The long-term persistence of microbial biospheres introduces a temporal bias into the Drake equation: implications for the search for extraterrestrial life. §

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Abstract

The Drake equation was designed to estimate the number of communicative technological civilisations, not the prevalence of life. Its lifetime term therefore describes a detectable technological phase that may represent only a small part of a planet's biological history. This emphasis introduces a temporal bias when Drake-style reasoning is extended from technological civilisations to life more generally, because microbial biospheres have persisted throughout nearly the entirety of Earth's inhabited history. In contrast, technological detectability is a very recent state. Insights from non-equilibrium thermodynamics and microbial energetics provide a mechanistic basis for understanding how biological systems can persist under extremely low energy flux. Geological evidence further shows that microbial biospheres arose early and persisted across major planetary transitions long before the emergence of complex ecosystems and technological civilisation. Here, we use the lifetime term as a residence-time variable describing the duration of a biological state. Under this interpretation, microbial-biosphere occupancy could account for most of the time during which an inhabited planet's biological history, including intervals in which complex ecosystems or technological civilisations coexist with microbial life. Biological prevalence, residence time and remote detectability are therefore not equivalent quantities. Planets such as Proxima Centauri b provide an important test case. If they retain habitable environments and develop life, they can potentially support long-lived microbial biospheres whose signatures remain weak or intermittent. We hypothesise that microbial biospheres may occupy a larger fraction of inhabited planetary histories than technological states on inhabited planets, producing a systematic temporal bias when Drake-style reasoning is extended from technological civilisations to life more generally. Microbial biosignatures and technosignatures should therefore be treated as complementary observational targets in the search for extraterrestrial life.

Keywords: Microbial biospheres; Drake equation; Residence time; Biosignatures; Technosignatures; M-dwarf stars

1. Introduction: The temporal bias of the Drake equation

The Drake equation was originally formulated to estimate the number of communicative technological civilisations in the Galaxy. Although it was not intended to measure the prevalence of life itself, its structure has strongly influenced how astrobiology probabilities are framed. The equation was devised as an organising framework for the 1961 Green Bank conference and first appeared in Pearman's account of that meeting; Drake subsequently published his own extended treatment (Drake, 1965; Pearman, 1963). In its classical form, the equation culminates in the lifetime parameter (L), which Pearman described as the "time spent in the communicative state" (Cirković, 2004; Pearman, 1963).

When this framework is extended from communicative technological civilisations to life more generally, the final detectable phase may obscure the much longer biological history that precedes it. However, on Earth during the first two billion years, the fundamental biogeochemical cycles of carbon, sulfur, nitrogen, and phosphorus were established by microorganisms within the early oceans. Microbial ecosystems therefore persisted long before the emergence of eukaryotic cells and the subsequent diversification of complex multicellular organisms (Knoll et al., 2016). Recent empirical reformulations of the Drake equation likewise retain technological species as their endpoint (Frank & Sullivan, 2016). If comparable temporal asymmetries occur elsewhere, microbial biosphere occupancy could span a larger fraction of planetary biological history than intervals of technological detectability. We refer to the resulting mismatch between biological residence time and technological detectability as a temporal bias.

The framework therefore predicts that microbial ecosystems could account for most of the time during which an inhabited planet remains biologically active. This idea also relates to the Fermi paradox, which asks why there is no clear evidence of technological civilisations if they are common (Webb, 2015). The absence of detectable technological signals need not reflect rarity alone, but may also contain a temporal sampling component (Brin, 1983; Ćirković, 2018; Shkurko, 2024): if microbial biosphere occupancy typically persists substantially longer than intervals of technological detectability, a randomly timed census of inhabited planets can be dominated by worlds lacking currently detectable technology. Here, we adopt the working assumption that once life emerges on a planet, microbial biospheres form a persistent biological baseline. Complex ecosystems and technological civilisations may arise as additional, potentially shorter-lived states rather than replacements for microbial life. This offers a complementary interpretation of the current absence of confirmed technosignatures. Unlike "Rare Earth"–type arguments, it does not require complex life or intelligence to be intrinsically improbable: the probability of entering a biological state, the time spent in it, and its detectability are treated as separate quantities. The next sections show how integrating thermodynamics, microbial ecology, and stellar demographics clarifies how residence time shapes expectations for life in the Galaxy.

