oid may have melted regions of ice on Titan. For periods of hundreds or even thousands of years, gradually cooling ice-covered lakes might have supported the first chemical steps in the path toward life, only to become frozen again. Such primitive biochemistry, though lost forever on Earth's scavenged surface, might conceivably survive in the deep-freeze of Titan.

But so much for speculation and conjecture. Observations of the living world, coupled with relevant experiments, will illuminate the emergence of life both here on Earth and even elsewhere in our solar system.

3

Looking for Life

Scientists turn reckless and mutter like gamblers who cannot stop betting.

Alan Lightman, *Einstein's Dreams,* 1993

The profound difficulty in crafting an unambiguous definition of what is (or was) alive came into dramatic focus in 1996 with the discovery of supposed cellular fossils in a meteorite from Mars. Of the countless thousands of meteorites that have been collected on Earth's surface, only a precious two dozen or so came to us from Mars. In the 1980s, chemists deduced the distant origins of these rocks from the diagnostic composition of gas trapped inside them—gas that matches perfectly the known idiosyncrasies of the Martian atmosphere. Theorists maintained that giant asteroid impacts on Mars could easily have hurled rocky debris into orbit around the Sun. And while the Sun and Jupiter, the two most massive objects in our solar system, eventually (often after millions of years) sweep up most of that Martian detritus, a tiny fraction of the rubble inevitably finds its way to Earth. With the discovery of Martian meteorites, scientists could, for the first time, investigate actual pieces of another planet.

Naturally, these nondescript chunks of dark-colored rock are highly prized and receive the closest examination by earthbound scientists. Most of them are hunks of ancient igneous formations—material formed from once-molten rock near the Martian surface. We expect such meteorites to be devoid of life. But one Mars meteorite proved strikingly different from the others, and it naturally attracted extra close scrutiny. Collected in 1984 from the Allan Hills region of Antarctica (hence its now famous designation, ALH84001), this meteorite held a suite of minerals that suggested to some scientists the possibility of ancient interactions with liquid water.

A team of biologists, planetary scientists, and meteorite experts led by NASA's David McKay subjected pieces of the two-pound rock to a battery of analytical tests. They probed the meteorite with X-rays, lasers, gamma rays, and beams of electrons, recording characteristics as small as a billionth of an inch across. No one had ever expected to find hard evidence for Martian life, but even a hint of freely flowing water on Mars would constitute a major discovery. Yet gradually, as the data piled up, McKay and his colleagues began to believe that they had found the smoking gun for Martian life.

LIFE ON MARS: THE ALLAN HILLS STORY

On August 7, 1996, the Allan Hills team publicly claimed the discovery of tiny elongated objects that were once alive. "LIFE ON MARS!" screamed the headlines, while the prestigious periodical *Science* published an article with the equally giddy title (at least for a scientific journal), "Search for Past Life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001." President Clinton got into the act by holding a national press conference, during which he basked in the reflected glory of NASA's triumph.

McKay and his eight co-workers pointed to five separate types of data, which they presented point by point like a zealous prosecutor at a jury trial. Point number one: The meteorite was found to contain a suite of organic molecules, including carbon-based compounds called PAHs (polycyclic aromatic hydrocarbons). These sturdy, long-lasting molecules, which feature interlocking rings of six carbon atoms, often arise when once-living cells are subjected to high temperature. Since carbon is the key element of life as we know it, its presence in ALH84001, which distinguished that specimen from the other Martian meteorites, was of extraordinary significance.

Point two: The meteorite held microscopic globules of carbonate minerals, similar to those that make the graceful formations on the walls of caves on Earth. Such carbonates are often deposited through the action of liquid water passing through a system of cracks and fissures. Liquid water is the presumptive medium of all cells and thus a necessary condition for life. What's more, their tiny structures, about a ten-thousandth of an inch in diameter, reminded some observers of minerals precipitated by microbes on Earth.

