

Contents

1 Stellar Nucleosynthesis

<i>Nikos Prantzos</i>	1
1.1 Introduction	1
1.2 Nuclei in the Cosmos	2
1.2.1 Solar and Cosmic Abundances	2
1.2.2 Cosmic Abundances vs. Nuclear Properties	3
1.2.3 Overview of Nucleosynthesis	6
1.3 Stars: from the Main Sequence to Red Giants	8
1.3.1 Basic Stellar Properties	8
1.3.2 H-Burning on the Main Sequence	10
1.3.3 He-Burning in Red Giants	12
1.4 Advanced Evolution of Massive Stars	15
1.4.1 Neutrino Losses Accelerate Stellar Evolution	15
1.4.2 C, Ne, and O-Burning	17
1.4.3 Si-Melting and Nuclear Statistical Equilibrium (NSE)	21
1.4.4 Overview of the Advanced Evolutionary Phases	24
1.5 Explosive Nucleosynthesis in Supernovae	26
1.5.1 Main Properties and Classification of Supernovae	26
1.5.2 Explosive Nucleosynthesis in Core Collapse Supernovae	27
1.5.3 Explosive Nucleosynthesis in Thermonuclear SN	32
1.5.4 Production of Intermediate Mass Nuclei (from C to the Fe peak)	34
1.6 Nuclei Heavier than Fe	35
1.6.1 Production Mechanisms and Classification of Isotopes	35
1.6.2 The S-Process	37
1.6.3 The R-Process	38
1.7 Summary	40
References	42

2 Formation of the Solar System: a Chronology Based on Meteorites

<i>Marc Chaussidon</i>	45
2.1 In Search for Ages	45
2.2 What is a Geochemical Age?	46
2.2.1 The Radioactivity	46

2.2.2	The Absolute Ages	47
2.2.3	The Relative Ages	48
2.2.4	Sources of Error or Uncertainty in Isotopic Dating	49
2.3	What are the Processes that can be Dated by Isotopic Analyses of Meteorites?	51
2.4	From the First Solids to the First Planets: When and How Fast?....	53
2.4.1	The Age of Meteorites and the Duration of Accretion Processes: the First Order Picture	53
2.4.2	A Relative Chronology Based on the Extinct Radioactivity of ^{26}Al	53
2.4.3	A Relative Chronology Based on the Extinct Radioactivity of ^{53}Mn	57
2.4.4	Absolute Calibration of the ^{26}Al and ^{53}Mn Chronologies.....	58
2.4.5	Longer Period Extinct Radioactivities and Chronology of the Differentiation	60
2.5	Remaining Questions	63
2.5.1	Disparities Between the Various Chronologies ^{26}Al , ^{53}Mn and ^{182}Hf	63
2.5.2	The Hypothesis of Homogeneity of the Distribution of Extinct Radioactivities in the Solar Accretion Disk: the Origin of Extinct Radioactivities	65
2.6	Conclusions	67
	References	69

3 The Formation of Crust and Mantle of the Rocky Planets and the Mineral Environment of the Origin of Life

<i>Francis Albarède</i>	75	
3.1	Chemical and Mineralogical Structure of the Earth.....	75
3.2	Dynamics of the Earth's Interior	77
3.3	The Origin of Continents	80
3.4	The Early Ages of Our Planet	83
3.5	From One Planet to the Next	88
3.6	Some Speculations	98
3.7	Questions for the Future	99
	References	100

4 Water and Climates on Mars

<i>François Forget</i>	103	
4.1	Introduction	103
4.2	Mars' Present-Day Climate	103
4.2.1	The CO_2 Cycle and the Seasonal Polar Caps	105
4.2.2	The Dust Cycle	106
4.2.3	The Water Cycle	107
4.3	A Few Million Years Ago: the Recent Martian Paleoclimates	110
4.3.1	Climate Changes Due to Orbital Parameter Variations	110

4.3.2	Liquid Water on Mars a Few Million Years Ago	113
4.4	More Than Three Billion Years Ago: the Youth of Mars	115
4.4.1	Evidence for Sustained Liquid Water on Early Mars	115
4.4.2	The Early Mars Climate Enigma	118
4.5	Conclusion	119
	References	119

5 Planetary Atmospheres: From Solar System Planets to Exoplanets

	<i>Thérèse Encrenaz</i>	123
5.1	What is an Atmosphere?	123
5.1.1	Atmospheric Structure	123
5.1.2	Atmospheric Circulation and Cloud Structure	126
5.1.3	Atmospheric Composition	128
5.1.4	Interaction with the Magnetosphere	130
5.2	Atmospheres of Solar System Planets	130
5.2.1	Formation and Evolution of Planetary Atmospheres in the Solar System	130
5.2.2	Terrestrial Planets and Giant Planets	132
5.2.3	Atmospheres of Outer Satellites and Pluto	139
5.3	Tools for Studying Planetary Atmospheres	141
5.3.1	Remote Sensing Analysis	141
5.3.2	<i>In Situ</i> Analysis: Chemical Composition from Mass Spectrometry	146
5.4	From Solar System Planets to Exoplanets	147
5.4.1	Properties of Detected Exoplanets: a Summary	147
5.4.2	Earth-Like Exoplanets: the Habitability Zone	148
5.4.3	Giant Exoplanets: Structure and Composition	149
5.5	Conclusions	151
	References	152

