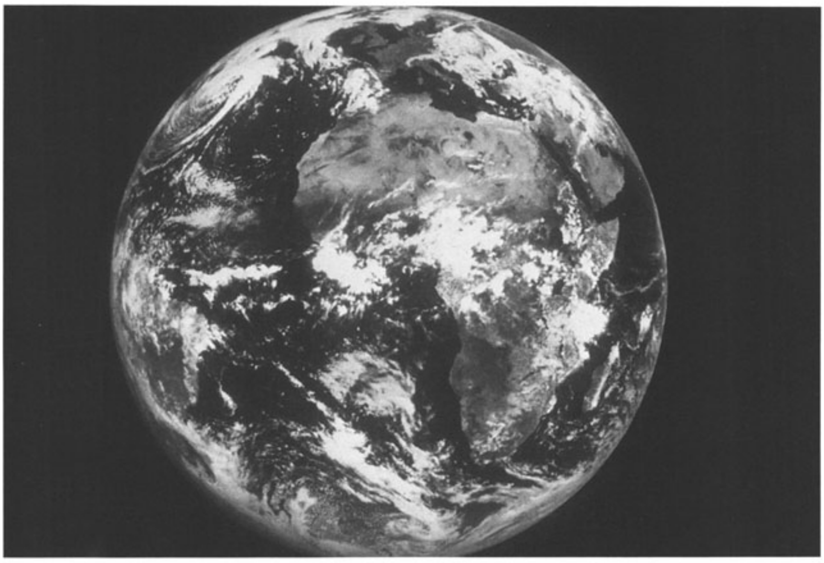
1 The search for life in the universe

The possible existence of life elsewhere in our solar system or in the universe is one of the most profound issues that we can contemplate. Whatever the answer turns out to be – whether life is present elsewhere or absent – our view of the world and our place within it will be dramatically affected. If a single example of even the most rudimentary life form can be found on another world, that will tell us that the origin of life is not unique to the Earth. We will not be able to help but wonder if intelligent life exists that is more advanced or more sophisticated than us. We will wonder whether the paths that we have chosen as a society are the most beneficial paths. Indeed, it would be a very humbling experience to realize that we are not alone in our existence. On the other hand, if no evidence is found suggesting other life, we may view the Earth and all its inhabitants with a narrow, pinhole focus that makes us unique, on an isolated plane within a vast universe. This view is well expressed in the thought, attributed variously to either the philosopher Bertrand Russell or the science-fiction writer Isaac Asimov, 'There are two possibilities. Maybe we're alone. Maybe we're not. Both are equally frightening.'.

Ours is the first generation that can begin to address in a thorough manner the scientific details of the origin of life on the Earth and the possibilities of the existence of life elsewhere in the universe. Although we do not understand the specific details of the origin of life on Earth, we have learned a great deal about the conditions that surrounded the earliest life. In addition, we have just begun to explore the rest of our solar system and to look for planets outside of it. Most of the planets in our solar system have been visited with spacecraft, and humans have walked on the surface of the Moon. Many details regarding the climate and habitability of the other planets are now understood, and the search for evidence of other life can begin. The *Viking* spacecraft was used to look for life on Mars in the late 1970s – none was found – but we now know that *Viking* might have been searching in the wrong place or with the wrong instruments.

The discovery in 1995 and 1996 of planets orbiting around other stars lends immediacy to the question of life in other solar systems. Although these planets were expected to exist, such expectations were built on theory rather than observation. Their actual detection is a discovery of paramount importance. Even though the new planets are for the most part more Jupiter-like than Earth-like, we can use their existence to begin constraining theories that apply to all planets. Certainly, Earth-like planets – planets with a solid surface, an atmosphere, and the possibility of liquid water on the surface – are expected to exist around other stars, but our telescopes are not yet able to detect them. Knowing that there are Jupiter-like planets, however, gives us impetus to search for Earth-like planets (Figure 1.1).



[Figure 1.1]
Satellite image of the whole Earth. Africa can be seen in the middle of the picture, and Saudi Arabia in the upper right. (NASA Photo.)