The third and fourth points relied on sophisticated analytical tools. The NASA team used an electron microscope to discover and characterize two iron-bearing minerals, an iron sulfide called pyrrhotite and an iron oxide called magnetite. Of particular interest were the curious chainlike arrays of minuscule magnetite crystals. Magnetite is a magnetic mineral found in abundance in rocks of all types, but the perfect shape of these alien crystals and their unusual chemical purity, coupled with their distinctive linear arrangements, seemed unlike anything ever seen except in a few remarkable types of bacteria. These "magnetotactic" microbes tend to live in thin layers of sediment where chemical conditions change rapidly with depth, and they use their internal magnets to distinguish "up" from "down," by sensing the inclination of Earth's magnetic field. So sensitive are these organisms to their vertical position that magnetotactic bacteria from the Northern Hemisphere move in the wrong direction and die when placed in Southern Hemisphere soils, where magnetic "up" and "down" are reversed. The NASA scientists claimed that no known inorganic process could have produced such an ordered crystalline array.

Finally, the fifth point: ALH84001 holds myriad tiny sausage-shaped objects reminiscent of some species of terrestrial bacteria. Though much smaller than any known Earthly microbes, these suggestive forms provided the public with its most convincing evidence for Mars life. Hundreds of newspapers and magazines reproduced the NASA electron microscope images with captions identifying them as "Martian microbes."

The main text of the McKay et al. six-page article in *Science* conveyed a sober and reasoned discussion of their findings, and they acknowledged that no single line of evidence was enough to trumpet the discovery of alien life. But the concluding sentence shifted tone and pushed the limits of most readers' credibility: "Although there are alternative explanations for each of these phenomena taken individually, when they are considered collectively, particularly in view of their spatial association, we conclude that they are evidence for primitive life on early Mars."

To paraphrase the late Carl Sagan, extraordinary claims require extraordinary proof. Predictably, controversy exploded around the

NASA scientists' bold claim. Experts pored over the paper, which was aggressively challenged on every point.

Point number one: PAHs and other carbon molecules litter the cosmos, notably in the interstellar dust that forms comets and asteroids—the raw materials that formed Mars. What's more, such molecules would have formed in abundance by natural chemical processes at or near the primitive surface of Mars. And PAHs are among the most common constituents of pollution on Earth; the meteorite could have become contaminated while sitting on the ice. There's no reason to conclude that these PAHs represent the remains of living cells.

Point two: The carbonate minerals could have formed in many ways other than by circulating water. Carbonates can occur in reactions of rock with carbon dioxide, the most common Martian atmospheric gas. Carbonates commonly grow as alteration products, long after the host rock forms, or directly from melts by igneous processes. Indeed, a number of researchers reanalyzed the minerals and found evidence that they had formed at temperatures well above the boiling point of water.

Skeptical experts also argued that the minute magnetite crystals prove nothing, since they are common constituents of meteorites that bear no possible signs of life. The chainlike arrays of exceptionally pure magnetite crystals are unusual, to be sure, but most observers feel that magnetite grains are insufficient by themselves to prove the existence of Martian life. Magnetotactic bacteria, furthermore, would have required a moderately strong Martian magnetic field—perhaps stronger than geophysical evidence suggests.

Finally, the purported fossil microbes are too small—an order of magnitude smaller than any known Earthly bacteria. In fact, they are so small that they could contain no more than a few hundred biomolecules—not nearly enough for a living cell. And there's no reason to characterize them as fossils, since inorganic processes (including sample processing in the lab) are known to produce similar elongated shapes.

The story became even more confused when scientists began examining other meteorites, Martian and otherwise, in the same meticulous detail afforded the Allan Hills specimen. Surprisingly, all meteorites reveal signs of life—Earth life. Meteorites smash into Earth, where our planet's ubiquitous microbes inevitably contaminate them. Almost every meteorite ever found has lain on the ground for periods

ranging from several days to many thousands of years. Once found, they are usually handled, breathed on, and otherwise exposed to more contamination. Unless hermetically sealed almost immediately, any meteorite will be compromised. In a matter of months, microbes migrate deep into a meteorite's interior, exploiting every crack and crevice in a search for the chemical potential energy that is stored in the meteorite's minerals. Given such a messy environment, how could anyone ever be sure about ALH84001?

