Lithopanspermia: A Drake-Like Framework for Transfer, Survival, and Establishment

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Abstract

Natural lithopanspermia is often framed as one question: can life move between worlds? That formulation is too coarse. Lithopanspermia is not an alternative theory of abiogenesis, but a transport, survival, and establishment hypothesis. A viable account must specify a source biosphere, biologically loaded ejecta, low-shock launch, orbital transfer, survival during transit, protection against radiation and desiccation, atmospheric entry, deposition into a habitable environment, and ecological establishment above a founder threshold. Building on recent equation-based astrobiology and transport-survival analyses, especially the Venus Life Equation and Turyshev's Earth-directed donor-class treatment, I develop a Drake-like factorization for the complementary Earth-to-Mars problem. The goal is not to explain how life originated on Earth, but to ask how the absence of confirmed Martian life constrains the fecundity of Earth-to-Mars panspermia. In event-count form, the expected number of successful seeding events is

$$\Lambda_{\rm pan} = N_{\rm launch} f_{\rm bio} f_{\rm lowshock} f_{\rm transfer} f_{\rm fast} f_{\rm shield} f_{\rm entry} f_{\rm hab} f_{\rm founder},$$

with $P_{\geq 1} = 1 - \exp(-\Lambda_{\rm pan})$. The novelty is not the existence of such filters, but the use of a transfer-centered factorization to turn Mars into a local null experiment. The paper positions this Earth-to-Mars inference against the nearest prior art: Turyshev's 2026 natural-panspermia kernel, the Venus Life Equation, recent Venus phosphine debates, dynamical lithopanspermia calculations, population-scale agnostic biosignature models, and new microbial impact-survival experiments. I then apply the framework to Earth-to-Mars transfer during the overlap between terrestrial microbial life and wet, potentially habitable Martian environments. Recent Mars observations strengthen the premise that ancient Mars preserved habitable settings and organic matter, while 2026 impact-pressure experiments raise the plausibility of survival through at least some low-shock ejection regimes. A fiducial Earth-to-Mars calculation gives of order 10^{11} viable cell arrivals, but this number is not the probability of Martian life. The relevant observable quantity is further reduced by persistence, preservation, erosion, weathering, radiation damage, search coverage, and detectability. The central result is a local null constraint: if natural panspermia were highly fecund from Earth to Mars, the present absence of unambiguous Martian life, fossils, or technology would be increasingly surprising. Conversely, a Martian null result constrains the product of transfer, establishment, evolutionary fecundity, preservation, and detection.

1 Introduction

The Drake equation did not solve the problem of extraterrestrial intelligence. Its enduring value was different: it organized ignorance. By separating star formation, planets, life, intelligence, technology, and longevity into distinct factors, it made disagreement inspectable.

Lithopanspermia needs the same discipline. The proposition that life can travel inside rocks from one world to another is sometimes treated as if dynamical transfer settles the question. It does not. A rock can move from Earth to Mars without carrying life; life can survive launch without surviving radiation; viable cells can reach Mars without entering a wet habitat; and cells in a wet habitat may still fail to establish a persistent population.

This paper proposes a deliberately simple Drake-like framework for natural lithopanspermia. The aim is not to prove that panspermia occurred, and it is not to explain the origin of life on Earth. It is to make the hypothesis decomposable enough that Mars can be used as a local constraint on panspermia fecundity. If Earth-to-Mars panspermia were easy, frequent, biologically robust, and evolutionarily productive, then a nearby wet Mars should have had many opportunities to record some consequence of that process. The fact that no unambiguous Martian life, fossil biosignature, or technological trace has been confirmed is therefore not merely negative background information. It is data, provided preservation and detectability are treated explicitly.

The nearest precedent is the Venus Life Equation, which expressed the likelihood of extant Venus life as the product of origination, robustness, and continuity factors (Izenberg et al., 2021). That framework was timely because the 2020 phosphine claim had made Venus life newly salient. Subsequent work has kept the phosphine question open but controversial: follow-up observations and reanalyses have challenged the original detection, while reviews continue to describe the source of any Venusian phosphine as unresolved (Bains et al., 2024). This history is instructive for lithopanspermia. Equation-based astrobiology is useful only when it clarifies uncertainty rather than laundering uncertainty into false precision.

The closest technical prior is Turyshev's 2026 analysis of natural panspermia, which treats the problem as a transport-and-establishment question and develops an Earth-directed donor-class kernel including launch, escape, transit, Earth interception, entry, terminal loading, and post-delivery establishment (Turyshev, 2026). That paper reaches a sharp hierarchy: hard panspermia is quantitatively serious mainly on Solar System scales, with early Mars as the only competitive external hard-panspermia donor for Earth. The present paper is complementary rather than substitutive. It reverses the direction of the question. Instead of asking whether Mars could have seeded Earth, it asks what Earth-to-Mars transfer would imply for Mars as a partially searched null experiment.

