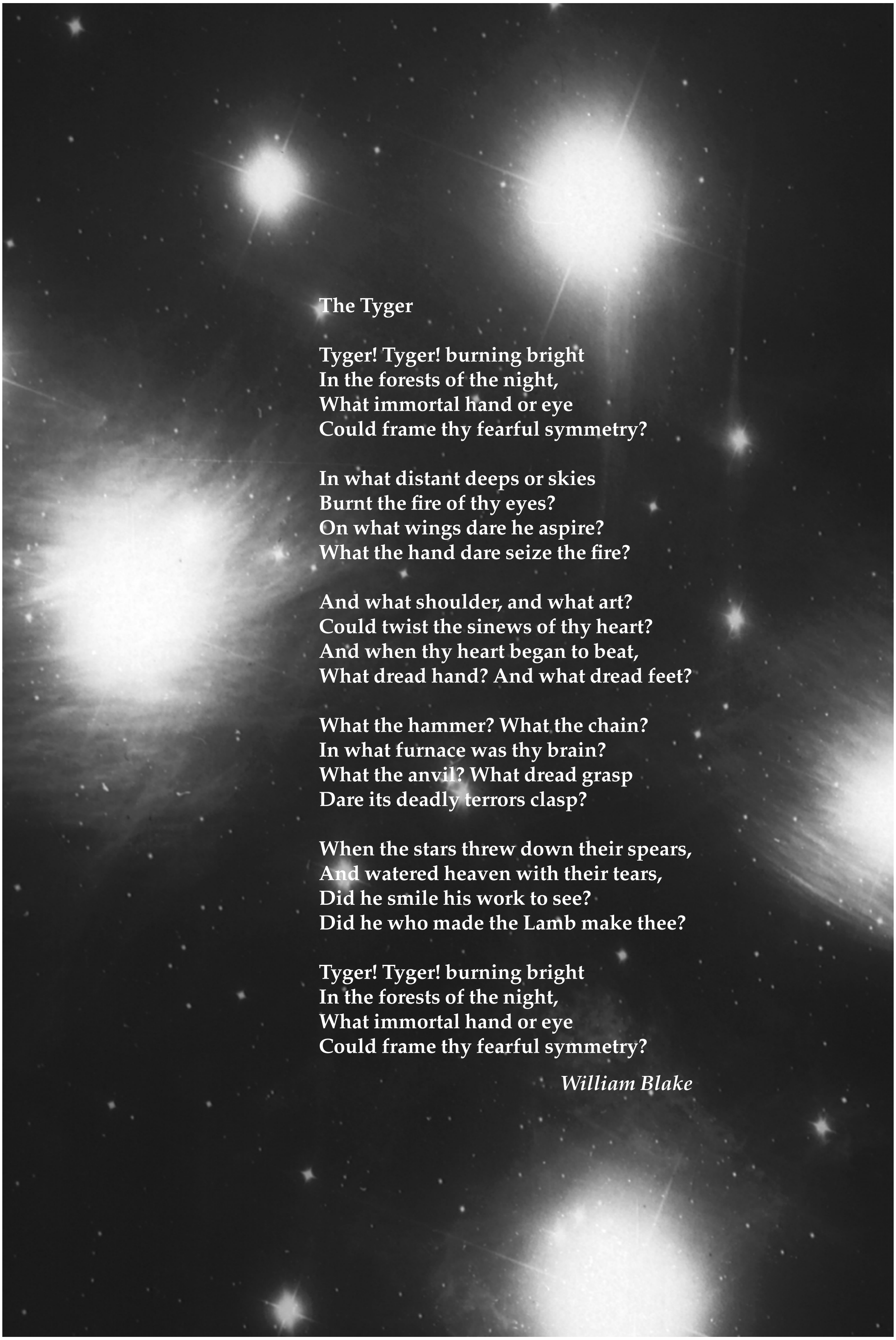
PART ONE

Why Do We Search?

To see a World in a Grain of Sand
And a Heaven in a Wild Flower.
Hold Infinity in the palm of your hand
And Eternity in an hour.

—WILLIAM BLAKE

THE HISTORY OF HUMAN AWARENESS of the universe has brought a steady increase in our desire to find the roots of our existence and to understand how humans fit into the cosmos. We now stand at the threshold of determining how life arose on this planet, and of applying what we know about life on Earth to our quest for life on planets that orbit other stars. But we should pause to ask some key questions: Why do we search? How has the search for our origins, and for evidence of our cosmic kin, proceeded in the past? And what does the search for extraterrestrial life tell us about our attitude toward the universe around us?



The Tyger

Tyger! Tyger! burning bright
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?

In what distant deeps or skies
Burnt the fire of thy eyes?
On what wings dare he aspire?
What the hand dare seize the fire?

And what shoulder, and what art?
Could twist the sinews of thy heart?
And when thy heart began to beat,
What dread hand? And what dread feet?

What the hammer? What the chain?
In what furnace was thy brain?
What the anvil? What dread grasp
Dare its deadly terrors clasp?

When the stars threw down their spears,
And watered heaven with their tears,
Did he smile his work to see?
Did he who made the Lamb make thee?

Tyger! Tyger! burning bright
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?

William Blake

CHAPTER 1

The Search from the Human Perspective

THROUGHOUT HISTORY, humans have speculated about the variety of intelligent beings that might exist in the heavens. Legends and images that describe visitors from the skies testify to a deep, inner longing to connect with the cosmos. Within the last five centuries, prevailing opinions about extraterrestrial life within the Western world have varied widely. At one extreme, some people harbored the intuitive belief that the Earth is the only inhabited planet, firmly situated at the center of the universe. At the other end of the spectrum were those who felt certain that the cosmos contains many planets much like our own, some of which have given rise to civilizations that might be vastly superior to ours.

During the seventeenth century, as science broadened its appeal as an interesting and useful way to enjoy nature, the idea that all the planets in our solar system are inhabited received widespread acceptance. Toward the end of the seventeenth century, the Dutch scientist Christiaan Huygens, famous for his achievements in the field of optics, wrote the first book on the subject of life on other worlds. Huygens speculated on the characteristics that the inhabitants of the different planets should possess in order to survive comfortably under the extremes of gravity and atmospheric composition that he imagined. Half a century later, the great French satirist Voltaire imagined a giant inhabitant of the planet Saturn visiting Earth and eating mountains for breakfast. During the next two centuries, belief in the possibility of life outside the Earth grew alternately stronger and weaker, as new discoveries concerning the nature and evolution of life on Earth and the conditions that exist on the other planets in our own system emerged from scientific investigations.

