CHAPTER 1

Introduction
13.7 Billion Years

> I do not feel obliged to believe that that same God who has endowed us with senses, reason, and intellect has intended to forgo their use. . . . He would not require us to deny sense and reason in physical matters which are set before our eyes and mind by direct experience or necessary demonstrations.
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> —Galileo Galilei, in "Letter to Madame Christina" (1615), translation by Stillman Drake, *Discoveries and Opinions of Galileo* (1957)

Astronomers are at an enormous disadvantage, compared with other scientists. A biologist can bring a collection of fruit flies into his laboratory, encourage a particular behavior among those flies, and apply all the tools of his trade to studying that behavior. A chemist can mix chemicals together, heat them up or cool them down, and study how they react in the controlled environment of her laboratory. A geologist can hike up a mountain, collect rocks from a particular outcrop, and return these samples to his laboratory for analysis. A physicist can power up a laser and test the mechanical properties of a newly-created polymer and can do this on her vibration-isolated, experimental table. Astronomers? They cannot drag the stars into their laboratories. They cannot make stars hotter or cooler to see how they behave when their temperatures change. They cannot slice open galaxies in order to peer into their cores. Astronomers can only take what the universe offers—light and a few small rocks—and make the most of it.

For centuries, astronomers have measured the brightnesses, colors,

and positions of objects in the nighttime sky, as one generation after another has sought to understand the nature and behavior of the remote objects shining in the heavens. Using basic principles of geometry, and the physics describing light, heat, and gravity, astronomers deduced that some of those glimmering objects in the sky are akin to our Sun: They are stars. They also discovered that stars have a wide range of sizes, masses, and temperatures, and that stars are born, live out their lives, and then die. Proving seemingly obvious things, however, like the fact that stars are distant (which prompted the thorny question, how distant?), was extremely difficult. To answer the question of how far away stars are—not to mention how hot, how massive, and how large or small they are—astronomers had to learn how to take detailed measurements of celestial objects that lie at great distances from our telescopes. Since the stars could not be brought to Earth to be weighed and measured, astronomers had first to develop the right tools for measuring stars. Then they were able to apply their knowledge of concepts like Doppler shifts, radioactivity, and nuclear fusion to the measured properties of stars, and answers to all sorts of previously unanswerable questions, including ones that had frustrated astronomers since antiquity, began to rain down from the heavens. This deluge of evidence led eventually to an astonishing and hard-won intellectual triumph on the grandest possible scale: the answer to one of the most fundamental questions ever to puzzle humanity, How old is the universe?

Astronomers have made great strides. Barely 200 years ago, they were unable to measure the distances to even the closest stars, let alone use the properties of stars to measure distances to galaxies 100 million light-years away. Now they boldly claim to know the age of our universe to an accuracy of better than 1 percent: 13.7 billion years. You now know the answer to the question on the cover of this book, and so it is clear that the book you are holding in your hands is not a mystery. But, it is *about* a mystery. How have 400 years of science brought us to this point at which astronomers, cosmologists, and physicists can claim that the universe came into existence at a specific moment, 13.7 billion years ago? And how much confidence should you have in this statement?

Ask any astronomer why she believes the universe is 13.7 billion years old, and she will tell you that she does not *believe* that the universe is 13.7 billion years; she *knows* that it is 13.7 billion years old—give or take a hundred million years. Why are astronomers so confident? It turns out that their certainty is not hubris. They know that this number is the only valid answer to the question of the age of the universe because it emerges from a meticulous interpretation of all the data—from rocks, stars, galaxies, the whole universe—that humanity has painstakingly gathered over the centuries. It is the only answer that is consistent with the laws of physics as we know them and with the firm logic of mathematics and justified by the collective labors of astronomers, as well as of chemists, mathematicians, geologists, and physicists. The answer rests, in fact, on very solid foundations.

But why *exactly* do twenty-first century astronomers think that 13.7 billion years is the right answer? Why not 20 billion years? Why not 6,000 or 50 million or 1,000 trillion years? How do astronomers know that the universe even has an age—that it is not eternal?

