The Case for Ancient Life on Mars

By Andrew J. LePage

Science Fiction Meets Fact

The H.G. Wells science fiction classic, *War of the Worlds,* begins with a large meteorite from Mars crashing to Earth with a cargo of mysterious technologically advanced beings bent on the conquest of the Earth. On August 7, 1996, scientists from a joint NASA/Stanford University collaboration publicly presented the results of their two-year analysis of a bona fide meteorite from Mars that ironically echoed this piece of fiction (1).

Instead of discovering the Hollywood version of evil sentient beings from Mars, the scientists found traces of minerals, organic chemicals, and submicroscopic structures that could lead to evidence of very modest single-cell life forms that existed on Mars 3.6 billion years ago. The data presented were eerily similar to evidence commonly found in similarly aged Terran rocks that scientists use to demonstrate the existence of life on this planet in that distant epoch.

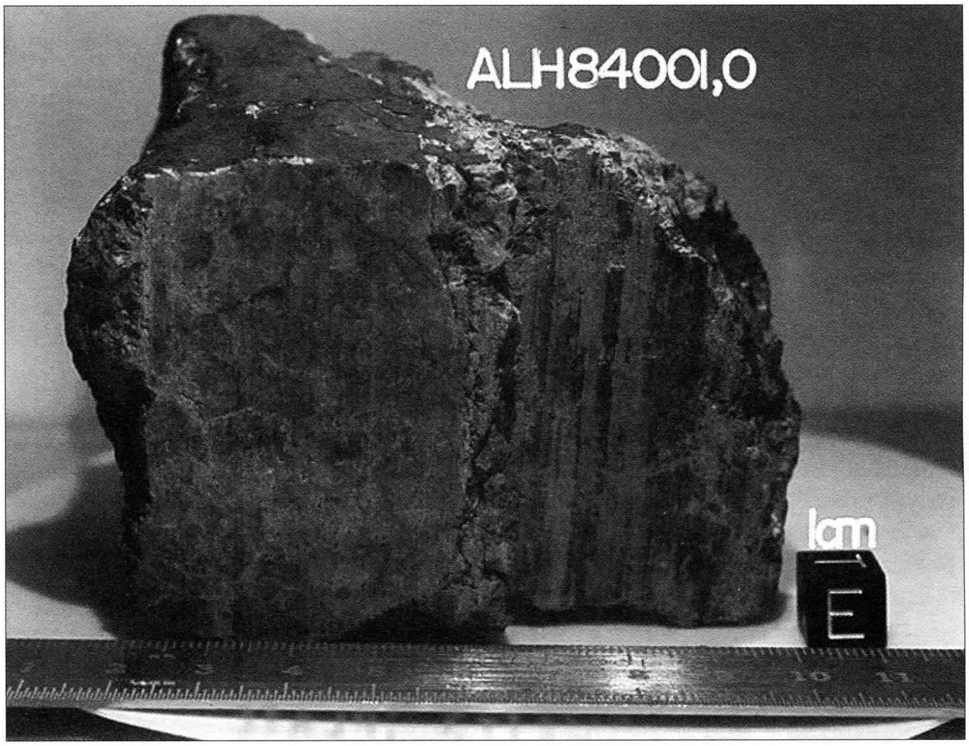

Figure 1: *This photograph documents the appearance of ALH84001 as it was being cataloged. The black fusion crust visible on the exterior was produced during the meteorite's entry into the Earth's atmosphere 13,000 years ago. (All photographs courtesy of NASA).*

Although all the evidence to date could be explained by a complicated series of inorganic geochemical processes, the investigation leaves open the possibility that life independently arose on a second planet in our supposedly average solar system. If true, there are immense implications of how commonplace life might be on other extraterrestrial bodies such as the Jovian moon Europa or on the estimated tens to hundreds of billions of other potentially habitable worlds scattered throughout our galaxy. Today we could finally be standing on the threshold of turning biology from the study of the results of a single biological genesis into a study of the immense range of life forms with independent origins.

