COSMIC BIOLOGY

How Life Could Evolve on Other Worlds

LOUIS NEAL IRWIN and DIRK SCHULZE-MAKUCH

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Professor Louis Neal Irwin
The University of Texas at El Paso
El Paso
Texas
USA

Professor Dirk Schulze-Makuch
Washington State University
Pullman
Washington
USA

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Contents

This book is dedicated to the people of the former Soviet Union, who opened the space age on 4 October 1957, to the people of the United States who first sent humans to another world on 20 July 1969, to the thousands of scientists and engineers of all nations whose hearts have been broken by the countless failed missions that inevitably occurred on the way to the spectacular successes of Luna, Venera, numerous Mars orbiters and rovers, Pioneer, Mariner, Viking, Magellan, and Hubble; and especially to the visionary government leaders, scholars, and technicians who funded, built, and sent forth the Voyager, Galileo, and Cassini-Huygens spacecraft to give us the incredible views we have of the other worlds in our cosmic neighborhood that may well hold our nearest neighboring forms of alien life.

Preface

This is a work of both science *and* imagination.

Science uses logic and demonstrable facts to reveal the nature of the material world. Imagination leads the search for facts in new directions, and stretches the limits of logical inference in creative ways. Both are needed to uncover the mysteries of the natural world.

Life is a dynamic manifestation of the material world – complex, incredibly variable, and constantly changing – but material nonetheless, and therefore subject to scientific study just as much as the stars that burn and the atoms that make them up. We strongly suspect that life extends as far as the stars do into the vastness of the cosmos. Unlike the stars that we can see with certainty, though, life lies hidden from view, of unknown extent, with properties that can be reasonably surmised but not yet confirmed on even our nearest planetary neighbor. Our science will reveal the nature of that life in due time. But where to look, what to expect, and how to interpret what we find, for now lies in the province of our imaginations.

So this is a book grounded in science but driven by imagination to predict the form that life *may have taken* on other worlds. It hasn't been easy to put a narrative together that genuinely attempts to stay well within the boundaries of scientific constraint, while at the same time stretching as far as we dare the limits of what ought to be possible. As scientists addicted to the comfort of known facts, we have had to grit our teeth with every use of the subjunctive case: *might be* instead of *is*, *may have been* instead of *was*, *could* instead of *did*, *ought* instead of *can*, *possibly* or *probably* instead of *certainly*, and so forth. But once we committed to writing a book about what we fully believe but of which we as yet have no certain knowledge, we had no choice. We have given the reader fair warning in the subtitle that this is ultimately a work of speculation, then we have forged ahead.

We wrote our first book, *Life in the Universe: Expectations and Constraints*, with the conviction that exobiology (morphing into NASA's astrobiology) needed a firm base of factual information, grounded in the physical sciences, with more than a token treatment of biology. We deliberately wrote a technical treatise, leaving to others the task of conveying a more accessible account for the general reader of life as it could exist in the rest of the universe. We made some pretty clear-cut predictions about the possibilities for life on other specific worlds, based on a logical extension of facts and principles. But we kept our predictions couched in technical language, and limited them simply to the existence of life, *per se*, without elaboration.

Encouraged by the success of *Life in the Universe*, we have decided that those predictions deserve full-blown elaboration, in a manner accessible to a reader without a higher education in science. Since everyone interested in the subject has a basic knowledge of our Solar System, we thought a case-history approach might be the best way to write an engaging narrative. This being a book of applied science, a certain amount of science can't be avoided. We have tried to provide this as painlessly as possible in the first three chapters – defining life precisely, reviewing the relevant essentials of chemistry and physics, and outlining the principles of evolutionary biology and ecology that most books on astrobiology avoid. Amateur and professional scientists alike can skip directly to chapter 4 without missing the basic message, though occasional reference back to the underlying principles and assumptions may prove helpful on occasion.

In chapter 4, we consider life on our home planet of Earth, not as we know it to be, but as an intelligent observer on another world could deduce it. We placed our hypothetical observer in the nearest solar system that we think could host a level of technology comparable to ours. By comparing what our alien scientists might infer about Earth, and why they would do so, we hope to illustrate *our* strategy for imagining how life could unfold on other worlds. Our exercise, beginning in chapter 5, takes a travelogue approach through our own Solar System, visiting first Mars, the planet with a climate and environment least different from Earth's, then Venus, as the other planet with Mars that resembled Earth most in its early history. We then consider the possibility of life in the unconventional habitats of the atmospheres of Venus and the gas giant planets. From there, we look at two exotic worlds circling Jupiter, Io and Europa (with a brief glance at Saturn's Enceladus). From there, our attention turns to the only other world besides Earth to host a nitrogen-rich atmosphere and abundance of organic chemicals – Saturn's giant moon, Titan – a featured attraction for every astrobiologist. But Neptune's captured satellite, Triton, and the biplanetary dwarfs, Pluto and Charon, may hold very different forms of life that we can't afford to disregard, so they will be our final destinations in the Solar System. Along the way, we'll look briefly at exoplanets and their capacity for hosting some forms of life. By the time we reach the outer reaches of our own Solar System, we will have concluded that we are very likely the only technologically-competent species in our region of the universe. We will therefore devote chapter 12 to an examination of why that might be, and what it says about the chances of our finding similar beings elsewhere (or of them finding us). Finally, we will conclude with a discussion in chapter 13 of the ultimate fate of life, on Earth in particular, but wherever it may arise in the universe.

