Praise for *Rare Earth* . . .

" . . . brilliant and courageous . . . likely to cause a revolution in thinking."

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"A pleasure for the rational reader . . . what good books are all about . . . "

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"If Ward and Brownlee are right it could be time to reverse a process that has been going on since Copernicus."

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"Although simple life is probably abundant in the universe, Ward & Brownlee say, 'complex life—animals and higher plants—is likely to be far more rare than is commonly assumed'."

—*Scientific American*, Editor's Choice

" . . . a compelling argument [and] a wet blanket for E.T. enthusiasts . . . "

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"Peter Ward and Donald Brownlee offer a powerful argument . . . ."

—*The Economist*

"[*Rare Earth*] has hit the world of astrobiologists like a killer asteroid . . . ."

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"A very good book."

—*Astronomy*

The notion that life existed anywhere in the universe besides Earth was once laughable in the scientific community. Over the past thirty years or so, the laughter has died away . . . . [Ward and Brownlee] argue that the recent trend in scientific thought has gone too far . . . . As radio telescopes sweep the skies and earthbound researchers strain to pick up anything that might be a signal from extraterrestrial beings, *Rare Earth* may offer an explanation for why we haven't heard anything yet."

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—*Sky & Telescope*

"It's brilliant . . . courageous. . . . It's rare in literature and science that a stance goes so far against the grain."

—Dr. Geoffrey W. Marcy
Extra-solar planet discoverer
University of California at Berkeley

"It's a thought that grips most everyone who stares into the unfathomable depths of a star-speckled night: Is there anybody out there? The odds, say Peter Ward and Don Brownlee, are probably more remote than you think."

—*The Seattle Times*

"Alien life is more likely to resemble the stuff you scrub off the tiles in your shower than Klingons, Wookies or Romulans, say Ward and Brownlee."

—*Popular Mechanics*

"Ward and Brownlee have taken an issue that is much in the public domain and treated it thoughtfully and thoroughly, but with a lightness of touch that draws the reader on . . . . *Rare Earth* is an excellent book for both specialists and non-specialists."

—*The Times Higher Education Supplement* (UK)

"A provocative, significant, and sweeping new book . . . *Rare Earth* is a fast-paced, thought-provoking read that I gobbled like popcorn. It's one of those rare books that is at once delightful, informative, and important: an end-of-the-millennium synthesis of science that tackles the central question of our past, place, and destiny."

—*Northwest Science & Technology*

" . . . well thought out and intriguing . . . "

—*Icarus*

" . . . a startling new hypothesis . . . Highly recommended."

—*Library Journal*

"*Rare Earth* will surely appeal to those who would dare to disagree with icons Carl Sagan and George Lucas."

—*San Gabriel Valley Tribune*

" . . . a timely, entirely readable account."

—*Toronto Globe & Mail*

" . . . a stellar example of clear writing . . . "

—*American Scientist*

" . . . thought-provoking and authoritative . . . "

—*Physics Today*

"In this encouraging and superbly written book, the authors present a carefully reasoned and scientifically statute examination of the age-old question—'Are we alone in the universe?' Their astonishing conclusion that even simple animal life is most likely extremely rare in the universe has many profound implications. To the average person, staring up at a dark night sky, full of distant galaxies, it is simply inconceivable that we are alone. Yet, in spite of our wishful thinking, there just may not be other Mozarts or Monets."

—Don Johanson
Director, Institute of Human Origins
Arizona State University

"A fabulous book! If we're to believe what we see in the movies, extraterrestrials thrive on every world. But this unique book, written by two of the top scientists in the field, tells a different story. As we know it on Earth, complex life might be very rare, and very precious. For those of us interested in our cosmic heritage, this book is a must-read."

—David Levy
Co-discoverer of Comet Shoemaker-Levy

"Ward and Brownlee take us on a fascinating journey through the deep history of our habitable planet and out into space; in the process they weave a compelling argument that life at the level of an animal should be vastly rarer in the universe than life at the level of a lowly bacterium."

—Steven M. Stanley,
Author of *Children of the Ice Age* and *Earth and Life Through Time*
The Johns Hopkins University

"Microbial life is common in the universe, but multicellular animal life is rare. A controversial thesis, but one that is well-researched and well-defended. A must-read for anyone who is interested in whether life exists beyond Earth."

—James Kasting
Pennsylvania State University

Rafted ice covering the subterranean ocean of Europa (moon of planet Jupiter), a possible life habitat in the outer solar system. NASA image from the Galileo spacecraft. Courtesy of NASA.

