

Supplementary Materials for

Terrestrial atmospheric ion implantation occurred in the nearside lunar regolith during the history of Earth's dynamo

Shubhonkar Paramanick[‡] *et al.* (2025)

[‡]Corresponding author. Email: shubhonkar.paramanick@rochester.edu

This PDF file includes:

- ☐ Supplementary Discussion
 - Section S1: Analytic scaling relations governing atmospheric mass loss flux in the MHD regime
 - Section S2: Limitations of the model
 - Section S3: Evidence for a very early geomagnetic field
- ☐ Supplementary Data
 - Figures SD1 to SD5
 - Tables SD1 to SD4

Analytic scaling relations governing atmospheric mass loss flux in the MHD regime

We compare the density dependence of empirical scaling relations for atmospheric mass-loss flux, obtained from different MHD simulations, with a simple fluid-flow model for both magnetized and unmagnetized cases, which offers some valuable insights into the complex plasma interaction model discussed earlier in this paper.

Escaping mass flux from unmagnetized Earth

Consider a SW flow with velocity $\vec{v}_{SW}$, and density and pressure given by ρ_{SW} and p_{SW} , respectively. This flow is incident on Earth's atmosphere, which is also modeled as a fluid. Let the atmospheric outflow velocity, mass density, and pressure be given by $\vec{v}_{AO}$, ρ_{AO} , and p_{AO} , respectively, in the quasi-steady state. Since the momentum (and energy) of the fluid interaction must be conserved, we can readily relate the flow parameters on the dayside as follows:

$$p_{SW}^{(Ram)} + p_{SW}^{(Th)} = \frac{\rho_{AO} v_{AO}^2}{2} + p_{AO} \quad (1)$$

The thermal and magnetic pressures exerted by the SW are assumed to be negligible compared to the SW ram pressure, as they are typically one to two orders of magnitude smaller. At the stagnation point, there is an exact balance between the SW ram pressure and the atmospheric thermal pressure, and the flow squeezes out from that point. Thus, the outflow speed is a manifestation of the thermal pressure. This results in the relation

$$\frac{\rho_{SW} v_{SW}^2}{2} = \frac{\rho_{AO} v_{AO}^2}{2} \quad (2)$$

Defining the outflow gas pressure in terms of the sound speed $c_{AO} = [\gamma_{AO} p_{AO} / \rho_{AO}]^{\frac{1}{2}}$ on the dayside, we obtain the expression for the escaping flux

$$\mathcal{F}_{A, UM}^{(Day)} = \rho_{AO} v_{AO} = \frac{\gamma_{AO} p_{AO} v_{AO}}{c_{AO}^2} \quad (3)$$

The atmospheric mass flux escaping from the nightside at the lunar location in the unmagnetized case is given by

$$\mathcal{F}_{A, UM} = \zeta_{UM} \sqrt{\rho_{AO} \rho_{SW} v_{SW}^2} \quad (4)$$

The dimensionless constant ζ_{UM} , determined from MHD simulations, represents the decrease in planetary flux from near the plasmopause to the Moon and any difference in mass loading fraction between the dayside and nightside. For unmagnetized Earth, the SW impinges on and ablates the top of the atmosphere. Thus, the above

expression for mass flux can be rewritten as a function of the atmospheric surface density:

$$\mathcal{F}_{A, UM} = \zeta_{UM} \left[\rho_{o, UM} \rho_{SW} v_{SW}^2 e^{-\frac{z_{PP}}{H_{UM}}} \right]^{\frac{1}{2}} \quad (5)$$

This implies that the flux is proportional to the square root of product of the base density and SW density (Figure SD5).

Escaping mass flux from magnetized Earth

For the present Earth with an intrinsic dipolar field, the total pressure in magnetized plasma is given as the sum of the kinetic pressure, the thermal pressure, and the magnetic pressure. Since the SW is dominated by the dynamic pressure, and the flow-frame pressure away from the current sheet in the magnetotail is dominated by the magnetic rather than the thermal pressure, the momentum conservation (Equation 1) in the dayside region is modified to

$$\frac{\rho_{SW} v_{SW}^2}{2} = \frac{\rho_{AO} v_{AO}^2}{2} + \frac{\rho_{AO} v_{Alf, AO}^2}{2} \quad (6)$$

Here $v_{Alf, AO} = [B_{GF}^2 / \mu_o \rho_{AO}]^{\frac{1}{2}}$ is the Alfvén velocity of the outflow. The nightside, where a significant amount of planetary material escapes, exhibits a low magnetic field strength. The escaping mass flux from magnetized Earth simplifies to

$$\mathcal{F}_{A, M} = \zeta_M \left[\frac{\rho_{o, M} e^{-\frac{r_{\beta p} - R_{\oplus}}{H_M}}}{\left[\frac{r_{MP}}{r_{\beta p}} \right]^{\xi}} \rho_{SW} v_{SW}^2 \right]^{\frac{1}{2}} \quad (7)$$

Thus, the mass flux again varies as the square root of product of the base density and SW density (Figure SD5).

Our semi-analytic scaling relations for the EW mass flux to the Moon depend only on the SW ram pressure, the terrestrial atmospheric surface density, the scale height, and a numerically determined geometric constant for both magnetized and unmagnetized Earth cases with different lunar orbits, corresponding to the contemporary and primordial Earth-Moon systems. The SW flux at the lunar location, on the other hand, exhibits an almost linear scaling with its ram pressure. These scaling relations are useful for estimating the SW and EW mass fluxes without having to extend the range of simulations.

