The PLANETARY REPORT

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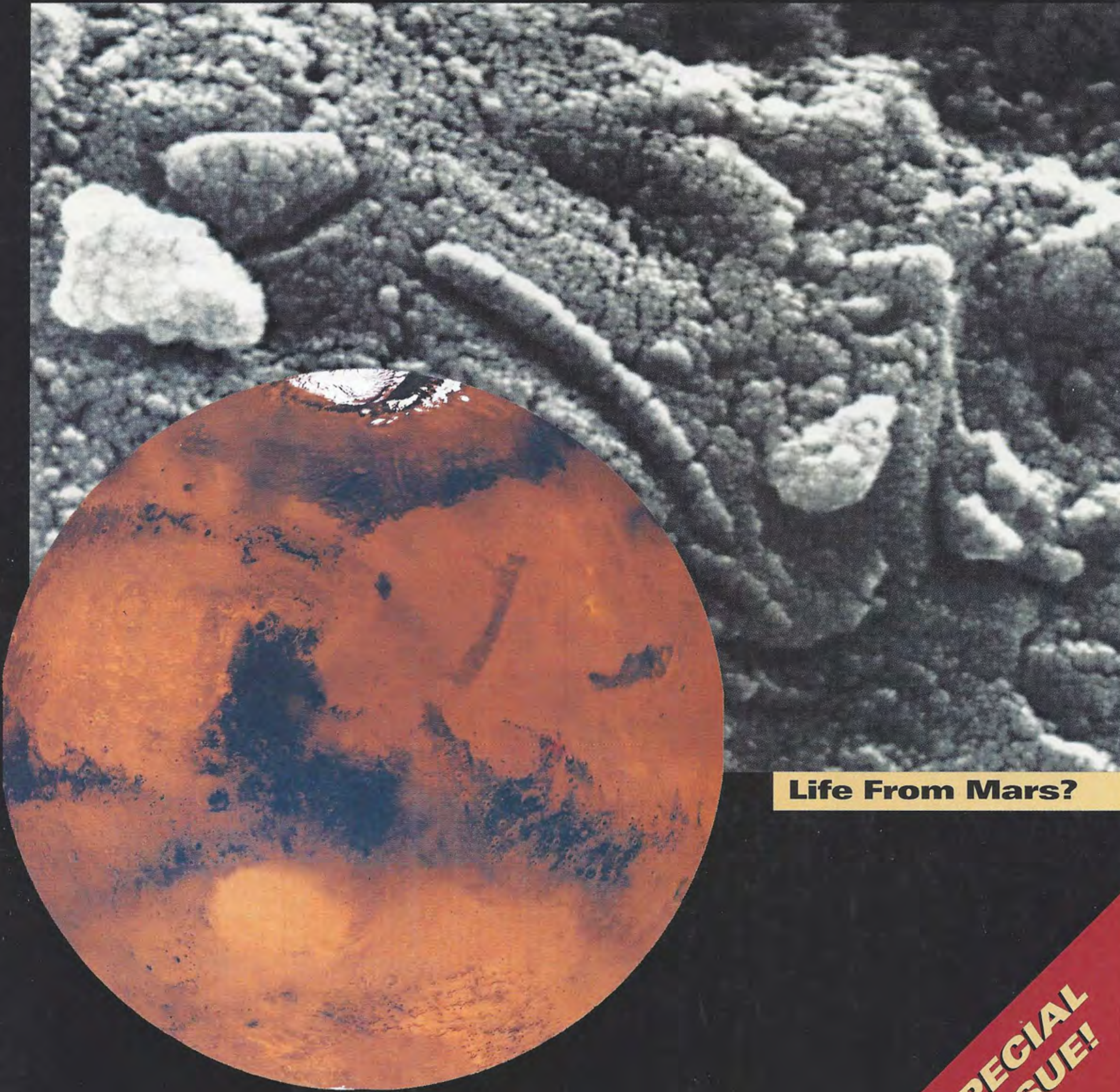

Life From Mars?

SPECIAL ISSUE!

On the Cover:

Is it life? Or is it a bit of dried clay that somehow assumed a shape that resembles the form of certain bacteria on Earth? The segmented object at center is one piece of evidence marshalled by a team of NASA and university scientists to suggest that a rock from Mars holds evidence of ancient life. Spacecraft have taught us that the Red Planet once possessed the conditions needed for life. Might life have arisen there, and could it exist today? These questions could be answered by future spacecraft, and the tiny, elongated forms found within a martian meteorite have renewed popular interest in exploring other worlds.

Top image: NASA/Johnson Space Center
Bottom image: *Viking* project, the Jet Propulsion Laboratory

From The Editor

Carl Sagan died just as we finished this special issue of *The Planetary Report.* The possibility of life on Mars was a topic close to his heart, and we are saddened that he will never read this issue. I hope it will be the first of many comprehensive reports on the possibility of life on other worlds. It may be a fond hope, for the evidence for martian life is not conclusive and, in fact, is being challenged on many fronts. Whether or not the evidence holds up, the hope that life exists on other planets will persist and will, in some measure, drive the exploration of those worlds.

Much of Carl's scientific work sprang from that hope, which has been with us for centuries. But, as he often pointed out, only in this one have we had the ability to seek out life on other worlds. It is the tragedy of Carl's early death that he did not live to see the confirmation of life on another world.

As members of The Planetary Society, we have a role to play in enabling that search; we may also witness its fulfillment. So many possibilities are opening up: life within the martian crust, an ocean beneath the icy shell of Europa, planets around other stars. We owe it to Carl to see that the search continues.

—*Charlene M. Anderson*

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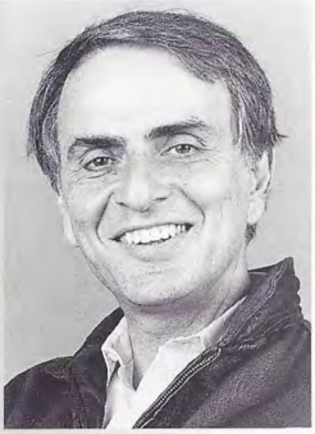
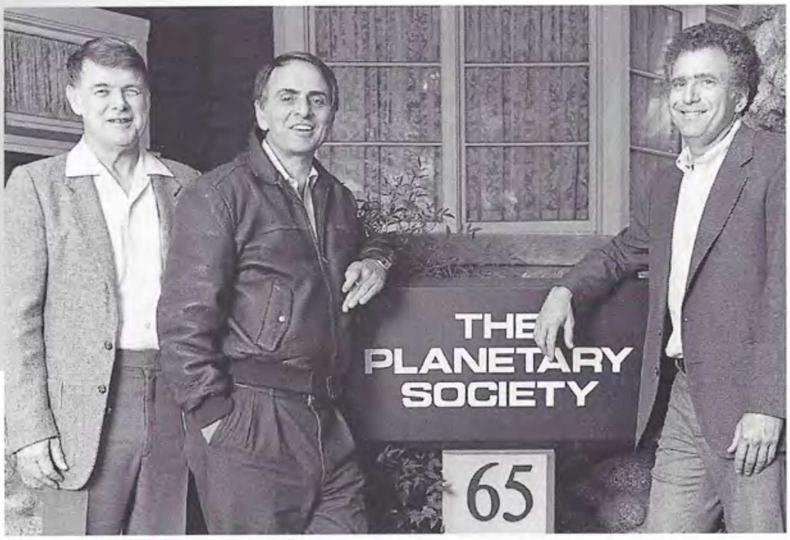


Carl Sagan

1934-1996

Carl Sagan's passion was to convey the joy and wonder of exploring other worlds to all the inhabitants of this world. The Planetary Society is one of his many legacies in that quest. We will rededicate ourselves to his passion.



Carl Sagan with Bruce Murray (left) and Louis Friedman (right) at Society headquarters.

On February 17, 1997, at 7:00 p.m. in the Pasadena Civic Auditorium, The Planetary Society will commemorate Carl Sagan's life. All are welcome. For information, call 818-793-5100.

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LIFE FROM MARS?
The Story and Its Implications

"Where were you when you heard President Kennedy was shot?" Or, "when men landed on the Moon?" Each generation asks questions like these about events that have marked turning points in history as well as in individual lives. In the world of planetary exploration, a new question is now being asked in hallway conversations and even at scientific meetings: "Where were you on August 7 when you heard the news about life on Mars?"

The announcement that scientists had found possible traces of ancient martian life riveted the world's attention on a small rock prosaically called ALH84001. The news of the discovery grabbed space and time in newspapers, magazines, tabloids, radio, television and the Internet. And, I have no doubt, somewhere a screenplay is being written to sensationalize the story. There were also more responsible and scholarly responses, including symposia and conferences at highly respected universities and institutes.

One of these institutions, the University of Colorado at Boulder, held a symposium on August 29, 1996, where scholars from a range of disciplines gathered to discuss the evidence for life on Mars and its implications. Boulder is one of the world's centers for planetary studies, and the university was able to call upon scholars in several fields for their responses. They then offered to share their thoughts in these pages with Planetary Society members.

We print here articles based on several of the talks given that night. Investigation of the meteorite ALH84001 has advanced since then, and new results have been incorporated into the text. To flesh out the story, we've included some pieces not included in the symposium: Dave Mittlefehldt's tale of discovering that the rock was from Mars, and Ray Bradbury's musings on the meaning of the discovery.

Carol Lynch, dean of the graduate school at the university, introduced the symposium, which was moderated by Larry Esposito, a professor at the Laboratory for Atmospheric and Space Physics, also at the university. We begin this special issue with excerpts from their remarks, and hope that you find the following articles interesting and enjoyable as you consider the meaning of what might be one of humanity's most important discoveries.

—Charlene M. Anderson

Remarks by Carol Lynch

Here we are focusing on meteorite ALH84001—a potato-sized hunk of rock weighing about 1.9 kilograms (4 pounds). Radiometric dating indicates that it congealed from magma to become part of the original martian crust about 4.5 billion years ago. This took place about 100 million years after Mars was formed, making this meteorite the oldest known rock that we have discovered from any planet.

Early in martian history, another meteorite shattered the rock and left fractures where, much later, minerals were deposited and the features thought to be fossils formed. Even later, yet another impact on Mars launched the rock into space. It wandered in space for about 16 million years, finally coming to rest on the Antarctic continent on Earth, where it lay for 13,000 years until discovered in 1984 by Roberta Score, then of NASA's Johnson Space Center.

What is it about this rock that indicates that there was, at one time, life on Mars? Most distinctively, microscopic features of the rock resemble several kinds of fossilized microorganisms found here on Earth, except that the Mars fossils are much smaller. These similarities, along with other attributes of mineral deposits and organic residues that could have been produced by living forms, provide strong evidence for the existence of primitive life on Mars. And life that could be very much like life here on Earth.

We invite you to examine the following contributions and reach your own conclusions.

Remarks by Larry W. Esposito

What do we need now? We need further evidence. We need to decide what sort of standards we're going to hold for life. And, particularly, we need expeditions on Mars. The best way to answer our questions and remove the uncertainty is to return some well-characterized martian rocks.

Perhaps this will be done robotically, but I'm sure we'll also have many paleontologists volunteering to go themselves. The human capability (which has not yet been matched by robots) to walk around in a geologic setting and find rocks that are meteorites or rocks that might contain fossils is called for here. And awaiting those human explorers is the same sort of thrill that Roberta Score and her teammates experienced on finding ALH84001.

The Thrill of the Search:

Finding ALH84001

by Roberta Score

Midday on December 27, 1984, while admiring the pinnacles at the edge of the farthest ice field at Allan Hills, Antarctica, I came across ALH84001, the martian meteorite that has caught the world's attention. I was there as one of seven scientific members of the 1984 Antarctic Search for Meteorites (ANSMET) team, a National Science Foundation–funded project. Although I had worked with Antarctic meteorites at the NASA Johnson Space Center (JSC) in Houston since 1978, this was my first Antarctic expedition. That year, my teammates were team leader William Cassidy, Catherine King-Frazier, Scott Sandford, John Schutt, Carl Thompson and Robert Walker.

Only 2,000 meteorites were known worldwide in 1969 when a Japanese expedition first discovered meteorites in Antarctica. To me, it is surprising that no one had searched for meteorites there earlier, because the ice is an ideal collection agent. Meteorites fall randomly all over Earth, with most of them falling into the ocean, to be lost forever. But those that fall on Antarctica get mixed in with the ice and are carried along as it moves to the sea. Where it passes over buried obstructions, or pushes against mountains, the ice is uplifted into the howling winds of the continental ice sheet and eroded, leaving a residual lag of meteorites.

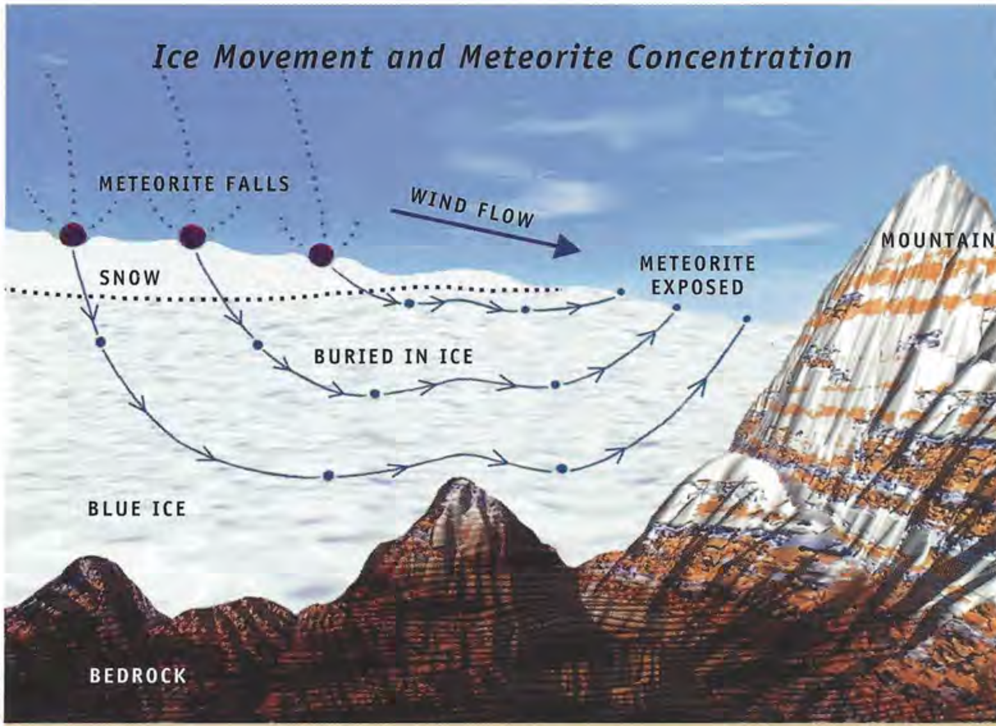
The Road to Allan Hills

The first step for a team going to Antarctica is to pass a stringent medical and dental exam—you don't want to get a toothache on the polar plateau, because you just can't find a dentist. Then we flew on a commercial airliner to Christchurch, New Zealand, where we ironically stepped into a tropical paradise. Here we were fitted for extreme cold-weather gear, including long underwear, wind-pant liners, wind pants, flannel shirt, down vest, polar jacket, heavy socks, thermal boots, glove liners, wool gloves, outer bear-claw gloves (to fit over the other two pairs of gloves), balaclava, hat and goggles. It is a bizarre experience getting fitted for subfreezing gear when it is 26 degrees Celsius (85 degrees Fahrenheit) outside.

From Christchurch to McMurdo Station, Antarctica, is an eight-hour flight aboard an LC-130, a cramped, ski-equipped transport plane. The first view of Antarctica is of a beautiful expanse of the snow-covered Royal Society Range and the station, which sits on the flank of Mount Erebus, an active volcano. McMurdo is the United States' main research station, housing 1,000 researchers and support staff. It is a very active small town, a cross between a college campus and an old mining town.

