Contents

Foreword by Benoit Mandelbrot xvii

Preface xxv

Prologue xxix

PART I THE SCIENCE OF COSMIC ORDER 1

Chapter 1 The birth of cosmological principles **3**

1.1 The seeds were sown – the myth explains the world 3

1.2 Celestial writing on the Babylonian sky 5

1.3 The Ionian Revolution 6

1.4 Anaximander solves the paradox of unfalling Earth 7

1.5 The sky becomes a sphere 8

1.6 Atomists see a glimpse of the microcosm 9

1.7 Plato's mathematical heaven 10

1.8 Aristotle's scientific method 12

1.9 The principle of circular motion 13

1.10 But what is actually rotating? 15

1.11 Towards the principle of no center 16

1.12 The Wisdom of Antiquity was kept alive 16

1.13 The world edifice of the Middle Ages 18

Chapter 2 The gate into cosmic order **21**

2.1 Roots of De Revolutionibus 21

2.2 New understanding on matters celestial 22
2.3 The young Rheticus visits the old Copernicus 24
2.4 Bruno breaks the stellar sphere 25
2.5 ...and Galileo opens the gate 27
2.6 The blurred new view through the magnifying tube 28
2.7 Kepler's laws of cosmic order 29
2.8 Nicholas of Cusa: the center is everywhere 30
2.9 Digges, Bruno, and the Copernican Principle 31
2.10 The first steps on the cosmic distance ladder 34
2.11 Stars are remote suns 35
2.12 Understanding the new cosmic order 37
2.13 The triumph of Newton's universal gravity 39
2.14 Just add one particle more... 40

Chapter 3 The Paradoxal Universe of Sir Isaac 41
3.1 Structure of the Heavens 41
3.2 Newton's Cosmology in a Nutshell 43
3.3 Cosmological paradox 43
3.4 Why do we not feel an infinite gravity force? 44
3.5 How to tame the infinite gravity? 45
3.6 If, however, a uniform infinite cloud of stars exists, why has it not collapsed? 47
3.7 Why is the night sky so dark? 48
3.8 The riddle of the shining stars 50
3.9 What has saved us from the ultimate heat death? 51

Chapter 4 The dream of a hierarchical world: protofractals 53
4.1 Stars and nebulae 53
4.2 Emanuel Swedenborg 54
4.3 Cartesian physics 56
4.4 The Swedenborg self-similar universe 57
4.5 Towards the origin of the Solar System 59
4.6 Hierarchies of Kant and Lambert 60
4.7 Finite or infinite? 62
4.8 Emerging protofractals 63
4.9 Inwards and outwards 65

PART II COSMOLOGICAL PHYSICS FOR THE REALM OF GALAXIES 67

Chapter 5 The new world of relativity and quantum forces 69
5.1 The Principle of Relativity 69
5.2 The relativistic physics of Poincaré and Einstein 70
5.3 Velocity of light 72
5.4 From classical space and time... 73
5.5 ...to relativistic space-time 74
5.6 Time travel into the future with a one-way ticket 75
5.7 Rest mass energy: $E = mc^2$ 75
5.8 Light, electricity, and magnetism 76
5.9 Least action, symmetry, conservation laws 77
5.10 Quantum physics of the microworld 78
5.11 Heisenberg's Uncertainty Principle: nebulous particle 79
5.12 The search for genuine atoms 80
5.13 Quarks hide inside protons 83
5.14 The quantum nature of fundamental forces 84
5.15 "Fur coat" of virtual particles and the boiling vacuum 85
5.16 Spiraling down into the microcosm? 87
5.17 From terrestrial to cosmic laboratory 88

Chapter 6 Gravity – the enigmatic creator of order 89
6.1 The nature of gravity 89
6.2 Newton's law and the gravitational constant 90
6.3 The riddle of inertial and gravitating masses 91
6.4 Relativistic gravity emerges in our Solar System 92
6.5 Geometry of curved spaces 93
6.6 General relativity as geometrical gravity theory 95
6.7 What causes gravity according to general relativity? 97
6.8 Big Bang, Black Hole, Time Machine... 98
6.9 ...but riddles still exist 99
6.10 Feynman's quantum field approach to gravity 100
6.11 Relativistic effects in quantum field gravity 102
6.12 Gravity as a builder of celestial structures 103
6.13 Energy flows and order from chaos 104
6.14 A star is a self-gravitating nuclear reactor 105
6.15 Exploding stars – the end of the fight? 106

