· Chapter One ·

Past Thinking about Earth-Like Planets and Life

Are there other planets like Earth and, if so, do they support life? These two questions motivate NASA's proposed *Terrestrial Planet Finder* missions, which are at the heart of this book. These missions, and much of what is discussed in this book, are entirely new. But the questions themselves are fundamental in nature and have been discussed for a long time. The issue of whether or not the Earth was unique was debated in the 4th century BC by the Greek philosophers Aristotle and Epicurus. Aristotle, like his teacher Plato, thought that there could be only one Earth:

> Either, therefore, the initial assumptions must be rejected, or there must be one center and one circumference; and given this latter fact, it follows from the same evidence and by the same compulsion, that the world must be unique.[1]

Epicurus, who lived slightly later, disagreed. Epicurus believed that all matter was composed of microscopic atoms, and this idea led him to postulate the existence of many different worlds. Around 300 BC, in a letter to Herodotus, he wrote: "There are infinite worlds both like and unlike this world of ours" inhabited by "living creatures and plants and other things we see in this world."[2]

Unfortunately, as Mike Devarian of NASA's Jet Propulsion Laboratory in Pasadena is fond of pointing out, Epicurus died painfully (of a bladder infection) in 269 BC, and support for his views died with him. And so the Earth-centered picture of the Universe prevailed for more than 1800 years after Aristotle's death. Aristotle's view of astronomy was further elaborated by another Greek philosopher, Ptolemy, who lived from AD 90 to 168. Ptolemy developed a complicated scheme for predicting the orbits of the five known planets: Mercury, Venus, Mars, Jupiter, and Saturn. This scheme, which became known as the Ptolemaic system, was remarkably successful, even though it was based on physically incorrect principles. To explain the apparent retrograde motions of the three outermost planets—the fact that they appear to reverse their motion across the sky at some times during the year—Ptolemy postulated that the planets moved in small circular *epicycles* superimposed on larger circular orbits around the Earth. This Earth-centric view of the Solar System was later backed by the Roman Catholic Church, whose clergy found this way of thinking to be in accord with their own teachings about God and about man's place in the universe. So it was not surprising that it dominated astronomical thinking for more than 1500 years.

The Ptolemaic system remained unchallenged until the early 16th century, when the Polish mathematician/astronomer Nicolas Copernicus published a new theory in which he postulated that the Sun was at the center of the universe and that the Earth and all the other planets revolved around it. In his theory, the apparent retrograde motion of the planets was explained by the changing vantage point of the Earth as it moved around the Sun and the fact that the Earth moves more quickly than do the planets beyond it. It was not until early in the next century that the critical test of the two theories was made. The Italian mathematician Galileo, using a telescope that he improved upon, but did not invent, discovered that Venus and Mercury exhibited phases, like the Moon. This observation was consistent with the Copernican view of the universe, but not with the older Ptolemaic view. Tycho Brahe had an intermediate theory, in which the other planets went around the Sun, while the Sun went around the Earth, and this could not be disproved by Galileo's observations. The Catholic Church supported the modified

Ptolemaic system, and Galileo was threatened with execution if he did not renounce his support for the Copernican model. As every graduate of a first-year general astronomy class knows, Galileo recanted and was spared, but he spent the remainder of his life under house arrest. So things continued to go poorly for astronomers who believed that the Earth was not unique.

The patron saint of planet-finders, though, is Giordano Bruno. Bruno was an Italian philosopher who lived in the late 16th century. Bruno was a gadfly who held all sorts of beliefs that conflicted with Catholic Church doctrine. He was also a believer in the existence of other Earths and in extraterrestrial life. In his book, *De L'infinito Universo E Mondi*, published in 1584, Bruno wrote:

> There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system . . . The countless worlds in the universe are no worse and no less inhabited than our Earth.

For this and other heretical statements, Bruno was sentenced to be burned at the stake. Unlike Galileo, Bruno refused to recant, and the sentence was carried out in the year 1600 in Campo dei Fiore, Rome, where a statue of Bruno can be found today (figure 1.1). Today, as Devarian notes when consoling frustrated would-be planet-finders, scientists may lose their funding, but the other consequences of their activities are fortunately much less severe.