Once in McMurdo, we settled into the routine of Antarctic life. Our first task was to gather all the field gear, spare parts, food and fuel we would need for the entire on-ice expedition. Since our team was to work in remote, heavily crevassed areas, we had to take a special survival course led by our resident crevasse expert, John Schutt. John led a two-day mock expedition that was both exciting and humbling. During this trip, we learned how to use all of the equipment, made sure it all worked properly, and learned basic mountaineering skills. Once put into the field, every team is on its own and must be able to fix anything that breaks, and ensure each person's safety.

During the first week of December, we packed up our gear and waited for transportation to the meteorite collection area. It took seven helicopter flights to get our team



The forbidding and remote ice fields of Antarctica are the best places on Earth to search for meteorites because of a natural "conveyor belt" that concentrates the rocks at the bases of certain mountains. The meteorites fall on and are buried within the ice fields, where they might remain but for one thing: Ice, being water, flows. In regions like the Allan Hills, the slowly flowing ice is forced upward when it reaches the mountain slopes. There the fierce winds of the southernmost continent blast away the surface ice, exposing the entrained meteorites for sharp-eyed explorers to find. Image: B.S. Smith, based on an original chart courtesy of Roberta Score and all of our gear into the field for a six-week meteorite search.

Our first look at the Allan Hills area was bleak. We landed in 30-knot (42-kilometer-per-hour) winds, and the four of us who were on our first expedition were beginning to wonder why we had volunteered. We did not know then that this would be the worst day we were to encounter the entire season. Once the last helicopter left, an immense feeling of isolation and remoteness suddenly hit—there were just seven of us and no one else for hundreds of miles in any direction.

We lived in two-person, tepee-like tents. Although it was light for 24 hours a day, we maintained a normal working schedule, starting with an 8 a.m. radio contact with McMurdo. However, the weather determined the activities of the day. Unfortunately, meteorites in Antarctica are usually found in cold and windy areas. Wind velocities range up to 30 knots. Temperatures are typically between minus 12 and minus 26 degrees Celsius (between 5 and minus 10 degrees Fahrenheit), but it feels much, much colder due to the windchill. Occasional storms with winds over 40 knots (56 kilometers per hour) may last up to a week—conditions too dangerous to work in, so we would stay in our tents and learn about our tentmates. The physical nature of the work took some getting used to, since most of us came from desk and laboratory jobs with a coffee pot at arm's length. All food had to be thawed before we ate, and all the water had to be harvested from the polar ice. Baths were few and far between.

Searching

In areas where meteorites were hidden among abundant terrestrial rocks, we searched on foot. However, on the Allan Hills ice fields, where there are few terrestrial rocks, we used snowmobiles. We would spread out across the ice on our snowmobiles, each person 30 meters (about 100 feet) from the next, and make traverses across the ice. Here it was easy to spot meteorites because they were the only black objects on the blue ice. When someone spotted a meteorite, the team gathered to document its collection.

On December 27, midway through the expedition, we were traversing a particularly flat, monotonous portion of the Allan Hills ice field. The temperature was a warm minus 26 degrees Celsius, and winds were calm at 10 to 15 knots (14 to 21 kilometers per hour). About midday, at the end of a traverse, we spotted an area we called the pinnacles, 5-meter-high (15-foot) ice sculptures or frozen waves formed by the ferocious Antarctic winds and colliding ice. These spectacular features fascinated us, and we headed off to explore them for an hour or so. Even more fascinating was the fact that meteorites were found in and among these features.

While we were forming up to start another systematic traverse, I spotted ALH84001. I signaled my teammates to come view the find. We had already collected over 100 specimens that season, so finding another one was fun, but not earthshaking. We noticed that the rock was a bit different from the others already collected; we were wearing dark glasses, and against the blue ice and the bright

Below: Photographed back in the laboratory at Johnson Space Center, ALH84001 is an ordinary dull gray, not the exotic green that Score thought she saw when she collected it. But its mundane appearance belied its extraordinary story that would be told a decade later.

Above: Meteorite search team members stay downwind of their quarry to avoid inadvertent contamination. Here the team collects an ordinary meteorite. There are, unfortunately, no photographs of ALH84001 in the field.

snow the meteorite appeared to be bright green. Many people want to hear that the rock spoke to me, or that I had some kind of cosmic experience, but I regret to say that was not the case. It stood out only because of the excitement of the day and the rock's size and seemingly odd color. Had it been found on one of the flat stretches of the ice field, I wonder if I would have remembered it.

The Journey Home

Wisely, we took care in collecting ALH84001, as we did in collecting all of the meteorites, to avoid contamination. The meteorites are not touched with bare hands, but collected in specially cleaned nylon bags provided by NASA, and quickly sealed with Teflon tape. Antarctic meteorites are kept frozen during their three-month journey to the Meteorite Curation Laboratory at JSC. There they are curated in special cabinets with a nitrogen environment. The dry nitrogen drives off any moisture and prevents alteration in the laboratory. The initial scientific classification of Antarctic meteorites is done there, and lab staff provide the appropriate samples for scientific studies.

Because of ALH84001's unusual color and my hope that it would be a unique meteorite, it was the first meteorite of the 1984 collection to be curated back in the lab in Houston. I gave the meteorite the designation ALH84001—ALH for Allan Hills, 84 for 1984 expedition, 001 for first sample curated. But, in normal laboratory light, ALH84001 was not bright green but had a dull-gray color, similar to that of many meteorites. It was classified as a diogenite, one of the more common rocks thought to be from the asteroid belt.

I was thrilled nine years later when David Mittlefehldt of JSC was studying a suite of diogenites and determined that ALH84001 actually belonged in the group of meteorites thought to be from Mars. (See page 11.) It was shortly afterward that Chris Romanek, also at JSC, became interested in studying the abundant carbonates. (Chris is one of the coauthors of the famous August 16 *Science* article.) Since my office was just down the hall from his, he came by many times to ask probing questions about the contamination history of this meteorite. It didn't take much to figure out from his concerns that his research group was onto something big. The study is continuing, and the debate has just begun. Much more work needs to be done!

The ANSMET project continues to provide planetary scientists with pieces of our solar system at a cost far lower than actual sample-return missions. With half of all known martian samples and all but one lunar meteorite being returned from the Antarctic, what other wonders are waiting for us out there on the ice?

Roberta Score works for the US Antarctic Program in Denver, Colorado. She is currently in Antarctica for five months where she is laboratory supervisor in the Crary Laboratory in McMurdo. She was the laboratory manager for the Antarctic Meteorite Laboratory at JSC for over 10 years.

Above: In one of Earth's bleakest landscapes, the martian rock was found. Geologist Score found ALH84001 lying exposed in this ice field.

Below: The highly trained and professional Antarctic meteorite search team for 1984 poses for a portrait. Roberta Score, the discoverer of ALH84001, is the one with the two fingers behind her head.

All photos courtesy of Roberta Score

Uncovering Martians Hidden Among Us:

The Source of ALH84001

by David W. Mittlefehldt

On the evening of August 7, 1996, my family and I were on an Air Canada flight from Toronto to Houston, returning from a vacation overseas. When the in-flight news video started, I debated whether I should get out the earphones and try to catch up with what I had missed in the world. I had just about convinced myself to ignore the news when a picture of a rock appeared on the screen. I mentally shouted, "Holy cow (euphemism substituted), I know that rock, and I know what this is about!" It was, of course, an announcement to the world that fossil martian life may have been found in a meteorite dubbed ALH84001 collected from the far western ice field in the Allan Hills region of Antarctica.

My connection with ALH84001 started in 1988, when I obtained a sample for analysis as part of a larger project on diogenites. ALH84001 was first classified as a diogenite, an igneous meteorite from an asteroid, quite possibly 4 Vesta. The original description included some uncommon minerals for a diogenite—unusually sodium-rich plagioclase (plagioclase is a calcium–sodium aluminosilicate mineral) and calcium–iron–magnesium carbonates.

Left and below: This is ALH84001, the starring player in the unfolding drama of life on Mars, with its interior visible in cross section at left and its exterior displayed below. By studying its distinctive mineralogy, David Mittlefehldt determined that the meteorite had come from Mars. This discovery set the stage for further analysis by the group led by David McKay, which found several lines of evidence suggesting that the interior of this rock had been modified by living things. (Each cube is 1 centimeter across.)

Right and below: There are 12 known pieces of Mars on Earth, and with the discovery of possible life-signs within one, they have all become extremely valuable specimens. This is martian meteorite ALHA7705—not yet a star, but who knows what surprises it might contain? At right is an interior view; the light and dark patches reflect subtle differences in mineral content and texture. Below is an exterior view. (Each cube is 1 centimeter across.)

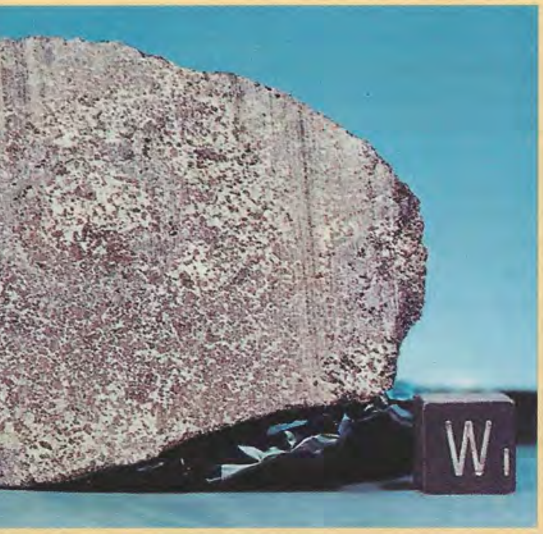
A Curious Situation

Plagioclase is rare in diogenites, and when it occurs, it is calcium-rich. Carbonates are unknown in diogenites, so I, and probably other meteorite researchers, assumed the carbonates were weathering products formed in Antarctica. During the summer of 1988, I performed a chemical analysis on a bulk sample of ALH84001 for a suite of elements that we normally determine in the lab I work in at Johnson Space Center (JSC). There was nothing in the bulk composition that suggested that the rock could not be a diogenite.

I had a grain mount (a few mineral grains glued to a glass slide and polished flat to provide a smooth analysis surface) made from chips left over from the bulk sample, and in the spring of 1990 I began using an electron microprobe to analyze the composition of the iron–chromium oxide mineral chromite. This instrument fires a narrow beam of electrons at a sample, exciting the near-surface atoms. The atoms give off X rays with an energy characteristic of the element, and with an intensity proportional to the amount of the element present. Hence this technique can be used to determine the major elemental constituents in a mineral.

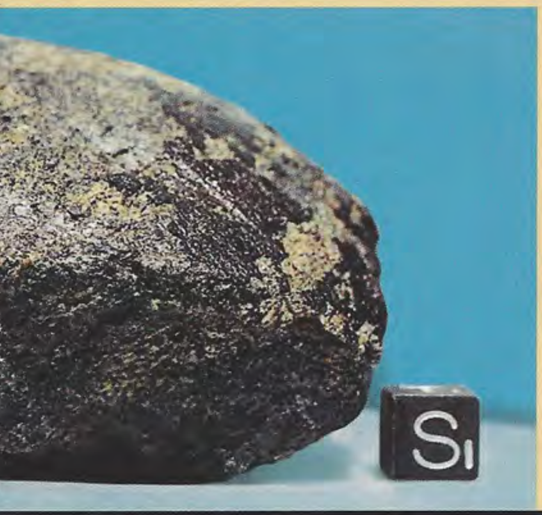
The grain mount I was using had a very small surface area, about 1 square millimeter (0.0016 square inch), so it was not truly representative of the rock. The only minerals it contained were orthopyroxene and chromite. Orthopyroxene, a calcium–iron–magnesium silicate, comprises 90 to 95 percent of the rock.

My earlier analyses of the orthopyroxene did not cause me to think there was anything strange about ALH84001; it was similar to orthopyroxenes in diogenites, only a little bit richer in iron. The chromite analysis, though, was strange. The calculated mineral formula contained quite a bit of trivalent iron, in addition to divalent iron. (Trivalent iron has lost three of its valence electrons; it is said to be in



Right and below: This rock, EETA79001, plays the role of Rosetta Stone in the current drama. At right is an exterior view, showing the black crust charred during the stone's fiery passage through Earth's atmosphere. Below, the cross section reveals black patches of glass formed by a meteorite impact while the stone was still on Mars. Trapped within this glass were pockets of martian atmosphere. Scientists analyzing this gas found it to be identical to the atmosphere measured by the Viking *landers. This linked EETA79001 to Mars, and further mineralogical studies traced the origins of 11 other meteorites back to Mars. (Each cube is 1 centimeter across.)*

All photographs: NASA/Johnson Space Center



ALHA7705

EETA79001

The History of ALH84001

4.5 billion years ago — ALH84001 is crystallized from molten rock.

4.0 billion years ago — It is shocked by an impact, but remains on Mars.

1.8 to 3.6 billion years ago — Carbonate minerals are deposited at an uncertain time, in warm or hot water circulating through the rock.

16 million years ago — ALH84001 is ejected into space by another impact.

13,000 years ago — It lands in Antarctica.

13 years ago — It is collected during a National Science Foundation/NASA Antarctic expedition.

4 years ago — It is reclassified as a martian meteorite.

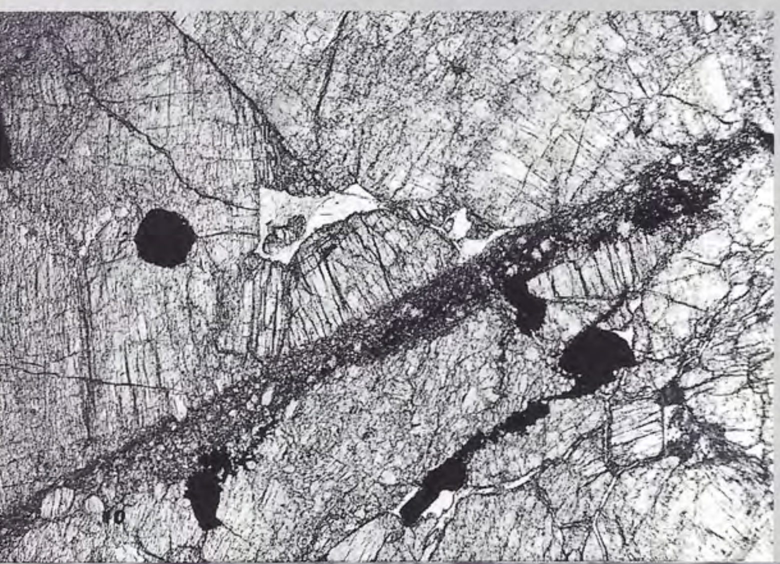
the +3 valence, or oxidation, state, and to have a charge of +3. Divalent iron, having lost only two valence electrons, is in the +2 valence state and has a charge of +2.) The electron microprobe cannot measure the charge on the atoms in the sample, only their concentration. Data-reduction routines calculate the charges on multivalent elements, elements like iron that can exist in more than one valence state, to fit mineral formulas.

I knew the calculated amount of trivalent iron couldn't be right, because diogenites were formed under conditions where it wouldn't exist. Magmas formed on the diogenite parent body were too reducing (had too little oxygen) to oxidize iron to the +3 valence state. In fact, diogenites contain some of their iron as the metal, the zero valence state. I assumed the analysis was not good, although I had performed it under the same conditions I had used for other diogenites.

