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A Bayesian analysis of the potential emergence of life in Europa's subsurface ocean and other icy exoplanets

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ABSTRACT

The search for extraterrestrial life has led to the discovery of thousands of potentially habitable worlds, but the possibility of life in our own solar system is still uncertain. The subsurface saltwater ocean on Europa is a likely candidate given its parallels to early Earth conditions. We describe a model to infer the probability a successful abiogenesis event on Europa and its rate parameter. This was done by gathering information on its water volume, biogenic element abundance and free energy in comparison to Earth. Based on our model, Europa has a rate parameter of either 0.718, 0.258 or 0 (2 being that of Earth, the maximum value), depending primarily on the model chosen for hydrothermal activity. This method can be extended to any exoplanet given the available data on those three parameters. Additionally, given the hypothetical detection of life on Europa or an exoplanet, we use Bayesian inference to determine potential rate parameters and experimented with different priors.

1. INTRODUCTION

The potential existence of extraterrestrial life has been at the forefront of human interest for thousands of years. Our search for extraterrestrial life has spread far beyond our solar system and has led to the discovery of thousands of exoplanets. This recent influx of discoveries of potentially habitable worlds has renewed excitement in the rapidly growing field of astrobiology, the study of the origin and evolution of life in the Universe. While there is currently no evidence for the existence of extraterrestrial life within our own solar system as of yet, the possibility can not be ruled out.

Unfortunately, having Earth being our sole example for the origins of life we have very little understanding of its prevalence, making it difficult to infer the existence of extraterrestrial life. We can only extrapolate what we know about life itself from what we know about life on Earth, which is why we must clarify that it is instead 'life as we know it' as it is the sole data point we can rely upon. This simultaneously restricts and focuses our search for life in the Universe. Studying the conditions under which life formed on Earth provides us with valuable information on life as we know it and gives us insight into what we should be looking for. Our search currently attempts to identify systems with conditions as similar to Earth as possible, the logic being that if life formed on Earth under these conditions, then it could theoretically evolve somewhere else under the same conditions.

We might not have to look very far to find a place where these conditions may be met. The subsurface salt water ocean on Jupiter's sixth moon Europa is a promising candidate considering the growing evidence of its habitability and its parallels to Earth's early environment [1]. How likely is the subsurface ocean of Europa to harbour life already, and is there potential for its emergence in the future?

This paper investigates the potential emergence of life on Europa using Bayesian methods of statistical analysis. This was done by inferring Europa's abiogenesis rate, or the rate at which a successful abiogenesis event occurs through a direct comparison to Earth's early environment. This is an extension of the work done by D. Kipping on the analysis of life's origins on Earth [2]. Additionally, we extend our analysis to inferring the abiogenesis rate of any exoplanet given the detection of life at a certain time after its formation.

2. THE PROBABILITY OF A SUCCESSFUL ABIOGENESIS EVENT GIVEN ITS HABITABILITY

2.1. *The Rate of Abiogenesis*

As described by Spiegel and Turner [3], abiogenesis can be described by a Poisson process, where there are a distinct number of successes within an interval of time. The rate at which successful events occur is described by the rate parameter, λ_L. There are likely several processes or pathways that may lead to abiogenesis, but this rate parameter considers any method that results in abiogenesis to be a success.

The probability of having at least one successful abiogenesis event ($X_L > 0$) after a time t_L is:

$$Pr(X_L > 0; \lambda_L, t_L) = 1 - Pr(X_L = 0; \lambda_L, t_L) = 1 - e^{-\lambda_L t_L} \tag{1}$$

where the time between successful events is an exponential distribution ($e^{-\lambda_L t_L}$) and can be understood as the probability of not having a successful event. This is why 1 - Pr($X_L = 0$; λ_L, t_L) is the cumulative probability of at least having one successful event by time t_L. D. Kipping uses this probability of abiogenesis to investigate life's early start on Earth, but assumes a uniform prior due to the current lack of information on λ_L [2]. We suggest a model in which λ_L is not uniform, but rather a function of the three necessary conditions for life. This allows us to not only determine a λ_L for Earth, but find a λ_L for any planetary body in comparison to Earth.

