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Early Martian Habitability and Directional Lithopanspermia Across the Solar System

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Early planetary habitats and conditional interplanetary seeding

Research manuscript draft • Nature • Conditional model study

Summary

A common-scale comparison of early planetary habitats is needed to interpret interplanetary biological seeding. We construct a Mars–Earth–Venus sensitivity model from 4.40 to 3.85 Ga, combining radioactive heating, mantle cooling, crustal geotherms, conserved water and conditional transport. Earth and Venus have identical absolute isotope inventories and major-element core and mantle compositions by assumption. Wet and hot-start Venus branches test uncertain ocean histories. Reference suitable-equivalent crustal water peaks occur at 4.40 Ga for Mars, 3.85 Ga for Earth and 4.20 Ga for wet Venus; window-boundary peaks do not date onset. Common-relief and sheltered-compartment controls test terrain and precursor concentration advantages without imposing homogeneous oceans. Conditional concentration tests describe parameter draws, not empirical origin probabilities. Published orbital kernels rank Earth-to-Venus above Mars-to-Earth, Mars-to-Venus and Earth-to-Mars under declared biological assumptions. Jovian return to Venus remains an uncalibrated probability and amplification sensitivity. No historical dynamo or plate-tectonic failure date is identifiable. The reproducible workflow defines observations and physical simulations needed to test a Mars-first origin and subsequent inward and outward dispersal.

Relevant competing ocean histories and transfer benchmarks are explicitly tested. [1,2,3]

Introduction

Could an early, topographically diverse Mars have offered concentrating chemical environments before exporting life-bearing material inward and toward Jovian moons? Could a habitable moon later

reexport descendants to Venus? The title names this eventual return route; the first stage tested here is Mars as a conditional source. Abiogenesis and primary microbial occupation are hypotheses, not input observations.

Archer 2023 supplies the fresh-crater motivation and the previous Mars Noachian Habitability study supplies the global-equivalent-layer and crustal-water accounting conventions. Crater diameter versus elevation is not a dated measurement of the atmosphere at 4.4 Ga. The previous project's multi-bar fits depend on entry physics, chronology and uncertainty treatment; this project therefore tests a roughly three-bar Mars branch without assigning it the status of a recovered early atmosphere. The modeled interval includes pre-Noachian conditions as well as part of the Noachian. [4]

The new controlled comparison changes bulk heat and water assumptions to make the planets comparable. It retains the previous 50 Myr age spacing, 50 m depth cells and common 0–80 °C score, with a 10–65 °C plateau. The old reference CSV is included unchanged for traceability. Different numerical values are expected because this experiment uses common bulk starting fractions and a different interior model; it is not a recalibration of the earlier Mars result.

Results

The common water comparison appears in Figure 1. Conditional transfer and the Jovian return sensitivity appear in Figures 2 and 3, respectively.

Crustal geotherms and common habitat metrics

In the reference cases, suitable equivalent volume peaks at 4.03×10^{16} m³ on Mars at 4.40 Ga, 5.75×10^{16} m³ on Earth at 3.85 Ga and 2.17×10^{16} m³ on wet Venus at 4.20 Ga. Mars and Earth peaks occur at the limits of the chosen window and must not be interpreted as global maxima or emergence dates. The hot Venus value is zero throughout because the prescribed crust is too hot and lacks condensed

pore water. Earth already has eligible water at 4.40 Ga, so these outputs do not establish that Mars became habitable first.

Terrain relief concentration and chemical diversity

The reference terrain endmember yields exposed Mars fractions of 0.64 at 4.40 Ga and 0.85 at 3.85 Ga before the imposed Tharsis relief addition; the latter becomes 0.89 after that addition. Wet Earth and Venus are ocean-covered under the selected low-relief endmember. The Tharsis term is a hypothetical growing 4 km relief component on ten percent of Mars, not a reconstructed emplacement chronology or a modeled volatile source. Surface-water GEL here includes frozen as well as liquid condensed water, so exposed fraction does not establish the presence of warm shoreline pools.