The worked example here is Earth-to-Mars transfer during the overlap between known terrestrial microbial life and wet, potentially habitable Martian environments. This case is scientifically attractive because the worlds are close, material exchange is dynamically established, Mars had ancient aqueous environments, and the required hypothesis is not galactic in scale. The example should not be read as a claim that Earth seeded Mars. It is an experiment in probabilistic bookkeeping and in null-result inference.

2 Community Priors and Epistemic Caution

Recent survey work by Vickers et al. (2025) provides a useful social and epistemic background. During February–June 2024, Vickers and colleagues surveyed researchers on whether basic, complex, and intelligent extraterrestrial life are likely to exist. Among broadly construed astrobiologists, 86.6 percent agreed that extraterrestrial life of at least a basic kind is likely somewhere in the universe. Agreement fell to 67.4 percent for complex life and 58.2 percent for intelligent life. Non-astrobiologist scientists showed similar agreement for basic life, 88.4 percent.

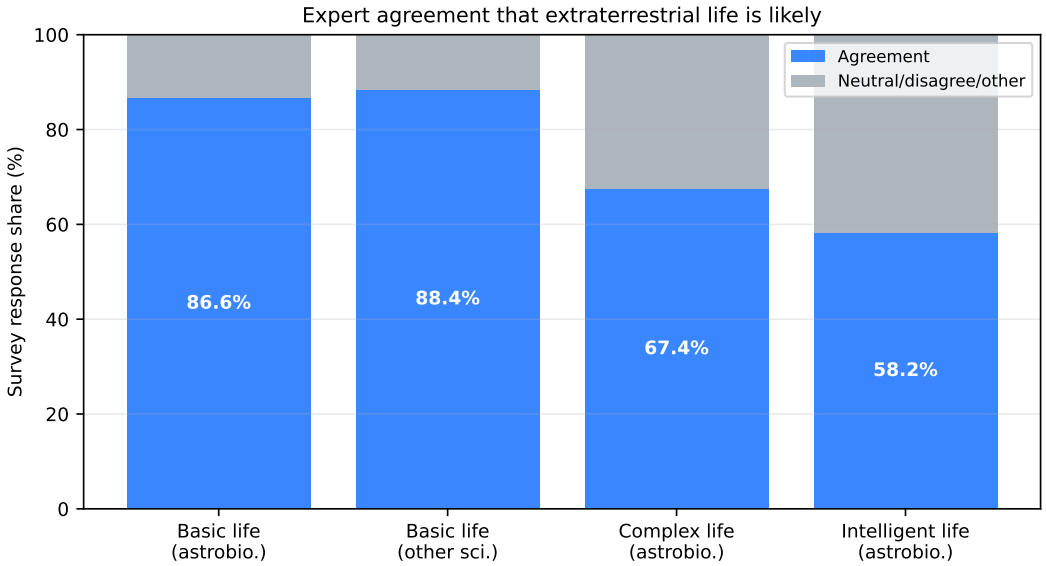

Figure 1: Expert agreement levels reported by Vickers et al. (2025). These data are useful as community-prior context, but they are not direct inputs to a panspermia probability calculation. A high level of expert agreement that basic life is likely somewhere does not imply high confidence in any particular transfer route.

The same work emphasizes a crucial distinction. High agreement plus limited direct evidence is not the same as high confidence. This point echoes the broader life-detection caution developed by Vickers et al. (2023): astrobiological claims must contend not only with known abiotic alternatives, but also with unconceived alternatives. For panspermia, the analogous danger is to mistake a convenient factorization for a complete causal model.

The factorization below should therefore be read in the spirit of the Drake equation and the Venus Life Equation. It is not a law of nature. It is a way to ask which uncertainty dominates.

3 A Lithopanspermia Transfer Equation

Let Λ_{pan} denote the expected number of successful panspermia seeding events from a source world to a target world over a specified time interval. A compact event-count form is

$$\Lambda_{\mathrm{pan}} = N_{\mathrm{launch}} f_{\mathrm{bio}} f_{\mathrm{lowshock}} f_{\mathrm{transfer}} f_{\mathrm{fast}} f_{\mathrm{shield}} f_{\mathrm{entry}} f_{\mathrm{hab}} f_{\mathrm{founder}}. \tag{1}$$

The probability of at least one successful seeding event is then

$$P_{\geq 1} = 1 - \exp(-\Lambda_{\mathrm{pan}}). \tag{2}$$

The factors are:

- N_{launch}: the number of biologically relevant launch opportunities or launch units.
- f_{bio}: the fraction of launch material carrying viable or dormant organisms.
- f_{lowshock}: the fraction launched under shock and heating conditions compatible with survival.
- f_{transfer}: the fraction reaching the target world.
- f_{fast}: the fraction arriving within biologically relevant survival timescales.
- f_{shield}: the fraction protected against radiation, vacuum, desiccation, and thermal stress.
- f_{entry}: the fraction surviving atmospheric entry, fragmentation, and deposition.
- f_{hab}: the fraction deposited into a habitable target environment.
- f_{founder}: the probability that the delivered inoculum exceeds ecological founder requirements.

