THERMAL AND MAGNETIC HISTORY OF THE MARTIAN METEORITE ALH84001: IMPLICATIONS FOR PAST MARTIAN LIFE AND PANSPERMIA.

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Introduction: The thermal and magnetic history of the Martian meteorite ALH84001 has critical implications for interpreting potential biological markers in the meteorite, the capability of meteorites to transfer life from Mars to Earth, and the degree to which the ancient Martian surface and atmosphere were shielded from high-energy particles. If the meteorite were found to have not been heated significantly since its last brecciation event, this would mean that the carbonate globules—which mostly postdate this major brecciation and which may contain evidence for past Martian life [1]—formed at temperatures amenable to life. This would also mean that the meteorite was not heat-sterilized either by the event that blasted it off Martian surface nor from its passage through the Earth's atmosphere and landing on Antarctica. A strong magnetic field could have prevented the solar wind from bathing the Martian surface with harmful radiation and from stripping the atmosphere of greenhouse gases. Records of both the maximum temperature experienced by the Martian meteorite in the past ~ 4 billion years and the strength of the ancient Martian magnetic field may be preserved by the meteorite's ferromagnetic minerals. Two groups have previously studied the magnetic properties of these minerals in the meteorite [2,3].

Comparison of Previous Studies: Immediately upon cooling through their blocking temperatures, individual ferromagnetic grains within the meteorite will be magnetized preferentially along the original direction of the local magnetic field. However, the meteorite experienced shock metamorphism and by 4.0 Ga, the interior had been significantly crushed. Kirschvink et al. [2] studied two individual mm-sized pyroxene grains from the interior crushed zone. They found that both of the grains had strong, stable, and nearly unidirectional natural remanent magnetizations (NRMs) which were equal in magnitude (~5×10^{-5} Am^2/kg) but strongly different in direction. They attributed these magnetizations to pyrrhotite since the samples continued to acquire isothermal remnant magnetism (IRM) in applied fields above 0.3 T (magnetite and titanomagnetites should saturate before reaching this level), and because scanning electron micron microscopy (SEM) revealed the presence of small iron-sulfur inclusions in the pyroxene grains. The magnetization level within the pyroxenes only requires the presence of about 1 ppm of single-domain pyrrhotite, dispersed in ~ 1 μm particles, which would be difficult to detect in thin section. These magnetizations remained constant over a three month period of exposure to the low-field environment of the magnetically-shielded clean laboratory. This confirmed that (a) ancient Mars had at least a local magnetic field, (b) the meteorite is essentially a micro-conglomerate that was brecciated after cooling, and (c) the meteorite has not been heated above an upper limit of 110 °C since the 4.0 Ga brecciation event. None of these results actually depends on a knowledge of the mineralogical composition of the meteorite, only on the blocking temperature of the individual grains. Since the carbonate globules formed after the brecciation event, they too must have formed at low temperatures. This also means that the meteorite was not significantly heated during its ejection from Mars or during its landing on Earth.

Collinson [3] measured the remanent magnetization of three ~5 g samples to each be ~2×10^{-7} Am^2/kg, nearly 300 times smaller than Kirschvink et al.'s value. The two studies are not contradictory since Kirschvink et al.'s measurements were done on individual mm-sized grains (12 and 2 mg) which were 100-1000 times smaller than Collinson's samples. It is only at this small size scale that the rock samples would show uniform magnetization. A measurement of bulk 5 g samples would yield a weak magnetization since the individual magnetic moments, which add vectorially, should nearly cancel. Collinson [3] attributed the magnetization to titanomagnetite and magnetite because of thermomagnetic evidence for two minerals with Curie temperature of 350-400 and 550-600 °C, respectively. However, depending upon lattice defect ordering, pyrrhotite can have Curie temperatures in the 300-350 range; for titanomagneties this can be anything below the magnetite Curie temperature at 580 °C, depending on the Ti concentration. Hence, Collinson's data are equally supportive of a pyrrhotite-based remanence. Unlike Kirschvink et al. [2], he observed that the magnetization of his samples changed significantly over just a few days; we attribute this unstable component to the drifting of superparamagnetic crystals, of a magnitude which is small compared with the moments of individual grains. In particular, interacting superparamagnetic magnetite has been directly observed in the rims of the carbonate globules [1], which may be responsible for this viscous component. Hence, Collinson's conclusion that some sort of fine-grained magnetite or titanomagnetite is giving the weak, unstable residual moment is probably not wrong but rather simply misses the nature of the main magnetic component.

New Results: We report two new experiments. The goal of the first was to calibrate the blocking temperature vs. coercive force relationship, and to roughly measure the strength of the ancient Martian magnetic field as recorded during final cooling of the meteorite. We first progressively demagnetized the large pyroxene grain described elsewhere [2] using an alternating field which we increased in small steps; after each increase we measured the remaining magnetization. This gave us the coercivity spectrum of the rock. We then heated the sample to 400 °C and cooled it in a constant 20 μT field. After another heating to 200 °C, we cooled it in a 20μT field orthogonal to the previous one. We then progressively demagnetized the sample using an alternating field in the same manner as before, to obtain a coercivity spectrum of the heated rock. Unlike magnetite, the magnetization of pyrrhotite is dominated by magnetocrystalline rather than shape anisotropy; this implies that the blocking field and blocking temperatures of single-domain particles both increase with particle volume. By observing the rotation of the magnetization vector with the increasing demagnetization, we found that a coercivity of 20 mT is associated with grains whose blocking temperature is ~200 °C, a result which is in good agreement with the upper heating limit inferred previously for this grain [2].

This linearity also means that a ratio of these two coercivity spectra will yield information concerning the intensity of the Martian magnetic field at the time of last cooling; we find this to be ~14 μT. Because we observed some reddening of the carbonates during heating (possibly from oxidation) and because the relationship between coercivity and blocking temperature is not perfectly linear, these results are preliminary and need to be checked directly by the Thellier/Thellier method (experiments in progress). We note that the magnetization level in these grains [2] is not enough to account for the magnetic anomalies observed recently by Mars Global Surveyor [4], so there must be another rock type on Mars which is much more strongly magnetized than the unbrecciated ALH84001 parent material.

The goal of the second experiment was to rule out the possibility that the difference in magnetization direction of the two grains studied by Kirschvink et al. [2] was due to anisotropic exsolution of the magnetic mineral during crystallization, rather than low-temperature grain rotation during brecciation. For this we first demagnetized the grains completely and subjected them to a strong magnetic pulse, and monitored the alignment of the remnant magnetization which resulted relative to the pulse direction. This was repeated this twice more in magnetic fields oriented along the other two cardinal directions. Since the direction of the induced magnetic moments measured after each field exposure agreed to within 1 degree with that of the applied fields, we conclude that there is no preferred direction for the grain to be magnetized. Thus the difference in magnetization direction between the two grains measured by Kirschvink et al. [2] is due to brecciation, not anisotropy.

We are currently attempting to directly measure the strength of the ancient magnetic field using a Thellier-Thellier analysis of many oriented pyroxene grains. This will determine the exact maximum temperature that the meteorite reached following crystallization, the exact strength of the ancient Martian magnetic field, and allow us to characterize the degree of brecciation since the meteorite crystallized.

References: [1] McKay, D. S. et al. *Science, 273,* 924-930. [2] Kirschvink, J. L. et al. (1997), *Science 275,* 1629-1633. [3] Collinson, D. W. (1997) *Meteoritics & Planet. Sci., 32,* 803-811. [4] Acuna, M. et al. (1999) *Science, 284,* 790-793.