2. Life as a non-equilibrium energetic process

Life is a non-equilibrium phenomenon: growth, maintenance and replication ultimately depend on exchanges of energy and matter with the surroundings (Haynie, 2008). Schrödinger described living systems as entities that maintain their biological order by expending energy while exporting entropy to their surroundings, consistent with the Second Law of Thermodynamics (Schrödinger, 1944). Later, the concept of dissipative structures showed that complex organisation can arise far from equilibrium (Prigogine, 1980). More recent statistical-physics work has explored thermodynamic constraints on self-replication and proposed dissipative adaptation as one account of driven self-organisation (England, 2013, 2015).

From a thermodynamic perspective, life is characterised in part by its ability to use environmental energy gradients to support metabolism. Microorganisms are particularly well suited to exploiting such gradients. Prokaryotes have remarkable metabolic diversity and can persist under extremely low energy flux (Hoehler & Jørgensen, 2013; Nealson et al., 2001). On Earth, microorganisms constitute a substantial fraction of global biomass and mediate many of the planet's major biogeochemical transformations (Bar-On et al., 2018; Flemming & Wuertz, 2019). This view echoes Vernadsky's 1926 concept of the biosphere, in which living matter acts as a geological force that reshapes planetary chemistry over long timescales (Vernadsky, 1998).

Geological evidence indicates that life emerged relatively early in Earth's history, although both its precise timing and environmental setting remain debated (Westall et al., 2023). Hydrothermal and geochemically driven environments constitute one important class of models for the origin of metabolism rather than an established single birthplace of life. Recent experimental and phylogenetic studies suggest possible links between environmental catalysis and the assembly of early metabolic pathways. These studies include reactions promoted by native transition metals and evidence that metabolism in LUCA was enzymatically incomplete, with metal catalysts inferred to have preceded some enzymes and cofactors (Mrnjavac et al., 2026). More broadly, the evolution of biological energy conservation has been closely coupled to changes in Earth's geochemical environment (Padalko et al., 2025).

3. Microbial biospheres as a persistent biological baseline

The earliest well-established Earth biosphere was microbial, and early ecosystems developed under largely anoxic conditions long before the emergence of complex multicellular life (Knoll et al., 2016; Westall et al., 2023). These early microbial ecosystems provide useful analogues for some anoxic and chemically driven settings considered in astrobiology. The early presence and long-term persistence of microbial ecosystems demonstrate that biological activity can be maintained under environmental conditions markedly different from those that support modern complex surface ecosystems, although the precise conditions and habitability of early Earth remain debated (Santosh et al., 2017; Westall et al., 2023). Life can persist in sustained

chemical disequilibria maintained by minimal energy gradients (LaRowe & Amend, 2015), providing a mechanism compatible with long-lived microbial activity under energy constraints. The energetic efficiency of microbial metabolism enables organisms to exploit extremely small redox gradients derived from trace chemical couples and geothermal fluxes (Hoehler & Jørgensen, 2013). Microbial ecosystems are often organised as stratified, cooperative communities that couple diverse metabolic pathways to environmental gradients, as exemplified by microbial mats, which have long been studied as model systems for early biospheres (Cohen & Rosenberg, 1989). This rationale is consistent with observations from Earth's deep biosphere and biofilm-based ecosystems, where microbial communities operate under extreme energy limitation over geologically extended periods (Hoehler & Jørgensen, 2013; Nealson et al., 2001).