The equation can be written with cells, spores, fragments, clumps, or protected inoculum packets as the unit of accounting. That choice matters. A cell-count equation is useful for delivery, while a packet-count equation may be more useful for establishment because microbial communities, shielding, and local clustering can be more important than total cell number.

For shorthand, I refer to Eq. 1 as the Earth-to-Mars lithopanspermia factorization. The name is less important than the structure: the equation forces a separation between transfer, survival, habitat encounter, and establishment. The factors should not be read as independent physical variables in a final generative model. Several are conditionally coupled through ejecta size, launch velocity, burial depth, transfer time, and entry state. The present form is an accounting scaffold; a mature version should replace the product of point factors with source-backed joint distributions.

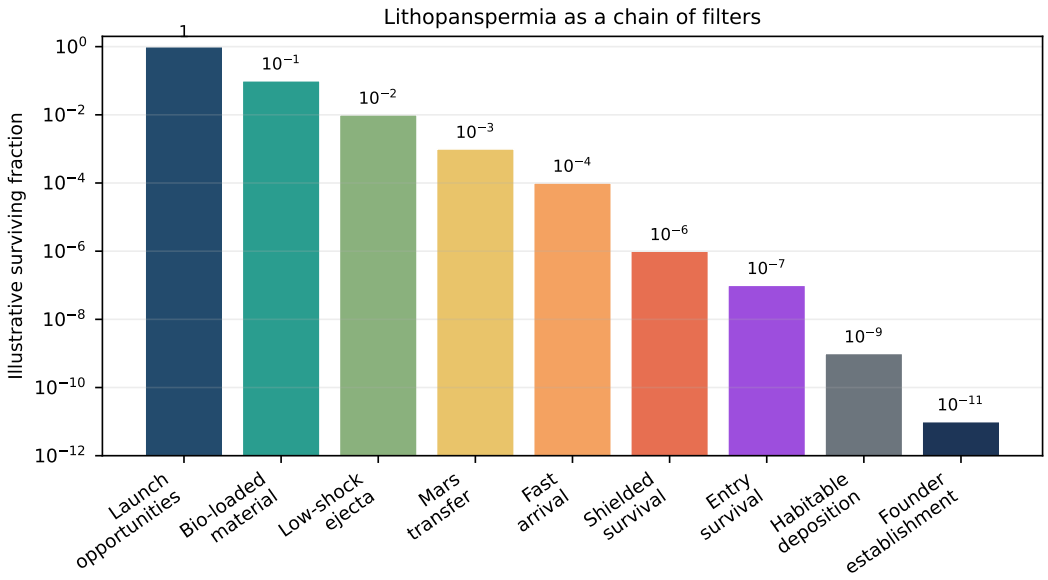

Figure 2: A visual form of the lithopanspermia transfer equation. The numbers shown are illustrative for the Earth-to-Mars worked example, not measurements. Each step can dominate the final probability if it is sufficiently small.

4 Relation to Current Panspermia Models

Several recent developments make an equation-centered treatment timely.

First, modern dynamical work supports the physical plausibility of Solar System exchange while sharpening its limits. Impact ejecta transfer among terrestrial planets was established by Gladman et al. (1996) and developed in biological terms by Mileikowsky et al. (2000). Later simulations of escaping Earth ejecta directly estimated collision probabilities with other Solar System bodies (Reyes-Ruiz et al., 2012), and broader lithopanspermia simulations showed that transfers among terrestrial planets are frequent compared with transfers to outer-planet moons (Worth et al., 2013). On larger scales, Adams and Napier (2022) revisited transfer between planetary systems. Work motivated by ‘Oumuamua-like interstellar objects found that Earth seeding by interstellar ejecta is unlikely in a specific Earth-origin calculation, but that galactic-scale panspermia may still be plausible for a small subset of habitable-zone Earth-sized worlds under optimistic assumptions (Cao et al., 2024). Turyshev’s 2026 Earth-directed donor-class analysis reaches the complementary conclusion that hard panspermia is quantitatively serious mainly on Solar System scales: early Mars is the only competitive external hard-panspermia donor for Earth, extrasolar and intergalactic hard panspermia are strongly suppressed, and soft panspermia is more plausible as chemical enrichment than as transport of living cells (Turyshev, 2026). This is directly relevant here because the same filters appear in reverse for Earth-to-Mars transfer: low-shock launch, fast transfer, shielding, entry, and post-delivery establishment.