RARE EARTH

Why Complex Life Is Uncommon in the Universe

Peter D. Ward
Donald Brownlee

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To the memory of
Gene Shoemaker
and
Carl Sagan

Contents

Preface to the Paperback Edition

On November 12, 2002, Dr. John Chambers of the NASA Ames Research Center gave a seminar to the Astrobiology Group at the University of Washington. The audience of about 100 listened with rapt attention as Chambers described results from a computer study of how planetary systems form. The goal of his research was to answer a deceptively simple question: How often would newly forming planetary systems produce Earth-like planets, given a star the size of our own sun? By "Earth-like" Chambers meant a rocky planet with water on its surface, orbiting within a star's "habitable zone." This not-too-hot and not-too-cold inner region, relatively close to the star, supports the presence of liquid water on a planet surface for hundreds of million of years—the time-span probably necessary for the evolution of life. To answer the question of just how many Earth-like planets might be spawned in such a planetary system, Chambers had spent thousands of hours running highly sophisticated modeling programs through arrays of powerful computers.

The results presented at the meeting were startling. The simulations showed that rocky planets orbiting at the "right" distances from the central star are easily formed, but they can end up with a wide range of water content. The planet-building materials in a habitable zone include dry materials that form locally, as well as water-bearing materials that originate further from the star and have to be scattered inward, mostly in the form of comets. Without water-bearing comet impacts, Earth-wannabes would just stay wannabes—they would *never* contain any water.

The model showed that the inbound delivery of water worked best in planetary systems where the intermediate planets, in the position of our giants Jupiter and Saturn, were far smaller. In solar systems such as our own, the efficiency of water being conveyed to the surface of an inner, Earth-like planet is relatively small. Yet in systems where the intermediate planets were much smaller—perhaps Uranus- or Neptune-sized—water delivery was relatively frequent. But then another problem arises: in such a system, the rate of water-bearing comet impacts is great; the rate of asteroid impacts, however, is also so great that any evolving life might soon be obliterated. And oddly, it is not only the asteroid impacts, with their fireballs, dust storms, meteor showers, and "nuclear winters," that cause a problem. An excess of water-bearing impacts can amount, in effect, to too much of a good thing: too much water produces planets entirely covered with water, and such an environment is not conducive to the rich evolution seen on our planet. Earth seems to be quite a gem—a rocky planet where not only *can* liquid water exist for long periods of time (thanks to Earth's distance from the sun as well as its possession of a tectonic "thermostat" that regulates its temperature), but where water can be found as a heathy *oceanful*—not too little and not too much. Our planet seems to reside in a benign region of the Galaxy, where comet and asteroid bombardment is tolerable and habitable-zone planets can commonly grow to Earth size. Such real estate in our galaxy—perhaps in any galaxy—is prime for life. And rare as well.

We, the authors of *Rare Earth*, were in the audience that November day. One of us raised his hand and asked the question: What does this finding mean for the number of Earth-like planets there might be—planets with not only water and bacterial life, but with complex multi-cellular life? Chambers scratched his head. Well, he allowed, it would certainly make them rare.

There was one other aspect of the lecture that struck us. Chambers matter-of-factly spoke of the necessity of planets having plate tectonics to be habitable, and of the effect of mass extinctions. We know that plate tectonics provides a method of maintaining some sort of planetary thermostat that keeps planets at a constant temperature for billions of years. We know, too, that mass extinctions can end life on a planet abruptly, at any time, and that the number of mass extinctions might be linked to astronomical factors, such as the position of a planet in its galaxy. Prior to the publication of the first edition of *Rare Earth* in January 2000, neither of these concepts had publicly appeared in discussions of planetary habitability. Now they do, as a matter of course, and this has been a great satisfaction to us. Our hypothesis that bacteria-like life might be quite common in the Universe, but complex life quite rare, may or may not be correct. But the fact that we've been able to bring new lines of evidence into the debate, evidence that was once controversial but is now quite mainstream, has been extremely gratifying.

With its initial publication, *Rare Earth* struck chords among a wide community. Because it took a rather novel position about the frequency of complex life, the discussion spurred by the book often left the realm of scientific discourse, where we'd intended it to take place, and entered the arenas of religion, ethics, and science fiction. Science has progressed since the publication, yet nothing we have read or discovered in the years since has caused us to change our minds. One of the most remarkable developments has been the continual discovery of new planets orbiting other stars (the count is now over 100). While this shows that planets are common, it also shows how complex and varied planetary systems are, and how difficult it is to make a stable Earth-like planet. Most of the extra-solar planets that have been discovered are giant planets in orbits that preclude the possibility of water-covered Earths with long-term stability.

This edition, then, is changed only in the removal of several egregious and sometimes hilarious typos and errors. We stand by our initial assessment and are proud to see that *Rare Earth* continues to spawn heated debate even as it makes its way into textbooks as accepted dogma.

