

## Cosmology

Advances in science have greatly changed our ideas on the nature of the universe. *Cosmology: The Science of the Universe* is a broad and elementary introduction to cosmology that includes aspects of its history, theology, and philosophy. The book explores the realm of receding galaxies, the fascinating properties of space and time, the bizarre world of black holes, the astonishing expansion of the universe, the elegant simplicity of cosmic redshifts, and the momentous issues of inflation. Its subjects cover modern views on the origin of atoms, galaxies, life, and the universe itself; they range from the subatomic to the extragalactic, from the beginning to the end of time, and from terrestrial to extraterrestrial life. Old problems (e.g., the cosmic-edge) are revived and new perplexities (e.g., the containment riddle) are reviewed. In this unique book, Professor Harrison shows how in every age societies devise universes that make sense of the human experience. He explores the cosmic scenery of the Babylonian, Pythagorean, Aristotelian, Stoic, Epicurean, Medieval, Cartesian, and Newtonian world systems and shows how these and other systems laid the foundations of the modern physical universe.

The first edition of this best-selling book received world-wide acclaim for its far ranging treatment and clarity of explanation. This eagerly awaited second edition updates and extends the first edition. The additional chapters discuss *Early Scientific Cosmology*, *Cartesian and Newtonian World Systems*, *Cosmology After Newton and Before Einstein*, *Observational Cosmology*, *Inflation*, and *Creation of the Universe*.

EDWARD HARRISON, distinguished university professor emeritus of physics and astronomy at the University of Massachusetts, was born in London at the end of World War I. He studied at London University and served for several years in action with the British Army in World War II. He was a scientist at the Atomic Energy Research Establishment and the Rutherford High Energy Laboratory in England until 1966 when he became a Five College professor at the University of Massachusetts and taught at Amherst, Hampshire, Mount Holyoke, and Smith Colleges. Professor Harrison is author of *The Masks of the Universe* (which gained the Melcher Award), *Darkness at Night: A Riddle of the Universe*, and numerous scientific articles that have contributed to the advance of modern cosmology. He has also written many articles on the history and philosophy of early cosmology. He is married to Photeni, has two children, John-Peter and June Zöe, and is now adjunct professor at the Steward Observatory, University of Arizona.

