PLANETARY SCIENCE

When the Moon had a magnetosphere

James Green[1]*[†], David Draper[1†], Scott Boardsen[2†], Chuanfei Dong[3†]

Apollo lunar samples reveal that the Moon generated its own global magnetosphere, lasting from ~4.25 to ~2.5 billion years (Ga) ago. At peak lunar magnetic intensity (4 Ga ago), the Moon was volcanically active, likely generating a very tenuous atmosphere, and, it is believed, was at a geocentric distance of ~18 Earth radii (R_E). Solar storms strip a planet's atmosphere over time, and only a strong magnetosphere would be able to provide maximum protection. We present simplified magnetic dipole field modeling confined within a paraboloidal-shaped magnetopause to show how the expected Earth-Moon coupled magnetospheres provide a substantial buffer from the expected intense solar wind, reducing Earth's atmospheric loss to space.

INTRODUCTION

The prevailing model for the generation of the Moon is the giant impact hypothesis in which an approximately Mars-sized object, named Theia, collided with the proto-Earth during the early formation of the solar system (1). The resulting debris formed Earth and the Moon, ending with the Moon lying just outside the Roche limit of ~2.9 R_E (2). Under this hypothesis, the resulting lunar iron core would be much smaller than the core Theia is thought to have had. For decades, it was assumed that the Moon would not have the ability to generate and maintain a substantial magnetic dynamo from this small core.

The magnetometer on the Soviet Luna 1 spacecraft that flew by the Moon on 4 January 1959 made the first lunar magnetic field measurements. The Luna 1 measurements showed that the Moon did not have an intrinsic magnetic field that was more than 1/10,000th that of Earth. It was not until the magnetometer that the Apollo 12 astronauts delivered to the surface of the Moon that a weak magnetic field, a thousand times weaker than Earth's present-day field, was finally measured. This field is a magnetic memory of the earlier eras of the Moon preserved in the rocks on the surface, of which many were brought back by the Apollo astronauts for laboratory analysis. Over the past several years, however, as paleomagnetists began a careful reexamination of all of the returned Apollo lunar samples using modern analysis techniques, a transformational concept has emerged. These paleomagnetic measurements now make clear that a substantial lunar magnetosphere must have existed for the first several hundred million years of the Moon's history. Reasons for the generation of the lunar magnetic field and when it finally dissipated are still being debated (3–4).

An overview of the evolution of the Moon's magnetic field is shown schematically in Fig. 1, adapted from (4). The solid curve is the range of magnetic measurements plotted against the ages of the Apollo samples analyzed. The inferred lunar dynamo maximum field ranges from 20 to 100 µT over the period ~4.25 to ~3.5 billion years (Ga) ago and then drops to ~5 µT by ~3.2 Ga ago. Recent work inferred ~5-µT field strength in impact breccias that are between 1 and 2.5 Ga old (3). Also shown on this figure is the surface minimum and maximum of Earth's current magnetic field, showing that in the

age range from 4.2 to 3.4 Ga ago, the Moon's field was at least as strong, or possibly stronger, than Earth's magnetic field of today on their respective surfaces.

Determining Earth's very early magnetic dynamo strength (i.e., before the late heavy bombardment ~3.9 Ga ago) has been difficult due to active geological processes that eliminated that rock record (5). It has been suggested that the strength of the early Earth's magnetic field might be scaled with rotation (6). Because, in the giant impact hypothesis, Earth is left with a 5-hour rotational period after the formation of the Moon 4.5 Ga ago, the resulting magnetic field may have been quite strong but others point to many unresolved issues in dynamo theory (7), leaving an understanding of the intensity of the very early magnetic field largely unresolved. The most recent 2 Ga of Earth's paleomagnetic record does indicate that the geodynamo has been nearly constant (8) and, if averaged over millions of years, appears like a simple dipole or bar magnet with magnetic poles paralleling Earth's rotational axis.

Zharkov (9) estimated that the Earth-Moon distance was only 21 R_E about 3.9 Ga ago, based on gravity measurements made by the Clementine spacecraft data. Thus, Earth and the Moon were in comparatively close proximity at a time when the Moon had an effective magnetic dynamo operating. How would these two magnetospheres interact, and what protection would such a combined magnetosphere afford to the atmospheres of early Earth and Moon?