Peter D. Ward, Donald Brownlee
Seattle, February 2003

Preface to the First Edition

This book was born during a lunchtime conversation at the University of Washington faculty club, and then it simply took off. It was stimulated by a host of discoveries suggesting to us that complex life is less pervasive in the Universe than is now commonly assumed. In our discussions, it became clear that both of us believed such life is not widespread, and we decided to write a book explaining why.

Of course, we cannot prove that the equivalent of our planet's animal life is rare elsewhere in the Universe. Proof is a rarity in science. Our arguments are *post hoc* in the sense that we have examined Earth history and then tried to arrive at generalizations from what we have seen here. We are clearly bound by what has been called the Weak Anthropic Principle—that we, as observers in the solar system, have a strong bias in identifying habitats or factors leading to our own existence. To put it another way, it is very difficult to do statistics with an *N* of 1. But in our defense, we have staked out a position rarely articulated but increasingly accepted by many astrobiologists. We have formulated a null hypothesis, as it were, to the clamorous contention of many scientists and media alike that life—barroom-brawling, moral-philosophizing, human-eating, lesson-giving, purple-blooded bug-eyed monsters of high and low intelligence—is out there, or that even simple worm-like animals are commonly out there. Perhaps in spite of all the unnumbered stars, we are the only animals, or at least we number among a select few. What has been called the Principle of Mediocrity—the idea that Earth is but one of a myriad of like worlds harboring advanced life—deserves a counterpoint. Hence our book.

Writing this book has been akin to running a marathon, and we want to acknowledge and thank all those who offered sustaining draughts of information as we followed our winding path. Our greatest debts of gratitude we owe to Jerry Lyons of Copernicus, who invested so much interest in the project, and to our editor, Jonathan Cobb, who fine-tuned the project on scales ranging from basic organization of the book to its numerous split infinitives.

Many scientific colleagues gave much of themselves. Joseph Kirschvink of Cal Tech read the entire manuscript and spent endless hours thrashing through various concepts with us; his knowledge and genius illuminated our murky ideas. Guillermo Gonzalez changed many of our views about planets and habitable zones. Thor Hansen of Western Washington University described to us the concept of "stopping plate tectonics." Colleagues in the Department of Geological Sciences, including Dave Montgomery, Steve Porter, Bruce Nelson, and Eric Cheney, discussed many subjects with us. Many thanks to Victor Kress of the University of Washington for reading and critiquing the plate tectonics chapter. Dr. Robert Paine of the Department of Zoology saved us from making egregious errors about diversity. Numerous astrobiologists took time to discuss aspects of the science with us, including Kevin Zahnlee of NASA Ames, who patiently explained his position—one contrary to almost everything we believed—and in so doing markedly expanded our understanding and horizons. We are grateful to Jim Kasting of Penn State University for long discussions about planets and their formations. Thanks as well to Gustav Ahrrenius from UC Scripps, Woody Sullivan (astronomy) of the University of Washington, and John Baross of the School of Oceanography at the University of Washington. Jack Sepkoski of the University of Chicago generously sent new extinction data, Andy Knoll of Harvard contributed critiques by E-mail; Sam Bowring spent an afternoon sharing his data and his thoughts on the timing of major events in Earth history; Dolf Seilacher talked with us about ediacarans and the first evolution of life; Doug Erwin lent insight into the Permo/Triassic extinction; Jim Valentine and Jere Lipps of Berkeley gave us their insights into the late Precambrian and animal evolution; David Jablonski described his views on body plan evolution. We are enormously grateful to David Raup, for discussions and archival material about extinction, and to Steve Gould for listening to and critiquing our ideas over a long Italian dinner on a rainy night in Seattle. Thanks to Tom Quinn of UW astronomy for illuminating the rates of obliquity change and to Dave Evans of Cal Tech, with whom we discussed the Precambrian glaciations. Conway Leovy talked to us about atmospheric matters. With Bob Berner of Yale, we discussed matters pertaining to the evolution of the atmosphere through time. Steve Stanley of Johns Hopkins gave us insight into the Permo/Triassic extinction. Walter Alvarez and Allesandro Montanari talked with us about the K/T extinction. Bob Pepin gave us insight into atmospheric effects.

Ross Taylor of the Australian University provided useful information to us, and Geoff Marcy and Chris McKay discussed elements of the text. Doug Lin of U.C. Santa Cruz discussed the fate of planetary systems with "Bad" Jupiters. We are grateful to Al Cameron for use of his lunar formation results.

Peter D. Ward, Donald Brownlee
Seattle, August 1999

Introduction: The Astrobiology Revolution and the Rare Earth Hypothesis

On any given night, a vast array of extraterrestrial organisms frequent the television sets and movie screens of the world. From Star Wars and "Star Trek" to *The X-Files,* the message is clear: The Universe is replete with alien life forms that vary widely in body plan, intelligence, and degree of benevolence. Our society is clearly enamored of the expectation not only that there is *life* on other planets, but that incidences of *intelligent* life, including other civilizations, occur in large numbers in the Universe.