2.2. *Habitability Model*

Based on our current understanding of life and its formation on Earth around 4 billion years ago, there are three essential conditions: liquid water, biogenic elements and a source of free energy, all of which must be present for habitability [4]. A missing component would result in the impossibility of life.

For Earth, we are fairly certain that it became habitable shortly after its formation 4.5 billion years ago [5], and that life developed relatively quickly. The earliest found evidence of life is around 4 billion years ago [6]. Assuming these two values are the times Earth became habitable and a successful abiogenesis event, we assume that life is likely to form once every 0.5 billion years, or twice every billion years ($\lambda_L = 2$). This is simply an estimation for the purposes of this paper. As we learn more about the origins of life on Earth, we will get a better idea of its true rate. This rate is assumed to be the highest possible as there are no other examples of life occurring in a shorter amount of time (or at all for that matter). Conditions similar to the formation of life on Earth are assumed to result in a similar abiogenesis rate parameter (2). A difference in the conditions on exoplanets would result in either a rate of 0, or less than 2

Our model is simple. We suggest that λ_L is a multiplication of the three parameters, water, biogenic elements and a source of free energy denoted δ_w, δ_b and δ_e, respectively. Each parameter has a maximum value of approximately 1.26 (the cube root of 2). Therefore, if all of the conditions are perfectly met we would observe that life appears at the same rate as it did on Earth.

In its simplicity, it both takes into account that if one of the necessary conditions were to be absent, then life would be an impossibility, and that when multiplied, each parameter having a max value can achieve Earth's rate parameter of 2. We believe that this is an appropriate model for λ_L based on life as we know it.

We propose three different models for determining each of these parameters depending on their empirical evidence. These are in the form of piecewise functions, where after the condition satisfies that of Earth, the parameter reaches its max value. The different models differ in the way that they get to the max value as whatever the parameter is measuring increases.

The first model is a step function, which suggests that if a given measurement is less than the condition on Earth, the parameter would be 0. This model assumes that the conditions for life on Earth was the minimum requirement. The second is a linear function before reaching the maximum. As the measurement increases, the parameter increases linearly. Similarly, the third model is a quadratic function and the parameter would increase exponentially before reaching its maximum. These models are shown in Figures 1, 2 and 3 for every parameter.

We have no evidence at this time to prefer one model over another, but it is clear that the models differ in their difficulty to achieve a high abiogenesis rate. For example, if all three parameters were to be step functions, then life would be impossible unless all conditions met that of Earth. Perhaps the model for water is a step function in reality, but is linear for biogenic elements and quadratic for free energy. Based on these 3 models for the 3 parameters, there are a total of 27 possibilities. We test multiple cases in Part 2.6.

The conditions for Earth that represent the minimum requirement for a max value are discussed below, as well as how well Europa meets those requirements based on empirical evidence.

2.3. *Liquid Water*

We assume that δ_w is a function of the amount of liquid water a body has. While there isn't direct evidence that suggests that the amount of water corresponds to likelihood of life, it can be intuitively expressed that an ocean of water is more likely to harbour life than a bottle cap would. We are simply saying that a larger volume presents more opportunities for a successful abiogenesis event. It is difficult to determine the amount of liquid water Earth had 4 billion years ago. While Earth's water reservoir has remained relatively constant [7], the percentage of that water being liquid is unknown. For simplicity, we assume that the amount of liquid water in Earth's oceans has stayed relatively the same over the course of its history. Earth has an estimated $1.37 \cdot 10^{18} m^3$ of liquid water [7] and this value was used as the minimum amount to have a maximum value. Once this amount of water is reached, any increase in the amount of water does not result in a higher δ_w. The 3 models are depicted below.