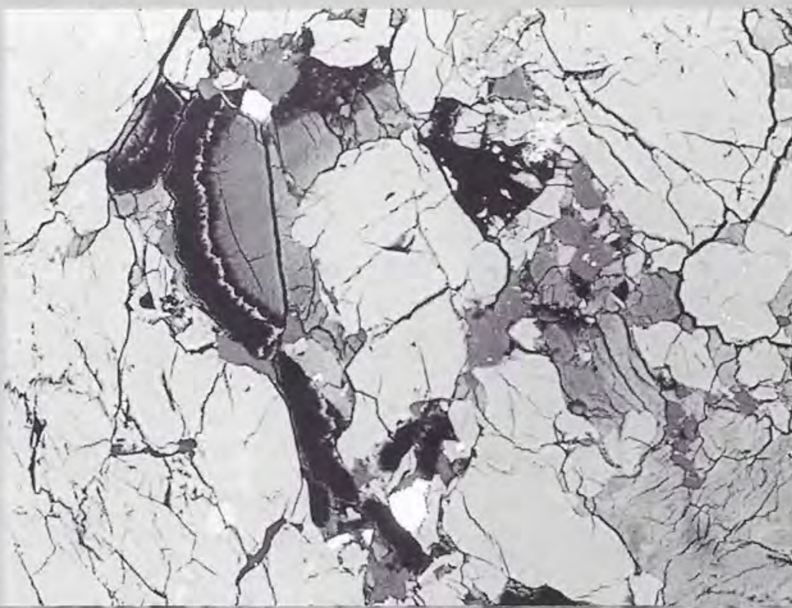
Could the Rock Be From Mars?

I let the matter lie until the spring of 1993, when I finally wrote a paper on diogenite origins. I puzzled over the

Even extremely close up and in thin section, ALH84001 shows the scars of its catastrophic history. The diagonal band across the image is a crushed zone formed by a meteorite impact—but not the one that sent the rock to Earth. The highly fractured mineral around it is orthopyroxene, while the black grains are chromite and the white patch is plagioclase glass.



The carbonates within ALH84001 are hosts to the possible martian microfossils. Here, within a matrix of light-gray orthopyroxene, is the medium-gray, iron-and-calcium-rich carbonate, edged by a black band of magnesium carbonate. The thin white band is possibly a mix of magnesium carbonate and very small iron-rich minerals. Images: David W. Mittlefehldt



strange chromites in ALH84001, but didn't come to any conclusions. One of the reviewers of the paper chastised me over those chromite analyses, and I decided that I needed to put more effort into understanding them. That summer, I checked my analyses of the ALH84001 chromites and the other diogenite analyses I had performed on the same day. I expended some effort and convinced myself that there could be no mistake; chromites in the other diogenites did not have trivalent iron, while those in ALH84001 did.

At this point, I was sure my analyses were correct and there was something strange about ALH84001. When I was back in my office, thinking about what I had learned, it struck me that the analyses would make sense if ALH84001 was not a diogenite but a martian meteorite. Martian igneous rocks formed under more oxidizing conditions than diogenites—that is, from magmas containing more oxygen—and martian rocks typically have trivalent iron in their chromites.

One problem with this scenario was that there were no known martian rocks composed predominantly of orthopyroxene, so ALH84001 was not like any other martian meteorite. Caution got the better of me, and I did not mention this thought to any of my colleagues. However, I did make plans to do more detailed sampling and study of ALH84001, and I half expected that it would turn out to be a martian rock.

Switched Samples

I had put in a request for a thin section of the diogenite EETA79002, which was found on the main ice field in the Elephant Moraine region of Antarctica, as part of my diogenite studies. I got it in September 1993 and began studying it early in October. I wanted some specific mineral composition data on this rock, so I put it in the electron microprobe without first looking at the thin section under a microscope to observe the textures and mineralogy. (I had already studied another sample of EETA79002, so I knew what it would look like.)

I began by analyzing chromites, and, to my surprise, I found they contained substantial trivalent iron, just like those in ALH84001, but quite unlike my previous analyses of EETA79002! The next week I was analyzing sulfides in EETA79002, but the results did not make sense. The sulfides had too much sulfur in them for diogenite sulfides, yet when I checked the calibration of the machine everything was in order.

I spent about a day and a half at this, because I knew from my other samples of EETA79002 what the sulfide composition was. Finally, I tried calculating the mineral formula for the sulfide, and came up with iron disulfide, FeS_2. This was totally screwy, because diogenites contain only the iron monosulfide, FeS.

At this point, I backed off from my narrow search for sulfides and began looking at the thin section as a whole. The texture was wrong for EETA79002, and I realized that it looked exactly like ALH84001. I had a mislabeled sample! All at once, everything clicked in one of those very satisfying "eureka!" events. I knew iron disulfide was a common sulfide mineral in martian meteorites, but uncommon in other igneous meteorites. And I knew from my past analyses that the chromite in ALH84001 contained trivalent iron, like the martian meteorites.

Within a split second, I knew I had a new martian meteorite, and a unique one at that. I just didn't know how special it would turn out to be! By this time, it was mid-October. I informed the meteorite curator at JSC that ALH84001 was not a diogenite, but a new type of martian meteorite, and the rest, as they say, is history.

David W. Mittlefehldt, a staff scientist with Lockheed Martin Engineering and Sciences in Houston, is a geochemist and meteoriticist specializing in the study of igneous meteorites from asteroids and Mars. He works in the geochemistry labs at Johnson Space Center supporting NASA's planetary materials research projects.

SNC Meteorites: Messengers From Another World

On Earth, we have 12 rocks that scientists believe came from Mars. There may be more martian rocks here, scattered across the continents or lying at the bottom of the ocean, but, as you've read in these pages, they are difficult to find and identify. These messengers from an alien world, literally fallen from the sky, are revolutionizing our sense of our place in the universe.

As a class, these martian rocks are called SNCs (pronounced *snicks*, as in *snickers*), an acronym derived from Shergotty, Nakhla and Chassigny, the landing sites of three early examples. They are all igneous rocks, having solidified from once-molten magma. Meteorite researchers knew these particular samples were unusual because they crystallized rather recently in geologic time, and because their abundances of volatile constituents, such as water, were quite different from those in all other igneous meteorites.

In 1983, D.D. Bogard and P. Johnson examined gases trapped in glassy bubbles within the SNC meteorite EETA79001, which had been found in the Elephant Moraine region of Antarctica. The relative abundances of neon, argon, krypton and xenon and the unusual isotopes of argon and xenon matched the measurements of these gases in the Mars atmosphere, as taken by the *Viking* landers in 1976. EETA79001, sometimes referred to as the Rosetta Stone of SNCs, demonstrated that there could be only one source for this and similar meteorites—the planet Mars. —*Charlene M. Anderson*

Laying Out the Evidence:

The Case for Life on Mars

by Bruce Jakosky

Although the supermarket tabloids scream at us every day about alien life visiting Earth, there exists no scientific evidence that is generally accepted as proof of the existence of extraterrestrial life. In the ongoing search for possible life on other planets, Mars appears to be the most likely place to look in our solar system.

Why might Mars be a suitable place for life? Are the "martian meteorites" actually from Mars, and what can we learn about the Red Planet from them? Is the evidence for fossil life convincing? In 1976, the *Viking* spacecraft landed on Mars and tested the soil for signs of life; no compelling evidence for life was found. Should we reconsider the *Viking* results in the light of these new findings? To address these questions, we first need to understand Mars as a planet.

Mars seems to have all the prerequisites for life—liquid water at the surface during at least part of its history, energy sources that can power life, access to the biogenic elements (such as carbon, oxygen, nitrogen and hydrogen), and a sufficiently stable environment to allow life to persist.

The planet's diameter is about half that of Earth, still large enough for it to hold on to its atmosphere over time (Figure 1, below). The atmosphere is composed primarily of carbon dioxide and is just under 1 percent as thick as Earth's. Because of the thinner atmosphere, and because Mars is about 1.5 times as far from the Sun, temperatures on Mars are much cooler than on Earth, with the daily average about minus 55 degrees Celsius (minus 67 degrees Fahrenheit), well below the freezing point of water.

Given the low atmospheric pressure from the thin atmosphere, any liquid water on the surface would quickly evaporate; the general absence of liquid water appears to be a serious problem for life on the martian surface. In addition, the lack of substantial ozone to protect the surface from ultraviolet radiation, and the probable abundant oxidants, such as hydrogen peroxide, that would react with any organisms would make it difficult for life to survive.

Geologic Processes

This may not always have been the case, however. The martian climate and environment at times during the past may have differed substantially from those at the present. We are able to look at Mars' past climate because geologic processes such as resurfacing by volcanic eruptions or by wind or water erosion have not destroyed all traces of the older surfaces. Some martian regions date back to about 4 billion years ago, and, based on the number of impact craters we can count on the different geologic units, there are surfaces representing all time periods from 4 billion years ago up to the present.

Thus, we have a window into the geologic history of Mars that allows us to understand how the different geologic processes have acted through time. We do not have this window on Earth or Venus, where resurfacing occurs much more rapidly. On Earth, it is almost impossible to find a rock that is 3.5 to 4 billion years old. On Mars, much of the heavily cratered southern hemisphere is that old.

The oldest surfaces on Mars show systems of valley networks that look like terrestrial river systems (Figure 2, page 13, top). They contain branching tributaries similar in size and appearance to terrestrial river valleys, and these tributaries often empty into enclosed basins, where they may have formed standing bodies of water, or lakes. It is not clear whether surface runoff of water or water-rich debris flows were the primary mechanism for eroding these valleys; they might even have been eroded by water flowing beneath a covering of ice. Regardless, liquid water would have to have been more

Figure 1: Two roughly similar planets travel through the same neighborhood of space. Is it possible that 3.6 billion years ago they both brought forth life? At that time, they both possessed the necessary ingredients: organic molecules, liquid water and heat enough to drive and sustain the chemical reactions we identify as biological. Images: NASA

Figure 2: Water in liquid form is a prerequisite for life, and in **Viking** *images such as this there is abundant evidence that liquid water once flowed on Mars. These channels cut by water tell us that ancient Mars possessed a denser, warmer atmosphere that might have supported life.* *Image: JPL/NASA*

abundant at the surface during the early epochs on Mars.

In addition, the impact craters on the older martian surfaces have been eroded substantially from their original appearances. Their ejecta blankets have been destroyed, crater rims and central peaks have been removed, and the crater interiors have been filled in with debris. A few craters have been only partly destroyed and show signs of having been eroded by the runoff of liquid water. Quantitatively, the erosion rates prior to about 3.5 billion years ago were about a thousand times larger than during the subsequent 3.5 billion years. Again, the simplest explanation is that water was then more abundant and more stable at the surface than it is today.

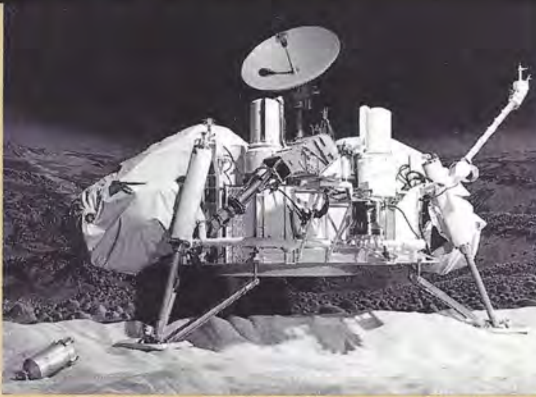
As the environment on early Mars allowed liquid water to exist at the surface, it is plausible to talk about an origin of life then. During the same period, life appears to have formed on Earth, possibly in similar shallow-water environments. The origin of life on Earth must have occurred very quickly, given the short period of time between the end of heavy bombardment by planetesimals (about 4.0 billion years ago; see page 18) and the first record of life in terrestrial rocks (no later than 3.5 billion years ago and possibly as long ago as 3.85 billion years). If life on Earth originated so quickly under the proper conditions, then life might have originated independently on Mars during this same time.

The younger surfaces on Mars exhibit two types of geologic features that also may be relevant to possible martian life. First, much of the northern hemisphere of Mars is covered with lava flows and flood basalts, and there are a number of large, discrete volcanoes (such as Olympus Mons, the largest). These features attest to the presence of sources of heat, and to their occurrence throughout all of Mars' history; Mars was volcanically active within the last

(continued on page 14)

What About *Viking*?

What about the *Viking* biology experiments in the late 1970s? Didn't they demonstrate that there was no life on Mars?



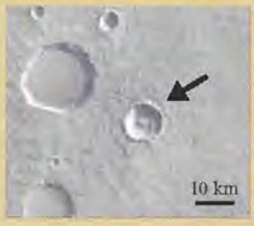
The **Viking** *landers each carried three experiments to test for signs of martian life. Although scientists continue to argue over the results of those tests, most believe that life is unlikely to exist on Mars today. However, Mars was very different 3.6 billion years ago, when the suggested microorganisms would have lived.* *Photo: JPL/NASA*

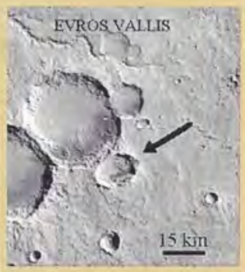
That interpretation was accepted at the time, based on the results of the three experiments that tested for biological activity, and on the absence of organic molecules in the surface materials. However, the *Viking* experiments were able to test for only a couple of the possible mechanisms by which martian organisms might obtain their energy. These involved the use of either carbon dioxide or organic molecules in the environment as a source of carbon. Possible martian bacteria might metabolize other substances to obtain their energy, or might do so under conditions very different from those of the *Viking* experiments.

Do the results in ALH84001 mean that we should reconsider the *Viking* conclusions? Probably not. The physical and chemical environments in the meteorite when the carbonates formed are very different from those on the surface of Mars today. Even if the meteorite does contain fossil life, life probably could not exist on the surface today—it rapidly would be destroyed by the highly oxidizing environment and general absence of liquid water. The fact that one of the *Viking* biology experiments gave a positive signal for life also does not affect this conclusion. The conclusion that life is present cannot be based on a single measurement; rather, several experiments together must be consistent with life. The overall conclusion from all of the *Viking* experiments is that there was active geochemistry at the *Viking* landing sites, but no biology. In other words, *Viking* might have been looking with the wrong experiments or in the wrong places. —*BJ*

Planetary scientist Nadine Barlow searched through **Viking** *images and identified two craters of the right age in terrain ancient enough to be the source of ALH84001. One crater lies near Evros Vallis, an ancient channel carved by flowing water. ALH84001 shows evidence that it was exposed to water 3.6 billion years ago.*

Images: Nadine G. Barlow, **Viking** *orbiter program*





(continued from page 13)

200 million years, based on the ages of some of the martian meteorites, and it may even be volcanically active today. Second, large catastrophic floods have occurred sporadically throughout martian history. The flood channels spring forth from the subsurface, suggesting that the crust of Mars has a large supply of water.

The presence of both crustal water and geothermal heat sources means that there must have been subsurface hydrothermal systems, allowing heated water to circulate through the crust. Also, the presence of volcanism up through the most recent times implies that these systems have operated up to, and perhaps including, the present. Hot springs are another possible site for the origin of life on Earth—their chemical environment can drive the production of organic molecules that are the precursors of life, and the heat can provide a source of energy. Hydrothermal systems on Mars thus provide an environment in which life could originate at almost any time, or in which life could exist up to the present. Clearly, the martian surface and subsurface would have provided, at different times in martian history, an excellent environment for life.

Transplanetary Connections

Even if life did not originate on Mars, there still could be life on the planet. A planet's crustal rocks can be ejected into space by an asteroid's impact. These rocks would be thrown into orbit around the Sun. Rocks ejected from Mars can find their way to Earth, and rocks from Earth can find their way to Mars. If some of these traveling Earth rocks contained bacteria—and some rocks deep within the crust actually do—then bacteria could have been transported to Mars. If the rocks fell onto a martian oasis, such as a hot spring where water is released to the surface, the bacteria might have been able to survive and multiply, and there might be Earth organisms living on Mars!