This bias toward the existence elsewhere of intelligent life stems partly from wishing (or perhaps fearing) it to be so and partly from a now-famous publication by astronomers Frank Drake and Carl Sagan, who devised an estimate (called the Drake Equation) of the number of advanced civilizations that might be present in our galaxy. This formula was based on educated guesses about the number of planets in the galaxy, the percentage of those that might harbor life, and the percentage of planets on which life not only could exist but could have advanced to exhibit culture. Using the best available estimates at the time, Drake and Sagan arrived at a startling conclusion: Intelligent life should be common and widespread throughout the galaxy. In fact, Carl Sagan estimated in 1974 that a million civilizations may exist in our Milky Way galaxy alone. Given that our galaxy is but one of hundreds of billions of galaxies in the Universe, the number of intelligent alien species would then be enormous.

The idea of a million civilizations of intelligent creatures in our galaxy is a breathtaking concept. But is it credible? The solution to the Drake Equation includes hidden assumptions that need to be examined. Most important, it assumes that once life originates on a planet, it evolves toward ever higher complexity, culminating on many planets in the development of culture. That is certainly what happened on our Earth. Life originated here about 4 billion years ago and then evolved from single-celled organisms to multicellular creatures with tissues and organs, climaxing in animals and higher plants. Is this particular history of life—one of increasing complexity to an animal grade of evolution—an inevitable result of evolution, or even a common one? Might it, in fact, be a very rare result?

In this book we will argue that not only intelligent life, but even the simplest of animal life, is exceedingly rare in our galaxy and in the Universe. We are not saying that *life* is rare—only that *animal* life is. We believe that life in the form of microbes or their equivalents is very common in the universe, perhaps more common than even Drake and Sagan envisioned. However, *complex* life—animals and higher plants—is likely to be far more rare than is commonly assumed. We combine these two predictions of the commonness of simple life and the rarity of complex life into what we will call the Rare Earth Hypothesis. In the pages ahead we explain the reasoning behind this hypothesis, show how it may be tested, and suggest what, if it is accurate, it may mean to our culture.

The search in earnest for extraterrestrial life is only beginning, but we have already entered a remarkable period of discovery, a time of excitement and dawning knowledge perhaps not seen since Europeans reached the New World in their wooden sailing ships. We too are reaching new worlds and are acquiring data at an astonishing pace. Old ideas are crumbling. New views rise and fall with each new satellite image or deep-space result. Each novel biological or paleontological discovery supports or undermines some of the myriad hypotheses concerning life in the Universe. It is an extraordinary time, and a whole new science is emerging: astrobiology, whose central focus is the condition of life in the Universe. The practitioners of this new field are young and old, and they come from diverse scientific backgrounds. Feverish urgency is readily apparent on their faces at press conferences, such as those held after the Mars Pathfinder experiments, the discovery of a Martian meteorite on the icefields of Antarctica, and the collection of new images from Jupiter's moons. In usually decorous scientific meetings, emotions boil over, reputations are made or tarnished, and hopes ride a roller coaster, for scientific paradigms are being advanced and discarded with dizzying speed. We are witnesses to a scientific revolution, and as in any revolution there will be winners and losers—both among ideas and among partisans. It is very much like the early 1950s, when DNA was discovered, or the 1960s, when the concept of plate tectonics and continental drift was defined. Both of these events prompted revolutions in science, not only leading to the complete reorganization of their immediate fields and to adjustments in many related fields, but also spilling beyond the boundaries of science to make us look at ourselves and our world in new ways. That will come to pass as well in this newest scientific revolution, the Astrobiology Revolution of the 1990s and beyond. What makes this revolution so startling is that it is happening not within a given discipline of science, such as biology in the 1950s or geology in the 1960s, but as a convergence of widely different scientific disciplines: astronomy, biology, paleontology, oceanography, microbiology, geology, and genetics, among others.

In one sense, astrobiology is the field of biology ratcheted up to encompass not just life on Earth but also life beyond Earth. It forces us to reconsider the life of our planet as but a single example of how life might work, rather than as the only example. Astrobiology requires us to break the shackles of conventional biology; it insists that we consider entire planets as ecological systems. It requires an understanding of fossil history. It makes us think in terms of long sweeps of time rather than simply the here and now. Most fundamentally, it demands an expansion of our scientific vision—in time and space.