6 What About Exoplanets?

	<i>Marc Ollivier</i>	157
6.1	Let's Talk About History	157
6.2	Statistical Analysis of the First Extrasolar Planets Discoveries	159
6.2.1	The Mass Distribution of Exoplanets	160
6.2.2	The Star Planet Distance Distribution	162
6.2.3	Orbit Migration	163
6.2.4	Mass/Distance Relation for Exoplanets	171
6.2.5	Eccentricity of Exoplanet Orbits	172
6.2.6	The Metallicity of Stars with Planets	174
6.3	The Atmospheres and Spectra of Giant Exoplanets	175
6.3.1	General Considerations	175
6.3.2	Pegasides: the Point of View of Theoreticians and Observers	176

6.4	Future Steps in Exoplanetology and Associated Instrumentation	180
6.4.1	Open Questions	180
6.4.2	Research and Study of Giant Planets	181
6.4.3	Research and Study of Telluric Planets	183
6.4.4	Characterization of Exoplanets by Direct Detection	186
	References	193

7 Habitability: the Point of View of an Astronomer

	<i>Franck Selsis</i>	199
7.1	Introduction	199
7.2	The Circumstellar Habitable Zone	201
7.2.1	The Inner Limit of the Habitable Zone	202
7.2.2	The Outer Limit of the HZ (or How to Warm Early Mars?) . .	206
7.2.3	Continuously Habitable Zone	210
7.3	Habitability Around Other Stars	210
7.4	The Influence of the Giant Planets on the Habitability of the Terrestrial Planets	214
7.5	Discussion	215
7.6	Conclusion and Perspectives	216
	References	217

8 Habitability: the Point of View of a Biologist

	<i>Purificación López-García</i>	221
8.1	Introduction	221
8.1.1	The Concept of Habitability	221
8.1.2	Habitability in Biological Terms	222
8.2	What is Life?	222
8.2.1	Life's Definitions	222
8.2.2	Is it Living?	223
8.3	The Cell	224
8.3.1	Properties	224
8.3.2	Prokaryotes and Eukaryotes	225
8.3.3	The Tree of Life	226
8.4	Common Denominators of Life on Earth	227
8.4.1	Elements and Molecules	228
8.4.2	Cellular Metabolism	230
8.4.3	The Limits of Terrestrial Life	233
8.5	Perspectives	235
	References	235

9 Impact Events and the Evolution of the Earth

	<i>Philippe Claeys</i>	239
9.1	Introduction	239
9.1.1	Terrestrial Craters	239
9.1.2	Historical Perspective of the Impact Process	241

9.2	Characteristics of Impact Craters	242
9.2.1	Magnitude and Frequency	242
9.2.2	Crater Morphologies	244
9.2.3	Formation Mechanism (Based Essentially on Melosh 1989 and French 1998)	246
9.2.4	Identification Criteria	249
9.3	Case Study: The Cretaceous-Tertiary Boundary and the Chicxulub Crater	254
9.3.1	The Chicxulub Crater	254
9.3.2	Distribution of Ejecta	257
9.3.3	Consequences for the Biosphere	262
9.3.4	Asteroid or Comet?	264
9.4	Stratigraphic Distribution of Impact Events	264
9.4.1	In the Phanerozoic (0 to 540 Ma)	264
9.4.2	Proterozoic Impacts (540 Ma to 2.5 Ga)	266
9.4.3	Archean Impacts (2.5 to 4 Ga)	267
9.4.4	Hadean Impacts (4.0 Ga to Formation of the Earth)	268
9.5	Discussion: Impact, Origin of Life and Extinctions	270
	References	273

10 Towards a Global Earth Regulation

	<i>Philippe Bertrand</i>	281
10.1	The Oxygen: an Energy Story	282
10.2	Nitrogen and Phosphorus: the Nutrient Feedback	287
10.3	What About the Atmospheric CO ₂ ?	291
10.4	Towards a Global Biogeochemical Regulation (Homeostasy)	296
	References	302

11 The Last Common Ancestor of Modern Cells

	<i>David Moreira, Purificación López-García</i>	305
11.1	The Last Common Ancestor, the Cenancestor, LUCA: What's in a Name?	305
11.1.1	Some Historical Grounds	305
11.1.2	The Hypothesis of a Cenancestor	306
11.2	How Did the Cenancestor Make Proteins?	308
11.3	What Was the Nature of the Genetic Material?	309
11.4	What Did the Cellular Metabolism Look Like?	310
11.5	Was the Cenancestor Membrane-Bounded?	311
11.6	Other Unresolved Questions	312
11.7	Perspectives	314
	References	315