Second, the life-detection community is increasingly comfortable with explicit scaffolds for uncertainty. The Venus Life Equation expresses the likelihood of extant Venus life as a product of origination, robustness, and continuity factors (Izenberg et al., 2021). A recent Venus cloud

panspermia calculation, explicitly inspired by that framework, used bolide-entry physics to estimate the rate at which Earth or Mars material could disperse cells into Venus's clouds, giving a best estimate of roughly 10^2 cells per Earth year (Guinan et al., 2026). This is not the same problem as Earth-to-Mars transfer, because it models delivery into an aerial niche rather than establishment in surface or subsurface environments. It is nevertheless important prior art: Drake-like astrobiological equations can be rigorous if their factors are transparent and their uncertainty is not hidden.

Third, panspermia is becoming a population-statistical idea as well as a transport idea. In a related framework, Smith and Sinapayen (2026) argue that panspermia and terraforming can create spatial and compositional correlations among planets, yielding a possible agnostic biosignature. The lesson for the present paper is conceptual. If life spreads, it may leave patterns at several scales: within one planet, between neighboring planets, and across populations of worlds.

Fourth, new survival experiments update one of the key priors in the chain. Earlier lithopanspermia experiments showed that some microbial rock inhabitants could survive hypervelocity-impact conditions relevant to ejection (Horneck et al., 2008; Stoffler et al., 2007). The 2026 pressure-shear impact experiments of Zhao et al. (2026) strengthen this point by showing high survivability of *Deinococcus radiodurans* after transient pressures up to about 3 GPa, a range relevant to some low-shock ejecta regimes. This does not make panspermia likely by itself, because radiation, transfer time, entry heating, deposition, and ecology remain severe filters. It does, however, shift the launch-survival factor away from being an obvious zero. It also reinforces a point made in evolutionary treatments of lithopanspermia: organisms are not merely passive cargo, because shock, desiccation, radiation, dormancy, bottlenecks, and repair can act as filters on survivable phenotypes (von Hegner, 2021).

Fifth, Mars observations since 2023 strengthen the case that the target-side factors should be represented explicitly rather than absorbed into vague habitability language. Curiosity observations at Gale Crater indicate sustained wet–dry cycling in early Martian surface environments (Rapin et al., 2023). Perseverance observations at Jezero Crater continue to document sedimentary settings, organic-mineral associations, and potential biosignatures that require careful abiotic evaluation (Mangold et al., 2021; O'Neil et al., 2025; NASA, 2025). In 2026, Curiosity's SAM TMAH experiment reported more than 20 organic molecules preserved in approximately 3.5-Gyr-old clay-bearing sandstones, including benzothiophene, methyl benzoate, and aromatic compounds (Williams et al., 2026). These findings do not demonstrate life on Mars, but they strengthen the case that ancient Mars had environments in which organic matter and potentially habitable chemistry could persist.

Sixth, the literature on reverse panspermia has widened the set of export channels that must be distinguished. Recent dust-grain calculations ask whether Earth-origin microbial material could reach Europa's surface over tens of Myr (Osmanov, 2026), and earlier work considered interstellar dust and planetary ejecta as carriers at galactic scales (Wallis and Wickramasinghe, 2004; Ginsburg et al., 2018; Cao et al., 2024). These mechanisms are not identical to rock-hosted Earth-to-Mars lithopanspermia. They are useful because they show how easily the word "panspermia" can mix different transport architectures. A Drake-like parameterization prevents that mixing: dust export, meter-scale spall, interplanetary meteorites, and interstellar objects should have different transfer, shielding, survival, and detectability factors.

Seventh, the Moon provides an independent archive for the export side of the problem. If large impacts on early Earth launched terrestrial material into space, some of that material should have reached the lunar surface. Modeling and hydrocode work suggest that terrestrial meteorites on

the Moon could survive under favorable low-velocity or oblique-impact conditions, and that lunar polar regions may be enriched in Earth-derived material relative to the lunar average (Crawford et al., 2008; Armstrong, 2010). This does not test Martian establishment directly, but it can calibrate the numerator of the Earth-to-Mars problem: how much Earth material is launched, how well biomarkers survive secondary impact, and whether ancient terrestrial biosignatures can persist outside Earth after export.