The second half of the twentieth century opened bold new perspectives on the possibilities for life elsewhere in the cosmos. Astronomers have found that our planet Earth orbits a rather ordinary star, one of hundreds of billions of stars within the giant assemblage of stars, gas, dust, and mysterious dark matter that we call the Milky Way galaxy. They have discovered that our home galaxy amounts to just one among trillions (or perhaps many more!) of similar galaxies that sprinkle the visi-

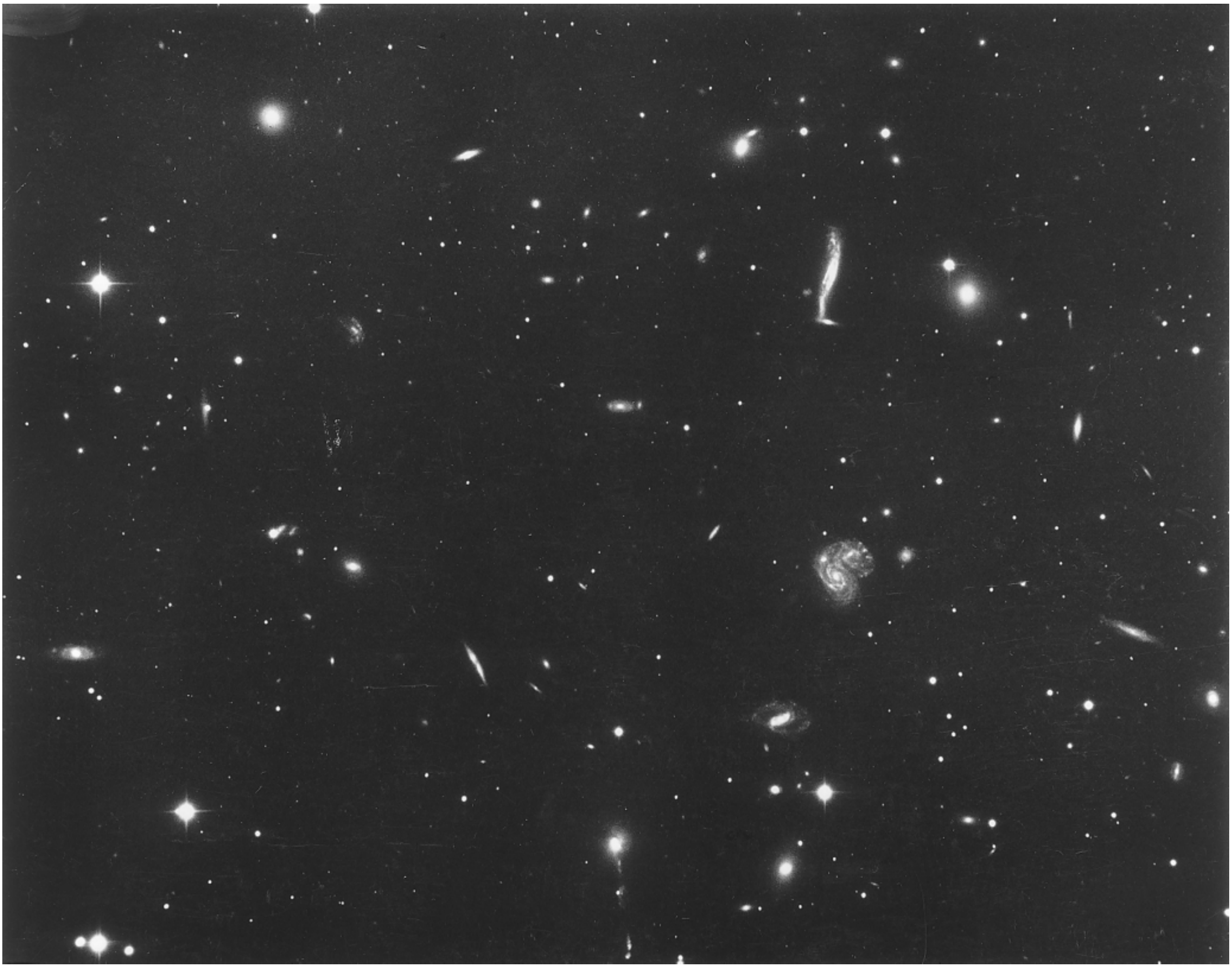


Figure 1.1 Each of the dozens of galaxies visible in this photograph of the Hercules galaxy cluster resembles our Milky Way galaxy in its overall size and shape and contains hundreds of billions of stars. These galaxies are so far away that their light has taken 450 million years to reach us.

ble universe (Figure 1.1). Quite recently they have also shown that many nearby stars have planets of their own. The enormous number of stars in the Milky Way, and in other galaxies as well, tempts us to imagine a correspondingly huge range of possibilities for the forms of life that might exist on the planets that may orbit these stars. On the other hand, astronomers have come to realize that the immense distances between neighboring stars imply that we on Earth may well remain physically isolated, unvisited by alien spacecraft, even if many other civilizations exist. The most effective way to find our cosmic neighbors may well be to detect their radio or television messages, which travel at the speed of light and cost almost nothing to produce.

The Quest for Life's Origins

While we attempt to detect such signals or await extraterrestrial visitors, we can explore other approaches to determine the prevalence of extraterrestrial life. If we could understand the origin of life on Earth, we might hope to estimate how common or how rare other forms of life may be among the starry systems that surround us. Knowledge of how life began on Earth would allow us to compare the conditions that gave birth to life here about 4 billion years ago with those that may exist on other planets, or even within interstellar clouds of gas and dust, and in still other locations where we can imagine that life may have arisen.

If we found life within our own planetary system, perhaps on Mars or Europa (one of Jupiter's large moons), this comparison would have even greater implications: We might discover that these life forms share so many fundamental characteristics with those on Earth (nearly identical DNA molecules, for example) that we and they must have had a common origin. In other words, life on Earth might have migrated from other planets, or might have spread to other planets from Earth, carried by material blown into space by giant impacts from comets or asteroids. If, on the other hand, life on Mars or Europa exists or has existed in forms fundamentally different from any life on Earth, then we could conclude that life must have arisen twice within a single planetary system. This would greatly strengthen the likelihood of finding life on other planets that orbit the sun's cousins in the Milky Way.

The search for life on Mars or Europa is underway. Here on Earth, biologists have already discovered unifying principles about life on Earth, embracing aspects of life that include the ways in which living cells reproduce themselves and the evolutionary forces that have produced the stunning diversity of life that we see today. Yet the mystery of life's origin remains elusive. The quest to solve the riddle of how living creatures first developed from inanimate matter has fascinated scientists for centuries. We may find the answer in our laboratories, or we may glean it from the evidence we hope to gather that will ultimately allow us to compare various forms of extraterrestrial life.