Because it involves such disparate scientific fields, the Astrobiology Revolution is dissolving many boundaries between disciplines of science. A paleontologist's discovery of a new life form from billion-year-old rocks in Africa is of major consequence to a planetary geologist studying Mars. A submarine probing the bottom of the sea finds chemicals that affect the calculations of a planetary astronomer. A microbiologist sequencing a string of genes influences the work of an oceanographer studying the frozen oceans of Europa (one of Jupiter's moons) in the lab of a planetary geologist. The most unlikely alliances are forming, breaking down the once-formidable academic barriers that have locked science into rigid domains. New findings from diverse fields are being brought to bear on the central questions of astrobiology: How common is life in the universe? Where can it survive? Will it leave a fossil record? How complex is it? There are bouts of optimism and pessimism; E-mails fly; conferences are hastily assembled; research programs are rapidly redirected as discoveries mount. The excitement is visceral, powerful, dizzying, relentless. The practitioners are captivated by a growing belief: Life is present beyond Earth.

The great surprise of the Astrobiology Revolution is that it has arisen in part from the ashes of disappointment and scientific despair. As far back as the 1950s, with the classic Miller–Urey experiments showing that organic matter could be readily synthesized in a test tube (thus mimicking early Earth environments), scientists thought they were on the verge of discovering how life originated. Soon thereafter, amino acids were discovered in a newly fallen meteorite, showing that the ingredients of life occurred in space. Radiotelescope observations soon confirmed this, revealing the presence of organic material in interstellar clouds. It seemed that the building blocks of life permeated the cosmos. Surely life beyond Earth was a real possibility.

When the Viking I spacecraft approached Mars in 1976, there was great hope that the first extraterrestrial life—or at least signs of it—would be found (see Figure I.1). But Viking did *not* find life. In fact, it found conditions hostile

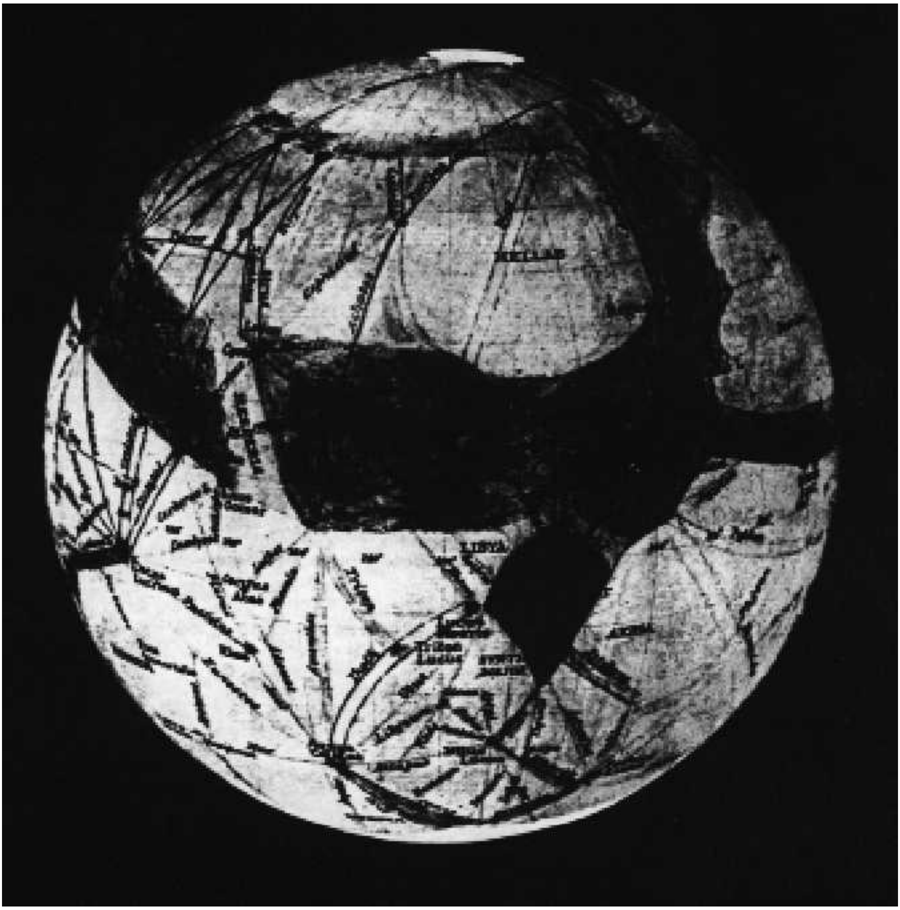

Figure I.1 *Percival Lowell's 1908 globe of Mars. Some thought that the linear features were irrigation canals built by Martians.*

to organic matter: extreme cold, toxic soil and lack of water. In many people's minds, these findings dashed all hopes that extraterrestrial life would ever be found in the solar system. This was a crushing blow to the nascent field of astrobiology.