CAMBRIDGE

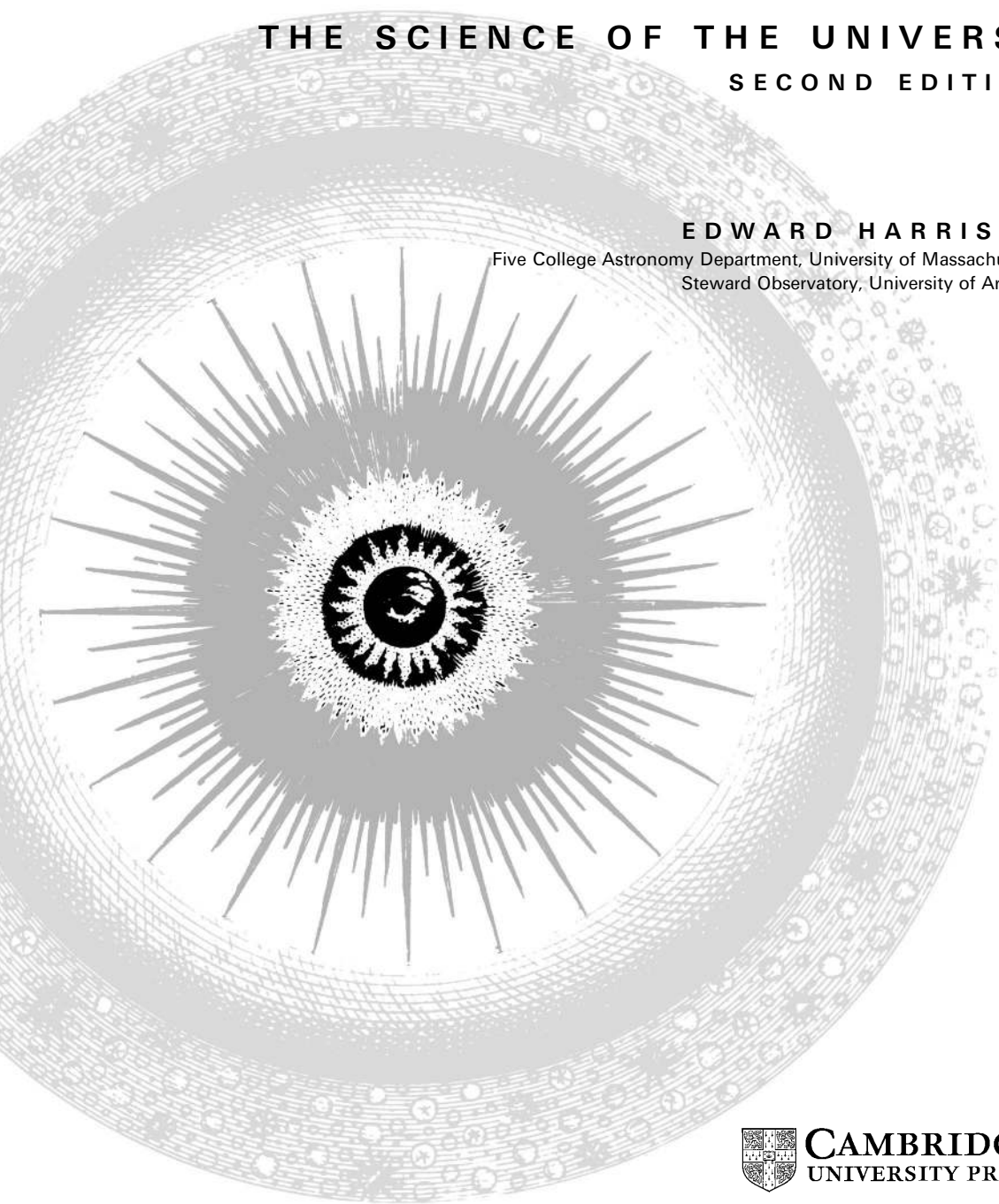
Cambridge University Press  
978-1-009-21570-1 — Cosmology: The Science of the Universe  
Edward Harrison  
Frontmatter  
[More Information](#)

# *Cosmology*

THE SCIENCE OF THE UNIVERSE  
SECOND EDITION

EDWARD HARRISON

Five College Astronomy Department, University of Massachusetts  
Steward Observatory, University of Arizona



 **CAMBRIDGE**  
UNIVERSITY PRESS

Cambridge University Press  
978-1-009-21570-1 — Cosmology: The Science of the Universe  
Edward Harrison  
Frontmatter  
[More Information](#)

## CAMBRIDGE UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom  
One Liberty Plaza, 20th Floor, New York, NY 10006, USA  
477 Williamstown Road, Port Melbourne, VIC 3207, Australia  
314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India  
103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9781009215701](http://www.cambridge.org/9781009215701)

© Cambridge University Press 1981, 2000

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 1981  
Reprinted 1985, 1986, 1988, 1989, 1991  
Second edition 2000  
8th printing 2013  
First paperback edition 2022

*A catalogue record for this publication is available from the British Library*

*Library of Congress Cataloging in Publication data*

Harrison, Edward Robert.

Cosmology: the science of the universe / Edward R. Harrison. —  
2nd ed.

p. cm.

Includes bibliographical references and index.