The Meteorite

The rather average looking 1.9 kilogram rock that started the recent furor is cataloged as simply ALH84001. The prefix "ALH" denotes that it was found in the Allan Hills of Antarctica while the number "84001" indicates that it was the first specimen gathered in the 1984 expedition there. Using a variety of analysis techniques, scientists composed a rough sketch of the history of this piece of Mars: ALH84001 is an igneous orthopyroxenite primarily composed of coarse grained orthopyroxene with minor traces of other minerals including maskelynite, olivine, chromite, pyrite, and apatite (2, 3, 4). According to measurements of various radioactive isotopes and their daughter products, it is estimated that the rock slowly crystallized from a molten mass 4.5 billion years ago (3). If true, this rock represents the oldest piece of any planetary crust yet known. It records the conditions on Mars only 100 million years after its formation and as it was beginning the process of segregating its structure into a core, mantle, and crust. The heavy nature of its minerals, which would normally be expected to be found far below the surface, hints that ALH84001 formed deep inside Mars.

Somehow this piece of ancient Martian crust survived the eons of geologic change to come, including the formation of a mature Martian crust composed of the lighter minerals typically found in planetary crusts today. About 4.0 billion years ago, ALH84001 experienced the first of two major, closely spaced shocks, probably as part of the final bombardment all bodies in the early inner solar system experienced (5). The crater-saturated highlands of the Moon record this final event in the planet formation process. As a result of these cratering events, fractures were created in ALH84001. About 3.6 billion years ago, small carbonate globules formed in these fractures as fluids flowed through them (6). The origin of these carbonates is central to the debate presently swirling around the meteorite.

According to measurements of cosmic ray exposure, the progenitor of ALH84001 was ejected from the surface of Mars due to an impact about 15 million years ago (7). After escaping the gravitational influence of Mars, ALH84001 entered an independent solar orbit. Some 13,000 years ago, its constantly evolving and unstable orbit intersected with the Earth and ALH84001 tumbled down in Antarctica during the closing days of the last Ice Age (8). Although this is a highly unlikely series of events, eleven other meteorites are believed to have been ejected from Mars as a result of at least two other cratering events and eventually landed on Earth. This class of meteorite, named after the location where the first three examples were found, is known as Shergotty-Nakhla-Chassigny or SNC meteorites.

In 1984, ALH84001 was found on a glacier in the Allan Hills of Antarctica. For years, scientists scoured such sites during the brief austral summer in search of meteorites of every kind. Meteorites that land on glaciers in Antarctica are carried along by the slowly moving ice, which also helps to protect them from weathering and other deleterious effects of terrestrial exposure. Certain parts of some glaciers erode as quickly as they can be replenished with fresh glacial ice from further upstream. In such locations, meteorites that fell onto the glacier become concentrated on the surface were they can be easily spotted by passing search teams. Such sweeps give scientists the most representative cross section of all the types of meteorites that fall onto the Earth's surface. After it was collected, ALH84001 was shipped to Johnson Space Center for study.

Is Meteorite ALH84001 from Mars?

When ALH84001 was first examined, it was mistakenly identified as a diogenite. Along with the related eucrites and howardites, diogenites are believed to be pieces of the mantle of the asteroid 4 Vesta. For a decade to come, analyses and studies of ALH84001 were generally considered to be in keeping with its misclassification (9,10). However, in 1993, Lockheed Engineering and Sciences Company's David W. Mittlefehldt analyzed a thin section of ALH84001 and discovered that the details of its chemical makeup were inconsistent with its classification as a diogenite. For instance, the iron oxides in this meteorite had an abundance of triply ionized iron. Diogenites normally contain only doubly ionized iron. Mittlefehldt also discovered that the composition of many of the minerals in ALH84001 were instead similar to that previously found SNCs (2). The presence of sulfides, carbonates, and an abundance of other carbon compounds along with the isotopic composition of its trace elements and trapped gases and water all pointed to a strong connection with SNCs which are generally believed to come from Mars (11, 12, 13).

The connection of ALH84001 with the previously found SNCs is fairly well established, but how do we know SNCs really originate on Mars? In reality there is no definitive "proof" that SNCs are from Mars. Only the detailed analysis of an actual sample of Martian rock could firmly establish this theory. This is possible because every planetary body has a unique elemental and isotopic fingerprint that can be found in its rocks. For example, a total of 15 meteorites are currently identified as being from the Moon because their isotope patterns match those of samples previously returned from the Moon and not those of any other source of meteorites. Detailed analysis of the SNCs show that they possess an elemental and isotopic signature that is unique among all other types of meteorites, as well as rocks known to be from the Earth or Moon.