What is the evidence that Mars actually did have living organisms? Recent discussions center on the meteorite ALH84001, collected in 1984 from the Allan Hills ice sheet in Antarctica (Figure 3, below). It is one of 12 meteorites in our scientific collections thought to be from Mars. (See page 11.)

Of the 12, this particular meteorite is the one that would be most likely to have evidence for martian life. It is the oldest, having formed about 4.5 billion years ago when the planet itself was forming. It is laced with abundant veins of carbonate minerals such as calcite (calcium carbonate, $CaCO_3$) that usually form when hot water passes through rock. About 10 percent of the meteorite is carbonate mineral, and the possible fossil evidence is found within these carbonates. The ages of the carbonates are not well determined, although the indications are that they were deposited within the middle epochs of martian history, possibly as recently as 1.8 billion years ago.

The research group led by David McKay of NASA, working out of NASA's Johnson Space Center in Houston and Stanford University, identified several lines of evidence suggesting that life was present at the time when the carbonates formed. Although no single line is convincing by itself, the combination of all of them may be indicative of life.

The Evidence in the Rock

The carbonate minerals fill fractures and cracks within the matrix of the rock, with discrete "globules" of carbonate up

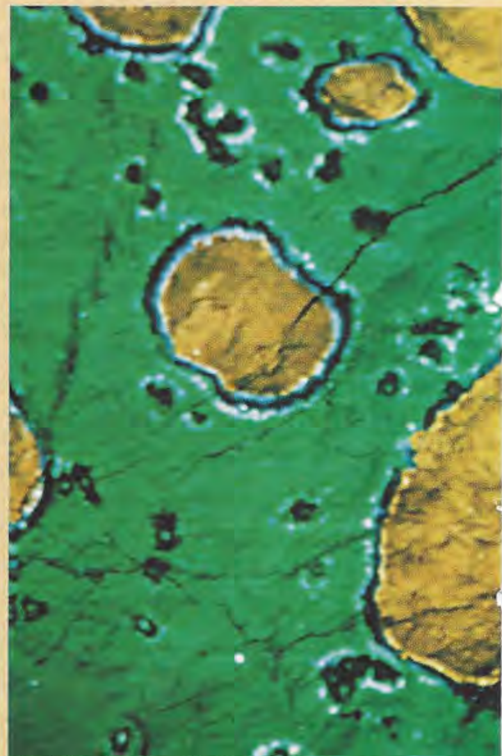


Figure 4, right: In this thin section of ALH84001, the now famous carbonate globules show as brown blobs rimmed by white and black layers. These "Oreo-cookie" layers are made of iron sulfide minerals of differing compositions, and one explanation is that they were deposited by martian bacteria. *Image: NASA*

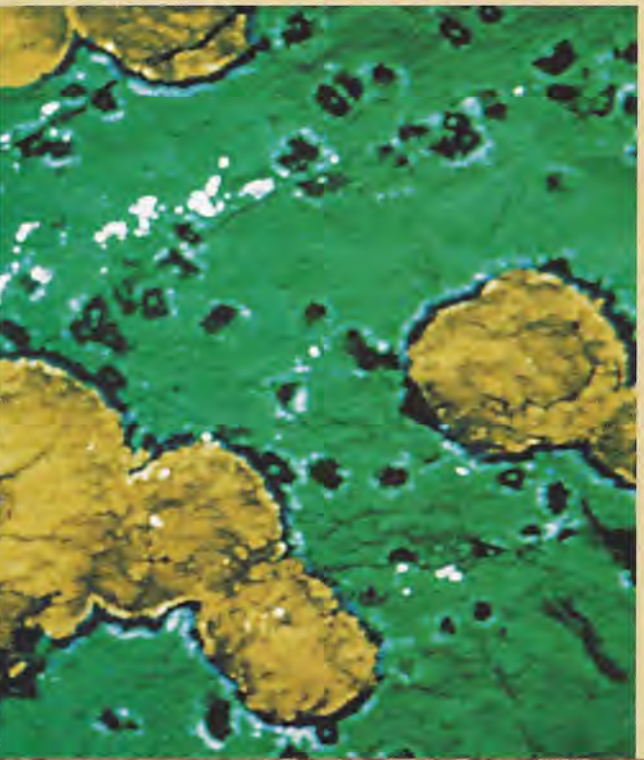
Figure 3: This is ALH84001, the oldest known martian meteorite. Some 4.5 billion years ago, it solidified from magma somewhere in the martian crust. Later impacts fractured the rock, allowing water to seep into its cracks and deposit globs of carbonate minerals. This process may or may not have been accompanied by biological activity.

Image: NASA

to several hundred microns (about 0.01 inch) across (Figure 4, below). These globules are layered, with iron-rich and calcium-rich mineral grain layers around the outside. The outermost layers contain iron sulfide–rich minerals and magnetite (iron oxide, Fe_3O_4) grains.

Although these minerals can form by nonbiological mechanisms, the NASA scientists argue that the magnetite, iron sulfide minerals and carbonates all form under different chemical conditions, and it is unlikely that all would be present at the same location. Terrestrial bacteria can produce these types of mineral grains, all at the same location and in a single environment. The scientists suggest that these minerals may have been formed in ALH84001 by martian bacteria. The size of the mineral grains (around 25 nanometers, or one millionth of an inch) and their shape are very similar to those produced by bacteria. However, similar layering in the carbonates can occur when they are deposited in very hot water (temperature around 680 degrees Celsius, or about 1,250 degrees Fahrenheit) that is undergoing a change in temperature.

The second piece of evidence is the presence within the meteorite of a type of organic molecule known as a polycyclic aromatic hydrocarbon, or PAH. PAHs are a very common class of organic molecule that consists almost entirely of carbon rings joined together. Each ring consists of six carbon atoms bonded together in a hexagon shape, and the multiple rings fit together somewhat like tiles on a patio. They can form on Earth either by the degradation of larger organic molecules associated with the decay of bacteria or other life, or by the incomplete burning of organic fuels. In each process, the hydrogen and oxygen are partly driven off, leaving the carbon behind to form these complex molecules.



PAHs can also form in interstellar space and be incorporated into meteorites. In fact, they are common in the most primitive meteorites—that is, those that have been altered the least since their formation 4.5 billion years ago. The processes by which PAHs form in meteorites are unique to interstellar space, however; it is not possible for PAHs to form in the martian meteorites while they are traveling in space between ejection from the martian surface and their landing on Earth. Also, it is unlikely that the PAHs in ALH84001 could have originated in interstellar space, been incorporated into meteorites, landed on Mars early in its history and then been incorporated into ALH84001 and ejected into space. The martian environment and its active geologic history almost certainly would have destroyed any PAHs, unless they could very quickly have been sequestered out of the surface environment.

The PAHs in ALH84001 are found within the carbonate minerals. Could they be contaminants, introduced on Earth or during the handling of the meteorite? This possibility appears to be unlikely. The PAHs are in much greater abundance than is typical on Earth or in Antarctica. In addition, measurements of the PAH abundance at different locations within the meteorite show that they are less abundant on the outside than on the inside, indicating that diffusion from the outside to the inside is unlikely. Also, examination of other Antarctic meteorites with the same history on Earth as ALH84001 shows no measurable PAHs. Finally, the meteorites were handled very carefully during their collection and in the laboratory, minimizing contamination.

Does the presence of PAHs require that life must have existed on Mars? Although the PAHs almost certainly originated on Mars, they do not require life. However, if they did not form from the decay of bacteria, they would have to have formed from other organic molecules in the martian environment. Either way, this is an exciting result that provides the first definitive measurement indicating that organic molecules occur on Mars. Because organic molecules are required for the existence of life, their presence automatically raises the level of the discussion regarding possible martian biota.

The final major evidence in the meteorite is perhaps the most intriguing: structures that appear very similar to fossils of terrestrial bacteria. These sausage-shaped structures are partly embedded within the carbonate mineral and, hence, must have been deposited at the same time as the carbonates (Figure 5, page 16). They are seen in fresh exposures of the carbonate where the rock has been broken apart. Perhaps the most telling anecdote regarding these structures was recounted by Everett Gibson of the Johnson Space Center. He took a photograph of one of these structures home, and his spouse, who is a microbiologist, saw it and asked him what kind of bacterium it was. They really do look like bacteria!

Although the structures in the meteorite appear to be very similar to earthly bacteria, there is one major difference—they are about 100 nanometers (about four millionths of an inch) across, some 10 to 100 times smaller

than terrestrial bacteria (Figures 6 and 7, page 17). This is about the same size as terrestrial ribosomes or viruses. (Ribosomes are parts of earthly cells that contribute to cellular reproduction.) Neither ribosomes nor viruses are able to reproduce by themselves and function independently, so neither is considered to be a living organism.

Are They Too Small?

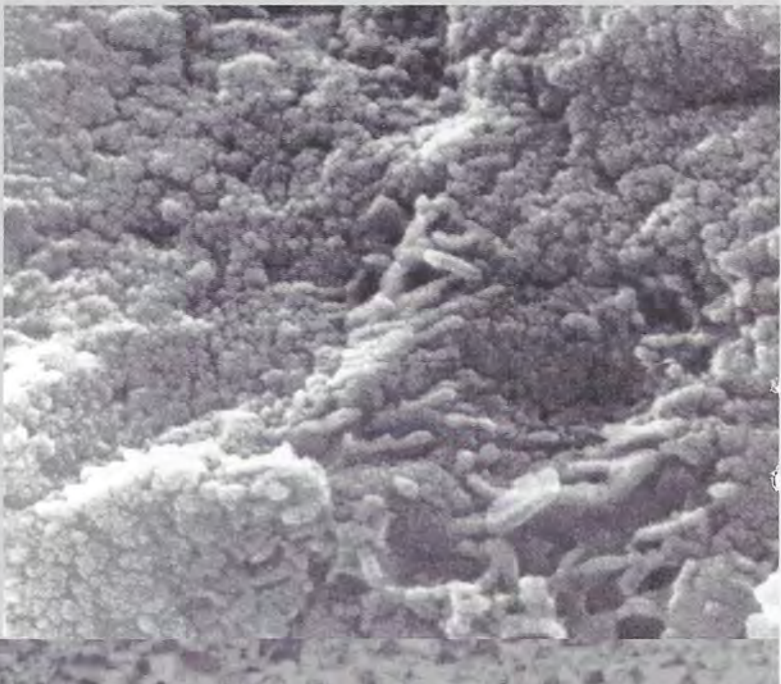
Are these martian structures so small that they could not be living entities? The answer is not clear. Despite their small size, they still are large enough to be able to contain the equivalent of 1,000 base pairs from a DNA chain. Their size is larger than what is thought to be a minimum size for life. In addition, although the oldest and smallest Earth bacteria are larger than the martian structures, they certainly do not represent the earliest terrestrial life. Rather, the first life must have been much simpler and much smaller, possibly similar in size to these martian fossils.

An important boundary condition on whether life could have existed in the martian carbonates is what the temperature was when they were deposited. If the carbonates were deposited at a temperature higher than about 150 degrees Celsius (about 300 degrees Fahrenheit), then life probably could not have existed.

Unfortunately, the evidence on temperature is ambiguous. Analysis of the specific minerals that are present in the carbonates led Ralph Harvey (of Case Western Reserve University) and Harry McSween (of the University of Tennessee) to suggest a formation at very high temperatures, perhaps above 650 degrees Celsius (about 1,200 degrees Fahrenheit). On the other hand, the NASA researchers suggested a formation temperature between about zero and 80 degrees Celsius (32 and 176 degrees Celsius) based on the ratio of the oxygen isotopes in the minerals; this ratio will vary in the carbonates depending on their formation temperature, and the use of the ratio to derive a formation temperature is a standard technique in terrestrial geochemistry. This lower estimate may be wrong, however, because the possible loss of oxygen to space also will affect the oxygen isotopes; including this effect increased the temperature range to 40 to 250 degrees Celsius (about 100 to 480 degrees Fahrenheit). This temperature range still will allow life to have existed, although only at the lower temperatures. These different estimates of temperature have not been resolved.

More recently, Ian Wright and the group at The Open University in England have examined two of the martian meteorites, ALH84001 and EETA79001 (another of the Antarctic meteorites). They confirmed the presence of organics in the first and also identified them in the second meteorite; EETA79001 is a much younger meteorite, less than 200 million years old, meaning that organic molecules

Figure 5, left and below: Along a fresh fracture surface of ALH84001, imaged by a high-resolution scanning electron microscope, we can see minuscule sausage-shaped things partly embedded within a carbonate globule. This indicates that these forms were present when the globule formed in a liquid water environment. They could be little rods of clay—or the remains of martian bacteria. ***Image: NASA***



must have existed on Mars until very recently. The group also looked at the ratio of the carbon isotopes, carbon 13 and carbon 12. Biochemical reactions generally will prefer the lighter isotope, so that living matter usually has less carbon 13 than its surroundings; this signature is characteristic of life on Earth and, in fact, has been used to suggest that life on Earth existed as long ago as 3.85 billion years. Wright's group also found a substantial depletion of the heavier isotope in some of the carbonate grains, possibly suggesting that biological activity has occurred!

Simple or Complex?

With all the evidence, is there a convincing case for ancient martian life? Each observation can be explained either by biological processes or by nonbiological processes. The science team working with the meteorites suggests that it is simpler to appeal to a single process—biology—to explain all the observations than to appeal to several unrelated geochemical processes to explain each observation; they suggest that martian biology is the simplest overall explanation. This is a powerful argument.

On the other hand, others argue that appealing to a biological explanation is inherently choosing the most complicated explanation, and that all nonbiological mechanisms must be ruled out before considering a biological mechanism. By this argument, even though biology appears to be the best explanation, it should not be favored over geochemistry.

Which is the better argument? Although the new results are exciting and stimulating, very few people believe that the case for martian life is convincing so far. More analysis of the existing meteorite, of other martian meteorites and of other locations on Mars will be required.

Where is the right place to look? To look for martian life, follow the water. Ancient lake beds, river tributaries or volcanic hot springs might be places where life could have existed in the past. For more recent life, even up to the present, possible sites might be hot springs associated with recent volcanism or subsurface liquid water.

Unfortunately, it is not clear what to look for at these sites. Life could be powered by so many different chemical mechanisms that, without knowing the geochemistry of the environment, specific chemical reactions cannot be targeted for investigation. We need to go to Mars with an open mind, to look for chemistry that might be indicative of life, and to choose the most plausible places where liquid water and life could have existed.

Bruce Jakosky is a professor of geology at the University of Colorado at Boulder. He is an investigator on the Mars Global Surveyor *spacecraft and has done research on the evolution of the martian surface and atmosphere.*

***Figure 6:** One argument against the tiny structures being martian organisms is their size—about 100 nanometers across. (A nanometer is one billionth of a meter.) Typical terrestrial bacteria are hundreds of times larger. But in 1990, Robert L. Folk and F. Leo Lynch of the University of Texas at Austin discovered some mineralized forms that they identified as nannobacteria, shown here. Not all scientists accept this identification, but if it is confirmed, these terrestrial organisms would be about the same size as the suggested martian bacteria.* Photo: Robert L. Folk

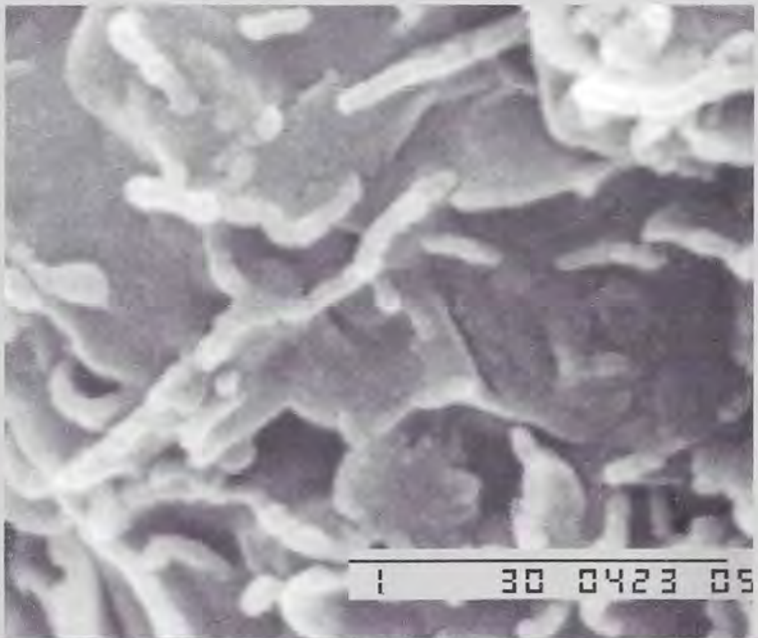


***Figure 7:** On Earth, many types of organisms produce minerals such as magnetite within their bodies. Here are bacteria with strings of magnetic grains running their length. The presence of similar mineral grains deposited within ALH84001 is one piece of evidence suggesting the possibility that the rock once harbored life. But the bacteria seen here are much larger than the proposed martian lifeforms, being some 350 to 500 nanometers in width.* Photo: Michael Nesson

Is the Case Persuasive?

