

Finding a Panspermia Signature with Poisson Process Simulations

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ABSTRACT

Understanding how biological life began on Earth is essential to determine if and how life may arise on other worlds. There are several theories that explain how life on Earth began, with one of the most intriguing being the concept of panspermia, or the idea that biological life can "hitch a ride" on an interplanetary object to populate new worlds. Previous work by Spiegel and Turner establish that panspermia events can be modeled as a Poisson process - an event whose probability is constant given a fixed interval of time (3). This paper builds on their work by developing a simulation of panspermia occurrences in a system of planets. A Monte Carlo simulation is composed of independent Poisson processes is developed to model whether or not a given system contains life. The model keeps tracks of several key metrics that are then used to determine a unique signature of panspermia. In the end, a unique signature for panspermia is found, which can help strengthen our understanding of the origins of life in the universe.

1. INTRODUCTION

Life began on Earth quickly. Although the earliest recorded fossils formed during the first billion years of Earth's existence, it is possible that life began even sooner (1). Despite being a fundamental question in biology, the origins of life are not well understood, making the study of life's genesis one of great importance to the scientific community. This paper examines two leading theories behind this issue: abiogenesis, and panspermia. The former suggests that life on Earth had spontaneously emerged from non-living matter. This theory gained popularity in the mid 1900's when Stanley Miller demonstrated that amino acids could be naturally produced from compounds similar to those on prebiotic Earth (2). The theory of abiogenesis builds on these results, suggesting that simple life began suddenly, and over billions of years of evolution transformed into life as we know today.

Panspermia, on the other hand, proposes that simple biological life can travel between inter-solar system bodies on comets and asteroids. On impact, these objects could theoretically populate different planetary bodies. Although there is no concrete evidence for this, the theory provides a simple explanation for the relative speed for the genesis of life on Earth. To cultivate a deeper understanding of panspermia in comparison to other theories, this paper details an approach to simulate panspermia and abiogenesis events in a planetary system. A Monte Carlo simulation is developed by modeling individual Poisson processes over the course of a planet's given lifespan, as detailed in depth in the Methods Section. The simulations are run several times for a multitude of different parameters. In the end, a unique signature of panspermia is characterized that can be used to determine if panspermia had occurred in a system or not.

2. METHODS

2.1. Poisson Processes

Spiegel and Turner establish that one can model the occurrence of abiogenesis and panspermia on a given planet as a Poisson process [(3)]. The Poisson process derives itself from the the Poisson distribution, a statistical model typically used to forecast infrequent, discrete events. The Poisson distribution is given by the following formula:

$$P(X = n|\lambda) = e^{-\lambda} \frac{\lambda^n}{n!} \quad (1)$$

where n represents the number of occurrences, and λ is the expected number of occurrences. The Poisson process offers an extension of this distribution by introducing a time factor. This allows one to model the rate of event occurrences over a time interval, T_{max} . The Poisson process is expressed as a function of the mean occurrence rate τ_A and time

interval T . Thus, the formula for the Poisson process is given by Equation 2:

$$P(X = n|\tau, T) = e^{-T/\tau} \frac{(T/\tau)^n}{n!} \quad (2)$$

By treating abiogenesis and panspermia occurrences as independent Poisson processes, a model can be developed to simulate life over the course of a planet's history.

2.2. Monte Carlo Simulations for Abiogenesis and Panspermia

The lifespan of a planet serves as the time frame, T_{max} , for a Poisson process to model life occurrence events. In this paper, the maximum time span in which a planet could theoretically host life, T_{max} , was 10 Gyrs (10 billion years). This is the upper-bound estimate established by Spiegel and Turner. The probability of abiogenesis occurring in each cell is itself a Poisson process, given by the following formula:

$$P(X \geq 1|\tau, T) = 1 - P(X = 0|\tau, T) = 1 - e^{-T/\tau} \quad (3)$$

The planet's history, from time $t = 0$ to $t = T_{max}$ is subdivided into $N = 100$ segments. The probability that each segment contains an abiogenesis event is calculated with Equation 3, after which the probability is compared to a uniformly distributed random variable to determine whether or not that segment introduces life to the planet. This allows for a Monte Carlo simulation to be created by chaining together independent Poisson processes over the lifespan of a planet's history. A simplified version of this process is given in Figure 1:

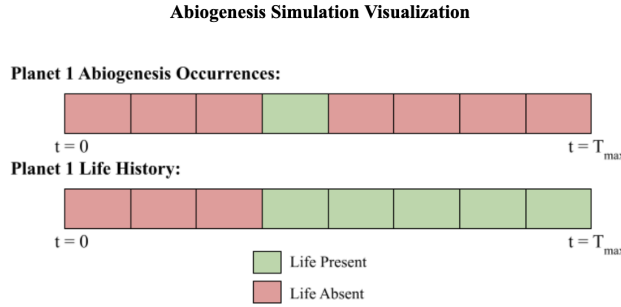


Figure 1. A visualization of the Monte Carlo simulation used to model abiogenesis on a given planet.