Affirming the widely-held assumption that scientific truth holds true throughout the universe, our logical inferences are based on application of physicochemical principles on other worlds just as they apply on Earth. We likewise have no reason to doubt that the principles of evolutionary biology and ecology are just as universal. Therefore, they too have been applied without regard to the specific world on which we assume they operate.

On the other hand, we have made a few concessions to the uncertainty of our subject matter. Several terms, like *species* and all other taxonomic units, and specific subcellular structures or organ systems which have a specific reality for living organisms on Earth, cannot be assumed for life on other worlds, and therefore have been avoided. Even the broadest categories, like *plant* and *animal*, are usually replaced with *plant-like* or *animal-like.* For the same reason, while we are tempted to assume that cellular dimensions and structures obey some fairly universal constraints, we have felt uncomfortable assuming anything about higher-level cellular organization in alien biospheres, and so avoid referring to "multi-cellular" organisms except when speaking of known examples on Earth. We hope that any reader who finds this form of dissimilation annoying will grant us the freedom to be imprecise, for the sake of avoiding the implication of knowing what we do not.

We are honored to offer this work in the year of the 400th anniversary of Galileo's discovery of the four Jovian satellites. Two of them, Io and Europa, are featured chapters in this book – worlds on which life could exist today. Or it may not. We simply hope that, in setting forth the possibilities, we have imagined today what the science of tomorrow will be able to confirm or refute.

Louis Irwin thanks his wife, Carol, for her constant support and encouragement. Dirk Schulze-Makuch thanks his wife and kids for their continuous patience. Both of us acknowledge with deep appreciation our many colleagues for their insights and valuable discussions with us over the years.

Louis Neal Irwin and Dirk Schulze-Makuch
El Paso and Pullman
April, 2010

Illustrations

1 Rare Earths and Life Unseen

A strategy for cosmic biology

Speculation that alien life might be found on other worlds can be traced to ancient times. Copernicus, Kepler, and Galileo fed those thoughts by showing that the Earth is not the center of the universe. Once it was understood that our planet is just one of several rotating around a solar center, thoughts of other solar systems naturally arose. By 1584, Giordano Bruno was asserting that there must be "... countless suns, and countless earths all rotating around their suns." The next conceptual step – that on some of those "countless earths" there might be life – was easy to take.

By the 19th Century, the possibility of alien civilizations on Earth's nearest sibling planets, Venus and Mars, was taken seriously in the educated world. Spurred by the human propensity for both fear and wonder, ideas ranged from a war-like race of Martians bent on conquering Earth, to the prospect of a peaceful paradise flourishing beneath the clouds of Venus. Percival Lowell, an American astronomer, fueled speculation of intelligent life on Mars by claiming to see long canals, built perhaps to transport water from the poles to drying equatorial regions. This inspired science fiction writers to imagine a technologically advanced but dying, warring world, especially in the work of Edgar Rice Burroughs in the early 20th century. Speculations about life on Venus were generally more benign. A dense cloud cover enshrouded the planet in mystery, giving free reign to romantic images of a verdant biosphere. From Ray Bradbury's short stories depicting incessant rainfall, to Robert Heinlein's vision of a Carboniferous swamp, the Venus of science fiction most often was seen as a warm, dripping-wet, water world, capable perhaps of supporting a prolific alien flora and fauna.

As the space age dawned, reality set in. Robotic probes to our nearest neighbors doused all thoughts of technological civilizations or even widespread but unintelligent forms of life, as cameras landing on the surface of both Mars and Venus saw no evidence of either. In 1969, humans first set foot on the Moon, finding it as sterile on site as it appeared through the telescope. Since Mercury resembles the Moon in both topology and torrid fluctuations between extreme heat and cold, life seems equally improbable on that planet. As scientific data on the nature of the gas giants and their satellites accumulated, it became clear that Earth-like conditions were not to be found on any other world in our Solar System – that our planet, at least within a radius of four light years (the distance to our nearest star), is not only rare but unique.

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Against this revelation, admittedly discouraging for those who dream of finding sister systems of life beyond Earth, came the counterbalancing realization of just how vast the universe truly is. Maybe, except for Earth, *our* Solar System isn't all that inviting for life, but there must be solar systems galore in a universe that measures over 13 billion light years across. With evidence accumulating over the past decade that planets orbit other suns in our Galaxy, the assumption that solar systems pervade the universe seems reasonable. Even if Earth-like planets are rare, given enough solar systems, planets as inviting for life as Earth must exist elsewhere. Since we know that life exists on Earth, we're most likely to find it and recognize it on other worlds that resemble Earth. This is the logic of the search for Earth-like planets in other systems, and the terracentric search for life on those worlds. It fuels the drive to "follow the water." It forms the basis for seeking planets where liquid water and protective atmospheres exist, preferably on medium-sized, rocky planets with stable near-circular orbits with diurnal and seasonal cycles that are not too extreme. It supports the concept of the "stellar habitable zone," which presumes that life is restricted to those planets at just the right distance from their central star for Earth-like conditions to exist. It fits perfectly with the search for life in our own image.