Here, we report qualitative results of magnetic field modeling to understand the extent to which the expected Earth-Moon coupled magnetospheres work together to protect the atmospheres of both Earth and the Moon within the solar wind environment ~4 Ga ago. Recent research has shown feasible conditions under which a tenuous atmosphere (tens to hundreds of pascals) would form owing to the degassing of voluminous lunar magmas during approximately the same time frame as outlined above (10). This early lunar atmosphere would necessarily play a key part in transporting any volatiles across the lunar surface to be sequestered into the cold traps of permanently shadowed lunar polar regions.

We modeled a dipole field simulating the main field of Earth with the range in its intensity as depicted in Fig. 1, which is Earth's field strength of today. We modeled conditions when the Moon was at 18 R_E from Earth and under two diurnal configurations. The first has the Moon at 12 hours local time (LT), i.e., noon, and the second at 0 LT, midnight. In other words, at 12 LT, the Moon is between Earth and the Sun, whereas at 0 LT, Earth is between the Sun and the Moon in geocentric solar ecliptic (GSE) coordinates.

[1]NASA Headquarters, Washington, DC, USA. [2]University of Maryland Baltimore County, Baltimore, MD, USA. [3]Department of Astrophysical Sciences and Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA.
*Corresponding author. Email: james.green@nasa.gov
†These authors contributed equally to this work.

MATERIALS AND METHODS

Model assumptions

The objective of this study was to develop a qualitative topology of the magnetospheres of early Earth and the Moon confined within a single magnetopause. To model the lunar dynamo magnetic field, certain assumptions must be made. A magnetic dipole is the simplest expression of a planetary intrinsic magnetic field; therefore, we used a dipole that is aligned to the rotational axis (normal to the solar ecliptic plane) with an intensity defined by the derived paleo field from the lunar samples. There are lunar crustal magnetic anomalies that imply possible paleo poles in many locations, some of which are near
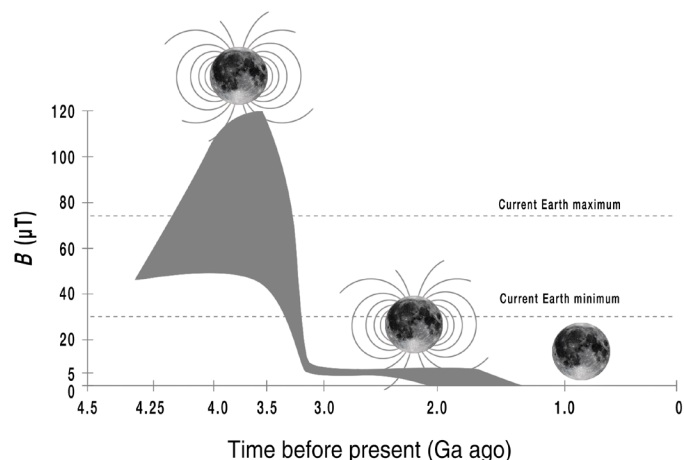

Fig. 1. The magnetic field intensity versus time of the Moon. This schematic is adapted from Fig. 4 of Mighani *et al.* (*4*), providing the history of the remnant magnetic field from Apollo lunar samples. The envelope shows the variation in the field and may indicate that the lunar magnetic field went through a number of reversals during its early history. Also shown as dashed lines is the surface minimum and maximum of the current Earth's magnetic field in comparison to that of the Moon.

antipodal from each other. There are not enough oriented paleomagnetic lunar samples to infer reversals occurring at some cadence, as occurs on Earth, but we do expect the lunar magnetic field to reverse polarity (*11*). Therefore, the modeling here will use a lunar dipole field that is both aligned and antialigned with Earth's magnetic field.

For simplicity, we exclude ring currents, Birkeland and Earth-Moon (field-aligned) currents, and tail currents. The magnetic fields of Earth and the Moon are approximated by dipoles with magnetic moments directed in the Z_{GSE} direction of -3×10^4 and $\pm 1 \times 10^3$ nT R_E^3, respectively, located along the aberration-corrected X_{GSE} axis.

