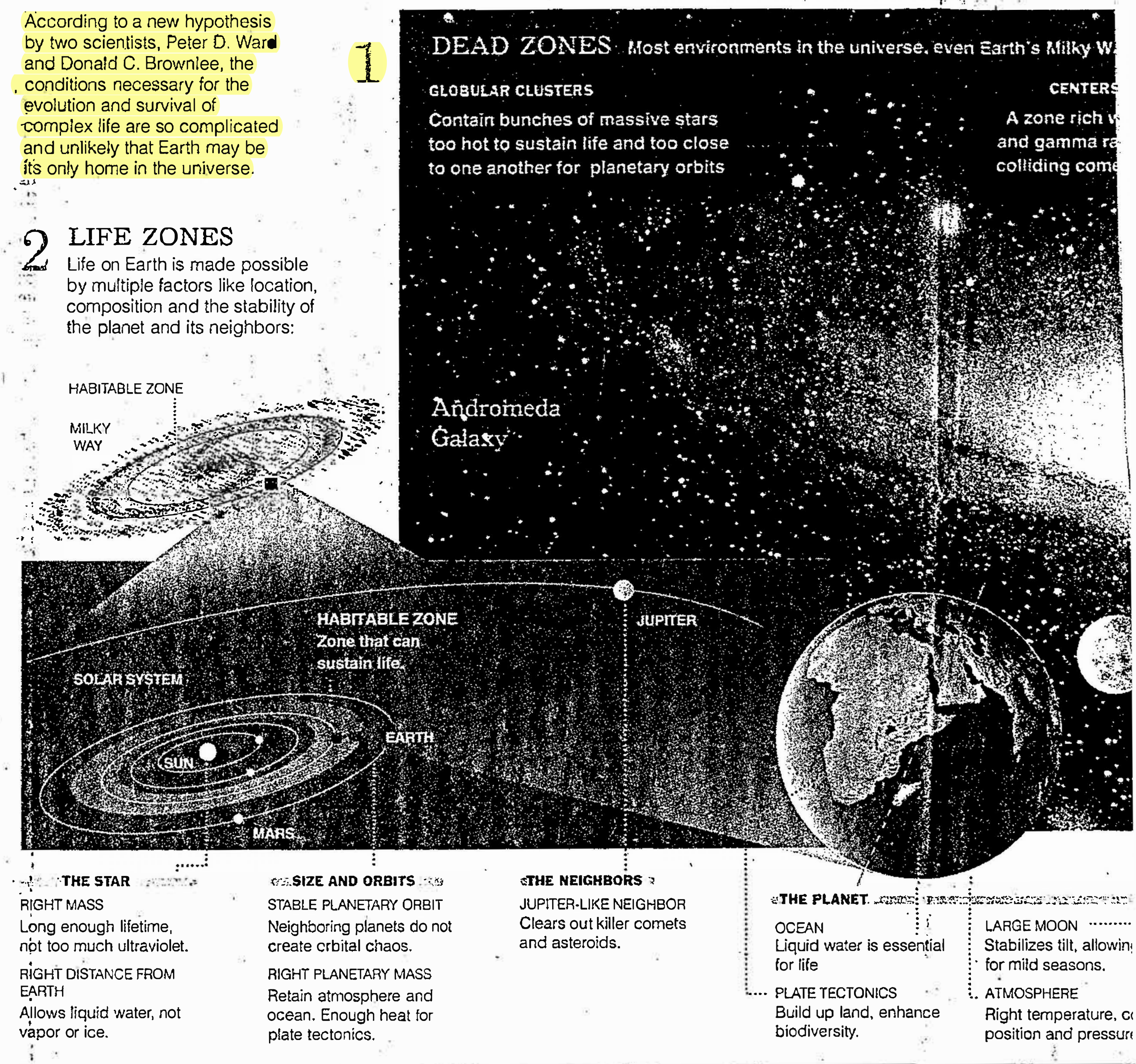
RARE EARTH,

by Peter D. Ward and Donald Brownlee (2000)

Why Complex Life is Uncommon in the Universe

Maybe We *Are* Alone in the



By WILLIAM J. BROAD

In the last few decades, a growing number of astronomers have promulgated the view that alien civilizations are likely to be scattered among the stars like grains of sand, isolated from one another by the emptiness of interstellar space. Just for Earth's own galaxy, the Milky Way, experts have estimated that there might be up to one million advanced societies.