Microbial persistence does not require continuous metabolic activity. Laboratory studies show that mineral- and salt-associated microbes can survive desiccation and resume activity after rehydration, illustrating mechanisms of cellular persistence through periods of metabolic inactivity (Gómez Gómez et al., 2014, 2016). Microbial communities can also distribute metabolic functions across populations and spatial microenvironments, providing ecological redundancy and resilience to local disturbance (Nealson & Conrad, 1999; Parrilli et al., 2022). These observations demonstrate mechanisms of cellular and community persistence, but they do not show that a planetary biosphere can remain intact for billions of years. They support the plausibility of long-term persistence rather than providing direct evidence for it.

At the planetary scale, models of Earth's future provide an independent precedent for prolonged microbial occupancy. O'Malley-James et al. predicted that as solar evolution progressively restricts Earth's surface habitability, microbial life would outlast plants and animals and become the final surviving component of the biosphere (O'Malley-James et al., 2013). Thus, both Earth's early history and models of its distant future place microbial-dominated intervals around the comparatively shorter interval during which complex ecosystems dominate. However, microbial persistence has limits. Extreme conditions such as total energy starvation, sterilising radiation, or irreversible atmospheric loss can constrain biological activity. We therefore do not treat microbial persistence as inevitable. Rather, under conditions that remain compatible with biological activity, the exceptionally broad metabolic and environmental tolerances of microorganisms make microbial biospheres plausible candidates for long residence times at the planetary scale (Cockell et al., 2016).

4. Energetic scaling and the persistence of complexity

Throughout evolution, increased complexity has often been accompanied by higher energy throughput (Chaisson, 2001). Energy availability can constrain organismal size, metabolism, and ecological organisation, but it does not impose a universal monotonic relationship whereby greater energy flux necessarily reduces biodiversity, stability, or robustness (Brown et al., 2004; McCarthy & Enquist, 2005). Microbial metabolisms can also remain active under

exceptionally low energy flux, while microbial ecosystems can distribute metabolic functions across diverse populations and pathways (Hoehler & Jørgensen, 2013; LaRowe & Amend, 2015). Between microbial biospheres and technological civilisations lies a continuum of increasingly complex multicellular ecosystems. These systems generally depend on additional physiological, ecological and environmental requirements beyond those sufficient for minimal microbial metabolism, potentially narrowing the range of conditions over which they can persist (Cockell et al., 2016; Levin, 1998).

Multicellular organisms rely on tightly coordinated processes, while technological civilisations depend on highly integrated energy and information infrastructures. Such integration can create additional dependencies and modes of failure, but it can also provide buffering, regulation and adaptive capacity. Complexity should therefore not be treated as intrinsically unstable. Critical-transition theory nevertheless illustrates how highly interconnected systems can undergo abrupt changes when environmental thresholds are crossed (Scheffer et al., 2009). Our claim is narrower: biological states that depend on a larger set of enabling conditions may, on average, persist for shorter periods than states viable across a broader range of conditions.

Nor should the residence time of complex life be assumed to be universally short. Recent three-dimensional climate modelling suggests that Earth's vegetative biosphere could persist for up to approximately another 1.8 billion years under some assumptions (Haqq-Misra & Wolf, 2026). Such results strengthen the need to treat residence times as quantities to be constrained rather than predetermined. Importantly, microbial occupancy includes the interval before complex life arose and continues throughout the existence of complex ecosystems.

These differences in environmental requirements motivate, rather than prove, a residence-time hierarchy of biological states. The persistence of biofilm-associated microbial communities has long been recognised across biological contexts (Costerton et al., 1999). More recent work has emphasised biofilms as adaptations to extreme conditions and as potential sources of lasting astrobiological signatures (Gonzalez-Henao & Schrenk, 2025; Parrilli et al., 2022). Consequently, we hypothesise that planetary histories are disproportionately occupied by microbial biospheres, even when complex life and technological civilisations also arise.