The alternative logic is one that starts from a different premise – that life on Earth is not representative necessarily of life elsewhere, and that therefore the conditions that led to and sustain life on Earth need not be viewed as limitations [1,2]. A nuanced version of this alternative is that, in fact, the life we see around us as humans is not even typical of the vast majority of biomass on Earth; that the unseen microbial world beneath our feet, in our oceans, and to a considerable depth within the crust of our planet is the rule for life on most worlds, including our own, with the larger organisms that catch our eye simply being the exceptions that command our attention.

Peter Ward and Donald Brownlee, a paleontologist and astronomer respectively, at the University of Washington tried to merge these disparate models into a unified hypothesis in their influential book, *Rare Earth: Why Complex Life Is Uncommon in the Universe* [3]. They defined their Rare Earth Hypothesis as, "the paradox that life may be nearly everywhere but complex life almost nowhere." They argued that complex life is likely to arise only under conditions (implicitly, Earth-like conditions) that come about through a very special combination of circumstances. Since that combination on statistical grounds is likely to occur very rarely, complex life itself must be a rarity. Microscopic (by inference, "non-complex") life, on the other hand, is known to be highly adaptable to the most extreme environments. Since extreme environments, by terracentric standards, are common, then microscopic forms of "simple" life may well be common throughout the universe.

In the sections that follow, we review these two major points of view, then offer our own strategy for a systematic study of cosmic biology. But first, since history matters for the way things are today, we need to understand how all the potential habitats for alien life, from rare earths, to snowball planets, to gas giants, came into being. We will therefore start by providing a brief overview of the history of the universe and our Solar System.

1.1 How habitats come about

An assumption we make is that life cannot exist in the midst of an actively burning star, because the chemical reactions that make up living processes cannot proceed stably at the temperatures present in them. Therefore, cosmic biology is really planetary biology (meaning planets, planetoids, and their satellites). So we begin by considering where planets come from.

Science has not always assumed that the universe had a finite beginning. The visionary cosmologist, Fred Hoyle, long championed the idea that mass and energy are products of a steady, continuous, and endless process of generation throughout space. But increasingly scientists have come to the mind-bending view that the universe did indeed begin at a singular point in both time and space. The evidence for this is that the universe is expanding now, that the oldest objects in the universe are at its furthest reaches, and that remnants of the violent birth of the universe – what Fred Hoyle facetiously called the "Big Bang" – still lurk in the form of a background of electromagnetic radiation that would be predicted to be left over from such an event.

1.1.1 Genesis: A scientific story of creation

No myth or metaphor from any of the world's religions can match the audacity and incredibility of the currently favored scientific explanation for the origin of the universe. Until evidence to the contrary comes along, though, most scientists give grudging credence to the "Big Bang" theory, which envisions the emergence of all the matter and energy of the universe according to the following model [4].

Space and time did not exist before the universe was born. Our universe came into being about 13.7 billion years ago, when something emerged from nothing with such violence and rapidity that matter and energy were indistinguishable.

In the first microsecond of its existence, the universe expanded from a singular point to a volume of space 100 billion kilometers across at a temperature of 10 trillion °C. This explosive expansion of space enabled matter in the form of subatomic quarks to differentiate from pure energy and coalesce into baryons (protons and neutrons).

By the end of the first second of the universe, neutrons started changing into protons by emitting more electrons. Once the ratio of protons to neutrons reached about seven to one, they started combining into combinations of (mostly) two protons and two neutrons, the nuclei for future helium atoms. Nearly all the free neutrons were soaked up by this process within a couple of minutes, leaving a huge excess of free protons to form the nuclei for hydrogen atoms.

It took 200,000 years or more for the universe to cool to 2700 °C, a temperature at which the protons and neutron-proton aggregates could start