ISBN 0 521 66148 X

1. Cosmology. I. Title. II. Title: Cosmology, the science of the universe.

QB981.H276 1999

523.1—dc21 99-10172 CIP

ISBN 978-0-521-66148-5 Hardback

ISBN 978-1-009-21570-1 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

<i>Preface</i>	ix	<b>3 Cartesian and Newtonian world systems</b>	<b>49</b>
<i>Introduction</i>	1	The decline of Aristotelian science	49
		The Cartesian world system	51
		The Newtonian world system	54
		Newton and the infinite universe	60
		The atomic theory	61
		Reflections	61
		Projects	63
		Further reading	64
		Sources	64
<b>PART I</b>		<b>4 Cosmology after Newton and before Einstein</b>	<b>66</b>
<b>1 What is cosmology?</b>	<b>13</b>	Hierarchical universes	66
The Universe	13	The nebula hypothesis	70
Cosmology	15	Cosmical islands	70
The magic universe	17	The new astronomy	73
The mythic universe	17	The Victorian universe	77
The anthropometric universe	19	The age problem	78
Cosmology and society	20	Fall of the Victorian universe	80
Reflections	21	Reflections	81
Projects	25	Projects	83
Further reading	26	Further reading	83
Sources	26	Sources	84
<b>2 Early scientific cosmology</b>	<b>28</b>	<b>5 Stars</b>	<b>87</b>
The beginning of western science	28	The distant stars	87
Plato's universe	29	A forest of stars	89
Three cosmic systems of the ancient world	29	Inside the stars	93
The Aristotelian universe	30	Nuclear energy	95
The Epicurean universe	33	Birth of stars	100
The Stoic universe	34	The star is dead! Long live the star!	103
The mystery religions	34	Reflections	105
The medieval universe	35	Projects	110
The heliocentric universe	37		
The infinite universe	38		
Reflections	42		
Projects	45		
Further reading	46		
Sources	46		

vi	CONTENTS	
Further reading	111	
Sources	112	
<b>6 Galaxies</b>	<b>113</b>	
Our Galaxy	113	
The distant galaxies	119	
Birth of galaxies	123	
Radio galaxies and quasars	126	
Reflections	129	
Projects	131	
Further reading	132	
Sources	132	
<b>7 Location and the cosmic center</b>	<b>134</b>	
The location principle	134	
The isotropic universe	137	
The cosmological principle	138	
Perfect cosmological principle	140	
Reflections	141	
Projects	145	
Further reading	145	
Sources	145	
<b>8 Containment and the cosmic edge</b>	<b>147</b>	
The containment principle	147	
The cosmic edge	149	
Containment of space and time	153	
Design argument	155	
Many physical universes	156	
Theistic and anthropic principles	157	
Whither the laws of nature?	159	
Containment riddle	161	
Reflections	162	
Projects	166	
Further reading	167	
Sources	167	
<b>9 Space and time</b>	<b>169</b>	
Space	169	
Space and time	171	
Time	172	
The “now”	176	
Time travel	178	
Atomic time	179	
Reflections	180	
Projects	184	
Further reading	185	
Sources	185	
		<b>PART II</b>
		<b>10 Curved space</b>
		<b>189</b>
		Euclidean geometry
		189
		Non-Euclidean geometry
		190
		Measuring the curvature of space
		194
		The “outstanding theorem”
		196
		Riemannian spaces
		198
		Reflections
		199
		Projects
		203
		Further reading
		204
		Sources
		204
		<b>11 Special relativity</b>
		<b>206</b>
		New ideas for old
		206
		The strangeness of spacetime
		207
		Travels in space and time
		210
		Reflections
		214
		Projects
		218
		Further reading
		218
		Sources
		219
		<b>12 General relativity</b>
		<b>220</b>
		Principle of equivalence
		220
		A closer look
		222
		Geometry and gravity
		224
		Tidal forces
		225
		Theory of general relativity
		228
		Tests of general relativity
		233
		Mach’s principle
		236
		Reflections
		239
		Projects
		243
		Further reading
		244
		Sources
		245
		<b>13 Black holes</b>
		<b>246</b>
		Gravitational collapse
		246
		Curved spacetime of black holes
		248
		Rotating black holes
		253
		Superholes
		257
		Miniholes
		258
		Black-hole magic
		259
		Hawking radiation
		260
		Black holes are heat engines
		263
		Reflections
		264
		Projects
		267
		Further reading
		268
		Sources
		268
		<b>14 Expansion of the universe</b>
		<b>270</b>
		The great discovery
		270