It is through the process of elimination that the source of the SNCs has been linked to Mars. First the ages of all previously discovered SNCs range from as old as 1.3 billion years to a geologically young 180 million years (14). Since even large asteroids could maintain their geologic activity only to about four billion years ago due to their limited stores of heat producing radioactive elements, the source of SNCs must be a larger planetary body. In addition, the segregation of minerals in some SNCs hints that they formed in a relatively high gravity environment again indicating that a planetary body is the source (14). These facts leave only Mercury, Venus, and Mars as potential sources. Based on our knowledge of the geology of these planets gleaned from closeup photography and radar mapping, Mars and Venus are more likely sources because they are known to have been geologically active during the period in question.

Figure 2: *A visible light photograph of some of the orange colored carbonate deposits. Note the sharp alternating black and white rims that have been shown to be rich in magnetite and iron sulfide minerals.*

Other forms of analysis have been used to build a case that Mars is the *likely* source of the SNCs. Simulations of the orbits of debris ejected from planetary surfaces show that it is possible for meteorites to come from any of the inner planets (15). These simulations indicate however that all else being equal, the vast majority of meteorites from the inner planets will be from Mars. The simulations predict, for example, that for every one meteorite from Mercury, there should be fifteen from Mars. Because of its higher gravity and dense atmosphere, ejected debris is much less likely to escape Venus, much less make it to Earth as a meteorite.

Still this is just a circumstantial connection between SNCs and Mars. Nature left a fingerprint that we can connect to Mars with currently available data. During the shock event that ejected some SNCs, small amounts of atmospheric gases were trapped in small globs of glass that formed in the SNC during impact. Fortunately, some information exists on the elemental and isotopic composition of the atmospheres of Venus and Mars because of direct mass spectrometer measurements made by numerous American and Soviet Venus probes and by the Viking landers on Mars. A comparison of the isotopic makeup of the carbon dioxide, nitrogen, and noble gases trapped in the SNC with these in situ measurements indicates that Mars is the most likely source of this distinctive group of meteorites (16, 17, 18, 19).

With the association of ALH84001 to other Martian meteorites established, detailed analysis of this unique find began in earnest. Although it is chemically more closely related to other SNCs than any other class of meteorite or terrestrial rock, it immediately began to standout as special even among this small family of meteorites. Its estimated age of 4.5 billion years is much older than any other identified SNC. ALH84001 also contained a higher concentration of carbonates than its younger siblings and there were indications that water was involved in its deposition (2, 3). Early studies also pointed out concentrations of polycyclic aromatic hydrocarbons (PAHs) that were associated with the carbonates (1). These multi-ring organic compounds were the first nontrivial traces of organic material known to be of Martian origin.

These and other findings all hinted at interesting hydrological and geochemical processes that could give some sense of the conditions on Mars during its early history when water likely flowed on its surface and conditions were more favorable for life.

