Investigating the ancient Martian magnetic field using microwaves

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Abstract

The new microwave palaeointensity technique has been used to investigate samples from the Martian meteorite Nakhla. This technique is a promising new way to obtain absolute palaeointensity information regarding the ancient Martian magnetic field as recorded by the Martian meteorites. Assuming that a part of the magnetic remanence is of thermal origin and originating on Mars the two samples studied yield estimates of 4 \( \mu \)T for the Martian magnetic field at 1.35 Ga. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

At present there is no significant planetary field of global scale detected on Mars [1]. However, in the past it is probable that Mars had a magnetic field produced by dynamo action in its then molten core [2] as has been found for the moon [3]. Recently it has been shown that some areas of Mars have a large crustal remanence, which is over an order of magnitude greater than that found on Earth. Frequently the Martian remanence displays a pattern of long EW trending stripes of oppositely magnetised material [4] reminiscent of the magnetic stripes associated with sea floor spreading on Earth. The magnetic stripes are an indication that Mars probably once had a reversing magnetic field produced by dynamo action in its then molten core.

At present, the only Martian material that can be studied on Earth is meteoritic. The Martian meteorites contain a natural remanent magnetisation (NRM). An NRM is acquired in the presence of a magnetic field by a number of possible processes, for example when the magnetic minerals are formed, undergo a later heating event, or are shocked. New evidence suggests that the Martian meteorite ALH84001 has not experienced temperatures greater than 40°C since before it was ejected from Mars [5] indicating that the journey to Earth from Mars did not expose the Martian meteorites to temperatures high enough to remove the existing NRM. It is therefore theoret-
ically possible to obtain from Martian meteorites information on the ancient Martian magnetic field.

If the NRM of a sample is a thermal remanent magnetisation (TRM) acquired as the magnetic minerals cooled through their Curie point then, in principle, it is possible to determine the strength of the field (palaeointensity) in which the TRM was obtained. If no part of the NRM is a TRM then it is not possible to obtain an accurate palaeointensity estimate. The Thellier method is often used to determine the absolute palaeointensity by comparing the intensity of an experimentally acquired TRM in a laboratory magnetic field to the natural TRM [6]. This technique which involves heating the sample often induces alteration. Once the samples have altered it is not possible to obtain an estimate of the intensity of the ancient magnetic field. Alteration during experimentation is a major cause of failure in conventional palaeointensity experiments using terrestrial material (e.g. [7]). The Martian meteorites are no exception and are highly susceptible to thermo-chemical alteration [2,8]. Attempts using standard, conventional, methods to obtain absolute palaeointensity information from Martian meteorites have been made but with little success [2,8].

Alternative palaeointensity methods that do not involve heating have been applied to Martian meteorites [2,9]. Whilst alteration of the samples does not occur there are other problems associated with these methods. The anhysteretic remanent magnetisation (ARM) method induces a laboratory ARM instead of a TRM. Where an ARM is the remanence acquired when a sample is subjected to a strong alternating field that cycles from zero up to a fixed maximum value and back to zero in the presence of a weak constant field. The ratio of TRM to ARM acquired in the same ambient field is needed in the palaeointensity calculation, this ratio is dependent on the magnetic mineralogy and is not known with any certainty. The other method used is the normalisation method. In this method the initial NRM intensity is normalised using the saturated remanent magnetisation of the sample, as this is a measure of magnetic mineral content. Using certain assumptions the normalised NRM intensities indicate relative palaeointensities between samples. Neither of these two non-heating palaeointensity methods allows for separate palaeointensity determinations over different blocking spectra, so it is also necessary to assume that there is no significant secondary component of magnetisation. Despite the inherent uncertainties and low quality of the relative palaeointensity data so far obtained the evidence suggests that there was an ancient magnetic field on Mars of strength 0.5-5 μT [2].