## CONTENTS

vii

The expanding space paradigm	275	Universes in compression	368
The expanding rubber sheet universe	275	Universes in tension	369
Measuring the expansion of the universe	285	Worlds in convulsion	371
The velocity–distance law	287	Kinematic relativity	373
Accelerating and decelerating universes	289	Continuous creation	374
Classifying universes	290	Scalar–tensor theory	376
Reflections	292	Reflections	379
Projects	299	Projects	383
Further reading	300	Further reading	384
Sources	300	Sources	384
<b>15 Redshifts</b>	<b>302</b>	<b>19 Observational cosmology</b>	<b>387</b>
Cosmic redshifts	302	Introduction	387
The three redshifts	306	Cosmography	387
Two basic laws	307	Local observations	388
Distances and recession velocities	309	Intermediate-distance observations	397
Cosmological pitfalls	309	Large-distance observations	400
Redshift curiosities	311	Is the universe open or closed?	403
Reflections	314	Reflections	404
Projects	320	Projects	407
Sources	321	Further reading	408
<b>16 Newtonian cosmology</b>	<b>323</b>	Sources	408
Static Newtonian universe	323		
Expanding cosmic sphere	326	<b>PART III</b>	
Cosmological constant	331	<b>20 The early universe</b>	<b>413</b>
Why does Newtonian cosmology give the same answer?	332	The primeval atom	413
Reflections	333	The last fifteen billion years	415
Projects	336	The first million years	416
Further reading	337	The first second	419
Sources	337	The first hundred microseconds	422
<b>17 The cosmic box</b>	<b>339</b>	Grand unified era	427
The universe in a nutshell	339	Reflections	428
Particles and waves	341	Projects	435
Thermodynamics and cosmology	344	Further reading	436
Where has all the energy gone?	348	Sources	436
Reflections	350	<b>21 Horizons in the universe</b>	<b>438</b>
Projects	353	What are cosmological horizons?	438
Sources	353	Horizons in static universes	439
<b>18 The many universes</b>	<b>355</b>	The horizon riddle	441
Static universes	355	The horizon problem	442
De Sitter universe	358	Hubble spheres	443
Friedmann universes	359	Reception and emission distances	444
Oscillating universes	362	The photon horizon in cosmology	446
Friedmann–Lemaître universes	363	The particle horizon	447
Classification of universes	365	Conformal diagrams	449
		Event horizons	451
		Reflections	454

vii

Projects	457	Reflections	506
Sources	457	Projects	513
		Further reading	513
<b>22 Inflation</b>	<b>458</b>	<b>25 Creation of the universe</b>	<b>515</b>
Perfect symmetry	458	Cosmogenesis I	515
The monopole problem	458	Creation myths	515
Discovery of inflation	459	Genesis	518
Cosmic tension	459	Cosmogenesis II	519
Inflation	460	Cosmogenesis III	520
Inflation solves the monopole problem	463	Fitness of the universe	522
Inflation solves the flatness problem	463	Fitness and creation	523
Inflation solves the horizon problem	465	Theistic theories	523
Nonluminous matter	467	Anthropic theories	524
The origin of galaxies	468	Spontaneous creation theories	524
Reflections	470	Natural selection theories	525
Projects	472	Eschatology	526
Further reading	472	Reflections	528
Sources	473	Projects	532
		Further reading	532
<b>23 The cosmic numbers</b>	<b>474</b>	Sources	533
Constants of nature	474	<b>26 Life in the universe</b>	<b>535</b>
The cosmic connection	479	Origin of life on Earth	535
Magic numbers	480	The exuberant Earth	537
Solving the cosmic connection	483	The evolution of life	538
Reflections	486	Natural selection	540
Projects	490	Intelligent life	542
Further reading	490	What is life?	542
Sources	490	Life beyond the Earth	543
<b>24 Darkness at night</b>	<b>491</b>	Epilogue	547
The great riddle	491	Reflections	547
Two interpretations	493	Projects	551
Halley's shells	494	Further reading	552
Bright-sky universes	497	Sources	553
The paradox resolved	499	<i>Appendix – Fundamental quantities</i>	555
“The golden walls of the universe”	502	<i>Index</i>	557
The celebrated hypothesis	503		
Expansion and darkness	503		

## P R E F A C E

This second edition of *Cosmology: The Science of the Universe* revises and extends the first edition published in 1981. Much has happened since the first edition; many developments have occurred, and cosmology has become a wider field of research.

