

# Cosmology for the Curious

Delia Perlov · Alex Vilenkin

# Cosmology for the Curious

 Springer

Delia Perlov  
Tufts University  
Medford, MA, USA

Alex Vilenkin  
Tufts University  
Medford, MA, USA

ISBN 978-3-319-57038-9      ISBN 978-3-319-57040-2 (eBook)  
DOI 10.1007/978-3-319-57040-2

Library of Congress Control Number: 2017938144

© Springer International Publishing AG 2017

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by Springer Nature  
The registered company is Springer International Publishing AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*To the memory of Allen Everett and Leonard Schwartz*

# Acknowledgements

We would like to express our sincere thanks to the Springer publishing team, and especially to Angela Lahee. Angela has been extremely helpful, accommodating and patient at each step of the way. We would like to thank the following people for reading some or all of the manuscript and offering useful feedback: Jose Blanco-Pillado, Peter Jackson, Jim Kernohan, Levon Pogosian, Michael Schneider and Brian Sinskie. A special thank you to Ken Olum for his extensive comments. Thanks also to Natalie Perlov for drawing several figures in the book, and to Gayle Grant and Caroline Merighi at Tufts University for their administrative help. DP: I wish to thank my husband Larry, my children Natalie, Alexa and Chloe, my mother Glenda, sister Heidi, and my late father Leonard for continued support and interest in this project. AV: It would have been hard to get to the end of this project without the support I had from my wife Inna. I thank her for her patience, advice, and for the wonderful cuisine that kept up my spirits.

# Contents

## Part I The Big Bang and the Observable Universe

<b>1</b>	<b>A Historical Overview</b>	3
1.1	The Big Cosmic Questions	3
1.2	Origins of Scientific Cosmology	4
1.3	Cosmology Today	7
<b>2</b>	<b>Newton's Universe</b>	13
2.1	Newton's Laws of Motion	13
2.2	Newtonian Gravity	16
2.3	Acceleration of Free Fall	19
2.4	Circular Motion and Planetary Orbits	20
2.5	Energy Conservation and Escape Velocity	22
2.6	Newtonian Cosmology	26
2.7	Olbers' Paradox	27
<b>3</b>	<b>Special Relativity</b>	31
3.1	The Principle of Relativity	31
3.2	The Speed of Light and Electromagnetism	35
3.3	Einstein's Postulates	39
3.4	Simultaneity	41
3.5	Time Dilation	42
3.6	Length Contraction	44
3.6.1	Speeding Muons	45
3.7	$E = mc^2$	46
3.8	From Space and Time to Spacetime	47
3.9	Causality in Spacetime	51

<b>4</b>	<b>The Fabric of Space and Time</b>	59
4.1	The Astonishing Hypothesis	60
4.2	The Geometry of Space	63
4.2.1	Euclidean Geometry	63
4.2.2	Non-Euclidean Geometry	66
4.3	Curved Space	67
4.3.1	The Curvature of Surfaces	67
4.3.2	The Curvature of Three-Dimensional Space	70
4.4	The General Theory of Relativity	72
4.5	Predictions and Tests of General Relativity	75
4.5.1	Light Deflection and Gravitational Lensing	75
4.5.2	Gravitational Time Dilation	77
4.5.3	Black Holes	77
4.5.4	Gravitational Waves	78
<b>5</b>	<b>An Expanding Universe</b>	83
5.1	Einstein's Static Universe	83
5.2	Problems with a Static Universe	86
5.3	Friedmann's Expanding Universe	89
<b>6</b>	<b>Observational Cosmology</b>	97
6.1	Fingerprints of the Elements	98
6.2	Measuring Velocities	99
6.3	Measuring Distances	101
6.4	The Birth of Extragalactic Astronomy	105
<b>7</b>	<b>Hubble's Law and the Expanding Universe</b>	109
7.1	An Expanding Universe	110
7.2	A Beginning of the Universe?	113
7.3	The Steady State Theory	114
7.4	The Scale Factor	115
7.5	Cosmological Redshift	116
7.6	The Age of the Universe	117
7.7	The Hubble Distance and the Cosmic Horizon	118
7.8	Not Everything is Expanding	120
<b>8</b>	<b>The Fate of the Universe</b>	125
8.1	The Critical Density	125
8.2	The Density Parameter	128

<b>9</b>	<b>Dark Matter and Dark Energy</b>	131
9.1	The Average Mass Density of the Universe and Dark Matter	131
9.2	Dark Energy	136
9.3	The Fate of the Universe—Again	140
<b>10</b>	<b>The Quantum World</b>	143
10.1	Quantum Discreteness	143
10.2	Quantum Indeterminism	145
10.3	The Wave Function	148
10.4	Many Worlds Interpretation	151
<b>11</b>	<b>The Hot Big Bang</b>	155
11.1	Following the Expansion Backwards in Time	155
11.2	Thermal Radiation	158
11.3	The Hot Big Bang Model	161
11.4	Discovering the Primeval Fireball	162
11.5	Images of the Baby Universe	165
11.6	CMB Today and at Earlier Epochs	168
11.7	The Three Cosmic Eras	170
<b>12</b>	<b>Structure Formation</b>	175
12.1	Cosmic Structure	175
12.2	Assembling Structure	179
12.3	Watching Cosmic Structures Evolve	180
12.4	Primordial Density Fluctuations	182
12.5	Supermassive Black Holes and Active Galaxies	183
<b>13</b>	<b>Element Abundances</b>	187
13.1	Why Alchemists Did Not Succeed	187
13.2	Big Bang Nucleosynthesis	189
13.3	Stellar Nucleosynthesis	193
13.4	Planetary System Formation	194
13.5	Life in the Universe	196
<b>14</b>	<b>The Very Early Universe</b>	201
14.1	Particle Physics and the Big Bang	201
14.2	The Standard Model of Particle Physics	205
	14.2.1 The Particles	206
	14.2.2 The Forces	206
14.3	Symmetry Breaking	208
14.4	The Early Universe Timeline	211