The Habitable Zone and the Importance of Liquid Water

In modern times, the question of whether habitable planets exist has been taken up by mainstream scientists. The idea that stars were other suns took hold, and researchers, including the French mathematician Laplace, developed theories for how planets might form around them. It did not take too long for some astronomers to again start speculating about whether any of them might be habitable. In a book written in 1953,

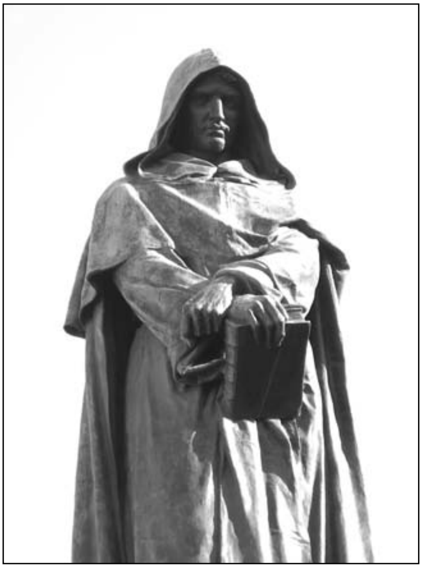

Figure 1.1 Statue of Giordano Bruno in Campo dei Fiore, Rome. Bruno was an early advocate of the existence of other worlds who was executed for his beliefs.[3]

the famous astronomer Harlow Shapley defined what he termed the "liquid water belt" as being that region in a planetary system in which liquid water could exist at a planet's surface.[4] In making this distinction, Shapley was acknowledging something that biologists had been aware of for many years, namely, that liquid water is essential for all known forms of life. Although some organisms, notably those that form spores, can survive for long time periods in the absence of water, none of them can metabolize or reproduce unless liquid water is available.

Biology depends on liquid water for reasons that make good sense from a chemical standpoint. The water molecule has a bent shape, as shown in figure 1.2. Electrons are more attracted to the oxygen atom in the middle than to the hydrogen atoms at the two ends. This makes water a highly *polar molecule*, and that in turn makes it a powerful solvent for other polar molecules. (A polar molecule is one, like the water molecule, in which the electrons are concentrated toward one end.) Terrestrial life consists of various complex, carbon-containing compounds, most of which are polar and thus soluble in water. One can, of course, imagine an alien life form that might utilize some other polar solvent, or

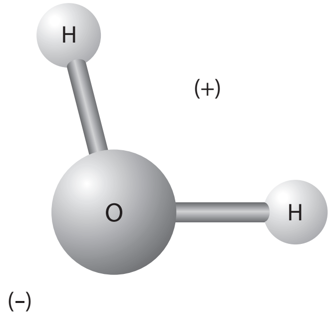

Figure 1.2 The geometry of the water molecule. The side closest to the hydrogen atoms is positively charged. The opposite side is negatively charged. The separation of charge in this molecule has important implications, both for planetary habitability and for life.

even one that is not carbon-based, like us. But for most biologists, and for astronomers like Shapley as well, the idea of looking for life on planets that contain water seems like a good place to begin.

Astronomers are not at all dismayed that liquid water is needed for life, because water is thought to be one of the most abundant chemical compounds in the universe. The two atoms from which it is formed, hydrogen and oxygen, are the first and third most abundant elements—helium is second—and they are present in high concentrations in nearly all stars. Hence, planets around most stars might be expected to contain H_2O. We shall see later on that the amount of H_2O may differ greatly from one planet to another, and so we should not expect that all planets should have as much water as does Earth. But this is not a reason to be pessimistic. There could still be many planets with enough water to support life.

Liquid water has other properties that may contribute to creating stable, life-supporting planetary environments. The highly polar nature of the H_2O molecule also gives liquid water an extremely high *heat capacity*. The heat capacity of a substance is a measure of how much heat, or thermal energy, must be added to it to raise its temperature by a given amount. The high heat capacity of water arises because the positively charged ends of some water molecules are attracted to the negatively charged ends of other molecules, forming what are referred to as *hydrogen bonds*. When water is heated, much of the added energy goes into loosening the hydrogen bonds between the individual molecules, and thus less of it is available to make the molecules move faster, and thereby raise its temperature.

The fact that the temperature of liquid water changes relatively slowly has important implications for Earth's climate. Coastal regions, for example, are more temperate than continental interiors. The reason is that the high heat capacity of the ocean greatly reduces its seasonal cycle in temperature. Land surfaces, by contrast, have relatively low heat capacities and more pronounced seasonal cycles. This difference between land and sea may become even more important on planets whose orbits are less circular (or more *eccentric*) than Earth's orbit, or whose *obliquities* are higher than Earth's. (A planet's obliquity is the tilt of its spin axis with respect to its orbital plane. Earth's obliquity is 23.5 degrees.) On such planets, land surfaces could become either extremely hot or extremely cold at different times during the year, rendering them uninhabitable. But ocean temperatures would fluctuate much less, and so marine life would be less likely to be affected by these factors. So liquid water is important both for the chemistry of life itself and for the habitability of planets on which life may evolve.

