Horizons of Cosmology
In our fast-paced and high-tech era, when visual information seems so dominant, the need for short and compelling books has increased. This conciseness and convenience is the goal of the Templeton Science and Religion Series. We have commissioned scientists in a range of fields to distill their experience and knowledge into a brief tour of their specialties. They are writing for a general audience, readers with interests in the sciences or the humanities, which includes religion and theology. The relationship between science and religion has been likened to four types of doorways. The first two enter a realm of “conflict” or “separation” between these two views of life and the world. The next two doorways, however, open to a world of “interaction” or “harmony” between science and religion. We have asked our authors to enter these latter doorways to judge the possibilities. They begin with their sciences and, in aiming to address religion, return with a wide variety of critical viewpoints. We hope these short books open intellectual doors of every kind to readers of all backgrounds.

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Contents

Preface: A Wondrous Place ix

Chapter 1: Cosmology Begins 3
Chapter 2: Case for the Big Bang 16
Chapter 3: Inflation Explained 38
Chapter 4: How Stars Form 52
Chapter 5: The Darkest Matters 63
Chapter 6: Cosmic Archaeology 74
Chapter 7: Detecting Dark Matter 102
Chapter 8: Finding Dark Energy 118
Chapter 9: Eminent Missteps in Cosmology 132
Chapter 10: The Universe in Seven Numbers 149
Chapter 11: Our Place in the Universe 160
Chapter 12: Cosmology’s Future 178

Glossary 187
Bibliography 193
Index 197
The universe is a wondrous place. Its marvels surpass human imagination. Stars form and die in incredibly colorful displays. The chemical elements are cooked in the hot interiors of stars and dispersed in immense explosions. Vast numbers of stars pirouette in giant galaxies. Immensely massive black holes seed huge outflows that illuminate the remote depths of the universe. All of this and more constitute the catalogue of objects that populate the universe.

Astronomical observations demonstrate that the universe began as a dense fireball. As it expanded and cooled down, matter and eventually massive gas clouds condensed out. Galaxies and stars formed. Ninety percent of the universe is dark, and not made of ordinary matter. The universe will continue to expand, essentially forever. Such was our past, and such will be the future, as revealed by the wonders of modern astronomy.

It is remarkable how much we have learned about our universe in the past century. When Albert Einstein said that “it should be possible to explain the laws of physics to a barmaid,” he was only half joking. We do have a fairly simple explanation of our universe. But behind that simplicity lurks a great deal of mystery and complexity. Cosmology is filled with puzzles and speculations. I have tried to tell this story simply enough for general readers, while also trying to retain enough technical detail for advanced students and professionals.

With that in mind, this book roughly falls into three parts. It
begins by narrating the basic story of our discoveries in cosmology over the past century—an expanding universe populated with galaxies and stars. The middle chapters look at a number of contemporary puzzles. These puzzles relate especially to galaxy formation and to the jarring new reality of dark matter and dark energy. All of these topics are of particular interest to cosmologists today. These middle chapters lean toward a more technical discussion. The reader will have noticed by this time that cosmology is a constant back and forth between observation, theory, and trying to test those theoretical predictions.

The last third of the book looks at the human side of cosmology and moves to the more speculative and philosophical frontiers with which cosmologists are also wrestling. Einstein once declared, “The man of science is a poor philosopher.” Still, when talking about the origins, nature, and future of the cosmos—or the concepts of universes and time travel—cosmologists unavoidably cross the line into speculation.

