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Investigating if Lightning-Induced Remanent Magnetization can Explain the Martian Magnetic Anomalies

Melissa De Andrade Nunes (IAG-USP), Ricardo Ivan Ferreira da Trindade (IAG-USP), Cauê Sciascia Borlina (EAPS - Purdue University), Brianna Petruccelli (EAPS)

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Abstract

Magnetic anomalies on Mars, some exceeding tens of A/m, contrast with regions of null magnetization such as the northern hemisphere and major impact basins. The Martian dynamo likely ceased over 3.9 Ga, raising questions about the origin of strong remanent magnetization in Terra Sirenum/Cimmera that could be hardly explained by an acquisition in the presence of a dynamo magnetic field. Notably, high remanence is usually associated with lightning-altered rocks on Earth, suggesting lightning-induced remanent magnetization (LIRM) as a possible mechanism. We investigated this hypothesis through high-current (~60 kA) discharge experiments on terrestrial igneous rocks analogous to Martian lithologies. After pulsing, Mr increased significantly, up to 490%, in some cases surpassing Martian crust and within REM values greater than 0.1 . These results support the feasibility of LIRM on Mars and point to potential paleoclimatic and geologic implications. Future work will focus on using martian meteorites to conduct lightning experiments, and to determine the magnetic record and properties of these samples through high-resolution magnetic characterization.

Introduction

Mars' crustal magnetism may offer insights into its early climate and internal dynamics. The Martian dynamo likely ceased >3.9 Ga (Arkani-Hamed, 2004). Impact basins like Hellas and Isidis likely formed post-dynamo (Robbins et al., 2013), implying demagnetization occurred without a global field (Gattacceca et al., 2010). Strong crustal magnetic anomalies of several tens of A/m are concentrated in after formed Terra Sirenum and Terra Cimmeria (Acuña et al., 1999; Langlais et al., 2004; Morschhauser et al., 2018; Osterloo et al., 2008), while a vast region of the northern hemisphere and large impact basins, like Argyre and Hellas, are magnetically null (Hood et al., 2003).

Thermoremanent magnetism (TRM) and shock remanent magnetism (SRM) mechanisms cannot fully explain the strongest Martian anomalies. This raises the hypothesis that lightning-induced remanent magnetization (LIRM) may have occurred on Mars, possibly during an active paleoclimate or during volcanic episodes persisting into the Late Amazonian (Segura & Navarro-González, 2005a,b, Bleacher et al., 2007).

To better understand the possible connection between lightning and Martian crustal magnetism, we perfomed a high-current experiment on igneous rocks, comparing our results with estimates of Martian remnant magnetism.

Methods

To test this hypothesis, we simulated lightning effects by applying ~60 kA discharges to terrestrial rocks analogous to Martian lithologies: (1) vesicular basalt from Trindade Island (TR) (Marques et al., 1999), (2) tholeiitic basalt from Vista Alegre (VA) (Pinto & Hartmann, 2011), (3) alkaline basalt from Planalto da Serra (RPS) (De Min et al., 2023), and (4) serpentinized harzburgite from the Quatipuru Complex (QT) (Hodel et al., 2019).

Three QT specimens and four from each other set were characterized magnetically using low/high-frequency susceptibility, hysteresis loops, First-Order Reversal Curves (FORC), Natural Remanent Magnetization (NRM) using JR-1A. Pulses were generated using a high-current generator at the Institute of Energy and Environment of the University of São Paulo

(IEE/USP), with samples placed 4 cm from the conductor. Post-experiment magnetizations were remeasured using the same instruments used before the experiment (Figure 1).

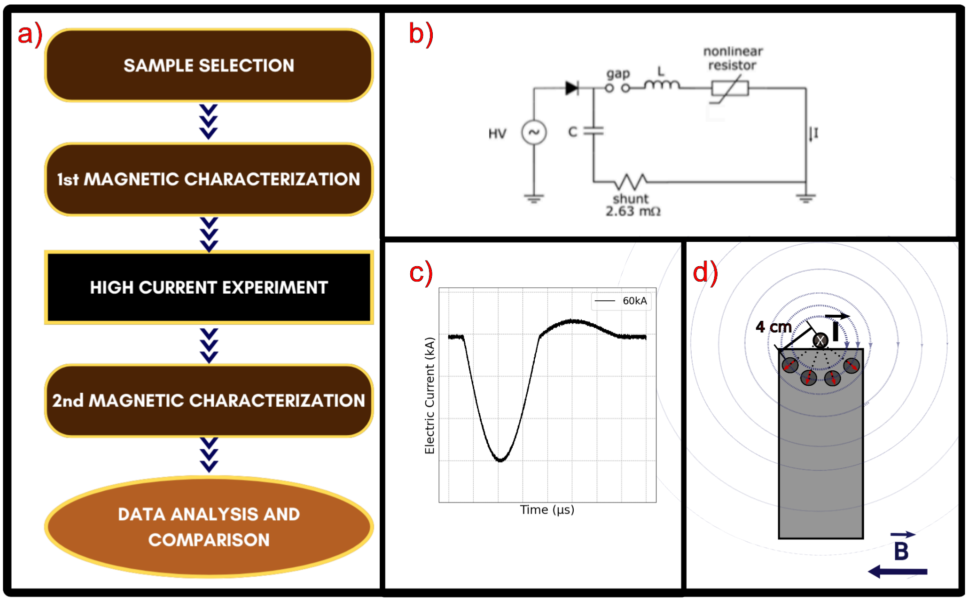

Figure 1: Experimental setup: (a) experiment flow, (b) circuit diagram, (c) waveform example, (d) specimen arrangement relative to conductor.