This extraterrestrial credo has fueled not only countless books, movies and television shows — not to mention hosts of Klingons, Wookies and Romulans — but a long scientific hunt that uses huge dish antennas to scan the sky for faint radio signals from intelligent aliens.

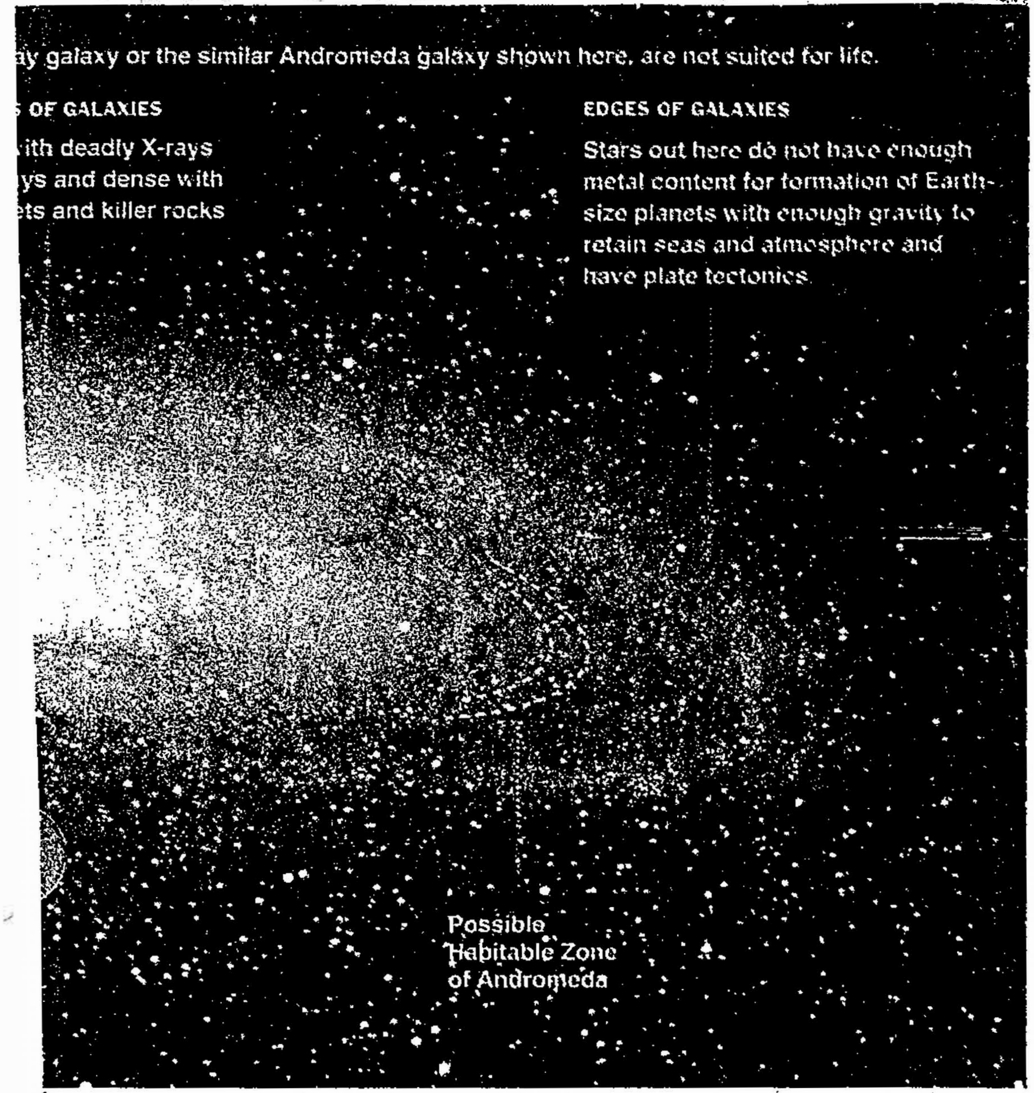
Now, two prominent scientists say the conventional wisdom is wrong. The alien search, they add, is likely to fail.

