Chapter 1
Introduction

Astrobiology studies the origin, evolution, distribution, and fate of life throughout the Universe, with no direct evidence that life exists anywhere in the Universe other than on Earth. But there are compelling reasons to assume that life exists pervasively throughout the cosmos. That assumption derives from empirical observations on the nature of the Universe and the natural laws that govern it, from analysis of the history and properties of the one case of life that we do know, and on a logical integration of fact and theory. The science of astrobiology is thus as strong, if not as revolutionary, as Darwin's theory of evolution before fossil humans were found to prove our animal origins; as firm, if not as precise, as the astronomical predictions that Neptune must exist before it was detected; and, in our view, as certain as the conclusion that the world was a sphere before Magellan sailed around it.

This book sets forth the argument that life occurs numerous times throughout the Universe. It further makes predictions about some likely characteristics of that life in most cases, explores the limits of diversity that might be found in forms of life on other worlds, and attempts to strain conventional thinking about the fundamental nature of living systems. At the same time, this book asks for no suspension of belief in or extension beyond the laws of chemistry and physics as we understand them now. It does not make predictions of a specific nature, where no basis for specificity exists. We offer our assessment about probabilities, but base those assessments on facts open to verification and a line of reasoning that invites the critical assessment of our fellow scientists. Like Darwin's arguments about the mechanism of evolution, we know that our vision of life in the Universe will change through subsequent insights and observations. As the predictable discovery of Neptune gave no indication of the altogether unpredictable planetoid Pluto yet to be discovered, we realize that surprises not anticipated by us will emerge when the reality of life on other worlds is confirmed. And finally, like Magellan, we fully expect some of our calculations about life in the Universe to miss their mark. But we do believe we have sketched a vision of cosmic biology that is tenable and therefore of predictive value in designing missions to search for and detect the life that is surely out there.

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The argument that life exists on other worlds is straightforward and simple. It begins with the definition of life as a self-perpetuating organization of complex chemistry that uses free energy to maintain disequilibrium with its environment. It continues with the observation that wherever chemical heterogeneity and a source of free energy are found, the capability for life exists. It notes that our own planet, which had an abundance of both energy and complex chemistry from its earliest age, gave rise to life (or was able to sustain life introduced from another place) almost as soon as the heavy bombardment of the planet receded. It assumes that the laws of chemistry and physics act in the same way throughout the Universe. It points to the vast numbers of stars in the Universe, and the possibility that the total number of planets will be even larger. The argument concludes: even if the probability on any given planetary body is low that an appropriate combination of energy and chemistry is available to enable the development of sufficient complexity for life to emerge, the enormous number of planetary bodies that must exist in the visible part of the Universe alone strongly suggests that life has arisen redundantly. Since the physical laws of nature pertain equally, we assume, over the entire extent of the Universe, wherever those laws allow the formation of life to occur, it will. Hence, life must be widespread as well as high in numerical frequency.

We should emphasize that we do not argue that life is common. The complexities of form and function that constitute the living state are highly improbable in a statistical sense, and probably arise only under a restricted set of circumstances. The second purpose of this treatise is to critically examine what those circumstances are. To the extent that our Solar System is exemplary (we cannot yet say that it is typical), the conditions that exist on Earth, where a large range of microscopic to macroscopic forms of life have diversified, appear to be very rare. We think, therefore, that the extent of biodiversity that we see on Earth is very seldom seen anywhere else. Among the organisms that thrive on our planet, however, are many microscopic forms that potentially could occupy a number of other sites in our Solar System, as carbon polymer and water-based life essentially as we know it. In addition, however, there are circumstances substantially unlike those with which we are familiar on Earth, under which life in forms unknown to us could arise and exist, in theory. Those circumstances are found within our Solar System, and are likely to be found beyond it in abundance. The circumstances that would allow for the origin and persistence of life are not unlimited, however. Much of this work is devoted to assessing what those limits might be.

Our analysis begins with four facets that are essential to life: energy, chemistry, solvent, and habitat. To provide the reader with an overview at the outset, a brief abstract of our analysis of the possibilities and limitations of each of these facets is given below.

Energy in many forms is abundant throughout the Universe. Electromagnetic energy at wavelengths visible to humans is a prominent product of the fusion reaction in all the visible stars. On Earth, a photosynthetic mechanism has evolved to capture that energy and transform it into chemical bonds with an efficiency that is difficult for any other form of energy to match. Where light is available, it thus provides an efficient, isothermal source of energy well matched to the needs of living systems. However, both inorganic and organic chemical bonds contain energy that is harvested by all non-photoautotrophs on Earth, so far as we are aware. As long as these sources of chemical energy remain available, either from cycling or a reserve not yet exhausted, they likewise provide an efficient basis for bioenergetics. Other forms of energy could in principle substitute to varying degrees light and chemical energy that support the forms of life with which we are familiar. Our theoretical calculations suggest that osmotic and ionic gradients, and the kinetic motion of convection currents, provide plausible alternatives. Thermal gradients are among the most widely available sources of energy flow, but the gradients are easily degraded and are thermodynamically inefficient. Magnetospheric energy, gravity, pressure, and other exotic forms of energy likewise could conceivably be harvested by living systems, but the amount of energy that they provide within our Solar System generally does not appear to make them competitive with light, chemistry, osmotic and ionic gradients, or convective currents as likely sources of free energy for the support of living systems.