Scientists now doubt that the fossil record of life on Earth can reveal the secret of life's origin, though once they held a different opinion. More than 125 years ago, in May 1876, Her Majesty's Ship *Challenger* returned to port after spending three and a half years away from England. Unlike earlier voyages of exploration that sought alien wealth or alien populations to exploit, the *Challenger* aimed to find the origins of life. During the ship's voyage around the world, scientists aboard the vessel systematically dragged the ocean bottoms for the first time in human history. Day after day, the crew brought samples of water and mud up from the abyssal depths, the bottom layers of the oceans of the world. They discovered marvelous sea creatures, previously unknown to humanity, as they sought to find "living fossils," early forms of life thriving in the ocean depths, where, they believed, conditions had barely changed since the time that life on Earth began.

The *Challenger*'s scientists had expectations that went beyond their quest for living fossils. Twenty years earlier, when the first transatlantic cable had been laid, the ship's crew had brought up a gelatinous ooze from the bottom of the ocean. According to leading scientists, this ooze probably represented the primitive proto-

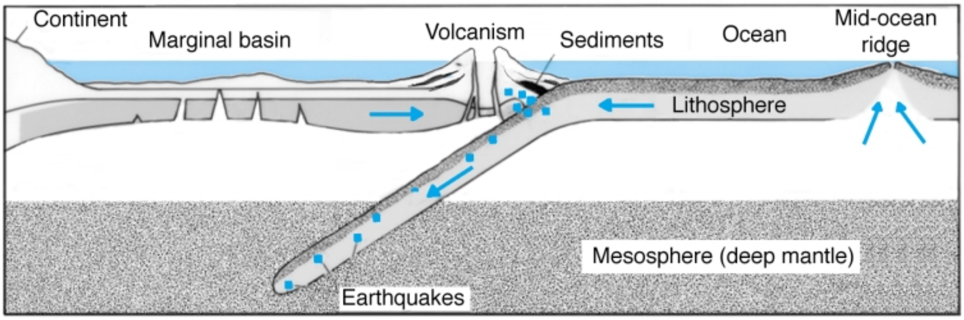


Figure 1.2 Plate-tectonic motions of the Earth's crust, driven by upwelling hot magma, slowly force one plate over another. These motions have buried the geological record of the first half billion years on Earth.

plasm, or *Urschleim* (original slime), from which all life on Earth had arisen. A careful study of this ooze, they thought, would surely unlock the secret of how life had begun.

But alas! The *Challenger* expedition found no living fossils, and the mysterious *Urschleim* turned out to be totally inanimate. Although the ooze changed its chemistry in ways reminiscent of the processes that living organisms undergo, these changes could be reproduced nicely by adding a strong solution of alcohol to ordinary sea water: Chemistry, not biology, ruled the ocean bottoms.

Today, well over a century later, we know far more about the Earth and its oceans. One key issue deals with what we have *not* found. The full history of the origin of life on this planet no longer exists, because all geological records of the Earth's first half-billion years have vanished. Erosion and the motions of the giant plates that form the Earth's crust have removed all traces of eras more ancient than 4 billion years in the past. As the crustal plates have moved, they have slowly but inexorably buried the material that once formed the Earth's surface below the present crust of our planet (Figure 1.2). The motion of the plates, called **plate tectonics**, has destroyed what would have been the best way to uncover the earliest history of Earth, including the epoch when life began.

What remains to be examined in our search for life's origins? We find an amazing variety of living organisms on Earth today, and we have a fossil record extending back in time more than 3 billion years, although the earliest, simplest organisms have left almost no fossil traces. But we cannot sift backward through this fossil record to examine the point at which life differentiated itself from inanimate matter. That record has vanished forever.

Despite our lack of definite information about the origin of life on Earth, no doubt exists concerning the interest of human beings in this subject. Every culture has its own creation myths, and even our own "sophisticated" civilization cares deeply about its origins. How then shall we proceed toward discovering the beginnings of life?

We can imagine two extreme approaches to answering these questions. One method constructs theories of the processes that began life and then attempts to duplicate these processes through laboratory experiments. The second method seeks to find examples in nature, in the hope that studying these examples will reveal the essential clues to this remarkable transformation of matter.

We shall examine the first method of attack, which has been modestly successful, in Chapter 8. We have already seen that the second method cannot be pursued to the beginning on Earth, for the early record of the planet's history has disappeared. This leaves other planets and their moons as places where life's origins might still exist as a fossil record. With modern technology, we can now investigate other worlds, and can even perform experiments within their atmospheres and on their surfaces. These experiments have begun to answer some of the questions that have fascinated human imaginations since intelligence first developed on Earth.

The Importance of Mars

For centuries, speculation about life beyond Earth has centered on a single object. For several reasons, the planet Mars draws human attention as an especially attractive abode for life beyond the Earth. Mars's reddish color, its great variations in brightness, and its peculiar motions in the sky have won the planet special attention since the dawn of history. These visible characteristics led ancient observers to name this planet after the god of war in the Greco-Roman pantheon. During the late seventeenth century, the first good telescopic observations of Mars, made by the same Christiaan Huygens who speculated about life on other worlds, showed

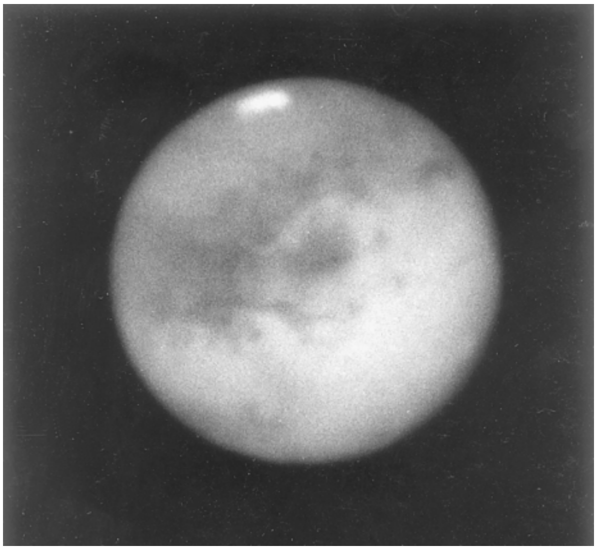


Figure 1.3 One of the best photographs of Mars taken from the Earth's surface shows a martian polar cap (top) and vague dark markings against a background of lighter material.

that the planet's surface has permanent markings (Figure 1.3). Viewed over a period of several hours, the positions of these markings changed, revealing the rotation period of Mars. Huygens's observations proved that we observe the martian surface rather than changing cloud bands, which we see on Jupiter, or a featureless cloud cover, which we find on Venus. During the next two centuries, astronomers improved their observations of Mars and found polar caps, clouds, and seasonal changes, both in the sizes of the polar caps and in the contrast of the light and dark markings on the planet's surface.

Late in the nineteenth century, a new dimension appeared in the Mars puzzle. Several European astronomers, among them Giovanni Schiaparelli of Milan, detected straight, faint markings on Mars, the famous martian "canals." (Writing in Italian, Schiaparelli used the Italian word *canali*, which means "channels" as well as "canals".) Today we know that these canals are not real. Instead, the canals of Mars were (and are) an optical illusion arising from the fact that human eyes and brains often perceive lines when only dots exist.