Drawing on new findings in astronomy, geology and paleontology, the two argue that humans might be alone, at least in the stellar neighborhood, and perhaps in the entire cosmos. They say modern science is showing that Earth's composition and stability are extraordinarily rare. Most everywhere else, the radiation levels are too high, the right chemical elements too rare in abundance, the hospitable planets too few in number and the rain of killer rocks too intense for life ever to have evolved into advanced communities. Alien microbes may survive in many places as a kind of cosmic shower ~~scum~~, they say, but not ex~~traterrestrials civilized enough to be awash~~ in technology.

Their book, "Rare Earth" (Springer-Verlag), out last month, is producing whoops of criticism and praise, with some detractors saying that the authors have made their own simplistic assumptions about the adaptability of life forms while others call it "brilliant" and "courageous."

"We have finally said out loud what so

Universe, After All



Jason Ware

THE ELEMENTS

RIGHT COMPOSITION
Oxygen (created by photosynthesis) and just enough carbon dioxide and other gases to preserve life without causing runaway greenhouse effect.

OTHER FACTORS

BIOLOGICAL EVOLUTION
Stable conditions during a long period allowed evolution of complex plants and animals.

WILD CARDS
Events like the shift of the continents or the ice ages also favored life.

Source: "Rare Earth," Peter D. Ward and Donald C. Brownlee.

J. Velasco/The New York Times

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many have thought for so long — that complex life, at least, is rare," said Dr. Peter D. Ward of the University of Washington, a paleontologist who specializes in mass extinctions and whose previous works include "The Call of Distant Mammoths" (Springer-Verlag, 1997). "And to us, complex life may be a flatworm."

The book's other author is Dr. Donald C. Brownlee of the University of Washington, a noted astronomer, member of the National Academy of Sciences and chief scientist of NASA's $166 million Stardust mission to capture interplanetary and interstellar dust.

"People say the Sun is a typical star," he said in an interview. "That's not true." Dr. Brownlee added: "Almost all environments in the universe are terrible for life. It's only Garden of Eden places like Earth where it can exist."

Dr. Geoffrey W. Marcy of the University of California at Berkeley, a leading seeker of planets around other stars, 31 of which have been found so far, hailed "Rare Earth" as likely to spark a revolution in thinking about extraterrestrial life.

"It's brilliant," Dr. Marcy said in an interview. "It delineates many things I've been thinking about but does a much more

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credible job of listing and explaining the various issues." For instance, he said, it shows how the giant planets discovered so far outside the solar system bode ill for the development of complex life.

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

The notion that alien civilizations are ubiquitous arose in a scientific sense four decades ago.

Dr. Frank D. Drake, then a young astronomer at a federal radio observatory in West Virginia, in 1960 was the first to scan the skies for faint alien signals, and was quickly joined by like-minded experts, including Dr. Carl Sagan, then a brash 27-year-old astronomer. Dr. Drake laid out his ideas in 1961, in what came to be known as the Drake Equation. The equation made educated guesses for the rate at which stars form, the

Support for a search for aliens, but scant hope of finding them.

fraction of stars with planets, the number of those planets on which life arises and so on, including the average lifetime of technological civilizations. By his logic, the Milky Way had about 10,000 civilizations capable of interstellar communication.

Later, Dr. Sagan revised the calculation and raised the estimate to a million alien worlds. Since the cosmos holds hundreds of millions of galaxies, by that analysis the total number of alien societies could be astronomical, one estimate putting the number at roughly 10 trillion.

New findings, however, according to the authors of "Rare Earth," show that the Drake Equation is riddled with hidden optimistic assumptions. Their stance, the authors say in the preface, is "rarely articulated but increasingly accepted by many astrobiologists," the general name for scientists who study the likelihood of extraterrestrial life.

Dr. Ward said he was drawn to the topic because of his studies of mass extinctions. Increasingly, top culprits are seen as speeding rocks from outer space that hit Earth in huge explosions, with one 65 million years ago killing off many plants and animals, including the dinosaurs.

New studies, Dr. Ward said, suggest that things could be worse. For instance, the rate of terrestrial impacts could be as much as 10,000 times higher but for of Jupiter, the solar system's largest planet, which absorbs many killer rocks and flings others into deep space.

"We're right on the edge of the abyss," Dr. Ward said, in terms of higher bombardment rates that have probably precluded the development of advanced life.