Chapter 7 The law of redshift in the kingdom of galaxies 109
7.1 The Island Universes 109
7.2 The distance to the "Little Cloud" is measured 111
7.3 Pulsating stars light up the way to Andromeda 111
7.4 The diversity of galactic geometries 112
7.5 Our home galaxy – the Milky Way 114
7.6 Spectra – fingerprints of stellar matter 115
7.7 Spectral line shift – a celestial message 116
7.8 Discovery of extragalactic redshifts 117
7.9 The search for a relation between redshift and distance 118
7.10 The law of redshifts: a new cosmic phenomenon 119
7.11 Galaxies live in swarms 121
7.12 Super energies in the galaxy universe 122
7.13 Anomalous redshifts – the exception to the rule? 125
7.14 Redshift quantization? 126

Chapter 8 The triumph of uniformity in cosmology 129
8.1 Friedmann's discovery of expanding universes 129
8.2 Cosmological redshift in expanding space 132
8.3 Uniformity gives rise to the Hubble law 133
8.4 The Hubble constant measures the age of the universe 134
8.5 The oldest stars – almost as ancient as the universe 135
8.6 The geometries of Friedmann's world models 137
8.7 The cosmic density of matter in the universe 138
8.8 George Gamow's hot beginning 139
8.9 Discovery of the cosmic thermal radiation 140
8.10 The 3 Kelvin glow – the cool relic of the hot bang 141
8.11 Cooking the light elements 142
8.12 After solving Newton's paradoxes of infinity... 143
8.13 ...new enigmas of Friedmann's uniform world appear 143
8.14 Inflation comes and resolves the paradoxes 144
8.15 The age of the inflationary universe 145
8.16 When were the galaxies and their clusters born? 146
8.17 The big bang triumph – its logic and components 147

PART III THE ELUSIVE SIMPLICITY OF UNIFORM SPACE AND MATTER 149

Chapter 9 The mysterious singularity 151
9.1 A uniform matter distribution leads to a singularity 151
9.2 What is a black hole singularity? 152
9.3 Einstein objects to the physical reality of the singularity . . . 153
9.4 Are there alternatives to singularity? 155
9.5 Gravastars, eternally collapsing objects, dark stars... 156
9.6 Relativistic astrophysics probes strong gravity 157
9.7 A binary pulsar – an ideal gravity laboratory 158
9.8 The search for gravity waves from collapsing stars 159
9.9 Two closest supernovae – signs of gravity waves? 161
9.10 X-rays betray black holes in binary stars 162
9.11 The best candidate sits at the center of the Milky Way 163
9.12 Supermassive objects in the nuclei of other galaxies 164
9.13 Approaching the horizon... 165
9.14 ...may offer unexpected surprises 166
9.15 The rapid variability of quasars as probe of gravity 167
9.16 Cosmology requires relativistic and quantum gravity 168

Chapter 10 Dark matter – the grey eminence 171
10.1 Early signs of dark matter 171
10.2 Invisible matter makes galaxies revolve rapidly 172
10.3 Gravity lenses probe the dark matter 173
10.4 MACHOs in the halo of the Milky Way 175
10.5 Do Arp's quasars reveal dark matter in galaxy haloes? 176
10.6 Much more in a cluster of galaxies than the eye sees 177
10.7 The total amount of dark matter in the universe 178
10.8 An ocean of massive neutrinos? 179
10.9 The search for dark matter goes on 181

Chapter 11 Dark energy – the new emperor 183
11.1 Revolution in cosmology – Einstein's lambda returns! 183
11.2 A short course in the physics of "nothing" 186
11.3 Dark energy, quintessence, spintessence... 187
11.4 A bit of history: redshift and de Sitter's effect 188
11.5 The age of an accelerating universe 189

11.6 The fifth element may rule in your backyard 190

Chapter 12 Expansion and curvature of space 193
12.1 The nature of redshift – Allan Sandage's 15th problem 193
12.2 Understanding the expansion of space 196
12.3 The Lemaître phenomenon versus the Doppler effect 198
12.4 What is the fate of energy in expanding space? 200
12.5 Superluminal recession of remote galaxies 202
12.6 Geometry and physics: views of Poincaré and Einstein 203
12.7 Absolutely soft and hard meter sticks 204
12.8 Geometry of space in the local galaxy universe 205
12.9 The classical cosmological tests of space geometry 206
12.10 The patchy microwave sky brings Euclid back 209
12.11 The enigmatic unity of space, matter, and energy 210

PART IV THE FRACTAL ARCHITECTURE OF THE UNIVERSE 213

Chapter 13 Cosmic hierarchies: from dream to science 215
13.1 Searching the heavens for nebulae 215
13.2 John Herschel's principle of subordinate grouping 217
13.3 Fournier d'Albe's brave new worlds 218
13.4 Gravity within Fournier's hierarchy 221
13.5 Carl Charlier wrestles with infinities 221
13.6 Charlier's criteria for infinite worlds 223
13.7 Towards hierarchic worlds without a middle point 224
13.8 Knut Lundmark's great plan 226