At about this time there was another major disappointment: The first serious searches for "extrasolar" planets all yielded negative results. Although many astronomers believed that planets were probably common around other stars, this remained only abstract speculation, for searches using Earth-based telescopes gave no indication that any other planets existed outside our own solar system. By the early 1980s, little hope remained that real progress in this field would occur, for there seemed no way that we could ever detect worlds orbiting other stars.

Yet it was also at this time that a new discovery paved the way for the interdisciplinary methods now commonly used by astrobiologists. The 1980 announcement that the dinosaurs were *not* wiped out by gradual climate change (as was so long thought) but rather succumbed to the catastrophic effects of the collision of a large comet with Earth 65 million years ago, was a watershed event in science. For the first time, astronomers, geologists, and biologists had reason to talk seriously with one another about a scientific problem common to all. Investigators from these heretofore separate fields found themselves at the same table with scientific strangers—all drawn there by the same question: Could asteroids and comets cause mass extinction? Now, 20 years later, some of these same participants are engaged in a larger quest: to discover how common life is on planets beyond Earth.

The indication that there was no life on Mars and the failure to find extrasolar planets had damped the spirits of those who had begun to think of themselves as astrobiologists. But the field involves the study of life on Earth as well as in space, and it was from looking inward—examining this planet—that the sparks of hope were rekindled. Much of the revitalization of astrobiology came not from astronomical investigation but from the discovery, in the early 1980s, that life on Earth occurs in much more hostile environments than was previously thought. The discovery that some microbes live in searing temperatures and crushing pressures both deep in the sea and deep beneath the surface of our planet was an epiphany: If life survives under such conditions here, why not on—*or in*—other planets, other bodies of our solar system, or other plants and moons of far-distant stars?

Just knowing that life can stand extreme environmental conditions, however, is not enough to convince us that life is actually *there.* Not only must life be able to *live* in the harshness of a Mars, Venus, Europa, or Titan; it must also have been able either to *originate* there or to travel there. Unless it can be shown that life can form, as well as live, in extreme environments, there is little hope that even simple life is widespread in the Universe. Yet here, too, revolutionary new findings lead to optimism. Recent discoveries by geneticists have shown that the most primitive forms of life on Earth—those that we might expect to be close to the first life to have formed on our planet—are exactly those tolerant life forms that are found in extreme environments. This suggests to some biologists that life on Earth *originated* under conditions of great heat, pressure, and lack of oxygen—just the sorts of conditions found elsewhere in space. These findings give us hope that life may indeed be widely distributed, even in the harshness of other planetary systems.

The fossil record of life on our own planet is also a major source of relevant information. One of the most telling insights we have gleaned from the fossil record is that life formed on Earth about as soon as environmental conditions allowed its survival. Chemical traces in the most ancient rocks on Earth's surface give strong evidence that life was present nearly 4 billion years ago. Life thus arose here almost as soon as it theoretically could. Unless this occurred utterly by chance, the implication is that nascent life itself forms—is synthesized from nonliving matter—rather easily. Perhaps life may originate on *any* planet as soon as temperatures cool to the point where amino acids and proteins can form and adhere to one another through stable chemical bonds. Life at this level may not be rare at all.

The skies too have yielded astounding new clues to the origin and distribution of life in the Universe. In 1995 astronomers discovered the first extrasolar planets orbiting stars far from our own. Since then, a host of new planets have been discovered, and more come to light each year.

For a while, some even thought we had found the first record of extraterrestrial life. A small meteorite discovered in the frozen icefields of Antarctica appears to be one of many that originated on Mars, and at least one of these may be carrying the fossilized remains of bacteria-like organisms of extraterrestrial origin. The 1996 discovery was a bombshell. The President of the United States announced the story in the White House, and the event triggered an avalanche of new effort and resolve to find life beyond Earth. But evidence—at least from this particular meteorite—is highly controversial.

All of these discoveries suggest a similar conclusion: Earth may not be the only place in this galaxy—or even in this solar system—with life. Yet if other life is indeed present on planets or moons of our solar system, or on far-distant planets circling other stars in the Universe, what kind of life is it? What, for example, will be the frequency of *complex metazoans,* organisms with multiple cells and integrated organ systems, creatures that have some sort of behavior—organisms that we call animals? Here too a host of recent discoveries have given us a new view. Perhaps the most salient insights come, again, from Earth's fossil record.

New ways of more accurately dating evolutionary advances recognized in the Earth's fossil record, coupled with new discoveries of previously unknown fossil types, have demonstrated that the emergence of animal life on this planet took place later in time, and more suddenly, than we had suspected. These discoveries show that life, at least as seen on Earth, does not progress toward complexity in a linear fashion but does so in jumps, or as a series of thresholds. Bacteria did not give rise to animals in a steady progression. Instead, there were many fits and starts, experiments and failures. Although life may have formed nearly as soon as it could have, the formation of *animal* life was much more recent and protracted. These findings suggest that complex life is far more difficult to arrive at than evolving life itself and that it takes a much longer time period to achieve.

