THE LITTLE BOOK OF COSMOLOGY

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the

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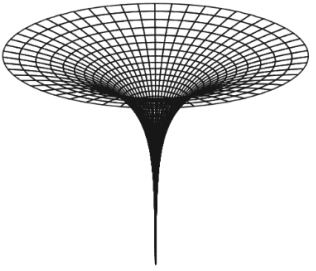
of

COSMOLOGY



LYMAN PAGE

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CONTENTS

	Preface	*ix*
	Acknowledgments	*xv*
CHAPTER ONE	The Basics	1
CHAPTER TWO	The Composition and Evolution of the Cosmos	28
CHAPTER THREE	Mapping the Cosmic Microwave Background	58
CHAPTER FOUR	The Standard Model of Cosmology	81
CHAPTER FIVE	Frontiers of Cosmology	98
	Appendixes	*111*
	Index	*119*

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PREFACE

THESE PAGES PROVIDE A BRIEF INTRODUCTION TO MODERN cosmology, the study of the universe at the most extreme scales of space, energy, and time. My hope is that they convey some essential aspects of what we know about the universe—including its composition, its geometry, its evolution, and the laws of physics that describe it—and how we know it. The subject of the universe is ripe for wild theories and speculation, but these hide perhaps its most amazing aspect: we can understand the universe at its grandest scales to percent-level accuracy through measurement.

As we shall see, the universe at the largest scales and earliest times is remarkably simple and can be characterized with just a few parameters. It is much easier to understand than, say, the fascinatingly complex Earth, with its atmosphere, oceans, moving continents, and magnetic field, to name just a few attributes. In this book, I will try to explain not only current observations and measurements, but also how they can be woven together via physical explanations into a unified picture of the cosmos. The picture I'll describe is not the only possible one, but it explains the data with a minimal set of assumptions. Continuing observations will reveal whether it is correct.

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Our knowledge of the universe is encapsulated in what we call the Standard Model of Cosmology, and it agrees remarkably well with observations. It is predictive, testable, and could easily be falsified or augmented if that were called for. Among other things, the model says that the universe is comprised of about 5% atomic material, the stuff of which we are made; about 25% "dark matter"; and 70% "dark energy." Based on Einstein's theory of gravity, the Standard Model specifies how the various components of the universe evolve from the very earliest times to the present. Put another way, we take from general relativity a way of thinking about space and use it as a foundation for describing how the cosmic components—the radiation, atoms, dark matter, and dark energy—fit together to make the universe we observe. All this said, although we have an excellent model of the universe, we do not yet have a fundamental understanding of its dominant constituents. There are exciting open questions in cosmology that continue to be investigated by scientists throughout the world, and we will cover some of them at the end of this book.

Following my own path to learning about cosmology, the focus of the book will be on understanding the universe through measurements of the Cosmic Microwave Background (CMB)—the faint thermal afterglow of the birth of our universe. The evidence in support of this interpretation is overwhelming. Though the CMB resembles radiant heat from the Sun or from an electric stove burner, it has a much, much colder temperature. Hinting at its ancient origin, it is a mere 2.725°C above absolute zero, or 2.725 K.[1] But, there is

1 The CMB is often called the "3K background" because 2.725 K is almost 3 K. The number of °C above absolute zero corresponds to the kelvin temperature scale. That is, 1°C above absolute zero is 1 K; there is no "°" sign for kelvin. A change of, say, 0.01°C is the same as a change of 0.01 K. In this system, which we will use

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much more to the CMB than just its temperature. Indeed, most of what we learn from it comes from tiny variations in its temperature from position to position across the sky. For example, the CMB is ever so slightly different in temperature in (to pick two arbitrary directions) the north and south celestial poles. Because the CMB can be measured in such exquisite detail, our understanding of it is the foundation for our cosmological model. However, before we delve into the various characteristics of the CMB and what they tell us, we will first need to develop some basic ideas of how to think about the universe as a whole.

In chapter 1, we will lay our foundations and cover some basics about the cosmos, guided by two observations: that the speed of light is finite and that the universe is expanding. The meshing of these two facts creates a framework that we will use in subsequent chapters. In chapter 2 we will review the composition of the universe, not in minute detail but rather, focusing on the components that dominate in different epochs of our cosmic history. It is the composition of the universe that tells it how to evolve. We will also discuss how the components of the universe work together to form stars, galaxies, and clusters of galaxies. In cosmology these are simply called "structure." The whole process of structure formation is rooted in the Big Bang and ultimately gave rise to Earth and, eventually, to us. In chapter 3 we will explain the tiny temperature variations in the CMB that are shown in plate 1. Through understanding this image we can understand a tremendous amount about the universe. Then

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from here on, absolute zero is −273.14°C, water freezes at 0°C or 273.14 K, and boils at 100°C or 373.14 K. The Sun is about 5500°C or 5773 K, which we will approximate as 6000 K from here on.

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in chapter 4, we will bring the pieces together and present the Standard Model of Cosmology. Though the standard model is wonderfully predictive, much remains unknown. Finally, in chapter 5, I'll describe some of the frontiers of theoretical and experimental research in cosmology.

Cosmology is a vibrant and exciting field. The search for ever deeper knowledge on both theoretical and experimental fronts is ongoing. For observers of the cosmos, such as myself, the CMB continues to offer insights—and continued measurements may yet lead us to look at elements of the standard model in a new light, and may also guide us to new discoveries.