A Skeptical View

by Michael Yarus

As a biologist interested in the origin of life on Earth, it appears to me that martian meteorite ALH84001 and its possible relation to life on Mars are best understood when compared with evidence for life on Earth in the same era.

That is, 3.5 billion years ago, it is likely that there was microbial life on Earth. These creatures are roughly the same distance in time from us as would be life on Mars, 3.6 billion years ago, as suggested after examination of the meteorite. To compare these two ancient biota, I will begin with the setting for the origin of life on Earth as we now understand it.

4.5 Billion Years Ago

According to well-established methods of isotopic dating, Earth formed 4.5 billion years ago from the aggregation of interstellar detritus wandering around in the area of the solar system. The heat of this union of planetary fragments melted out an iron core, which settled to the center of the forming Earth. Lighter material, destined to be the crust of Earth, floated around on the surface. By 4.2 billion years ago, that surface had started to congeal into a crust. This ushers in the so-called Hadean era in the Archean period of Earth's history —"Hadean" because conditions were hellish by any definition in that archaic time on Earth. During that period, not only was the rind of Earth mostly molten, but the forming planet was hit by giant impactors, planetesimals whose energy was sufficient to remelt the surface if it started to congeal and boil off any oceans if they had formed. The primordial oceans probably boiled off several times, vaporizing all likely habitats for early life, before early life could settle down permanently.

By about 3.8 billion years ago, it is clear that conditions had become more congenial to life; at this time, we find the first sedimentary rock. To have sedimentary rock, you must have stable bodies of water and a crust. After this period, cataclysmic impacts trailed off, and the crust of Earth extended and evolved toward its modern size and shape.

3.5 Billion Years Ago

At 3.5 billion years ago, only relatively shortly after crust became possible, we find good evidence of life—not only life, but complex microorganisms that look like some that persist in Earth's biota today. Thus, life appeared surprisingly early on Earth. A vast period, 2.9 billion years, elapsed while the only living residents of Earth were such single-celled microorganisms.

A First Impression

Thus, the first conclusion I want to draw about life on Mars is emphatically positive. The planets of the inner solar system formed at the same time, from the same materials and by similar processes. While Mars and Earth later diverged dramatically, at 3.5 billion years ago and earlier they appear to have been much more similar than today (see page 12). Therefore, despite the hellish aspects of early planetary history, and seemingly against all probability, we know of a parallel experiment in which a Mars-like planet evolved relatively complex microorganisms shortly after congealing, at a time and in a situation similar to that proposed for martian meteorite ALH84001. That parallel experiment took place on Earth.

I find this precedent quite compelling. Evidence of ancient bulk water on the martian surface is frequently cited in favor of life on Mars. However, ancient water erosion on the martian surface seems to me part of, but less compelling than, the early parallel with events on Earth.

Ancient Earthly Life

To get further, we need the details of the evidence for ancient microorganisms on Earth. In particular, we need the evidence gathered by J. William Schopf of the University of California at Los Angeles, who is a specialist in ancient microfossils.

Schopf's most ancient microfossils can be seen by looking through thin sections of rock from northwest Australia. In this region, there are bands of rock that contain millimeter-size nuggets. In the light microscope, you can see, within thin slices of the nuggets, cell-like objects that are not in the surrounding rock. Looked at closely, these resemble chains of cells, each a space enclosed by an apparent cell wall. The chains look very much like chains of modern cyanobacteria. They are the right size, the periodicity of the cells is right and the chains end with a cell of unique shape—all like modern blue-green bacteria. One even sees cells that appear to be dividing.

These images we believe to be microfossils, formed after cyanobacterial ancestors were caught and embedded in an ancient sediment. For the purposes of later comparison, remember that the fossils are themselves rock. They result from replacement of the bits and pieces of these cyanobacteria, if that's what they were, by contrasting minerals. Today you can go and pick out a nugget, slice it thin and see, not the organism, but a sort of a cast of the organism made of rock that has lasted billions of years.

A first remarkable thing is that these objects are of the size and appearance of creatures that we recognize. There's a continuity, perhaps an evolutionary continuity, between the most ancient fossils and modern creatures. Admittedly, there is a potential logical circularity in this conclusion; were they too novel, we might not recognize them.

Second, we know the age of these images very well. Because the surrounding rock can be dated, again using isotope dating methods, the tiny fossils are datable if they are of the age of the rock. That seems very likely, because features of the embedding rock go right through the fossils, joining them to a rock matrix that can be dated.

Rock layers in this area of northwest Australia have been extensively mapped by geologists. The fossil-rich nuggets lie in the Apex layer. Apex is underlain by the so-called Duffer (3.465 billion years old) and overlain by the Panorama Formation (3.458 billion years old). Thus the sandwiched Apex

layer dates from 3.46 billion years ago, and the nuggets and their microfossils within must be at least that old.

Finally, these microfossils are reproducible, in that they have been found multiple times. I can virtually guarantee that if I gave you Schopf's map and you took a rigorous walking vacation in northwest Australia, you could rediscover related fossils. They are not some rare geochemical anomaly, but findings of the kind conventionally valued in science, findings that can be confirmed.

Possible Ancient Martians

Now let's look at the hypothetical Martians, as they appear in the analysis by David McKay and other investigators in the August 16, 1996, issue of the journal *Science*. The suggestive findings are small elongated objects on the surface of the carbonate globules, believed by these investigators to be biological in origin. A very generous estimate is that the largest of these wiener-like objects measures 50 by 200 nanometers. This is very small, about 1/500 to 1/1,000 the size of a typical earthly bacterium.

Size matters: What an earthly bacterium does, with roughly 1,000 molecules, the potential Martian must accomplish with one molecule. The martian microbe, nevertheless, uses this small molecular repertoire to live a rather complex life. That is, it is a free-living creature that worms its way into cracked martian rocks in flowing water and leaves carbonate deposits as a result of its self-sufficient metabolism.

As an example of the difficulty, a small free-living creature necessarily has strong cell walls. The reason is that without such walls, influx of water ultimately explodes the cell. An earthly bacterial wall adequate for this job is 25 nanometers (about one millionth of an inch) thick. In other words, if the martian microbe had such a wall, there would be no space whatsoever for cellular components in its interior.

This kind of argument can be made with other specifics. A terrestrial cell needs rather complex machines called ribosomes to make its major catalysts, the proteins. Ribosomes are 25 nanometers across, so even if the cellular space were completely filled with ribosomes there would be only 16 of them, with no space left for any of the other components required for active metabolism, or even for the information-storage molecule (like DNA) that would carry the genetic information of the creature.

Thus these objects don't seem to be free-living microbes as we see them on Earth.

It can be objected that any such argument is hopelessly geocentric. But arguing that there is some other smaller, perhaps more high-tech, solution to the problems of being a cell requires the renunciation of what we know about the function of biomolecules on Earth. The limits of chemistry, according to all indications, are the same on Mars as on Earth. Therefore, it seems improbable to me that the aggregate of everything needed for independent cellular life could be made 500 to 1,000 times smaller than the examples we know. And notable among the examples we know are earthly microfossils from the same era.

The Martians as Fossils

Let's look at the martian relics again in terms of the criteria we apply to the Archean fossils on Earth.

Are they reproducible? No, but that's not a fair criterion to apply to a potential discovery. Perhaps in other meteorites they will be reproduced. In fact, this notion points to the appeal of a relatively cheap Earth-bound meteorite hunt whose goal would be to find many more such examples as ALH84001. In any case, until they are reproduced, proponents of life on ancient Mars cannot take comfort from this criterion.

Can the age of the putative martian microbes be determined? Unfortunately, this currently seems unlikely. The elongated martian objects are bumps of nanometer size sitting on rocks, detected in scanning electron micrographs. That is, they are too small for separate examination and are not necessarily a part of the underlying minerals. Unless or until technical advances make it possible to collect numbers of them separately for more complete analysis, their ages may remain unknown.

Finally, and most significantly, consider the nature of the objects themselves. A bacterium will not last for 3.6 billion years, especially exposed in the oxidizing conditions detected by the *Viking* landers near the martian surface. Thus, these microscopic objects are very unlikely to be ancient martian organisms, persisting in place.

But it also seems unlikely that these tiny objects are microfossils. Fossils of this age are rocks themselves, usually embedded in exceptionally durable rocks, as pointed out earlier. The candidate Martians are instead bumps on a surface. If they are not the original organisms, they are presumably made of something durable that replaced the organism. But to replace the organism with something capable of surviving 3.6 billion years, and of the organism's exact shape, seems to require formation of a mold, injection of the durable substance to take the shape of the organism, then decay of the surrounding mold material to leave a long-lived, freestanding replica of the original microbe. This complicated series of events seems unlikely, to say the least.

Thus, in the study of possible martian life we are far from the status of the evidence for earthly life of the same age. But it is surely early yet. Crucial evidence, such as isotopic ratios, which can point strongly toward or away from life, is sure to emerge soon. It seems reasonable to be cautious. A betting person should be correspondingly cautious in upping the bet for martian life, at least on the basis of the evidence we have seen.

The Crucial Evidence Is Out There

Even if the chemical evidence is added, martian meteorites have not yet added greatly to evidence for early life on Mars. Nevertheless, martian life remains likely on other grounds. I suggest that we take the meteorite's evidence as a question, not as the answer. The question of life on Mars is a compelling one, and all the more so after the furor about ALH84001 has focused our attention.

Furthermore, we're going to Mars five times in the next few years. Bits and pieces of Mars will be returned to Earth in the year 2005, perhaps before. And in those rocks, or in rocks from Mars already on Earth, there may be more definitive evidence. Within the lifetime of most everyone now reading these words, we will likely have our answer.

Michael Yarus is a professor of molecular, cellular and developmental biology at the University of Colorado at Boulder.

Standard of Evidence:
How High for Ancient Life on Mars?

by Carol Cleland

In the original press briefing on the Mars meteorite (August 7, 1996), UCLA paleontologist J. William Schopf quoted Carl Sagan in cautioning that "extraordinary claims require extraordinary evidence." Schopf suggested that the scientific community should hold the hypothesis that the martian meteorite contains traces of ancient life on Mars to a very high standard of evidence. My concern, as a philosopher of science, is that the standard he proposes is too high—higher than what is required for comparable scientific hypotheses.

Hypothesis and "Fact"

Scientists often characterize well-accepted hypotheses as "facts." Insofar as this characterization suggests that scientific hypotheses can be conclusively proven, it is at best misleading. Consider the hypothesis that all copper expands when heated (under "standard" conditions). This hypothesis applies to all copper—past, present and future. But it is impossible to test all copper. One can only conjecture about copper that was heated a million years ago and copper that will be heated a million years hence. Thus one cannot conclusively prove that all copper expands when heated. This may seem like a pedantic point, since no disconfirming instances are known. But we can't completely eliminate the possibility that they exist, and that is what is required for conclusive proof.

Given the impossibility of conclusive proof, let's consider the martian-life hypothesis. It is a fact that the martian meteorite contains certain chemical and structural features—for example, iron sulfide minerals and carbonate globules (see page 12). However, we can only speculate on the origin of these features, since we cannot go back in time and observe their formation. Indeed, even if we discovered that there was life on Mars, we couldn't conclusively prove that the meteorite known as ALH84001 contained fossilized life. We could never completely exclude the possibility that the carbonate globules in this particular meteorite were produced in some other way by inorganic processes.

So what standard of evidence is normally required by the scientific community for the acceptance of a hypothesis like the martian-life hypothesis?

Hypotheses About the Past

The first thing to note about the martian-life hypothesis is that it is a historical hypothesis about a particular thing. It is not a timeless, universal generalization about a type of thing, but a conjecture about the origins of some unusual features of a particular rock. It is thus more like the geologic hypothesis that Africa and South America were once part of a single continent than the physical hypothesis that all copper expands when heated.

Most historical hypotheses have the peculiar feature of being used to explain the data that provide confirmatory evidence for them. The hypothesis that Africa and South America were once part of a single continent explains a number of mysterious geographic and geologic features (the complementary shapes of South America and Africa, similarities between rocks of the east coast of South America and the west coast of Africa, and so forth), and these features supply the main confirmatory evidence for the hypothesis. Similarly, the martian-life hypothesis explains the chemical and structural features of the martian meteorite, and these features supply the main confirmatory evidence for the martian-life hypothesis. Confirmation and explanation go hand in hand in the case of most historical hypotheses.

Historical hypotheses are required to provide the best explanation of the phenomenon to be explained. The plausibility of the martian-life hypothesis derives from its being the best explanation for the chemical and structural features of the martian meteorite. The best explanation is never the only explanation. One can always invent alternative explanations for a given phenomenon. Indeed, this is one of the favorite strategies employed by creationists against the hypotheses of evolutionary biologists; the creationists propose alternative, more Bible-friendly explanations of the fossil record. The mere existence of an alternative explanation is not, however, a threat to the viability of a hypothesis unless the alternative provides a better explanation of the phenomenon.

Why "Cold Fusion" Failed

This brings us to the question of what features raise a scientist's confidence in the plausibility of an explanation: What leads a scientist to conclude that one explanation is better than another? Other things being equal, an explanation will be judged as better if it is (1) simpler in the sense of requiring fewer ad hoc assumptions (new and sometimes implausible claims advanced solely to support the preferred explanation) and (2) more compatible with well-accepted scientific theory.

The crucial role played by these two features in a scientist's judgment of the quality of an explanation is clearly illustrated by the cold-fusion fiasco. The cold-fusion hypothesis was advanced by two electrochemists, Martin Fleischmann and Stanley Pons, to explain excess heat generated in an electrochemical cell in their laboratory. They hypothesized that the heat was produced by a nuclear fusion reaction occurring at room temperature.

The cold-fusion hypothesis violated two major tenets of nuclear physics: First, that nuclear fusion requires tremendous energy, energy that cannot be obtained at room temperature, and, second, that nuclear fusion produces enormous amounts of radiation (fusion by-products), enough to literally fry the unprotected Pons and Fleischmann. How did Pons and Fleischmann respond to these anomalies? They postulated a new and utterly unknown nuclear process. Not unexpectedly, alternative explanations that did *not* violate tenets of nuclear physics or require ad hoc assumptions were quickly accepted by the scientific community over the cold-fusion hypothesis; the alternative hypotheses were judged to provide a better explanation of the excess heat than the cold-fusion hypothesis.

