Preface

■ Cosmology Becomes Data-driven Science

Cosmology, our study of the nature, formation, and evolution of the universe, has been transformed in an extraordinary fashion since the two authors of this book were students in the 1960s. When we were doctoral students at Chicago (JPO) and Cambridge (SM), two powerful but competing models were in the air: the big bang and the steady state models of the universe. There were passionate advocates for each, and a scientist's views of the subject were considered to be a matter of *belief*. On almost a daily basis we were exposed to the strong opinions and arguments of the great minds that were battling to understand the universe. At any gathering of professional astronomers one might be asked, "Do you believe in the steady state theory?" or "What do you make of this big bang universe?" Popular writings about cosmology—then and to this day—reflect that early, almost theological, intellectual atmosphere. Cosmology rested precariously on a series of beliefs, because data and hard facts were so scarce.

In the past half century, cosmology has changed totally. It is now an information-driven precision science, thanks to spectacular progress in instrumentation and information technology. Of course, there are still big ideas, but those ideas are shaped and constrained by the flood of data from telescopes on Earth and in space. Observations have amply and thoroughly confirmed the big bang model as essentially correct. The Hubble Space Telescope and many other instruments have now given us an inventory and mapped the detailed geography of our local patch of the universe and, more dramatically, provided direct observations from further and further back in time and space, so that we are now able to consider the telescopes with which we peer at the cosmos as time machines. When the Hubble Space Telescope lets us study a piece of the sky distant from us by seven billion light-years, we are seeing the world as it was seven billion years ago, half the current age of the universe. Thus we can directly see and measure the differences between then and now, to chart the evolution of the cosmos. There is no need for speculation. Or, speaking more accurately, speculations over cosmic evolution can be checked by direct observations. Although we cannot see all the way back to the Big Bang, 13.7 billion years ago, we can directly chart the evolution of normal galaxies to almost the period of their birth pangs. Furthermore, orbiting radio telescopes allow us to see all the way back to the moment when photons finally emerged from the primal soup that had imprisoned them during their first 300,000 years since the big bang, thus giving us a view of the radiation that is the residue of that period. Hence, we can directly view and measure the tiny primordial fluctuations, which grew through the action of gravity to become the rich, nearby world of galaxies, stars, and planets.

In today's cosmological discussions, any theory *must* be consistent with the panoply of X-ray, ultraviolet, optical, infrared, and radio information accumulating in our databases, the observations that show us concretely what the universe is at our epoch, how it came to its present state, and how it started. Cosmological investigations are still not as grounded and verifiable as those in other disciplines, such as engineering, but they have largely lost that intoxicating whiff of natural theology. Just as our present knowledge of the geological and biological facts concerning our mother Earth has banished to science fiction the speculations over "monsters from the vasty deep," so also our previously untethered cosmic fantasies must now be constrained by the awesome and growing libraries of cosmological information.

Complementary to this grounding in fact, we have developed quantitative and testable theories based on the known laws of chemistry, physics, and mathematics, which provide the framework on which to hang these new observations. In principle, determining the growth of fluctuations due to gravity in the primordial matter from which stars and galaxies developed, based on Isaac Newton's well-tested laws of physics, is just as straightforward as calculating the path of a baseball hit into the grandstand or the motion of a ship in water. The calculations may be more complex, but they do not require mathematics or science about which we are uncertain. In a parallel development, the equipment needed to solve these equations is now available.

Computers, following Gordon Moore's famous law for the speedup of electronic chips, have increased in their power to do arithmetic by more than a factor of one million since the 1960s. Today we can code any given theory into large-scale computer simulations, start with the initial state as observed by our radio telescopes, crank the machines forward, using the physics of Isaac Newton, Albert Einstein, and Niels Bohr, and see if we do indeed reproduce, in the computer and the visualizations made from its output, the pictures of our locally observed world in all its rich detail. This process could work out correctly or it could fail. But there is no cheating possible. As the observations and the calculations become more and more accurate, there is less and less room for the hand-waving arguments about how things "must work" out in order to save the appearances.

We have discovered that we can actually follow this course both observationally (using our telescopes as time machines) and computationally; and we can chart the evolution of the universe with fair precision. The animations made from our computer simulations really do resemble the observed course of the universe's development as seen by using our cosmic time machine. However, our success is contingent. Our model of how the universe grew to what we see today can succeed only if we invoke the existence of two fantastic components that we call, for lack of better names, dark matter and dark energy. The discoveries of both of these entities were surprises, and there were at first many scientists who (understandably) resisted their introduction. They argued that we were simply adding extra wheels to a complex and inherently rickety mechanism to make things work. Worse, the initial proposals appeared to violate the modern scientific method, because there was no independent evidence for the presence of dark matter and dark energy. We have not yet found direct evidence for these substances in our earthbound laboratories. They are too dilute to detect easily on Earth (although many efforts to do so are under way) and only over the vast volumes of space does their presence make a real, observational difference.

