

TESTING WHETHER A DYNAMO MAGNETIC FIELD AMPLIFIED BY IMPACT PLASMAS CAN EXPLAIN THE MAGNETIZATION OF THE MOON. I. S. Narrett¹, R. Oran¹, B. P. Weiss¹, Y. Chen², G. Toth³, and Katarina Miljković⁴, ¹Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA (narrett@mit.edu, roran@mit.edu), ²Princeton University, Plasma Physics Laboratory, Princeton, New Jersey 08543, ³Climate and Space Sciences and Engineering, College of Engineering, University of Michigan, Ann Arbor, MI, USA, ⁴Space Science and Technology Centre, School of Earth and Planetary Science, Curtin University, Perth, WA 6102, Australia.

Introduction: The Moon lacks a present-day core dynamo magnetic field. Yet, spacecraft observations of the crust and laboratory analyses of Apollo samples have identified natural remanent magnetization that formed in an ancient magnetic field [1]. In particular, analyses of Apollo samples containing thermoremanent magnetization (TRM) provide evidence of past magnetic fields between 4.25 and 1.5 Ga ago [2, 3] and possibly reached high values ($>35 \mu\text{T}$ as indicated by Apollo 11 basalts) [1]. However, scaling laws suggest that a dynamo generated in a convecting metallic core would be expected to only produce surface paleointensities up to $\sim 1 \mu\text{T}$ [1] given the small size of the lunar core ($\sim 14\%$ of Moon's radius) [4].

This discrepancy motivated a longstanding alternative hypothesis that the ancient field was the product of impact plasmas that amplified the local interplanetary magnetic field (IMF) [5]. Nevertheless, magnetohydrodynamic (MHD) simulations indicate that the latter process cannot produce paleointensities $>0.1 \mu\text{T}$ [6]. Alternatively, it was proposed that impact plasma amplification of a weak core dynamo (with a field strength that is compatible with dynamo scaling fields) could have produced the ancient field. Here, we report MHD simulations that quantitatively test the hypothesis that the Moon was magnetized by impact-generated plasmas in the presence of a past weak dynamo field and the solar wind.

Objectives and frameworks:

The viability of dynamo field amplification by impact plasmas as the source of lunar crustal magnetization depends on whether this mechanism can produce field magnitudes as large as the paleofield that magnetized the crustal anomalies and the Apollo samples. The inferred paleofield magnitude depends on whether the magnetization acquired is due to TRM or shock remanent magnetization (SRM). As discussed above, some lunar rocks magnetized by TRM would require a paleofield of $\sim 20 \mu\text{T}$ given the TRM susceptibility and thickness of the lunar surface materials [6]. For SRM, this would require $\sim 60 \mu\text{T}$ given that SRM susceptibility is a few times higher than that of TRM [7].

For the lunar magnetosphere geometry, we consider a dipole field, consistent with the limited available constraints on the ancient field [8]. The size and shape

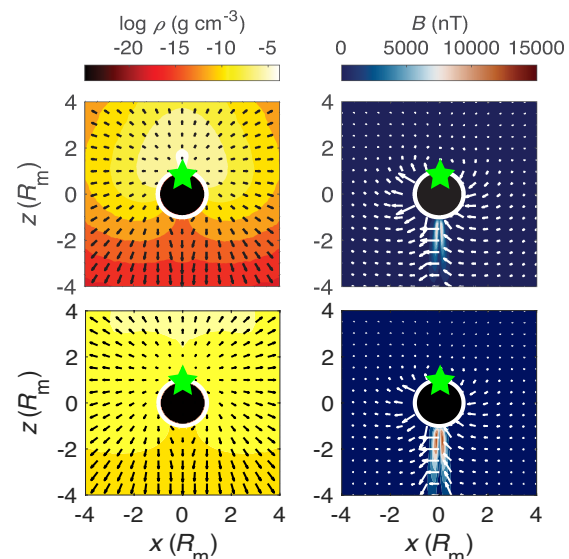


Fig. 1: MHD simulation of impact vapor expanding within an ancient lunar magnetosphere of $1 \mu\text{T}$ equatorial surface field strength. The left column depicts the vapor expansion by the log scale of density, ρ , at an early timestep (top left) and at the point of maximum magnetic field amplification (bottom left). The right column depicts the magnetic field strength, B , in nT, at an early timestep (top right) and at the point of maximum magnetic field amplification (bottom right). The impact vapor enters into the domain from the area marked by the green star. The black vector lines represent the velocity flow and the white vector lines are magnetic field lines (which denote the direction and relative intensity of the field). As the vapor expands around the Moon, the magnetic field lines are distorted perpendicularly by the convection of the impact generated plasma. The maximum magnetic field magnitude reached is $\sim 14000 \text{ nT}$ (bottom right), which is an amplification of the dynamo field by a factor of ~ 14 . The white circle represents the surface of the Moon. The solar wind is moving in the positive z -direction. The solar wind IMF is oriented along the negative x -direction. The dimensions of the grid are represented in units of lunar radii, R_m .