The boundary between a magnetosphere and the surrounding solar wind is the magnetopause. Its location is determined primarily by the balance between the solar wind pressure and the magnetic pressure of Earth's magnetic field. When the Moon is on the dayside, the shape of the composite magnetopause formed by the Earth-Moon system is expected to be complex. A complex, pressure balance–modeled magnetopause shape and its resulting shielding magnetic field are beyond the scope of this study; thus, we used a paraboloidal shape for the magnetopause as a proxy.

Stern (*12*) showed, for a magnetopause with a paraboloidal shape symmetric about the *x* axis and with internally generated magnetic fields given by magnetic dipoles of arbitrary orientation located along the *X* axis, that the shielding field can be given by an infinite sum of magnetic potentials [Eq. 16 of (*12*)]. For each of the Earth-Moon magnetosphere configurations used here, we computed the coefficients of Eq. 16 (one set for each dipole) of Stern (*12*) using his Eqs. 19 and 20. As in Stern (*12*), we computed the first 20 coefficients of the infinite sum with $A = 20$ (shielding is valid to about ~200 R_E down the tail). To define the paraboloidal shape of the magnetopause, the nose of the paraboloid is located at the subsolar point, whose location is computed using pressure balance ($P_{SW} = 2B_D^2/\mu_0$), where P_{SW} is the solar wind dynamic pressure, B_D is the magnetic field from the sum of the two dipoles, and μ_0 is the magnetic permeability. For
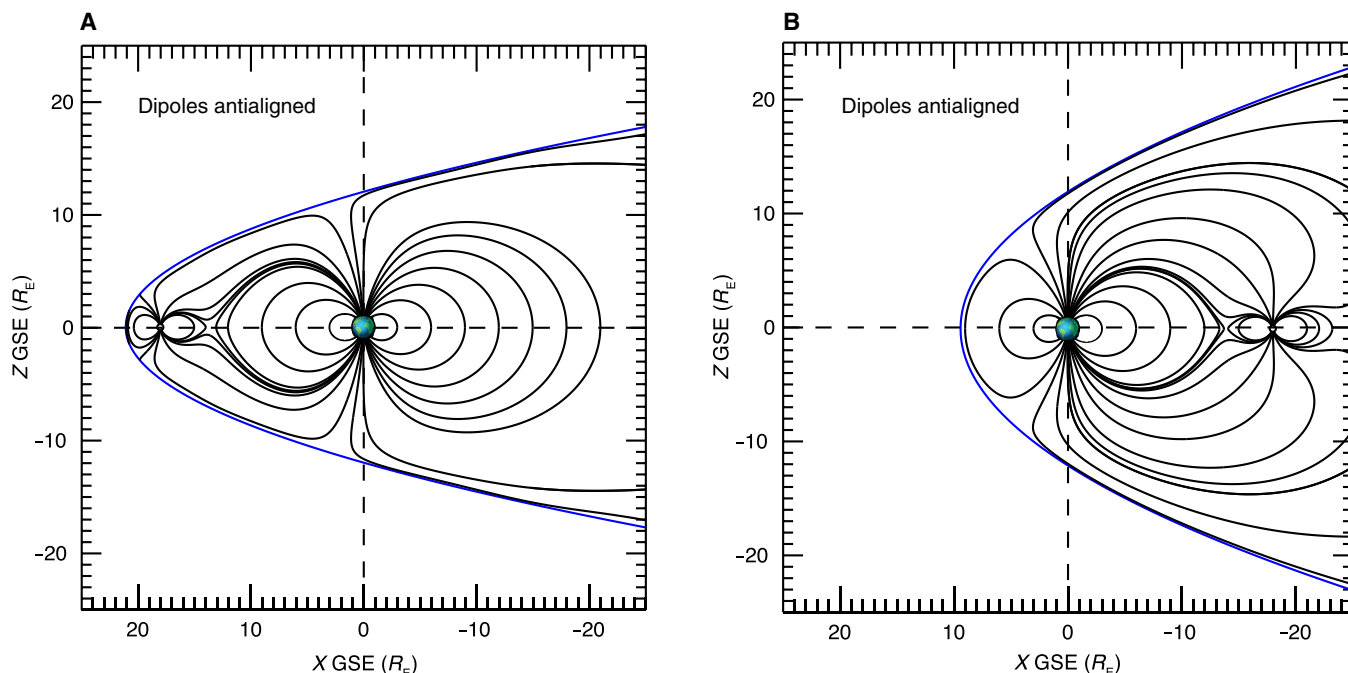

