to take the time required for a careful reading and the preparation of detailed criticisms of individual chapters, and eventually the entire text. These include Dr. Richard Stothers and Dr. Andre Adler for the chapters on the contents of the Universe, cosmology, and the birth and death of stars; Dr. Michael Gaffey for the chapter on the Solar System; Dr. Christian Koeberl for the chapter on the Moon; Dr. Vivien Gornitz for the chapters on Mars and Venus; Dr. Dennis Kent for the chapters on the geology of Earth and plate tectonics; Drs. Andre Lapenis and Tyler Volk for the chapter on climate; Drs. Robert Shapiro, Edward Berger, and Stephen Small for the chapter on the origin of life and evolution (Dr. Shapiro made considerable contributions to that chapter); Dr. Nick Butterfield for the chapter on the early history of life; Dr. David Varricchio for the chapters on the dinosaurs and mammals; Dr. Donald Johansson for the chapter on human evolution; and Dr. Robert Shapiro for the chapter on life in the Cosmos.

Earlier versions of the manuscript were used as class notes for introductory level science courses at Columbia University,

Dartmouth College, and New York University. We thank our students and teaching assistants for their many comments and criticisms of the material as we continued to refine it.

We are especially indebted to Matt Lloyd, our editor at Cambridge University Press, whose detailed reading and criticism of the entire manuscript strengthened the book enormously.

Abstract We briefly examine the question of the origin of life, both terrestrial and extraterrestrial, in the light of latest findings and point out that the data is consistent with a dual mode origin: Some of the ingredients including possibly sugars being brought to earth from outer space which together with other ingredients for example proteins already present on the earth would lead to the formation of life. 1 Introduction. In any case the vast life span of the universe and its great variety in different parts provides a stage where it is plausible that primitive life forms could have been synthesised. Based on these considerations Sir Fred Hoyle and Prof. Chandra Wickramasinghe have proposed[3] that life has been transported to the earth from outer space.