As before, the treatment is elementary yet broad in scope, and the aim is to present an outline that appeals to the thoughtful person at a level not requiring an advanced knowledge in the natural sciences. Cosmology has many faces, scientific and nonscientific; in this work the primary emphasis is on cosmology as a science, but the important historical, philosophical, and theological aspects are not ignored. Mathematics is avoided except in a few places, mostly at the end of chapters, and the treatment is varied enough to meet the needs of both those who enjoy and do not enjoy mathematics.

At the end of each chapter are two sections entitled *Reflections* and *Projects*. The Reflections section presents topics for reflection and discussion. The Projects section raises questions and issues that a challenged reader might care to tackle. Cosmology impels us to ask deep questions, read widely, and think deeply. It is not the sort of subject that lends itself readily to simple yes and no answers. On most issues there are conflicting arguments to be investigated, weighed, rejected, accepted, or modified according to one's personal tastes and beliefs. Cosmology challenges the

mind, shapes our way of thinking about the world in which we live, and leaves impressions and ideas that last a lifetime.

Many texts on cosmology and general relativity tend to be too technical for college students and nonspecialists. Numerous less-technical treatments now exist that are often too brief and of insufficient scope and depth for a course of study. At the end of each chapter are suggestions for further reading to help the reader explore alternative treatments (sometimes in greater depth and detail) of the subjects discussed in the chapter. Also provided is a list of sources containing references that are usually readable and not too technical; the few that are more technical are included for their historical interest.

The first edition of this book evolved from class notes used for teaching elementary cosmology in the Five College Astronomy Department of Amherst College, Hampshire College, Mount Holyoke College, Smith College, and the University of Massachusetts. At that time the method of grading consisted of brief weekly papers, mostly on topics (germane to the lectures) of each student's choice. It was evident that a text of broad scope was needed that might hold the attention of students of different backgrounds and interests, and provide the information needed for discussions and the preparation of papers. After the publication of the first edition, the method of grading changed and consisted of four equally spaced take-home examinations



followed by an end-of-semester examination. Many questions included in the examinations did not require mathematical skills. Both methods of grading have their advantages and disadvantages. There must be a better way!

I am indebted to many persons for their comments and helpful suggestions, particularly Thomas Arny (University of Massachusetts, Amherst), Gregory Benford (University of California, Irvine), Robert Brandenberger (Brown University), Mario Bunge (McGill University), Thomas Dennis (Mount Holyoke College), James Ellern (University of Southern California, Los Angeles), George Ellis (University of Capetown), Stephen Gottesman (University of Florida, Gainesville), George Greenstein (Amherst College), Gary Hinshaw (NASA/Goddard Space Flight Center), Paul Hodge (University of Washington), Duane Howells (Hughes Research Laboratories), John Huchra (Harvard–Smithsonian Center for Astrophysics), John

Lathrop, Charles Leffert, William McCrea (University of Sussex), A. J. Meadows (Loughborough University of Technology), Heinz Pagels (University of California, Santa Cruz), Joel Primack (University of California, Santa Cruz), Martin Rees (Cambridge University), Joe Rosen (University of Central Arkansas), Rick Shafer (NASA/Goddard Space Flight Center), Stephen Schneider (University of Massachusetts, Amherst), Joseph Snider (Oberlin College), Joseph Tenn (Sonoma State University), Virginia Trimble (University of California, Irvine), David Van Blerkom (University of Massachusetts, Amherst), Gerard de Vaucouleurs (University of Texas, Austin), and Robert Wilson (Smithsonian Astrophysical Observatory).

I am particularly grateful to Fred Stevenson (University of Leeds) for his helpful comments and corrections.

EDWARD HARRISON

*Mesilla, New Mexico, May 1998*