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Extraterrestrial life: **Life on Mars – then and now**

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The recent claim to have discovered evidence of extraterrestrial life on a meteorite from Mars is not compelling, but the study nevertheless has useful heuristic value.

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The recent claim to have identified possible signs of ancient life on Mars [1] has been widely publicized and discussed. The authors conceded that none of the half-dozen pieces of evidence adduced in their paper individually provided strong support for extraterrestrial life, though they argued that the pieces added up to a case worth considering. Most — perhaps all — of the observed phenomena have counterparts in the inorganic world, so even the combination does not make a compelling case that there was ever life on Mars. Nevertheless, the importance of the problem has justified bringing the results to general attention. The paper has focussed interest on the origin and possible ubiquity of life, and on how we can design techniques capable of giving a more definitive answer to the question of whether there is, or has ever been, life elsewhere in the Universe.

Historical roots

With the breakthrough of the heliocentric concept of the solar system, philosophical correctness mandated the acceptance, given the assumption of an orderly creation, that extraterrestrial life forms must exist. Consequently, it was taken for granted by orthodox 19th century philosophers, including Immanuel Kant, that beings of some kind must exist on all planets. Astronomers, such as Schiaparelli and later Lowell, selected Mars for astronomical verification of extraterrestrial life because of its relative closeness and transparent atmosphere. From observations of Mars, they inferred the presence of polar ice caps, seasonal changes in the planet's albedo that they attributed to plant growth, and the existence of linear structures, *canale*, that were thought to be the work of intelligent beings.

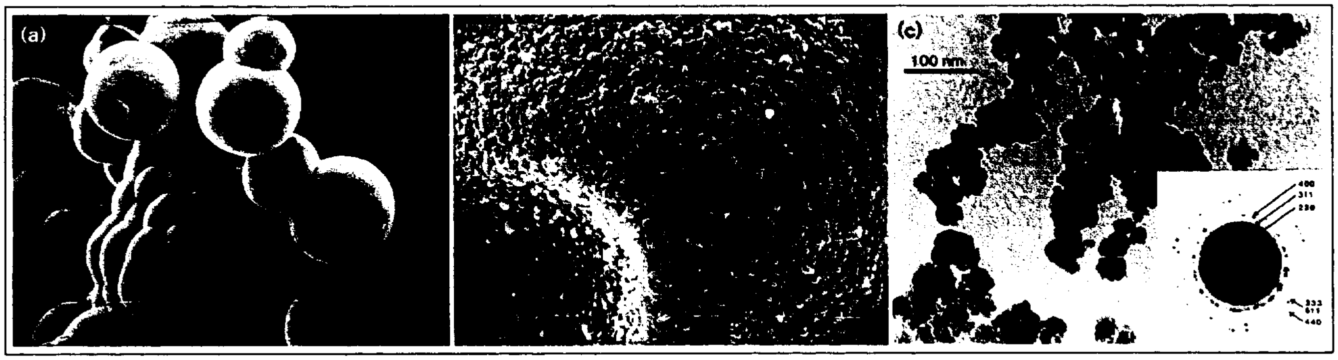
In the latter part of the 19th century, the notion of extraterrestrial life, or exobiology, was discussed as an extension of the laws of thermodynamics. An authoritative opinion was expressed by Sir William Thompson (later Lord Kelvin), who in his presidential address to the British Association in Edinburgh in 1871, stated: "because we all confidently believe that there are at present, and have been from time immemorial, many worlds of life besides our own, we must regard it as probable in the highest degree that there are countless seed bearing meteoritic stones moving about through space." It would be another century or so, however, before it would become possible to test this confident belief.

Missions and meteorites

Besides Earth, the only inner-solar system body with thermal and atmospheric conditions capable of harboring life — at least in the past when it was likely to have had a more substantial atmosphere — is Mars, the surface of which appears to have been marked by ancient flowing water. One of the early targets of United States and Soviet space efforts was exploration of the martian surface and the search for life there. The instrumentation of the first successful martian landings, during the Viking mission in 1976, was particularly designed for *in situ* experiments aimed at checking the martian soil for the presence of organic matter and of life. The outcome of these experiments was ambiguous, and it became clear that, to find remnant water and organic compounds of biological or nonbiological origin, it would be necessary to search below the ultraviolet-irradiated surface. Such experiments consequently play a central role in the future Mars missions planned by the United States and Russian space agencies.