Limitations of the model

Planetary Rotation

We do not include the effect of the planet's rotation in our simulations. Given the Earth's relatively low angular velocity, we find that the axial components of both the centrifugal and Coriolis forces are typically negligible

compared to the magnetic force in the interaction region $\left(|2 \vec{\Omega} \times \vec{v}| / \rho, | \vec{\Omega} \times \vec{\Omega} \times \vec{r} | / \rho \ll \frac{B^2}{2} \right)$. Hence, we do not benefit much from using a frame of reference co-rotating with the planet.

Cartesian Grid and Diffusion

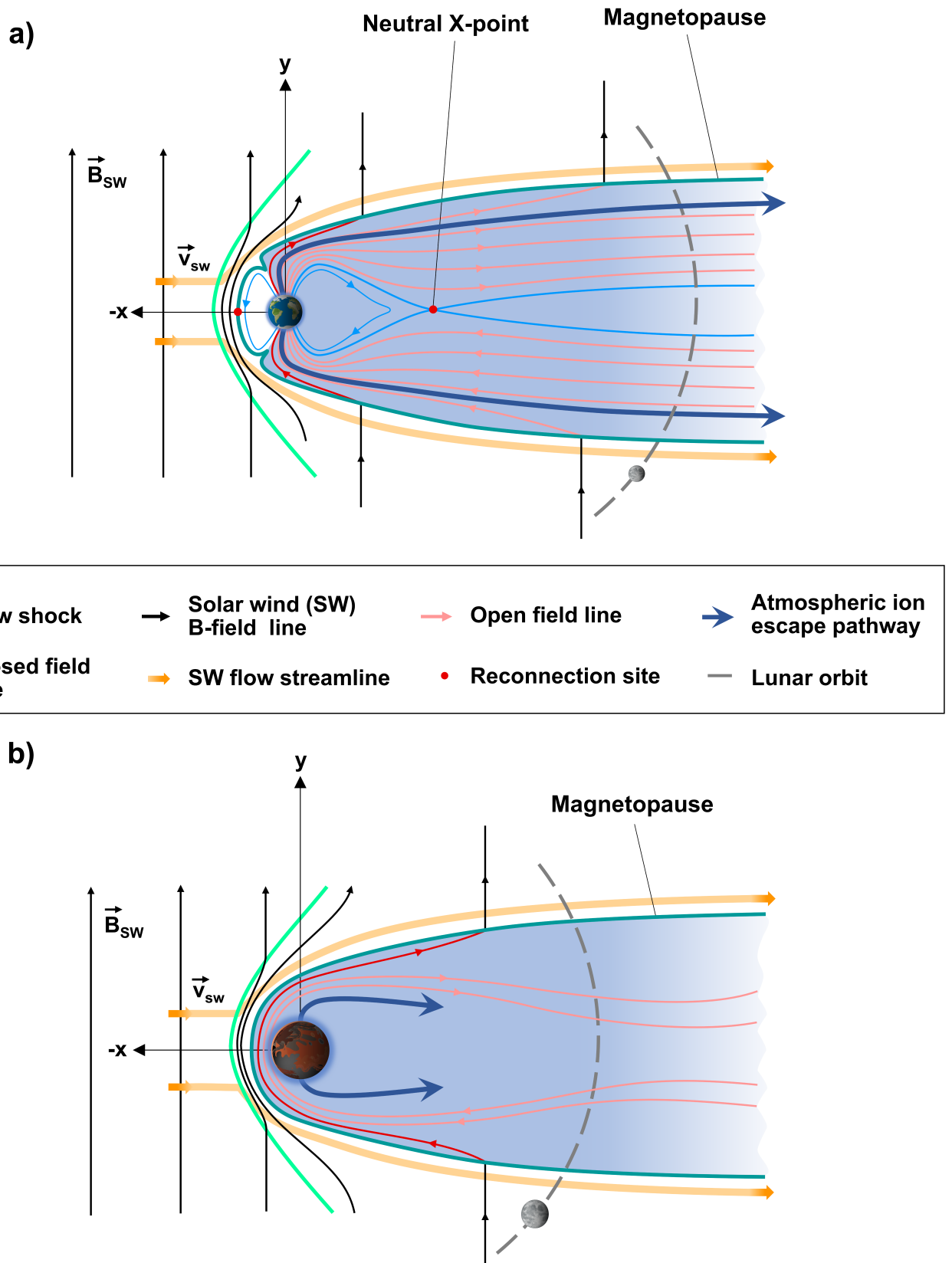
AstroBEAR currently lacks the capability to conduct simulations in spherical coordinates, resulting in minor, stair-step-like artifacts within our planetary grid models. These artifacts tend to diminish as the resolution or mesh refinement level is increased, but the incremental gain in computational precision does not justify the additional time and resources required.

For simulations involving the present-day geomagnetic field, we observed that certain cells at reconnection sites became over-saturated with magnetic field values, leading to a reduction in the global time step size and eventual simulation slowdown. To address this issue, we implemented controlled numerical diffusivity within the simulation box, which facilitated faster attainment of steady-state convergence and effectively mitigated the problem.