Recent advances in our understanding of terrestrial biochemistry also fuel the search for extraterrestrial life. They demonstrate that life can exist within a much wider range of environmental conditions and can utilize a much wider variety of sources of energy than was previously thought (Figure 1.2). They also suggest that there are many distinct ecological niches on the Earth that could have served as the location for the origin of life. Although we do not know for certain where life on Earth originated, we can appreciate that other planets might have life that began in any of several places. If life is as flexible as it appears to be based on our experience on Earth, then it is possible that a wide variety of planets, both within and outside our own solar system, might have originated life and be harboring it at the present. As much as the advances in astronomy and planetary science have opened up our view of the solar system and the universe, the advances in biology have opened up the possibility of abundant life in the universe.

The goal of this book is to present a broad-based view of the scientific underpinnings of the search for extraterrestrial life. And, we know more today than we have at any time in the past about what qualities a planet must possess in order to potentially contain life. We should recognize up front that there is no unambiguous evidence today that suggests the existence of any life in the universe other than on our own planet. This does not mean that there is no life, only that we have just begun the search. Our tools for scientific exploration are just reaching the point where we can

[Figure 1.2]
Photograph of tube worms located near a hydrothermal vent at an oceanic spreading center. They are typically up to two feet long and get their energy, ultimately, from geochemical energy contained in the mineral-rich hot water. (Photo courtesy of J. Childress.)

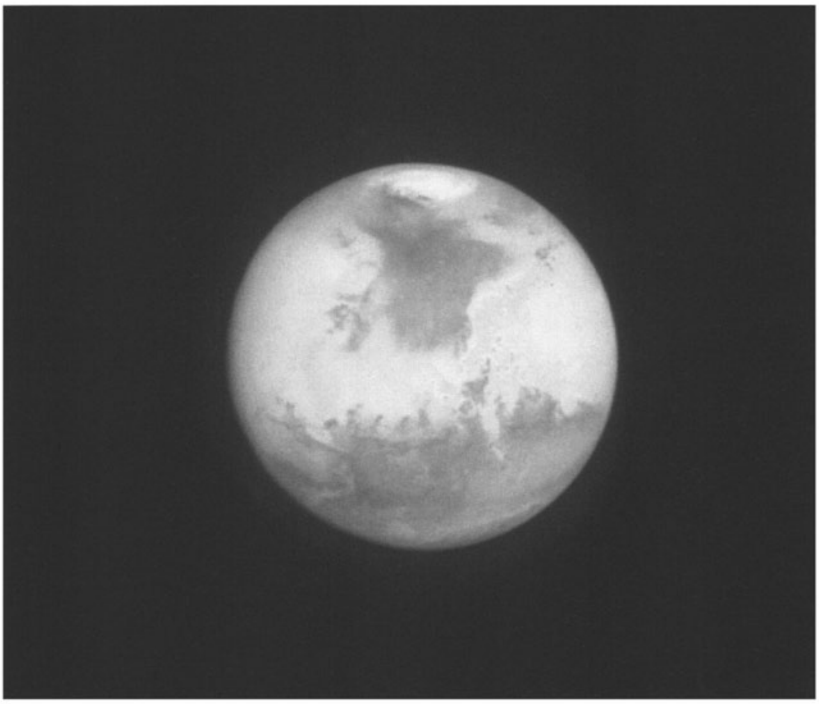
begin to address these questions meaningfully. The lack of evidence for life should be perceived as an absence of information rather than an absence of life or an indication that life might be unlikely to exist elsewhere.

The field of exobiology (or bioastronomy) – which deals with the study of extraterrestrial life – should be viewed in the broadest sense. Exobiology does not refer only to the study of biological activity on other planets (especially since we know of none today). It also refers to the occurrence of nonbiological and prebiological chemical processes, the distribution of planets within the universe, and the habitability of all planets. As such, it lies at the intersection of the traditional fields of geology, astronomy, planetary science, chemistry, and biology. Exobiology is an interdisciplinary field, touching on all aspects of science. And, because of the implications of the results of the search for extraterrestrial life, it also touches on issues that usually are the concerns of philosophy, theology, and other areas that normally are not considered to be a part of natural science.