Meanwhile, straying asteroids and comets have proved Lord Kelvin's prediction that "when two great masses come into collision in space, it is certain that a large part of each is melted, but it seems also quite certain that in many cases a large quantity of debris must be shot forth in all directions, much of which have experienced no greater violence than individual pieces of rock experience in a landslip or in blasting by gun powder." Nondestructive escape of such debris is more likely if the gravitational field is relatively low, as is true of Mars. In the 1960s, it was realized that three meteorites, Shergotty, Nakhla and Chassigny, had unusual petrological features and solidification ages, defining the 'SNC' type of meteorite; they were suspected to derive from other planets, most likely Mars because of its vicinity and the likelihood of Earth intersecting their orbits and capturing them. The Viking mission revealed that, compared with Earth, the Mars atmosphere is strongly enriched in ^{15}N relative to the lighter isotope ^{14}N, which can slowly leak away from the relatively weak gravitational field of Mars. This has provided an isotopic signature that has proved useful in identifying the origin of the SNC meteorites (see below).

Figure 1



(a) Calcium–magnesium carbonate globules grown in sterile laboratory conditions by precipitation at 25 °C and annealing for two days at 60 °C. The size of the globules is about 20 μm (scale bars 10 μm). **(b)** Microglobules and various irregular particles growing on the surface of the globules (shown at higher magnification: scale bars 100 nm). These growth features show similarities to those found on the carbonate deposit in ALH 84001. (Panels (a) and (b) reproduced with permission from [9].) **(c)** Magnetite microcrystals of inorganic origin, formed by partial oxidation of ferroferric hydroxide (green rust). The insert shows electron diffraction from the single domain particles. They resemble their terrestrial biogenic counterparts, and the magnetite particles in the martian meteorite.

The Antarctic ice fields provide a propitious environment for the collection, preservation and delivery of fallout from the atmosphere and outer space. Meteorites falling in the high-altitude region of accumulating snow become imbedded in the compacting ice, travel downhill towards the ocean in the slow-moving ice sheet, and are gradually exposed in low-altitude areas as the stagnating and rising ice — pushed up by obstacles such as mountain ranges — is slowly evaporated by the dry, gale-force winds. Some of the hundreds of meteorites collected in the Antarctic are of the SNC type, and so probably of martian origin. Most resemble rocks formed on Earth, but within some SNC meteorites — for example, Elephant Moraine 79001 and Nakhla — shock melted glass inclusions and veins with cavities containing trapped gases were discovered, which were found to have the isotope signature characteristic of the martian atmosphere. Since this discovery, it has been assumed that all the SNC meteorites came from Mars, including a rock of ~4 kg found in 1984, named Allan Hills 84001 (ALH 84001): it is this object that is the focus of all the recent excitement about the possibility of there having been life on Mars [1].

Signs of life in ALH 84001?

ALH 84001 is unique in several ways. It consists mainly of heavy, coarsely crystalline iron magnesium silicates known as pyroxenes. The mineralogical composition and rock fabric suggest that ALH 84001 is a 'cumulate' and that the heavy crystals have selectively settled to the bottom of a molten magma reservoir. Such aggregation requires a substantial gravitational field and contributes to the case for a martian origin. The crystallization age, determined from the proportion of the two parent uranium isotopes, ^{238}U and ^{235}U, and the stable end-product isotopes of lead, places its age at 4550 million years (Myr). This is practically identical to the age inferred from meteorites for the earliest condensed and aggregated solids in our solar system, and is much older than the other SNC meteorites, which crystallized in the age range 150–1300 Myr. These late crystallization ages are probably due to late episodes of volcanic activity on the parent body, again pointing to Mars as being sufficiently large for such crustal evolution.

About 4000 Myr ago, ALH 84001 experienced a shock event that reset its $^{40}Ar/^{40}K$ clock. This may have been related to the excavation of the planetary surface. A second shock occurred 15 Myr ago; it is possible that this was the ejection event, as the meteorite is estimated to have been exposed in orbit for a similar length of time before capture by Earth. This 'exposure age' is measured by the amount of nuclear spallation products, induced by cosmic ray bombardment of the unshielded meteorite. The length of the stay of the meteorite on Earth is limited by the age of the ice in which it is carried, estimated from the flow rate of the ice and the maximum distance of transport to < 13 000 years.