For half a century, however, the "canals" on Mars generated a series of bitter controversies. The high-water mark of the belief in canals on Mars was reached after Percival Lowell, a wealthy Bostonian who had become fascinated by Mars, built his own observatory in Flagstaff, Arizona, where he carefully studied the red planet with a 24-inch telescope. Lowell drew maps of a fine network of canals, completely covering the planet except for the polar frost caps (Figure 1.4). He found that this canal network underwent seasonal changes that synchronized with changes in the contrast of the large dark areas on Mars: The canals would always grow darker as the martian summer began. Lowell concluded that intelligent, technologically capable martians had built a vast series of canals to carry water from the melting polar caps to irrigate their fields (the dark areas), which otherwise could not produce crops. The seasonal increase in contrast between the light and dark areas, he said, arose from plant growth in the dark areas during the summer season.

Lowell's arguments made up in passion what they lacked in proof. During the first few decades of the twentieth century, astronomers developed the techniques of modern astrophysics. Their application to studies of Mars struck hard at Lowell's assertions. Measurements revealed that most of Mars's surface always remains colder than the freezing point of water, and falls to a full 100° C below freezing during the martian night. Astronomers found neither water vapor nor oxygen in the martian atmosphere, and their conclusion grew stronger that this atmosphere must be extremely thin in comparison with Earth's.

Despite the scientific evidence that Mars should be hostile to life, and despite the negative results from a search for radio signals from Mars that was made in 1924, the idea that an advanced civilization might exist there became so deeply entrenched in the public mind that a serious panic erupted on the evening of October 30, 1938, when Orson Welles presented a radio dramatization of H. G. Wells's novel *War of the Worlds*. Hundreds of thousands of listeners rushed outdoors to flee from the wave of martian invaders who, Welles reported, were overrunning New Jersey (Figure 1.5).

The explanation that this "invasion" was simply entertainment soon satisfied

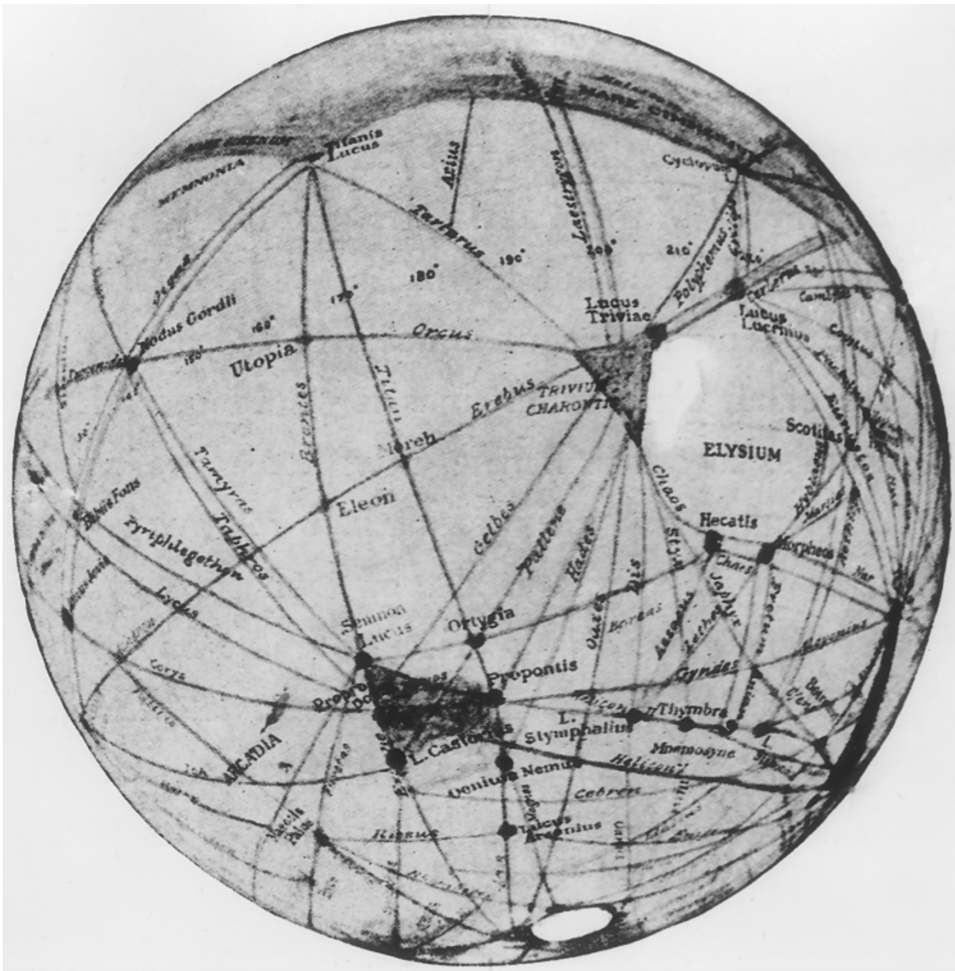


Figure 1.4 During the early years of the twentieth century, Percival Lowell drew this map of Mars, based on his telescopic observations from Arizona. Lowell's map includes numerous straight "canals," which he thought had been built to carry water from Mars's polar caps to its dry equatorial regions.

everyone, but the *War of the Worlds* broadcast remains an outstanding example of the depth of human interest in aliens and the fear of what they might do to us. If today a television broadcast simulated an alien invasion, we can be sure that millions of viewers would be taken in, not simply because humans are easily deceived, but because we retain a deep-seated urge to believe in the existence of cosmic civilizations. The Welles broadcast also reminds us of our curious ambivalence toward ex-

New York T

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NEW YORK, MONDAY, OCTOBER 31, 1938.

Radio Listeners in Panic, Taking War Drama as Fact

Many Flee Homes to Escape 'Gas Raid From Mars'—Phone Calls Swamp Police at Broadcast of Wells Fantasy

A wave of mass hysteria seized thousands of radio listeners throughout the nation between 8:15 and 8:30 o'clock last night when a broadcast of a dramatization of H. G. Wells's fantasy, "The War of the Worlds," led thousands to believe that an interplanetary conflict had started with invading and radio stations here and in other cities of the United States and Canada seeking advice on protective measures against the raids.

The program was produced by Mr. Welles and the Mercury Theatre on the Air over station WABC and the Columbia Broadcasting System's coast-to-coast network, from

Figure 1.5 When Orson Welles dramatized H. G. Wells's *War of the Worlds* in a 1938 radio broadcast, many panicked listeners believed that invaders from Mars had landed in New Jersey. The next day's *New York Times* reported the incident on its front page.

traterrestrial visitors. We expect them to be far wiser, stronger, and more sophisticated than ourselves, but we cannot decide whether they will be gentle and loving or belligerent and homicidal. The one certain belief that we maintain is that they will find us fascinating. Humans have always feared and loved their gods, so it should not surprise us that similar emotions arise when we speculate about advanced forms of extraterrestrial life and their possible interactions with technically "inferior" forms of life on Earth.