Recent finds of giant Jupiter-like planets outside the solar system offer no solace. Most of their orbits, he said, are wildly eccentric, which would abet destructive chaos among smaller planets rather than shielding them. "All the Jupiters seen today are bad Jupiters," Dr. Ward said. "Ours is the only good one we know of. And it's got to be good, or you're thrown out into dark space or into your sun."

Dr. Marcy, the planet finder, said such analyses were adding to his doubts about the existence of extraterrestrials.

Even if some distant Jupiters are in stable, circular orbits, Dr. Ward said, other factors might overwhelm their protective effect and demolish any life. For instance, closer to the center of the galaxy where star populations are far denser, the frequent passage of one star past another could trigger cascades of comets, trillions of which are thought to orbit most stars' icy fringes. "If you're in the interior of the galaxy," he said, "you're always getting bombarded."

Added to that fury, he said, is the intense radiation and explosions of galactic interiors. The star-filled sky conveys a false impression of immutability. New studies show that the cosmos, especially galactic centers, are hotbeds of violence swept by killing waves of X-rays, gamma rays and ionizing radiation.

"So I don't think there's any life in the centers at all," Dr. Ward said.

Dr. Brownlee, the astronomer and co-author, said the odds for complex life were similarly bad at galactic edges. The analysis of starlight from the fringes shows they are relatively poor in elements like iron, magnesium and silicon, partly because of less recycling of stellar materials over the eons and partly because of the rarity in such regions of supernovas, the stellar blasts that help make heavy elements in enormously hot explosions.

These elements, Dr. Brownlee said, and even heavier ones that are radioactive and also made in supernovas, appear to be prerequisites to the formation of terrestrial-type planets that have sufficient gravity to retain seas and atmospheres and that have plate tectonics, which is powered largely by the heat of radioactive decay.

According to the book, the slow movement and recycling of planetary crust into a planet's hot interior are key ingredients for the evolution of complex life. Plate tectonics, the authors say, promotes biodiversity by producing mountain chains and other kinds of environmental complexity, lessens the odds of extinctions, helps keep planetary temperatures even through the recycling of carbon and makes dry land on which advanced civilizations can flourish.

"We're critically dependent on mass," said Dr. Brownlee. "Being bigger or smaller might rule out plate tectonics."

Whole galaxies are metal-poor and therefore probably devoid of animal life, Dr. Brownlee added. Only spiral galaxies like the Milky Way and its nearby neighbor in Andromeda appear rich in metals, and even then, only in their inner regions. In contrast, elliptical and irregular galaxies, he said, are barren.

"Lower metal abundance means you can't make a planet as big as the Earth," Dr. Brownlee said. "It seems like something a lot of people don't want to hear."

The scientists discuss other planetary characteristics that are probably rare in the universe but are increasingly seen as critical for making Earth so favorable to complex life. Among them are these:

¶An orbit that keeps a planet at exactly the right distance from its star to ensure that water remains liquid, not vapor or ice.

¶A large moon at just the right distance to minimize changes in a planet's tilt, ensuring climate stability.

¶Enough carbon to aid the development of life but not so much to allow for runaway greenhouse conditions, as occur on superheated Venus.

In the book's conclusion, the authors say the Rare Earth hypothesis is testable, and they strongly encourage such work. Powerful new telescopes will shed light not only on gas giants but on the abundance of smaller, terrestrial planets around distant stars, and will also show whether their orbits are stable and protected by larger planets from cosmic bombardment. New telescopes also might find evidence of planets enshrouded in ozone and oxygen, which in sufficient concentrations imply the existence of life.

The two scientists also call for searches of Mars, the Jovian moons Europa and Ganymede, and Saturn's moon Titan for signs of alien microbes. That discovery would answer the question of whether life is an inherent property of matter, as most scientists believe.

The two support radio hunts for signs of advanced alien civilizations, but add that "it is very difficult to know" whether the search "is an effective use of resources."

Some advocates of the search for extraterrestrial intelligence, known

ON THE WEB

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Mary Levin/University of Washington

Pond scum, yes; Mr. Spock, no, say Peter Ward, left, and Donald Brownlee of life beyond Earth.

as SETI, see the new book as a heretical assault that could endanger the financing of the hunt. More than $100 million has been spent to date, with most money now coming from silicon moguls and other private donors.