14.5	Physics Beyond the Standard Model	213
14.5.1	Unifying the Fundamental Forces	213
14.6	Vacuum Defects	215
14.6.1	Domain Walls	216
14.6.2	Cosmic Strings	217
14.6.3	Magnetic Monopoles	220
14.7	Baryogenesis	220

## **Part II Beyond the Big Bang**

<b>15</b>	<b>Problems with the Big Bang</b>	<b>227</b>
15.1	The Flatness Problem: Why is the Geometry of the Universe Flat?	227
15.2	The Horizon Problem: Why is the Universe so Homogeneous?	229
15.3	The Structure Problem: What is the Origin of Small Density Fluctuations?	232
15.4	The Monopole Problem: Where Are They?	232
<b>16</b>	<b>The Theory of Cosmic Inflation</b>	<b>235</b>
16.1	Solving the Flatness and Horizon Problems	235
16.2	Cosmic Inflation	236
16.2.1	The False Vacuum	236
16.2.2	Exponential Expansion	238
16.3	Solving the Problems of the Big Bang	240
16.3.1	The Flatness Problem	240
16.3.2	The Horizon Problem	241
16.3.3	The Structure Formation Problem	242
16.3.4	The Monopole Problem	242
16.3.5	The Expansion and High Temperature of the Universe	242
16.4	Vacuum Decay	243
16.4.1	Boiling of the Vacuum	243
16.4.2	Graceful Exit Problem	244
16.4.3	Slow Roll Inflation	245
16.5	Origin of Small Density Fluctuations	247
16.6	More About Inflation	249
16.6.1	Communication in the Inflating Universe	249
16.6.2	Energy Conservation	250

<b>17</b>	<b>Testing Inflation: Predictions and Observations</b>	255
17.1	Flatness	255
17.2	Density Fluctuations	256
17.3	Gravitational Waves	260
17.4	Open Questions	264
<b>18</b>	<b>Eternal Inflation</b>	269
18.1	Volume Growth and Decay	269
18.2	Random Walk of the Inflaton Field	271
18.3	Eternal Inflation via Bubble Nucleation	274
18.4	Bubble Spacetimes	275
18.5	Cosmic Clones	279
18.6	The Multiverse	281
18.7	Testing the Multiverse	284
18.7.1	Bubble Collisions	284
18.7.2	Black Holes from the Multiverse	285
<b>19</b>	<b>String Theory and the Multiverse</b>	291
19.1	What Is String Theory?	292
19.2	Extra Dimensions	294
19.3	The Energy Landscape	295
19.4	String Theory Multiverse	296
19.5	The Fate of Our Universe Revisited	297
<b>20</b>	<b>Anthropic Selection</b>	301
20.1	The Fine Tuning of the Constants of Nature	302
20.1.1	Neutron Mass	302
20.1.2	Strength of the Weak Interaction	303
20.1.3	Strength of Gravity	303
20.1.4	The Magnitude of Density Perturbations	303
20.2	The Cosmological Constant Problem	304
20.2.1	The Dynamic Quantum Vacuum	304
20.2.2	Fine-Tuned for Life?	305
20.3	The Anthropic Principle	307
20.4	Pros and Cons of Anthropic Explanations	309
<b>21</b>	<b>The Principle of Mediocrity</b>	313
21.1	The Bell Curve	313
21.2	The Principle of Mediocrity	314
21.3	Obtaining the Distribution by Counting Observers	315

21.4	Predicting the Cosmological Constant	316
21.4.1	Rough Estimate	317
21.4.2	The Distribution	317
21.5	The Measure Problem	319
21.6	The Doomsday Argument and the Future of Our Civilization	321
21.6.1	Large and Small Civilizations	322
21.6.2	Beating the Odds	323
<b>22</b>	<b>Did the Universe Have a Beginning?</b>	<b>327</b>
22.1	A Universe that Always Existed?	327
22.2	The BGV Theorem	329
22.2.1	Where Does This Leave Us?	330
22.2.2	A Proof of God?	331
<b>23</b>	<b>Creation of Universes from Nothing</b>	<b>333</b>
23.1	The Universe as a Quantum Fluctuation	333
23.2	Quantum Tunneling from “Nothing”	336
23.2.1	Euclidean Time	337
23.3	The Multiverse of Quantum Cosmology	338
23.4	The Meaning of “Nothing”	339
<b>24</b>	<b>The Big Picture</b>	<b>343</b>
24.1	The Observable Universe	343
24.1.1	What Do We Know?	343
24.1.2	Cosmic Inflation	344
24.2	The Multiverse	345
24.2.1	Bubble Universes	345
24.2.2	Other Disconnected Spacetimes	346
24.2.3	Levels of the Multiverse	346
24.2.4	The Mathematical Multiverse and Ockham’s Razor	347
24.3	Answers to the “Big Questions”	350
24.4	Our Place in the Universe	351
	<b>Appendix A</b>	<b>353</b>
	<b>Further Reading</b>	<b>361</b>
	<b>Index</b>	<b>365</b>