Mars could offer complementary evaporative, freeze-concentrating, impact-hydrothermal and water–rock environments, with spatial variations in mineral substrate, pH and redox disequilibrium. Serpentinization can produce H_2 while consuming water; wet–dry cycling and varied geothermal gradients provide specific mechanisms to test. Modern rover evidence and later Noachian deposits support the existence of relevant processes but cannot by themselves date those processes to 4.4 Ga. [5,6,7]

Rotation tides and conditional precursor tests

Three like compartments are compared on every wet planet: open water at its modeled depth, a 10 m pore refuge and a 0.5 m shoreline pool, with coupling factors 1, 10^{-6} and 10^{-8} to external mixing. The model source J, chemical lifetime τc and background concentration Cb are common controls. Equilibrium concentration $C*$ is calculated in μM using a year-based mixing rate; increasing mixing draws local concentrations toward the background. The model does not assert that every potential compartment exists or that its chemicals can polymerize.

At 4.40 Ga the fraction of paired draws with higher Mars concentration than Earth is 0.977 for open water and 1.000 for each sheltered class; versus wet Venus it is 0.883, 0.995 and 1.000. Yet the mean

Mars advantage versus wet Venus is only 0.0010 dex in pores and 0.0036 dex in shoreline pools. A tiny systematic difference can therefore generate a small permutation p value in a large deterministic design. These diagnostics quantify the declared input experiment; they are not observational significance, independent evidence for Mars-first chemistry or probabilities of life. Threshold exceedance tables at 1, 10 and 100 μM retain this interpretation.

Conditional interplanetary exchange and the Jovian return route

Under flat source flux, 4.40 Ga Mars occupation onset and the declared biological ranges, mean conditional rates rank Earth-to-wet-Venus, Mars-to-Earth, Mars-to-wet-Venus and Earth-to-Mars. Their age-averaged values are respectively 2.38×10^{-3}, 6.11×10^{-5}, 3.69×10^{-5} and 5.78×10^{-6} establishments per Myr under that normalization. The numerical scale is arbitrary until viable exported flux and survival are constrained. A declining impact-source scenario and later Mars occupation are supplied separately; they shift peak source windows. Zero rates to hot Venus and delayed-ocean moon branches are imposed habitat controls, not evidence that no other habitats ever existed.

In the flat-source reference, the largest conditional launch-age rates occur at 3.90 Ga for Earth-to-wet-Venus and Earth-to-Mars, 4.05 Ga for Mars-to-Earth and 4.40 Ga for Mars-to-wet-Venus. These peaks depend on prescribed occupation and habitat histories and on excluding arrivals beyond the 3.85 Ga boundary; they are not reconstructed biological export events. Earth is conditionally occupied in this comparison, independently of the Mars-source hypothesis. The peak-window table also reports the declining source and delayed Mars occupation alternatives.

Moon ocean availability is bracketed by an effective receiver factor of 0.1 and a delayed-ocean factor of zero. Io is a dry control. No life or early continuous ocean is assumed as an observational fact. Recent Europa differentiation modeling underscores the dependence on accretion history and composition, so arrival at a moon's surface is not equivalent to transport into a habitable ocean. [8]

Tectonic dynamo and impact timing limits

Martian basin magnetization does not uniquely date dynamo cessation because reversing fields and cooling histories can alter the record. Venus's present lack of an intrinsic dynamo does not establish when an earlier dynamo ceased, or whether one existed. Early wet stagnant-lid scenarios are possible without modern plate tectonics. We therefore cannot infer a unique tectonic or dynamo failure time for Mars or Venus, and the hypothetical multi-bar atmosphere cannot be dated as pre-dynamo-loss solely from these calculations. [9,10]

Impacts can create hydrothermal niches and simultaneously destroy local habitats or interrupt chemical assembly. The latest Abramov and colleagues model identifies a conditional Hadean RNA-world window and permits severe near-surface disruption before about 4.4 Ga; it does not support universal immunity to sterilization at all depths on all three planets. Deep refugia, surface thermal tolerances, largest impacts and the definition of sterilization must be tested separately. This project begins at 4.4 Ga and does not couple impact heating into the geotherm time series. [11]

Discussion

A Mars-first nursery remains possible, especially if concentrating terrain and persistent protected pores preceded comparable environments elsewhere. The present model does not establish that chronology. Returned samples should combine dated low-lying aqueous deposits with diverse Noachian highland lithologies, hydrothermal minerals, impact melts and alteration profiles. Ancient martian zircons can preserve very old crustal records, but Noachian highlands as a whole should not be called the oldest known terrestrial-planet crustal material; older terrestrial zircon material also exists. Dating the actual sampled units and alteration episodes is essential. [12]

Priority tests are a coupled atmospheric climate and escape calculation; mineral-specific redox and precursor sorption experiments across identical planet classes; independent relief and hydrology

constraints; early orbital-architecture transfer ensembles including Venus-origin ejecta; irradiation and shock tests of multi-member consortia; and moon surface-to-ocean penetration and reexport models. Reject or weaken the Mars advantage if common-relief and sheltered-habitat controls erase it. Reject a specific Jovian return scenario if its required amplification, survival or arrival window is incompatible with a dated moon ocean and clement Venus.

