Someone who “missed” the late part of the twentieth century, perhaps by being in a coma or a deep sleep, or by being marooned on a desert island, would have many adjustments to make upon rejoining civilization. The largest would probably be the galloping progress in computers and telecommunications and information technology. But if their attention turned to astronomy, they would also be amazed by what had been learned in the interim. In the last third of the century, Mars turned from a pale red disk as seen through a telescope to a planet with ancient lake beds and subterranean glaciers. The outer Solar System went from being frigid and uninteresting real estate to being a place with as many as a dozen potentially habitable worlds. They would be greeted by a cavalcade of exoplanets, projecting to billions across the Milky Way galaxy. Their familiar view of the sky would now be augmented by images spanning the entire electromagnetic spectrum, revealing brown dwarfs and black holes and other exotic worlds. Finally, they would encounter a cosmic horizon, or limit to their vision, that had been pushed back to within an iota of the big bang, and they would be faced with the prospect that the visible universe might be one among many universes.

This book is a story of those discoveries, made by planetary probes and space missions over the past forty years. The word “world” means “age of man” in the old Germanic languages, and that proximate perspective took centuries to expand into a universe filled with galaxies and stars and their attendant planets.
missions at the heart of this narrative have not only transformed our view of the physical universe, they’ve also become embedded in culture and inspired the imagination—this book is also a story about that relationship. But people were dreaming of other worlds long before the space program and modern astronomy.

Almost nothing written by Anaxagoras has survived, so we can only imagine his dreams. He was born around 500 BC in Clazomenae in Ionia, a bustling port city on the coast of present-day Turkey. Before he moved to Athens and helped to make it the intellectual center of the ancient world, and long before he was sentenced to death for his heretical ideas, we can visualize him as an intense and austere young man. Anecdotes suggest someone who was far removed from the concerns of everyday life. He believed that the opportunity to understand the universe was the fundamental reason why it was better to be born than to not exist.¹

Anaxagoras’ mind was crowded with ideas. Philosophy is based on abstraction—the power to manipulate concepts and retain aspects of the physical world in your head. He believed that the Sun was a mass of fiery metal, that the Moon was made of rock like the Earth and did not emit its own light, and that the stars were fiery stones. He offered physical explanations for eclipses, for the solstices and the motions of the stars, and for the formation of comets. He thought the Milky Way represented the combined light of countless stars.² We imagine him standing on the rocky Ionian shore at night, with starlight glittering on dark water, gazing up into the sky and sensing the vastness of the celestial vault. The dreams of such a powerful and original thinker were probably suffused with the imagery of other worlds.

This is speculation. As with most of the Greek philosophers, and especially the pre-Socratics, very little of their writing has come down to us unaltered. Typically, there are only isolated fragments and commentaries, sometimes by contemporaries and often written centuries later. Each historical interpreter added their own predilections and biases; the result is a view of the original ideas seen through a gauzy veil.³ Modern scholars pore over the shards and often come up with strikingly different interpretations. Anaxagoras thought that the original state of the cosmos was undifferentiated, but contained all of its eventual constituents. The cosmos was not
limited in extent and it was set in motion by the action of “mind.” Out of this swirling, rotating mixture the ingredients for material objects like the Earth, Sun, Moon, and planets separated. Although the nature of the animating agent is not clear from his writings, Anaxagoras was the first person to devise a purely mechanical and natural explanation for the cosmos, without any reference to gods or divine intervention. His theory sets no limit to the scale of this process, so there can be worlds within worlds, without end, either large or small. A case can be made that he believed that our world system is not unique, but is one of many formed out of the initial and limitless mass of ingredients.

Radical ideas often come with a price. For daring to suggest that the Sun was larger than the Peloponnesian peninsula, Anaxagoras was charged with impiety. He avoided the death penalty by going into exile in Asia Minor, where he spent the remainder of his life. Pluralism—the idea of a multiplicity of worlds, including the possibility that some of them harbor life—had antecedents in work by Anaximander and Anaximenes, and in speculation passed down by the Pythagorean School. But Anaxagoras was the first to embed the idea in a sophisticated and fully fledged cosmology. By the time of the early atomists Leucippus and Democritus, plurality of worlds was a natural and inevitable consequence of their physics. There were not just other worlds in space, but infinite worlds, some like this world and some utterly unlike it. It was a startling conjecture.

