

Planetary Scale Replication as an Agnostic Biosignature

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Abstract

ALife is primed to address the biggest challenges in astrobiology by simulating systems which capture the most general and fundamental features of living systems. One such challenge is how to detect life outside of the solar system—especially without making strong assumptions about how life would manifest and interact with its planetary environment. Here we explore an ALife model meant to overcome this problem, by focusing on what life may do, rather than what life may be: life can spread between planetary systems (panspermia) and can modify planetary characteristics (terraformation). Our model shows that as life propagates across the galaxy, correlations emerge between planetary characteristics and location, and these correlations can function as a biosignature. This biosignature is agnostic because it is independent of strong assumptions about any particular instantiation of life or planetary characteristic. We demonstrate (and evaluate) a way to prioritize specific planets for further observation—based on their potential for containing life. We consider obstacles that must be overcome to practically implement our approach, including identifying specific ways in which better understanding astrophysical and planetary processes would improve our ability to detect life.

Introduction

Attributing with certainty observable features of exoplanets to extraterrestrial life is problematic due to insufficient theories (or definitions) of life, and due to the growing number of false positives for traditional biosignatures (Tasker et al., 2017; Harman and Domagal-Goldman, 2018; Smith and Mathis, 2023). While efforts to develop agnostic biosignatures—signs of life that are not particular to Earth-life or any other hypothetical instances of life—aim to overcome these issues, they often rely on restricted concepts of habitability or focus on simple anomaly detection (Cleland, 2012; Janin, 2021; Smith et al., 2021). Another approach involves statistical biosignatures, which integrate multiple lines of evidence to increase confidence in a discovery, yet they may rely on assumptions about the prior probability of abiogenesis or on the existence of as-of-yet undiscovered unambiguous biosignatures (Lin and Loeb, 2015; Walker et al., 2018; Affholder et al., 2021).

Here we ask, can we detect the presence of life if we postulate that life is spreading between, and terraforming, planets?¹ We use an agent-based model to show that statistical correlations between the spatial distribution of planets around different host stars, and their observable characteristics *would itself* be evidence of life, without the need for a separate biosignature that could reliably detect life on any given planet in isolation. The agnosticism of this biosignature is inseparable from its emergence at the scale of a population of planets—singleton planetary anomalies might be explained away by unknown geochemical processes, or targeted simply because they are anomalous (without a clear hypothesis of why they should be explained by life). Hypothesizing that life spreads via panspermia and terraformation allows us to search for biosignatures while forgoing any strong assumptions about not only the peculiarities of life (e.g., its metabolism) and planetary habitability (e.g., requiring surface liquid water), but even the potential breadth of structure and chemical complexity underpinning living systems (Solé and Munteanu, 2004; Kim et al., 2019; Bartlett et al., 2022).

Modeling Panspermia and Terraformation

We created an agent-based model to simulate life² spreading between planets orbiting different host stars. The model is initialized with 1000 planets (1 of which is terraformed/panspermia-capable), fixed in a frame of reference, and uniformly randomly distributed in a continuous 3D volume. All planets are assumed to be in different star systems (i.e., we assume one planet per star). “Planets” have compositions representing the observable characteristics of the planet, and “life” agents have compositions representing the observable characteristics of the planet which the life originates from. Both “life” and “planets” compositions

¹Here, “life spreading” refers to interstellar panspermia, and “terraforming planets” refers to modifying observable characteristics of planets.

²In this work, we use *life* specifically to refer to an agent (used strictly in the “entity” sense of the word agent) traveling from a parent terraformed planet to a target non-terraformed planet, and whose arrival at the target planet triggers terraformation.

are abstractions represented by vectors of 10 real numbers (each element $\in [0, 1]$), used as a means to compare the compatibility of any given life and planet. During simulation, terraformed planets³ create and send out a “life” agent towards a target non-terraformed planet at a constant velocity⁴. The target planets are selected based on proximity in position and in composition. When life arrives at a planet, the planet’s composition is modified (terraformed) based on both the initial composition of the planet and the composition of the incoming life. Life originating from that terraformed planet will then reflect its new composition. We assume that the time required for terraformation is negligible compared to the time required to travel between planets. Terraformed planets create and send out “life” agents at a fixed rate, provided suitable target planets exist. The simulation ends when all planets are terraformed, or no suitable target planets remain.