Dr. Drake, now president of the SETI Institute, a private group in Mountain View, Calif., that is searching for alien civilizations with the huge dish antenna at Arecibo, P.R., said the book's main failing was undue pessimism about life's tenacity.

"The basic flaw in all those arguments," Dr. Drake said, "is that they don't allow for the opportunistic nature of life, its ability to accommodate or alter itself to cope with environmental change."

As for politics, Dr. Drake said, most SETI researchers are more interested in honest debate than trying to suppress critics out of fear of cuts in financing. "Maybe we're politically naïve," he said. "But we don't try to stamp out this stuff."

Dr. Drake added: "The only way you can find out the truth is to search and discover either the prevalence of intelligent life, or its total absence."

If the rarity hypothesis turns out to be true, the book says, it greatly increases the loss each time a plant or animal is driven to extinction and strengthens the responsibility for humans to be good stewards of the planet.

Also, Dr. Ward remarked in an interview, if the Milky Way is truly devoid of alien hordes, then it might be humanity's destiny over the eons to spread into the wilderness of stars, unopposed by ancient legions.

"If we are as rare as we think we are," Dr. Ward said, "it raises the stakes, intellectually and morally."

1.6 Million Cyberlings Go a-Hunting for Aliens

By WILLIAM J. BROAD

Earthlings are so enamored of aliens that 1.6 million of them in 224 countries have recently joined an effort that harnesses home and office computers to the job of sifting through a few zillion radio bands to hunt for signs of intelligent life among the stars.

The SETI@home project of the University of California at Berkeley uses idle computers linked to the Internet to plow through signals collected by the huge dish at Arecibo, P.R., searching for intelligently made radio signals amid the celestial static. The biggest of all the world's radio telescopes, at 1,000 feet in diameter, it is also the best single antenna for gathering faint signals.

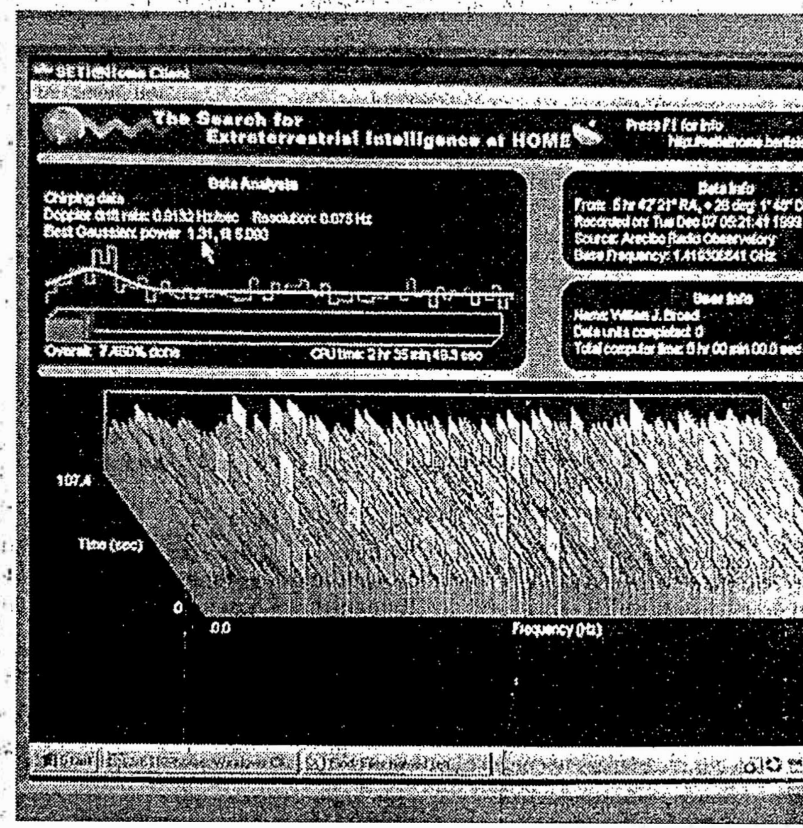
Through the Internet, the project distributes software that enables home computer users to help scientists crunch Arecibo data in what its creators call the world's largest ad hoc supercomputer. The software works as a screen saver, analyzing data only when computers are idle. Once the data have been analyzed, a process that can take days, they are returned to Berkeley for another slice of the sky.