Fifty years after Lowell's assertions, and 25 years after Welles's broadcast, humanity sent its first spacecraft to study Mars. Chapters 13 and 14 tell the story of *Mariner 4*, which took the first close-up pictures of the red planet, of the succeeding Mariner missions, of the *Viking* landings on Mars in 1976, of *Mars Pathfinder*'s landing in 1997, and of *Mars Global Surveyor*, which was still photographing the red planet as the twenty-first century began (Figure 1.6). With these and other missions, the past four decades have carried us from dim and distant views of the planets into the era of planetary exploration—with a continuing emphasis on the search for life on Mars.

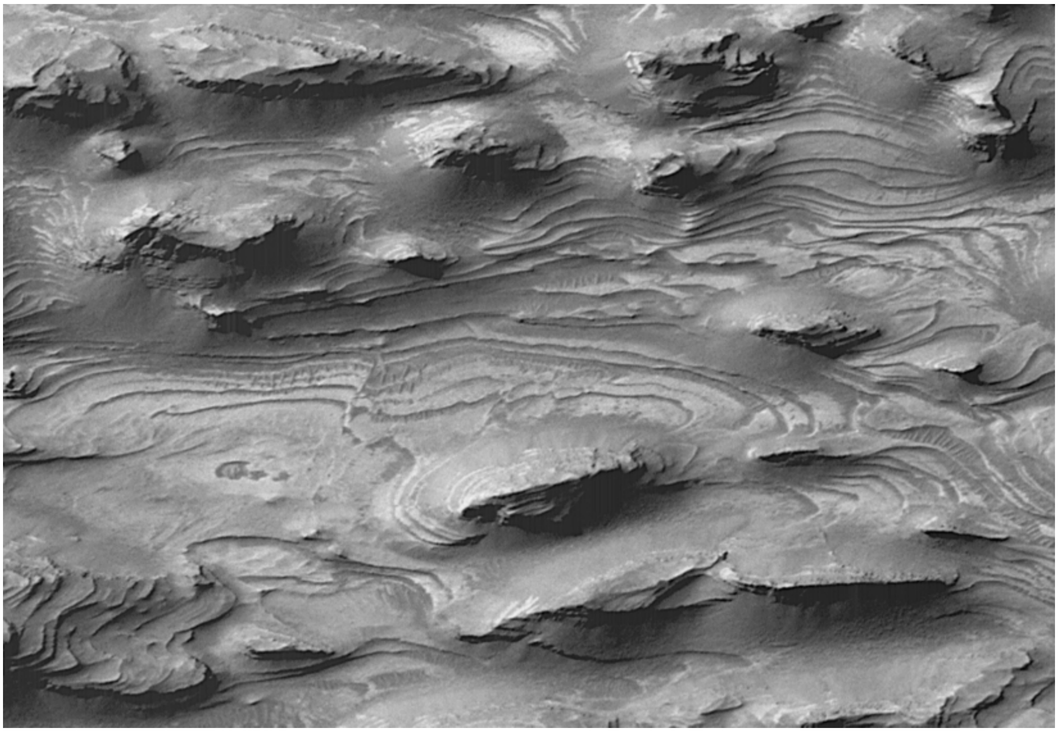

Figure 1.6 In the fall of 2000, the *Mars Global Surveyor* spacecraft obtained this close-up view of the martian surface, showing evidence of sediments deposited under water. The image spans a region about 3 kilometers wide.

The Scientific View of the Universe

This book describes the universe from the time of its birth to the present, with an emphasis on the clues we can find to the twin mysteries of life's origins on Earth and its distribution throughout the cosmos.

Because we have no definite answers to these mysteries, we must attempt to draw conclusions from life on our planet, including both its existing forms and its fossil record, and from the observations that we can make of conditions on other planets and at other possible life-bearing sites. We must then speculate, as best we can, in order to judge the probability of finding life elsewhere in the universe. In following these lines of argument, we shall see that a great difference exists between unbounded speculation and speculation that draws on what we know, encompassing both specific facts and the laws of nature.

Scientific speculation stretches what we know about the universe, creating new hypotheses that can be tested against existing data and the general principles that we have derived from previous experiments. The scientific method for understanding the world relies upon testing and verification, never simply upon bold assertion. Only those ideas that withstand the best attacks of their originators and of other scientists will become part of our scientific framework of knowledge, and these ideas will remain subject to possible overthrow by new observational results, or by newer theories that more convincingly explain a particular set of data. If scientist A claims a detection of gravity waves, or of cold fusion, or of fossil life in a meteorite from Mars, a host of fellow scientists will insist on reproducing the result independently before it can receive general acceptance. Scientists B, C, D, and others will point to possible flaws in the observations, will repeat the experiment in different ways, and will perform new experiments that will test the conclusion of scientist A. Neither the fame of the scientist nor the appeal of the announcement matter in the long run. Even though powerful or fraudulent investigators have successfully imposed their convictions on many others for a time, the truth eventually wins out, precisely because scientists stress the need to reproduce experimental results before accepting them. Either an experiment works or it does not; either observations turn out to be accurate or they do not; either the theory makes a correct prediction or it does not. The success of the scientific approach to speculation provides the reason why we rely on scientists for the principles that let us fly in airplanes, for example, rather than on those who simply claim that they know what will make an airplane (or a carpet) fly.

The Laws of Nature

Scientific hypotheses that survive testing by a large number of different types of experiments achieve the status of *laws*, by which scientists mean *general rules that describe how nature works*. These laws of nature form the underlying basis of scientific speculation, allowing us to predict phenomena that have not yet been observed. Newton's laws of gravitation and motion, for example, apply not only to our own vicinity but also to the universe at large. They allow astronomers to predict the relationship between the speed with which a newly discovered planet moves in its orbit around a star and the size of that orbit, even though the star and its planet are trillions of kilometers from our solar system.

On rare and happy occasions, some new and startling fact seems to contradict one of the scientific theories that summarize what we know about the universe. To scientists these are intensely exciting opportunities. Thus, for example, Newton's laws of motion work perfectly for objects that move relatively slowly, but they fail completely for velocities that approach the speed of light. Here we need Einstein's special theory of relativity, which also gives correct results for low velocities. Similarly, Newton's law of gravitation requires correction by Einstein's general theory of relativity; but in most situations, in which gravitational forces are weak, Newton's approach yields sufficiently correct answers.