To be able to determine absolute palaeointensity estimates from Martian meteorites with greater certainty, a new method needs to be used. The microwave palaeointensity technique recently developed [10] using terrestrial material is just such a method. During the experiment high frequency microwaves are used to directly excite the magnetic system of the sample [11] instead of bulk heating of samples in an oven. Increasing microwave power is analogous to increasing temperature and as such the method is very similar to the conventional thermal Thellier method. However, the microwave technique minimises sample alteration during the experiment, as the magnetic minerals are targeted directly leaving the bulk of the sample unchanged. The application of high frequency microwaves directly excites the magnetic system of a sample creating spin waves (magnons). This excitation allows the individual domain magnetisations to reverse and the whole sample to demagnetise in zero magnetic field. Phonons (lattice vibrations) are created in the subsequent decay of the high energy magnons which results in heating of the bulk sample but to a much lesser extent than in conventional heating. The microwave palaeointensity technique has been successfully used on studies of ceramics [12,13] and lava [10,14]. 5 mm diameter cores are the maximum possible sample size used in this technique. These are much smaller than the more usual 25 mm diameter cores conventionally used. Hence the microwave palaeointensity technique is particularly suitable for meteorites and other studies where material is limited. This letter presents results obtained from the Martian meteorite Nakhla using the microwave palaeointensity technique.
2. Experimental results and discussion

The Nakhla meteorite which fell in Egypt in 1911 is classed as a clinopyroxenite [15] and has a likely igneous age between 1.32 and 1.37 Ga [16]. Rock magnetic investigations (Fig. 1) indicate the presence of titanomagnetite with pseudo single domain bulk magnetic grain size, in accordance with previous magnetic studies [2,8]. Fig. 1a illustrates how heating to 700°C alters the magnetic hysteresis properties. This sample is therefore unsuitable for conventional palaeointensity analysis as has been found for other samples from Nakhla [8].

Two samples from the Nakhla meteorite NAK54 (mass 0.039 g) and NAK62 (mass 0.086 g) were investigated using the 8.2 GHz microwave system in Liverpool. Both of the samples are

![Fig. 1. Rock magnetic results for Nakhla. (a) Day plot [21] of the ratio of saturation remanence, \( M_r \), and saturation magnetisation, \( M_s \), against the ratio of remanence coercivity, \( H_{cr} \), against coercivity, \( H_c \). The plot is an indicator of bulk magnetic grain size with the multi domain MD, pseudo single domain PSD and single domain SD regions depicted. (b) Curie curve indicating that Nakhla has a Curie temperature of 530°C. (c) Plot of isothermal remanent magnetisation (IRM) acquisition, saturation is reached by 300 mT indicating the presence of titanomagnetite. (d) Plot of back field IRM. (e) Hysteresis loop for Nakhla.](image)
much smaller than the maximum sample size for the microwave system (typically 0.25 g). Both samples were found to be dominated by a stable single directional component of magnetisation (as has also been found previously [2,8]). These samples were therefore suitable for microwave palaeointensity analysis.

In the microwave palaeointensity technique used here the magnetising field is placed perpendicular to the direction of the NRM [10,17]. In conventional Thellier palaeointensity experiments the magnetising field is applied in an arbitrary fixed position. Two heating steps are required at each temperature, one in the magnetising field and one in zero field. With the magnetising field perpendicular to the NRM only one microwave application is required at each power. This reduces both the amount of heat the sample experiences and experimental time. Importantly, it also eliminates the need to be able to accurately reproduce the microwave power absorbed in the sample. During the experiment the magnetisation vector

Fig. 2. Stereo plots indicating the direction of magnetisation of the two samples of Nakhla during the microwave palaeointensity experiment in which the direction of the laboratory induced TRM (T_RM) is perpendicular to the direction of the NRM; all data points for samples (a) NAK54 and (c) NAK62; high power points used in the palaeointensity analysis for samples (b) NAK54 and (d) NAK62. MAD is the mean angular deviation of the plane [18].