Identifying the Presence of Terraformed Planets

We hypothesize that the process of panspermia and terraformation in our model will lead to a population of planets with anomalously high positive correlations between their spatial locations and compositions, compared to random permutations of these planets’ compositions. We find this is the case, as quantified by the Mantel test—a statistical test common in ecological science (Mantel, 1967). The p-value of our Mantel test indeed decreases as planets become terraformed, and after $\approx 8\%$ of planets are terraformed, $p \leq 0.01$.

We next attempted to select planets with high potential for having undergone terraformation. We can begin to do this by clustering (DB-SCAN) (Hahsler et al., 2019) on the planet compositions. From these initial clusters, we select those localized in space (via their interquartile range, IQR), because we hypothesize that life would not only change the distribution of planetary compositions, but would also do so in a relatively compact portion of the galaxy (Fig. 1, left, below dashed line). Here we use an arbitrary IQR threshold of 25.2. We further select clusters which, when removed, cause a decrease in the Mantel coefficient of the residual space of planets (Mantel contribution > 0 ; Fig. 1, left, color-scale). With both of these selection criteria applied, we detect a total of 247 clusters across all terraformed ratios (Fig. 1, left below horizontal line)—the earliest first appearing at a terraformed ratio of 0.04 (Fig. 1, left, lower-left most point).

After selecting clusters, we evaluate if they actually con-

³We specifically avoid saying living planets, because our methodology cannot distinguish between living planets incapable of panspermia and non-living planets.

⁴This approach is most similar to directed panspermia by intelligent life, but could also be envisioned as undirected lithopanspermia, where we refrain from burdening the simulations with agents that won’t ever be able to interact with planets under the rules of our model.

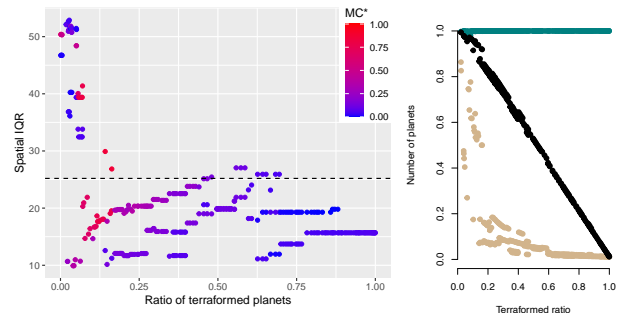


Figure 1: Planet clusters selected by our spatial IQR and Mantel contribution criteria (left) and evaluation of our detection method’s specificity, sensitivity, and accuracy at each time step (right). See text for figure explanation.

tain terraformed planets (Fig. 1, right). We find that across the full range of terraformed ratios, they have extremely high specificity (teal)—close to 1.0—correctly rejecting non-terraformed planets as being non-terraformed. However, detected cluster sensitivity (tan)—a measure of correctly detecting terraformed planets as being terraformed—ranges from 1.0, down to near 0.0. The highest sensitivity clusters appear when fewer planets are terraformed. Accuracy—the proportion of all planets correctly classified (black)—also decreases with ratio of planets terraformed. Our results indicate that we find few false positives, but more and more false negatives as planets become terraformed.

Summary and Discussion

While we only walk through a simulation under a single set of parameters here, our goal was to identify a best possible case scenario for applying a technique where we assume life should be able to drive correlations in planetary position-composition space based on hallmarks of life like proliferation and environmental bi-directional feedback. Our model results show promise that life could be detected at the scale of a population of planets, using information from only ≈ 1000 (perhaps fewer) planetary atmospheres, even in the absence of any information about what kinds of planetary environments are most suitable to life, or without knowing anything about the origins of life, or the peculiarities of life’s metabolic outputs. We showed how our distributed biosignature can be further refined to detect specific clusters of terraformed planets in this space, even when they only comprise a few percent of all planets. Again, this approach does not require an independent way to “detect” life, like a smoking gun biosignature atmospheric gas. Instead this approach depends on two key assumptions about what life can do, and derives observable consequences directly from them, providing a statistical approach which can be refined by astronomical surveys, and therein lies its biggest promise.

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