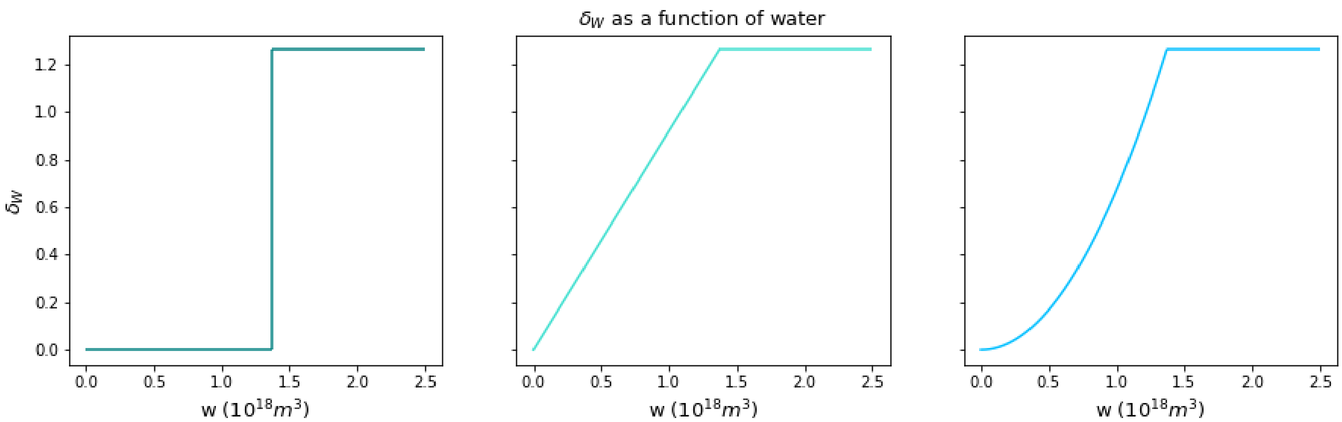


Figure 1: The 3 models for δ_w as a function of amount of liquid water: Step function (left), Linear (middle) and Quadratic (right). The cutoff point for a maximum value is $1.37 \cdot 10^{18} m^3$.

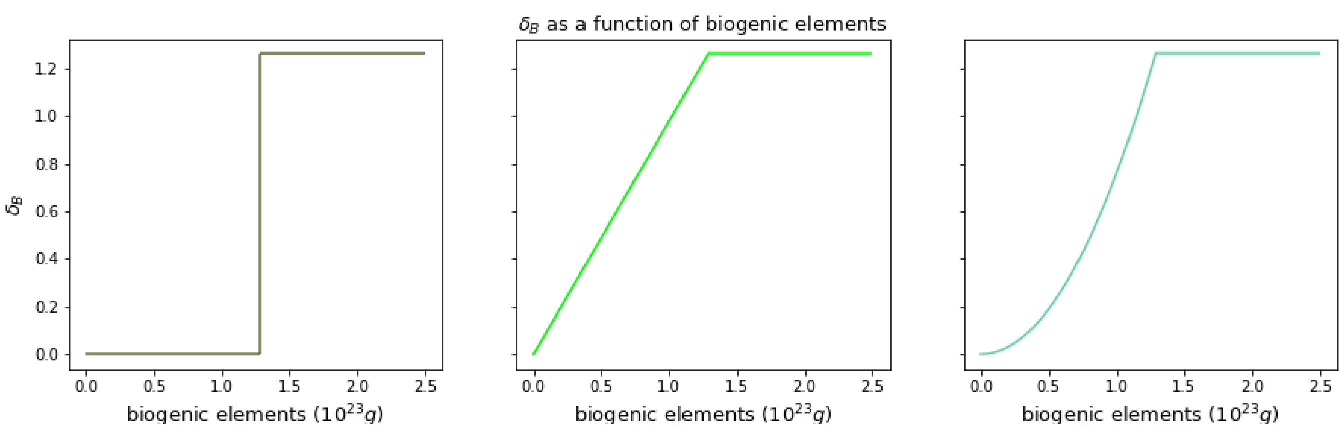


Figure 2: The 3 models for δ_b as a function of the amount of biogenic elements: Step function (left), Linear (middle) and Quadratic (right). The cutoff point for a maximum value is $1.288 \cdot 10^{23} g$.

2.4. *Biogenic Elements*

The second parameter δ_b is a function of the amount of biogenic elements available in the oceans for the chemistry of life. These are the chemical elements present in all forms of life and are essential for the growth of biomass. Some of these essential elements include carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorus. The amount of excess volatiles in Earth's early oceans (almost all of which are biogenic elements) is estimated to be around $1.288 * 10^{23} g$ [8]. This was used as the cutoff point for the maximum.

2.5. *Hydrothermal Activity*

And lastly, δ_e is a function of average heat flow due to hydrothermal activity at the bottom of the ocean. These are the types of environments that life on Earth are theorized to have originated from as they provide both the necessary ingredients and energy required for the chemistry of life (as far as we understand it). The average heat flow at the base of Earth's ocean is around $63mWm^{-2}$) [9] and is the cutoff point for the maximum value.