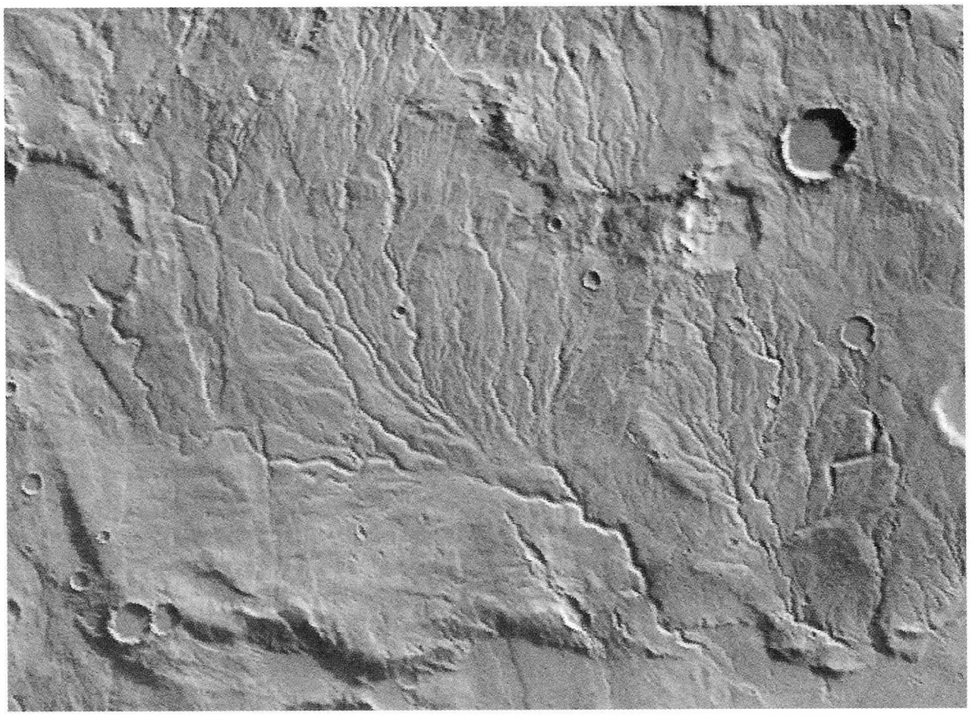

Figure 3: *Mars was a much wetter and milder planet 3.6 billion years ago when the carbonates in ALH84001 were formed. Pictured here are a network of channels cut by running water that were produced during the same epoch as the carbonates in ALH84001. Before the recent discovery of possible Martian fossils, planetary scientist had hoped to search for fossils in the sedimentary deposits made by ancient channels such as these.*

Progressively more detailed studies using the best cutting edge technology were performed to tease the secrets from within ALH84001. Although at first the investigators were hoping to determine prebiotic conditions on Mars during its early history, the deeper that scientists looked into the samples, the more intriguing and controversial their findings became. Eventually the team of scientists lead by NASA exobiologist David S. McKay came to the startling realization that a biological explanation for all of their findings was possible.

The Composition of Carbonates

Early analysis of ALH84001 showed that it had a higher concentration of carbonate minerals than any other SNC (2). These minerals are found in fractures in the meteorite and come in the form of discoid shaped globules between 1 and 250 microns across. The minerals appear orange when viewed in visible light and many display sharp alternating black and white rims. Chemical analysis shows that the dominant carbonate in the core is calcium carbonate with important traces of manganese. The larger carbonate globules displayed broad alternating bands rich in iron or magnesium and devoid of manganese that range in composition from ferroan magnesite to pure magnesite (1). While complicated geochemical processes can form such carbonate deposits, biogenic processes frequently produce carbonates with the observed banding of carbonate types here on Earth.

Petrographic studies indicated that these carbonates formed at temperatures around 700 C (2, 20). Measurements of the ratios of stable isotopes of oxygen, which can be used to gauge the temperatures of chemical reactions, instead show that the carbonates formed in an aqueous environment at more moderate temperatures between 0 C and 80 C (21). The source of the carbonate is thought to be atmospheric carbon dioxide dissolved in water percolating through the rock. The ratio of stable carbon isotopes displays a greater range of variability than the carbonates in any other SNC or in inorganically formed terrestrial carbonates. On Earth, only biogenic activity is known to produce carbonates that show such discordant and varying carbon and oxygen isotopic patterns.

The possibility that these carbonate minerals formed after ALH84001 fell in Antarctica can be effectively ruled out. The isotopic composition of the carbonates studied is totally different than any carbonates that are known to form in meteorites due to terrestrial weathering (8). This finding, as well as the fact that some of the carbonates show signs of shock faulting that occurred either on Mars or in space, strongly suggests that the carbonates are indigenous to ALH84001 (2, 8).

A detailed examination of the thin black and white rims surrounding the larger carbonate inclusions yielded some more interesting findings. These rims were rich in magnetite with minor amounts of the iron sulfide mineral pyrrhotite (1). The magnetite grains examined are perfect single domain crystals 10 to 100 nanometers long that do not contain any detectable trace elements. The pyrrhotite crystals display a variety of sizes and shapes and showed no trace of oxygen. In the core of the carbonate globules, there exist porous regions where the surrounding carbonate matrix seems to be partially dissolved. These areas are also rich in the magnetite as well as the iron sulfide mineral greigite (1).