One of the most vocal critics of the Martian claim was UCLA paleontologist J. William Schopf. A leading expert on microfossils and an authority on Earth's most ancient life, Schopf was outraged at what he regarded as the NASA team's shoddy analysis and unwarranted conclusions. At the well-publicized August 1996 NASA press conference to discuss the discovery, Schopf was invited to participate as an objective, dissenting voice. "I was like Daniel in the lion's den," he recalls. Not wanting to publicly denigrate the NASA crowd, he may have pulled his punches in that public forum ("I had tried to be reasonable, even gentle"), but he underscored his criticisms of the NASA work in a scathing addendum to his popular book, *Cradle of Life* (1999). There he attacked the NASA team with a withering analysis, which he intensified by juxtaposing his critique of ALH84001 with stories of the most egregious paleontological blunders of all time. Of the late famed meteorite, he wrote: "The minerals can't prove it. The PAHs can't either. The 'fossils' could—but they don't, and there are good reasons to question whether they are in any way related to life."

Schopf concluded on a more philosophical note: "There are fine lines between what is known, guessed, and hoped for, and because science is done by real people these lines are sometimes crossed. But science is not guessing." Little did he suspect that within a few years those righteous proclamations would come back to haunt him.

EARTH'S OLDEST FOSSILS—THE SCHOPF–BRASIER CONTROVERSY

The top-down approach to life's origins requires that we ferret out and characterize Earth's most ancient fossil life. Those fragile, fragmentary clues may help us bridge the gulf between geochemistry and biochemistry, and thus deduce key steps in life's emergence.

Fossil microbial life should be vastly easier to detect in Earth's ancient rocks than in the handful of meteoritic fragments from Mars. After all, we can collect tons of specimens, scrutinize their geological setting, and check any critical measurements in many different laboratories. No matter how remote the rocks or treacherous the journey, it's well worth the effort, for Earth's earliest fossils not only provide a glimpse of the size and shape of ancient life but also reveal the timing of life's opening act.

Planet Earth formed about 4.5 billion years ago as a giant, molten, red-hot glowing sphere—the result of the accumulation of countless comets, asteroids, and other cosmic debris. For another few hundreds of millions of years, an incessant meteoritic bombardment pulverized every square inch of Earth's surface. What's more, every few million years an epic impact of an object a hundred kilometers or more across punctuated the steady rain of smaller boulders. Such catastrophic events would have repeatedly vaporized any nascent oceans and blasted much of the primitive atmosphere into space. No imaginable life-form could have survived the hellish onslaught of that so-called Hadean eon.

We don't know exactly when cellular life arose, but the window of opportunity appears to have been surprisingly short. It's almost certain that life could not have persisted before about 4 billion years ago, when the last of the great globe-sterilizing events is estimated to have occurred. It's always possible that life began several times before that, only to be snuffed out by the periodic impact of devastating asteroids. In any case, chemical evidence for life in Earth's oldest known rocks—formations 3.5 to 3.8 billion years old from Greenland, South Africa, and Australia—seem to establish a remarkably ancient lower age limit for life. Such a narrow time window suggests that life's emergence was rapid, at least on a geological timescale.

Paleontologists devote their lives to scrutinizing fragmentary signs of life in rocks. It's not always a glamorous business, mucking about in inhospitable, remote landscapes, but there's always the possibility for making a big splash. Paleontologists, perhaps more than scientists in any other discipline, can generate gripping headlines. Discoveries of history's biggest shark, most massive dinosaur, or oldest human inspire the public imagination. We live in an age of Guinness-style records; we are obsessed with superlatives. One recent report in *USA Today* even trumpeted the discovery of the oldest known fossilized penis in a 400-million-year-old crustacean!

With such a fossil-obsessed press corps, it's little wonder that paleontologist Schopf made the evening news (and *Guinness World Records*) in April 1993 with his announcement in *Science* of the discovery of Earth's oldest fossils ("Microfossils of the Early Archean Apex Chert: New Evidence of the Antiquity of Life"). Schopf claimed to have identified actual single cells, preserved in the 3.465-billion-year-old Apex Chert from the sun-baked northwestern corner of Western Australia. Even more surprising, these cells occurred in filament-like chains strongly reminiscent of those formed by modern photosynthesizing microbes—cells with the relatively advanced chemical capability to harvest sunlight.