It has always been assumed that attaining the evolutionary grade we call animals would be the final and decisive step: that once this level of evolution was achieved, a long and continuous progression toward intelligence should occur. However, another insight of the Astrobiological Revolution has been that *attaining* the stage of animal life is one thing, but *maintaining* that level is quite something else. New evidence from the geological record has shown that once it has evolved, complex life is subject to an unending succession of planetary disasters that create what are known as mass extinction events. These rare but devastating events can reset the evolutionary timetable and destroy complex life, while sparing simpler life forms. Such discoveries again suggest that the conditions hospitable to the evolution and existence of *complex* life are far more specific than those that allow life's *formation.* On some planets, then, life might arise and animals eventually evolve—only to be quickly destroyed by a global catastrophe.

To test the Rare Earth Hypothesis—the paradox that life may be nearly everywhere but complex life almost nowhere—may ultimately require travel to the distant stars. We cannot yet journey much beyond our own planet, and the vast distances that separate us from even the nearest stars may prohibit us from ever exploring planetary systems beyond our own. Perhaps this view is pessimistic, and we will ultimately find a way to travel much faster (and thus farther), through worm holes or other unforeseen methods of interstellar travel, enabling us to explore the Milky Way and perhaps other galaxies as well.

Let's assume that we do master interstellar travel of some sort and begin the search for life on other worlds. What types of worlds will harbor not just life, but complex life equivalent to the animals of Earth? What sorts of planets or moons should we look for? Perhaps the best way to search is simply to look for planets that resemble Earth, which is so rich with life. Do we have to duplicate this planet exactly to find animal life, though? What is it about our solar system and planet that has allowed the rise of complex life and nourished it so well? Addressing this issue in the pages ahead should help us answer the other questions we have posed.

Rare Planet?

If we cast off our bonds of subjectivity about Earth and the solar system, and try to view them from a truly "universal" perspective, we also begin to see aspects of Earth and its history in a new light. Earth has been orbiting a star with relatively constant energy output for billions of years. Although life may exist even on the harshest of planets and moons, animal life—such as that on Earth—not only needs much more benign conditions but also must have those conditions present and stable for great lengths of time. Animals as we know them require oxygen. Yet it took about 2 billion years for enough oxygen to be produced to allow all animals on Earth. Had our sun's energy output experienced too much variation during that long period of development (or even afterward), there would have been little chance of animal life evolving on this planet. On worlds that orbit stars with less consistent energy output, the rise of animal life would be far chancier. It is difficult to conceive of animal life arising on planets orbiting variable stars, or even on planets orbiting stars in double or triple stellar systems, because of the increased chances of energy fluxes sterilizing the nascent life through sudden heat or cold. And even if complex life did evolve in such planetary systems, it might be difficult for it to survive for any appreciable time.

Our planet was also of suitable size, chemical composition, and distance from the sun to enable life to thrive. An animal-inhabited planet must be a suitable distance from the star it orbits, for this characteristic governs whether the planet can maintain water in a liquid state, surely a prerequisite for animal life as we know it. Most planets are either too close or too far from their respective stars to allow liquid water to exist on the surface, and although many such planets might harbor simple life, complex animal life equivalent to that on Earth cannot long exist without liquid water.

Another factor clearly implicated in the emergence and maintenance of higher life on Earth is our relatively low asteroid or comet impact rate. The collision of asteroids and comets with a planet can cause mass extinctions, as we have noted. What controls this impact rate? The amount of material left over in a planetary system after formation of the planets influences it: The more comets and asteroids there are in planet-crossing orbits, the higher the impact rate and the greater the chance of mass extinctions due to impact. Yet this may not be the only factor. The types of planets in a system might also affect the impact rate and thus play a large and unappreciated role in the evolution and maintenance of animals. For Earth, there is evidence that the giant planet Jupiter acted as a "comet and asteroid catcher," a gravity sink sweeping the solar system of cosmic garbage that might otherwise collide with Earth. It thus reduced the rate of mass extinction events and so may be a prime reason why higher life was able to form on this planet and then maintain itself. How common are Jupiter-sized planets?

In our solar system, Earth is the only planet (other than Pluto) with a moon of such appreciable size compared to the planet it orbits, and it is the only planet with plate tectonics, which causes continental drift. As we will try to show, both of these attributes may be crucial in the rise and persistence of animal life.