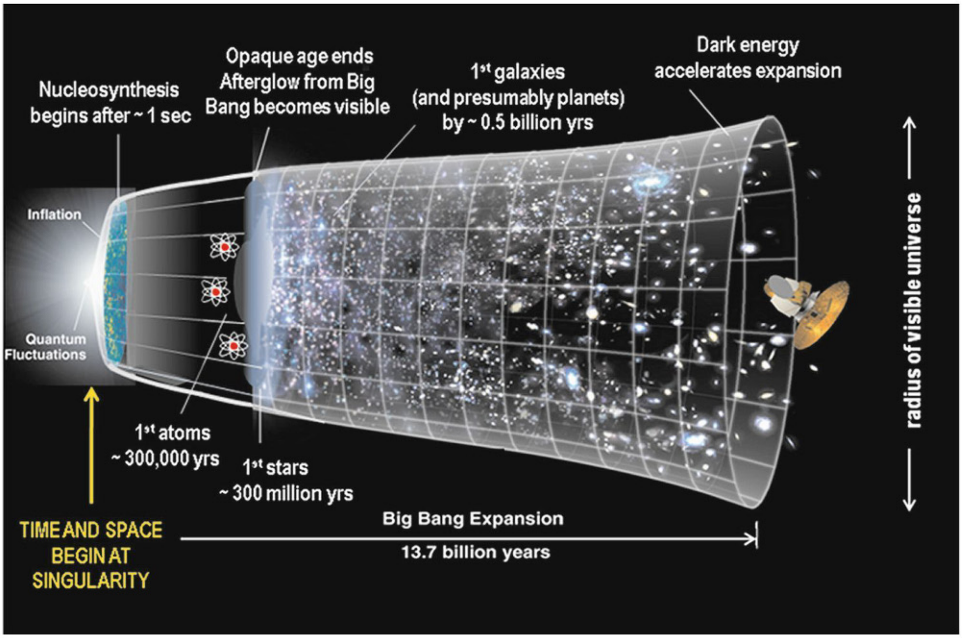

Figure 1.1 Conceptual scheme for the "Big Bang" formation of the Universe. According to this model, all matter and energy in the universe had a singular point of origin in space and time. With expansion, energy and matter differentiated, and matter in time coalesced into galaxies consisting of stars, planets, and related objects (Modified from art by NASA/WMAP Science Team).

capturing the free flying electrons to form the first atoms of hydrogen and helium. As the dense fog of electrons condensed into newly formed atoms, the opaqueness cleared and photons could stream without interruption across the vastness of space, which now filled a volume of a hundred million light years.

By 300 million years into its life span, the universe was filled almost but not quite uniformly with mostly hydrogen, a little bit of helium, a tiny amount of lithium (the three smallest atoms), a lot of energy, and a whole lot of "dark matter" whose nature is still not understood today. Another fundamental force of nature, gravity, now worked on those discontinuities in the density of the "normal matter" in the universe. Clouds of hydrogen and helium began to collapse in regions where the gases were slightly more concentrated. When the clouds became massive enough, gravity sucked the atoms into a ball that gradually became compressed enough to force atoms of hydrogen to fuse together, forming helium and emitting energy as light and other forms of electromagnetic and particle energy. The first stars were born.

The stars of the early universe were massive by comparison with the average size of stars today. This meant more gravity, which meant a faster fusion at their cores. When all the hydrogen at the center of a star was consumed, the helium atoms started fusing into heavier elements like carbon, nitrogen, and oxygen.

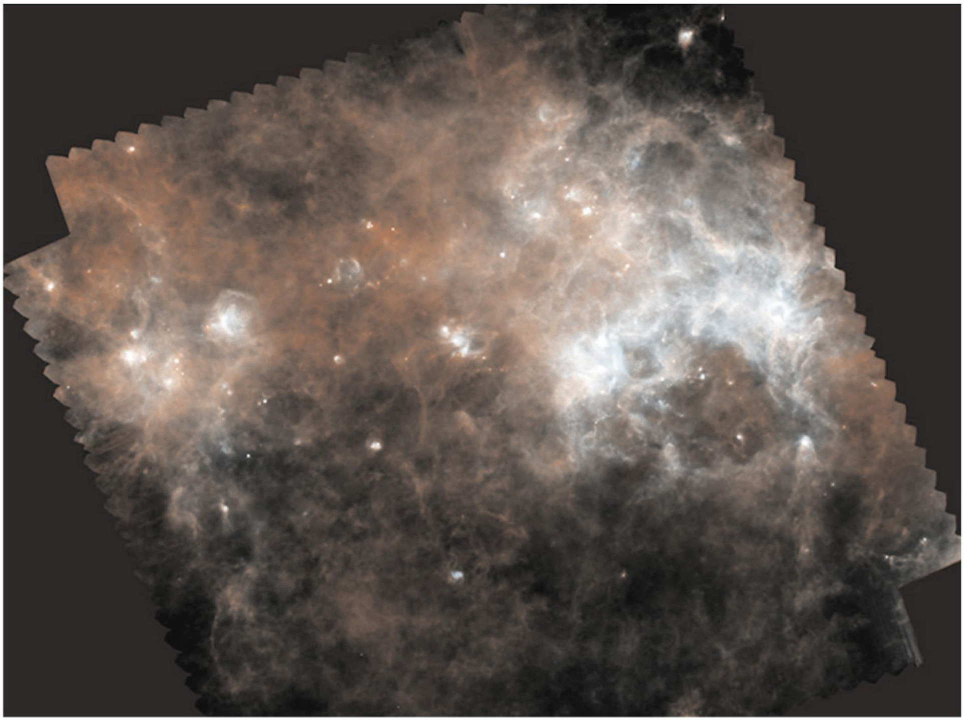

Figure 1.2 Star formation. Cool, dark clouds of gas and dust are just starting to condense in this region of our Milky Way Galaxy. There is a surprising amount of turmoil: the interstellar material is condensing into continuous and interconnected filaments glowing from the light emitted by new-born stars at various stages of development. The image was acquired by Herschel's spectral and photometric imaging receiver. Herschel is a European Space Agency mission with important participation from NASA (ESA/NASA/JPL-Caltech).