All numerical outcomes are reproducible conditional scenarios. The project provides a completed first sensitivity experiment and a workflow for a more complete physical inference. It supplies no measurement of ancient pressure, microbial occupancy, abiogenesis probability, tectonic cessation or actual panspermia.

Conclusion

The controlled experiment supports testing a terrain and concentration advantage on early Mars while preserving plausible competing habitats on Earth and wet Venus. It does not establish a first inhabited planet. Published transport kernels provide conditional inward and outward comparisons, and the Jovian return route remains a measurable threshold problem rather than a demonstrated event.

Methods

We use 384 paired parameter draws at 12 ages from 4.40 to 3.85 Ga, with 50 m crustal cells to 25 km. Actual masses and radii are retained. Common starting bulk H_2O, CO_2-equivalent and N_2-equivalent fractions are 2.474771×10^{-4}, 2×10^{-5} and 10^{-6}. Earth and Venus have identical absolute radioactive isotope inventories and major-element mantle and core compositions by assumption; their trace concentrations therefore differ. Radioactive decay, parameterized core–mantle cooling and Arrhenius viscosity feed conductive geotherms. Prescribed surface temperature and gas-reservoir histories are not a coupled climate model. Water is conserved among outgassed, bound, escaped, vapor, surface and

pore compartments. A common 0–80 °C score with a 10–65 °C plateau defines suitable equivalent volume; porosity, saturation and vapor-pressure eligibility are applied cell by cell. Gaussian hypsometry is tested both with thermal relief and with common imposed relief. Equilibrium-tide and compartment-mixing proxies give conditional precursor concentrations. Seeded sign-permutation tests diagnose the paired input design, not observational evidence. Orbital hit fractions are imported from Worth et al. 2013 and use present architecture, not new early-history integrations. Occupancy, launch survival, consortium survival, transit survival and receiver access are imposed sensitivity factors. Receiver habitat is evaluated at arrival age, with arrivals after 3.85 Ga excluded. Unknown Venus-origin and Jovian-origin probabilities and reexport amplification are swept explicitly. Historical tectonic and dynamo failure dates are not identified. Full parameter ranges, equations, structural limitations, source provenance and reproducibility instructions accompany the master technical document and executable code.

$$W_0 + W_{\mathrm{out}} = W_{\mathrm{bound}} + W_{\mathrm{escape}} + W_{\mathrm{vapor}} + W_{\mathrm{surface}} + W_{\mathrm{pore}}$$

$$H_V = 4\pi R^2 \int \phi(z) S(z) s(T)\, \mathrm{d}z, \qquad F_H = \frac{H_V}{V_{\mathrm{pore}}}$$

$$\lambda_{s\to d} = R_s \frac{H_{V,s}}{10^{16}\ \mathrm{m}^3} f_{\mathrm{occ}} p_{s\to d} S_{\mathrm{launch}} S_{\mathrm{cons}} \exp(-\tau/\tau_s) f_{\mathrm{est}} f_{\mathrm{recv}}$$

Data and code availability

All data and executable source accompany this draft in the shared project package. A permanent public repository DOI is to be supplied by the author. Figure uncertainty shading is mean ±1 standard deviation across the declared parameter design; it is not a confidence interval on ancient planetary conditions.

Author statements

Author list and order, affiliations, corresponding contact, contributions, funding, competing interests and AI-assistance disclosure require author confirmation. No unsupported negative declarations or coauthor approval statements are made. This manuscript is an alternative to the other journal drafts, not an instruction for simultaneous submission.