We should also note, right from the start, that planets that lack liquid water at their surfaces, and so are outside of Shapley's "liquid water belt," could still be habitable if they have subsurface liquid water. Mars is one example of such a planet. Although its surface is entirely frozen, computer models predict that liquid water might be present at a depth of several kilometers, as a consequence of the continuing flow of heat from the planet's interior. If so, then microbes similar to terrestrial methanogens, single-celled organisms that make a living converting carbon dioxide and hydrogen (and assorted organic substrates) into methane, could conceivably be present. Reported observations of methane in Mars' atmosphere, discussed further in chapter 8, could be evidence for such subsurface life. Jupiter's moon, Europa, may also harbor subsurface water, and so could be an abode for carbon-based life. (This idea was anticipated many years ago by science fiction author Arthur C. Clarke in his novel *2010: O dyssey T wo*. Clarke envisioned squid-like creatures swimming in Europa's subsurface seas.) Both Mars and Europa are high on NASA's priority list as destinations for unmanned, and eventually manned, planetary probes. These priorities are well justified—after all, nothing would be of greater interest to astrobiologists than the chance to actually find and study an extraterrestrial organism.

For astronomers interested in the possibility of life on planets around other stars, however, Shapley's restriction of the liquid water belt to planets possessing surface liquid water makes sense. For the time being, at least, the stars are too distant for us to explore directly. Any observations that we may make of planets orbiting around them will be obtained using telescopes based either on Earth or, more likely, in space. We may indeed be able to study such planets by using spectroscopy, as pointed out in the preface to this book. But we will be looking at the planet's atmosphere and surface, not at the (putative) organisms themselves. For life to be able to modify a planet's atmosphere in a detectable way, it needs to be present at the planet's surface.* That way, it can take advantage of the abundant energy from the planet's parent star to colonize the planet's surface and to modify its atmosphere, just as photosynthetic organisms have done on Earth. We will return to the topic of the liquid water belt, also called the *habitable zone* or *ecosphere*, in chapter 10, as it is a key concept in the search for Earth-like extrasolar planets.

Carl Sagan and the Drake Equation

In the last 40 years, the question of whether life might exist elsewhere in the universe has been popularized by the famous astronomer Carl Sagan. Sagan was interested not just in whether life exists elsewhere, but also in whether intelligent beings might exist, with whom we might one day make radio contact. In his 1966 book, *Intelligent Life in the Universe*,[5] coauthored with Soviet astrophysicist I. S. Shklovskii, Sagan expressed the odds of making contact in the form of a mathematical relationship

*The possible detection of methane in Mars' atmosphere, which *may* be biogenic, could negate this statement. The upper limit on martian methane, however, is 10–100 parts per billion, which is just barely detectable from nearby Earth, and far too low to detect from interstellar distances. Thus, from a practical standpoint, life does need to be present at a planet's surface in order to create a detectable atmospheric signature.

that is usually called the Drake equation, although Sagan himself had a hand in crafting it and is said to have preferred the name "Sagan-Drake equation." Frank Drake is a radio astronomer who headed the SETI (Search for Extraterrestrial Intelligence) Institute for many years. Drake and Sagan developed their equation to help guide the discussion at a meeting on intelligent life in the universe held at the Green Bank Radio Observatory in 1961. The equation estimates the number of advanced, communicating civilizations in the galaxy, N, to be equal to the product of seven parameters:

$$N = N_g f_p n_e f_{cl} f_i f f_L$$

Here, N_g is the number of stars in our galaxy; f_p is the fraction of stars that have planets; n_e is the number of Earth-like planets per planetary system; f_l is the fraction of habitable planets on which life evolves; f_i is the probability that life will evolve to an intelligent state; f_c is the probability that intelligent life will develop the capacity to communicate over long distances (for example, by radio telescope); and f_L is the fraction of a planet's lifetime during which it supports a technological civilization.

The Drake equation cannot actually be solved, as it involves several terms—the last four in particular—that no one knows how to evaluate. We will nonetheless make an attempt to do so in chapter 15, using information gleaned from the studies described in this book. For now, let us stick to what was already known before the modern extrasolar planet-finding era began. Based on detailed star counts in representative areas of our galaxy, the leading term, N_g, is about 4×10^{11}, or 400 billion. Hence, if the other factors are anywhere close to one, then N should be a large number, and there might well be intelligent civilizations that would be close enough to converse with, albeit slowly, using radio telescopes like the giant Arecibo telescope shown in figure 1.3 (see color section). Sagan himself was an unapologetic optimist on this question. His estimated value for N from his later book *The Cosmic Connection*[7] was 1 million. If that number is correct, then the nearest intelligent civilization is probably no further than a few hundred light-years from Earth.

Whether other intelligent beings exist is, as Sagan realized, the question that we would all ultimately like to answer. And the SETI Institute exists to try to do just that. Many scientists, however, would be happy for now if we could just evaluate the first four terms of the equation, which together would give us the probability of the existence of habitable planets and life. We will focus on those terms in this book, bearing in mind that even if we are successful in estimating them, the ultimate question of whether extraterrestrial intelligence exists remains to be addressed.