Running the simulation several times allows one to determine the probability of life starting on a given planet for any specified value of τ_A . Simulation-based probabilities were obtained for several values of τ_A and compared with analytically derived probabilities calculated from Equation 2.

Then, the same process was repeated to model abiogenesis events in a system of $n = 10$ planets. The multi-planet simulation was repeated several times for three different values of τ_A , $\tau_A = 10^9 \ll T_{max}$, $\tau_A = 10^{10} = T_{max}$, $\tau_A = 10^{11} \gg T_{max}$, offering the following three parameters:

1. The percentage of simulations where the system became inhabited. (S)
2. The percentage of simulations where all the planets in the system became inhabited. (A)
3. The average percentage of worlds that were populated in each simulation. (W)

These metrics were subsequently used to compare the spread of life in an abiogenesis-only system to that of a system containing both abiogenesis and panspermia, as detailed in the following paragraph.

Panspermia events were treated as another Poisson process with their own independent mean rate of occurrence: τ_P . The same process for simulating a system of multiple planets was performed, with the addition of panspermia events. These events were subject to the constraints that panspermia events could only propagate inward. This is because the system's star would likely cause asteroids that broke off of a planet to travel towards it, not away. The target planet

for each panspermia event was randomly chosen from a uniform random distribution covering all the planets in lesser orbits compared to that of the origin planet. Additionally, a planet could only produce a panspermia event given that it currently had life on it, obtained through either an abiogenesis event or a separate panspermia instance. The same three metrics, S, A, and W, were evaluated from this simulation.

3. RESULTS AND ANALYSIS

The first part of the experiment compared the analytic probabilities of abiogenesis occurring on an individual planet by time T_{max} with their respective simulated probabilities for different values of τ_A . Based on the results, it was determined that the projected probabilities from the Monte Carlo simulation closely match the analytic probabilities (Table 1).

Table 1: Analytic and Simulated Probability of Abiogenesis Event of Planet Lifetime (T = 10 Gyr)

τ_A	Simulated Probability	Analytic Probability	% Error
10^9	1.000	1.000	0.00
10^{10}	0.865	0.865	0.000
5×10^{10}	0.635	0.632	0.475
10^{11}	0.094	0.095	1.064

Table 1. Comparison between simulated and analytically derived probabilities for abiogenesis on a planet with a given mean rate τ_A

The data displayed in Table 1 displays a high degree of precision between the simulated and analytic probabilities for abiogenesis events. When the mean abiogenesis rate was a factor of ten smaller than the planet lifespan (10 Gyr), there was no error between the simulated and analytic probabilities. However, as the value for τ_A increases, the error between the two probabilities increases, with the largest being when $\tau_A = 10^{11}$. This is explained by the fact that larger values of τ_A causes abiogenesis events to be far less frequent. Individual runs of the simulation are therefore subject to greater trial-based error. Therefore, running the simulations for a larger amount of repetitions may reduce the error. Regardless, these results suggest that the Monte Carlo simulation accurately represents the Poisson process of abiogenesis, and can therefore be used for a multi-planetary system. The results of the multi-planet simulation are shown in Table 2 below:

Table 2: Simulation Metrics for Abiogenesis Simulation

Slow Abiogenesis $\tau_A = 100$ Gyr	Modest Abiogenesis $\tau_A = 10$ Gyr	Fast Abiogenesis $\tau_A = 1$ Gyr
S = 0.653	S = 1.000	S = 1.000
W = 0.098	W = 0.633	W = 1.000
A = 0.000	A = 0.018	A = 1.000

Table 2. Results for the multi-planet Monte Carlo simulation of abiogenesis events. S represents the percentage of simulations in which the system was populated, A represents the percentage of simulations where all planets were populated, and W represents the average percentage of all planets populated per simulation.

Analysis of Table 2 reveals a clear trend in the system's metrics as the unit rate of abiogenesis, τ_A increases. When $\tau_A = 100$ Gyr, 65 percent of the simulations recorded at least one planet with life. However, none of the simulations resulted in every planet having life, and on average less than 1 planet would become populated per simulation. As expected, increasing the value of τ_A increases each of the simulations' three metrics. It is also worth noting that for the Modest Abiogenesis run, $\tau_A = 10$ Gyr, there is still a relatively low percentage of simulations where all the planets become populated, despite the fact that the average number of worlds populated vastly increased. The data in Table 2 is most useful when compared to the data obtained from running a simulation modeling both panspermia and abiogenesis events, as displayed in Table 3:

Table 3: Simulation Metrics for Panspermia and Abiogenesis Simulation

Fast Panspermia $\tau_P = 1$ Gyr	S = 0.627 W = 0.263 A = 0.004	S = 0.999 W = 0.890 A = 0.399	S = 1.000 W = 1.000 A = 0.999
Modest Panspermia $\tau_P = 10$ Gyr	S = 0.642 W = 0.131 A = 0.000	S = 1.000 W = 0.720 A = 0.047	S = 1.000 W = 1.000 A = 1.000
Slow Panspermia $\tau_P = 100$ Gyr	S = 0.620 W = 0.098 A = 0.000	S = 1.000 W = 0.646 A = 0.016	S = 1.000 W = 1.000 A = 1.000
	Slow Abiogenesis $\tau_A = 100$ Gyr	Modest Abiogenesis $\tau_A = 10$ Gyr	Fast Abiogenesis $\tau_A = 1$ Gyr

Table 3. Results for the multi-planet Monte Carlo simulation of abiogenesis and panspermia occurrences. S represents the percentage of simulations in which the system was populated, A represents the percentage of simulations where all planets were populated, and W represents the average percentage of all planets populated per simulation.