However, evidence that dark matter and dark energy dominate the universe steadily piled up. Before long, a variety of independent lines of argument developed that forced astronomers to take dark matter and dark energy seriously. To clinch the argument, these several independent methods gradually converged on essentially the same values for the amounts of dark matter and of dark energy. Generally speaking in science, if the solution to each mystery requires a new substance with its own special properties, deep skepticism is justified. But the evidence has progressed in the opposite way, with each new observed phenomenon reconfirming our previous estimates for the amounts of dark matter and dark energy.

One example suffices to make the point. As we will see in chapter 6, dark matter was first found, in the 1930s, in giant clusters of galaxies, the largest self-gravitating entities in the universe. It was thought to reside in the space between the galaxies. Then in the 1970s it was found lurking in the outskirts of nearby normal galaxies, surrounding them like dark halos. When detailed calculations were made, the same cosmic abundance of dark matter could explain both of these observed phenomena and, more fundamentally the formation and evolution of both galaxies and clusters. In chapters 5 and 8, we will consider how all cosmic structure grew from tiny seed fluctuations under the influence of gravity to what we now find in the local universe. Gravity, as Newton showed in the seventeenth century, comes from concentrations of matter. In the 1990s, we discovered that the amount of matter and consequent gravity needed to cause the growth of structure was again "just right." The same amount of dark matter is required to explain the origin of structure as for the other two phenomena, the properties of clusters of galaxies, and the dark halos. Finally, we will discover in chapter 8 how our giant optical telescopes have recently found bright, distorted images of extremely distant objects, images that could only be understood as caused by the intervening lumps of matter acting as gravitational lenses, amplifying the image of the much more distant objects—an effect predicted by Einstein. Again, the amount of intervening matter needed to produce the images was just the amount needed to cause the other phenomena detailed above. Check, check, check.

Our modern cosmological edifice seems to have been constructed in a robust fashion—but, of course, only time will tell. We think that we have the picture essentially correct, but it would be a naive (and foolish) scientist who would assert that we are approaching the end of discovery, and that now, at last, "we have it right." When we have, at present, no strong clues as to the physical nature of either dark matter or dark energy, there is obviously still much to be learned. But, should we expect that there would be revolutionary discoveries that will contradict what seems now to be such a coherent story? Does scientific history go through jumps, when the paradigm changes, and all pictures are turned upside down? There is a school of thought that questions the validity of the normal scientific method and the concept of scientific progress. Its supporters find a compelling narrative in describing our changing views of the world as contingent and based more on social networking among investigators than on a real grasp of nature.

We think that a careful reading of the history proves this attitude to be incorrect. Throughout the long history of cosmology the principal thinkers typically did believe that they had the correct model, even as the model was changing. The fact is, since the emergence of modern science in the Renaissance, they usually were correct—but their views were also incomplete. Their observations and theories were founded on the "local" world available to them, with the bigger picture only unfolding as their horizons expanded. The journey that we will take is one of steady expansion as both our mental and observational horizons grew from our planet to our solar system to our galaxy to the expanding universe. And our temporal horizon has grown at a corresponding rate from the human, historical time of thousands of years to the several-billion-year history of the Earth to the possibly unbounded cosmic time scales. What we have discovered again and again is that our essentially correct picture of the local universe was embedded in a much larger cosmos, and that in this emerging world new and strange forces and materials were the dominant components, with the familiar constituents of the earlier model now seen as relatively minor local parts.

It would be wrong, of course, to overstate this evolution as a steady march of progress. In antiquity and the medieval period those who tried to understand the mechanism of the heavens would often resort to the adoption of ad hoc fixes to their models. The inclination to find a patch for any gaping hole in theory is always with us. Even Einstein made such a move when he introduced an arbitrary constant into his equations to make possible a static universe, in harmony with his preconceptions. But today, the flood of data from our ever multiplying observatories, examining the cosmos from above the Earth's obscuring atmosphere in ever greater detail, in an expanding array of wavelength bands, leaves little room for this type of error. Present-day scientists, driven by the facts as they find them, are confident that they have reached a plausible consensus view of the origin, the history, and the present state of the universe, that the modern paradigm, supported by so many disparate lines of evidence, does seem to be truly robust. But of course there will be new discoveries and new surprises ahead.