A thorough and persuasive answer to the question of the age of the universe requires that we follow in the footsteps of Galileo and of the many other curious scientists who have come before us, and that we explore the great breadth of knowledge that lies at the core of modern astronomy. The answer to our title question is derived from evidence gleaned from many areas of inquiry that fits together, much like foundation stones in the base of a solid wall. Science in general progresses when curious people pose smart questions and then answer them, or identify problems (the stones in a foundation that do not fit well and consequently make the wall unstable) and then solve them, thereby making the entire scientific structure sturdier and more reliable. The astronomers and other scientists who have made some of the greatest achievements leading to our discovery of the age of the universe will appear in these pages. Some of them may be utterly unfamiliar to most readers, while others bear names that have become iconic. They include William Herschel, Joseph Fraunhofer, Friedrich Wilhelm Bessel, Edward Charles Pickering, Annie Jump Cannon, Henrietta Leavitt, Ejnar Hertzsprung, Henry Norris Russell, Vesto Slipher, Harlow

Shapley, Edwin Hubble, Fritz Zwicky, George Gamow, Walter Baade, Vera Rubin, Arno Penzias, Robert Wilson, Robert Dicke, and James Peebles.

These scientists, and many others, advanced our knowledge of the universe through their work, often correcting errors in our collective wisdom and enabling the entire field of astronomy to leap forward. In these pages, you will learn about these discoveries and their significance. By walking in the steps of the astronomers who ascertained the ages of certain objects in the universe and hence deduced the age of the universe itself, you will learn just how solid are the foundations of our astronomical knowledge. When you have finished this book, you will understand the central claims that strongly support the conclusion that the universe is just under 14 billion years old:

- The oldest known meteorites in the solar system are 4.56 billion years old. From all of our knowledge about how stars, planets, and asteroids—the parent bodies of meteorites—form, astronomers are confident that the Sun and all the other objects in our solar system were born at nearly the same time as these meteorites. This age for the Sun is consistent with all observations and theorists' understanding of the physics of the Sun, of other stars, and of the life cycle of stars. As the universe must be older than every object contained in it, including our solar system, the universe clearly must be at least 4.56 billion years old.
- The oldest white-dwarf stars in our own Milky Way Galaxy have been cooling off (as white dwarfs) for about 12.7 billion years. Since the white dwarfs formed from stars that lived and then died, and since those stars that died had lifetimes of a few hundred million years, this age requires that the Milky Way, and certainly the universe, must be older than about 13 billion years.
- The oldest globular clusters in the Milky Way have measured ages of about 13.4 billion years. Therefore, the Milky Way and the universe itself must be at least marginally older than these oldest globular clusters.
- Cepheid variable stars in galaxies out to distances of 30 megaparsecs (100 million light-years) trace the expansion of the universe. They

permit astronomers to calculate how long the universe has been expanding at the current rate in order for the galaxies to have achieved their current separation distances. Assuming that the expansion rate of the universe has been constant over the history of the universe, which all evidence suggests is very close to a correct assumption, the age of the universe is just a bit greater than 13.5 billion years.

- Maps of the cosmic microwave background radiation contain information about the range of temperatures and the sizes of the structures in the universe when this radiation was emitted. When combined with information about dark matter and dark energy and the rate of expansion of the universe, the most thorough and rigorous analysis of the maps of the cosmic microwave background reveals that the age of the universe is close to 13.7 billion years.

These claims only make sense if one knows what white dwarfs, globular clusters, Cepheid variable stars, and the cosmic microwave background are. Our story, an intellectual voyage of discovery spanning centuries, will be interwoven with the science that elucidates the nature of these celestial objects and explains how astronomers have learned their ages, and how, in turn, they can claim to know the precise age of our universe. But, where to begin? As it turns out, the search to uncover the age of the universe started right here at home, with the mystery of the age of the Earth.