Fig. 2. Earth-Moon coupled magnetospheres antialigned. Simulation results for the Earth-Moon coupled magnetospheres with the dipoles antialigned and the Moon located at 18 R_E from Earth in GSE coordinates. (A) has the Moon located at 12 LT and (B) at 0 LT with the solar wind flowing left to right.
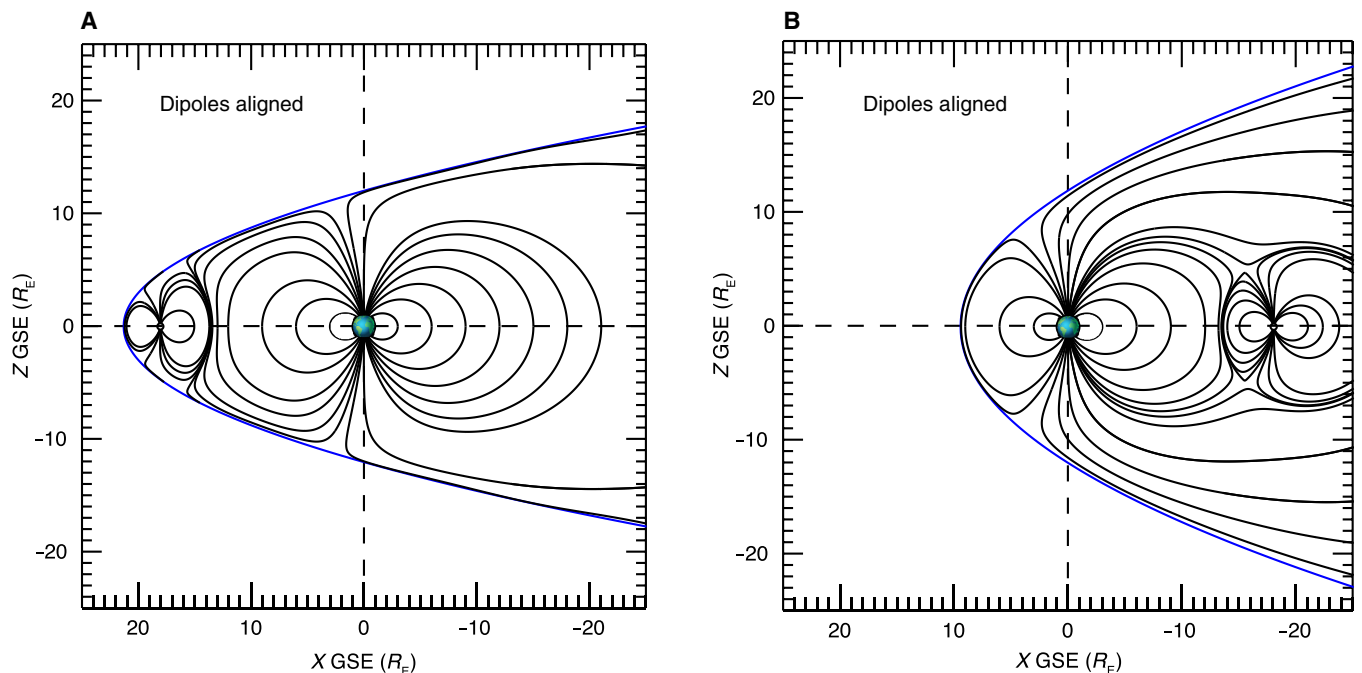
Fig. 3. Earth-Moon coupled magnetospheres aligned. Similar to Fig. 2 but with Earth-Moon magnetospheres generated from dipoles aligned with the solar wind flowing from left to right.

Figs. 2 (A and B) and 3 (A and B), the total magnetic field used is the sum of Earth and lunar dipole fields plus the field from the sum of the 40 shielding magnetic potentials. The magnetic topology, reported here, is created by field-line tracing within this total magnetic field framework.