Einstein's special and general theory of relativity have been tested again and again, and remain the subject of increasingly sophisticated experiments. So far, they have proved entirely correct. Nevertheless, the scientific approach constantly seeks new tests, stretching itself to look for weaknesses in what we call the laws of nature, which may reveal new insights. However, because what we know now rests on a wealth of interrelated theories and observations, scientists remain reluctant to change their conclusions on the basis of a new observation *until* they become convinced that they can reasonably exclude all alternative explanations. In this way, the scientific model of the physical universe not only has the power to explain observations and to make accurate predictions of future events. It also requires that changes must occur in the framework of our understanding as new discoveries occur. These changes often provoke great debate among scientists, who disagree about the conclusions but firmly agree on the *principles* through which they ultimately alter their framework of knowledge.

This book contains numerous examples of this sort of debate as it presents key areas in which we seek to enlarge our view of the universe and to improve our understanding of our place in the cosmos. The absence of evidence on important issues such as the number of planets suitable for life gives these debates liveliness and vigor, but does not reduce (indeed it enhances!) the need to adhere to the principles of scientific skepticism if we are to make any progress beyond an "anything is possible" attitude.

Applying Scientific Thinking in Everyday Life

The scientific approach of ingrained skepticism, of never believing results until they have been thoroughly tested, may seem to resemble a secret ritual, understood only by dedicated practitioners. In fact, however, each of us applies the scientific method more often than we might think. Suppose, for example, you seek to buy a good used car, and a dealer offers you a lovely, year-old Porsche for just $3000. Your heart leaps at the chance to drive that beauty into the sunset, but a bit of the scientific method quickly balances your emotions, as you ask yourself, "Why should the price be so low? Does the car run? Has it been wrecked and poorly rebuilt? *How can I find answers to these questions, and how will I know I can believe them when I find them*?" The last question captures the essence of science. In life, you may talk with your friends, or consult automotive authorities, and, best of all, you yourself may perform some crucial experiments. You take the Porsche out for a drive to test its cornering, panic stops, and general working order, or, in a more detailed experiment, you may take the car to be examined by a mechanic you trust.

In all of this, you are "being scientific," skeptical and hungry for the greater confidence in drawing conclusions that comes from experimental evidence. If the car checks out, then, like a scientist with a new discovery, you will celebrate the pleasure of your success. Of course, in much of our lives, applying the scientific method would seem inappropriate; no one would rightly use it, for example, in choosing a friend. In our daily lives, we understandably mix the scientific with other methods of learning about the world, applying different methods to different situations.

To some people, the scientific approach may appear to offer far less emotional appeal than the more traditional forms of human conjecture. Indeed, scientific speculation deliberately works against our emotions, which do not favor a continuous attitude of asking, Why should I believe that? even when considering one's own idea or apparent discovery. Nor do our emotions argue for making sure that our explanations of the world all fit together; we are each quite capable of holding contradictory views on different subjects, which we carefully, though often unconsciously, keep separate in our minds.

In this book, we shall encounter many areas of knowledge within which profound changes are now occurring, along with realms where our understanding seems firm and secure. As a result, we shall meet more than one highly informed opinion on controversial topics. This offers a chance to embrace the most exciting aspect of science: the human quest to pass beyond the knowledge that we have, marvelous though it may be, to attain new knowledge that changes our perspectives about the universe and about ourselves. On occasion, scientific skepticism does lead to amusing anomalies. Two centuries ago, for instance, the French Academy of Sciences went on record as declaring the notion of stones falling from the sky (which we now call meteorites) to be complete nonsense. The reason for the Academy's stance was that from their point of view, scientific evidence for this hypothesis was lacking. But from our perspective, the members of the Academy fell into error by being too dogmatic in their refusal to accept the conclusion that meteorites fall from the sky. Sure enough, even as the Academy rejected the true conclusion about meteorites, a physicist named Ernst Chladni (who had been first trained as a lawyer, and therefore had a sharper understanding of eyewitness testimony than most scientists had then or have now) had assembled a good case for the extraterrestrial origin of these stones. Chladni's hypothesis received spectacular confirmation when a widely observed shower of meteorites fell near L'Aigle, France, in 1803.

The Scientific Method in the Search for Extraterrestrial Life

As we shall discuss in Chapter 20, an event similar to the l'Aigle meteorite shower would certainly change current scientific conclusions about popular reports of UFOs (Figure 1.7). So far, however, no such event has occurred. In contemplating the possibilities of extraterrestrial life, the scientific approach may seem a drag on our imaginations, a weight that prevents our fancies from soaring free, unfettered by science's search for a coherent explanation of events. Many people find the notion of life beyond Earth so strange and exciting that they conclude that anything goes, that no sort of life should be more improbable than any other, or that laws of nature yet unknown to science appear in everything from extrasensory perception to the terrors of the Bermuda Triangle. The choice is yours: You can maintain the cautious enthusiasm of someone with a chance to buy a fine car at a bargain price, or throw skepticism out the window and risk acquiring an overpriced lemon. Either approach offers its own rewards, one the delight of knowing why you believe in a particular conclusion, the other the fun of concluding that whatever feels right to you must therefore be true.

Figure 1.7 During the 1980s and 1990s, mysterious "crop circles," often more complex than simple circular swaths through a field of wheat, appeared in southern England and eventually in other countries as well. Popular theories suggested that extraterrestrial visitors had made them, but later confessions by pranksters revealed that humans flattened these patterns to provoke attention and to have some fun.

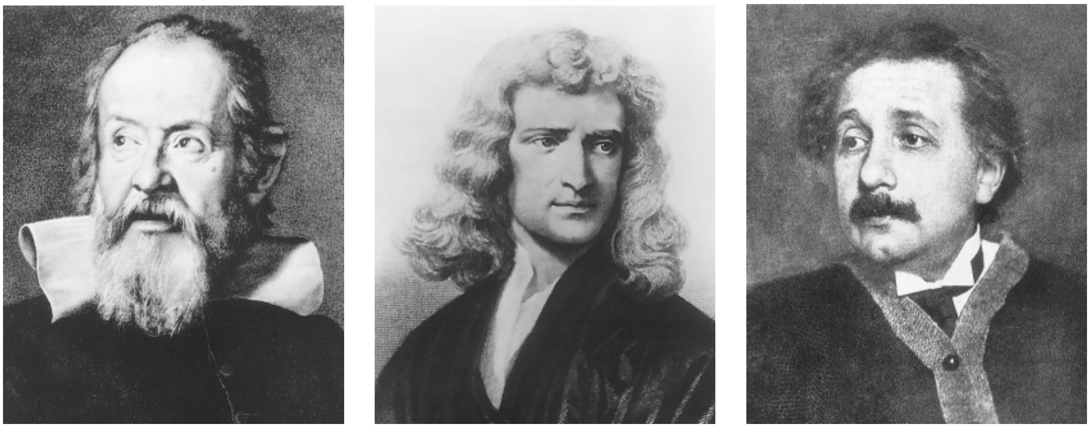

Figure 1.8 Our understanding of physics owes a great debt to three great scientists: Galileo Galilei, Isaac Newton, and Albert Einstein. Newton built on the framework of Galileo's ideas and experiments; Einstein refined and enlarged Newton's laws of gravitation and motion, showing how they apply to motion at speeds close to the speed of light.