Since May, when the project started, volunteers have donated 165,000 years of computing time to analyzing radio emissions from outer space.

Among the top performers listed on the Web site: Sun Microsystems (287 years of computer time), Intel Performance Labs (199 years), the Computer Aided Engineering lab at the University of Wisconsin-Madison (89 years), America Online (71 years), Microsoft (41 years), Fermi National Laboratory (59 years), Pixar (29 years), Compaq Telecom Engineering (26 years), A. W. Spence Middle School in Dallas (25 years), Frank Terhaar in Yonkers (24 years) and someone named Jean-Luc Picard (6 years).

"So far we don't have any really exciting signals," said Dan Werthimer, the project's chief scientist. "But it's early in the game. We've only just begun and Earthlings are pretty primitive in this field. We're just scratching the surface."

Free hunt software can be downloaded from www.setiathome.ssl.berkeley.edu, which has been done 1.6 million times, Mr. Werthimer said. Among the effort's sponsors are the Planetary Society, the University of California, Sun Microsystems, Fuji Film, Paramount Pictures, Intel, the SETI Institute and private donors.



Tony Cenicola/The New York Times

Since last May, millions of people have donated 165,000 years of combined computer time searching for intelligent life beyond Earth.

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. Radio-telescope 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

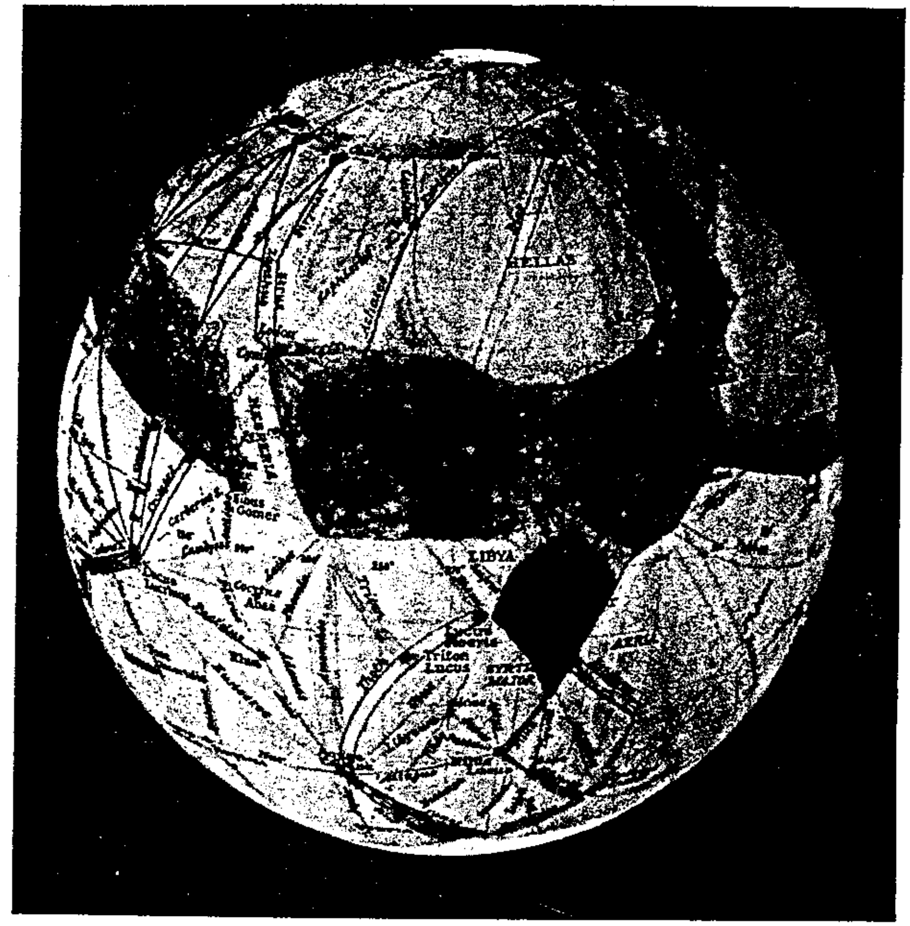


Figure I.1 *Percival Lowell's 1907 globe of Mars. Some thought that the linear features were irrigation canals built by Martians.*

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 Danish 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 photosynthesis. 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.