The main body of the meteorite serves mainly as a dated time capsule, but interesting information from the point-of-view of exobiology has come from secondary carbonate minerals, formed from solutions that penetrated cracks in the rock. Such crack fillings from circulating, carbonate-containing solutions are a common geological feature. The age of deposition has recently been estimated at 1400 Myr [2]. The temperature at which the carbonate minerals were deposited is a subject of disagreement. On the basis of compositional features, this was estimated to be 500–700 °C [3], which would eliminate any relationship to live organisms.

Oxygen isotope measurements [4], however, suggest a temperature of 0–80 °, compatible with life. This issue will no doubt be further debated.

The view that the carbonate deposit is biological in origin is based on a number of arguments [1]. Each of these is, as the authors admit, not very convincing and does not preclude an inorganic origin. One argument concerns the globular and other shapes of the crystalline carbonate aggregates. The surface of the carbonate vein deposit is covered with microscopic globules and segmented oblong shapes, taken as evidence for a live source. Alone, such growth features would not make anyone jump to the conclusion of a biogenic origin. On Earth, such formations are, in low-temperature deposits, often associated with microoganisms, but they also occur commonly under circumstances where life is excluded. Carbonate globules with shapes similar to those found in ALH 84001 can be grown inorganically (Fig. 1a,b). The segmented oblong shapes observed on the surfaces of the meteorite carbonate globules and the intricate features of the inorganically grown carbonate raise the question of how complex such features have to be in order to be safely considered as the products of live organisms.

The suggestion that the vein fillings in ALH 84001 are of biological origin was based not only on the shapes of the carbonate deposits, but also on the nature of the associated mineral assemblage in the form of compositional zoning and apparent phase disequilibria. As often found in nature, the composition of carbonate minerals may be modified during growth as a reflection of physiochemical changes in the environment. These changes introduce zones of manganese carbonate, iron carbonate and magnesium carbonate in solid solution, either into the isostructural calcium carbonate or as separate phases. In low-temperature mineral assemblages on Earth, it is difficult, if not impossible, to decide whether such phenomena are caused by living organisms. This is because the entire Earth's surface is now infested by microbes, which affect the environment even several thousand meters below the surface. It is difficult to find a low-temperature environment guaranteed to be sterile. At sterilizing high temperatures, however, zoning is also common and is clearly of inorganic nature.

Magnetite, in association with iron sulfide in the carbonate globules, has similarly been taken to be indicative of life [1]. Microcrystals of magnetite are found in magnetotactic bacteria, and are thought to serve as a guiding compass in insects and birds. The similarity between bacterial magnetite and that occurring in the meteorite has been pointed out, but similar magnetite microcrystals (Fig. 1c) are formed upon slow oxidation of ferroferric hydroxide, a common precipitation product in natural iron-bearing solutions under mildly reducing conditions. The association of the magnetite with iron sulfide in the carbonate globules was claimed to be a sign of thermodynamic disequilibrium precipitation [1], often characteristic of biological systems. In equilibrium, these minerals would not form simultaneously, except at high pH. Their coexistence in the same deposit can, however, also be ascribed to changing redox conditions during formation of the deposits, which again are often observed in nature. The Murchison meteorite, one of the most intensely investigated objects from an organic geochemical point of view, typically contains within small volumes magnetite, iron sulfide and calcium sulfate, reflecting a range of redox conditions during its formation and alteration history.

The discovery that many find the most compelling indicator of extraterrestrial life is that of organic molecules — polycyclic aromatic hydrocarbons (PAHs) — directly associated with the carbonate globules, with strong evidence presented against contamination [1]. The PAHs detected by McKay *et al.* [1] consist of fused, variably derivatized

The lesson from 'organized elements'

The idea that meteorites contain remnants of live organisms goes back at least to the last century when 'fossils' were found in carbonaceous meteorites by the German physicist H.D. Richter. The idea was renewed in the 1960s when H.C. Urey [10] took an interest in similar claims by G. Claus and B. Nagy [11]. Claims and counterclaims from different laboratories, aroused by this discussion, led to the view that the fossil-like 'organized elements' were not extraterrestrial or ancient life forms. Some were convincingly suggested by K. Fredriksson to be corroded and deformed hexagonal crystals of iron sulfide, which had acquired complex shapes and a cell wall-like structure. This dampened somewhat the enthusiasm for the exobiological interpretation, but the thought, with proper scientific reservations, remained as a "*neppur, forse si muove*" [12].