RESULTS

Simulation results for the Earth-Moon dipoles that are antialigned are shown in Fig. 2, with the Moon located at 12 LT in Fig. 2A and the Moon at 0 LT in Fig. 2B. The major feature shown in Fig. 2 is a consequence of the reconnected field lines between Earth and the Moon, which occur primarily at high and midlatitudes. Direct solar wind precipitation occurs through the location of the two field lines that split their direction from dayside to nightside, termed the "polar cusp." When comparing Fig. 1A with Fig. 1B, it is clear that for the Moon on the dayside, the cusp moves poleward by ~10°, largely cutting off direct solar wind access and reducing the solid angle of the polar cap. Polar cap field lines that connect into the solar wind (called open field lines) enable ionospheric plasma to escape. Reductions in the solid angle of the polar cap would also contribute to the reductions in ionospheric plasma loss. In addition, Fig. 1A clearly shows how the lunar magnetosphere would take the brunt of the solar wind, no matter how intense, and provide an additional effective shield to Earth's atmosphere. Fig. 1B shows the extensive reconnection of the lunar magnetic field in the region of Earth's plasma sheet. The plasma sheet contains both Earth's ionospheric plasma, which comes from the electromagnetic drift of this evaporated plasma from polar and midlatitude field lines, as well as solar plasma into Earth's magnetic equator. The addition of the Moon's magnetosphere disrupts the traditional near-Earth plasma sheet and captures much of the evaporated Earth's ionospheric plasma onto the Moon.

Figure 3 presents the simulation results with both the Earth-Moon magnetospheric dipoles aligned. The meaning of these results is that the Moon's magnetosphere, confined by the solar wind and Earth's

magnetosphere in Fig. 3A and enveloped by the Earth's magnetosphere in Fig. 3B, becomes a protective magnetic bubble. Even in this configuration, the polar cusp moves poleward in Fig. 3A with a reduced solid angle of the polar cap. In Fig. 3B, the normal location of the plasma sheet is, once again, disrupted, but in this example, Earth's midlatitude field lines maintain connection with the opposite hemisphere, which would create a larger than normal plasmasphere.

DISCUSSION

The magnetosphere topology presented here, using the recent findings of the Moon's early magnetic field cited here, demonstrates that the magnetosphere of the Moon creates a previously unrecognized barrier to the solar wind that must be taken into account and which may mitigate many of the effects of solar radiation extremes. Previous research called into question the ability of the early Earth's magnetic field to shelter its atmosphere from erosion by intense solar wind, ultraviolet, and x-ray radiation from the young Sun, which would have promoted the loss of volatiles, including water (5). The ability of a magnetosphere to shield an atmosphere from erosion by the solar wind has been studied extensively [e.g., (13)]. Weak intrinsic magnetic fields, those in which the resulting magnetopause would be located below an induced magnetosphere boundary, would actually enhance ion escape. These conditions typically occur when the magnetopause is within one radius of the planetary body in the solar wind. Earth is a strongly magnetized body producing substantial shielding [e.g., (14)] with a magnetopause at up to 10 planetary radii away (see Fig. 2B). As shown in Fig. 2A, the lunar magnetosphere is also sufficiently strong that the lunar magnetopause is at ~8 lunar radii from the lunar surface. As shown in Fig. 1, a strong lunar magnetosphere would exist between ~4.2 and ~3.1 Ga ago. The rapid decline of the lunar magnetic field would be accompanied by a rapid loss of the lunar atmosphere, bringing it to the condition we measure today.