12 An Extreme Environment on Earth: Deep-Sea Hydrothermal Vents Lessons for Exploration of Mars and Europa

<i>Daniel Prieur</i>	319
12.1 Some Features of Oceanic Environment	319
12.2 Deep-Sea Hydrothermal Vents	320
12.3 Highly Efficient Symbioses	324
12.3.1 Vestimentifera	325
12.3.2 Molluscs	325
12.3.3 Polychaetous Annelids	327
12.3.4 Crustaceans	328
12.4 Life at High Temperature	328
12.4.1 Novel Microorganisms in the Bacteria Domain	329
12.4.2 Novel Microorganisms in the Archaea Domain	329
12.5 Response to Hydrostatic Pressure	335
12.6 Other Specific Adaptations	336
12.6.1 Fluctuations of Environmental Conditions	336
12.6.2 Heavy Metals	337
12.6.3 Ionizing Radiations	337
12.7 Lessons from Microbiology of Hydrothermal Vents	337
References	342

13 Comets, Titan and Mars: Astrobiology and Space Projects

<i>Yves Bénilan, Hervé Cottin</i>	347
13.1 An Astrobiological Look at the Solar System	348
13.1.1 The Origin of the Organic Matter	348
13.1.2 Follow the Water	354
13.2 The Space Exploration of Comets	356
13.2.1 General Considerations	356
13.2.2 Past Missions	359
13.2.3 Current Missions	369
13.2.4 Future Space Missions	382
13.3 The Space Exploration of Titan	382
13.3.1 Observations and Models of Titan Before Space Missions	382
13.3.2 Voyager Missions at Titan	385
13.3.3 Similarities and Differences Between Titan and the Earth	388
13.3.4 Cassini–Huygens Mission	392
13.4 Mars Exploration	398
13.4.1 Mars Before Space Missions	398
13.4.2 The Beginning of Martian Exploration	399
13.4.3 Current Space Missions	408
13.4.4 Future Exobiological Missions	412
13.5 Conclusion	420
References	420

14 Quantum Astrochemistry:**Numerical Simulation as an Alternative to Experiments**

<i>Yves Ellinger, Françoise Pauzat</i>	429
14.1 The Methods of Quantum Chemistry	429
14.1.1 Definition of Quantum Chemistry Calculations and Approximations	429
14.1.2 Wave Function-Based Methods	437
14.1.3 DFT Methods	447
14.1.4 Wave Function Versus DFT Methods	454
14.2 Applications of Quantum Chemistry	455
14.2.1 Radio Millimeter Observations	458
14.2.2 Infrared Observations	463
14.2.3 Modeling of Chemical Processes	472
14.2.4 Exobiology	482
14.3 Conclusions and Prospective	485
References	487

15 Artificial Life or Digital Dissection

<i>Hugues Bersini</i>	491
15.1 Introduction to Artificial Life	491
15.2 The History of Life Seen by Artificial Life	500
15.2.1 Appearance of a Chemical Reaction Looped Network	500
15.2.2 Production by this Network of a Membrane Promoting Individuation and Catalyzing Constitutive Reactions	502
15.2.3 Self-Replication of the Elementary Cell	503
15.2.4 Genetic Coding and Evolution by Mutation, Recombination and Selection	506
15.3 Functional Emergence	509
15.3.1 Emergence Within Networks: a Short Introduction to the Three Networks Studied at IRIDIA	512
15.3.2 Small Worlds	525
15.3.3 Emergence in Cellular Automata	529
15.3.4 Useful Emergence	534
15.4 Plasticity and Adaptability	535
15.5 Environmental Autonomy and Significant Integration	540
15.6 Conclusions	542
References	544

Appendix

1 Some Astrophysical Reminders

<i>Marc Ollivier</i>	549
1.1 A Physics and Astrophysics Overview	549
1.1.1 Star or Planet?	549

1.1.2	Gravitation and Kepler's Laws	550
1.1.3	The Solar System	550
1.1.4	Black Body Emission, Planck Law, Stefan–Boltzmann Law . .	551
1.1.5	Hertzsprung–Russel Diagram, the Spectral Classification of Stars	553
1.2	Exoplanet Detection and Characterization	555
1.2.1	Planet Detection by the Radial Velocity Method	555
1.2.2	Planet Detection by Astrometry	557
1.2.3	Planet Detection by the Transit Method	558
1.2.4	Exoplanet Direct Detection by Nulling Interferometry (Bracewell's Interferometer)	560
1.3	List of Exoplanets as Detected the 31th of January 2005 (Schneider 2004; see References in Chap. 6)	562
2	Useful Astrobiological Data	567
2.1	Physical and Chemical Data	567
2.2	Astrophysical Data	574
2.3	Geological Data	579
2.4	Biochemical Data	589
3	Glossary	595
	Authors	659
	Index	665