ALH84001: The Continuing Debate about Past Life on Mars
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Introduction

In 1984, a small meteorite, ALH84001, was found in the Allan Hills region of Antarctica. Mittlefehldt (1994) identified it as having come from Mars, from which it had been ejected 15-16 million years ago (Eugster 1994) by an asteroid impact on the Martian surface. The meteorite had spent most of that time in space and finally fell to Earth about 13,000 years ago (Jull et al. 1989). In 1996, David McKay and his team at NASA’s Johnson Space Center published an extraordinary paper claiming they had found evidence of past Martian biological activity in the meteorite.

To say the announcement caused a stir would be an understatement. NASA was forced to release news of discovery nine days before McKay’s paper was published (Nasaweb), and President Bill Clinton spoke about it from the White House lawn (Clintonweb). However, “extraordinary claims require extraordinary evidence” (Sagan 1980), and this claim is no exception. A debate rages to this day over whether or not ALH84001 really does provide evidence of past Martian life, and since 1996 more than 300 journal and conference papers have been published on the meteorite.

The Claims

The primary claims of biological origin by McKay et al. (1996) are based on analysis of carbonate globules found in fissures in the meteorite. These globules are ~50 μm in diameter, shaped like flattened discs, and cover the walls of the cracks. They were likely deposited by a water-rich fluid that was present in the cracks after the meteorite formed. The carbonates contain two major features that could indicate a biological origin: the presence of organic molecules called polycyclic aromatic hydrocarbons (PAHs), and tiny iron oxides (Figure 1, Figure 2) called magnetite (Fe3O4) that are similar to those formed by terrestrial bacteria. McKay also proposed a number of other, more circumstantial, pieces of evidence. While none of this evidence, by itself, guarantees a biological origin, the combination was considered to be a strong case for biogenesis.

Before analyzing the evidence, two assumptions must be tested: did ALH84001 really come from Mars, and is it possible that the supposed biogenic features are the result of terrestrial contamination? A combination of isotopic analysis (Valley et al. 1997) and analysis of trapped gas bubbles (Bogard & Johnson 1983; Grady et al. 1996) leaves little doubt that ALH84001 was originally formed on Mars. While there is some dispute about contamination, substantial research says that most of the material is extraterrestrial. Radioactive dating of the carbonate globules yields ages more than 3.9 Gyr old (Borg et al. 1999; McKay et al. 2002) and the carbonates are more enriched in 13C than any materials on Earth (Gibson & McKay 1997). The origin of the PAHs is contentious, but the most compelling argument for a non-terrestrial origin is that the region of Antarctica where the meteorite was discovered contains PAHs at a level three orders of magnitude below that found inside the rock. Since the PAHs are mostly insoluble in water, there’s no obvious way for them to have been concentrated. Finally, there is no known source of magnetite in the Antarctic environment (McKay et al. 1996, 2002).
The Evidence

Looking at the evidence for biogenesis, it’s important to note that PAHs are ubiquitous in the galaxy. Astronomers have detected them in the interstellar medium (Léger et al. 1991), planetary nebulae (Bernard-Salas et al. 2008), and in non-Martian meteorites (Becker & Bada 1995). The presence of PAHs, by itself, does not imply a biological origin. However, all of the PAHs found in ALH 84001 are known decay products of microbes on Earth (Gibson & McKay 1997) and have an isotopic composition that could come from methanogenic bacteria (Wright et al. 1997).

Given that PAHs are so ubiquitous, the proof of biological origin has focused on two other features: the morphology of the magnetite, and the presence of magnetite chains. To understand why these features can imply biogenesis, we must first discuss magnetotactic bacteria.

Magnetotactic bacteria, first discovered on Earth by Blakemore (1975), usually live in an aquatic environment in the transition zone between the oxygen-rich upper waters and the oxygen-depleted, sulfur-rich lower waters. They contain magnetosomes, magnetite particles arranged in a chain and encased in a phospholipid membrane (Figure 3). The magnetite particles are of a precise size (40-100 nm in length) that optimizes their performance as single-magnetic-domain crystals. The chain connects the crystals end-to-end so that their moments add together. The result is that the magnetosome, and thus the bacterium, aligns with Earth’s magnetic field. The bacterium then swims forward or backward along this line. Because Earth’s magnetic field has a vertical component, this allows the bacterium to position itself higher or lower in the oxygen gradient of its environment (Blakemore 1982; McKay et al. 2003).
Magnetite Crystal Morphology

Magnetite can be formed by both biotic and abiotic processes. Thomas-Keprta et al. (2001) proposed six properties that could be used to identify biogenic magnetite: a narrow size range, chemical purity, few crystallographic defects, hexa-octahedral crystalline structure, elongation along the crystal’s [111] axis, and chains of crystals. Thomas-Keprta et al. (2000, 2002) showed that approximately 25% of the magnetite crystals in ALH84001 met the first five of these six biogenic markers. The other 75% are likely of abiotic origin, but the mechanism of their creation is still a mystery. Various problems make in-situ creation of any of the magnetite unlikely, and thus it was probably formed on Mars outside of the meteorite and deposited by fluid flow. There’s also no reason that an organism would develop magnetotaxis living in a tiny crack (Friedmann et al. 2001).