Finally, compact exoplanetary systems show why the Mars case is a conservative local test rather than the most favorable possible geometry. Models of TRAPPIST-1 find that close-packed habitable-zone planets could exchange material more rapidly and efficiently than Earth and Mars (Krijt et al., 2017; Lingam and Loeb, 2017). If panspermia is highly fecund, the strongest correlations may appear in systems more compact than ours. But Mars remains uniquely valuable because it is the only nearby case where transfer is dynamically established, the target is partly sampled, and the null result is observational rather than purely theoretical.

5 Earth-to-Mars as a Worked Example

Earth-to-Mars lithopanspermia is the cleanest hard-panspermia case for a worked example. Earth had microbial life early in its history, while Mars preserves extensive evidence for ancient aqueous environments. The late Noachian and early Hesperian record includes valley networks, lakes, deltas, groundwater systems, wet–dry cycles, organic-bearing sediments, and sedimentary settings relevant to habitability (Wordsworth, 2016; Grotzinger et al., 2014; Mangold et al., 2021; Rapin et al., 2023; Williams et al., 2026). Some climate models extend potentially habitable surface conditions by about 500 Myr into the late Hesperian (Way et al., 2022). Recent Perseverance observations at Jezero Crater also strengthen the motivation for treating Mars as a biologically serious target, while remaining careful about abiotic alternatives (O'Neil et al., 2025; NASA, 2025).

The appropriate claim is not that ancient Mars supported complex multicellular life. The defensible claim is that Mars likely had wet, chemically diverse, and potentially habitable environments capable of supporting microbial life or complex microbial ecosystems if life was present.

For a cell-count version of the worked example, define

$$V = M_{\mathrm{tot}} C_{\mathrm{rock}} f_{\mathrm{transfer}} s, \tag{3}$$

where V is the expected number of viable source-world cells delivered to the target, M_{tot} is total biologically loaded low-shock ejecta, C_{rock} is cells per kilogram of source rock, f_{transfer} is the transfer fraction, and s is the full-chain survival probability:

$$s = f_{\mathrm{lowshock}} f_{\mathrm{fast}} f_{\mathrm{shield}} f_{\mathrm{entry}}. \tag{4}$$

Table 1: Illustrative Earth-to-Mars parameters for the lithopanspermia worked example. Ranges are intentionally broad; they are scenario ranges, not measured confidence intervals. The upper survival range reflects new impact-pressure experiments; the fiducial value remains conservative because it compresses shock, transit, shielding, entry, and deposition survival into one term.

Quantity	Meaning	Scenario range	Fiducial
T_{overlap}	Earth life and wet Mars overlap	0.3–1.0 Gyr	0.5 Gyr
M_{tot}	biologically loaded low-shock ejecta	10^{10}–10^{15} kg	10^{13} kg
C_{rock}	cell loading in ejectable rock	10^{6}–10^{11} kg^{-1}	10^{8} kg^{-1}
f_{transfer}	fraction reaching Mars	10^{-4}–10^{-2}	10^{-3}
s	full-chain survival	10^{-12}–10^{-1}	10^{-7}
R_{eff}	effective colonization opportunities	10^{2}–10^{7}	10^{4}
N_f	founder threshold	1–10^{6} cells	10^{3}–10^{6}

With $M_{\mathrm{tot}} = 10^{13}$ kg, $C_{\mathrm{rock}} = 10^{8}$ cells kg^{-1}, $f_{\mathrm{transfer}} = 10^{-3}$, and $s = 10^{-7}$,

$$V = (10^{13})(10^{8})(10^{-3})(10^{-7}) \simeq 10^{11}. \tag{5}$$

This number is not the answer. It is the input to the establishment problem. The parameter ranges in Table 1 are deliberately illustrative scenario ranges. They should be treated as a sensitivity scaffold until each row is replaced by a source-backed distribution.