All of these minerals are known to form by either inorganic or biogenic processes. Simultaneous precipitation of magnetite and pyrrhotite is known to occur only under alkaline conditions. The partial dissolution of the carbonate matrix surrounding these minerals points to acidic formation conditions instead. While a complicated series of geochemical processes could be invented to explain the apparent paradox, the chemical disequilibrium resulting from biogenic processes could also produce the same effects. In addition, the magnetite crystals found in the carbonates are chemically, structurally and morphologically similar to terrestrial magnetofossils (1). These are the fossil remains of bacterial magnetosomes. Some of the magnetite crystals also resemble extracellular superparamagnetic percipitants produced by the growth of some strains of anaerobic terrestrial bacteria. While all this data is not proof of a biological origin of the carbonates, the evidence to date is consistent with, and does not exclude, a biological origin.

Additional analysis will be performed to determine if there are any other biological fingerprints left in ALH84001. Examination of the sulfur isotopes by a team of scientists located at the University of New Mexico revealed no signs of the type of signature left by some terrestrial life forms (22). While this is disappointing, it is not fatal to the biological interpretation for the origin of the carbonates. Carbonates from the other SNCs, meteorites, and a variety of terrestrial sources will probably be examined in more detail to help shed light on the origin of the carbonates formed in ALH84001.

A Good Case of the PAHs

Another major find in ALH84001 was its relatively high concentration of PAHs. PAHs are found throughout ALH84001 and seem to be most concentrated near the previously described carbonates (1). This family of large organic molecules can be produced by many biological or inorganic processes and are found in a variety of places including some classes of primitive meteorites, in fossil fuels and their combustion products. ALH84001 contains higher concentrations of PAHs than any other SNC. Measurements made by the gas chromatograph on the two Viking landers showed no traces of organic molecules on the Martian surface (23). The PAHs in ALH84001 are the first nontrivial traces of organic compounds known to come from Mars.

A variety of tests seem to indicate that the PAHs are indigenous to the meteorite and are not the result of terrestrial contamination. The concentration of the PAHs was measured at various depths into the meteorite from its fusion crust (1). The fusion crust forms as the outer portions of a meteorite melt due to the heating caused by friction with the atmosphere during its descent to Earth. Any PAHs present here would be destroyed by the heating event that produced the fusion crust. In the outer 0.5 millimeter of the meteorite, PAHs are almost totally absent but the concentration of PAHs climbs to the parts-per-million level in the interior, especially along the fractures in the meteorite. If the PAHs originated from a simple terrestrial contamination process, their concentration would display the opposite pattern with the concentration being greatest near the exterior.

A detailed examination of the mass spectrum of these compounds shows a complex pattern with several distinct peaks at 178, 202, 228, 252, and 278 atomic mass units. These peaks are believed to be caused by the presence of phenanthrene, pyrene, chrysene, perylene (or possibly benzopyrene), and anthanthracene (1). These PAHs are the byproduct of the breakup of larger parent molecules. The parent skeletons for these PAHs are believed to possess alkylated side chains with varying degrees of hydrogenation.

The mass spectrum of these PAHs is totally different from that produced by man-made pollution. Common anthropogenic PAHs, such as dibenzothiophene, display a higher degree of alkylation and have abundant aromatic heterocycles. Such PAHs, which would normally be present only in the ten parts per trillion to parts per billion level in Antarctic ice, are not seen in ALH84001 (1). Tests performed on other meteorites in the same laboratory showed that the labs were sterile and probably could not have contaminated ALH84001 during analysis.