In this book, we take the scientific approach of believing that we must proceed carefully from what we understand, by making multiple experiments and observations, to refining our speculations about what we do *not* understand. How does this differ from Percival Lowell's careful observations of Mars, which led him to the logical conclusion that intelligent Martians had built the canals that he saw? The answer lies in the interplay among scientists that we described above. When other scientists studied Mars carefully and failed to see the long, straight markings that Lowell had reported, the martian canals lost scientific credibility. Lowell never changed his mind, but the world of science rejected his assertions, simply because the evidence Lowell claimed to have found could not be verified.

Taking a skeptical approach similar to those who doubted the existence of canals on Mars, we suggest that you should not conclude, for example, that UFO reports imply extraterrestrial visitors to Earth until you have eliminated human error, psychological explanations, natural phenomena, and fraud as the causes of UFO reports. On the other hand, a well-documented UFO sighting, including reliable witnesses, video footage, photographs from different and credible sources, and substantiating physical data, would provide good evidence for another civilization's visit to Earth. Even then, you should want more than a single incident to be sure. A key question to ponder is: What *would* provide firm evidence that UFOs have an extraterrestrial origin, given the fact that video and photographic evidence can now be easily faked in a convincing manner? No one would welcome such convincing evidence more than skeptical scientists, including the authors of this book; no one notices the absence of such evidence more than scientists do. Because we lack this evidence, we turn to the more complex task of building on what we know in order to speculate scientifically about the possibilities of other forms of life in the universe (Figure 1.8).

Cosmic Loneliness

For millennia, humans have generally held that an ever-watching cosmic force guides all events on Earth. During the past few centuries, some of the population has changed its perspective, placing the responsibility for human events entirely on persons acting as individuals. This change in viewpoint has emphasized the importance of humanity, as a greater sense of our power over our own lives has produced an increased awareness of our growing ability to alter the world. We have now entered a new phase of human attitudes toward the natural world, in which we have begun to recognize our responsibilities for taking care of the planet that we inhabit and so noticeably affect. This new perspective carries a price: a feeling of loneliness, that we exist in terrible solitude within a vast, uncaring cosmos. This reaction, usually not accessible at a conscious level, ignores the fact that we form part of the vast cosmic web of particles and forces that holds the stars in their courses and gave birth to our planet and ourselves. Logic, however, does not diminish the pain of isolation felt by many of us, some of whom reject the notion that our planet was once entirely devoid of humans for thousands of millions of years, and that an immensely slow and complex process of evolution brought us to our present state. In fact, the prehuman period includes more than 99.9 percent of the Earth's history.

Modern ideas of how life achieved its present condition date from 1859, when Charles Darwin proposed his theory of the evolution of species. Darwin sought to explain how a planet without human beings, or other types of animals and plants, came to acquire them through the transformation of one species into others. The immediate and widespread opposition to Darwin's theory demonstrated, as it still does, how much humans cherish the belief that Earth has always had humans living upon it, and that our planet was, in fact, created for the purpose of providing a habitat for humanity. Despite adverse public reaction, Darwin's theory has received detailed confirmation through scientific discovery, as scientists have uncovered the greater part of the fossil history of life on Earth, which now extends more than 3.5 billion years into the past (Figure 1.9).

Today, die-hard "creationists" continue to oppose the theory of evolution, claiming that sacred texts pronounce it wrong, or that the loose ends of the theory demonstrate its fundamental errors. This desire to reject evolution as a viable model of natural processes closely corresponds, on an emotional level, to human reluctance to abandon the concept of a cosmos centered on the Earth. The great Russian rocket pioneer Constantin Tsiolkovsky once wrote that "the Earth is the cradle of humanity—but one cannot live in the cradle forever." Tsiolkovsky, who dreamed of humans colonizing space, meant this statement literally, but it also holds true on a figurative level. We on Earth form part of the cosmos—a fragile and extremely young part, but joined nonetheless to the history and evolution of the universe. To recognize this fact has been one of the triumphs of the modern age, a triumph that remains muted to the extent that most people on Earth miss this perspective on our existence.

Darwin's model for the evolution of life on Earth has received verification in a host of ways, from the fossil record that starts 3.5 billion years ago with simple bac-