The next two thousand years saw the idea of the plurality of worlds ebb and flow, as different philosophical arguments were presented and were molded to accommodate Christian theology. The pluralist position was countered by the arguments of Plato, and particularly Aristotle, who held that the Earth was unique and so there could be no other system of worlds. European cultures were not alone in developing the idea of plurality of worlds. Babylonians held that the moving planets in the night sky were home to their gods. Hindu and Buddhist traditions assume a multiplicity of worlds with inhabiting intelligences. For example, in one myth the god Indra says, “I have spoken only of those worlds within this universe. But consider the myriad of universes that exist side by side, each with its own Indra and Brahma, and each with its evolv-
ing and dissolving worlds.” In cultures around the world, dream-
er’s imaginations soared. The Roman poet Cicero and the historian
Plutarch wrote about creatures that might live on the Moon, and
in the second century CE, Lucian of Samosata wrote an extraordi-
nary fantasy about an interplanetary romance. A True Story was
intended to satirize the epic tales of Homer and other travelers,
and it began with the advisory that his readers should not believe
a single word of it. Lucian and his fellow travelers are deposited
by a water spout onto the Moon, where they encounter a bizarre
race of humans who ride on the backs of three-headed birds. The
Sun, Moon, stars, and planets are locales with specific geographies,
human inhabitants, and fantastical creatures. This singular work is
considered a precursor of modern science fiction.

For more than a millennium it was dangerous in Europe to es-
pouse the idea of fully fledged worlds in space with life on them.
Throughout medieval times, the Catholic Church considered it
heresy. There was an obvious problem with this position: if God
was really omnipotent, why would he create only one world?
Thomas Aquinas resolved the issue by saying that although the
Creator had the power to create infinite worlds, he had chosen
not to do so, and this became official Catholic doctrine in a pro-
nouncement of the Bishop of Paris in 1177. Nicolas of Cusa sorely
tested the bounds of this doctrine. In 1440, he produced a book
called Of Learned Ignorance where he proposed that men, ani-
mals, and plants lived on the Sun, Moon, and stars. He further
claimed that intelligent and enlightened creatures lived on the Sun
while lunatics lived on the Moon. It’s said that friendship with the
Pope shielded him from repercussions, and he went on to become
a cardinal.

Giordano Bruno was less fortunate. The lapsed Dominican
monk had deviated from Catholic orthodoxy in a number of ways,
but his espousal of the Copernican system, which displaced the
Earth from the center of the universe, brought him extra scrutiny.
He believed that the stars were infinite in number, and that each
hosted planets and living creatures. Bruno was incarcerated for
seven years before his trial and was eventually convicted of her-
esy. A statue in the Campo de’ Fiori in Rome marks the place
where he was burned at the stake in 1600 as an “impenitent and
pertinacious heretic.” Religion had cast an ominous shadow over the idea of the plurality of worlds.

The same year Bruno was put to death, a twenty-nine-year-old mathematician named Johannes Kepler, an assistant to Tycho Brahe, was working with data that would cement the Copernican model of the Solar System. As he published his work on planetary motion in 1609, he dusted off a student dissertation he had written sixteen years earlier, where he defended the Copernican idea by imagining how the Earth might look when viewed from the Moon. Kepler elaborated on his youthful paper and added a dream narrative to turn it into a sophisticated scientific fantasy: *Somnium*. Kepler was inspired by Lucian and Plutarch’s earlier work, but unlike them, and unlike the mystic Bruno, he was a rational scientist who wanted to realistically envisage space travel and aliens. His narrative is rich with comments on the problems created by acceleration and varying gravity. The geography and geology of the Moon are realistically rendered. He even speculates on the effect of the physical environment on lunar creatures, foreshadowing Darwin and Lyell. Kepler had every reason to take refuge in a dream. He was frail and bow-legged, covered in boils, and was cursed with myopia severe enough that he would never see the celestial phenomena he enunciated so elegantly. *Somnium* was known to Jules Verne and H. G. Wells, and it’s a crucial step in the progression toward rational speculation about other worlds.