The idea that life might exist on other worlds is not new to our generation, of course. As far back as the time of the ancient Greeks, several thousand years ago, the possibility of the existence of other worlds created substantial debate. Strong arguments were advanced on both sides. In favor, it was felt that the Earth and life on Earth were simply the agglomeration of a large number of smaller elements, and that these elements could come together elsewhere just as easily. Against, the Earth was felt to be at a special place in the universe – the center – and terrestrial life must be unique. Copernicus was able to argue more than ten centuries later, in the sixteenth century, that the Earth was not the center of the universe. With the recognition that the stars were objects similar to our own Sun, it was felt by many that planets must be located around them – otherwise the stars' existence would be wasted. As recently as the beginning of this century, the presence of advanced life on Mars was generally accepted by the public. Orson Welles' radio broadcast of *The War of the Worlds* in 1936 highlighted this belief and fueled the idea of alien invasion that now has become so popular.

Today, the views on other life in the universe are incredibly diverse. At one end of the spectrum are those who believe that the universe is widely populated by intelligent beings, that the Earth is regularly visited by aliens from outer space, that aliens show themselves to the world in the form of UFOs but have not formally announced their existence, and that humans and other animals are routinely being abducted by aliens for experimental study. At the opposite end, some argue that the Earth is absolutely unique in having life, and that there can be no other occurrence of life anywhere else in the universe. In between, a large fraction of the people – including many, but certainly not all, scientists – believe that life on Earth is a natural consequence of physical and chemical processes, and that life might have arisen independently any number of times throughout the universe.

If there is life on other worlds, the consensus among scientists is that the most likely form to be encountered would be analogous to terrestrial bacteria. On the Earth, bacteria-like, single-celled organisms formed very quickly after the Earth's formation, and they dominated the biosphere literally for billions of years. In fact, it wasn't until about two billion years after the formation of life on Earth, some 2.5 billion years ago, that any



[Figure 1.3]
Hubble Space Telescope image of Mars. The various bright and dark regions are visible, and the north polar ice cap is at the top. (NASA photo courtesy of S. Lee and P. James.)

entities larger than the simplest single cells left their mark; and, it wasn't until about 600 million years ago – after about 6/7 of the Earth's history to date had passed – that substantially more-complex life forms began to appear. In many ways, bacteria still can be considered the most widespread form of life on the Earth. Much of the discussion in this book will focus on the ability of the simplest life to occur and to exist. It is not likely that we will encounter intelligent or advanced beings in our search of the universe, given the low probability of intelligence arising elsewhere. However, this does not negate the importance of finding other life: from the philosophical perspective, finding life of any sort is just as important as finding intelligent life. It would demonstrate that life was widespread within the universe rather than concentrated only on a single world.