I have been privileged to be a witness to many of the discoveries in cosmology since the 1960s, and have tried my own hand at several specific problems. Cosmology began with a few lone figures who had arrived at some of the greatest insights about the structure and dynamics of our universe. It now is a collective project. There are too many notable people in the field to name them all in these pages. In this new century, we all face the challenges of finding the budgets necessary to build larger instruments to test our best theories. However, as I say at the end of this book, we are not necessarily in a great hurry. If all goes well, we have many centuries ahead in which to find out the true nature of the cosmos around us.
Horizons of Cosmology
Modern cosmology began in the 1920s when two men with different backgrounds, and about as separate geopolitically as could be imagined, entered the scientific scene. Both shared a love of physics and a fascination with Einstein’s recently launched theory of gravity, which said that on the largest scales of the universe, space-time was like a curved fabric that was being pulled inward. The great problem for Einstein’s mathematics, and the debate that followed, was why the universe looked stable when it should have been collapsing from the force of gravity.

This is where the two founders of modern cosmology, Russian physicist Alexander Friedmann (d. 1927) and Belgian physicist Georges Lemaître (d. 1966), started to make their revolutionary proposals about the universe.

Friedmann was a meteorologist, a military pilot in World War I, and a professor of mathematics and physics in the Soviet Union. He died prematurely of typhoid within a month of setting the world altitude record for a balloon flight in 1925 at seventy-four hundred meters. But three years earlier he made a major discovery regarding mathematical problems in the field equations of Einstein’s theory of gravity. Friedmann had studied Einstein’s theory of general relativity in detail, and was one of the very few who understood it. Friedmann discovered what we call today the expanding universe solution to Einstein’s equations, which explains why the universe is not collapsing, despite the implications of Einstein’s general relativity theory of gravity.
The Russian corresponded with Einstein, who promptly criticized Friedmann’s result as erroneous. But Einstein retracted his attack the following year, and Friedmann became famous, at least in Russia. Einstein eventually realized he had made an elementary mathematical mistake and missed the new solution.

In the 1920s, when communications between scientists in Russia and the west were hardly optimal, Lemaître also began to look at the cosmological implications of Einstein’s theory of gravity. He, too, arrived at a solution, coming a bit after Friedmann but not knowing the Russian’s work, some years later. In Belgium, Lemaître was a Roman Catholic priest. He eventually became president of the Pontifical Academy of Sciences and the principal science advisor to Pope Pius XII. Lemaître began this rise in his field with a graduate studies fellowship at the Massachusetts Institute of Technology. His American visit was also marked by a trip to the California Institute of Technology, a visit crucial to Lemaître’s later theories about an expanding universe.

Pasadena was home to the small organization (funded by the Carnegie Institution) that operated the world’s largest telescope, which had a one-hundred-inch-diameter mirror and sat atop Mount Wilson, east of Los Angeles. On his California trip, Lemaître met cosmologist J. P. Robertson and also Edwin Hubble (d. 1953), the chief observational astronomer at Mount Wilson. Hubble was not interested in theory the way that Robertson was. But with his Mount Wilson telescope, he was experimenting with the measurement of redshift, which refers to the way the light of distant galaxies moves toward the red end of the spectrum when those galaxies are moving away from the observer.

Lemaître got a firsthand look at the difficulties of measuring redshifts. With this new kind of information in tow, he returned to Belgium and began his attack on the problems in Einstein’s theory of gravity. In 1925, quite independently of Friedmann, Lemaître also discovered the expanding universe solution to Einstein’s equations. Lemaître formulated a law that he believed would relate redshift
and the distance of galaxies to the expanding universe. With this idea, Lemaître had conceived of the first modern cosmological test: a theory that could be measured by observational data.

In the meantime, back in Pasadena, Hubble was developing his own interpretation based on his observations. In 1929, he came up with what is now called Hubble’s law, which asserted that the recession rate of the galaxies is linearly proportional to distance. In short, galaxies move faster as they are farther away from the observer, which also was a prediction of, and evidence for, the expanding universe theory. The story of Hubble is itself an early account of American astronomy.