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swings from the direction of the NRM to the direction of the perpendicular laboratory induced microwave thermal remanence (T_MRM) with the vector end point plotting a great circle (Fig. 2). Deviation from a great circle path can indicate instability of the NRM direction, or alteration of the magnetic minerals during the experiment. The mean angular deviation about the plane [18] for all data points is 7.4° for sample NAK54 and 9.3° for sample NAK62. The scatter is mainly due to the weak magnetisation of the samples (as compared to the sensitivity of the SQUID magnetometer used).

The results from the microwave palaeointensity experiment are shown in Fig. 3. The Martian magnetic field strength is estimated from the slope of the NRM remaining/T_MRM gained plot. Ideal data produce a linear plot but as can be seen in Fig. 3 both Nakhla samples produce curved plots. These results could be due to a number of possibilities. Alteration may be one cause although the microwave technique is known to reduce the heating of the bulk sample during the experiment and therefore produces far less alteration than conventional techniques. Using larger samples (where material quantities allow) would reduce scatter.

Fig. 3. Microwave palaeointensity analysis on a plot of normalised NRM remaining against normalised laboratory T_MRM gained, ideally this should be linear. If the chosen laboratory field intensity, H_{lab}, is the same as the intensity of the magnetising field contained in the sample, H_{a}, the plot will be linear with the gradient of the line unity. Otherwise, H_{a} is given by H_{lab} times the slope of the line. All data points are shown in left upper and left lower panels and the high power region in which the palaeointensity estimate is made are shown in right upper and right lower panels.
in the data and allow alteration tests to be carried out simultaneously. If alteration is occurring then it is the low power portion that will be least affected. This assumption would give large and differing estimates of the ancient field of $12 \mu T$ and $30 \mu T$ for the two samples, which are comparable to the Earth’s field.

Another interpretation is that there are two components of magnetisation present (both in the same direction). The lower microwave power corresponds to a lower blocking temperature region and is more likely to have been contaminated by a later heating or shock event. The high power region corresponding to higher blocking temperatures is more likely to be a TRM of Martian origin.

The directions from the high power region are shown in Fig. 2b and d. Palaeointensity analysis using just the high power regions (Fig. 3, right upper and right lower panels) gives estimates of the Martian magnetic field of $5 \pm 3 \mu T$ and $3 \pm 1 \mu T$. The uncertainty in the palaeointensity estimate was evaluated using the reciprocal of $q$, the quality factor as defined by [19]. These absolute palaeointensity estimates are similar to the relative estimates of the ancient Martian field, $0.5^\circ-5.0^\circ$ [2] and are about 10% of the present day Earth’s field. A magnetic field of this magnitude is significantly greater than the present Martian magnetic field and is similar to lunar palaeointensity estimates at 3–4 Ga [3].

The high power remanence is most likely to have been formed when Nakhla crystallised on Mars. Future magnetic mineralogical studies should help verify the assumption that the remanence is of thermal origin (a TRM). An alternative explanation is that the sample may have become magnetised by being close to one of the bands of strongly magnetised Martian crust. Nakhla is not the same material as the magnetic crust as the intensity of magnetisation is far less. Furthermore, it has been suggested that multi domain haematite may be a source of the crustal remanence [20] and there is no rock magnetic evidence for haematite in Nakhla. While it is possible that Nakhla gained its magnetisation by being formed very near to the strong crustal remanence the probability is low.

3. Conclusions

Assuming the high power remanence is due to a TRM gained in the ancient Martian magnetic field this study of absolute palaeointensity provides support that Mars once had a convecting core producing a surface magnetic field of $4 \mu T$ at 1.35 Ga. A hot convecting Martian core would produce higher heat flow than present resulting in elevated surface temperatures. A stable magnetic field would also produce a magnetosphere. Both of these imply more Earth like conditions in the early evolution of Mars.

This study has demonstrated that it is possible to investigate the magnetic field recorded by Martian meteorites using the microwave palaeointensity technique. Further studies of this type (using larger samples and incorporating alteration tests) and further magnetic mineralogical studies on Nakhla and the other Martian meteorites will allow a greater understanding of the development of the ancient Martian magnetic field and the evolution of Mars.

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