All life as we know it resides in complex polymeric chemistry based on a covalently bonded carbon backbone. A systematic examination of carbon chemistry provides an impressive list of advantages that carbon has over any other compound, not only in forming the vast array of molecules required for complex systems, but by enabling the right combination of stability and flexibility for molecular transformations that underlie the dynamic complexity of life. In aqueous systems at temperatures common on Earth, carbon is so far superior to any other atom as a polymeric unit, that it has come to be the only basis for the structure of biomolecules essential for all basic metabolic processes. Silicon is the one other atom with properties similar to carbon, and its potential usefulness in living systems is shown by the fact that it too is an important constituent of many living cells. In most cases, it serves a rather passive structural role, as in the cell walls of plants, and the exoskeleton of diatoms and some other organisms. These examples could represent residual functions from a time in the history of life when silicon played a more central role, only to be replaced more effectively by carbon at a later stage. A detailed look at the chemistry of polymeric silicon reveals that it conceivably could have the combination of stability and lability exhibited by carbon, but under very different conditions, both at temperatures much higher and much lower, and in the presence of solvents other than water. Carbon bonds with oxygen and nitrogen to form parts of the polymeric chains of biomolecules, and mixed atomic backbones involving other compounds are a possibility. They already occur in some biomolecules of terrestrial life such as DNA but may be much more common elsewhere. A few other atoms have the capacity for the formation of covalent polymers, but they either occur in such low abundance, or have such inferior characteristics, that they seem a highly unlikely basis for an alternative living system.

Life as we know it requires a liquid medium. It can survive periods of dehydration, but appears to need a liquid for its dynamic transactions. We examine in some detail why life is much less likely to reside exclusively in a gaseous or solid medium. We also consider whether water is the only suitable solvent for a living system. Water does have some striking advantages, particularly with respect to carbon-based molecular interactions. At temperatures and pressures prevailing on Earth, and beneath the surfaces of numerous other planets and planetoids in our Solar System, water can exist in liquid form, and thereby provide the potential reservoir that carbon-based molecules need for their vast array of interactions. On the other hand, most of the Solar System, like most of the Universe, is very unlike Earth. For smaller planetary bodies distant from a star, temperatures are much colder than on Earth. This probably represents the vast majority of planetary bodies. At those sites, water cannot be liquid (absent a source of internal heat), but methane, ammonia, ethane, methyl alcohol, and related organic compounds might be. In principle, many of them are compatible with carbon-based polymeric chemistry, and thus should be considered as possible solvents capable of supporting life. On very large planetary bodies, or on those that are tectonically active or close to a central star, very high temperatures may prevail. Under those circumstances other compounds can exist in the liquid form. In some of those cases, silicon-based polymers appear more feasible. There is no question that water is an excellent solvent for living systems, but under conditions where it cannot exist as a liquid, a few other solvents can exist in that state, and could support living processes.

Habitats can be divided grossly into those that are constant and those that are variable. The surface of a planetary body under rare circumstances as on Earth may be quite variable, providing the opportunity for fragmentation of the environment into a great variety of subhabitats with specific but periodically changing characteristics. These variations and their changes over time represent selective pressures that generate through the evolutionary process a great variety of living forms. When, as on Earth, energy and appropriate chemical environments are abundant, life can assume macrobiotic forms of great complexity. The cost of this biodiversity and complexity, however, is frequent extinction, as changing conditions in variable habitats often render biological features that were advantageous under one set of circumstances, suddenly disadvantageous under others. The cycle of speciation followed by extinction generates the biodiversity and great deviation from primordial forms of life with which we are familiar. We must remind ourselves, however, that the primordial forms are still with us as well. They are sequestered primarily below the surface, where the constancy of conditions places a premium on stabilizing selection, or the retention of successful living processes that have experienced no pressure for change for a long time. Only now are we beginning to appreciate the vastness of this subterranean, unseen biosphere; but it probably represents the most favorable and most common habitat for life throughout the Universe as a whole. The consequences of subsurface life are two-fold: First, the minute size of the living spaces available restrict the size of living organisms to microscopic dimensions. Secondly, the long-term stability of the environment places a premium on stabilizing selection, which likely maintains life in an ancestral form. In those rare planetary bodies that have gaseous atmospheres, life may exist as well, but it likely is microscopic in that sphere also, though is much more likely to have deviated significantly from its ancestral form.

In the chapters that follow, we elaborate on these arguments in greater detail and discuss how life can be detected. We focus on previous attempts such as the Viking life-detection experiments and the controversy about possible fossilized life in the Martian meteorite ALH84001. The lessons from the past inform us on how we would attempt to detect life today and how reliable various geological and biological signatures of life are. We continue with an in-depth discussion of the astrobiological potential of the planetary bodies in our Solar System and selected planets outside of our Solar System. The discovery of over 3800 confirmed exoplanets to date has been one of the most exciting developments in the last decade and revealed some promising candidate planets that might be hosting life. On some of these planets life might even have advanced to a high degree of complexity, perhaps even to intelligent and technologically advanced organisms like us. However, no evidence so far exists for this conjecture, which is further discussed in the chapter on the search for extraterrestrial intelligence. Finally, we introduce our ideas to optimize space exploration, which involves both robotic and human missions.

Our vision of astrobiology is driven by our sense that life, like all of nature, is knowable in principle wherever it exists. We are strongly persuaded by scientific evidence and logic that it exists in profusion on other worlds. We believe it is likely that it exists elsewhere in our Solar System in at least a few instances, though probably in microbial form. We hope to see the day when this belief is confirmed by direct evidence. If we do not, we nonetheless are confident that a perceptive form of life somewhere, someday, will encounter life on a world other than its own. How similar or how different those forms of life will be is one of the most enticing questions of our age. This book is meant to explore the range of answers that might be offered.