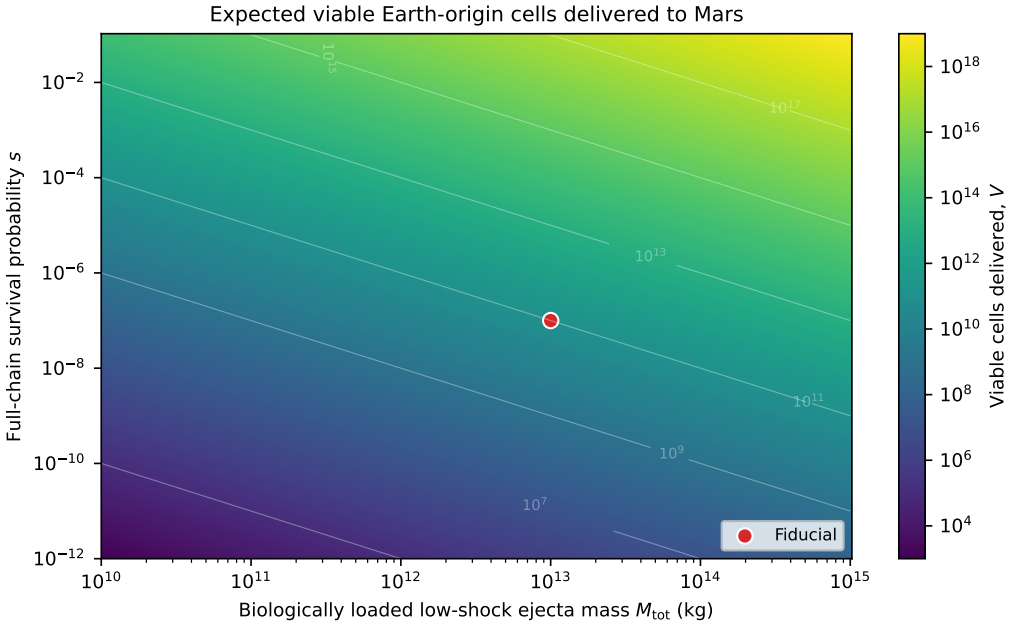

Figure 3: Sensitivity of viable Earth-origin cells delivered to Mars, using $V = M_{\mathrm{tot}} C_{\mathrm{rock}} f_{\mathrm{transfer}} s$ with $C_{\mathrm{rock}} = 10^{8}$ cells kg^{-1} and $f_{\mathrm{transfer}} = 10^{-3}$. The star marks the fiducial value. The main lesson is the enormous leverage of the full-chain survival factor.

6 Delivery Is Not Establishment

The largest conceptual error in simple panspermia arguments is to stop at V. A large number of viable arrivals may still fail if arrivals are spatially diluted, temporally mistimed, chemically incompatible, or below a founder threshold in any one habitable site.

Let R_{eff} be the number of effective colonization opportunities: not merely the number of craters, lakes, or aquifers, but the number of spatial-temporal ecological chances for viable arrivals to encounter a wet, chemically usable niche. If viable arrivals are distributed randomly, the number arriving at site j can be modeled as

$$X_j \sim \text{Poisson}(\lambda), \qquad \lambda = \frac{V}{R_{\text{eff}}}. \tag{6}$$

For founder threshold N_f, the probability that one specified site exceeds the threshold is

$$P_{\text{site}} = P(X_j \geq N_f) = 1 - \sum_{k=0}^{N_f - 1} e^{-\lambda} \frac{\lambda^k}{k!}. \tag{7}$$

The probability that at least one effective site exceeds the threshold is

$$P_{\text{est}} = 1 - (1 - P_{\text{site}})^{R_{\text{eff}}}. \tag{8}$$

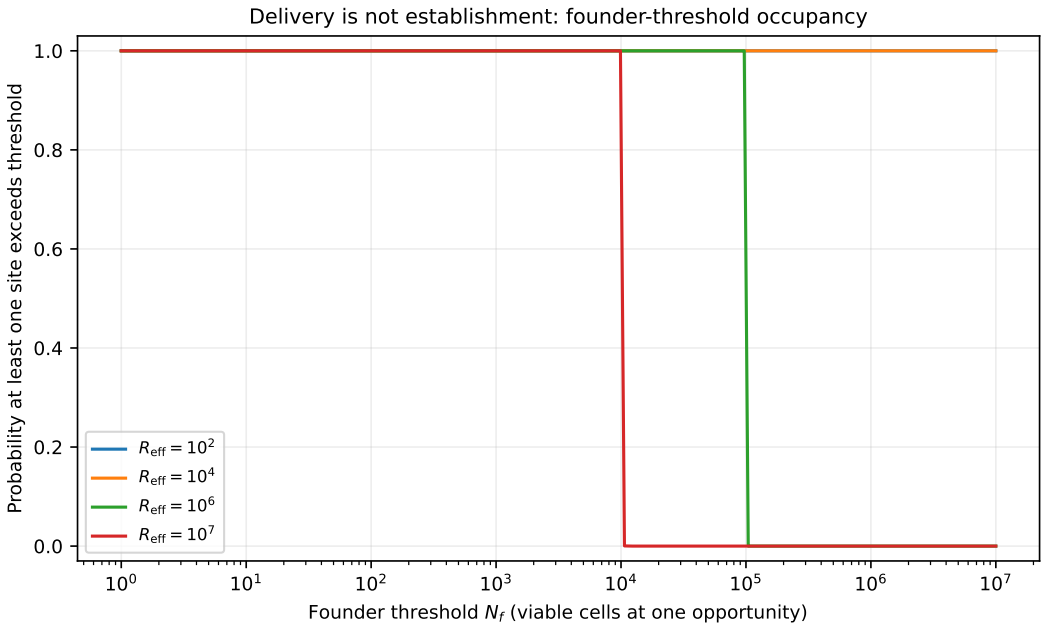

Figure 4: Founder-threshold occupancy. A fiducial delivery of $V = 10^{11}$ viable cells can be decisive for permissive founder thresholds, but marginal or irrelevant for stringent thresholds or many effective colonization opportunities.