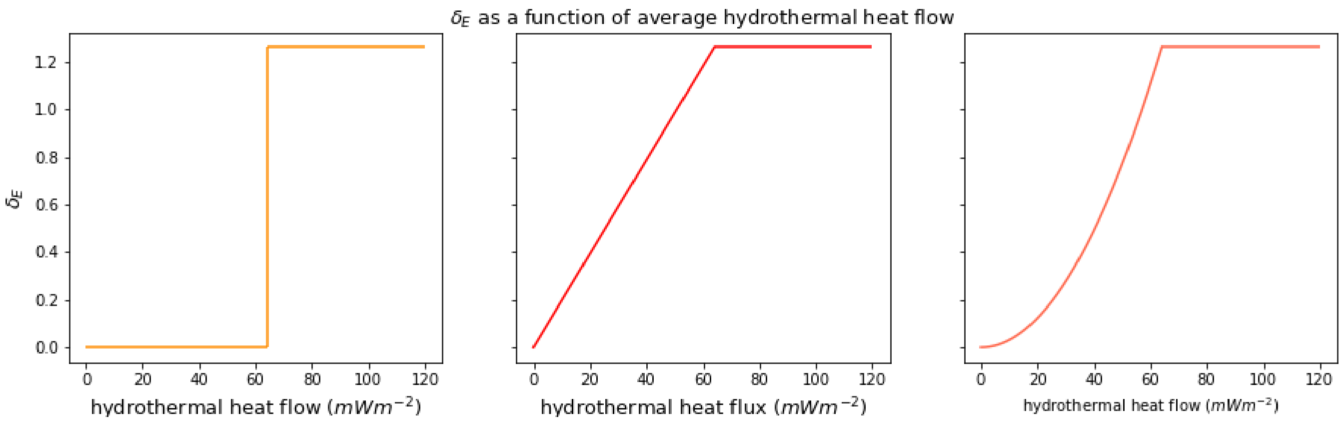


Figure 3: The 3 models for δ_e as a function of average heat flow due to hydrothermal activity at the bottom of the ocean: Step function (left), Linear (middle) and Quadratic (right). The cutoff point for a maximum value is $63mWm^{-2}$).

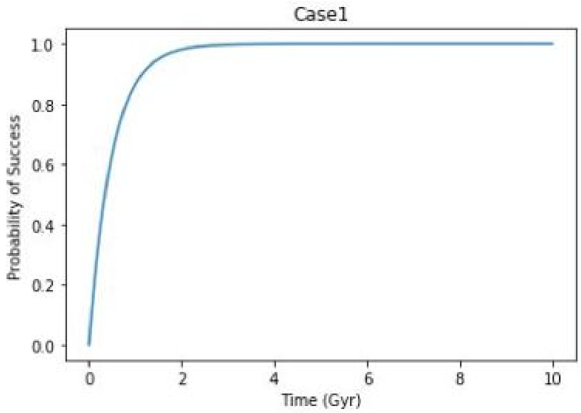
2.6. *Model Testing*

Various cases were tested to determine different abiogenesis rates and to plot the likelihood of a successful event over the history of the solar system. The age of the solar system will be the Sun's lifetime, around 10 billion years. These plots are shown in Figure 4.

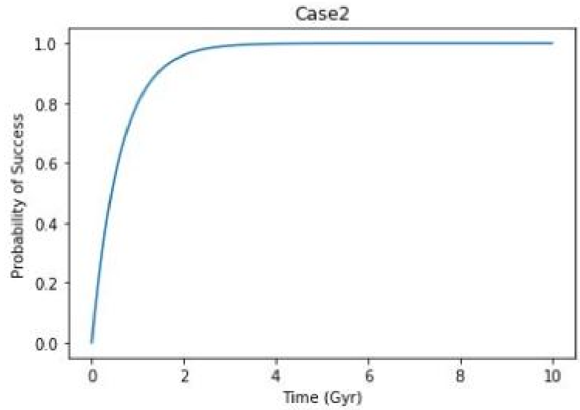
Case 1 assumed all the necessary conditions meet that of Earth, resulting in a maximum λ_L of 2. In this case, whatever model was chosen did not affect λ_L. The probability of success rises quite quickly, consistent with the appearance of life on Earth.