■ Outline of the Journey We Will Take

This book shows how humankind has reached its present state of understanding of the universe in which it lives. Although it is no longer intellectually fashionable to see the advance of our understanding as a course of inevitable progress, the earlier worldviews have not, typically, been proved wrong. Rather, as we noted earlier, they have been found to be incomplete and were incorporated into larger and more accurate pictures. In the prologue, we summarize the knowledge accumulated from the ancient world through the Renaissance and the early period of quantitative, observational science. Two thousand years ago the Greeks had a fairly accurate geometric model of the Earth-Moon-Sun system, they had discovered the precession of the equinoxes, and they had compiled the first star catalogs. The Copernican revolution, extended and enriched by the mathematical physics of Johannes Kepler, by Galileo's telescopes, and by Newton's universal law of gravitation, embedded that picture into a precise model for the solar system. During the eighteenth and nineteenth centuries, our solar system came to be known as part of a much larger disk of stars seen in the night sky and called the Milky Way. Surrounding this galaxy were the puzzling nebulae, and speculations raged as to whether these were gaseous phenomena in the outer parts of our own galaxy or alternate, island universes.

Chapter 1, "Einstein's Toolkit, and How to Use It," starts with the twentieth-century revolutions of relativity and quantum mechanics that produced the physical laws to be used in understanding the world around us. In chapter 2, The Realm of the Nebulae," our cosmic exploration commences, as telescopes in the dark skies of the new world became powerful enough to show Vesto Slipher, Edwin Hubble, and others that the mysterious spiral nebulae were part of an expanding system of galaxies, many of them similar to our own Milky Way. Chapter 3, "Let's Do Cosmology" and its more mathematical appendix (appendix 1), shows how we can understand some core physical ideas of cosmology, the mysteries of an expanding universe, with no more mathematics and physics than a good high school education would provide. In chapter 4, "Discovering the Big Bang," we put this world into the context of Einstein's equations and outline the modern synthesis of an expanding, evolving, originally very hot universe called the Big Bang. Discoveries made during the last half of the twentieth century, that the sky is filled with microwave (radio) background radiation and that the lighter chemical elements had been cooked in a cosmological furnace, confirmed this picture, and what has become the standard hot, big bang model of cosmology was accepted as verified by all who cared to study the matter.

Up until this point, theoretical investigations had focused on the evolution of the universe as a whole and on whether it would expand forever or ultimately stall and re-collapse. The actual objects in the universe, such as galaxies and the groups and clusters in which they are arrayed, were somehow taken for granted. In cosmology they were treated as just "there" and of unspecified origin. No one asked when and how these things, the observable building blocks of the universe, had been formed. But then, as we show in chapter 5, "The Origin of Structure in the Universe," finally, in the last quarter of the twentieth century, the modern synthesis for the origin of cosmic structure finally developed and with it ideas for the formation of galaxies and other large-scale, cosmological structures. This paralleled the growing realization that there were two fundamental, additional, rather strange components—dark matter and dark energy—whose nature was unknown but whose presence was essential to make the whole machine work.

The exciting discoveries of these two vital components at the heart of our universe, made in the last decades of the twentieth century, are detailed in chapter 6, "Dark Matter—or Fritz Zwicky's Greatest Invention" and in chapter 7, "Dark Energy, or Albert Einstein's Greatest Blunder." The gravitational forces arising from the dark matter drive the concentration of ordinary matter into galaxies. But, the ordinary chemical stuff that the planets and the stars are made of, the material that emits and absorbs light, is now known to be only some 4 percent of the whole— the icing on the cake. The cake itself is made of dark matter, dark energy, and electromagnetic radiation, with the dark energy apparently the yeast inflating the cake in an uncanny fashion.

This is the itinerary for the cosmic voyage on which we will take the reader in the following chapters. We summarize the journey, its conclusion, and the still open questions in chapter 8, "The Modern Paradigm and the Limits of Our Knowledge," and chapter 9, "The Frontier: Major Mysteries that Remain." It is exciting, it is new, and, dare we say, it is likely to be fundamentally correct. But it is by no means complete, since, as noted, we still have no idea what constitutes the dark matter and the dark energy. We embark on our voyage in the period of western history called classical antiquity, but quickly reach the Renaissance, when the wisdom of the ancients, preserved, refined, and transmitted by Islamic savants, began to filter into an intellectually backward but awakening western Europe. A growing reliance on three aspects of rational inquiry would transform not only astronomy but also all human inquiry into nature. The three key concepts were these: the application of direct measurement and observation, the introduction of mathematical modeling, and the requirement that hypotheses should be testable and verifiable.

Thus, the scientific method, as we now know it, was born during these Renaissance attacks on the astronomical model of scholastic philosophy. This new scientific method, whose test bed was the astronomical world around us, became the foundation upon which all future technological progress would be based, from electronics to the revolutions in biology. It has carried us to our current vision of the universe, as detailed in the final chapters, and there is no doubt that it will carry us further in the future.