of the magnetospheric cavity created around the body depends on its ability to deflect the ancient solar wind, whose momentum flux was much higher than at present day. We used the estimation of the ancient (3.6–4.2 Ga) solar wind conditions at $\sim 1 \text{ AU}$ from ref. [9]. Because the hydrogen ion thermal and bulk gyroradii in the

ancient solar wind are $\sim 1\%$ and $\sim 10\%$ of the lunar radius (1,737 km), respectively, the single-fluid MHD approximation is valid for a global scale study of a lunar dipole-solar wind interaction. To assess a range of ancient lunar magnetosphere-asteroid impact scenarios, we are modeling different combinations of solar wind parameters [speed: (400 and 700 km/s), IMF: (30 and 100 nT)], solar wind density (26 and 35 amu/cm³), equatorial surface field strengths (0.1, 1, and 10 μ T), and impact locations (north magnetic pole, mid-latitude, and upstream/downstream magnetic equator). Each simulation starts by modeling the solar wind interaction with the lunar dipole field without an impact. Once this solution reaches steady-state, we then launch the impact generated plasma into the computational domain, simulating a basin-scale lunar impact (i.e., Imbrium) [6].

Numerical Model: For MHD modeling, we used the Block Adaptive Tree Solar-wind-type Roe Upwind Scheme (BATS-R-US) code [10]. BATS-R-US numerically solves the single-fluid MHD equations for the evolution of mass, momentum, energy, and magnetic field inside and outside of the body using a spherical grid, distinguishing between resistive and conductive regimes. The impact vapor properties were derived from previous simulation results using the impact-Simplified Arbitrary Lagrangian Eulerian (iSALE) code, as used by ref. [6]. For the MHD simulations, the parameter initial conditions set the magnetic field strength, resistive profile [6], the solar wind properties, and the computational domain, configuration, and resolution. The boundary conditions of the spherical grid are periodic in the azimuthal and latitudinal directions. In the radial direction, the outer boundary permits inflow or outflow depending on the orientation of the solar wind. The inner boundary is set at the core of the Moon. At the boundary between the body and the ambient plasma, the magnetic field is allowed to smoothly vary, while flow boundary conditions vary adaptively according to the flow density (solar wind is absorbed, dense impact vapor is emitted from the impact basin, and then free-slips outside the basin). We inject the impact-generated plasma into the domain using a time-dependent emitting boundary consistent with the iSALE simulations.

Results: We began by modeling a steady-state 1 μ T equatorial surface field strength lunar dipole magnetosphere in the ancient solar wind (bulk speed of 400 km/s, number density of 26 amu/cm³, temperature of 200,000 K, and IMF strength of 30 nT) followed by the injection of impact-generated plasma (Figure 1).

The simulation then proceeds as follows. The vapor expands due to the high plasma thermal pressure overpowering the lunar gravity and local

magnetospheric magnetic field pressure. As this vapor cloud expands around the Moon, the generated plasma sweeps up the dynamo generated field and compresses it towards the antipodal region, as previously proposed by ref. [5]. Since the vapor cloud expands in all directions with expansion speeds larger than the lunar escape velocity, this limits the pressure and energy exuded by the vapor cloud in the antipodal region of convergence, resulting in a much smaller magnetic field amplification than predicted in ref [5]. As the magnetic field becomes compressed in the antipode (Figure 1), opposite polarity magnetic field lines converge and form an X-line reconnection site. This reconnection region works to dissipate magnetic field energy, as it is converted into kinetic and thermal energy.

For this simulation of the lunar magnetosphere, our initial results show a maximum magnetic field amplification factor of ~ 14 , producing a maximum field of 14 μ T. This maximum amplification of the dynamo generated magnetic field persists on the order of a couple of minutes. However, we are testing the sensitivity of these results to the choice of grid resolution and details of the boundary conditions.

Given the timeline of the youngest known basin formation (Imbrium), impact-generated plasma amplification of the lunar dynamo cannot account for the magnetization in samples younger than 3.7 Ga [1, 2]. On the other hand, the maximum amplified field in our simulations is not far from the 20-35 μ T lower limit for TRM. Furthermore, it is possible that a slightly stronger dynamo and/or different solar wind conditions than those we have modeled thus far could produce even stronger amplified fields. However, the source rocks for most lunar crustal anomalies and magnetized mare basalts cooled far too slowly (100 d to 100 Ma [1, 3]) to record the minutes-long amplified fields observed in our models. To assess the full range of lunar paleomagnetic records, we are continuing to explore models over the full parameter space of solar wind plasma conditions and dynamo field strengths.

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