In this context, let us return to the martian-life hypothesis and see how it fares against alternative explanations of the structural and chemical features of the martian meteorite. The martian-life hypothesis does not violate any well-entrenched scientific theories. It is generally conceded by planetary scientists that conditions on Mars 3.6 billion to 4 billion years ago were compatible with life. Moreover, the chemical and structural features of the meteorite are very similar to those produced by terrestrial bacteria; there are even sausage-shaped structures that look like terrestrial bacteria.

Is There a Better Explanation?

Admittedly, there are some problems. As Michael Yarus emphasizes, the sausage-shaped structures are much smaller than terrestrial bacteria. (See page 18.) They are too small to contain all the stuff required by a modern terrestrial bacterium for metabolism and reproduction. But this doesn't violate any fundamental tenet of contemporary biology. Also, there is no reason to suppose that extraterrestrial prokaryotes must be exactly like terrestrial prokaryotes. In short, unlike the cold-fusion hypothesis, the martian-life hypothesis doesn't violate accepted scientific theory.

In closing, let us return to the quote from Sagan: "Extraordinary claims require extraordinary evidence." The word "extraordinary" has at least two meanings. It can be used to characterize something that violates well-accepted and fundamental beliefs about the world, or it can be used to describe something as wonderful and delightful. It is important that we restrict Sagan's maxim to claims that are "extraordinary" in the former but not the latter sense. That is to say, we don't want to hold a scientific hypothesis to a higher standard of evidence just because it is wonderful and delightful. The martian-life hypothesis is a very good candidate for being the best explanation of the structural and chemical features of the martian meteorite. The question is, are there any better, or at least equally good, explanations? If scientists convince themselves that there are not (and this will require thinking up alternative explanations), the martian-life hypothesis will attain the status of a scientific "fact." It will not, however, be conclusively proven, for that is impossible, and it will not be the only explanation, for there are always alternative explanations.

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Life on Another World:

Can Religion Cope?

by Rodney L. Taylor

How is the religious search for meaning affected by the potential for life on Mars? Long before the present debate on evidence for life on Mars, the philosopher W.T. Stace made the following observation: "Religion could survive the discoveries that the sun, not the earth, is the center; that men are descended from simian ancestors; that the earth is hundreds of millions of years old. These discoveries may render out of date some of the details of older theological dogmas, may force their restatement in new intellectual frameworks. But they do not touch the essence of the religious vision itself, which is the faith that there is a plan and purpose in the world, that the world is a moral order, that in the end all things are for the best." He goes on to say, "Religion can get on with any sort of astronomy, geology, biology, physics. But it cannot get on with a purposeless and meaningless universe."

Religion offers a structure of meaning and purpose for the individual and community. It often accomplishes this task by putting such meaning and purpose within the context of a story or root metaphor. Across the history of religions there have been many such stories. The interactions between such stories and our changing knowledge of our world and the universe suggest a fluid and dynamic state of challenge, change and transformation. As Stace has suggested, religion can "get on" with any science. It is the question of meaning and purpose in the world and humankind's place within it that remains critical to the continued existence of religion.

For some, there is an embracing of the new knowledge; for others, there is adaptation; and, for still others, there is resistance to the fullest possible extent. And what does this variety of response say about the religious story, be it Jewish, Christian, Muslim, Hindu, Buddhist, Confucian, Taoist, Shinto, Native American or any other? It suggests that some of the stories are more suitable as a vehicle for communicating new knowledge and assimilating this knowledge. Stories that remain fixed upon a theological centrality of the human enterprise and those that view the universe in a short time frame may have the greatest difficulty accommodating themselves to the possibility of life from another world.

I would suggest two premises about religion and its relationship to scientific knowledge. First, the range of meaning within a religious tradition may be as great as the range of meaning between traditions. Second, a root metaphor can be expanded to cover any situation. There is no practical limit to the possible ways in which the meaning of a root metaphor, and thus its application, might be expanded in response to a changing world. A need for an explanation of life on another world might provoke a reinterpretation of a root metaphor that seems a radical disjunction, yet flows from within its originating religious tradition. The process is not unlike that which occurs in the scientific community when new data compel a modification to well-accepted theory. Any religious tradition may recast its root metaphors to reach compatibility with what is known about the universe around us.

Speaking of religion in general, it may be a tautology but the only religions we know are human religions. If life is truly ubiquitous in the universe, and the Mars evidence provides a step toward this conclusion, then there is the possibility that we will see the human-centered position pushed off center! There is even the possibility of our coming to understand nonhuman religious expressions, though it is unlikely that our present microbial candidate for life will add to our understanding of the dimensions of religiosity. But that microbe, if that be its nature, engages our capacity to contemplate the expansion of life in many forms throughout the universe.

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Our Martian Destiny

by Ray Bradbury

Is there anyone alive who hasn't seen those troublesome specks trapped in the vitreous humor, swimming across his sight; here it comes, there it goes? That, it seems to me this special month, is the Mars metaphor; always on the rim of our vision, swiftly skimming the surface of our perception, then vanishing.

But now, it also seems, Mars may well be here to stay. Or at least to rivet our attention for more than a fortnight.

This latest fragment of data—the apparent discovery of life on the Red Planet—is only worth our hyperventilation if we allow it to lead us to the larger metaphor: Mankind sliding across the blind retina of the Cosmos, hoping to be seen, hoping to be counted, hoping to be worth the counting.

All this in one fragment, one leftover particle ricocheted through space and fast-frozen in the Antarctic, waiting for revelation?

Why not? If the influenza bacterium, invisible, can slay 10 million in a month, why not this mote to energize souls, uplift the Will, and march us as to war? If we look upon it as a mute flake in time, we will deep-freeze ourselves. But if we see in it a chance to examine a nearby world where life began in similar fashion, it will truly be a passionate revelation.

For that world exists. A world that fired out of the sun billions of years ago, took more billions to cool, and still more for rains to fall and seas to fill until at last, in the soups and broths of the cooling land, the first inanimate stuff, jump-started by lightning, decided to live, re-create, and prevail.

That planet is Earth. That mysterious stuff is us. We began as Mars began, but it did not change or grow. From the primal soups to the caves to *Apollo* landfalls, Mankind has grown outsize, ripe for self-recognition.

Once we have looked at our own planet with new wonder and recognition, we should turn back to this Martian rock and let it be the touchstone that sends us on a predestined flight across space and time, seeking some ramshackle sort of immortality. Thus the damned speck will seed a Beanstalk, with us as Giants.

Why Mars as destination? Because we cannot help but echo our old doubts and wonders: Why was the Universe created? Why were we given birth? Why is it our task to look with awe at a billion stars and wonder at the responsibility that has fallen to us?

For what is the use of a Universe if no one is here to see it? Why this miraculous display if no one is here to record it? We were raised up from the swamps to be the seers. We are the Recorders.

In a multibillion-year pageant was it God's 20/20 X-ray vision that focused us when He, the Life Force Enforcer, decided to light the Light, fireball the Earth, rainfall the oceans and fling wide the Garden portals? And if so, how come? What was in His mind?

Or, conversely, did Darwin's mindless lightning storm across the world to summon up brains, minds, and eyes to see with? How come? What was on accidental, dumb, brute Nature's mind?

Choose God, or Darwin, or both. We simply don't know.

We only know that we are the privileged. No other beast in sea, on land or on hill has looked upon the stars and known what it was seeing. So finally it is the seeing and the knowing that put us in motion. The simple fact is, we are *it*. It falls to us to see, to try to know, to fail at interpretation but succeed at immortality.

We do not know why penicillin kills disease. It simply does. We do not know why or how the silent heart of a fetus suddenly beats. Something *tells* it.

So we do not know exactly why we wish to become immortal. We simply do. We think we are worth the price, worth saving, worth being set free to seed our minor corner of the Universe. It is in our blood and bone. To refuse it is to give in to ruin and death.

Yes, we need to make and eat our daily bread to feed our blood. But the Universe is greater food to feed our souls.

Let us take inspiration from Verrazano, sent by King Francis I to chart an unknown continent. He was the only one of the three Italian navigators who actually walked on the shore of what was to become America.

And where did he touch our wilderness?

Kitty Hawk.

Yes. Sound the name.

Kitty Hawk!

Thus the arrivals and departures of our history, 400 years apart, are fused in astonishing fact.

We made a mysterious arrival on Earth thousands of millennia ago. Now is the threshold for our going-away.

We have already twice landed on Mars with photographic extensions of our sight. Next time we must ship out our bodies to stare close-up at the wonder that must be Mars and its great canyon Abyss, as long and as wide as the United States.

The child that lay on the summer night hill wondering at the constellations must be the great child wandering from Earth to Moon and then at last to a Red World waiting to be inhabited. Mars is a dead world waiting to be stirred awake. We must be the ghosts that inhabit its cities that were never built, populated with beings that never were.

There is a fine and moving line in one of the old Khayyam quatrains: *We came like water and like wind we go*. But we can choose to stay. And stay by deciding to go.

That is, to move up once more with new *Apollo* missions to Space Station the Moon and move on to Mars. And from there? Not the whole damn Cosmos, no, but some small part of it where the Nina, the Pinta and the Santa Maria, the Argos, the rocket bireme, the Viking longboat, the Sun Chariot, all can put down; a billion feet shod in one boot, a billion gene-chromosomes in one footprint. To live in worlds where the sun will never set on brute mankind, wondrous mankind, awful mankind, lovely mankind. Brother and sister to Ivan the Terrible, Baldur the Beautiful, Helen of Troy, Bugs Bunny and Medici monster, Bluebeard and Jonas Salk, Jesus of Nazareth and Ghengis Khan, Moses and Cortez.

The Universe invites us all, bids us welcome to behave or not behave. The Cosmos is wide, accepting, frightening, and incredible in its beauty.

Some say we cannot afford the expense. We can't afford not to.

At the end of my *Martian Chronicles,* an immigrant spaceman, on an excursion across the dead Martian landscapes, tells his children he is taking them, at last, to meet the lost race of Martians.

At the rim of a lonely canal, the father speaks.

"There." He points down. "*There* are the Martians."

His children stare down into the canal waters.

And see their own images looking back up at them from a million waiting years of time.

Ray Bradbury is the author of, among other works, Fahrenheit 451 *and* Quicker Than the Eye, *a collection of stories published by Avon Books. This article has been reprinted from the August 21, 1996, issue of* The Wall Street Journal. *Copyright © Ray Bradbury.*

The Launch and Loss of Mars '96

by Louis D. Friedman

A cold and beautifully clear night on the absolutely flat steppes of Kazakhstan. Absolutely flat except for the one hill, on which we stood, waiting for the *Proton* to launch *Mars '96* on its way to the Red Planet. On the hill was a model of the *Proton*, which, as we drove up, I mistook for the rocket itself. Were we really going to be this close? No, the real *Proton* was 4 to 5 kilometers (about 2 to 3 miles) away.

It was nearly midnight, Moscow time (local time at the Baikonur launch site is two hours later—13 time zones from Pasadena). The *Proton* was poised, ready to go at 11:48 p.m. Moscow time, November 16. There were a lot of visitors crowded into the small observation building in which was set a lovely table of *zakuski*—light snacks. Outside, the temperature was about minus 7 degrees Celsius (21 degrees Fahrenheit); a steady breeze made it seem colder. Standing still for more than five minutes was difficult. Trying to hold the camera steady was also difficult.

Without any fanfare, only a countdown in minutes, a broad band of fire lit under the *Proton*. The rocket just stood there—no sound, just fire. Then a slight movement up, then sound, then blasting away it steadily rose. It was a fantastic and impressive sight—after all, this is now the biggest rocket in the world. Up and up it went, and its light in the sky glowed for a very long time.

The public-address announcer intoned, "Everything normal." It was wonderful, beautiful, perfect, without a hesitation, hold or hiccup. The leaders of the Russian Space Agency and the *Mars '96* project were all beaming. We congratulated everyone, had a drink and, after about 25 minutes, boarded our bus for the 40-kilometer (25-mile) ride back to the Cosmodrome hotel.

We arrived there some 70 minutes after launch, about the time the fourth stage of the *Proton* should have fired for the trans-Mars injection. Our hosts had prepared a small celebratory banquet for the group of international visitors, including scientists from many nations involved with the mission, as well as many participating Russians.

During dinner (about 2 a.m. Moscow time, 4 a.m. local time) we heard the announcement we were waiting for—a successful fourth-stage burn! We were on our way to Mars. We enjoyed cheers, toasts, a warm feeling from vodka, good food, good company and excitement—and, finally, a one-hour nap just before sunrise. Then we would catch our plane back to Moscow. It had been a great all-nighter.

Then came morning and the news that *Mars '96* never left Earth orbit.

What happened? Why were we told that the injection on the martian trajectory was successful? Why did it take so long to tell us the bad news? Apparently the spacecraft had sent telemetry indicating it had separated from the booster and deployed perfectly. The Russian tracking station was following the spacecraft—but the timing was wrong. The spacecraft was in fact in Earth orbit, not on an escape trajectory. Yes, the fourth-stage burn had been observed, but to inject to Mars, two fourth-stage burns were required, and the second firing was out of range of any Russian tracking station. No one knew at that point that the second firing never occurred.

For previous missions, the Russians had tracking ships in position to observe the entire launch. This time, due to bad luck and shortage of funds, they did not. It took a little while to interpret the spacecraft data and trajectory timing. The spacecraft thought it was on the way to Mars, but, trapped in Earth orbit, it could never get its pointing routines and attitude control to work correctly. Its computer would try, fail, and ultimately shut down.

A hunt for the spacecraft followed, with Russian and American civil and military tracking systems cooperating in the search. There was hope that if the spacecraft could be contacted, controllers could fire its engine and send it to a higher orbit, outside Earth's atmosphere, where it could be safely parked. The effort was also doomed. The spacecraft was in such a low orbit that Earth's atmosphere quickly captured it. The best guess is that *Mars '96* fell to Earth within two to three orbits after launch—its mission lasted only three to four hours.

So the mission ended, after years of delay and worry, and international arrangements involving more than 20 nations and 22 experiments. I was there with scores of others involved in the mission. The disappointment was greater than after other space failures I have witnessed (excepting the loss of human life). There was a sense that Russia's once-hopeful future in space had also fallen back to Earth.

Why did the fourth-stage booster, called Block D, fail? Was it an engine failure, a fuel leak or improper propulsion-

Visions of Mars: Gone, But Not Forgotten

Along with 22 science instruments and the hopes of hundreds of scientists from more than 20 nations, our own *Visions of Mars* went down with *Mars '96*. This CD had been placed on board the two small stations that were to land on Mars. Our offering—which included an anthology of science fiction literature; the recorded greetings of Carl Sagan, Arthur C. Clarke and others; the radiation recording experiment devised by the Jet Propulsion Laboratory; and the 100,000 names of Planetary Society members—fell to Earth, probably to the bottom of the Pacific Ocean.

Space is a risky business. But the act of trying made us better. The effort we expended on the CD is still worthwhile because its replica, sold on Earth, drew attention to the space program. We'll try again—maybe with a later flight of the *Mars '96* small-station design, or maybe on a different type of mission. The vision remains, and we will try to fulfill it. —*LDF* system control? Block D is built by the RKK Energia company, and this was a special version for planetary missions. The control system was part of the spacecraft, built by NPO Lavochkin. This was the second Block D firing failure. As I write this, there is lots of speculation, but no one yet knows the reason for the failure. A review board is being set up to investigate.

The implications of the loss of *Mars '96* cannot yet be known. In part, they will depend on the assessment of the failure and the manner in which the review is conducted. This was an international mission in an international program. Russian management and organizational capability are in question. Will the Russian Space Agency step up to the challenge of dealing with these problems and conduct a thorough, broad and open review? Will it—as NASA did after its mistakes in the space shuttle, *Mars Observer* and Hubble Space Telescope programs—make changes reflecting decreased budgets and new ways of doing business?