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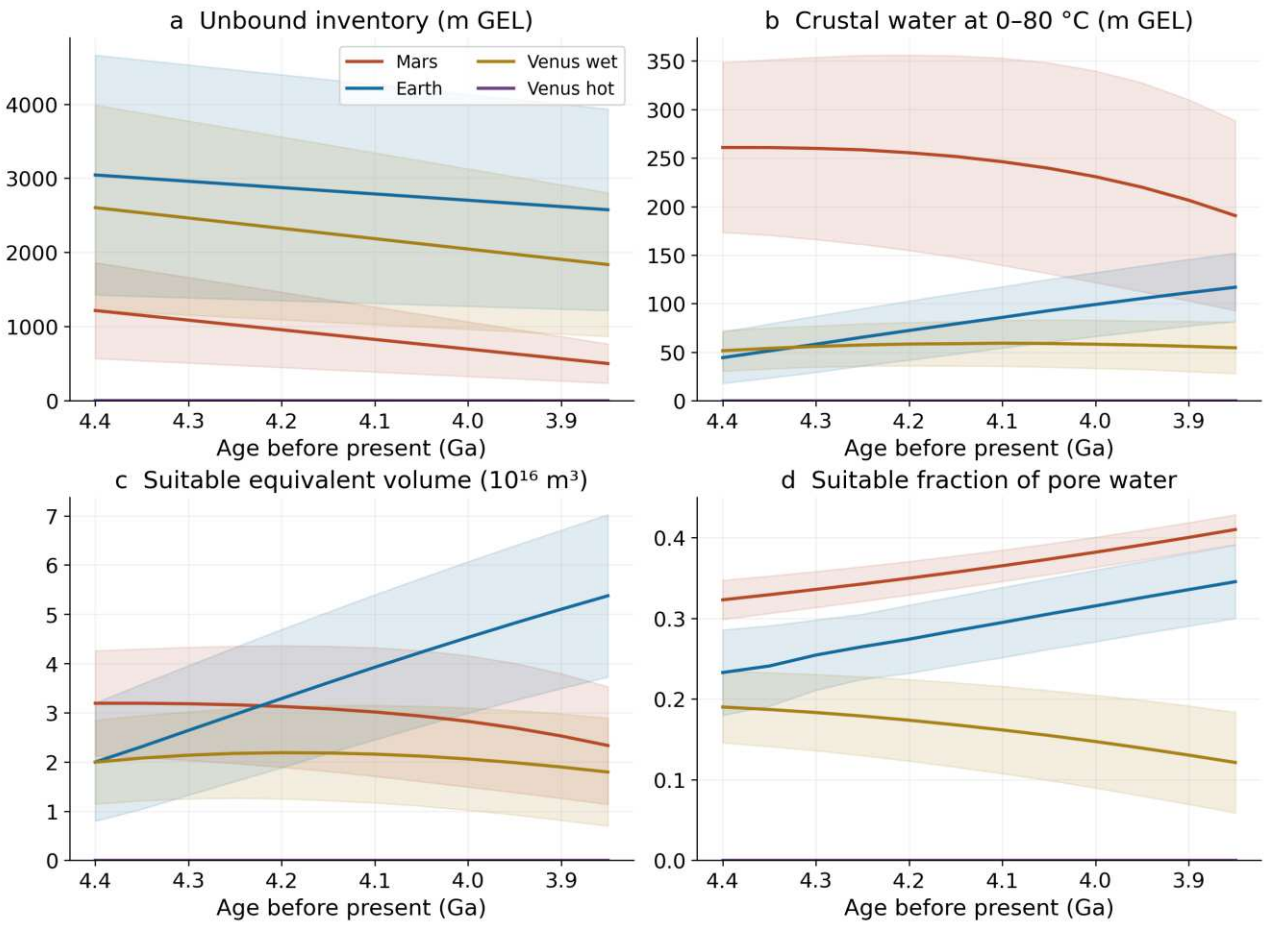
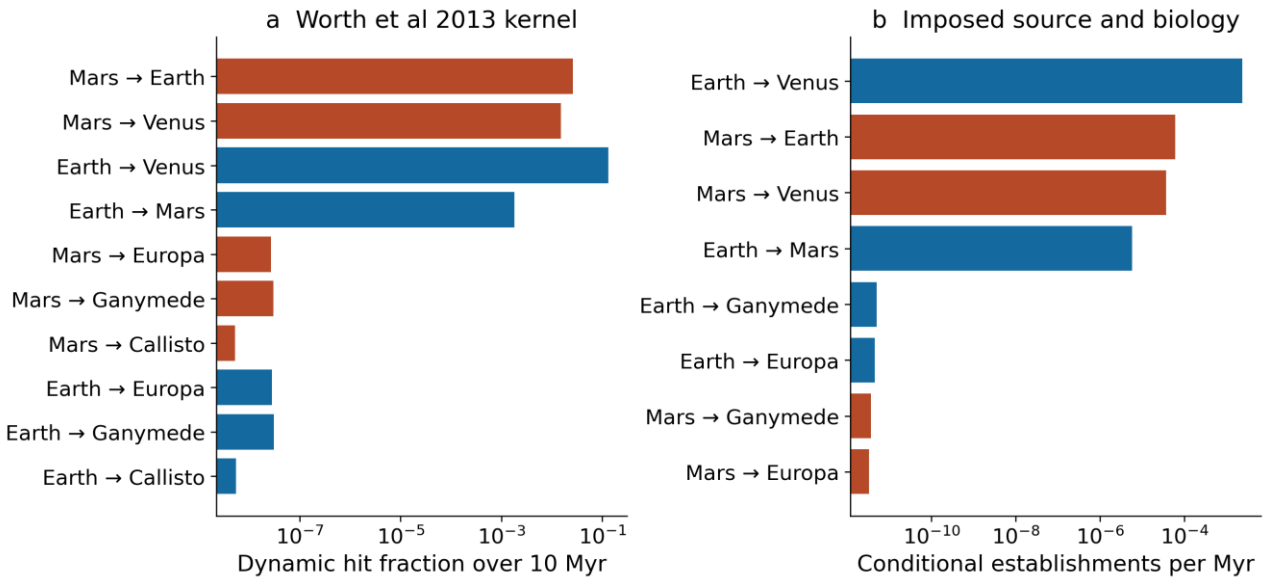
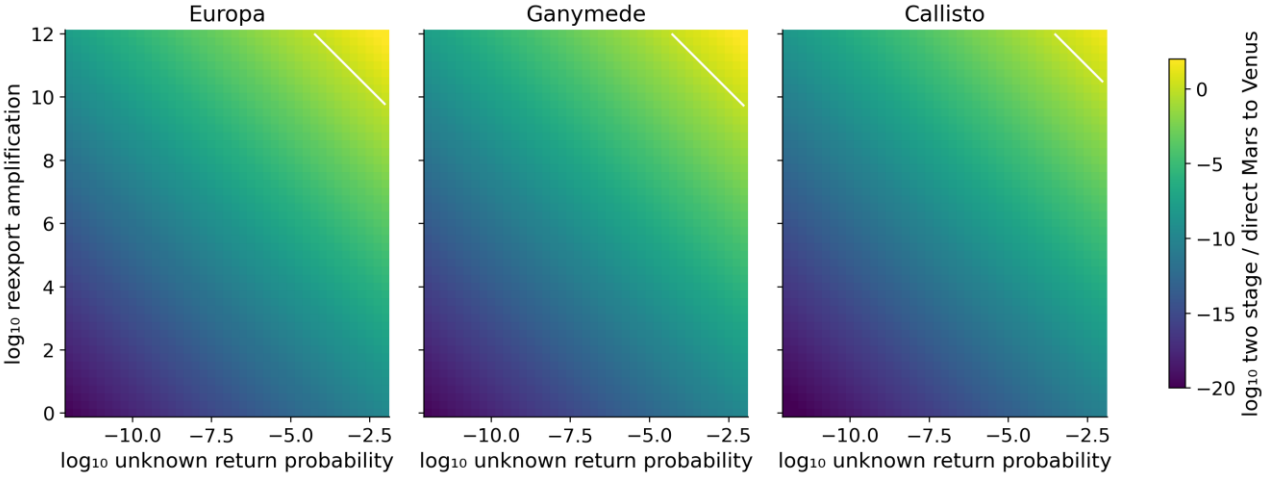


Figure 1. Water budgets and normalized habitats on common scales. Lines are means and shaded regions ±1 standard deviation across 384 paired parameter draws, not confidence intervals on planetary history. Hot Venus has zero modeled suitable crustal water. Suitable equivalent volume applies a common 0–80 °C score and is not occupied biomass.



197

198 **Figure 2. Physical delivery and conditional establishment are different quantities. Left: published ten-million-year dynamical**
199 **fractions from Worth et al. 2013, using present orbital architecture. Right: mean conditional establishment rates with a common**
200 **one-million exported-carrier normalization per Myr, flat source history and imposed biological factors; values are averaged over**
201 **the modeled launch ages. Venus-origin and Jovian-origin routes are not calibrated and are excluded from this ranking.**



202

203 **Figure 3. Two-stage Mars to Jovian moon to Venus sensitivity. Colour is the log ratio to direct Mars–Venus transfer under**
204 **imposed biological factors of 0.01 per stage. The white contour is parity. Neither the unknown return probability nor biological**
205 **reexport amplification is measured. Wet receiver and functioning moon habitat are necessary conditions; no second-leg orbital**
206 **calculation is represented.**