Case 2 assumed that the water and biogenic element conditions meet that of Earth, but hydrothermal flux is less than Earth. The linear model was chosen for hydrothermal. This resulted in a λ_L of 1.6, which rose slightly slower than the previous plot. A successful abiogenesis event is expected once every 0.625 Gyr.

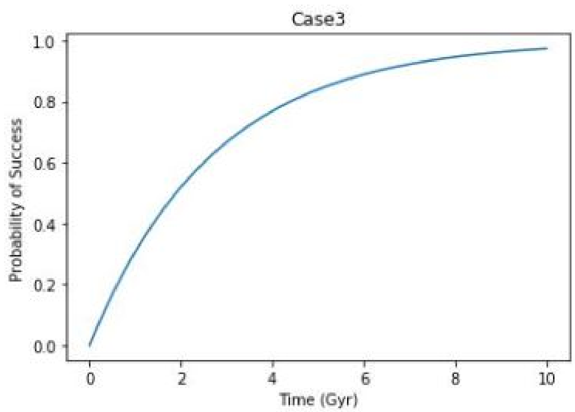
Case 3 assumed that the biogenic elements meet the condition, but both water and hydrothermal are less than Earth. A linear model was used for water, and a quadratic for hydrothermal. This resulted in a λ_L of 0.365 and clearly, the probability of success rise much slower. In fact it never reaches a probability of 1 over the course of 10 billion years. Case 4 assumed that both biogenic and hydrothermal met that of Earth, but water did not. A step function was used for water, therefore resulting in a λ_L of 0. Life is impossible.



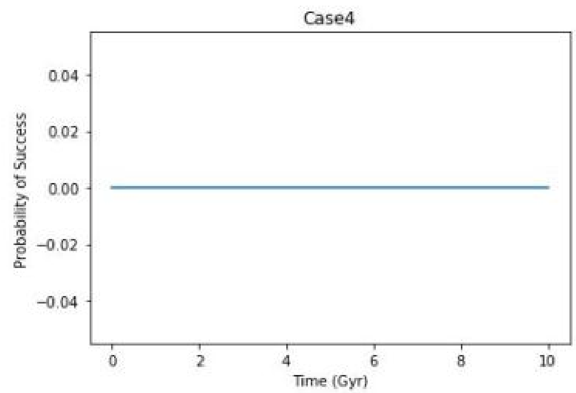
(a) All conditions are met. $\lambda_L = 2$



(b) Hydrothermal (linear) less than Earth. $\lambda_L = 1.6$



(c) Water (linear) and Hydrothermal (quad) less than Earth. $\lambda_L = 0.365$



(d) Water (step) less than Earth. $\lambda_L = 0$. A successful abiogenesis event is impossible

Figure 4: The probability of a successful abiogenesis event over the course of the history of the solar system. Different cases test different conditions on a given exoplanet while varying the models.

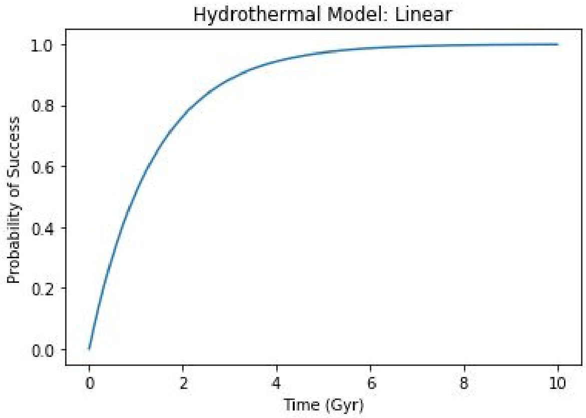
2.7. *Europa's Abiogenesis Rate*

Given the empirical evidence we have for Europa's habitability, we determined potential abiogenesis rates.