If so, the future will still be hopeful. Russia has a significant space science infrastructure—second only to that of the United States. This year the Russians launched two successful science missions (Interball), and they have their Marsokhod (Mars Rover) in development for *Mars 2001*—in a cooperative program with the US, with European participation. Russia is the only country, besides the US, working on developing Mars sample-return missions, a goal that has become even more important since the possible discovery of past life on Mars.

Russia still has the most reliable and diverse stable of launch vehicles suitable for planetary exploration. The *Proton* has an outstanding success record and would be enormously useful for Mars sample returns and for the Pluto Express mission. Russia is the major partner in the international space station, which remains a precursor to any human Mars mission. The Russians also have two major astronomy missions in development.

The issue is, will the Russian government support space science and planetary exploration with an adequate budget? Will it make the necessary industry and organizational reforms? If the loss of *Mars '96* serves as a wake-up call for change, then the failed mission may still serve a noble purpose.

Meanwhile, Mars *Global Surveyor* and *Pathfinder* are on their way to Mars. One solar panel on *Global Surveyor* has not fully deployed, but mission leaders say they will have enough power to complete the mission even if they cannot fix the panel. We will report on the progress of these two US missions in our next issue.

Louis D. Friedman is Executive Director of The Planetary Society.

Society News

A Thank-You

Don Erway of South Pasadena, California, entered a national essay contest and won—and so did The Planetary Society. Erway very, very generously donated his prize, a DEC workstation, to the Society. It was immediately put into use at Society headquarters in our Worlds of Information Resource Center. Every member will benefit from Don Erway's generosity. We thank him. —*Louis D. Friedman, Executive Director*

Come to a Hale-Bopp Party

To celebrate the arrival of Comet Hale-Bopp, The Planetary Society and the United States Naval Observatory will join forces in April to host a comet watching party on the Naval Observatory grounds in Washington, DC. Look through the observatory telescopes and those of local amateur astronomers, take a tour of the observatory facilities and get the latest information from the experts. Admission will be free but by advance ticket only. Send us a note as soon as possible and ask for an event flyer and ticket order form. —*Susan Lendroth, Manager of Events and Communications*

Join Us in New Orleans

The 1997 National Science Teachers Association Convention will be held in New Orleans, and Planetary Society Day is Saturday, April 5. David McKay, leader of the martian meteorite team, Rick Sternbach, senior illustrator and technical consultant for *Star Trek Voyager*, and our Executive Director, Louis Friedman, will be among the speakers. Our event is open to all interested in attending. For registration details, contact me. —*SL*

Alternative Ways to Give

The Society's programs are in large part funded by members' donations, as with Don Erway's donation, and occasional bequests. We have just set up a life insurance giving program in conjunction with a major insurer, with donations earmarked for a special endowment fund whose purpose is to build up capital for 21st century activities. Fittingly, we will call it the New Millennium Endowment Fund. The program was arranged by New Millennium Committee member J. Tyler Lee, himself a leading insurance company executive. No commissions will be charged for the Society or for members participating in the program. We will be sending out a letter about this program, or you may write to me for details.
—*Lu Coffing, Financial Manager*

Countdown to Planetfest Begins!

Planetfest '97 is near— make your vacation plans now and join us in Pasadena on July 3 to 6 for this once-in-a-lifetime event. For information, call or write us, or see the November/December 1996 *Planetary Report*. We have also made special arrangements for discounts at the Holiday Inn (818-449-4000) and the Doubletree Hotel (818-792-2727). Make your reservations early and mention Planetfest '97 to get the discount. —*Cindy Jalife, Manager of Program Development*

More News

The Mars Underground News:
The tragedy of *Mars '96*...evidence of life on Mars...*Global Surveyor* in flight to the Red Planet.
The Bioastronomy News:
Special reports on the possible ocean —and perhaps life—on Europa.
The NEO News:
The computer revolution reaches asteroid detection...impact craters on Earth.

For more information on these newsletters, please contact Planetary Society headquarters; see page 2.

News and Reviews

by Clark R. Chapman

With the approach of Comet Hale-Bopp, 1997 is destined to be the year of the comet—or at least the year of the cosmic impactor, whether cometary or asteroidal. Actually, the differences between comets (ice-rich bodies from the outer solar system) and asteroids (rocky and/or metallic bodies formed in the inner solar system) continue to dwindle the more scientists learn. Were an impactor to strike our planet, which is extremely unlikely anytime soon, such distinctions would be moot. All that would matter would be the instant conversion of the object's immense kinetic energy of motion into a gargantuan explosion, and the resulting rain of fiery debris around the globe.

Cosmic Calamities

Cosmic terrors will visit your living room TV set during February's ratings week. The networks are vying to outdo one another in dramatizing doomsday ends to civilization and planet Earth. As I write this column, I'm returning from my own brief role: being filmed by Fox TV at Chicago's venerable Adler Planetarium, which I first visited—as an awestruck boy—over 40 years ago. What I and my colleagues have tried to do for these documentaries is lend an air of reality to calm the sensationalism that threatens to run amok. The awful calamities of *Independence Day* will surely be eclipsed when fictionalized dramas of cosmic impacts hit the Big Screen later this year.

To start learning about Hale-Bopp and cosmic impacts, I suggest picking up the November/December 1996 issue of *Mercury,* the general readers' magazine of the Astronomical Society of the Pacific (ASP). An authoritative account of the impact hazard, and what we might do about it, is by Alan Harris (page 12). He argues that we can deal with about half the risk—that posed by mile-wide asteroids—by building the proposed Spaceguard telescopes to search for any asteroid headed for Earth. At just $10 million per year, the survey might have a benefit-to-cost ratio as high as a hundred to one. On the negative side, Harris finds dealing with the rest of the risk (from Hale-Bopp-like long-period comets and other objects sneaking up on us) to be technologically impossible, too costly or—in the case of maintaining a trigger-ready nuclear arsenal—more dangerous than the hazard it would protect us from.

Two sets of book reviews in *Mercury* guide us to further reading. James Jay Klavetter evaluates two postmortems on the Shoemaker-Levy 9 comet crash, an introduction to meteoritics (the scientific study of rocks from space), and two books about the impact hazard. The second set of reviews, by John E. Isles, recommends comet codiscoverer Alan Hale's book among three published in anticipation of Hale-Bopp's arrival. (As I write, Hale-Bopp isn't quite living up to its most optimistic billings, but it should still be a pretty sight, very different in appearance from last year's Hyakutake.)

Year of the Comet

Whatever happens this spring, we can recollect the beautiful passage of Hyakutake. If you were unfortunate enough to have missed it, or tried to watch it with city lights or moonlight washing out its diaphanous tail, get the incomparably gorgeous video by Canadian amateur astronomers: *Comet Odyssey* costs $29.95 from Cyanogen Productions (1-800-835-6794).

One person who missed Hyakutake was planetary scientist Heidi Hammel. From her account in *Mercury,* I guess she first looked at it from the hazy East Coast. I'm mystified why she was so unimpressed with it from a remote site in Wales. In an otherwise insightful account of how Joe Average and Jane Q. Public relate to astronomy, Hammel is just wrong about Hyakutake. If you got to a really dark site (and that vital qualification was often enough promulgated by TV weathercasters) while Hyakutake passed from Arcturus to the Dippers, the comet was the most obvious thing in the sky, not the small, disappointing "smudge" of just another overhyped, "run-out-of-steam" comet, as Hammel would have it.

Essays by Kevin Yau, Katherine Bracher and ASP President Bruce Carney provide historical backdrops to Hale-Bopp's arrival—from the comet records of the ancient Greeks and Chinese through Halley and Hyakutake. Brian Marsden and Gareth Williams trace the record-keeping of small-body discoveries since the first asteroid was found nearly two centuries ago. James White tells nonexperts how to record their own observations of Hale-Bopp.

The best article of all in this generally fine issue is Chris McKay's reflections on the roles comets may have played in the origin of life on Earth, such as delivery of the water and nutrients required for life, or even delivery of already-existing life from planets around other stars. Life may even have formed within some comets. And, McKay reminds us, early cometary bombardment may have sterilized Earth before evolution finally gained a foothold, eventually leading to ourselves.

One article missing from *Mercury* is the one that would have told us directly about comets. There will be a second chance for that, after Hale-Bopp has come and gone and astronomers have sifted their data and learned even more about these mysterious visitors from the extremities of the solar system.

Clark R. Chapman has written, coauthored or coedited books on amateur astronomy, the terrestrial planets, the planet Mercury, cosmic catastrophes and Voyager*'s encounter with Neptune.*

Basics of Spaceflight:

End-to-End Data Flow—The Uplink Part

by Dave Doody

This installment, together with the next one (the downlink part), builds upon many of the topics we've discussed in previous installments and shows how they work together as a whole system, bringing home measurements of distant bodies in our solar system. At one end of the system are the people who plan and operate the interplanetary robotic spacecraft. At the other end of this pipeline is the public; the results are delivered to your doorstep in the form of news and images on your TV and your computer, in schoolbooks and scientific journals, in coffee table books and technical texts.

"Uplink" is a general term given to a radio signal sent "up" from Earth to a spacecraft. The signal is a highly directional microwave radio beam, normally in frequencies around 2 billion to 6 billion hertz (2 to 6 gigahertz) and at power levels of less than 10,000 watts. The purposes for an uplink include commanding (which we'll concentrate on in this issue), tracking (see "Making Tracks," the July/August 1995 installment of this column) and radio science.

"Downlink," as you'd expect, is a general term for a radio signal sent "down" to Earth from a spacecraft. The signal is usually in the same radio-frequency bands as the uplink. Downlink serves the purposes of tracking, telemetry and radio science (covered in the November/December 1995 "Telemetry and Command" installment).

The Planning Process

On the radio-frequency uplink to the spacecraft, we place command signals that the spacecraft receives, decodes and acts upon. But before that can be done, a bit of planning is required, and it is a complex process because there are millions of possibilities to consider, and many decisions to be made. For example, the process has to take into consideration what scientific observations the spacecraft is going to make, and when to make them; exactly when to fire its rocket engine or thrusters, and how the spacecraft must be oriented when it fires them; what kinds of measurements to send to Earth, and what data rates to use. So the commanding process begins long before sequences of commands are actually placed on the uplink.

The process starts with the scientists (also called investigators) associated with the spacecraft's instruments. These scientists are typically located at universities and aerospace companies worldwide and are usually supported by their own research assistants and graduate students. To carry out the scientists' investigations requires that the spacecraft operate its instruments to make observations, and perform experiments under just the right conditions and at just the right time. To match the desired scientific investigations with exactly the right commands requires a good amount of information about the spacecraft and about the target planetary system. For example, exactly where will the spacecraft be at a particular time, and what will its orientation in space be? When, and in what direction, must it turn to capture a view of the targets of interest? How long must an instrument's shutter remain open to obtain the right exposure? What other settings will the instrument need?

Determining the path, or trajectory, of the spacecraft is the job of a team of navigators. They obtain their information from the intricate process of tracking the spacecraft, which we talked about in "Making Tracks." They determine where the spacecraft will be at any given time in relation to the objects to be studied.

Of course, to do that, they need to know where those objects are going to be. The predicted locations of solar system bodies, such as Jupiter, its ring, its moons and so on, are data known as ephemerides (singular, "ephemeris"). These are maintained by the worldwide astronomical community. The spacecraft navigators take the ephemerides and the spacecraft tracking data into account in their processes, using highly developed computer programs. After lots of number-crunching, they provide the predictions necessary for planning how and when the spacecraft will be able to make observations. These programs are also made to provide information on what the spacecraft must occasionally be commanded to do in order to make small adjustments in its trajectory (see "Propulsion Systems" in the March/April 1996 issue) so it will be exactly where it needs to be at the proper time.

More Details

OK, we know where everything is. And, from the ephemeris and trajectory information, we also know how things will be illuminated, so we know the answers to questions like these: How bright will the sunlight be as it shines on the planet or its moons? At what angle (called phase) will the sunlight be striking the objects from the spacecraft's point of view at a certain time? Exactly when, for example, will *Galileo* see the Sun set behind Jupiter's cloud tops? We also know what the spacecraft's attitude will be at any given time, based on the last sequence of commands sent to the spacecraft (see "Attitude Control" in the September/October 1995 issue). This is needed so the spacecraft can be commanded to point its instruments in the right direction and point the communications antenna toward Earth to beam these valuable bits of data down to the waiting scientists.

This is a huge amount of information that needs to be considered for planning operations. But wait, there's lots more! We need to consider many details about the spacecraft's onboard subsystems, too. How much power will be required to operate the desired instrument? Will that power be available at the required time, or will we first need to turn off something else? What other "consumables"—such as electrical power and propellant—will be affected? If we rotate the spacecraft, will we lose communication with Earth? If so, for how long? Can we afford to do without tracking data for that long at that point in time? When the spacecraft rotates, is there any danger of sunlight entering a sensitive instrument and causing damage? Exactly where in memory should the data from this observation be stored? Do we need to do any onboard "housekeeping"?

Of course, a lot of planning for the achievement of major goals is accomplished many years before launch, and has been incorporated into the spacecraft's design, the choice of launch vehicle, and the original design of the overall mission. But all the planning can't be done at once; it has to be an ongoing process.

The resources to be considered during planning include special opportunities for making observations, time available from the Deep Space Network tracking system (DSN), human workforce availability, spacecraft consumables and so on. It is not uncommon for the various scientific investigators to desire conflicting observations, nor is it uncommon for more than one spacecraft to desire conflicting use of the DSN's precious time—it tracks *Voyager 1, Voyager 2, Galileo,* Mars *Global Surveyor,* Mars *Pathfinder* and many others. Conflicts are resolved in high-level meetings with the principal people concerned.

Implementing the Plan

Once the planners have done their job, all the details of a plan of action for a given period are passed to another team, usually called a sequence team, that is responsible for creating the actual commands to be uplinked. This team relies on highly advanced computer programs to help with such tasks as selecting and time-tagging the proper commands, placing them in the correct order, checking that no operating constraints are violated and making sure that all of the instructions to the spacecraft will fit into the spacecraft's available computer memory. The commands produced for a particular time period are typically called a sequence.

The sequence is then passed to the team member who will actually send it to the spacecraft. The previous installment of this column ("Flying a Robotic Interplanetary Spaceship," November/December 1996) identified the "Ace" as that person. In addition to the sequence, there may be other commands, usually called real-time commands, the Ace needs to send. These are typically much shorter than sequences, and sometimes need to be sent on short notice, such as when scientists want to make quick adjustments to their instruments' states.

The Ace chooses or checks the proper time for transmitting the command loads and real-time commands to the spacecraft during an appropriate DSN tracking period. Next, the command data are formatted for transmission and sent electronically, using the ground communications facility (GCF), to the proper site in the DSN, where they are loaded onto disk in the remote command computer. The GCF uses a combination of communications satellites, conventional surface means and undersea cables to electronically link the remote DSN sites.

Ready to Go

At this point, the sequence of command data is finally ready to go to the spacecraft. The Ace makes sure the DSN's transmitter is on, radiating a carrier signal to the spacecraft. Then he or she manipulates the command computer under remote control from the Jet Propulsion Laboratory, causing the sequence to be modulated ("vocalized," if you will) onto the uplink; the commands begin their journey to the spacecraft, which may take hours. The spacecraft reports, via telemetry, the fact that each command in the sequence has been received and properly stored on board. Once the timed commands are in the spacecraft's memory, the onboard clock will cause each of them to be executed at the proper instant.