Evidence for a very early geomagnetic field

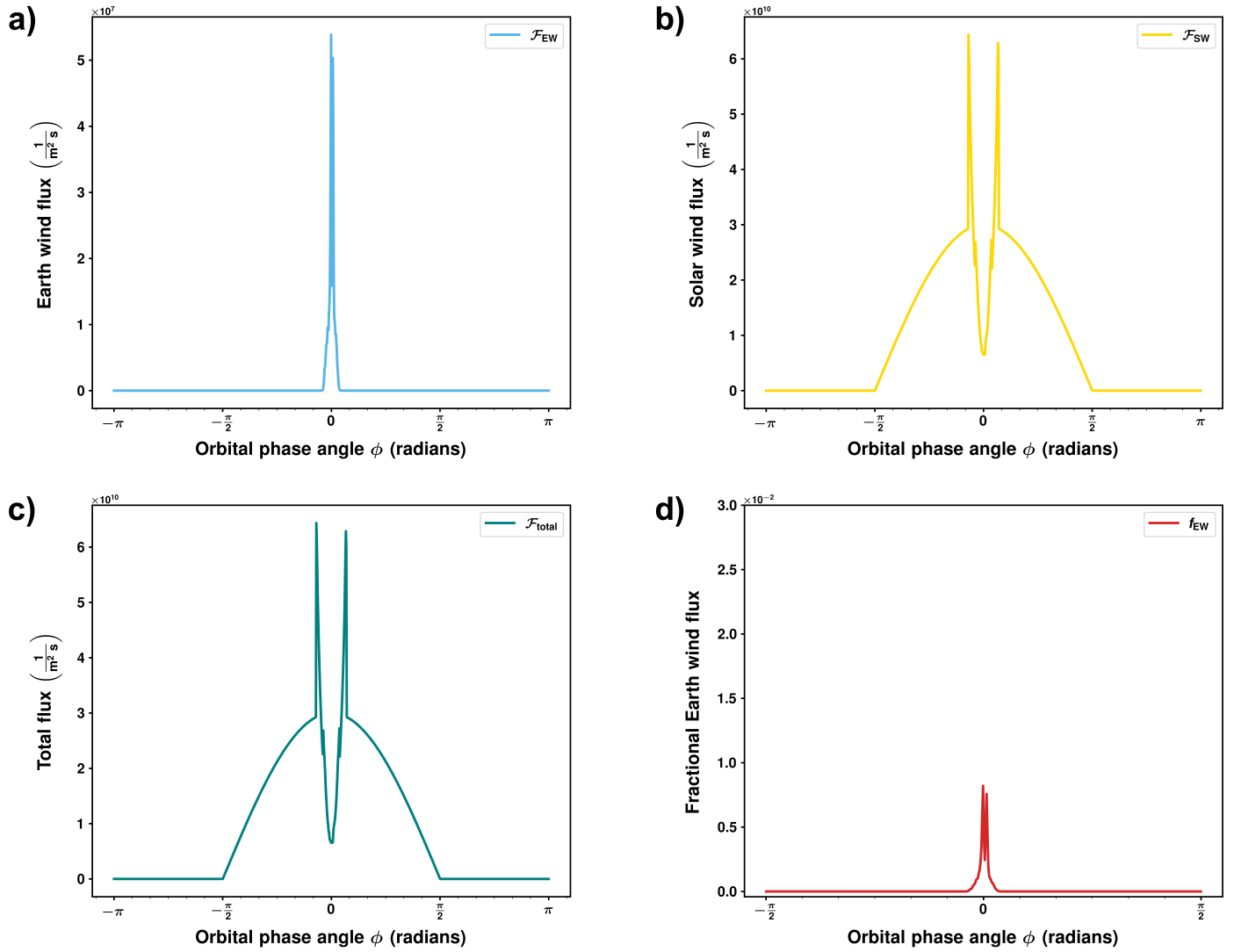
Earth's oldest extant rocks have been affected by ubiquitous metamorphism and are therefore not suitable for analyses to determine past geomagnetic field strengths¹. However, detrital minerals now found in younger, weakly metamorphosed sedimentary rocks may contain primary magnetic inclusions that preserve this history. The oldest evidence for the geomagnetic field comes from detrital zircons from the Jack Hills of Western Australia². Since this report, efforts have been made to disprove these results (e.g., Tang et al.³), but subsequent systematic geochemical, radiometric, and electron microscopy studies have demonstrated the presence of primary magnetite, replicated paleointensity-age histories, and other associated paleomagnetic tests that support the original evidence^{4–6}.