As in the subsequent ALH84001 incident, the claims were extraordinary and consequently demanded extraordinary proof. In this case, however, the geological community was generally quick to accept Schopf's assertions, because he had established a reputation as one of the world's leading experts in finding and describing ancient single-celled microbes. Schopf and his students had already catalogued dozens of new microbial species from 2-billion-year-old rocks around the world, while establishing rigorous standards for the cautious identification and conservative reporting of new finds. The latest fossils merely pushed back the record for the world's oldest life a few hundred million years.

A straightforward UCLA protocol had become standard for the maturing field of micropaleontology. Visit Earth's geological formations of the Archean eon (4 billion to 2.5 billion years ago), identify layers of sediment that were deposited in ocean environments, and scour the region for outcrops of distinctive carbon-rich rocks called black chert. Field-workers collect hundreds of pounds of Archean rocks, break off hunks of the most promising specimens, and ship them back to California, where they are sliced into 2 × 3-inch transparent thin sections, a few hundredths of an inch thick.

The research protocol for finding ancient microbes can be exceptionally tedious. Graduate students are coaxed and coerced into spending thousands of hours examining every part of every slide, micron by eye-straining micron. It turns out that black chert isn't really black at all. Illuminated from beneath and viewed in a powerful microscope, thin sections provide a window on the ancient world. The typical cherty matrix is chockablock full of little black blobs and smudges. Most black chert is seemingly barren of life, but once in a while a thin section reveals a host of tiny spheres, disks, rods, and chains—dead ringers for modern bacteria. Schopf was fortunate that in 1986 one especially sharp-eyed and conscientious student, Bonnie Packer, scrutinized the most promising Australian specimens. Most thin sections yielded nothing of interest, but her discovery of unambiguous microfossils in several ancient units led to a prominent publication and set the stage for the Apex controversy.

Appearances can be deceiving. Lots of inorganic processes produce round specks and enigmatic squiggles. It's all too tempting to see what you want to see in an ancient rock. That's why Schopf and his colleagues had developed an arsenal of confirmatory tests. For one thing, size matters. Single-celled organisms can't be too small or too big (though some remarkable ancient single-celled organisms are monsters by modern standards). Even more critical, microbial populations tend to cluster tightly around one preferred size, in contrast to the more random sizes of structures produced by nonbiological processes. Consequently, a statistical analysis of size distributions often accompanied Schopf's papers. Uniformity of shape is another key; no fair photographing one or two suggestively contoured black bits while ignoring a multitude of shapeless blobs. Schopf also demanded rigor in the description of local geologic setting and in the proper dating of his samples. As a result, his work on the Apex Chert was initially accepted; he had established a solid reputation for cautious, conservative science.

But one aspect of Schopf's 1993 study—the claim that some of the microbes were photosynthetic and hence oxygen-producing—remained puzzling. Geochemical evidence from Earth's oldest rocks points to an oxygen-poor atmosphere prior to about 2.2 billion years ago, a time that most researchers identify with the rise of photosynthesis. How could oxygen-producing microbes be present more than a billion years earlier? Nevertheless, within a few years Schopf's claims for the earliest fossils were standard textbook fare; his pictures of Apex fossils had become among the most frequently reproduced of all paleontological images. Schopf himself highlighted the historic findings in *Cradle of Life.* [Plate 2]

Controversy erupted in March 2002, after Oxford paleontologist Martin Brasier and a team of seven British and Australian colleagues conducted a careful reexamination of the original type specimens of the Apex Chert fossils, which had been deposited at the Natural History Museum in London. Brasier employed a microscopic technique

called image montage, which allowed him to use sharp images of the original thin sections at many different levels within the rock slice to reveal three-dimensional details that were not previously obvious.

Brasier's microscopic investigation cast the Apex fossils in a new light. Their 3-D structures seemed to differ sharply from those of any known cellular assemblages. In some cases the "filaments" appeared to be more like irregular planes or sheets. In others they branched, a feature never observed with cells. Brasier gave some of the more curious shapes nicknames like "wrong trousers" and "Loch Ness monster." What's more, the thin sections with the most convincing cell-like objects contained numerous additional black shapes that bore no resemblance at all to cells—forms that Schopf must have seen but failed to detail in his *Science* paper.