As a footnote to this discussion, I should note that at the time of this writing (early 2008), the Arecibo radio telescope is in danger of being shut down because of lack of funding (most of which comes from the U.S. National Science Foundation). The reasons for its financial troubles have nothing to do with SETI, which does not even use the telescope at the present time, and which only "piggybacked" on other, unrelated telescopic searches even at the best of times. The closure of Arecibo would eliminate a powerful tool that could potentially be used to search the galaxy for evidence of extraterrestrial life. But there may be other ways to do this (see chapter 15), and so I will leave it to the astronomers to decide how best to deal with the future of Arecibo.

Other Perspectives on Planetary Habitability: Rare Earth and Gaia

Not all modern authors are as optimistic as Carl Sagan about the possibilities for life elsewhere. In their book *Rare Earth*, published in 2000, Peter Ward and Donald Brownlee offered up a direct challenge to his ideas.[8] Ward is a paleontologist who has studied impacts and mass extinctions and who has written several other popular books. Brownlee is an astronomer (and a distinguished member of the National Academy of Sciences) who is famous for his measurements of the interplanetary dust particles that fall into Earth's atmosphere from space. Indeed, these tiny bits of material are sometimes referred to as "Brownlee particles" in his honor.

The thesis of *Rare Earth* is that complex life—by which the authors mean animals and higher plants—is rare in our galaxy, and presumably throughout the universe. Humans and hypothetical aliens are both animals, of course, and so this would imply that intelligent life is also rare. Simple, unicellular life may be widespread, according to this hypothesis; the authors do not suggest that life itself is uncommon. But, from their point of view, Earth offers a uniquely stable environment for the development of higher plants and animals, for a variety of reasons. High on their list are the operation of plate tectonics (which Ward and Brownlee consider to be an unusual geological process) and the stabilization of Earth's spin axis by the Moon (which, as virtually everyone agrees, formed as the result of a statistically unlikely glancing collision with a body the size of Mars). In their view, these and other cosmic accidents permitted complex life to evolve on Earth, but it is highly unlikely that this same evolutionary pathway would have been followed on any other rocky planet. Humans are therefore probably alone in the galaxy.

The predictions of *Rare Earth* are not likely to be directly tested in the near future. The planet-finding missions discussed in this book will most likely be incapable of distinguishing between microbial life and complex, multicellular life. We shall return to *Rare Earth* in chapter 9, however, because many of the issues that Ward and Brownlee raise are relevant to more general issues of planetary habitability and thus bear directly on the question of whether other Earth-like planets exist. Also, we will need to consider the question of complex life as well if we hope to make an estimate for the number N in the Drake equation.

An alternative, completely different approach to planetary habitability is the *Gaia hypothesis* put forward by James Lovelock and Lynn Margulis. The name is taken from Greek mythology, in which Gaia was the goddess of Mother Earth. Lovelock is a British scientist and inventor who has written a series of books on his hypothesis.[10-13] Margulis is an American biologist, previously married to Carl Sagan, who is famous for her contributions to evolutionary theory, particularly her development of the concept of *endosymbiosis*—the idea that certain organelles within eukaryotic organisms (including plants and animals) are the result of the past incorporation of other free-living organisms. In their

Figure 1.4 Painting of Gaia, the Greek goddess of Mother Earth.[9]

papers and books, Lovelock and Margulis have argued that life itself has played a critical role in keeping the Earth habitable throughout its 4.5-billion-year history. The theory stemmed originally from Lovelock's analysis of the *faint young Sun problem*, which we discuss in chapter 3. Lovelock suggested that photosynthetic organisms drew CO_2 out of the atmosphere at just the right rate to compensate for steadily increasing solar luminosity over time. Although the biota in Lovelock's model exerted no conscious control over this process, he nevertheless suggested that they act as a cybernetic control system that counteracts such perturbations and that has moderated Earth's climate throughout its history. If this hypothesis is valid, a planet might need to be inhabited in order to remain habitable. And if this in turn is true, then the question of whether other habitable planets exist is inextricably linked to the question of whether life has originated elsewhere than on Earth. We will return to Gaia, too, in chapter 9 to see whether or not we agree with Lovelock's theory.

The foregoing brief history of thinking about habitable planets is by no means complete. Many other scientists and philosophers have speculated about whether habitable planets and life might exist elsewhere. As we have seen, the debate has been carried out sporadically for literally thousands of years and remains unresolved at the present time. But this question is now timely and exciting because, as we shall see, astronomers are on the verge of being able to answer these questions observationally. If they can manage to do so, and especially if evidence for Earth-like planets and life is found, the philosophical implications would be profound. Indeed, such a discovery would be no less world-shaking than Galileo's proof that the Earth goes around the Sun.