These values are displayed individually as heatmaps in the following figure:

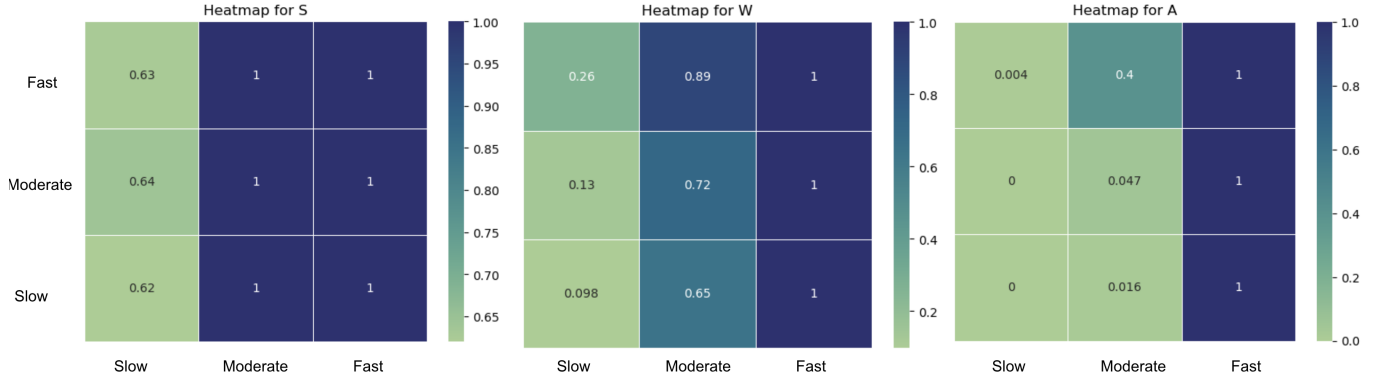


Figure 2. Heatmaps of S, W, and A metrics for the multi-planet Monte Carlo simulation of abiogenesis and panspermia occurrences.

Particular attention should be paid to Table 3’s slow abiogenesis column ($\tau_A = 100$ Gyr). For each value of τ_P , the simulation’s A metric remained at 0.0, indicating that there was never a system where all the planets became populated. Additionally, the percentage of simulations where life emerged also remained relatively constant. This can be explained by the fact that panspermia is dependent on abiogenesis. That is, for life to transfer from planet to planet, there must be life already present in the system. Therefore, the unit rate of panspermia has no effect on the presence of life in the system. However, as τ_P increases, the average percentage of planets that become populated also increases. This means that increasing the unit rate of panspermia events increases the number of worlds populated. This makes sense, given that increasing τ_P indicates that there are more potentially life-starting interactions between planets.

By comparing the data from Table 3 to the data from Table 2, a signature for panspermia can be defined. Specifically, by comparing the two table’s slow abiogenesis columns, one can see that the W metric, the average percentage of worlds populated in a system, is greater, especially when panspermia occurs quickly. This metric, in combination with the S and A metrics provides a good indicator for panspermia. If A is low ($A \approx 0$), but W is fairly large ($W \geq 0.2$), then it is likely that panspermia had occurred. This trend is also evident when comparing the modest abiogenesis columns, where the fast panspermia simulation resulted in higher W and A metrics. This signature also makes logical sense. Since panspermia only occurs inwards, if a planet on the outer edge of the system is never populated through abiogenesis, it will never be populated. This leads to the small proportion of systems with all planets populated

observed in both tables. However, increasing the parameter for panspermia makes it far more likely life to transfer between planets, resulting in Table 3's W metric being greater than Table 2's. Therefore, the simulated data reveals a trend in panspermia populated systems that allows one to define a signature for when panspermia happens.

4. CONCLUSION

The simulation detailed in this paper was successful in developing a unique signature for panspermia in a planetary system. That is, similar metrics recorded from an observed system would suggest that panspermia played a role in populating it. However, there are several caveats to these results. The limited scope of the methodology, namely, the fact that the model assumes all planets to be equally hospitable, in addition to the uniformly distributed target planets, are two simplifications that are not likely to be observed in a real planetary system. If these factors were taken into account, the simulation's metrics would all likely be lower across the board. Regardless, the simulation offers a great baseline for future work in the development of more robust models, offering a key insight in the quest to understand how life begins in the universe.

REFERENCES

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