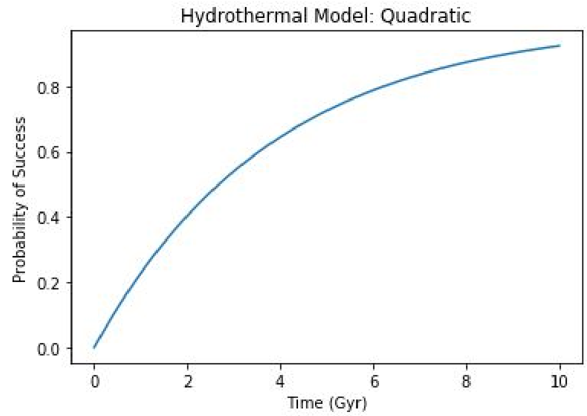
There is growing evidence for the existence of a liquid water ocean beneath Europa's icy surface, namely the detection of ejected water plumes [10], a temporarily varying magnetic field [11] and a young and fractured surface [12]. While Europa is way beyond the habitable zone (the region between where liquid water boils and where greenhouse gases freeze) tidal interactions with Jupiter flexes and deforms the icy moon, supplying frictional heat that could sustain a liquid water ocean under kilometers of ice [13].

Based on current estimations for the amount of liquid water on Europa, it easily meets the requirement. There is an estimated 2-3 times as much liquid water as there is on Earth, or around $3 \cdot 10^{18} m^3$ [14]. Choosing a model for δ_w is therefore unnecessary.

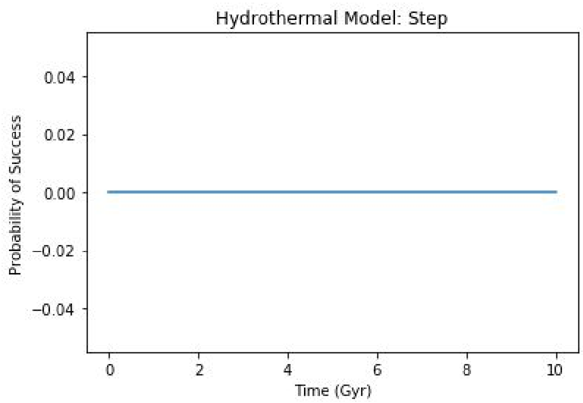
Europa formed at roughly the same time as the other bodies in the solar system and likely already had a certain amount of biogenic elements [15]. Additionally, a large amount of biogenic elements could have been delivered over 4.4 Gyr through cometary impacts [16]. Unfortunately at this time, there are no direct measurements on the abundance of these biogenic elements in the subsurface ocean. However, the composition of Europa is commonly thought, "to be that of a carbonaceous chondrite meteorite, in which case biogenic elements would be abundant" [15]. While little is known observationally, for the purpose of this paper we assume that it also meets the requirements for biogenic elements.



(a) Case 1: Linear Hydrothermal Model. $\lambda = 0.718$



(b) Case 2: Quadratic Hydrothermal Model. $\lambda = 0.258$



(c) Case 3: Step Hydrothermal Model. $\lambda = 0$

Figure 5: The probability of a successful abiogenesis event for Europa over the history of the solar system.

While there are other potential sources of free energy on Europa, similar to the reason for liquid water, tidal flexing likely resulted in volcanic activity and hydrothermal vents at the base of the ocean [17]. If lifeforms were to exist clustered around these hydrothermal vents, they would be endoliths (extremophiles that live in places inhospitable to most organisms). Unfortunately, this is where the limiting factor of Europa's habitability is likely to be based on our model. The average heat flow due to hydrothermal activity is an estimated $24mWm^2$ [9], less than half that of Earth. The lower acceleration of gravity would result in individual vents being much weaker than on Earth [18].

With all this in mind, the abiogenesis rate as well as the probability of success for Europa was determined for the three cases of hydrothermal and plotted in Figure 5.

Case 1 assumed a linear model for hydrothermal and resulted in the highest λ_L of 0.718, 35% that of Earth's. This abiogenesis rate states that a successful abiogenesis event should occur once every 1.4 Gyr. If hydrothermal heat flow is indeed described by a linear function then this is extremely promising for the potential of life on Europa.

Case 2 assumed a quadratic model for hydrothermal and resulted in a λ_L of 0.258, 13% that of Earth's. This rate describes a successful event once every 3.87 Gyr. While this is a much greater time interval than the linear model, the quadratic still presents the opportunity for life currently existing on Europa.

