PREFACE

The Men of the Great Assembly had three sayings: "Be patient before reaching a decision; Enable many students to stand on their own; Make a fence around your teaching."

Ethics of the Fathers 1:1

There are two aspects of cosmology today that make it more alluring than ever. First, there is an enormous amount of data. To give just one example of how rapidly our knowledge of the structure of the universe is advancing, consider galaxy surveys which map the sky. In 1985, the state-of-the-art survey was the one carried out by the Center for Astrophysics; it consisted of the positions of 1100 galaxies. Today, the Sloan Digital Sky Survey and the Two Degree Field between them have recorded the 3D positions of half a million galaxies.

The other aspect of modern cosmology which distinguishes it from previous efforts to understand the universe is that we have developed a consistent theoretical framework which agrees *quantitatively* with the data. These two features are the secret of the excitement in modern cosmology: we have a theory which makes predictions, and these predictions can be tested by observations.

Understanding what the theory is and what predictions it makes is not trivial. First, many of the predictions are statistical. We don't predict that there should be a hot spot in the cosmic microwave background (CMB) at $RA = 15h$, dec$= 27°$. Rather, predictions are about the distribution and magnitude of hot and cold spots. Second, these predictions, and the theory on which they are based, involve lots of steps, many arguments drawn from a broad range of physics. For example, we will see that the distribution of hot and cold spots in the CMB depends on quantum mechanics, general relativity, fluid dynamics, and the interaction of light with matter. So we will indeed follow the first dictum of the Men of the Great Assembly and be patient before coming to judgment. Indeed, the fundamental measures of structure in the universe — the power spectra of matter and radiation — agree extraordinary well with the current cosmological theory, but we won't have the tools to understand this agreement completely until Chapters 7 and 8. Sober minds have always knows that it pays to be patient before pronouncing judgment on ideas as lofty as those necessary to understand our Universe. The modern twist on this "Be patient" theme is that we need to set up the framework (in this case Chapters

1–6) before we can appreciate the success of the current cosmological model.

Pick a random page in the book, and you will see that I have tried very hard to fulfill the second part of the aphorism. The hand-waving and qualitative arguments that facilitate understanding are here, but the main purpose of the book is to give you the tools to get in the game, to do calculations yourself, and follow cosmological arguments from first principles. Once you have mastered these tools, you will be prepared for any changes in the basic theoretical model. For example, much of the book is predicated on the notion that inflation seeded the structure we see today. If this turns out to be incorrect, the tools developed to study perturbations in Chapters 4 and 5 and the observations and analysis techniques described in the last half of the book will still be very relevant. As a more exotic example: all of the book assumes that there are three spatial dimensions in the universe. This seems like a plausible assumption (to me), but many theoretical physicists are now exploring the possibility that extra dimensions may have played a role in the early universe. If extra dimensions do turn out to be important, perturbations still need to be evolved and measured on our 3D brane. The tools developed here will still be useful.

The final part of the quote above is particularly relevant today since cosmology is such a broad subject. Many important papers, discoveries, and even subbranches of cosmology must be left ouside the fence. I think I have built the fence in a natural place. Enclosed within is the smooth expanding universe, with linear perturbations generated by inflation and then evolved with the Boltzmann–Einstein equations. The fence thus encloses not just the classical pillars of the Big Bang — the CMB, the expansion of the universe, and the production of the light elements — but also the modern pillars: the peaks and troughs in the CMB anisotropy spectrum; clustering of matter on large scales at just the right level; dark matter production and evolution; dark energy; inflation; the abundance of galaxy clusters; and velocity surveys. It also leaves room for important future developments such as weak lensing and polarization.

Outside the fence are some topics that will stay there forever, such as the steady state universe and similar alternatives. Other topics — notably cosmic strings and other topological defects — have been relegated beyond the fence only recently. Indeed, given the exciting research still being carried out to understand the cosmological implication of defects, it was a difficult decision to omit them entirely. Still other topics are crucial to an understanding of the universe and are the subject of active research, but are either too difficult or too unsettled. The most important of these is the study of nonlinearities. It would have been impossible to do justice to the advances over the last decade made in the study of nonlinear evolution. However, the linear theory presented here is a necessary prerequisite to understanding the growth of nonlinearities and their observational implications. A hint of the way in which our understanding of linear perturbations informs the nonlinear discussions is given in Section 9.5, where I discuss the attempts to predict the abundance of galaxy clusters (very nonlinear beasts) using linear theory.

Who is this book for? Researchers in one branch of cosmology wishing to learn about another should benefit. For example, inflation model builders who wish to understand the impact of their models on the CMB and large scale structure can learn the basics here. Experimentalists striving to understand the theoretical implications of their measurements can learn where those theory curves come from. People with no previous experience with statistics can use Chapter 11 to get up to date on the latest techniques. Even theorists who have heretofore worked only in one field, say large scale structure, can learn about new theoretical topics such as the CMB, weak lensing, and polarization. I have tried to emphasize the common origin of all these phenomena (small perturbations around a smooth background). More generally, researchers in other fields of physics who wish to understand the recent advances in cosmology can learn about them, and the physics on which they depend, here.

My main goal though is that the book should be accessible to beginning graduate students in physics and astronomy and to advanced undergrads looking to get an early start in cosmology. The only math needed is ordinary calculus and differential equations. As mentioned above, quite a bit of physics impacts on cosmology; however, you needn't have taken classes in all these fields to learn cosmology. General relativity is an essential tool, so a course in GR would be helpful, but I have tried to introduce the features we will need when we need them. For example, while we won't derive the Einstein equations, we will use them, and using them is pretty easy as long as one is comfortable with indices. Similarly, although inflation in Chapter 6 is based on field theory, you certainly do not need to have taken a course in field theory to understand the minimal amount needed for inflation. It can be easily understood if you understand the quantum mechanics of the harmonic oscillator.

To make the book easy to use, I have included summaries at the ends of some of the chapters. The idea is that you may not be interested in how the Boltzmann equations are derived, but you still need to know what they are to obtain the main cosmology results in Chapters 7–10. In that case, you can skip the bulk of Chapter 4 and simply skim the summary.

Writing the book has been almost pure pleasure in no small part because it forced me to read carefully papers I had previously been only dimly aware of. Thus a big acknowledgment to the many people who have pushed cosmology into the 21$^{\text{st}}$ century with all of their hard work. In the "*Suggested Reading*" sections at the end of each chapter, I have pointed to other books that should be useful, but also to the papers that influenced me most while working to understand the material in the chapter. These references, and others sprinkled throughout the text, are far from complete: they simply offer one entry into a vast literature which has grown dramatically in the last decade.

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