Detailed analysis of the composition of Apollo surface material shows that nitrogen is imbedded in the lunar soils. From isotope analysis, Ozima *et al.* (*15*) concluded that nitrogen and some of the other volatiles trapped in lunar soils may actually have come from Earth's atmosphere rather than from the solar wind. To make this a viable conclusion, the authors invoked a scenario in which the early Earth and Moon had no protective magnetospheres, but aided by direct solar wind stripping of Earth's atmosphere, the nitrogen would be implanted in the lunar soils. Earth's atmospheric components N^+ and N^{++} are routinely observed in the modern-day plasmasphere (within closed magnetic field lines), with N^+ ions also seen flowing out of the polar cap on open field lines (*16*). In a similar way, O^+ and O^{++} have also been observed in Earth's magnetosphere (*17*). With the recent knowledge of the existence of an early lunar magnetosphere, which would inhibit solar wind implantation, we propose that the connection of the two magnetospheres, as illustrated in both panels of Fig. 2, would greatly facilitate Earth-to-Moon atmospheric implantation. The existence of the process modeled here means that there was an epoch of early Earth-Moon history, during which the combined magnetospheres protected primordial volatiles on these two worlds from being stripped away by the solar wind, and this epoch coincides with the era of the "faint young sun." Previous work from modeling and simulations along with observations of younger sun-like stars indicate that during times of the faint young sun, the space weather of the solar system was much more extreme, with many more frequent coronal mass ejections that carried 10 to 100 times more solar mass than the solar wind is capable of ejecting in a given time. (*18*). The age relationships shown on Fig. 1 indicate that the epoch of Earth-Moon coupled magnetospheres lasted for hundreds of millions of years, from ~4.1 to ~3.5 Ga ago. Our modeling shows that the joined magnetospheres can protect even against this more active early Sun and provides a more realistic explanation of the results from Ozima *et al.* (*15*).

NASA's return to the Moon via the Artemis program will provide an extremely important opportunity to test the sequence of events hypothesized here. One of the main scientific goals of the Artemis program is to collect and analyze cores from the permanently shadowed cratered regions of the lunar south pole. These cores will collect regolith within which volatile-rich materials, including water ice, are thought to reside in some form (*19*, *20*). If analyzable ices are recovered in these cores, their isotopic compositions, preserved within a time-stratigraphic relationship, may reveal the presence of volatile components with early terrestrial provenance, which would be strong support for the existence of conjoined magnetospheres as outlined here. Such a finding would provide crucial clues necessary to unravel the history of the evolution of the Earth-Moon system.

Coupled planet-moon magnetospheres are likely to be of great importance for the study of exoplanets that are exposed to extreme stellar wind and particle radiation conditions. It is well recognized [e.g., (*21*, *22*)] that stellar winds from M-type stars can be extremely harsh to the point of blowing away atmospheres from rocky exoplanets residing within the habitable zones of the host stars. In addition, M-type stars are highly magnetically active. For example, rocky exoplanets orbiting M-type stars would experience flares 1000 times stronger than our G-type Sun produces in modern times. To understand the long-term evolution of exoplanetary atmospheres and their suitability for creating a habitable environment that may lead to life, we must understand not only the strength of stellar emissions from supersonic stellar winds to high-energy radiation, but now also whether these planets and their associated moons have strong magnetospheres.

CONCLUSIONS

The results of our magnetic field topological modeling demonstrate a critical and previously unrecognized condition: that Earth-Moon coupled magnetospheres work together to protect the early atmospheres of both Earth and the Moon. The configurations studied place the Moon at 18 R_E from Earth at 12 LT and at 0 LT with a dipole-generated magnetosphere consistent with what is expected from the analysis of lunar samples. These results indicate that during times of opposite magnetic polarity, the two closely spaced magnetospheres will reduce the size of Earth's magnetic polar cap that has "open" field lines. At times when the Moon is on the dayside of Earth, the lunar magnetosphere would provide a substantial additional buffer from the expected intense solar wind regardless of polarity alignment, reducing Earth's atmospheric loss to space. In addition, during times when the magnetospheres had opposite polarity, magnetic reconnection would create a critical pathway for the atmosphere of the early Earth to be implanted into the lunar soils.

Our identification of the magnetic topology of coupled planetary magnetospheres, from a planet and its moon, is relevant not only for the study of the early Earth and Moon but also for the habitability of exoplanets. Having now established this concept, additional modeling can be conducted with more complicated, and potentially more realistic, configurations. Our hypothesis of a conjoined magnetosphere protecting these early atmospheres will be testable upon the return of volatile-bearing regolith cores from the lunar poles as part of NASA's Artemis program.