Case 3 assumed a step function, and as average heat flow is less than that of Earth, life is therefore not possible. If hydrothermal activity was described by a step function, the search for life on Europa would be futile according to our model.

Our model successfully managed to determine several potential abiogenesis rates for Europa as well as plotting the probability of success over the history of the solar system. As more and more data comes in to give us a better idea of each of these conditions on Europa, these rates can be updated. We do not expect for the δ_W or δ_B parameters to eventually be proven smaller than the maximum value, but observational evidence is required for confirmation.

Narrowing down the hydrothermal heat flow at the base of Europa's ocean would also isolate the δ_E parameter and give us a more accurate measurement of λ_L.

This model can be applied to essentially any exoplanetary system. While ours specifically discusses hydrothermal vents in subsurface oceans, different parameters can be discussed for sources of free energy.

3. BAYESIAN ANALYSIS OF λ_L PARAMETER GIVEN DETECTION OF LIFE

3.1. *The Detection of Life*

In this section we investigate the inverse problem. Instead of calculating λ_L to determine the probability of success, we assume that life has been detected on Europa or an exoplanet, and infer λ_L from that information.

We assume that a group of observers are able to observe Europa or an exoplanet over the course of its entire history, checking every so often to see if life appeared. In other words, they are able to travel to the given planet over the course of the planet's life to check for any indication of a successful abiogenesis event.

With knowledge of when we observed the presence of life on the planet, we are able to do the opposite problem and infer λ_L. Had the observers been able to record the presence of life on Europa, we would be able to infer how quickly it appeared. This method can be extended to any exoplanet.

The planets used in this exercise are purely hypothetical since we can't observe activity on extraterrestrial bodies over the course of billions years. The limitation being that humanity has only been around for several thousand years. The planet's total lifetime used in this section is assumed to share the age of the solar system.

3.2. *Uniform Prior*

Bayes' theorem tells us,

$$p(\lambda_L|time) \propto p(time|\lambda_L)p(\lambda_L) \tag{2}$$

In our first case, the observers decided to visit the planet once and made a single observation of life at 5 billion years, as shown in Figure 6 (left).

Given that the observers showed up on this planet at 5 billion years, with no concrete knowledge on the exact time life first appeared, they are forced to conclude that λ_L could have been anywhere between $0.2Gyr^{-1}$ and $2Gyr^{-1}$. Given no other information on λ_L we assume a uniform prior. The reasoning for the maximum of 2, similar to above is that we assume life could not have appeared faster than it did on Earth. Life on Earth is believed to have appeared 500 million years after its birth which means 2 successful abiogenesis events are observed per 1 billion years, yielding the upper limit on λ_L.

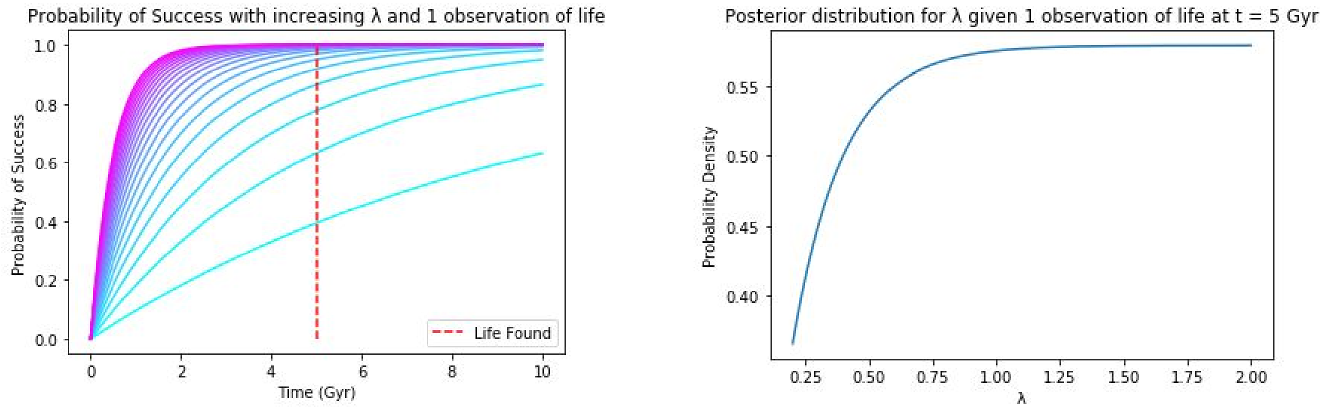
The observers are also forced to conclude that life could have appeared only minutes before they showed up to observe it which would signify 0.2 successful abiogenesis events are observed per 1 billion years (1 event in 5 billion years), yielding the lower limit on λ_L.