This occupancy model is deliberately crude. It ignores impact clustering, local growth after arrival, dormancy, multispecies cooperation, repeated deposition into the same basin, and heterogeneous site lifetimes. But it captures the point that the transfer equation is not only a physics equation. The last factors are ecological.

7 Mars as a Null Experiment

The central use of the framework is not to infer the origin of terrestrial life. It is to ask what Mars should have looked like if Earth-to-Mars panspermia were a highly fecund process. This changes the direction of the inference. Instead of asking whether Earth life proves anything about Mars, we ask whether the lack of confirmed Martian life constrains the product of delivery, establishment, persistence, evolution, preservation, and detection.

The phrase "lack of life on Mars" must be used carefully. Mars has not been exhaustively searched, and the best recent data include organic molecules, habitable ancient settings, and possible biosignatures that remain under active abiotic evaluation. The relevant observation is therefore not proven sterility, but the present absence of unambiguous evidence for extant life, extinct life, or technology.

Let $\eta_{\rm bio}$ be the probability that one successful seeding event leaves an observable biological trace today. This term is not simply a biological probability. It includes persistence or extinction, burial, exposure, preservation, destruction by radiation and oxidation, weathering, erosion, sampling coverage, instrument sensitivity, and interpretive ambiguity. Mars biosignature studies emphasize that preservation is environment-specific and that water can both support habitability and destroy biosignatures through oxidation, weathering, and diagenesis (Summons et al., 2011; Hays et al., 2017). Surface radiation exposure is also a major degradation pathway for organic and biological records (Hays et al., 2017). If the expected number of observable Martian biosignature detections is

$$\mu_{\rm bio} = \Lambda_{\rm pan}\eta_{\rm bio}, \tag{9}$$

then a simplified Poisson null result gives

$$P(0 \text{ confirmed biosignatures} \mid \Lambda_{\rm pan}, \eta_{\rm bio}) = \exp(-\Lambda_{\rm pan}\eta_{\rm bio}). \tag{10}$$

Equivalently, a null result at confidence level $1-\alpha$ implies

$$\Lambda_{\rm pan} \lesssim \frac{-\ln \alpha}{\eta_{\rm bio}}. \tag{11}$$

For $\alpha = 0.05$, this is approximately $3/\eta_{\rm bio}$. The bound is strong if $\eta_{\rm bio}$ is large and weak if preservation and detection are poor. That is precisely the point: erosion, fossil loss, oxidative weathering, burial, radiation damage, and limited search coverage do not invalidate the null argument, but they must appear explicitly in the denominator.

The same logic can be extended to technological traces, but this extension is speculative and should not carry the main argument. If one assumes that imported terrestrial life would not merely establish but would, with Earth-like evolutionary fecundity, diversify, complexify, and sometimes produce technology, then the absence of obvious Martian technology constrains a longer product:

$$\mu_{\rm tech} = \Lambda_{\rm pan} f_{\rm persist} f_{\rm complex} f_{\rm intel} f_{\rm tech} f_{\rm pres,tech} f_{\rm det,tech}. \tag{12}$$

This is not a claim that life should inevitably become technological. It is a way of locating the assumption. Panspermia arguments often slide from "life can move" to "life will flourish elsewhere under similar conditions." If that stronger claim is made, Mars becomes a powerful local test. The absence of visible technological remnants on Mars constrains the product of establishment, persistence, evolutionary contingency, technological emergence, preservation, and detection.

This argument is complementary to the cosmic-history argument of Frank and Sullivan (2016). Frank and Sullivan used the large number of habitable-zone planets over cosmic time to ask how small the probability of technological species must be for humanity to be unique in the observable universe. The Mars argument runs in the opposite direction. It uses a nearby, dynamically coupled, partially searched world to ask how fecund panspermia can be before the lack of confirmed Martian life becomes unlikely. The former is a large-N abundance argument; the latter is a small-N local null experiment with unusually strong transfer priors.