With heavier elements raising the density of their cores, the crushing gravity of the biggest stars caused the collapse of atoms down to their positively charged nuclei, which repulsed one another with such explosive force that the star blew apart. This first generation of stars thus spewed the heavier elements it had made into space, giving rise to metallic particles of dust as well as free-floating lighter elements to join the hydrogen and helium gas already in abundance. These clouds of dust and gas would eventually collapse into the next, more chemically enriched generation of stars and the cycle would repeat itself. In this way, the heavier elements that would give rise in time to all the worlds and all the living things in the universe were created.

1.1.2 How solar systems and planets form

The laws of angular momentum dictate that as matter collapses on itself, it must begin to spin. In many if not most cases, as the dust and gas fell into the compacted gravity well of a protostellar mass, some of the matter would be kept by centrifugal force from falling into the central star. The matter spinning at the periphery would flatten into a disk, resulting in a spherical ball at the center with a smattering of material spinning around the central mass in a flat plane.

Thus compressed into a flattened space, dust particles, water, and other molecules that had formed in the interstellar void would collide with increasing frequency, often sticking together at the frigid temperatures that prevailed some distance from their growing sun at the center of their orbital trajectories. Discontinuities again played a role, with slightly heavier grains growing more massive slightly faster than those around them. The trend would continue for millions of years, leading to boulder-sized aggregates that coalesced into larger boulders, until masses of rock and ice called *planetesimals* had grown to several kilometers in diameter.

Planetesimals are large enough to generate gravitational attraction. The larger ones would pull in the smaller ones in a runaway process of accretion. At this point, the process would accelerate toward survival of a small number of planetesimals evolving toward *protoplanets* in a relatively short time. The larger the protoplanets became, the more fragments from the formative protostellar disk they would pull in.

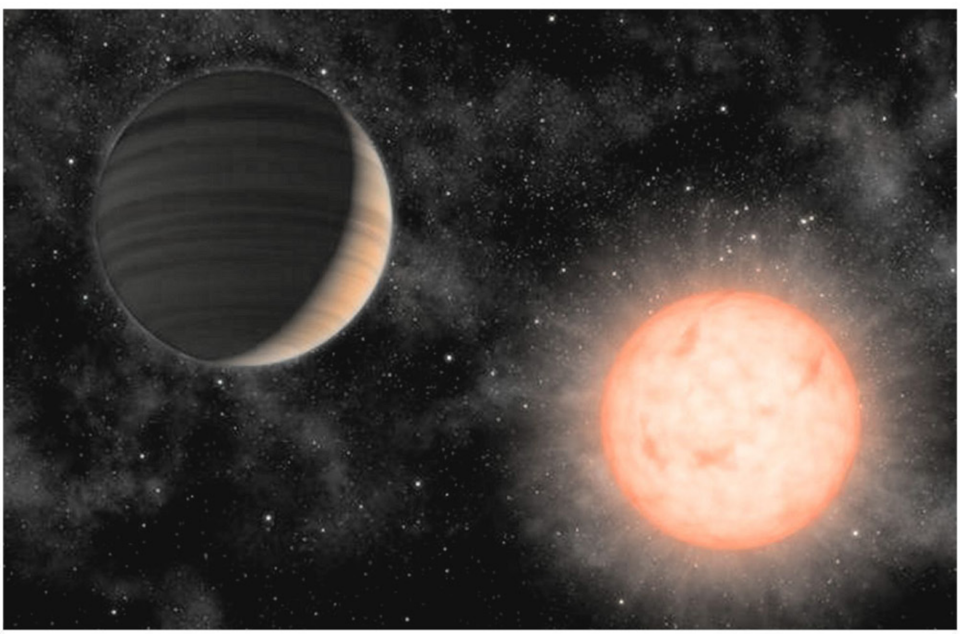

Figure 1.3 Exoplanet orbiting a red dwarf. This is an artist's conception of the smallest star known to host a planetary system. The dim red star, a red dwarf about the size of Jupiter named VB 10, is orbited by a planet of approximately the same size, about 20 light years away in the constellation Aquila (NASA/JPL-Caltech).

The newborn planets that were large enough became bombarded with so much matter and energy that their interiors melted, allowing the heaviest elements like iron and nickel to sink to the center. An outer crust of lighter metallic compounds like silicates formed a solid surface that underwent a high level of bombardment for millions of years more. This delivered both matter and energy to the growing planet's surface, while radioactive decay of the heavier elements in its interior generated heat from inside out.

Like the protostellar disk, the planetesimals that had collapsed to form the protoplanets were set spinning themselves, sometimes generating satellites that rotated around their central planet, as the planets rotated around their central star. As planets formed, they scooped up gases like hydrogen and nitrogen. The planet's size and temperature (depending on its distance from the central sun) dictated whether these light gases would evaporate back into space, be held as gases in an atmosphere, or be pulled with enough gravitational pressure to form a liquid shell around the planet's rocky core. The latter became characteristically massive "gas giants."

Our own Solar System was born about 4.6 billion years ago. The protostellar disk that gave rise to our local part of the universe generated a somewhat larger than average sun encircled by four rocky planets (Mercury, Venus, Earth, and Mars), four gas giants (Jupiter, Saturn, Uranus, and Neptune), and an assortment of smaller bodies including at least one binary dwarf planetary system (Pluto and Charon). All but the innermost two of our Solar System's planets have satellites of their own. The two largest giants, Jupiter and Saturn, also have the largest number of satellites, while the smaller inner planets have none (Mercury and Venus) to one (Earth) to two (Mars), perhaps because their parent planets had less starting material to begin with, or because keeping satellites in stable orbit that close to the immense gravitational pull of the Sun is more difficult.