5. **Residence time and the Drake equation**

The temporal interpretation developed here extends an idea already present in the earliest formulations of the Drake equation. Pearman (1963) defined (L) as the “time spent in the communicative state,” and Cameron (1963) subsequently expressed the communicative lifetime relative to a longer planetary interval (Cameron, 1963; Pearman, 1963). Drake's own published treatment likewise emphasised the importance of the duration of the

communicative phase (Drake, 1965). Here, we generalise this state-duration logic from communication to the residence times of biological states.

The Drake equation can be written as:

$$(1)\ N = R_* f_p n_e f_l f_i f_c L$$

where *N* represents the number of technologically communicative civilisations currently existing in the Galaxy, R_* is the mean rate of star formation, f_p the fraction of stars hosting planetary systems, n_e the number of potentially habitable planets per system, f_l the fraction on which life arises, f_i the fraction on which intelligence evolves, f_c the fraction that develop detectable communication technologies, and L the mean lifetime during which a technological civilisation remains in the communicative state.

In this formulation, (L) represents the residence time of a communicative technological state—the duration during which a civilisation remains detectable. The Drake equation therefore counts systems during the interval in which they satisfy the communicative criterion, rather than over their entire biological histories. For microbial biospheres, the intelligence and communication factors f_i and fc are unnecessary, while the technological lifetime (L) is replaced by a biological residence time, L_{micro}. Modern exoplanet observations increasingly constrain some astrophysical terms in Drake-like formulations, while the biological and technological terms remain substantially more uncertain (Frank & Sullivan, 2016). Related work has also explicitly compared searches for primitive and intelligent life as distinct observational problems (Lingam & Loeb, 2019). Drake-like formulations have likewise been applied to the abundance and longevity of biotic planets (Wandel, 2015).

Here, we adopt the working assumption that once life emerges on a planet, microbial biospheres constitute its persistent biological baseline. In contrast, more complex biological organisations may arise within that baseline as additional states. For microbial biospheres, the relevant quantity is the mean residence time of a biological state, defined here as the average duration over which a given biological configuration persists on a planet. The states considered here need not be mutually exclusive: L_{micro} denotes the duration of microbial-biosphere occupancy, even during periods when complex ecosystems or technological civilisations coexist with microbial life. This definition leads to a simplified expression for microbial biospheres:

$$(2)\ N_{micro} = R_* f_p n_e f_l L_{micro}$$

where L_{micro} represents the typical duration of a microbial biosphere, a corresponding expression for technological civilisations can be written as:

$$(3)\ N_{tech} = R_* f_p n_e f_l f_i f_c L_{tech}$$

Taking the ratio of these expressions highlights the temporal bias inherent in the Drake framework:

$$(4)\ \frac{N_{tech}}{N_{micro}} = f_i\, f_c\, \frac{L_{tech}}{L_{micro}}$$

Equations (2)–(4) assume that the relevant formation and transition rates are approximately stationary. Over gigayear timescales, they are not: Galactic star formation, chemical evolution and planetary demographics change (Cirković, 2004; Madau, 2023). A fully time-dependent treatment would require integration over Galactic history and lies beyond the present model.

The purpose of this simplified comparison is not to replace the Drake equation, but to ask how state duration affects instantaneous occupancy. Numerical simulations could explore this parameter space explicitly (Forgan, 2009). If microbial biospheres commonly persist for billions of years while technological phases are shorter, longer-lived states contribute more strongly to a random-time census, all else being equal. Figure 1 illustrates this hypothesis.