The Copernican revolution was not a single event; it was a series of realizations over a period of a century that the cozy idea of Earth as a singular place at the center of the universe was wrong. Displacing the Earth into motion around the Sun was the first wrenching step, but another was recognizing that the Earth was one of many worlds in space. The Copernican principle is more than just a cosmological model; it’s a statement that the Earth is not in any central or favored position in the universe. A heuristic that extends from the work of Copernicus is the principle of mediocrity, which goes much further by supposing that there’s nothing special or unusual about the situation of the Earth, or by extension, the fact that humans exist on this planet. That is of course a central tenet of modern astrobiology, but four hundred years ago it was a radical idea.
The Scientific Revolution recast the debate over the plurality of worlds. Within months of Kepler’s dream piece, Galileo pointed his telescope at the Moon and affirmed it as a geological world, with topography similar in scale to the Earth. He also showed that Jupiter had orbiting moons and that the Milky Way resolved into points of light that seemed to be more distant versions of the bright stars.\textsuperscript{16} The word *world* was no longer confused with *kosmos*; it meant a potentially life-bearing planet orbiting the Sun or, hypothetically, a distant star.\textsuperscript{17} Speculation about life on the Moon became routine, almost mundane. However, theology and philosophy still colored the debate in several ways. One theological concept was the principle of plenitude—everything within God’s power must have been realized, so inhabited worlds should be abundant. Another was the strong influence of teleology—purpose and direction in nature that implies a Creator, who would surely not have gone to the trouble of creating uninhabited worlds.\textsuperscript{18}

For a long time, scientific arguments could do no more than support the general plausibility of the plurality of worlds. Telescopes could easily track the motion of stars and planets, but gaining a physical understanding was much more challenging. The blurring effect of Earth’s atmosphere prevented astronomers from resolving anything smaller than continent-sized surface features on any Solar System body other than the Moon. Even the nearest stars are a hundred thousand times farther from us than the size of the Solar System. In addition, planets do not emit their own light, so astronomers must gather the hundred million times dimmer light that they reflect from their parent stars. Three centuries of improvements in telescope design after Galileo yielded only two new planets, a dozen or so moons, and no success in detecting worlds beyond the Solar System.

And so the dreamers held sway. Many of them were grounded in science so they advanced the Copernican idea that our situation in the universe was not special.\textsuperscript{19} One striking work from the beginning of the Age of Enlightenment was *Conversations about the Plurality of Worlds* by Bernard de Fontenelle, published in 1686.\textsuperscript{20} He wrote about intelligent beings inhabiting worlds beyond the Earth, and incorporated the biological argument that their characteristics would be shaped by their environment. Fontenelle also
followed Galileo’s lead by writing in his native language, French, rather than the scholarly language of Latin, and he was forward-looking in having a female protagonist and explicitly addressing female readers. A much later high-water mark was *On the Plurality of Habitable Worlds* by Camille Flammarion, which reached a wide audience in 1862. By the early twentieth century, scientific speculations and fictional accounts of worlds beyond the Earth proliferated, but technology and research weren’t able to address such conjectures. There’s an unbroken thread between earliest Greek thinkers and more recent explorations of science fiction writers. Anaxagoras was a visionary, but it would probably have taken his breath away to know that one day we would actually visit other worlds.

Isaac Newton’s *Mathematical Principles of Natural Philosophy*, a three-volume masterwork published in 1687, is a landmark in the history of science. *Principia*, as it is known, laid down the foundations of classical mechanics and gravitation. Tucked away in one of the volumes is the drawing of a cannonball being launched horizontally from a tall mountaintop. This “thought experiment” sustained the dreams of space travel for nearly three centuries. October 4, 1957 was a pivotal moment in the history of the human race; on that day a metal sphere, no bigger than a beach ball and no heavier than an adult, was launched into orbit. The world was transfixed, and amateur radio operators monitored Sputnik’s steady “beep” for three weeks until its battery expired. Within two years the Soviets had crashed a probe into the Moon—the first manmade object to reach another world—and the Space Age was in full flight. Humans have never been any farther than the Moon but we’ve sent our robotic sentinels through most of the Solar System and slightly beyond.