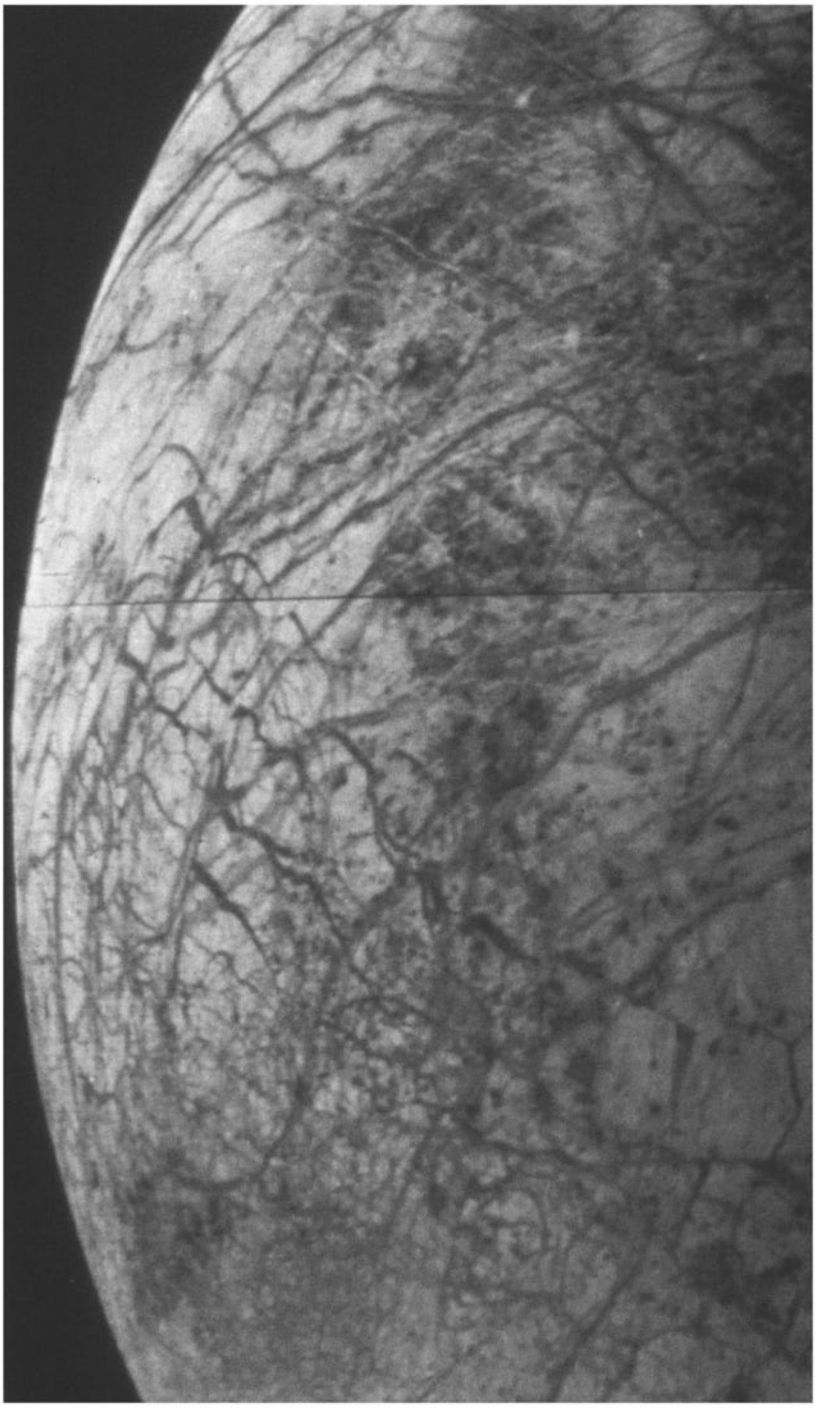
The most likely place within our own solar system for finding other life is the planet Mars (Figure 1.3). Although Mars is relatively cold and dry on its surface today, it certainly was not so in the past. The geological evidence that we see shows that liquid water has been present on Mars throughout much of its history. Liquid water is the single environmental requirement thought to be essential for life. With abundant water being present, environmental conditions on early Mars may have been similar to the conditions on the Earth at the same time. This was a time when life was forming on the Earth, and life may have been forming on Mars independently from the Earth. In addition, it is possible that terrestrial life might have been exported to Mars in its early history, by the impact of an asteroid onto the Earth's surface and by the ejection of rocks containing bacteria into space. Even if Mars does not harbor life today, it still is an important target in the search for extraterrestrial life. If there is no life on Mars, and no evidence for a past existence of life, it would then be important to understand what caused the Earth and Mars to differ so dramatically in their outcomes.

There are other possible abodes of life in our solar system, however. It is possible to imagine that life might exist on Europa or Io, both of which are satellites orbiting around Jupiter (Figure 1.4). Although Io does not have any visible evidence of water, it has an obvious source of energy in its abundant volcanic activity. Europa, on the other hand, has large amounts of water – as ice on the surface and maybe as a 'mantle' of liquid only kilometers below the surface. In fact, even Jupiter could conceivably harbor life in its atmosphere, feeding on the organic compounds that are present there (Figure 1.5).