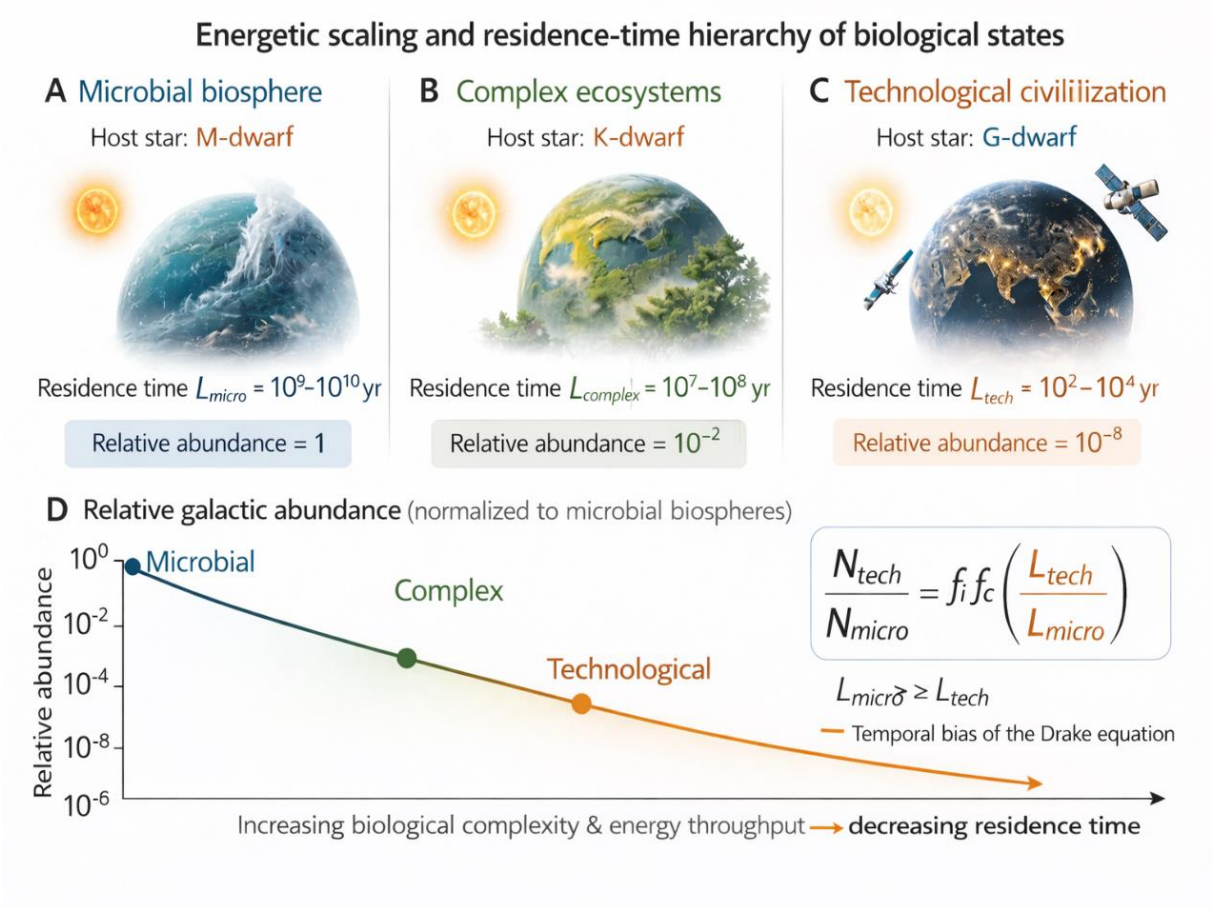

Figure 1. Energetic scaling and residence-time hierarchy of biological states.

A schematic representation of three illustrative biological regimes arranged along a hypothesised gradient of increasing biological and organisational complexity and decreasing residence time. (A) Microbial biospheres represent the persistent biological baseline considered in this framework. (B) Complex multicellular ecosystems and (C) technological

civilisations may arise as additional states within that baseline and are therefore not intended to represent mutually exclusive evolutionary replacements of microbial life. The host-star associations shown in panels A–C are illustrative stellar contexts only and do not imply a deterministic relationship between stellar spectral type and biological complexity. Likewise, the residence-time ranges and relative-abundance values shown in the figure are illustrative assumptions used to visualise the conceptual framework; they are not observationally inferred, model-derived, or proposed as universal values. (D) The schematic relative Galactic abundance illustrates the contribution of residence time to the simplified ratio: $\frac{N_{tech}}{N_{micro}} = f_i\, f_c\, \frac{L_{tech}}{L_{micro}}$, all else being equal. It should therefore be interpreted as a conceptual representation of the residence-time effect developed in Section 5 rather than as a quantitative prediction of Galactic abundances. This figure was initially generated with assistance from ChatGPT (OpenAI, GPT-5.3, accessed March 2026) and subsequently edited and finalised by the authors.