Supplementary Data

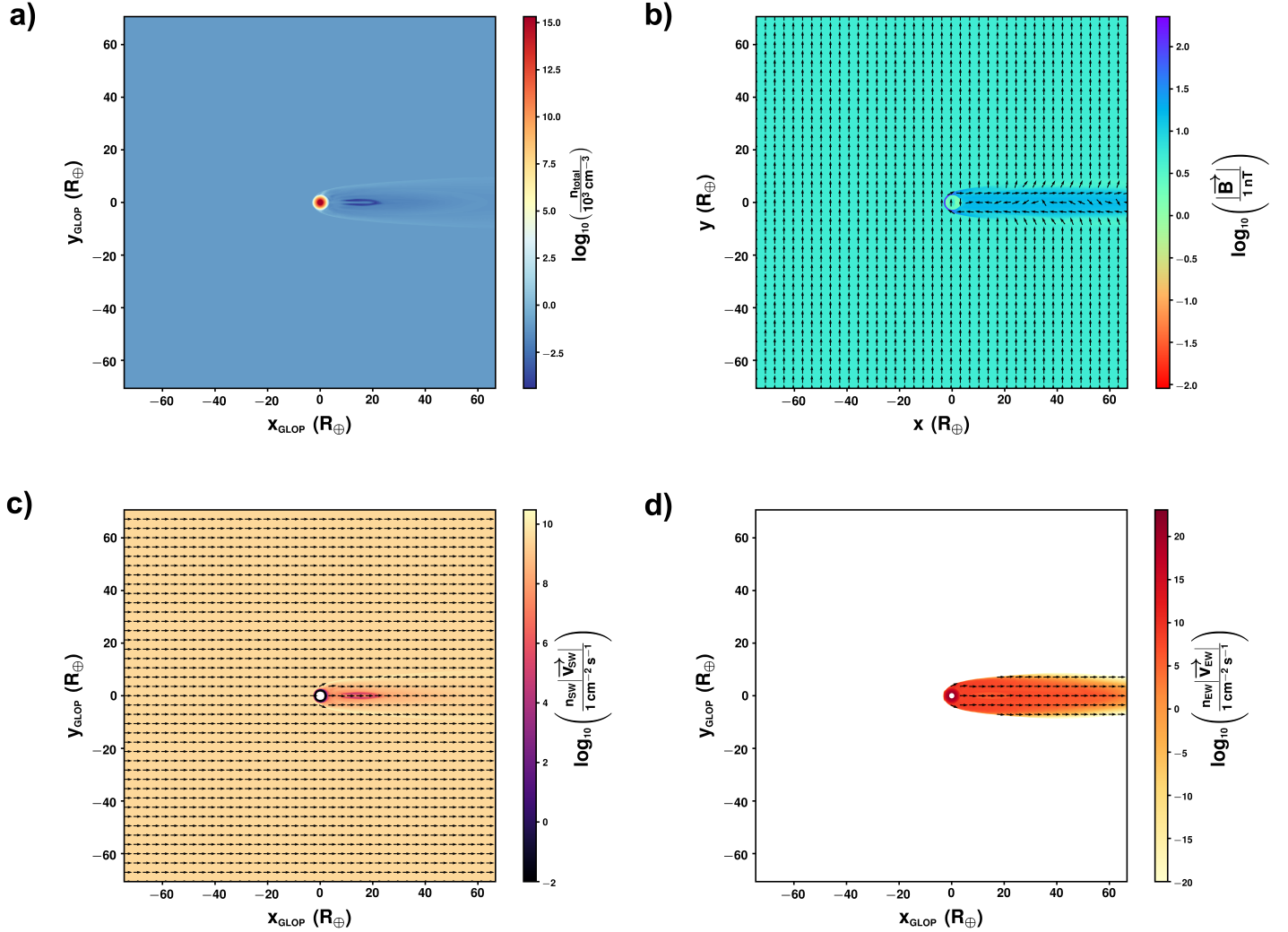


Supplementary Data Figure SD1: Description continued on the following page.

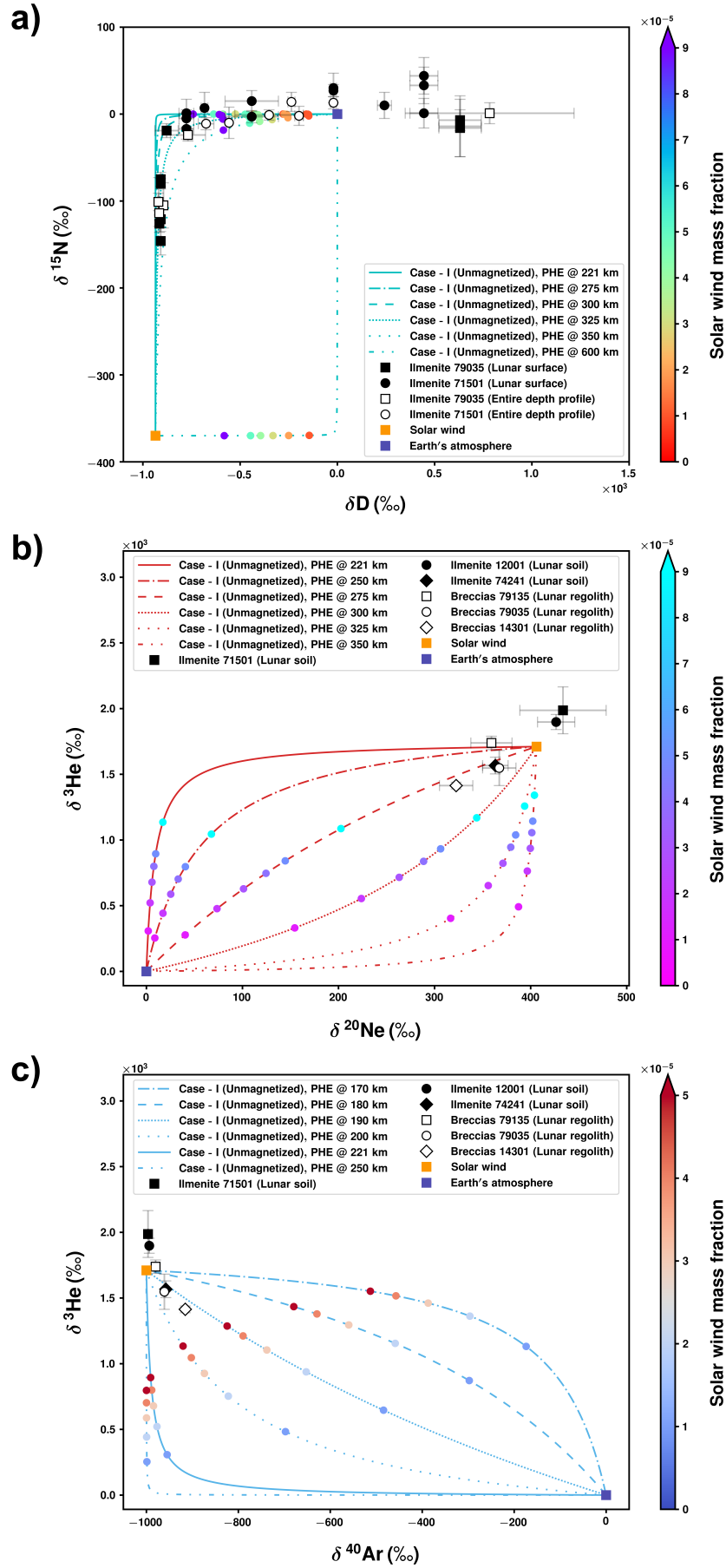
Supplementary Data Figure SD1: **Effect of the geodynamo on terrestrial atmospheric ion escape.** *Top [panel (a)]*: Schematic representation (not to scale) of the solar wind magnetic field and the intrinsic dipolar field in the magnetosphere, along with the escaping plasma outflow from the present-day upper terrestrial ionosphere [modified after Lockwood et al.⁷]. The bluish-gray color depicts the region where atmospheric ions are commonly observed, and the Prussian blue lines highlight their escape pathways. Magnetic fields are represented by the black lines, while the Moon's orbit is indicated by the dashed gray line. *Bottom [panel (b)]*: Illustration (not to scale) of atmospheric ion escape in an induced magnetosphere during a hypothetical phase when Earth lacked a core dynamo. The atmosphere acts as a conductive barrier to the supersonic and super-Alfvénic SW, deflecting it around due to the magnetic pressure generated by induced currents, resulting in the formation of a plasmopause boundary on the dayside and a magnetotail on the nightside. Black lines represent SW magnetic fields, while the green lines show the field induced by the interaction of the wind with the planetary atmosphere.