Hundreds of other solar systems are now known to exist, and protostellar clouds can be seen in various stages of formation both near and far, suggesting a universe filled with recurrent and ongoing acts of creation.

1.1.3 Exoplanets

The first planets beyond our own Solar System were not discovered until 1992. Prior to that, we had no reason to doubt that the logic of our own system – smaller rocky planets and light atmospheres near the sun, with gas giants hosting dense atmospheres further out – was a general rule for the structure of solar systems everywhere. That assumption was dispelled with the discovery of gas giants larger than Jupiter orbiting their central stars much closer than the Earth orbits our Sun. Planets the size of our own rocky members, being much harder to detect, are just now being discovered, but enough have been found to suggest a far greater diversity of organizational structures for other solar systems, than our own "logical" planetary arrangement, or the rapidly revolving giant planets first found near their central suns, would suggest. This includes, for example, many

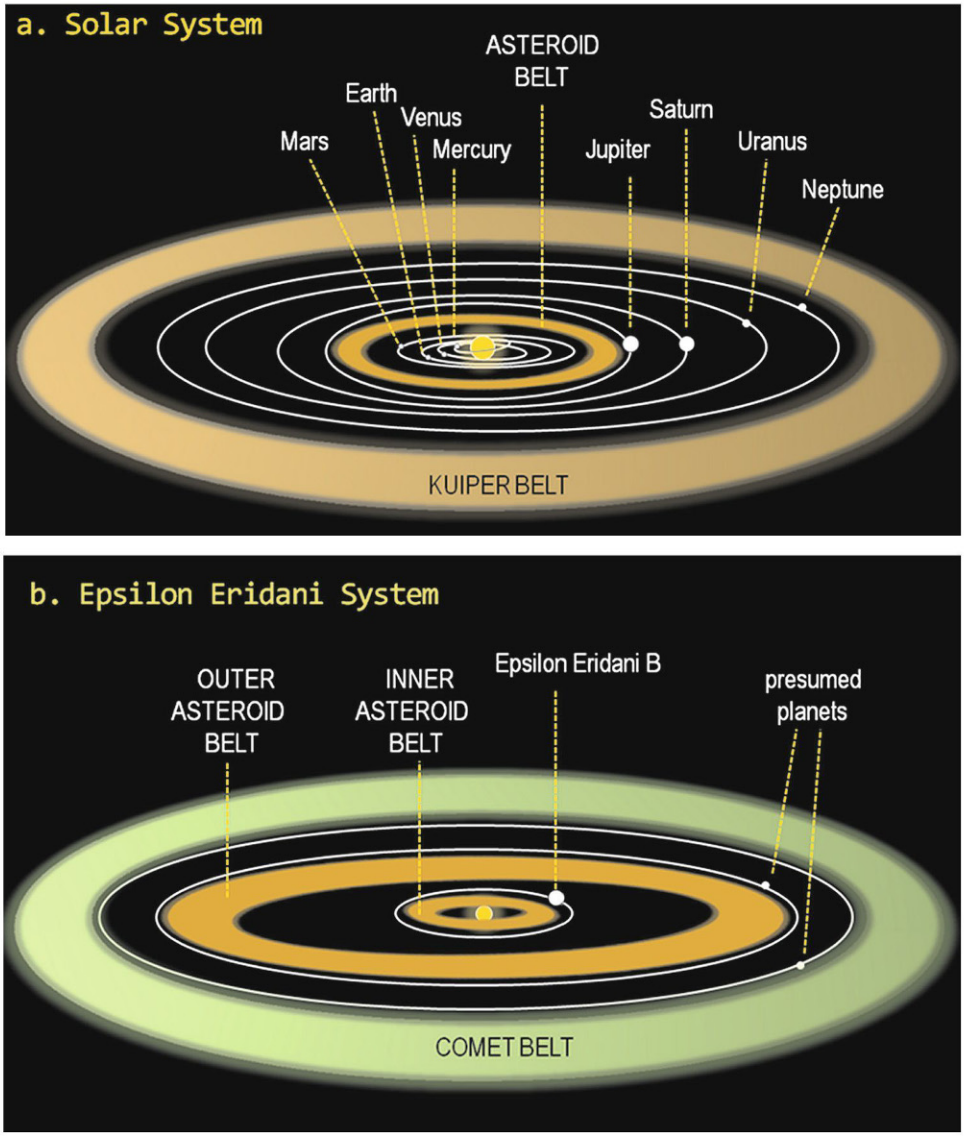

Figure 1.4 Planetary formation. Schematic representation of two different planetary systems forming around their central stars (sizes and distances not to scale). (a) In our Solar System, four inner rocky planets and four larger gas giant planets orbit the Sun, with an asteroid belt between the inner and outer planets, and another comet forming belt beyond the furthest planet. (b) A smaller, younger star, Epsilon Eridani, a little over 10 light years away is surrounded by an inner asteroid belt with a Jupiter-sized planet at its outer edge. Two more asteroid belts suggest the presence of at least another two planets, orbiting within the regions of uncoalesced planetary debris between the belts (Art by Louis Irwin, adapted from original by NASA/JPL-Caltech).

exoplanets with very eccentric orbits, circling a wide variety of stars from red dwarfs to giants to multiple star systems.