The Commanding Uplink Process

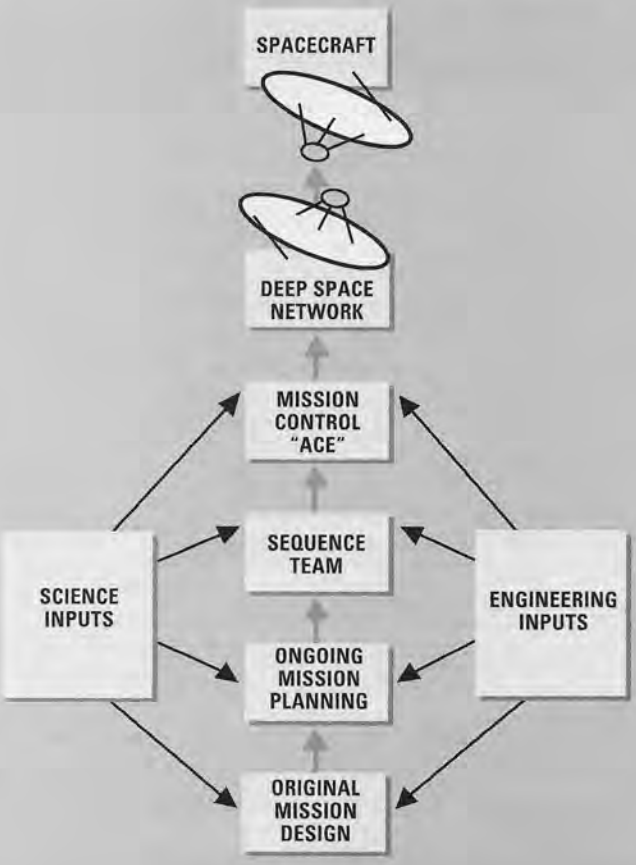

CHART BY DAVE DOODY; REDRAWN BY B.S. SMITH

The Ace, and others including spacecraft engineers and instrument scientists, will watch the downlink over the period of time covered by the command sequence, making sure all is going according to plan. That's where we'll start in the next installment, the downlink part of end-to-end data flow.

Dave Doody is a member of the Jet Propulsion Laboratory's Advanced Mission Operations Section and is currently working on the Cassini *mission to Saturn.*

If you have access to the World Wide Web
(via a Web browser like Netscape or Mosaic), be sure to
look in on JPL's *Basics of Space Flight* manual, on-line at
http://www.jpl.nasa.gov/basics/.

Questions and Answers

When we refer to listening for extraterrestrial signals, why do we always speak of a certain number of channels? Why can't we just sweep across the entire possible range of frequencies like a scanner? The sweep would have to be quite slow, of course, but it seems that it would be much simpler than having to provide all those discrete channels. Surely there would be time enough to notice any response if the scan were slow enough. It seems to me that when you look for distinct frequencies you might miss those that are in between.
—Louis H. Eisen,
Oceanside, California

Great question. We *could* build a scanner, but we wouldn't be happy, and here's why: Let's say we want to use a scanner to replace the Billion-channel Extraterrestrial Assay (Project BETA), which covers 250 million channels of 0.5 hertz each (125 megahertz in all). The scanner's single 0.5-hertz channel has to dwell for two seconds sequentially on each frequency (that's how long it takes to achieve that channel width), so the sweep through all 250 million channels would take 500 million seconds. That comes to about 16 years. And that's why we work so hard to achieve *simultaneous* multi-megachannel coverage.

In the case of BETA, it takes just two seconds to cover all those channels. (By the way, Frank Drake's pioneering Project Ozma did it your way—a single-channel receiver, patiently sweeping across the 360 kilohertz that Ozma observed in total during its two months of operation in 1960.)

Fortunately, a multichannel receiver doesn't have any "in between." The channel coverage is contiguous, with no cracks, and a good strong signal can't escape. Now all we need is the good strong signal!
—PAUL HOROWITZ,
Harvard University

What happened to Mars' ancient atmosphere?
—Colin Espiner, Essex, England

Most scientists who have thought about this problem would agree that during Mars' first billion years the atmosphere was much thicker than it is today. This argument is commonly based on the observation of dry riverbeds on the oldest martian terrain. At some point, water ran freely on the martian surface, but today the low atmospheric pressure precludes that possibility. There is still much uncertainty about how thick that early atmosphere was, how long it lasted and what happened to it. One thing almost everyone agrees on is the composition: The missing atmosphere was mostly made of carbon dioxide (CO_2) and nitrogen (N_2), probably in a ratio of about 40 to 1.

Some scientists believe that the CO_2 and N_2 dissolved in water and combined with the rocks on Mars to form carbonates and nitrates. This is similar to what happened to carbon dioxide on Earth, where we now have huge deposits of carbonate rocks such as limestone. If we could heat up these rocks to the point where they would decompose, we would find that Earth at one time had a dense, CO_2-dominated atmosphere with about 70 times the surface pressure we find today. (In fact, Earth would then have resembled Venus!)

Other scientists think that the early atmosphere of Mars has escaped from

The Billion-channel Extraterrestrial Assay (Project BETA) scans the skies for that alien radio signal that we speculate is out there. BETA's multichannel receiver provides coverage so seamless that a good, strong signal can't be missed.

Painting: Lisa Rosati

the planet. There are several processes that could lead to this result. The most effective would be impacts by asteroids. Calculations by Jay Melosh and Ann Vickery of the University of Arizona show that repeated impacts during those early days should have removed at least 100 times the present atmosphere. On a much smaller scale, atoms steadily escape into space from the upper atmosphere of Mars, at rates depending on their masses and the processes that energize them.

In fact, all of these effects must have occurred, so how can we decide which ones were most important? A vital clue to the history of the atmosphere is provided by the relative abundances of the isotopes of the gases that we can measure today. The isotopes of a given element have the same number of electrons, so their chemical properties are essentially the same. But additional neutrons change the mass of the nucleus, so physical processes such as velocity-dependent escape have different effects. The light isotope of hydrogen (ordinary hydrogen, which has one proton and no neutrons) has only half the mass of the heavy one (which has one proton and one neutron and is sometimes called deuterium), so it escapes more readily from Mars. Indeed, we find deuterium is about six times more abundant in water on Mars than in water on Earth, indicating that a large amount of hydrogen has escaped from Mars. We also find that the isotope of xenon with 129 atomic mass units (xenon 129) is 2.5 times as abundant on Mars as it is on Earth. But xenon cannot escape from Mars the way hydrogen does because it is too massive. Forming carbonates and nitrates will also not explain this difference.

The best explanation we have at present is that most of the early atmosphere of Mars with its normal xenon was blown off the planet by impacts, and this xenon 129 was subsequently enriched as a product of the decay of radioactive iodine 129. Of course, some carbonates must have formed too, and atoms are continually escaping into space even today, but it seems that impact erosion was the dominant process in diminishing the early martian atmosphere to its present state.

—TOBIAS OWEN,
University of Hawaii

If every time a comet approaches the Sun, the ice of the nucleus vaporizes, what happens to the comet when all that ice has gone? Is it still a comet or does it become an asteroid? Can we estimate how much time that ice will last, or how many approaches to the Sun it will resist before it's all gone?

—Pablo Cafiso,
Capital Federal, Argentina

These questions are on the frontiers of current comet research. The answers aren't well known. It is sometimes said that for many comets, given typical orbits and rates of vapor loss, the ice supply might last for something like 1,000 trips around the Sun. (The number could vary widely, depending on the orbit.)

What is left after the ice is used up? That depends on the amount of "dirt" (it is probably black, carbonaceous dust) in the comet, and the structure of the comet. The dirt is probably disseminated finely through the ice; this is what gives comets their black color. One important question is, how much dirt is left behind? Some of it flies off into the coma and tail as the ice sublimes into gas. If all of it flies off, a comet dissipates entirely. On the other hand, larger particles and concretions of dirt might be left behind, and might compact into a volatile-poor body that ends up looking like an asteroid. Such an "asteroid" might be a porous aggregation of black, carbonaceous material.

Another uncertain factor is the initial structure of the comet nucleus. If it is a strong, coherent body, it might follow one evolutionary track as the volatiles are used up; but if it is a loose aggregation it may "fall apart" into smaller and smaller pieces. This idea is favored by observations of comets spontaneously splitting into two, three or more fragments. It might again mean that not much is left by the time a comet has used up its ices.

A final answer may not emerge until we have close-up composition, density and structural information from five, ten or more comet/asteroid rendezvous and flyby missions.

—WILLIAM K. HARTMANN,
Planetary Science Institute and San Juan Institute

Factinos

The new planets detected within the last year probably had violent beginnings, mainly because they were born in solar systems with two or more massive planets the size of Jupiter, according to astrophysicists from the Massachusetts Institute of Technology (MIT).

"The properties of these new planets are completely different from those of the planets in our own solar system," said Frederic A. Rasio. What makes the new planets (all of which are Jupiter-sized themselves) different may be the result of instabilities that developed when they formed, propose Rasio and student Eric B. Ford. These instabilities, in turn, were caused by the planets' proximity to one or more other Jupiter-sized planets in their respective planetary systems.

"A system like our solar system, which has one dominant massive planet (Jupiter) and is very stable over long timescales (several billions of years) may be very rare," said Rasio.
—from MIT

Although Jupiter is more than twice as massive as all the other planets in our solar system combined, it's still too small to pass muster as a star. However, a new study suggests that Jupiter's atmosphere is just as turbulent and stormy as that of a bona fide star.

With the help of a Hubble Space Telescope spectrograph, researchers have deduced that hydrogen atoms in the giant planet's upper atmosphere are moving at supersonic speeds. Moreover, their velocities fluctuate wildly on a timescale of less than 10 minutes, note Claude Emerich of the Institute of Spatial Astrophysics in Paris, John T. Clarke of the University of Michigan and their colleagues. The team reported its findings in the August 23, 1996 issue of *Science.*
—from *Science News*

If you were standing on the surface of Mars at night and looked up, would you see any "shooting stars"? The answer, according to recent work by Lars Adolfsson and Bo Gustafson of the University of Florida and Carl Murray of Queen Mary and Westfield College in London, is an emphatic yes. The researchers have shown that even though Mars' atmosphere is much thinner than Earth's, it's still dense enough at high altitudes to cause incoming dust particles from space to burn up, thereby producing meteors or "shooting stars." These trails of light would be visible from the martian surface, and by measuring their location in the night sky scientists would have new insights into the sources and distribution of dust in the solar system.

The group used computer simulations of the flight of a variety of dust particles to show that Mars' atmosphere is sufficiently dense where it matters—at altitudes of about 100 kilometers (62 miles)—to cause the incoming dust to burn up.
—from the Royal Astronomical Society

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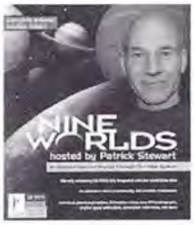

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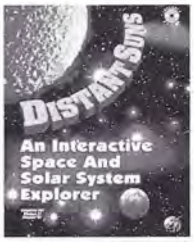

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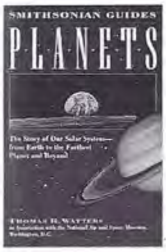

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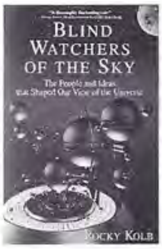

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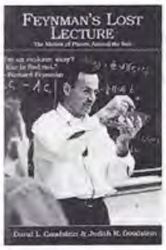

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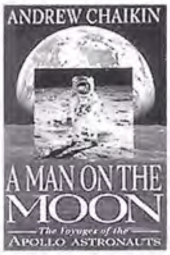

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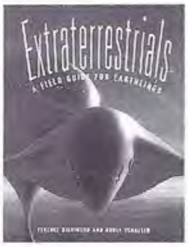

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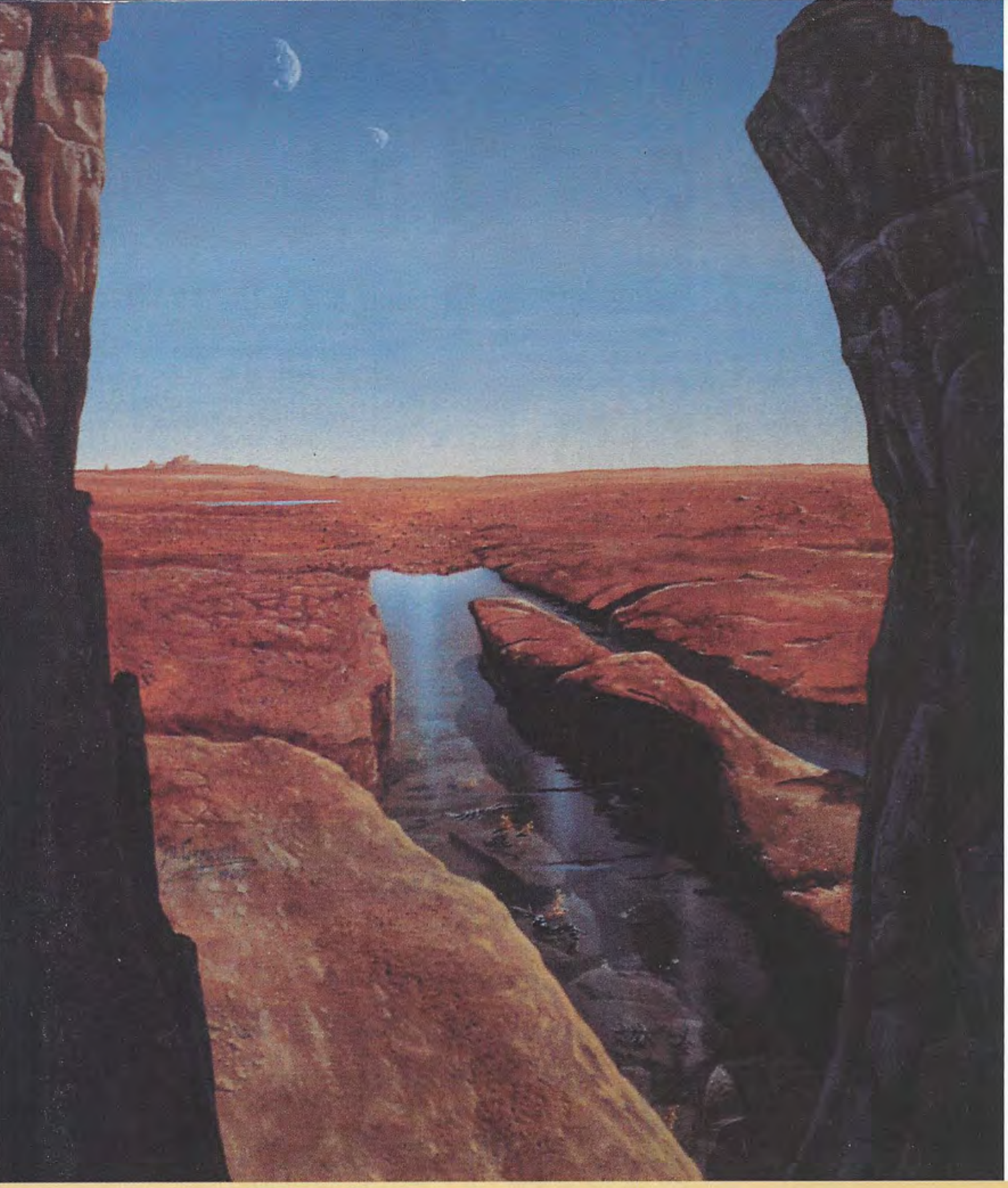

The Mars we know today is a barren, freeze-dried world. But thanks to the vast amount of data returned by the *Mariner* and *Viking* probes, scientists now realize that our ruddy neighbor once had an atmosphere as well as rivers and seas of liquid water. Did those conditions also give rise to primitive life? The answer may lie inside a single rock. "The Last Oasis," by Michael Carroll, depicts the beginning of the end of those temperate times.

Michael Carroll is working on a book for young people about Jupiter and its moons, due out in 1997 from John Muir Publishing. One of Michael's paintings of Mars is probably soaking in the Pacific Ocean somewhere between Easter Island and Chile, sunk with the *Visions of Mars* CD-ROM on the *Mars '96* spacecraft.

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