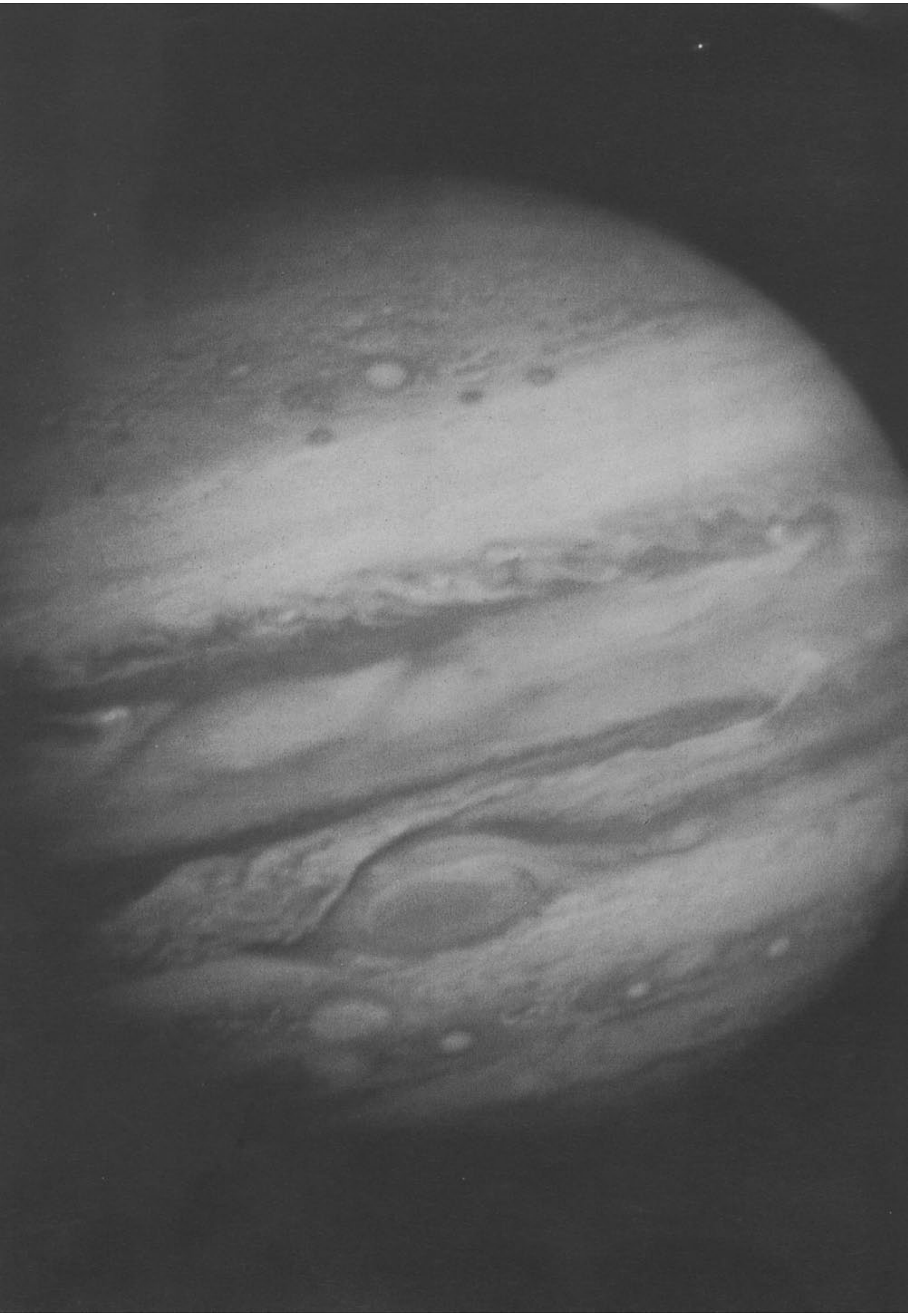
And, of course, there is the possibility of life existing on planets around other stars. Based on theory (and now on observations), we expect to find planets around other stars, and we expect some of them to have conditions that are suitable for the origin and the continued existence of life.

Throughout the rest of this book, we will proceed systematically through the issues pertaining to the possible existence of extraterrestrial life. Of course, such a discussion requires knowledge of the properties of life on the Earth, since that is our only example of life. We will begin with a discussion of the requirements for the occurrence of life on Earth: What were the environmental conditions on the Earth just after its formation? When did the climate and environment first become suitable for the continuous existence of life? What was the earliest life like and, based on the geological evidence, when did it first appear? How does life function? How does it obtain energy from its environment and use this energy to power metabolism and reproduction? In what types of environments can life exist? These will serve as constraints for discussing the origin of life. Although we do not know for certain how life first began, we do have an understanding of what the relevant processes were likely to have been.