Perhaps even a planet's placement in a particular region of its home galaxy plays a major role. In the star-packed interiors of galaxies, the frequency of supernovae and stellar close encounters may be high enough to preclude the long and stable conditions apparently required for the development of animal life. The outer regions of galaxies may have too low a percentage of the heavy elements necessary to build rocky planets and to fuel the radioactive warmth of planetary interiors. The comet influx rate may even be affected by the nature of the galaxy we inhabit and by our solar system's position in that galaxy. Our sun and its planets move through the Milky Way galaxy, yet our motion is largely within the plane of the galaxy as a whole, and we undergo little movement through the spiral arms. Even the mass of a particular galaxy might affect the odds of complex life evolving, for galactic size correlates with its metal content. Some galaxies, then, might be far more amenable to life's origin and evolution than others. Our star—and our solar system—are anomalous in their high metal content. Perhaps our very galaxy is unusual.

Finally, it is likely that a planet's *history*, as well as its environmental conditions, plays a part in determining which planets will see life advance to animal stages. How many planets, otherwise perfectly positioned for a history replete with animal life, have been robbed of that potential by happenstance? An asteroid impacting the planet's surface with devastating and life-exterminating consequences. Or a nearby star exploding into a cataclysmic supernova. Or an ice age brought about by a random continental configuration that eliminates animal life through a chance mass extinction. Perhaps chance plays a huge role.

Ever since Polish astronomer Nicholas Copernicus plucked it from the center of the Universe and put it in orbit around the sun, Earth has been periodically trivialized. We have gone from the center of the Universe to a small planet orbiting a small, undistinguished star in an unremarkable region of the Milky Way galaxy—a view now formalized by the so-called Principle of Mediocrity, which holds that we are not the one planet with life but one of many. Various estimates for the number of other intelligent civilizations range from none to 10 trillion.

If it is found to be correct, however, the Rare Earth Hypothesis will reverse that decentering trend. What if the Earth, with its cargo of advanced animals, is virtually unique in this quadrant of the galaxy—the most diverse planet, say, in the nearest 10,000 light-years? What if it is utterly unique: the only planet with animals in this galaxy or even in the visible Universe, a bastion of animals amid a sea of microbe-infested worlds? If that is the case, how much greater the loss the Universe sustains for each species of animal or plant driven to extinction through the careless stewardship of *Homo sapiens*?

Welcome aboard.

Dead Zones of the Universe

Early Universe	The most distant known galaxies are too young to have enough metals for formation of Earth-size inner planets. Hazards include energetic quasar-like activity and frequent supernova explosions.
Globular clusters	Although they contain up to a million stars they are too metal-poor to have inner planets as large as Earth. Solar-mass stars have evolved to giants that are too hot for life on inner planets. Stellar encounters perturb outer planet orbits.
Elliptical galaxies	Stars are too metal-poor. Solar-mass stars have evolved into giants that are too hot for life on inner planets.
Small galaxies	Most stars are too metal-poor.
Centers of galaxies	Energetic processes impede complex life.
Edges of galaxies	Many stars are too metal-poor.
Planetary systems with "hot Jupiters"	Inward spiral of giant planets drives the inner planets into the central star.

Planetary systems with giant planets in eccentric orbits	Environments too unstable for higher life. Some planets lost to space.
Future stars	Uranium, potassium and thorium are perhaps too rare to provide sufficient heat to drive plate tectonics.

Rare Earth Factors

Right distance from star

Habitat for complex life. Liquid water near surface. Far enough to avoid tidal lock.

Right mass of star

Long enough lifetime. Not too much ultraviolet.

Stable planetary orbits

Giant planets do not create orbital chaos.

Right planetary mass

Retain atmosphere and ocean. Enough heat for plate tectonics. Solid/molten core.

Jupiter-like neighbor

Clear out comets and asteroids. Not too close, not too far.

A Mars

Small neighbor as possible life source to seed Earth-like planet, if needed.

Plate tectonics

CO_2–silicate thermostat. Build up land mass. Enhance biotic diversity. Enable magnetic field.

Ocean

Not too much. Not too little.

Large Moon

Right distance. Stabilizes tilt.

The right tilt

Seasons not too severe.

Giant impacts

Few giant impacts. No global sterilizing impacts after an initial period.

The right amount of carbon

Enough for life. Not enough for Runaway Greenhouse.

Atmospheric properties

Maintenance of adequate temperature, composition and pressure for plants and animals.

Biological evolution

Successful evolutionary pathway to complex plants and animals.

Evolution of oxygen

Invention of photo-synthesis. Not too much or too little. Evolves at the right time.

Right kind of galaxy

Enough heavy elements. Not small, elliptical, or irregular.

Right position in galaxy

Not in center, edge or halo.

Wild Cards

Snowball Earth. Cambrian explosion. Inertial interchange event.

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