Because the PAHs are indigenous to ALH84001 does not necessarily imply they have a biological origin. Some classes of carbonaceous chondrites possess PAHs that are obviously produced abiotically. The mass spectrum of the PAHs in ALH84001 is much more complex and displays a completely different pattern than that seen in other PAH-rich meteorites (1). This hints that the PAHs in ALH84001 have a much different origin than the

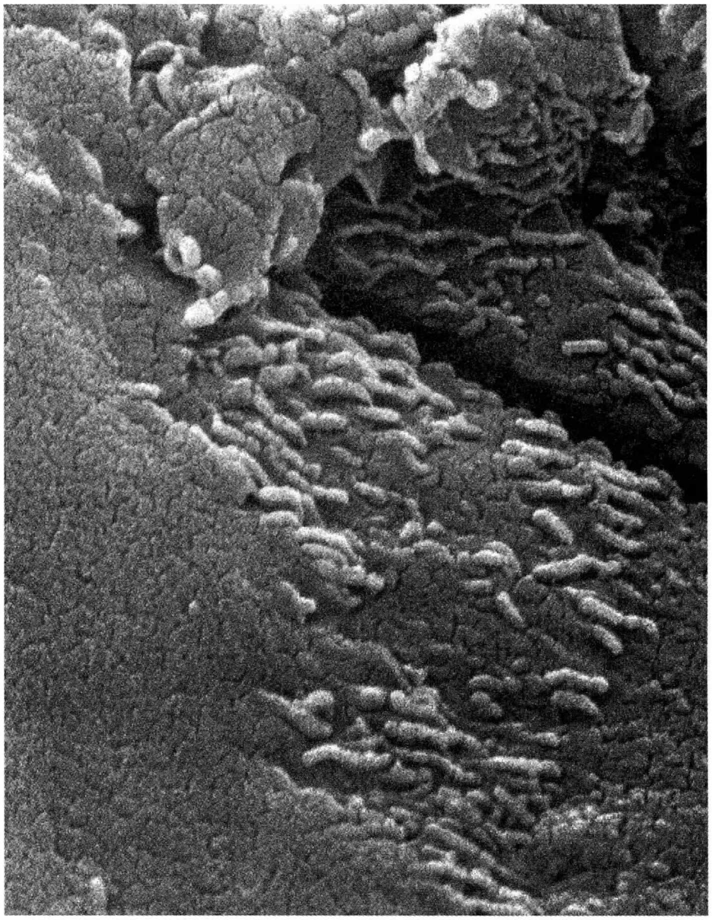

Figure 4: *This is a recent electron microscope image of a cluster of the alleged Martian microfossils found in the porous regions of the carbonate globules. Except for their small size, they look remarkably similar to microfossils found in terrestrial biogenic carbonate deposits. Further analysis will be needed to prove that these structures are actually the fossils of Martian nanoorganisms.*

abiotic PAHs found in other meteorites. While the mass spectrum of terrestrial PAHs known to be of biological origin is much more complex still, the mixture of PAHs associated with the carbonates in ALH84001 which, as discussed earlier, *could* be the result of a biogenic process hints at a biological origin for these organic compounds also. Follow up investigations will examine the isotopic composition of the PAHs to see if it is similar to typical Martian carbon isotope ratios. Tests will also be performed to find traces of other biologically important compounds such as amino acids.

Microfossils or Something Else?

By far the most controversial and visually striking evidence presented to date are textured patches on the carbonate consisting of small structures that resemble terrestrial microfossils (1). These structures are found in the same porous areas where the magnetite and iron sulfide minerals are found. They range in shape from ovoids to elongated rods. In addition, these alleged microfossils are in the same 10 to 100 nanometer size range as the magnetite crystals again hinting at a possible connection. A variety of tests with other meteorites displaying a wide range of states of terrestrial weathering as well as lunar samples prepared and analyzed under similar conditions showed no hint of similar structures. This seems to eliminate the possibility that these structures are caused by laboratory processing or other forms of terrestrial contamination.

A conclusion could be reached that these structures are the result of how the carbonates crystallized, but they seem to lack crystal growth faces. Experience with terrestrial samples, however, indicates that such structures are common in biogenic carbonates. One problem with the interpretation of these structures as the remains of nanoorganisms is the size of these putative fossils. They are 100 times smaller than comparable terrestrial fossils. While they are similar in size to terrestrial nanobacteria, they do press the lower size limit for what biologist would consider living organisms.

Among the most important follow-up investigations will be to study these structures much more closely. Searches may turn up fossils of life forms caught in the midst of reproducing. Investigators would also like to slice open one of these putative fossils to see what if any internal structures were preserved. Scientists need to determine the composition of the structures and see what if any organic molecules are associated with them. The unimaginably tiny size of these fossils will definitely push the limits of analysis techniques that are available through current technology.