Once we understand the conditions that allowed life to occur on the Earth, we can begin to address the question of life elsewhere. Is there life in the rest of our solar system? Rather than proceed through a lengthy discussion of each planet, we will focus on the most likely and most interesting



[Figure 1.4]
Image of the Europa surface, taken from the *Voyager* spacecraft. (NASA photo.)



habitats for life. Could life have originated on Mars, and could it possibly have survived up until the present? Can we reach any conclusions about martian life based on the recent analysis of meteorites that are thought to have come from Mars? Although Venus is not a suitable location for life today – because of its extremely high surface temperatures – might it have been at some time in the past? What about Io and Europa, where sources of energy and water might exist and potentially could be tapped by life? What about Titan, a satellite of Saturn, which has an atmosphere rich in organic compounds that may be similar to the prebiotic terrestrial atmosphere? Although not a part of exobiology *per se*, we will include a brief discussion concerning the possibility of 'terraforming' Mars – of changing its environment to one more like that of the Earth, on which terrestrial plants or animals might survive – and we will address the moral and ethical issues involved.

Finally, then, we will turn our attention to the rest of the universe. Based on our understanding of how stars and planets form, do we expect planets, and Earth-like planets in particular, to be a common occurrence? What are the properties of the planets that have been discovered, and what do they tell us about our understanding of the processes by which planets can form? What are the prospects for detecting planets around other stars, and Earth-like planets in particular? What conditions would make other planets habitable, given what we know of the requirements for life? Are habitable planets likely to be abundant, or are they likely to be rare? And, what about the possibility of intelligent life elsewhere in the universe? Is intelligent life likely to exist? How can we communicate with other intelligent species if they do exist?

Life in the context of the universe

In order to begin a discussion of whether life can exist elsewhere in the universe, and to be able to put the relevant issues into the proper broad context, it is useful to begin with a simple framework describing the rest of the universe. This will provide us with a larger context into which we can place the specific details regarding life. In the rest of this chapter, then, we will summarize the origin and evolution of the universe, the galaxy, and the solar system. This will provide us with a sense of the physical scale and of the timescales with which we are dealing.

The universe is estimated to have originated about 15 billion years ago. This estimate was calculated by looking at the current rate of expan-

[Figure 1.5]
Jupiter, as seen from the *Voyager* spacecraft. The Great Red Spot is visible, along with the belts and zones in the clouds. (NASA photo.)

sion of the universe, since all of the galaxies in the universe currently are moving away from each other. Extrapolating backward in time, 15 billion years ago is the time at which the entire universe would have been concentrated in a single point. Because the universe was much denser at that time than it is today, it was much hotter; at time zero, when everything was theoretically at a single point, the temperature would have been infinite. What existed prior to the occurrence of this singularity? There is no way to know. Time would have had very little meaning at that instant, so there may not have been a time prior to the existence of our present universe. Because the universe appears to be expanding from a single point, this theory for the origin of the universe is referred to as the Big Bang theory. Although there still is debate about the exact age of the universe and the rate at which it is expanding, the uncertainties do not affect the overall conclusion that it is expanding or the subsequent history of galaxies, stars, and planets.

As the universe expands, it slows down due to the gravitational pull from all of its mass. Will it eventually slow down enough to stop expanding? If it does, it will then begin to collapse, and would end up the same way it began – as an infinitely dense singularity. We do not know if this will happen – it depends upon the total mass of the universe and the rate of expansion. The mass that we can identify, in the form of galaxies, stars, and clouds of dust and gas, is not sufficient to stop the expansion and make the universe 'closed'. However, there may be large amounts of mass that we have not yet identified – planets that haven't been detected, stellar or substellar objects too faint to be seen, black holes, or even undetectable elementary particles – so no conclusions can be drawn yet as to whether the universe is open or closed.

At the time of the Big Bang, matter composed of atoms as we think of them would not have existed. Rather, the universe would have consisted of pure energy. As it expanded and began to cool off, from initial temperatures so large that the number is essentially meaningless to us, the energy would convert into matter, first to elementary particles and then to protons, neutrons, and electrons. As mass is created out of energy, about 90% of the mass would be in the form of hydrogen and 10% as helium. Essentially none of it would be composed of the heavier elements; these came later. Some of the energy from the earliest periods remained in the form of radiation; as the universe expanded, the radiation cooled and can be detected today as what is called the '3 degree background radiation', which is detected uniformly in all directions in the universe.

As the universe continued to expand, local swirls and eddies of matter produced regions that were dense enough to begin to collapse under their