Supplementary Data Figure SD2: **Orbital variations of species-total number fluxes impinging on the lunar surface in the unmagnetized Earth case.** Angular distributions of (a) planetary atmosphere flux, (b) solar wind flux, (c) total flux (aggregate flux of the terrestrial atmosphere and solar wind), and (d) fractional contribution of the planetary wind to the total flux over a full lunation. At phase angles $-\pi$ and π rad, the Moon is in the dayside upstream solar wind along the sub-solar line of Earth. The double-horned solar wind and total flux profiles result from shocked material located between the magnetosheath and the magnetotail lobe.

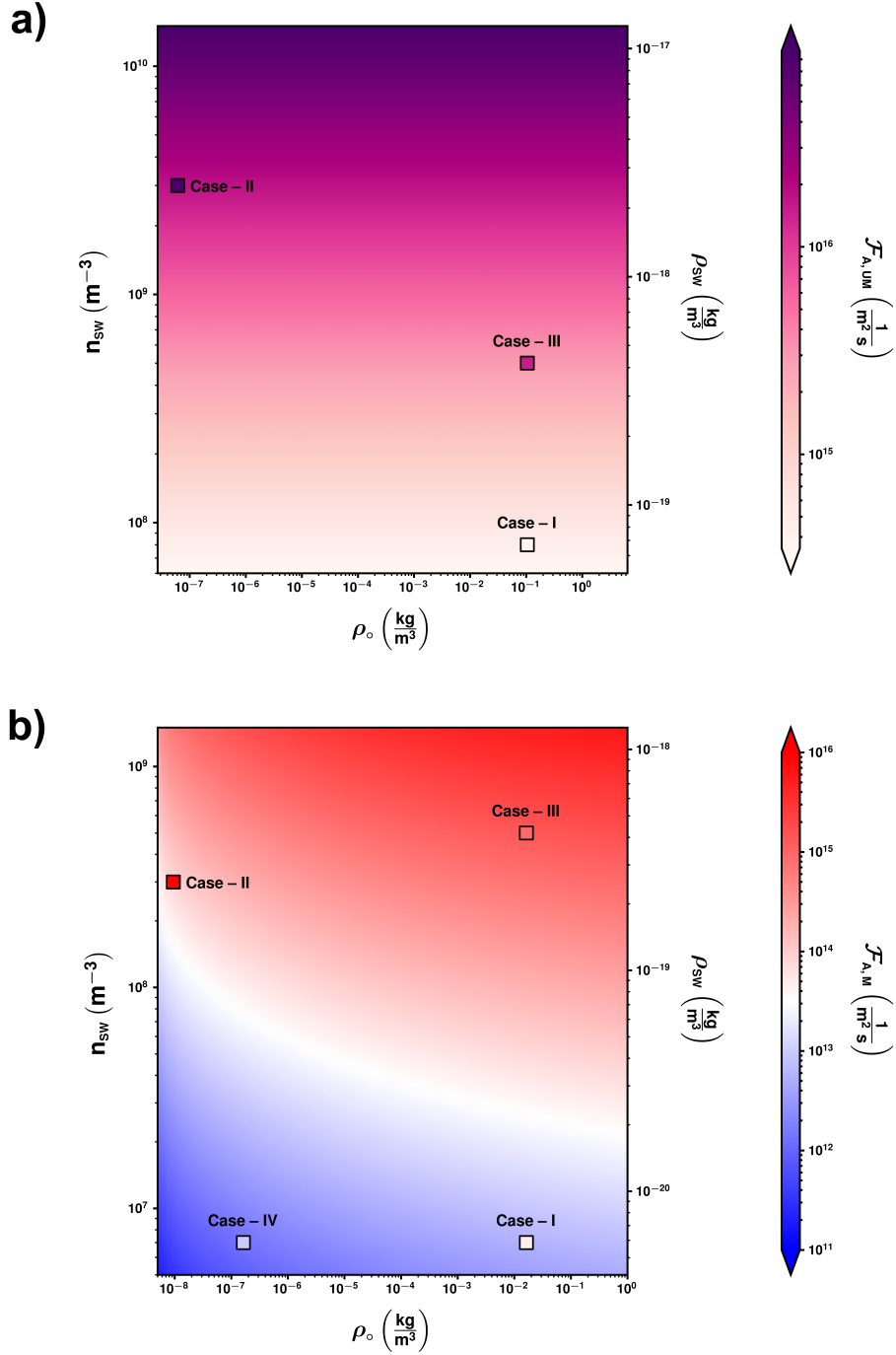


Supplementary Data Figure SD3: **Results from our 3D-MHD simulation model for the case in which the planet lacks an intrinsic dynamo (Case – I).** *Panel (a):* Total number density plot depicting the large-scale structure of the wind-atmosphere interaction up to the lunar orbit in the quasi-steady state. *Panel (b):* Polar-cut view of the topology of the planet's induced magnetosphere under the influence of the primordial magnetized solar wind. Quivers represent the induced magnetic field. *Panel (c):* 2D slice of the normalized solar wind flux in the lunar orbital plane. The flux drops by ~ 3 orders of magnitude inside the magnetotail compared to the shocked solar wind region between the bow shock and the plasmopause boundary, where it exhibits a gradual gradient. *Panel (d):* Terrestrial atmospheric number flux in the magnetotail region. The quiver arrows denote the plane-projected bulk velocity component, indicating the escaping pathways. The filled white circle represents the planet's core, which is not included in the passive advective tracers.



Supplementary Data Figure SD4: Description continued on the following page.

Supplementary Data Figure SD4: **Mixing diagrams for Archean Earth without an intrinsic dipole field.** *Top panel (a)* [$\delta^{15}\text{N} - \delta\text{D}$ mixing diagram]: A mixing curve between the solar wind component (orange square) and the Earth wind component (navy square) in the unmagnetized case (Case – I), representing the Eoarchean eon, is constructed with the estimated parameters. The elemental ratios of the end members are inferred from fluxes given in Tables SD2 and SD4. The mixing hyperbolae are for different probable hydrodynamic escape boundary heights for a non-magnetic Earth. The solid line indicates the profile for the primitive Earth's PHE at ~ 221 km. Observational data for lunar ilmenite samples from Apollo-17 breccias are plotted with squares and circles, respectively, along with their corresponding error bars. For solar wind isotope ratios, we used $^{15}\text{N}/^{14}\text{N} = 2.32 \times 10^{-3}$ and $\text{D}/\text{H} = 1.01 \times 10^{-5}$. We used the Archean epoch terrestrial atmospheric isotope ratios, $^{15}\text{N}/^{14}\text{N} = 3.68 \times 10^{-3}$ and $\text{D}/\text{H} = 1.56 \times 10^{-4}$, for the Earth wind composition⁸. *Middle panel (b)* [$\delta^3\text{He} - \delta^{20}\text{Ne}$ mixing diagram]: Mixing curves were generated for different hydrodynamic escape boundary altitudes with respective solar and planetary abundances estimated from Tables SD2 and SD4. Data for ilmenite grains (solid markers) and regolith breccias (open markers) were obtained from lunar samples returned to Earth. For the solar wind composition (orange square), we used $^3\text{He}/^4\text{He} = 4.26 \times 10^{-4}$ and $^{20}\text{Ne}/^{22}\text{Ne} = 13.78$. For the Earth wind isotopic ratios (navy square), we used the commonly accepted value of $^{20}\text{Ne}/^{22}\text{Ne} = 9.8$ and the primordial terrestrial ratio of $^3\text{He}/^4\text{He} = 1.57 \times 10^{-4}$ following Ozima et al.^{8–10}. *Bottom panel (c)* [$\delta^3\text{He} - \delta^{40}\text{Ar}$ mixing diagram]: Six mixing curves are plotted with different elemental abundance ratios but fixed isotopic ratios assumed for the end-members. We chose the generally accepted values of $^3\text{He}/^4\text{He} = 4.26 \times 10^{-4}$ and $^{40}\text{Ar}/^{36}\text{Ar} = 3 \times 10^{-4}$ for the solar wind ratio (orange square). For the ancient Earth wind components (navy square), we used $^3\text{He}/^4\text{He} = 1.57 \times 10^{-4}$ and $^{40}\text{Ar}/^{36}\text{Ar} = 150.0$ to construct the mixing curves⁸. Colored dots in each subplot illustrate the corresponding increments in f_{sw} .