For the universe beyond our backyard in the Solar System, we have no direct evidence and we cannot gather and analyze physical samples. The data are limited to electromagnetic radiation. Newton improved on Galileo’s simple spyglass with a design for a reflecting telescope. All research telescopes are now reflectors. In understanding distant worlds, the complement to direct exploration
with spacecraft is remote sensing with telescopes. A succession of larger and larger telescopes over the past century have now expanded our horizons, and extended the Copernican revolution. We know that we orbit a middle-aged, middle-weight star, one of 400 billion in the Milky Way, which is one of 100 billion galaxies in the observable universe. The pivotal moment in the remote sensing of distant worlds happened on October 6, 1995, when Michel Mayor and Didier Queloz announced that they had discovered the first planet beyond the Solar System. We’re now “harvesting” Earths from deep space, and our dreams have moved on to the nature of life that might be found there.

This book explores how our concepts of distant worlds have been shaped and informed by space science and astronomy in the past forty years. Scientific understanding of the universe has been intertwined with culture since the time of Anaxagoras, and the popular imagination continues to be fueled by insights from space probes and large telescopes. What follows is not a survey of the many facilities that have furthered our understanding of the cosmos. Rather, it’s an exploration of twelve iconic space missions that have opened new windows onto distant worlds. Most are in NASA’s portfolio, but all have non-U.S. investigators, as space science and astronomy have become increasingly international. In general, the arc of the book is chronological and moves from the proximate toward the remote. From comets to cosmology, from the Mars rovers to the multiverse, these missions have given us a sense of our cosmic environment and have redefined what it means to be the temporary tenants of a small planet.

The journey starts with Mars. Six years to the day after humans left their first footprints on the Moon—still the only world humans have ever visited in half a century of the Space Age—the first Viking lander touched down on Mars, with its twin reaching the opposite side of Mars six weeks later. The Vikings dashed hopes that Mars might be habitable, but they opened up the modern age of exploration of the red planet. Nearly three decades later, another pair of intrepid machines bounced to a safe landing on their cushioning airbags. The Mars Exploration Rovers were embraced by the public as they trundled across the rocky red soil, inspecting interesting rocks, sending back pictures in 3D, and gathering evi-
dence for a warmer and wetter Mars in the distant past. Mars may have hosted life in the past, and life might still be there in underground aquifers, and it is this oscillation in the popular imagination between hostile and hospitable that makes it an uneasy doppelganger of the Earth.

Next up are two spacecraft that made a grand tour of the outer Solar System during the 1970s. Where before we had had nothing more than rough sketches, the Voyagers painted detailed portraits of the gas giant planets and their moons. These epic missions each ventured billions of miles from home, and they taxed the ingenuity of the scientists and engineers involved, many of whom aged and retired in the years between the first concept and its completion. The successor to the Voyagers was Cassini, which will soon enter its second decade of exploring the Saturn system. Cassini bristles with complex instruments and it dwarfs its predecessors. Together, these three missions have recast our understanding of the frigid realm beyond the asteroid belt. Giant planets may be cold and miniature versions of the Sun, but their moons are anything but dull and lifeless. Some have active geology and liquid water under their crusts. Others spew out sulfur or tiny ice particles. Many of them have distinct “personalities,” like the more familiar worlds in the inner Solar System.

The planets and moons of the Solar System are intriguing enough to have earned the names of gods and mythological figures. Yet they are just side shows in a process that concentrates most of the mass into a central sphere of glowing gas. The star is the central character in this drama, and the plot line is alchemy: the creation of the heavy elements that make up the planets and moons. Stardust was the mission that caught not just one but two comets by the tail and in doing so told us how the Solar System was likely to have formed. The story of Stardust is our story, since most of our atoms were forged in the central cauldrons of long-dead stars. The Solar and Heliospheric Observer, by contrast, focused on the Sun itself and taught us what it means to live with a star. Belying its steady light, the Sun leads an active life that manifests in invisible forms of radiation. Distant worlds will also have to deal with the vagaries of their nurturing stars. After that, we drop back to take in a view of the solar neighborhood, from the unsung but impres-
sive Hipparcos satellite. Hipparcos has refined the work of William Herschel over two hundred years ago by placing us accurately within the city of stars we call the Milky Way. If the Copernican principle holds, the “grit” from stellar fusion that gathered to form the Earth is not unique to our region of space, and similar worlds have formed across the galaxy.