The Potential Impact

The scientists involved with this investigation continually stress the point that their findings thus far do not prove the existence of life on Mars over three billion years ago. As has been stated many times before in science, extraordinary claims require extraordinary evidence. Years of additional research will be required to either prove or disprove the biological interpretation of the finds to date. A Martian sample return mission would be of considerable help in determining the origin of the carbonates and other compounds.

Before the announcement of these findings, NASA plans called for a series of simple robotic missions to Mars launched at each biennial launch window. Along with complimentary Russian, Japanese, and proposed European missions, the NASA missions would survey Mars in a systematic fashion from orbit and the surface. Plans call for a sample return mission possibly around 2005. With the excitement generated by this find, additional funding for NASA missions to Mars will hopefully be made available to accelerate this time table. NASA administrator Daniel S. Goldin has stressed that they will continue to proceed in a conservative measured fashion so that the most return on investment can be made of a sample return mission. While there have been some who have claimed that a sample return mission could be launched as early as 1998, realistically such a mission will likely be launched no earlier than about 2003.

If further studies continue to support the biological interpretation of these finds, it will have a profound influence on the search for life elsewhere in the universe. It may be possible that Martian life forms have retreated below the currently hostile surface. Such subterranean microorganisms are found on Earth, and it may be revealed that Mars might possess similar oases (24). Even if life on Mars became extinct long ago, the fact that it arose at all as well as on the Earth indicates that the origin of simple life forms is inevitable on planets in or near a star's habitable zone. This means that the galaxy could potentially harbor planets where at very least simple life has evolved.

Given that the putative Martian nanoorganisms are similar in appearance and produce many of the same chemical and mineral byproducts that terrestrial organisms are known to produce, it seems likely that any Martian biology and possibly the biology of other worlds would have many similarities to our own. The meteorite raises many questions, including the profound question: Is there a remote possibility that the Earth was seeded with life from Mars billions of years ago in a process similar to that which brought ALH84001 and the other SNCs to Earth? Echoing Ray Bradbury's *Martian Chronicles*, could *we* be Martians after all?

Finally, this meteorite, along with the long-awaited discovery of extrasolar planets, has given a boost to SETI in general. While much disagreement still persists among scientists as to the likelihood of extraterrestrial intelligence, all would agree that the more ubiquitous simple life forms are and the more planets they can inhabit, the more likely we are to find ETI. With the public and scientific awareness generated by all these discoveries, it seems quite likely that astronomy, the search for habitable planets, and SETI in particular will enjoy a surge in interest and funding in the coming years.

REFERENCES

1) David S. McKay, Everett K. Gibson Jr., Kathie L. Thomas-Keprta, Hojatollah Vali, Christopher S. Romanek, Simon J. Clemett, Xavier D.F. Chillier, Claude R. Maechling, and Richard N. Zare, "Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001," ***Science,*** Vol. 273, No. 5277, pp. 924-930, August 16, 1996

2) D.W. Mittlefehldt, "ALH84001, A Cumulate Orthopyroxenite Member of the Martian Meteorite Clan," ***Meteoritics,*** Vol. 29, No. 2, pp. 214-221, 1994

3) G. Dreibus, A. Burghele, K.P. Jochum, B. Spettel, F. Wlotzka, and H. Wanke, "Chemical and Mineral Composition of ALH84001: A Martian Orthopyroxenite," ***Meteoritics,*** Vol. 29, No. 4, p. 461, 1994

4) E. Jagoutz, A. Sorowka, J.D. Vogel, and H. Wanke, "ALH84001: Alien or Progenitor of the SNC Family?", ***Meteoritics,*** Vol. 29, No. 4, pp. 478-479, 1994

5) R.D. Ash, S.F. Knott and G. Turner, "A 4-Gyr Shock Age for a Martian Meteorite and Implications for the Cratering History of Mars," ***Nature,*** Vol. 380, pp. 57-59, March 7, 1996

6) S.K. Knott, R.D. Ash, and G. Turner, ***Lunar and Planetary Science,*** Vol. 26, p. 765, 1995

7) O. Eugster, "Orthopyroxenite ALH84001: Ejection from Mars 15 Ma," ***Meteoritics,*** Vol. 29, No. 4, p. 464