Further study by Brasier's geological colleagues in Australia pointed to other discrepancies. Schopf had visited the site only briefly and, based on the linear character of the outcrop, reported a classic layered sedimentary sequence with the black chert lying between other layers—a typical ocean-floor scenario. But after detailed field mapping of the site, Australian geologists Martin van Kranendonk and John Lindsay realized that the geological setting of the Apex Chert was much more complex than the simple layered formation Schopf had described. Indeed, the Apex Chert formed at the site of significant hydrothermal activity, where hot volcanic fluids circulated through cracks and fissures. According to their reinterpretation, the black chert formed as a consequence of fluids circulating through this dynamic system as part of a cross-cutting vein. Given this relationship, with the vein of chert cutting across older rocks, the exact age of the Apex Chert was called into question. More damning still, the hydrothermal setting suggested that the chert formed at temperatures far above the permissible limits for life.

Brasier et al. challenged Schopf's claims in an article titled "Questioning the evidence for Earth's oldest fossils," published in 2002 in the widely read journal *Nature.* Their bold conclusion: "We reinterpret the purported microfossil-like structure as secondary artifacts." The article was a very public attack on Schopf's credibility.

In an unusual move, the editors of *Nature* had delayed the Brasier et al. article for more than a year, to allow Schopf time to prepare a rebuttal, "Laser-Raman imagery of Earth's earliest fossils." The two conflicting articles appeared back-to-back in the March 7, 2002, issue. An accompanying "News and Views" analysis by *Nature* staffer Henry Gee emphasized the irony of Schopf's predicament.

Seldom has a scientific debate held such high drama. Schopf had made his reputation in part by staking claim to Earth's oldest life, while cutting no slack for the questionable claims of others. More than any other scientist, he had thrown cold water on the NASA pronouncement of life on Mars. He reveled in reminding the public of past paleontological follies. No wonder then that science journalists were quick to highlight the controversy: "CRADLE OF LIFE OR CAULDRON OF CRUD?" one news headline asked.

This debate came to a head on April 9, 2002, at the second biennial NASA Astrobiology Science Conference, with Schopf and Brasier squaring off like graying, bespectacled wrestlers. The entertaining spectacle took place deep inside the gargantuan antique dirigible hanger of Moffett Field, 30 miles south of San Francisco, which is home to the NASA Ames Research Center. A sturdy lectern embossed with the NASA logo stood on the stage, to the left of a large projection screen about 12-feet square. Both speakers were seated on the stage, before a rapt audience of several hundred scientists.

Schopf spoke first. A flamboyant presenter even under the calmest of circumstances, Bill Schopf was fighting to preserve his scientific reputation. Barely controlling his anger, his voice booming, he lectured Brasier as if the Englishman were a recalcitrant schoolchild. Step by step, in a talk rich in withering rhetorical questions and exaggerated dramatic pauses, he reviewed the dozen or so necessary and sufficient criteria to establish the authenticity of ancient fossil cells. Step by step, he provided the data to back up his Apex claim, though he did soften his assertion that the microbes were oxygen-producing cyanobacteria.

After 15 minutes or so, the moderator gestured that Schopf's allotted time was almost up. Like a magician pulling a rabbit out of a hat, Schopf concluded by displaying new analytical data that he claimed would prove his case once and for all. The smudgey black Apex Chert "fossils" are composed principally of carbon, the essential element of life. Carbon concentrations may arise by both biological and nonbiological processes, so carbon in and of itself is not diagnostic of life. However, Schopf claimed, there is a difference: The carbon remains of fossil cells are less perfectly ordered than crystalline carbon deposited as a lifeless mineral. The degree of crystallinity, furthermore, can be revealed by the established technique of Raman spectroscopy. Schopf

grandly presented a suite of Raman spectra: Indeed, sharp spiky peaks characteristic of inorganic carbon stood in sharp contrast to the "obviously biological" broad humps in the Raman spectra from the Apex Chert. Schopf concluded by summing up all the evidence he had mustered: "If it fits with all other evidence of life, well follks, most likely it's life." [Plate 3]

