LUNAR CRUSTAL MAGNETIZATION FROM IMPACT-GENERATED PLASMA AMPLIFICATION OF THE LUNAR DYNAMO. I. S. Narrett¹, R. Oran¹, Y. Chen², K. Miljkovic³, G. Toth⁴, and B. P. Weiss¹, ¹Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA (narrett@mit.edu), ²Boston University, Center for Space Physics, Boston, MA, USA, ³Space Science and Technology Centre, School of Earth and Planetary Science, Curtin University, Perth, Australia, ⁴Climate and Space Sciences and Engineering, College of Engineering, University of Michigan, Ann Arbor, MI, USA.

Introduction: The Moon lacks a present-day global magnetic field, yet spacecraft and in situ measurements of the crust and laboratory analyses of Apollo samples have identified natural remanent magnetization (NRM) that formed in an ancient magnetic field (paleofield) [1, 2]. Analyses of Apollo samples provide records of past magnetic fields between 4.25 and 3.56 billion years (Ga) ago. The vast majority of these NRMs are thought to have been acquired as a theromorenmant magnetization (TRM) over periods of days to millions of years [1] in the presence of fields that possibly reached high paleointensities (>10–100 μT) [1]. A few Apollo samples may have also gained an NRM through exposure to high pressures (>0.1 gigapascal, GPa), resulting in the acquisition of shock or pressure remanent magnetization (SRM, PRM) [3]. Furthermore, the lunar crust has large regions (spanning >10^2 km) that are magnetized, producing anomalies >10 nT at spacecraft orbits (~30 km) [4]. Interestingly, some anomalies are located antipodally to large impact basins younger than 3.9 Ga (e.g., Imbrium) [5].

The source of the high inferred paleointensities is a central unknown in lunar science, eliciting various proposals for potential field sources. A past core dynamo magnetic field is consistent with the long cooling timescales required by the lunar sample TRMs. However, given the Moon’s small core (~14% of the lunar radius, RMoon [1]), convective dynamo scaling laws can only easily explain surface magnetic fields of ~1 μT [1]. This conundrum has allowed for an alternative proposal that the high fields were produced by impact plasma amplification of a solar wind field [5]. However, impact amplification of the solar wind cannot produce paleointensities above ~0.1 μT [6]. Here, we report three-dimensional (3D) magnetohydrodynamic (MHD) simulations that test the alternative hypothesis that the Moon was magnetized by impact-generated plasmas amplifying a past weak (~1 μT) core dynamo-generated magnetic field.

Objectives and models: We conducted the first self-consistent 3D-MHD simulations of impact plasma interacting with a dynamo field (Fig. 1). Our goal was to estimate the amplification of the field as a function of time and space. We modeled the formation of an Imbrium-sized impact basin and the subsequent vapor (plasma) ejecta using the iSALE-2D shock physics code [7]. We then incorporated the ionized vapor as a plasma source in our MHD simulations, utilizing the Block Adaptive Tree Solar-Wind Roe Upwind Scheme (BATS-R-US) code [8]. The MHD simulations comprised two stages: 1) simulation of the steady-state lunar magnetosphere’s interaction with the ancient solar wind; and 2) initiation of the expansion of the impact-generated plasma from the basin. For all lunar magnetosphere simulations, a lunar-centric magnetic dipole was prescribed such that the surface field is 2 μT at the magnetic pole [1], which is sufficiently strong to
form a 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, representative of the solar wind at 3.8 Ga [6]). The BATS-R-US code allows for the prescription of an electromagnetic response profile for a planetary body, thus allowing us to incorporate the resistive, magnetic-dissipative effects of the lunar crust [6]. To test various impact scenarios, we modeled the impact location at the magnetic pole (Case 1) and magnetic equator (Case 2). The simulation results were achieved using the most refined grid given computational limits (~17 km cell size in the radial and angular directions at the lunar surface). Because previous simulations with larger surface grid cells indicate that the maximum antipodal magnetic field is not resolved [9], the maximum antipodal amplified magnetic field values in each case represent minimum estimates.

**Results:** Just after the impact, the impact plasma expands out of the basin, forming a “magnetic cavity” in which the field is diminished by a factor >5 relative to the background value. As the vapor engulfs the Moon, the perfectly conducting impact plasma compresses the lunar magnetic field towards the antipodal region. The dominant mechanism for amplifying the dipole field is the conservation of magnetic flux, as analytically, the initial dipole field is compressed and amplified according to the ratio of surface areas between the antipodal convergence zone and the lunar hemisphere [5]. However, our MHD simulations show that the duration and magnitude of the maximum antipodal amplified magnetic field are inhibited by the magnetic dipole field geometry and the ohmic dissipative effects of the lunar crust.

For Case 1 (impact at the magnetic pole, Fig. 1), the antipodal magnetic field is maximized as parallel field lines are compressed together in the convergence zone. Thus, there is no current layer separation nor magnetic reconnection dissipation (see Case 2). Starting at ~40 minutes after impact, we find a maximum magnetic field of 180 μT at ~700 km above the lunar surface and a field of 42 μT in the antipodal surface center. The surface field strength remains above the initial polar surface field for ~40 minutes.

For Case 2 (impact at the magnetic equator), the maximum antipodal amplified magnetic field is inhibited due to the compression of anti-parallel field lines, forming a reconnection region where magnetic energy is converted into thermal and kinetic energy (physical reconnection is not captured by our simulations). This impact results in an antipodal magnetic field amplified to ~6 μT and lasting ~15 minutes. Additionally, this geometry causes the antipodal compression region area to be larger (relative to impact from the magnetic pole) due to the required spatial separation of the current layers, which are produced to decouple the anti-parallel magnetic field lines.

Lunar seismic observations and global impact simulations suggest that basin-forming impacts can induce seismic surface waves (~1.2-1.66 km/s) and body waves, which focus at the antipode and impart pressures of 0.1-2 GPa in the crust [10, this study]. Given that these pressures are imparted in the antipode between 55 and 75 minutes after impact, they may enable antipodal material to record the maximum amplification of the impact field seen in the MHD simulations between 50 and 70 minutes after impact as an SRM or PRM. In the presence of a 42 μT paleofield, a 30-km radius, <1 km thick cylindrical crustal disk with an SRM susceptibility of ~10⁻¹ (typical of chondritic impactor material [4]) can produce the observed 10 nT crustal field anomaly at 30-km altitude. As the Imbrium antipodal region is within the South-Pole Aitken (SPA) basin (~4.2 Ga) [4], which formed prior to the Imbrium impact event, it is possible that chondritic material from the SPA impactor was present in this region [4]. Furthermore, given the higher range of initial surface field strengths (~10⁻¹ μT) of other lunar dynamo mechanisms (basalt magma ocean, core and mantle precession [1, 2]), this same crustal magnetic field could be produced by lunar material in 5-10 km thick layers, with SRM magnetic susceptibility ~10⁻³ (typical of mafic impact-melt breccias) and paleofield of ~400 μT.

**Conclusion:** Our MHD simulations of an Imbrium-sized impact show that it is possible that the large lunar crustal magnetic field anomalies could be produced by impact plasma amplification of an ancient core dynamo magnetic field with a weak strength compatible with dynamo scaling laws. Future lunar sample return and surface magnetometry missions like the Endurance rover [11] can explore the large basin antipodes and search for evidence of SRM or PRM from ancient lunar dipole amplification.


*Extending the radius of the magnetized surface area to ~100-km allows for a factor of 2 decrease in the required thickness of the magnetized layer [4].