During the writing of this book, nearly 500 planets outside our Solar System (exoplanets) have been detected, and that number will probably double within a year. Recent advances in exoplanet research can be exemplified by discovery of the Gliese 581 planetary system. An M-category star, also known as a red dwarf, Gliese 581 lies 20.3 light years distant from Earth and is orbited by at least four planets, ranging in estimated size from 1.9 to 13 Earth masses. These exoplanets are likely to be rocky planets with thick atmospheres ranging in size from that of Earth to Neptune.

The assumption that many exoplanets must have exomoons of their own is implicit, and some of those satellites must be of an appropriate size and composition to provide conditions suitable for life. Until a fuller repertoire of solar systems has been studied, we can't be sure how common rocky planets, water worlds, barren moons, snowball satellites, and gas giants are in the rest of the universe. We have every reason to believe, though, that all of them exist somewhere. Fortunately, our Solar System has examples of each, so that a science of cosmic biology can well begin by focusing on the planetary habitats nearest our home.

1.2 The Rare Earth model

In its starkest form, the Rare Earth model postulates that conditions suitable for life are restricted to the conditions that happen to be present on Earth. Those conditions, in turn, arise from a set of coincidental factors that collectively are highly unlikely to be found very often throughout the universe. Hence, Earth-like planets are a rare occurrence, and therefore life itself is a rare phenomenon. To reiterate, the focus of the book by Ward and Brownlee was on the frequency with which *complex* life is likely to arise, not on the chances for *any* form of life. We describe it in this more restrictive form, however, because the notion has given rise to related concepts like the "stellar habitable zone" and the "galactic habitable zone," which to different degrees assume that rocky planets with Earth-like properties are required for the support of life in general.

To be sure, in our own Solar System, the Earth is unique. It orbits the Sun at a convenient distance to receive plenty of sunlight but not so much that the atmosphere is boiled away. Its size is right to hold an atmosphere thick enough to protect against all but the larger meteorites, but not so dense that heat is trapped inescapably. The uniquely high percentage of oxygen in the air supports an efficient form of energy metabolism, and the ozone arising from oxygen filters out dangerous ultraviolet radiation. Above all, Earth is a planet with an average temperature of about 15°C that allows most of the water on its surface to be liquid most of the time. It has an axis inclined to the plane of its orbit around the Sun that ensures seasonal fluctuations in temperature, air and water currents, and precipitation. More frequent cycles arise from a rotation on its axis and the tidal pull of the Moon and the Sun that generate daily cycles of light and dark, tides that rise and fall, and temperatures that go up and down. The cyclic nature of the biosphere provided by these fluctuations, combined with the complex topography of the land and the global prevalence of interfaces between the water and the land, produce a rich diversity of environments. These then serve as the tapestry through which life can splinter into an ever increasing degree of complexity.

The weakness of the Rare Earth model lies, not in its requirement that environmental diversity is necessary for the evolution of biological complexity – we think that is more likely than not correct – but in the assumption that planets with a high degree of environmental fractionation are rare. They may be. We don't have enough data yet to answer that. Even if they are, and we therefore conclude that the evolution of complex life is rare, that doesn't necessarily mean that the evolution of any kind of life is rare. Therefore, the concept that the habitable zone is restricted to that region of a solar system where rocky planets with liquid water can stably exist is not very useful. If we assume that solid substrates interfacing with liquids are at a minimum necessary for the emergence of any kind of life, the galactic habitable zone, within which rocky planets can exist, makes a little more sense. But even here, the environmental requirements for life in general are not yet specified well enough to rule out many potential worlds that lie beyond the galactic habitable zone.

As a search strategy for life on other worlds, looking *first* within the stellar "habitable zone" makes sense, because life that evolves under conditions familiar to us is more likely to be recognizable by us. The galactic "habitable zone" is an interesting theoretical concept but one lacking in relevance at the level of our current technological capacity to search for alien life.

Life on Earth clearly confirms that multicellular macroorganisms require a narrower set of environmental conditions for survival than microorganisms. The history of life on Earth further shows that multicellularity and large size evolved over long periods of time under fairly stable conditions on a planet with liquid water and continental land masses. Whether that much time and those particular conditions are inherently required for the evolution of biological complexity, is unknown. Furthermore, the rarity with which the geophysical conditions peculiar to Earth are found throughout the universe cannot be assessed at this time. Nonetheless, the overall view that large, more complex organisms are relatively uncommon compared to the much higher prevalence of microorganisms on other worlds is likely correct.

1.3. The Life Unseen model

In *its* starkest form, the Life Unseen Model states that the life we can't see is the life that is most common and most typical in the universe. We as humans can't see it with our naked eyes because it's too small. We know it exists, though, because we *can* see it through a microscope, and we can study its biochemistry and metabolism through a variety of elegant techniques.