REFERENCES AND NOTES

1. R. M. Canup, E. Asphaug, Origin of the Moon in a giant impact near the end of the Earth's formation. *Nature* **412**, 708–712 (2001).
2. E. Kokubo, S. Ida, J. Makino, Evolution of a circumterrestrial disk and formation of a single Moon. *Icarus* **148**, 419–436 (2000).
3. S. M. Tikoo, B. P. Weiss, D. L. Shuster, C. Suavet, H. Wang, T. L. Grove, A two-billion-year history for the lunar dynamo. *Sci. Adv.* **3**, e1700207 (2017).
4. S. Mighani, H. Wang, D. Shuster, C. Borlina, C. Nichols, B. Weiss, The end of the lunar dynamo. *Sci. Adv.* **6**, eaax0883 (2020).
5. J. A. Tarduno, E. G. Blackman, E. E. Mamajek, Detecting the oldest geodynamo and attendant shielding from the solar wind: Implications for habitability. *Phys. Earth Planet. Inter.* **233**, 68–87 (2014).
6. D. J. Stevenson, Planetary magnetic-fields. *Rep. Prog. Phys.* **46**, 555–620 (1983).
7. P. H. Roberts, G. A. Glatzmaier, Geodynamo theory and simulations. *Rev. Mod. Phys.* **72**, 1081–1123 (2000).
8. P. E. Driscoll, Simulating 2 Ga of geodynamo history. *Geophys. Res. Lett.* **43**, 5680–5687 (2016).
9. V. N. Zharkov, On the history of the lunar orbit. *Solar System Research* **34**, 1 (2000).
10. D. H. Needham, D. A. Kring, Lunar volcanism produced a transient atmosphere around the ancient Moon. *Earth Planet. Sci. Lett.* **478**, 175–178 (2017).
11. F. Takahashi, H. Tsunakawa, H. Shimizu, H. Shibuya, M. Matsushima, Reorientation of the early lunar pole. *Nat. Geosci.* **7**, 409–412 (2014).
12. D. P. Stern, Parabolic harmonics in magnetospheric modeling: The main dipole and the ring current. *J. Geophys. Res.* **90**, 10851–10863 (1985).
13. H. Egan, R. Jarvinen, Y. Ma, D. Brain, Planetary magnetic field control of ion escape from weakly magnetized planets. *Mon. Not. R. Astron. Soc.* **488**, 2108–2120 (2019).
14. C. Dong, M. Jin, M. Lingam, Atmospheric escape from TOI-700 d: Venus versus Earth analogs. *Astrophys. J. Lett.* **896**, L24 (2020).
15. M. Ozima, K. Seki, N. Terada, Y. N. Miura, F. A. Podosek, H. Shinagawa, Terrestrial nitrogen and noble gases in lunar soils. *Nature* **436**, 655–659 (2005).
16. C. R. Chappell, R. C. Olsen, J. L. Green, J. F. E. Johnson, J. H. Waite Jr., The discovery of nitrogen ions in the Earth's magnetosphere. *Geophys. Res. Lett.* **9**, 937–940 (1982).
17. W. T. Roberts Jr., J. L. Horwitz, R. H. Comfort, C. R. Chappell, J. H. Waite Jr., J. L. Green, Heavy ion density enhancements in the outer plasmasphere. *J. Geophys. Res.* **92**, 13499–13512 (1987).
18. S. R. Cranmer, Mass-loss rates from coronal mass ejections: A predictive theoretical model for solar-type stars. *Astrophys. J.* **840**, 114 (2017).

19. A. Colaprete, P. Schultz, J. Heldmann, D. Wooden, M. Shirley, K. Ennico, B. Hermalyn, W. Marshall, A. Ricco, R. Elphic, D. Goldstein, D. Summy, G. D. Bart, E. Asphaug, D. Korycansky, D. Landis, L. Sollitt, Detection of water in the LCROSS ejecta plume. *Science* **330**, 463–468 (2010).

20. V. R. Eke, L. F. A. Teodoro, R. C. Elphic, The spatial distribution of polar hydrogen deposits on the Moon. *Icarus* **200**, 12–18 (2009).

21. C. Dong, M. Jin, M. Lingam, V. S. Airapetian, Y. Ma, B. van der Holst, Atmospheric escape from the TRAPPIST-1 planets and implications for habitability. *Proc. Natl. Acad. Sci. U.S.A.* **115**, 260–265 (2018).

22. J. Linsky, *Host Stars and their Effects on Exoplanet Atmospheres* (Springer, 2019), vol. 955.

Citation: J. Green, D. Draper, S. Boardsen, C. Dong, When the Moon had a magnetosphere. *Sci. Adv.* **6**, eabc0865 (2020).