Before we begin, let me add a brief note about the level of this book. One of the challenges in presenting recent developments in science is to pitch ideas at the right level for the reader. While I define various terms and concepts with scientific specificity, throughout the book I do make some assumptions about the reader's background knowledge and inherent level of interest. This said, I have added a few appendixes to provide a little more detail on certain topics, if needed. For example, I assume that readers will know that light is a wave of a certain wavelength that carries energy; however, appendix A.1, entitled, "The Electromagnetic Spectrum," provides a short guide to various sources of radiation[2] and their wavelengths, in case the reader wants further information on the subject. Also, I expect that most readers will know that the speed of light is finite and a fundamental constant of Nature. However, what is less widely appreciated is that, no matter where you are in the universe or how fast you are moving, you will measure that the speed of light in a vacuum is

2 I'll use the terms "light" and "radiation" synonymously.

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186,000 miles per second. This is one of the foundations of Einstein's special theory of relativity. To keep this book concise, I will not delve too deeply into relativity (there are many books that do this well already) or other such topics; but, as we go along, I will explain physical concepts related to our understanding of the cosmos in a little more detail than you may have encountered in the past. By necessity, I will be somewhat quantitative, but rest assured that the math needed will be at the level of *distance* = *speed* × *time*; and most of the time, we will use approximate numbers as they are easier to grasp.

A tricky element in cosmology is that the distances and timescales are so large they can be difficult to imagine. To make them easier to comprehend, we will count things in "billions." To put this number in some context, there are somewhat more than seven billion people on Earth; the tip of your little finger contains about one billion cells; and one billion M&Ms would slightly overfill a cubic box about six meters on a side. Since this is a popular-level book (and hoping my colleagues forgive me), there are no scientific references, and the attribution of specific ideas and findings is minimal.

There is a lot to cover in this short book—a whole universe—so let's get going!

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ACKNOWLEDGMENTS

I HAVE HAD THE GOOD FORTUNE TO LEARN COSMOLOGY from many of the leaders in theory. David Spergel has been a close collaborator for over two decades. Jim Peebles and Paul Steinhardt have answered many questions; both made critical suggestions for this book. Dick Bond has tutored me since I was a postdoc. Slava Mukhanov taught me about the early universe.

Of course, all the errors are mine: one can always be a better student. Both Steve Boughn and Shyam Khanna read earlier versions in detail and made multiple suggestions that I have included. Jeff Aumuller advised on how to make it understandable as have Kevin Crowley, Oriel Farajun, Bryant Hall, Neha Anil Kumar, Loki Lin, Christian Robles, Allan Shen, Mona Ye, and Kasey Wagoner. Ingrid Gnerlich, my editor, gave the book its current form, made suggestions too numerous to mention, and was a delight to work with.

A special acknowledgement is due to my colleague, Steve Gubser, who initiated a series of "little books" in physics—one on string theory and another on black holes, with Frans Pretorius—and thereby set out the footsteps in which this book follows. Steve tragically died while rock climbing in 2019. This book is one of the many ways in which he will be remembered.

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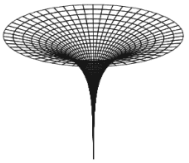
CHAPTER ONE



THE BASICS

1.1 The Size of the Universe

HOW BIG IS THE UNIVERSE? IT IS REALLY, REALLY BIG! MORE seriously, this is a deep question. Addressing it will take us to the heart of cosmology. However, before we get to what the question even means, let us first consider some typical distances. In cosmology, distances are truly vast. To set the scale we will start locally and then work our way out. The Moon is about 250,000 miles away and is considered nearby. Its distance is close to the typical mileage on a car before it breaks down. With a really good car you could imagine driving to the Moon and possibly even making it back. However, if we go beyond the Moon, it becomes cumbersome to keep measuring distances in miles. Because the universe is so vast, we typically measure distances another way—with light. We can ask how long it takes light to travel from an object to us. Since the speed of light is a constant of Nature, it is a

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INDEX

age of universe, 18, 79
angular size, 6, 84
anisotropy, 58

B-modes and E-modes, 103
baryon acoustic oscillations, 89
beach balls as photons, 32, 34
big bang, 15, 20
big bang nucleosynthesis, 90, 92
blackbody radiation, 30, 112
Bullet Cluster, 43, 99, plate 6

clusters of galaxies, 57, 105
CMB hot spot size, 73, plate 8
CMB lensing, 99
CMB polarization, 30, 94, 102
CMB, where it comes from, 38
compactness, 17, 20, 114–116
COsmic Background Explorer (COBE), 4, 63
cosmic densities, 28, 50
cosmic triangle, 83
cosmological constant, Λ, 48, 98, 109
cosmological principle, 8, 22, 107
cosmological redshift, 36
cyclic model, 20, 88

dark matter, 29, 41
decoupling of CMB, 55, 69, 115
density, 17, 28
deuterium, 39, 90
Diffuse InfraRed Background Explorer (DIRBE), 4, plate 3
dinosaurs, 21, 28
Doppler effect, 35

expansion of space, 14, 113

Friedmann, Alexander, 50

galactic plane, 2, plate 2
gravitational lensing, 45
gravitational waves, 102

homogeneity, 8
Hubble Ultra Deep Field, 6, 22, 68, plate 4
Hubble's constant, 10
Hubble-Lamaître law, 10
humans, 21, 25
hydrogen ionization, 36
hydrogen to helium ratio, 52, 90

ice cream, 24
inflation model, 20, 86
isotropy, 8, 58

Kamiokande detector, 25

Lagrange point, 66
Large Hadron Collider, 37, 45

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