8 Bayesian Interpretation

The equation also clarifies the Bayesian question. Life on Earth does not automatically imply life on Mars, and the absence of confirmed life on Mars does not automatically refute panspermia. Under strict independence,

$$P(L_{\mathrm{Mars}} \mid L_{\mathrm{Earth}}) = P(L_{\mathrm{Mars}}). \tag{13}$$

But Earth and Mars are not independent if they exchange life-bearing material or share correlated habitability histories. A minimal decomposition is

$$P(L_{\mathrm{Mars}} \mid L_{\mathrm{Earth}}) = P(L_{\mathrm{Mars}}^{\mathrm{ind}}) + P(L_{\mathrm{Mars}}^{\mathrm{trans}} \mid L_{\mathrm{Earth}}), \tag{14}$$

where the second term is precisely the class of processes organized by Eq. 1. A fuller model would also include a shared-environment term for correlated but independent origin probabilities: the fact that both planets formed in the same young Solar System, received similar classes of exogenous organics, and experienced early impact and aqueous histories. Recent Bayesian work on abiogenesis emphasizes that inferences from Earth's early life depend sensitively on priors and on how many conducive sites were available (Lingam et al., 2024). The same lesson applies here: the relevant prior is not a single number for "life on Mars," but a partition among independent origin, transferred origin, shared prebiotic enrichment, failed establishment, post-establishment extinction, and non-detection.

This is where Vickers-style caution matters. Community agreement that basic extraterrestrial life is likely may justify taking the hypothesis seriously. It does not justify assigning a precise prior to a specific Earth-to-Mars transfer route. The prior belongs on the model class; the posterior must be earned by the factors. In the present paper, the crucial posterior update is not "there is no life on Mars." It is that a strong panspermia-fecundity hypothesis must pay every term in the null-result likelihood: establishment, persistence, preservation, and detection.

9 What Would Improve the Equation?

The most valuable future work is not choosing a single preferred number. It is replacing each factor with a source-backed distribution.

For Earth-to-Mars, the highest-value improvements are:

- better constraints on biologically loaded low-shock ejecta during the overlap interval;
- transfer-time distributions, not only eventual collision fractions;

- survival experiments that combine shock, shielding, radiation, desiccation, entry heating, and deposition;
- evolutionary models of bottlenecking, dormancy, mutation, repair, and selection during the launch–transit–entry sequence;
- geological maps of long-lived wet Martian environments as effective colonization opportunities;
- preservation and destruction models for fossil, organic, isotopic, mineralogical, and textural biosignatures under Martian radiation, oxidation, weathering, burial, and erosion histories;
- explicit search-completeness estimates for rover, orbiter, returned-sample, subsurface, and meteorite-based life detection;
- lunar searches for terrestrial meteorites and ancient Earth biomarkers as an independent calibration of Earth ejecta export and preservation;
- comparative applications to compact exoplanet systems, where the transfer kernel may be much larger than in the Earth–Mars case;
- microbial ecology models for founder thresholds, dormancy, and consortia.

This also suggests a practical use for the equation. Each observation or experiment can be scored by which factor it constrains. A Mars sample showing clear terrestrial ancestry would constrain a different term than an experiment showing high shock survival. A map of persistent Noachian groundwater systems would constrain f_{hab} and R_{eff}, not f_{transfer}.

10 Conclusion

The proposed Drake-like scaffold for lithopanspermia is:

$$\Lambda_{\mathrm{pan}} = N_{\mathrm{launch}} f_{\mathrm{bio}} f_{\mathrm{lowshock}} f_{\mathrm{transfer}} f_{\mathrm{fast}} f_{\mathrm{shield}} f_{\mathrm{entry}} f_{\mathrm{hab}} f_{\mathrm{founder}}.$$

It converts a vague claim into a chain of testable filters. Applied to Earth-to-Mars transfer, the equation shows why panspermia can be physically plausible and biologically uncertain at the same time. The illustrative calculation gives $\sim 10^{11}$ viable arrivals, but successful seeding depends on the last filters: habitable deposition, clustering, and establishment. Observable consequence depends on still more filters: persistence, fossil or chemical preservation, erosion, weathering, radiation damage, search coverage, and detectability.

The far-reaching implication is not that Earth seeded Mars. It is that Mars supplies a local null experiment for natural panspermia. If panspermia is easy, fecund, and evolutionarily productive, then the lack of confirmed Martian life, fossils, or technology becomes increasingly informative. If the Martian record remains null after better sampling and preservation modeling, the constraint does not fall on transfer alone. It falls on the full product: transfer, survival, establishment, persistence, evolutionary fecundity, preservation, and detection. In that sense, Mars can constrain panspermia in the same way that cosmic abundance arguments constrain the rarity of technological life, but from the opposite direction: not by multiplying the universe, but by interrogating the nearest coupled pair of habitable worlds.

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