Supplementary Data Figure SD5: **Correlation of the planetary flux scaling laws ($\mathcal{F}_{A,UM}$ & $\mathcal{F}_{A,M}$) with the terrestrial atmosphere surface density (ρ_o) and solar wind density (n_{SW}) in (a) the absence and (b) the presence of a geodynamo.** Overlaid on the 2-D colormaps of the scaling relations are the planetary flux values (represented by squares) computed from the 3-D MHD simulations (refer to Table 2). The abscissa limits for the unmagnetized case are determined by maintaining the total atmospheric mass constant. The simulation datapoints best follow the analytic expressions in Equations 5 and 7 when their color matches that of the background.

Supplementary Data Table SD1: **Stellar wind and planetary atmosphere parameters used in the simulations for the unmagnetized cases.**[†] The ambient medium here refers to the region outside the plasmopause boundary at the start of the simulation, where we adopt the same values as those of the solar wind. Across the different simulation cases, most parameters remain constant, except for those directly affecting atmospheric escape, which are varied in order to study their effect.

Stellar parameters	Value used	Notation	Units
Wind density	Refer to Table 2	ρ_{sw}	$\frac{1}{\text{cm}^3}$
Wind magnetic field	10.0	B_{sw}	nT
Wind velocity	Refer to Table 2	v_{sw}	$\frac{\text{km}}{\text{s}}$
Planetary parameters	Value used	Notation	Unit
Atmosphere surface density	Refer to Table 2	$\rho_{o, UM}$	$\frac{\text{kg}}{\text{m}^3}$
Ambient parameters	Value used	Notation	Unit
Ambient density	Same as SW density	ρ_{Amb}	$\frac{1}{\text{cm}^3}$
Ambient magnetic field	10.0	B_{Amb}	nT
Ambient velocity	Same as SW velocity	v_{Amb}	$\frac{\text{km}}{\text{s}}$

[†] The physical parameters of the star-planet system, along with the values used to initialize the winds during the period when the Earth lacked an intrinsic magnetic field, are outlined in this table. The remaining parameters are set to the same values as those presented in Table SD1.

Supplementary Data Table SD2: **Relative contribution of each species to the solar wind flux reaching the Moon.** The relative elemental abundances of the solar wind are estimated from observational data obtained by the Ulysses and SOHO spacecraft¹¹. The solar wind flux is then computed by multiplying these fractions with the orbit-averaged flux obtained from 3D-MHD simulations (Table 2).

Element	Relative fraction	Solar wind flux in Case – I $\left(\frac{1}{m^2 \cdot s}\right)$		Solar wind flux in Case – II $\left(\frac{1}{m^2 \cdot s}\right)$		Solar wind flux in Case – III $\left(\frac{1}{m^2 \cdot s}\right)$		Solar wind flux in Case – IV $\left(\frac{1}{m^2 \cdot s}\right)$		Solar wind flux in Case – V $\left(\frac{1}{m^2 \cdot s}\right)$	
		Mag. Earth	Unmag. Earth	Mag. Earth	Unmag. Earth	Mag. Earth	Unmag. Earth	Mag. Earth	Unmag. Earth	Mag. Earth	Unmag. Earth
H	9.59×10^{-1}	6.31×10^8	8.89×10^9	2.74×10^{10}	3.20×10^{11}	4.63×10^{10}	5.55×10^{10}	6.24×10^8		1.01×10^{12}	
He	4.12×10^{-2}	2.71×10^7	3.82×10^8	1.18×10^9	1.37×10^{10}	1.99×10^9	2.39×10^9	2.68×10^7		4.35×10^{10}	
N	6.65×10^{-5}	4.37×10^4	6.16×10^5	1.90×10^6	2.22×10^7	3.21×10^6	3.85×10^6	4.33×10^4		7.02×10^7	
Ne	2.29×10^{-6}	1.51×10^3	2.13×10^4	6.55×10^4	7.64×10^5	1.11×10^5	1.33×10^5	1.49×10^3		2.42×10^6	
Ar	1.44×10^{-4}	9.46×10^4	1.33×10^6	4.11×10^6	4.79×10^7	6.95×10^6	8.32×10^6	9.36×10^4		1.52×10^8	

Supplementary Data Table SD3: **Relative contribution of each volatile species to the planet wind flux reaching the Moon in the magnetized case.** The relative elemental abundance of the Earth wind is computed for different hydrodynamic escape boundary heights using the ion fluxes escaping from the present-day terrestrial atmosphere (Subfigure 4 (a)). The Earth wind flux is then calculated by multiplying this fraction with the orbit-averaged planetary flux obtained from 3D-MHD simulations (Table 2). Only the values for a pairwise hydrodynamic escape boundary height of 401 km are tabulated here.

Element	Relative fraction	Atmos. wind flux from mag. Earth in Case – I $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from mag. Earth in Case – II $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from mag. Earth in Case – III $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from mag. Earth in Case – IV $\left(\frac{1}{m^2 s}\right)$
H	4.12×10^{-1}	1.82×10^6	9.95×10^7	1.94×10^6	1.96×10^4
He	5.88×10^{-1}	2.59×10^6	1.42×10^8	2.77×10^6	2.79×10^4
N	7.23×10^{-8}	3.19×10^{-1}	1.74×10^1	3.41×10^{-1}	3.43×10^{-3}
Ne	1.02×10^{-8}	4.48×10^{-2}	2.45	4.78×10^{-2}	4.82×10^{-4}
Ar	9.98×10^{-17}	4.40×10^{-10}	2.41×10^{-8}	4.70×10^{-10}	4.74×10^{-12}

Supplementary Data Table SD4: **Relative contribution of each volatile species to the planetary wind flux reaching the Moon in the unmagnetized case.** The relative elemental abundance of the Earth wind is computed for different hydrodynamic escape boundary heights using the ion fluxes escaping from the Eoarchean epoch atmosphere (Subfigure 4 (b)). The Earth wind flux is then calculated by multiplying this fraction by the orbit-averaged planetary flux obtained from 3D-MHD simulations (Table 2). Only the values for a pairwise hydrodynamic escape boundary height of 221 km are tabulated here.