Hubble had studied mathematics and astronomy at the University of Chicago, but he also excelled in boxing. He turned down an offer to train for the world heavyweight championship in favor of a Rhodes scholarship at Oxford where he obtained a law degree. On returning to the United States, he practiced law for a while but returned to his first love, astronomy. He obtained his doctorate at the Yerkes Observatory, operated in Wisconsin by the University of Chicago. Then, in 1919, he joined the staff at the Mount Wilson Observatory. His timing was fortuitous. Two years earlier, the one-hundred-inch telescope had begun operation.

Hubble exploited the new telescope to explore the frontiers of the universe. He resolved individual variable stars in the spiral nebulae and demonstrated that they were Milky Way–like galaxies, which astronomers of that period referred to as island universes. The eighteenth-century philosopher Immanuel Kant had speculated that island universes are distant galaxies, but it was only wishful thinking without the data to support this viewpoint. Indeed, no physicist, especially Einstein, had anticipated that the Milky Way was only a minor and inconsequential constituent of the universe, surrounded by uncountable numbers of neighbor galaxies.

Edwin Hubble developed one of the most unusual partnerships in modern science. His accomplice was a former mule driver and Mount Wilson janitor, Milton Humason, who began work as a night
assistant for the telescopes and eventually was hired as Hubble’s chief assistant. Humason, who had left school at fourteen, became one of the world’s most skilled astronomers. Humason’s expertise was in using the telescope to take photographs of galaxies and develop them at sensitivities that no one has previously attained. It was this skill that played an important role in his and Hubble’s joint quest to identify and measure the most distant galaxies.

As is common in astronomy, one discovery builds on another. Hubble’s new distances attained significance only after being combined with data obtained by Vesto Slipher, who in 1915 had first reported that most nearby galaxies were receding from us. And it took some years before all the best theories and data—from Friedmann, Lemaître, Hubble, and Slipher—were being looked at together.

At the now-historic Lowell Observatory in Flagstaff, Arizona, Slipher had used a twenty-four-inch refractor telescope. It was painstaking work. Each exposure took up to forty hours. He used the technique of spectroscopy, which relies on the Doppler effect, well known by how the sound waves of a train whistle change when it moves away from the observer. Slipher used this same approach to measure the radial velocity of galaxies, that is, the components of motion away from us. Indeed, he found that entire galaxies moved predominantly away from the earth. The light that reached his telescope, called spectral lines, shifted to longer wavelengths, again showing the redshift effect. However, without knowing accurate distances for the galaxies, Slipher could not possibly deduce much more than a large systematic motion of the apparently nearby objects.

During the 1920s, in fact, all the evidence for an expansion of the universe remained conjectural, even though it was a topic of lively debate, orchestrated most notably by Knut Lundmark in Sweden, as well as by others. As always, the weak link remained the uncertainty in nebular distances. Hubble broke that stalemate in 1929 when he announced his correlation between the distance to a gal-
axy and its redshift, now called Hubble’s law. This was promptly interpreted as a measure of the velocity of the galaxy away from the observer. Most but not all galaxies were receding, Hubble announced.

Lemaître jumped on the new data. Amid the 1920s speculation, it was proposed that the universe expanded from a singular point of origin in time. The concept of an initial infinitely dense singularity was an idea Lemaître could not accept. The great cosmologist Yaakov Zel’dovich, speaking later on this choosing of a model of origins, famously joked that “the point of view of a sinner is that the church promises him hell in the future, but cosmology proves that the glowing hell was in the past”—at the first fiery explosion.

Motivated by a more metaphysical logic, Lemaître instead proposed that the universe began its expansion from a finite size. He dubbed it the primeval atom. He supported the idea of a tiny initial universe by adopting Einstein’s mathematical trick, which was to introduce a cosmological constant—a hypothetical force—that holds back the universe from collapsing under its own gravity. While Einstein had lost interest in this antigravity constant once it was clear that the universe expanded, Lemaître revived the idea. He used the constant to explain how his finite initial state, the primeval atom, had managed to exist at the beginning. One advantage of Lemaître’s model was that it could account for the age of the universe. In the absence of a cosmological constant, Hubble’s method dated the universe as being even younger than the earth.