Results

After pulsing, remanent magnetization values increased, ranging from 0.05 A/m (QT49AB) to 133.55 A/m (TR9A2). Percentual increases reached up to 490% (TR9A2). REM ratios (NRM/Saturation Remanent Magnetization at 1T) exceeded 0.1 in all tested specimens (Figure 2a). TR and VA samples showed values surpassing Martian estimates (Langlais et al., 2004; Arkani-Hamed, 2002). REM values in our pulsed samples are statistically similar to those of lightning-struck rocks (Wasilewski & Kletetschka, 1999) and greater than almost all SNC meteorites (Rochette et al., 2003) (Figure 2-b,c), even greater than the higher REM-values in SNC meteorites, that are possibly associated with hand-magnets manipulation, which can imply a similar LIRM effect on DaG489, DaG670, La1-s and La1-l (Rochette et al., 2003)

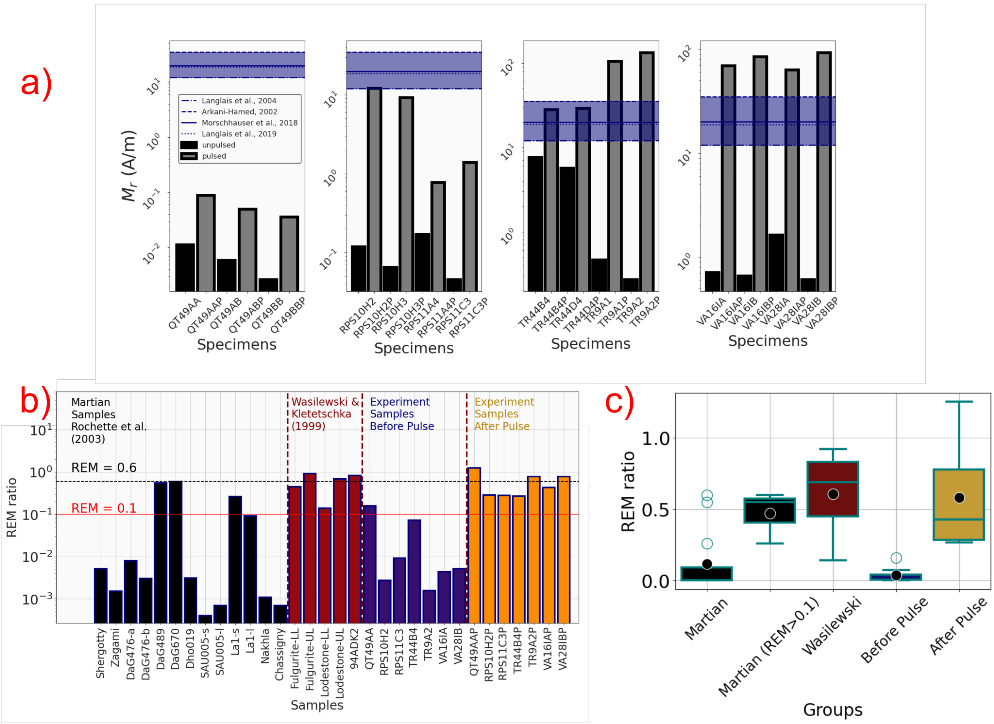

Figure 2: a) Remanent magnetization (Mr) values before (black bars) and after (grey bars) the discharge for each specimen. Dashed and shaded blue lines indicate estimated Mr values for the Martian crust based on orbital magnetic data (Arkani-Hamed, 2002; Langlais et al., 2004, 2019; Morschhauser et al., 2018). b) Comparison of REM (NRM/SIRM) ratios. Martian meteorite values (Rochette et al., 2003) are shown in black, lightning-struck terrestrial rocks (Wasilewski & Kletetschka, 1999) in red, and our experimental specimens before (purple) and after (yellow) the electric discharge. c) Boxplot of REM ratio distributions across the same groups shown in (b), highlighting statistical compatibility between our pulsed samples, lightning-altered rocks, and high-REM Martian meteorites, altered by hand-magnets. The black dot indicates the mean; the blue line inside the boxes shows the median.

Conclusions and perspectives

Our experiments reproduced remanent magnetization values comparable to those inferred for Mars. The results support lightning-induced remanent magnetization (LIRM) as a plausible mechanism for some Martian magnetic anomalies, which may imply a different climatic or geological context—one involving atmospheric conditions capable of generating lightning or associated with volcanic electrical activity (Rakov, 2016; Cimarelli & Genareau, 2022). Motivated by these findings, we are now conducting similar rock magnetic experiments on the Zagami and Tissint Martian meteorites (courtesy of Arizona State University) to enable new comparisons of *Mr* and REM ratios.

To further investigate the magnetic carriers, we initiated high-resolution analyses at the SIRIUS synchrotron, including microtomography at the MOGNO beamline and nanoscale imaging at the CARNAÚBA beamline. Additional high-current discharge experiments will be conducted on Martian meteorites to enable new comparisons of Mr and REM ratios.

Acknowledgments

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