Element	Relative fraction	Atmos. wind flux from unmag. Earth in Case – I $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from unmag. Earth in Case – II $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from unmag. Earth in Case – III $\left(\frac{1}{m^2 s}\right)$	Atmos. wind flux from unmag. Earth in Case – IV $\left(\frac{1}{m^2 s}\right)$
H	4.29×10^{-1}	2.09×10^5	1.33×10^9	2.75×10^7	5.24×10^9
He	3.57×10^{-2}	1.74×10^4	1.11×10^8	2.29×10^6	4.37×10^8
N	5.35×10^{-1}	2.61×10^5	1.66×10^9	3.43×10^7	6.53×10^9
Ne	8.88×10^{-5}	4.33×10^1	2.75×10^5	5.69×10^3	1.08×10^6
Ar	1.29×10^{-6}	6.32×10^{-1}	4.02×10^3	8.30×10^1	1.58×10^4

Supplementary References

- [1] J. A. Tarduno, E. G. Blackman, E. E. Mamajek, Detecting the oldest geodynamo and attendant shielding from the solar wind: Implications for habitability, *Physics of the Earth and Planetary Interiors* **233**, 68-87 (2014). URL <https://www.sciencedirect.com/science/article/pii/S0031920114001332>.
- [2] J. A. Tarduno, R. D. Cottrell, W. J. Davis, F. Nimmo, R. K. Bono, A Hadean to Paleoarchean geodynamo recorded by single zircon crystals, *Science* **349**, 521-524 (2015). URL <https://www.science.org/doi/abs/10.1126/science.aaa9114>.
- [3] F. Tang, R. J. M. Taylor, J. F. Einsle, C. S. Borlina, R. R. Fu, B. P. Weiss, H. M. Williams, W. Williams, L. Nagy, P. A. Midgley, E. A. Lima, E. A. Bell, T. M. Harrison, E. W. Alexander, R. J. Harrison, Secondary magnetite in ancient zircon precludes analysis of a Hadean geodynamo, *Proceedings of the National Academy of Sciences* **116**, 407-412 (2019). URL <https://www.pnas.org/doi/abs/10.1073/pnas.1811074116>.
- [4] J. A. Tarduno, R. D. Cottrell, R. K. Bono, H. Oda, W. J. Davis, M. Fayek, O. van 't Erve, F. Nimmo, W. Huang, E. R. Thern, S. Fearn, G. Mitra, A. V. Smirnov, E. G. Blackman, Paleomagnetism indicates that primary magnetite in zircon records a strong Hadean geodynamo, *Proceedings of the National Academy of Sciences* **117**, 2309-2318 (2020). URL <https://www.pnas.org/doi/abs/10.1073/pnas.1916553117>.
- [5] J. A. Tarduno, R. D. Cottrell, R. K. Bono, N. Rayner, W. J. Davis, T. Zhou, F. Nimmo, A. Hofmann, J. Jodder, M. Ibañez-Mejia, M. K. Watkeys, H. Oda, G. Mitra, Hadaean to Palaeoarchaeon stagnant-lid tectonics revealed by zircon magnetism, *Nature* **618**, 531-536 (2023). URL <https://doi.org/10.1038/s41586-023-06024-5>.
- [6] J. A. Tarduno, T. Zhou, W. Huang, J. Jodder, Earth's magnetic field and its relationship to the origin of life, evolution and planetary habitability, *National Science Review* **12**, nwaf082 (2025). URL <https://academic.oup.com/nsr/article/12/5/nwaf082/8051343>.
- [7] M. Lockwood, S. W. H. Cowley, Magnetosphere-Ionosphere Coupling: Implications of Non-Equilibrium Conditions, *Frontiers in Astronomy and Space Sciences* **9**, 908571 (2022). URL <https://www.frontiersin.org/journals/astronomy-and-space-sciences/articles/10.3389/fspas.2022.908571>.

- [8] 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). URL <https://www.nature.com/articles/nature03929>.
- [9] P. R. Mahaffy, T. M. Donahue, S. K. Atreya, T. C. Owen, H. B. Niemann, Galileo Probe Measurements of D/H and $^3\text{He}/^4\text{He}$ in Jupiter's Atmosphere, *Space Science Reviews* **84**, 251-263 (1998). URL <https://link.springer.com/article/10.1023/A:1005091806594>.
- [10] H. Busemann, H. Baur, R. Wieler, Primordial noble gases in "Phase Q" in carbonaceous and ordinary chondrites studied by closed system stepped etching, *Meteoritics & Planetary Science* **35**, 949-973 (2000). URL <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1945-5100.2000.tb01485.x>.
- [11] R. C. Wiens, P. Bochsler, D. S. Burnett, R. F. Wimmer-Schweingruber, Solar and solar-wind isotopic compositions, *Earth and Planetary Science Letters* **222**, 697-712 (2004). URL <https://www.sciencedirect.com/science/article/pii/S0012821X04002092>.