Chapter 14 The charm of self-similarity 229
14.1 The "fractal orbit" of Mandelbrot 229
14.2 The concept of the fractal 231
14.3 Koch's curve or snow flake 233
14.4 The simple measure of complex structures 234
14.5 The fractal dimension of Fournier-Charlier worlds 236
14.6 Creativity of fractals 237
14.7 Random fractals and Brownian motion 239
14.8 Percolation – a process leading to fractals 240

14.9 Fractal structures versus smooth distributions 240
14.10 Fractal view of Nature 242
14.11 The fractal dimension of abstract art 244

Chapter 15 Fractal and chaos: planets, stardust, dark haloes 247
15.1 Order and chaos revealed by the Solar System 247
15.2 Chaos, strange attractors, and fractals 250
15.3 How a pendulum connects chaos and fractals 252
15.4 "Protochaos" in Swedenborg's vision of evolution 254
15.5 To the microcosmos – and back to the planets again: Nottale's fractal space-time 255
15.6 Rugged planetary landscapes 258
15.7 Dense dust clouds – cocoons of stars 260
15.8 A case study of natural fractals: interstellar clouds 262
15.9 Dark clouds, molecular complexes, cirrus filaments... 264
15.10 Galaxy haloes – dark mass hiding in fractals? 266
15.11 Fractal gas clouds between galaxies 268

Chapter 16 Redshift – the quiet cosmographer 269
16.1 Hubble's law of redshifts is a distance indicator 269
16.2 The Hubble constant measured before Hubble... 271
16.3 The Hubble constant: 100 or 72 or 50? 272
16.4 Distances to galaxies – a mission impossible? 272
16.5 The notorious Malmquist bias 276
16.6 What, after all, is the value of the Hubble constant? 277
16.7 Galaxy clusters painted on the celestial sphere 278
16.8 The origin of the debate on superclusters 279
16.9 Abell's rich clusters of galaxies 281
16.10 Looking through the dusty window 282
16.11 3-D astronomy from the vertex of a space cone 284
16.12 Excursions into the local galaxy universe and beyond 287
16.13 The mysterious quietness of the Hubble flow 289
16.14 The redshift of quasars as a distance indicator 292

Chapter 17 Fractal structure of the galaxy universe 295
17.1 Einstein's Cosmological Principle 295
17.2 Many faces of the Cosmological Principle 297
17.3 The derivation of uniformity from local isotropy 298

17.4 The galaxy universe may seem rather smooth... 300
17.5 ...but the uniformity is elusive 301
17.6 Carpenter – de Vaucouleurs's law of galaxy clustering 302
17.7 Mandelbrot's fractal view of galaxy clustering 305
17.8 Does isotropy always imply uniformity? 306
17.9 Do we live on the peak of a mountain? 308
17.10 Modern redshift surveys of galaxies 311
17.11 Pietronero and the five megaparsec mystery 312
17.12 The Great Fractal Debate 314
17.13 The correlation function points at 5 Mpc 317
17.14 The conditional density comes and finds fractality 318
17.15 To search for or to count on uniformity? 321
17.16 Towards Einstein–Mandelbrot concordance 322
17.17 Everything we know about the cosmos? 324
17.18 Opening the millenium: the race to a fair sample 325

Chapter 18 The Origins of Megafractals 329
18.1 The ladder of key discoveries 329
18.2 The three whales of cosmology 331
18.3 The art of making universes 332
18.4 Art is long, life is short 334
18.5 Growth of large scale structures in big bang cosmology 336
18.6 The smooth Hubble law ignores local roughness 339
18.7 Gravitational redshift inside a fractal structure 342
18.8 A Friedmann universe with fractal galaxy distribution 343
18.9 Dark energy drives the remote and the local universe 343
18.10 Early work around fractal dimension one... 345
18.11 ...and intriguing aspects of fractal dimension two 345
18.12 The fractal state of many gravitating particles 347
18.13 Cosmological questions within quantum field gravity 350
18.14 The cosmic architecture of complexity 351
18.15 What is the message of the megafractals? 353
18.16 Through deeper observations to novel perspectives 355

Appendix A 359
A.1 Definition of the astronomical magnitude 359
A.2 The mass of the Milky Way 359
A.3 A standard candle in the Hubble diagram 360

A.4 The classical electron and gravitational radiuses 360
A.5 The cosmological gravitational redshift 360

Suggestions for Reading 361

Index 363