Brasier gently ascended the stage and began his rebuttal with a dismissive putdown of his rival's presentation: "Well, thank you, Bill, for a truly hydrothermal performance. More heat than light, perhaps." In soft-spoken Oxford English, the tone in sharp contrast to what had come before, he began to cast doubt on Schopf's case. The most damning evidence were the fossils themselves. With the right lighting, field of view, and level of focus, the Apex features do look like strings of cells. The size is right, the shape more than a little convincing, and there are even regularly spaced dark divisions that look like cell walls. But raise or lower the focus slightly, or shift to another field of view, and doubts arise. What are all those shapeless black blobs next to the "fossil?" How can that supposed straight chain of cells suddenly branch like a "Y"?

As Brasier warmed to his task, an agitated Schopf stood up and began to pace distractingly a dozen feet behind the podium. Back and forth he walked, hunched over, hands clasped firmly behind his back—a tense backdrop to Brasier's staid delivery.

Ignoring these diversionary tactics, Brasier fired salvo after salvo. Schopf had the geology all wrong, he claimed. A new detailed geological map of the Apex area suggested that the black chert filled a cross-cutting vein—evidence that the chert had formed much later than the surrounding rocks, through the agency of hot circulating water. He outlined chemical experiments that produced cell-like chains of precipitates in a purely inorganic setting—nonliving structures similar to the supposed Apex fossils form with ease under the right chemical circumstances. He demonstrated how carbon-rich deposits might have formed nonbiologically through a familiar industrial process called the Fischer–Tropsch synthesis. He even showed his own Raman spectroscopic data of inorganic carbon that had the same broad features as the purported biological carbon of Schopf's fossils.

As Brasier calmly outlined his arguments, the scene on stage shifted from awkwardly tense to utterly bizarre. We watched amazed as Schopf paced forward to a position just a few feet to the right of the speaker's podium. He leaned sharply toward Brasier and seemed to glare, his eyes boring holes in the unperturbed speaker. After a few seconds, Schopf retreated to the back of the stage, only to return and stare again. Perhaps Schopf was just trying to hear the soft-spoken Brasier in the echoing hall, but the audience was transfixed by the scene.

The two presentations ended in due course and, after an extended period for audience questions and comments, the session concluded. Many of us breathed a sigh of relief that no blows had been exchanged, and then we tried to figure out who won. We all knew, of course, that science isn't about winning. The black smudges in the Apex Chert were either the remains of ancient microbes or they weren't. Eventually, we all assumed, the truth would be found out. A debate like the Schopf–Brasier bout did little but outline the problem and establish our collective state of ignorance. Still, we wondered: Who won?

To be sure, Schopf's intense delivery and unconventional antics hadn't won him any points among my acquaintances. Many scientists were also struck by the sudden softening of his previous claims that his fossils were cyanobacteria. Such waffling undermined a decade of confident, highly public interpretations. But Schopf is also a fine scientist with a long track record; and his systematic point-by-point analysis of the fossils, however quirky in its delivery, appeared both logical and persuasive.

Brasier's cool detachment, by contrast, seemed calculated to provide a veneer of objectivity, yet that very lack of passion and intensity may have cost him some points. So much of the Apex story relied on interpretation of fuzzy objects in a fuzzier context. As doubtful as Schopf's claims might be, it was equally difficult to *disprove* any biological activity by pointing to irregular black shapes. We have no way of knowing what 3.5 billion years of decay might have done to ancient microbes, and in many ways Brasier's arguments were just as subjective as Schopf's. Rather than providing the audience with the smoking gun that would thoroughly discredit Schopf, Brasier seemed merely to have raised a number of serious doubts—knotty technical issues that deserved further study.

Meanwhile, paleontologists around the world, Schopf and Brasier included, keep searching thin sections of ancient rocks in hopes of finding Earth's earliest fossils.

If there is a moral to the Allan Hills meteorite and Apex Chert controversies, it is that unambiguous identification of ancient life from microscopic structures is fraught with difficulty. Tiny rods and spheres are not always useful indicators of biology. The older the rock, the more difficult the interpretation of such vague features becomes. If fossils are to provide any clues about life's ancient emergence, then we have to look beyond microscopic structures to the tiniest fossils of all.