6. M-dwarf planets and Proxima Centauri b as a local test case

M-dwarf planetary systems provide some of the nearest and most numerous stellar environments in which the temporal bias described above may manifest. These low-mass stars dominate the stellar population of the Galaxy and possess lifetimes far exceeding those of solar-type stars (Seeds & Backman, 2019; Shields et al., 2016). Kepler observations indicate a substantial occurrence rate of small and potentially habitable-zone planets around M dwarfs (Dressing & Charbonneau, 2015). Observations of nearby systems, particularly TRAPPIST-1, have also demonstrated the occurrence of compact terrestrial-planet systems around M dwarfs and highlighted the difficulty of constraining their atmospheric properties.

At the same time, M-dwarf systems can undergo extended early phases of elevated stellar activity, including high XUV fluxes and frequent flaring, which may drive atmospheric loss or severe surface environmental stress (Dong et al., 2018; Luger & Barnes, 2015; Ribas et al., 2016). The duration and intensity of this activity vary strongly with stellar mass and age, and stellar longevity does not by itself imply planetary habitability. Atmospheric loss, tidal evolution and geophysical processes can limit a planet's habitable lifetime to much less than the main-sequence lifetime of its star (Shields et al., 2016; Tarter et al., 2007).

Low stellar luminosity should also not be equated directly with a “low-energy” biosphere: habitable-zone planets orbit M dwarfs at smaller orbital distances. They can receive irradiation compatible with the presence of liquid water on their surfaces. The relevant differences include stellar spectral energy distribution, activity history, tidal environment and atmospheric evolution (Shields et al., 2016). Moreover, M-dwarf planets should not be assumed to exclude oxygenic photosynthesis or complex life; both remain possible under suitable atmospheric and irradiation conditions (Gale & Wandel, 2017; Wandel & Gale, 2020). If habitable environments survive or re-emerge despite these challenges, the exceptional longevity of M

dwarfs could permit long intervals of biological occupancy, provided planetary habitability itself persists. Subsurface or chemically driven microbial ecosystems represent one possible mode of persistence when surface conditions are less favourable.

Within the framework proposed here, planets such as Proxima b serve as illustrative local examples, not as expected microbial outcomes. If Proxima b retains habitable environments and life has arisen there, microbial ecosystems could, in principle, persist over long intervals while remaining difficult to detect with current remote-sensing methods (Meadows et al., 2018; Ribas et al., 2016). Stellar demographics may amplify this effect because M-dwarf stars are both numerous and extremely long-lived. Stellar lifetime places only an upper bound on potential biological residence time; it does not establish either habitability or a planet's biological complexity. Consequently, the residence-time framework does not entail a one-to-one mapping between M-dwarf hosts and microbial biospheres (Lingam & Loeb, 2018).

7. Implications for biosignature and technosignature searches

If microbial biospheres represent a particularly persistent biological state, observational strategies in astrobiology should reflect this asymmetry. However, residence time alone does not determine the probability of detection. A long-lived biosphere may produce weak signatures, while a shorter-lived state may generate a disproportionately conspicuous signal (Kopparapu, 2026). Searches for microbial biosignatures and technosignatures should therefore be treated as complementary rather than as alternatives ranked solely by expected lifetime (Lingam & Loeb, 2019).

Technosignatures associated with technological civilisations may be temporally sparse and highly context-dependent. Active signals such as radio emissions, artificial illumination or industrial atmospheric products may persist for only part of a civilisation's lifetime. However, some technological artefacts or engineered environments can remain detectable long after their creators have disappeared, and technology could, in principle, spread beyond a single inhabited planet (Wright et al., 2022). The biological residence time of a technological civilisation should therefore be distinguished from the lifetime of its technosignatures.