Treiman (2003) provided the first broad hypothesis to explain the abiotic origin of magnetite in ALH84001. His hypothesis incorporated the geologic history of the meteorite, as well as its composition and morphology, into a five step history: carbonate globules were deposited from liquid water, the globules were subjected to an impact shock event, the shock heated the rock to 500-700 °K and decomposed some carbonates to magnetite, the temperature declined slowly allowing chemical equilibria, and the CO-CO2 gas emitted by the carbonate decomposition reacted with hydrogen to produce PAHs.

For several years a game of scientific ping pong has been played by teams trying to prove the biotic or abiotic origin of the magnetite. Golden et al. (2003, 2006) showed experimentally that chemically pure magnetite could be produced from the heating of carbonate globules. On the other hand, Thomas-Keprta et al. (2004, 2008a, 2008b, 2008c) refuted these claims by showing that chemically pure magnetite was not produced when the same experiments were reproduced, and claiming that Golden’s experimental methods were insufficient.

There is also some doubt about the heating event that could have decomposed the carbonates. Paleomagnetic and inert gas measurements (Kirschvink et al. 1997; Weiss et al. 2002a, 2002b) show that the rock was not heated above ~40 °C in the last Gyr prior to its ejection, and in fact it is likely that the rock had not exceeded –70 °C during that time.

Magnetite Chains

The sixth biogenic characteristic of magnetite crystals, the presence of chains, has also been investigated. Although the mere existence of magnetite chains strongly suggests a biological origin, since a more energetically favorable condition is clumping, Friedmann et al. (2001) proposed a more thorough set of five properties of biogenic magnetite crystal chains that could be used to distinguish them from those of abiotic origin: uniform crystal size and shape, gaps between the crystals resulting from inter-crystal membranes, chaining along their long axis, traces of a membrane around the chain, and smooth postmortem bending of the chains facilitated by the organic support structure. All five of these characteristics are present in some amount in ALH84001 magnetite.
One complication is that it is very difficult to analyze the large number of sub-micron magnetite crystals to determine if they have a chain structure. Weiss et al. (2004a) proposed several techniques that were able to rapidly screen large amounts of material for magnetofossils, and that were particularly sensitive to magnetite crystals arranged in chains. Unfortunately, when Weiss et al. (2004b) applied these tests to ALH84001, they found that no more than 10% of the crystals are aligned in chains. However, because of the predicted postmortem disruption of chains, these results do not completely rule out a biological origin.

**Analysis**

If one thing has been learned from the last 13 years’ worth of analysis, it is that proving the biological origin of extraterrestrial material is a difficult, if not impossible, endeavor. The analysis is constrained by two key issues.

The first issue is that scientists only have a single example of life – that present here on Earth. Thus, the easiest life to look for is that with which we are already familiar. However, in order for early Mars to have had Earth-like life, it is necessary to make one of two assumptions: either life evolved independently on Earth and Mars and convergent evolution caused the development of near-identical organisms in a very short time, or life was transferred from Earth to Mars or Mars to Earth at an early time.

The carbonates in ALH84001 are 3.9 Gyr old. The fossil record on Earth has revealed magnetotactic bacteria only within the past ~2 Gyr on Earth, but the record is undoubtedly incomplete and they could have evolved earlier, leaving open the possibility of transfer from Earth to Mars. However, another possibility is that they evolved on Mars and were transplanted to Earth (McKay et al. 2003). This theory has its own issues. If the bacteria evolved on Mars, this implies liquid water, a strong planetary magnetic field, and oxygen in the atmosphere. The first two requirements have strong evidence in their favor (Squyres et al. 2004; Rochette et al. 2006), but the presence of oxygen doesn’t (McKay et al. 2003).

Regardless of the direction of transfer, it is debatable whether or not life could have survived such a trip. For example, Artemieva & Ivanov (2004) modeled a Martian ejection event, and determined that the temperature of the rock may stay below 200°C, thus allowing for the survival of some organisms. On the other hand, Min & Reiners (2007) used isotopic analysis of ALH84001 to show that its ejection event caused a temperature rise to 400°C, making the survival of life unlikely.

The second issue is that, for every piece of evidence supporting a biological origin, it is possible to find an abiotic method of producing the same evidence. This reduces the proof of biological origin to the level of circumstantial evidence.

**Conclusion**

In the 13 years since McKay and his team claimed that ALH84001 contained evidence of early Martian life, the scientific community has tried hard to both prove and disprove this theory. In the process, much has been learned about the steps required to prove biological origin, as well as about the details of meteorite ejection, magnetotactic bacteria, and magnetite morphology. However, in the end, neither side has produced a clear-cut case supporting their position, and the question of biogenesis remains open.
In order to take the next step, a more sophisticated *in-situ* analysis needs to be performed on the Martian surface. This could take the form of a more sophisticated rover, such as the Mars Science Laboratory (MSLweb), or a sample-return mission. Assuming we are seeing evidence of early Martian life, it is likely that any other organic evidence was long ago destroyed by the oxidizers in the Martian soil. Magnetite may be the only remaining evidence of early life on Mars today (McKay et al. 2003). However, there is always the chance that there is still life on Mars. The recently discovered methane plumes (Mumma et al. 2009) may have a biological source, implying an active colony of methanogens. Since the PAHs in ALH84001 are known decomposition products of methanogens on Earth, the search for life may yet yield positive results.

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