The unseen world of life on Earth turns out to be far more massive, widespread, variable, and adaptable than those forms of life that garner most of our attention most of the time. Prokaryotes alone, the simplest and most ancient forms of unicellular life, beneath the surface of the soil and the floor of the ocean may approach in biomass that of all plants [5]. When more complex but still microscopic organisms, like protists and yeasts, are added to the larger plants, animals, and fungi that remain sequestered out of sight in the ocean and beneath the ground, their total biomass adds to much more than all the plants and animals we can readily perceive.

It is among the smallest creatures that we find the greatest adaptations to environmental extremes. Especially among the prokaryotes, forms are known that live at temperatures close to the boiling point and below the freezing point of water, that flourish in alkaline lakes and acidic pools at the extreme ends of the pH scale in both directions, that survive crushing pressures, decades of desiccation, the vacuum of space, and levels of radiation that no human could come close to tolerating [6]. These "extremophiles" give little evidence of being bound by a habitable zone of any dimensions. To be sure, under physicochemical conditions that prevent normal chemical interactions from taking place, life has not nor is it likely to be found. Short of that limitation, however, no intrinsic restriction on living processes is evident.

The existence of the extremophiles on Earth has weakened the meaning of the stellar habitable zone in space. Since conditions considered "extreme" on Earth are common on other worlds, the existence of extremophiles in those habitats must be regarded as a distinct possibility, and maybe even a common occurrence. Thus, the whole concept of a "habitable zone" may have little meaning within the Life Unseen framework.

As noted, the extremophiles on Earth tend to be small (though not inevitably microscopic), so they may well be small wherever they exist. This means they will be unseen, at least directly. Detecting biosignatures of unseen life is a major area of astrobiology, with the technology for doing so steadily advancing. There is good reason, therefore, to expect that sequestered forms of life will be detected, to the extent that they exist, as exploration of alien worlds intensifies.

1.4. Strategy for the study of cosmic biology

As our own planet demonstrates, the Rare Earth model of complex life and the Life Unseen model for a biosphere of sequestered and mostly microscopic forms of life can co-exist. The relationship is not symmetrical, however. There is almost certainly no complex life without the coexistence of simpler, microscopic forms. Surely more common, however, are worlds harboring biospheres consisting entirely of microscopic ecosystems but totally lacking in larger, more complex organisms.

Assuming these two models frame the boundaries of what is possible, the form and variety of life that appears on any given planet is going to be a function of both history and circumstance. History determines what the starting point for life must have been, and the sequence of conditions through which it had to evolve to reach its present form. Circumstance dictates the nature of life that is currently sustainable. Earth, Venus, and Mars provide an illuminating example.

Earth and Venus are fraternal, if not quite identical, planetary twins. Born at the same time from the same protostellar matter, they were aggregated into rocky planets of almost the same size, spinning around the Sun in adjacent orbits. From what we know about the origin of solar systems in general, we have every reason to believe that both were bathed in warmth from the Sun and bombarded with an abundance of water and organic matter from asteroids and meteorites in their early existence. Yet today, the surface of Venus is a crushing cauldron of desiccated heat while the Earth teems with a massive and diverse biosphere. Given such a similar starting point, how could two worlds go in such different directions for the support of life? History clearly explains some of the difference. Something happened a long time ago to knock Venus upside down on its axis, so that it spins in the opposite direction from the Sun and the Earth. Whatever water and atmosphere existed at that time may well have been totally discarded. More recently, perhaps a billion years ago or less, convulsive volcanic activity resurfaced the planet and generated a crushing atmosphere of carbon dioxide and sulfuric acid that turned the planet into a runaway greenhouse oven. Current circumstance makes matters worse, in that the Sun's increasingly intense output of energy, combined with the closer orbit of Venus to the Sun, make the greenhouse effect even more severe. That nearness is also slowing the rotation of Venus, which will eventually lock the planet into holding its same face toward the Sun all the time.

Meanwhile, life flourishes on Earth as it orbits the Sun at a more comfortable distance, with just enough atmosphere to be protective and keep water liquid on the surface, but not (yet) enough greenhouse gases to trap heat inescapably. Fifty percent further from the Sun orbits Mars, the smaller sibling of Venus and Earth. Considerably colder and with a much thinner atmosphere than Earth's, Mars appears to be as lifeless as Venus on the surface. Yet it too began its voyage through time as a warmer, water world. Its smaller size and greater distance from the Sun apparently led to an insurmountable inability to hold onto its earlier, thicker atmosphere, and to the eventual loss of its large surface oceans. Thus, we see the contrast between three planets, born at the same time within the same region of the Solar System, driven by history and circumstance to three different endpoints in their ability to support life. Surprisingly, perhaps, there may still be some forms of life on Mars, and possibly even Venus, but the life there is clearly going to be different from the life on Earth. The purpose of this book is to explain why that might be, and how alternative life histories could be playing out in other parts of our Solar System and the rest of the universe.

Our strategy for visualizing a cosmic biology will be to consider the starting point of a planet's history and its geophysical transformations to the present day, generating a narrative of planetary history and circumstance that provides the fabric within which the evolutionary life on that world could have unfolded.