The two missions that follow illustrate the revolution in astronomy when astronomers’ blinders were removed after centuries of learning about the universe through visible light. Spitzer and Chandra are two of NASA’s Great Observatories, straddling the electromagnetic spectrum from waves hundreds of times longer to hundreds of times shorter than the eye can see. Each telescope looks at regions of space that are hidden from view. Spitzer penetrates the murk of gas and dust that permeates interstellar space and reveals new worlds being formed. Young stars and planets are shrouded in placental dust that is opaque to light but nearly transparent to long infrared waves. This is a huge advantage when looking for exoplanets because their contrast relative to the host star is hundreds of times better at infrared than at optical wavelengths. Chandra, by contrast, has revealed the violence of dark objects like neutron stars and black holes, where such tiny worlds distort space-time and accelerate particles beyond any capability of our best accelerators. We would be ignorant of all these phenomena without space-based telescopes.

Closing the book are two missions that venture to the edges of space and time. The Hubble Space Telescope is the only space facility that has embedded itself deeply into the consciousness of the general public, to the level where the prospect of not servicing the telescope generated a backlash and an eventual reversal of NASA’s original decision. Hubble has contributed to every area of astrophysics, but in particular it has quantified the limits of our vision, a region spanning 46 billion light-years in any direction, which contains roughly 100 billion galaxies. The inferred hundred thousand billion billion stars, with their attendant (and similar number of) habitable worlds, form the prodigious real estate of the observable universe, a census inconceivable to Anaxagoras and his colleagues. The Wilkinson Microwave Anisotropy Probe was a specialist mission to map the microwave sky and pin down conditions in the
infant universe. By gathering exquisitely precise data, this satellite has confirmed the big bang model in great detail. It has also shown that there are likely to be innumerable distant worlds out there whose light hasn’t yet had time to reach us since the big bang.

The journey ends with the near future, and efforts to measure realms of the universe that are currently at the edge of our vision. Close to home the goal is to see whether Mars has hosted or could host life—finding Life 2.0 would reset our views of biology beyond the home planet. In the proximate universe, we have the hope of detecting Earth clones and seeing if these worlds have had their atmospheres altered by a metabolism. At the frontier of cosmology, the hope is to test the multiverse concept, where the planets around $10^{23}$ stars are just part of the story, and a suite of alternate universes may exist, with properties perhaps egregiously different or perhaps uncannily similar to our own. In this extreme version of plenitude, everything that can happen has happened, and the set of events that led to our existence are neither special nor unique.

The authors are grateful to the two Steves—Dick and Garber—from NASA’s History Program Office for their careful attention to this project, and to NASA for financial support during the writing of the manuscript. We acknowledge Ingrid Gnerlich at Princeton University Press for her epic patience during the long and winding road that led to the completion of the project, and to the staff at the Press for their assistance during production.

CI is also grateful to the Aspen Center for Physics, which is supported by the National Science Foundation, for providing a congenial setting for substantial work on the manuscript in 2010 and 2011, and to his astronomy colleagues at the University of Arizona for answering questions too numerous to count when he strayed from his expertise. CI also acknowledges the hospitality of his colleagues in the Department of Astrophysical Sciences at Princeton University, where he finished work on the manuscript during an appointment as the Stanley Kelley Visiting Professor for Distinguished Teaching.

HH would like to especially thank NASA for supporting the project and the research. She also wishes to thank the administra-
tors, faculty, and staff at the College of Arts and Letters, the Department of English, the Office of Academic Research and Sponsored Programs, and the Pfau Library at the California State University, San Bernardino, for their assistance throughout the project. HH is extremely grateful to the many colleagues, friends, and family members who discussed and recommended topics and sources. It has been a great pleasure to research and explore the breadth of ideas that inform the study and that affirm our deep connection to the universe around us.