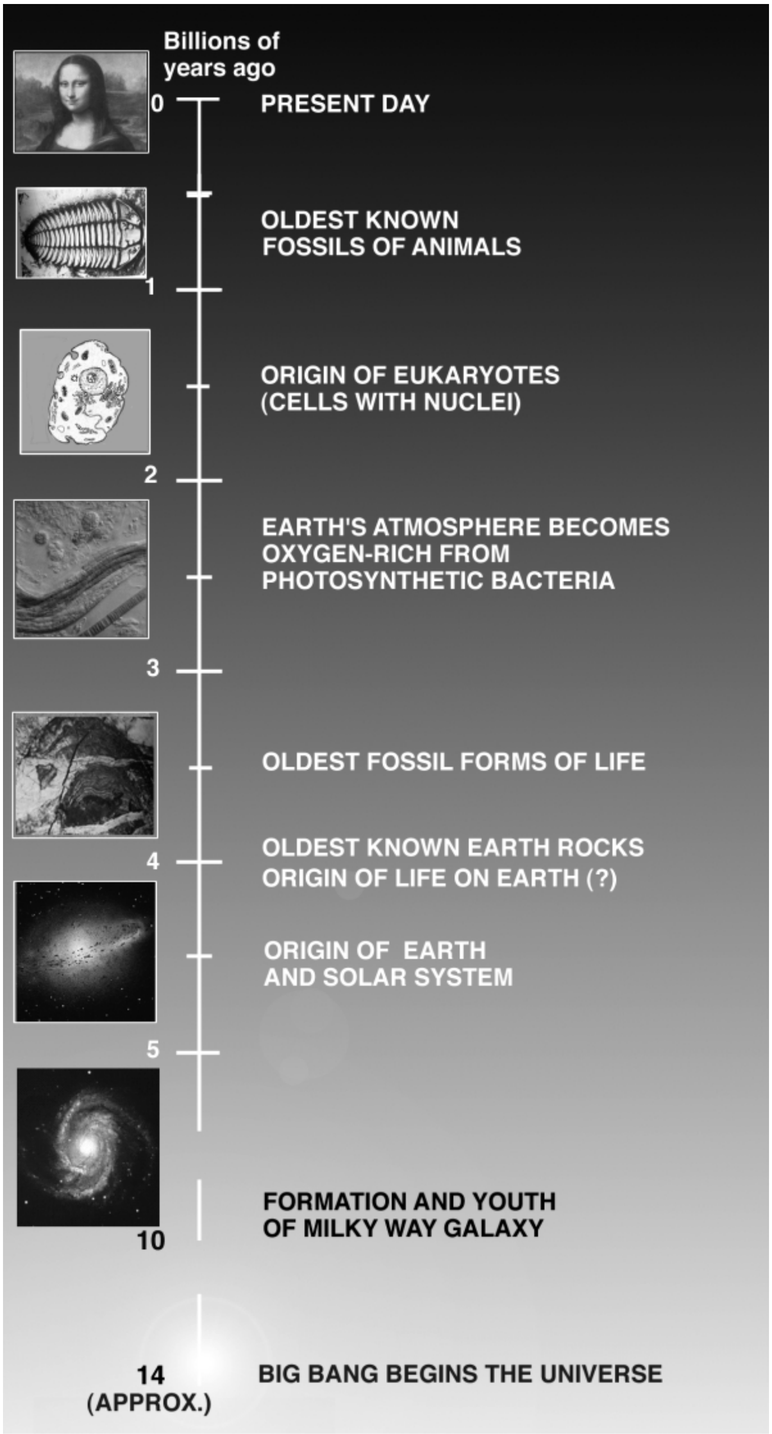

Figure 1.9 A timeline of the history of Earth and of our Milky Way galaxy shows that life has existed for most of our planet's 4.6-billion-year history. In constrast, complex forms of life (those with more than one cell) appeared only within the last one-sixth of the Earth's lifetime.

teria to the measured evolutionary changes in the genes that govern how creatures grow and function in life. But the existence, let alone evolution, of life beyond Earth remains completely speculative. Some feel that this reduces all such speculations to a fool's pastime. How can we study what we know nothing about? The answer to this question lies in the fact that we do know a great deal about the general principles of life in the universe, provided that life on Earth provides a fairly typical example. In simple terms, *if evolution made us what we are, then roughly similar conditions should have led to the development of roughly similar forms of life elsewhere*. This assumption frames the discussion throughout this book. Under it, our study of the evolution of the universe extends our perspective from life on Earth now, and the fossil record of bygone life, to the still more varied possibilities of life elsewhere, perhaps flourishing now, perhaps existing only in the past or yet to arrive in the future.

To study how life might have arisen and evolved far from Earth, we should first study how the universe itself has evolved. Then we can look for the likeliest sites for the origin and development of life, and see what "pre-life conditions" will most likely appear spontaneously in astronomical settings. We can then proceed to consider life on Earth and the conditions that prevail on objects within our solar system. Our goal will be to estimate the likelihood of life, and life's development into technologically advanced civilizations, throughout our galaxy and beyond. Could millions of civilizations already exist among the stars, perhaps delighting in the exchange of music, art, and recipes through radio and television contact? If so, it seems reasonable that we should seek to learn how we might join the galactic network, ending our cosmic loneliness forever.

A Conservative Approach to the Search for Life

On the other hand, we might be the only form of intelligent life in the Milky Way galaxy. This sobering thought arises from the fact that we have yet to discover a single form of extraterrestrial life. We must therefore engage in scientific speculation on many of the topics that bear upon the search for life in the universe.

In doing so, the authors have applied a conservative approach, one that recognizes a range of possibilities and attempts to examine most carefully those that appear most reasonable. For example, in Chapter 18, when we come to consider other civilizations that may exist in the Milky Way galaxy and beyond, we shall apply this approach in at least two different ways. First, we shall restrict ourselves to attempting to estimate the number of civilizations in our own galaxy and leave aside those that may exist in the numberless billions of other galaxies. We do this because the Milky Way provides a good example of a giant spiral galaxy, but even more because whatever civilizations may exist in other galaxies lie at distances so much greater than any distance within the Milky Way that two-way communication would be nearly impossible, according to our current understanding of astronomy and physics. Any civilizations outside the Milky Way therefore provide an "extra," possibly an enormous one, to add to our estimates, while our conservative approach concentrates on those civilizations with whom we might communicate.

Second, in examining how we might discover other civilizations, we shall focus our interest on civilizations that use means of communication, and in particular radio and television, much as we do. Other civilizations may well exist that have long since passed beyond this stage, or never entered it. Quite obviously, we can speculate far less intelligently about those civilizations than about civilizations that more closely resemble our own. In our conservative approach, we shall attempt to estimate the number of civilizations most like our own, leaving the others as a bonus, an additional contribution to the total that we should not forget, but that does not enter our calculations directly.

This conservative approach toward speculation on extraterrestrial life will also appear in our attempts to estimate the number of places in the Milky Way where life might have arisen, as well as the number of those places in which life did indeed appear and has evolved to produce what we would call an intelligent civilization. Our goal will be to obtain a range of estimates that reflects our uncertainties within a consciously conservative approach, one that recognizes the fact that we deliberately omit some of the possible "far-out" situations, such as life based on silicon atoms, in order to concentrate on those that appear more likely, or about which we have more certain knowledge. If some of the far-out forms of life actually exist, they will simply add to the total number of examples in our estimates.

Let us begin, then, to examine the universe, seeking to answer the age-old question, Are we alone? As is true in much of science, we shall start with basic, well-established facts, then proceed through new discoveries about the cosmos to reach arenas of fascinating speculation, grounded in reality and subject to verification, but embracing a universe of amazing possibilities.

Summary

Ever since scientists concluded that the origin and evolution of life on Earth has proceeded through natural causes, they have attempted to derive general principles from our knowledge of a single inhabited planet that would allow useful speculation about the possibility of finding living creatures on other worlds. In following these efforts, we should continue to use the organized skepticism that lies at the basis of science, attempting to test hypotheses against the evidence that may allow us to accept or reject them, and to find new tests and new evidence that will improve our knowledge of the universe. We now stand at the threshold of the era in which we should be able to establish communication with other civilizations in our galaxy, provided they are sufficiently numerous. By analyzing the situations likely to give rise to life and to communicating civilizations, we can estimate the difficulty of this effort and also gain new insight into the patterns of structure and evolution throughout the universe.

Key Term

plate tectonics

Questions

1. Why has the geological record of the Earth's first half-billion years completely disappeared?
2. How would you explain the public's fascination with Mars during the past few centuries? Compare your interest in Mars with your assessment of the general public interest.
3. What are the martian "canals"?
4. Compare the scientific approach to understanding the cosmos with others, such as theological, spiritual, and astrological efforts, in attempts to estimate the probability of life elsewhere in the universe. Do you feel that the scientific attitude is basically different from the others? Why?
5. Do you feel a sense of loneliness in contemplating the vast distances that separate planets and stars from one another? How do you imagine that your great-grandparents felt when they thought about the planets and the stars?
6. Do you believe that human beings have slowly evolved from other forms of living creatures, or instead that humans have their origin in the relatively recent past? What arguments can be made for each point of view? How can they be tested?

Further Reading

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