8) James L. Gooding, "Soil Minerology and Chemistry on Mars: Possible Clues from Salts and Clays in SNC Meteorites," ***Icarus,*** Vol. 99, No. 1, pp. 28-41, 1992

9) Richars O. Sack, William J. Azeredo, and Michael E. Lipschuts, "Olivine Diogenites - The Mantle of the Eucrite Parent Body," ***Geochimica et Cosmochimica Acta,*** Vol. 55, pp. 1111-1120, April 1991

10) G.W. Fowler, J.J. Papike, M.N. Spilde, and C.K. Shearer, "Orthopyroxenes as Recorders of Diogenite Petrogenesis: Al-Cr-Ti Systematics," ***Meteoritics,*** Vol. 28, No. 3, p. 350, 1993

11) T.D. Swindle, M.K. Burkland, and J.A. Grier, "Noble Gases in ALH84001: Not Just Another SNC," ***Meteoritics,*** Vol. 29, No. 4, p. 538, 1994

12) M. Wadhwa and G. Crozaz, "First Evidence for Infiltration Metasomastism in a Martian Meteorite, ALH84001," ***Meteoritics,*** Vol. 29, No. 4, p. 545

13) L.L. Watson, S. Epstein, and E.M. Stolper, "D/H of Water Released by Stepped Heating of Shergotty, Zagami, Chassigny, ALH84001, and Nakhla," ***Meteoritics,*** Vol. 29, No. 4, p. 547, 1994

14) Harry Y. McSween, Jr., "SNC Meteorites: Clues to Martian Petrologic Evolution?," ***Reviews of Geophysics,*** Vol. 23, No. 4, pp. 391-416, November 1985 (and references therein)

15) Brett J. Gladman, Joseph A. Burns, Martin Duncan, Pascal Lee, and Harold F. Levinson, "The Exchange of Impact Ejecta Between Terrestrial Planets," ***Science,*** Vol. 271, No. 5254, pp.1387-1392, March 8, 1996

16) D.D. Bogard and P. Johnson, "Martian Gases in a Antartic Meteorite?," ***Science,*** Vol. 221, pp. 651-654, August 12, 1983

17) R.H. Carr, M.M. Grady, I.P. Wright, and C.T. Pillinger, "Martian Atmospheric Carbon Dioxide and Weathering Products in SNC Meteorites," ***Nature,*** Vol. 314, pp.248-250, March 21, 1985

18) R.O. Pepin, "Evidence of Martian Origins," ***Nature,*** Vol. 317, pp. 473-475, October 10, 1985

19) K. Marti, J.S. Kim, A.N. Thakur, T.J. McCoy, and K. Keil, "Signatures of the Martian Atmosphere in Glass of the Zagami Meteorite," ***Science,*** Vol. 267, No. 5206, pp.1981-1984, March 31, 1995

20) Ralph P. Harvey and Harry Y. McSween, Jr., "A Possible High-Temperature Origin for the Carbonates in the Martian Meteorite ALH84001," ***Nature,*** Vol. 382, pp. 49-51, July 4, 1996

21) C.S. Romanek, M.M. Grady, I.P. Wright, D.W. Mittlefehldt, R.A. Socki, C.T. Pillinger, and E.K. Gibson, "Record of Fluid-Rock Interactions on Mars from the Meteorite ALH84001," ***Nature,*** Vol. 372, pp. 655-657, December 15, 1994

22) John Fleck, "Similar UNM Meteorite Study Found No Evidence of Mars Life," ***Albuquerque Journal,*** August 8, 1996

23) K. Biemann, J. Oro, P. Toulmin III, L.E. Orgel, A.O. Nier, D.M. Anderson, P.G. Simmonds, D. Flory, A.V. Diaz, D.R. Rushnek, J.E. Biller, and A.L. Lafleur, "The Search for Organic Substances and Inorganic Volatile Compounds in the Surface of Mars," ***Journal of Geophysical Research,*** Vol. 82, No. 28, pp. 4641-4658, September 30, 1977

24) James K. Fredrickson and Tullis C. Onstott, "Microbes Seep Inside the Earth," ***Scientific American,*** Vol. 275, No. 4, pp. 68-73, October 1996