Urey's view was unique: he regarded the possible life forms as representing the earliest life on Earth, and the meteorites as ejection fragments from the Moon. He thought that the Moon, captured from solar orbit by tidal exchange with Earth, would have approached so close that extensive water and primordial terrestrial organic debris 'splashed' onto it from our planet [12]. Returned lunar samples would therefore be likely to reveal the earliest life forms from Earth, preserved in the carbonaceous meteorite–lunar surface material, but destroyed on our geologically active planet. This authoritative proposal was formally adopted by NASA as a scientific motivation for the Apollo missions to the Moon. Protests were voiced by Sir Fred Hoyle, who forecast on the eve of the Apollo 11 mission that the Moon would instead be found to be "an uninteresting slag heap". His prediction that the Moon is a lifeless body, scorched by accretion was soon vindicated by the returned lunar samples, with the exception that the slag heap, far from uninteresting, was a key to understanding the process of planetary accretion.

benzene rings; such compounds are rather toxic and are not known to participate in biochemical reactions. The detection technique was highly specific for aromatic compounds, however, so the analysis did not exclude the presence of other, more life-friendly organic compounds. PAHs can be formed from biological material by aromatization (charring) at elevated temperatures — they are constituents of petroleum and coal, formed by long-term thermal metamorphism of organic remains. PAHs are relatively abundant in carbonaceous meteorites and in the space medium, and were again at the center of attention in the 'life in meteorites' controversy in the 1960s (see box). At that time, an experimental model study of space plasmas [5] revealed a narrow mass range of PAHs, mainly pyrene, chrysene, coronene and fluoranthracene. The compositional range reported from ALH 84001 is also relatively narrow and similar to that found in the space plasmas and carbonaceous meteorites, but with some differences considered suggestive by McKay *et al.* [1].

A large reservoir of organic molecules, of unspecified structures, had in fact been shown to exist in ALH 84001 a few years ago [6]. Remarkably, this earlier paper has remained in obscurity for three years, although, as pointed out in a recent article [7], it constituted corroborating evidence for life. The evidence is in the form of a uniquely biogenic — so far as we know — enrichment of the light isotope of carbon ^{12}C. The problem is that the observed isotopic signature [6], if it were martian in origin, would represent a record high fractionation of more than 6 % relative to the coexisting heavy martian carbonate, and exceeding that of known bacteria and of the oldest preserved biogenic matter on Earth [8]. An alternative, and more pedestrian, explanation is that it corresponds to a routine 20 % fractionation relative to the terrestrial inorganic carbon reservoir, typically generated by our own microorganisms and thus suggesting contamination of the martian sample

The people's response

When Giordano Bruno publicized his exobiological beliefs, he was burned at the stake. The extensive publicity given to the 'martian-life' paper [1] has, in contrast, mostly been measured, attesting to the generally high level of technical and scientific sophistication in the media. Profound interest has been melded with caution and with analytical comments solicited from the scientific community. Scientists' criticism of the publication as premature has largely been tempered by approval. Scientific results with such a relatively high degree of uncertainty would normally not be able to breach negative peer review, but in this case they have met with more sociopolitical than scientific objections. The most obvious reason is the impact that the present results, if verified, would have on the way in which we view life and the universe. The care with which the authors of the article have prepared the results, and the caution with which they have interpreted their findings, have also contributed to the acceptance of the material as an interesting basis for discussion of criteria for extraterrestrial life. Few specialists in the field of geochemistry and cosmochemistry, however, would at this stage concur with the authors' exuberant final statement "... we conclude that they are evidence for primitive life on early Mars" [1].

Regardless of its possible biological significance, the identification of organic molecules of probable martian origin is, in itself, of considerable interest, in view of the failure of the Viking mission to find organic matter in the martian surface soil. It is understandable that NASA, as the main sponsoring agency for exploration and research in this field, has regarded it as useful and desirable to draw renewed attention of the public to the depth and ambiguity of the matter, the profound questions addressed, and the possibilities for a future resolution of the problem of the plurality of worlds.

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