Persistence, metabolic activity, and detectability should be treated as separate properties. A biosphere may persist for billions of years while producing only weak or intermittent geochemical signatures. Conversely, detectable biosignatures may appear only episodically, depending on planetary conditions and observational sensitivity. Earth itself illustrates this problem: atmospheric biosignatures such as oxygen and methane would have been weak or ambiguous during substantial portions of its inhabited history despite the presence of an active biosphere (Reinhard et al., 2017). More generally, false negatives may arise from the abundance, activity, location, and appearance of life; the preservation of its traces; and limitations of the methods used to detect them (ten Kate et al., 2026). The absence of strong biosignatures or technosignatures, therefore, does not necessarily imply the absence of life.

This distinction is particularly relevant for planets orbiting M-dwarf stars. Atmospheric biosignature detectability around such planets depends strongly on stellar spectral properties and the planet's atmospheric state (Meadows et al., 2018; Rugheimer & Kaltenegger, 2018). Life confined to subsurface or chemically driven ecosystems would be even harder to identify remotely; Solar System subsurface environments provide useful analogues for this problem (Tarnas et al., 2021). Such worlds could contribute substantially to biological residence time while contributing little to a remotely detectable biosignature census. Population-level surveys may reveal patterns that individual detections cannot. Bioverse simulations suggest that correlations between stellar UV environments and biosignature occurrence could help test specific hypotheses about the emergence of life (Schlecker et al., 2025).

8. Conclusion: residence time across biological states

Recent community-wide assessments of astrobiology research priorities emphasise the importance of stellar context, biosignature persistence, and observational bias in interpreting future detections (Parenteau et al., 2026). Geological evidence suggests that life emerged relatively early under Hadean-early Archean conditions (Westall et al., 2023), and Earth's subsequent history demonstrates prolonged microbial occupancy before and throughout the emergence of complex life. Together with evidence that microorganisms can operate across extraordinary energetic and geochemical constraints (Hoehler & Jørgensen, 2013; LaRowe & Amend, 2015; Nealson et al., 2001; Nealson & Conrad, 1999), this motivates the hypothesis that microbial biospheres may constitute particularly long-lived biological states.

This hypothesis does not imply that evolution inevitably converges toward microbial simplicity, nor that complex life or intelligence must be rare. Instead, it proposes that different biological states can have substantially different emergence probabilities and mean residence times. Because microbial life can precede complex ecosystems, coexist with them, and potentially persist after their disappearance, microbial biospheres could occupy the largest fraction of an inhabited planet’s history. When Drake-style reasoning is generalised from communicative civilisations to biological states, the lifetime term can therefore be interpreted as a residence-time variable. Under the simplifying assumptions developed here, states with longer mean durations contribute more to the expected instantaneous occupancy of inhabited planets. The apparent tension between the occurrence of potentially habitable planets and the current absence of confirmed technological signatures could therefore be partly reconciled without requiring that the emergence of life is intrinsically uncommon.

Microbial persistence is also compatible with the emergence of intelligence: complex and technological states can arise within a continuing microbial baseline. In a broader historical sense, this nested view echoes Vernadsky's later description of the noosphere as a new state of the biosphere arising through human activity (Vernadsky, 1945); here, however, the states are treated operationally through their residence times. Residence time must also remain

distinct from observational detectability: persistent biospheres may remain cryptic, whereas comparatively short biological states may generate strong or long-lived signatures.

If microbial biospheres dominate planetary residence times—and if M-dwarf stars dominate the stellar population—a randomly observed inhabited world may be more likely to host a microbial biosphere without a coexisting technological civilisation than to be in a technological-civilisation state. This prediction is conditional rather than deterministic and can ultimately be tested only through comparative observations of planetary environments and biological signatures beyond Earth. Under these conditions, long-lived microbial biospheres may frequently characterise inhabited worlds.

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Competing interests

The authors declare none.

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