Reluctant at first, Hubble finally conceded that his 1929 discovery meant that the universe might indeed be expanding via the recession of the galaxies. The evidence began to seem overwhelming despite the fact that Hubble’s first approach gave an unacceptably young age for the universe. Hubble explained his change of mind in his 1936 book, *The Realm of the Nebulae*: “Redshifts resemble velocity shifts, and no other satisfactory explanation is available at the present time: redshifts are due either to actual motion of recession or to some hitherto unrecognized principle of physics.”
By 1942, the recession velocities measured by Hubble and his colleagues had reached speeds of up to twenty-five thousand miles per second, or one-seventh the velocity of light. These rates were enormous. But even earlier, Hubble could not accept the image of a rapidly expanding universe. His skepticism obliged him to choose the other alternative stated in his book: that the light in the universe operated under some new principle of nature, such as might be contained in some as yet undiscovered new physics.

At this point, Hubble proposed the idea of tired light to explain the redshift. This hypothesis represented a fundamentally new physics, though Hubble was not a physicist by training. To give him credit, Hubble did realize that the discovery of tired light would be as great a revolution in physics as was the expanding universe, and he was fully aware of the lack of any contemporary evidence for this phenomenon. The argument that photons lose energy traveling across space, hence shifting to the red, has now been definitively discarded on experimental grounds.

More to the point was a demonstration of the reality of the expansion. To convince himself and others of the reality of the expansion, Hubble devised a new test. In an expanding space, the phenomenon of time dilation occurs. If distant space is expanding, the rate of arrival of photons from those distant sources must decrease. It is the perfect test, though the results came in long after Hubble’s heyday. The test was implemented in 1990 by measuring the light curves of the brightest known objects in distant galaxies, which are Type Ia supernovas (star explosions). The current theory is that all supernovas, as perfect bombs, emit the same rate of light. Once this light is corrected for time dilation, supernovas that are nearby and distant all show identical light curves. This proves time dilation and hence the expansion of the universe.

Hubble’s erroneous age of the universe was due to the fact that his constant was far too large. Why was Hubble so far off the modern value for the expansion rate? Hubble’s original diagram seems largely wishful thinking to the modern observer. The spread in his
data is enormous. After all, the inferred value for Hubble’s constant (some six hundred kilometers per second per megaparsec)\(^1\) was too large by a factor of ten. However, his later data vindicates, if not the modern value, certainly the underlying trend of the expansion law with distance that was caught by Hubble’s inspired intuition.

A vigorous debate continued in the post-Hubble decades. Rival schools argued for a low or a high value of Hubble’s constant, considered to be either fifty or one-hundred kilometers per second per megaparsec. Neither view was grossly wrong, although it required the aptly named Hubble Space Telescope to settle the controversy. Today, the accepted value of the Hubble constant is seventy-two kilometers per second per megaparsec, with an uncertainty of about 10 percent. This gives us a universe that is 14 billion years old, comfortably older than the ages of the oldest stars.

With all of these advances, there was no reason to go back to Lemaître’s cosmology of the primeval atom. First of all, the primeval atom would be unstable and collapse, which would be a disaster for the early universe. Another strike against the primeval atom theory came later in the twentieth century, when it was discovered that the entire universe had an evenly spread heat, what we today call the cosmic microwave background, which proves to be the ovenlike warmth left over from a hot big bang beginning of the universe. This was the death knell for any theory that lacked a dense and hot beginning. But for the big bang theory to win the day, it too had to gradually build up its evidence, explaining the data, as we see in the next chapter.

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1. The parsec, a distance of about 19.2 trillion miles, or 3.26 light years, is a basic measure for galaxy distances. A kiloparsec is a thousand parsecs, and is typically used to measure between parts of galaxies or in groups of galaxies. A megaparsec is a million parsecs. It typically is used to measure between different galaxies or different clusters of galaxies.)