For the likelihood, we used the following function,

$$p(time|\lambda_L) = 1 - e^{-\lambda_L t} \tag{3}$$

This equation is the same used above which was taken from David Kipping's analysis [2].

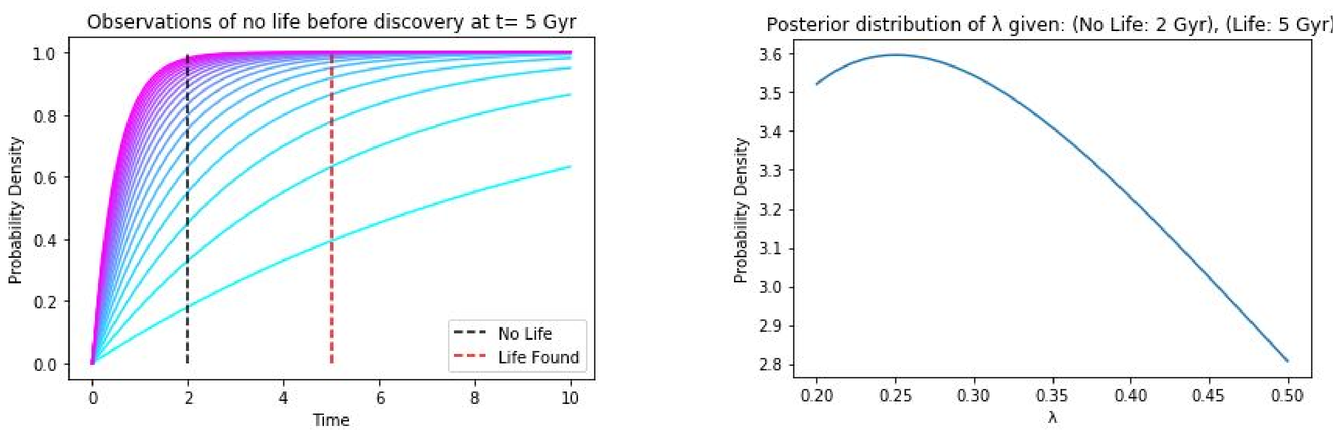
With time fixed at 5 Gyr, Figure 6 (right) tells us that as λ_L increases, the probability increases and asymptotes at a value just below 0.6. This means that with the little knowledge we have, Bayes' theorem tells us that the most probable value of λ_L is 2 in Figure 6 (right). In other words, Bayes' theorem tells us that life probably did not appear only minutes prior to the observers' arrival, which makes sense intuitively.



(a) Detection of life (red) from a single measurement. Posteriors are plotted with increasing abiogenesis rates. (From blue to pink)

(b) The posterior distribution for λ_L given a single detection of life at 5 Gyr. λ_L has a lower limit of 0.2 and a higher limit of 2.

Figure 6: The probability of a successful abiogenesis event given a single detection of life (left) and the posterior distribution of the rate parameter (right).



(a) The probability of success with increasing rate parameters. 1 observation of no life at 2 with the discovery of life at 5.

(b) The posterior distribution for λ_L given several detections of no life and then discovery at 5 Gyr.

Figure 7: The probability of a successful abiogenesis event given a detection of no life before a detection of life (left) and the posterior distribution of the rate parameter (right).

We now would like to know what value λ_L is given that we have multiple observations. In this second demonstration, the observers visited the planet twice and found there to be no life on this planet at 2 billion years and did find life at 5 billion years, as shown in Figure 7 (left). Unlike before, we would expect λ_L to be somewhere in between 0.2 and 0.5, which is also our new prior on λ_L.

If we take our two measurements to be independent which means our likelihood is,

$$p(t_1, t_2|\lambda_L) = p(t_1|\lambda_L)p(t_2|\lambda_L) \tag{4}$$

and we take t_1 to be the observation at 2 billion years and t_2 to be the observation at 5 billion years, respectively.

If equation 1 is the probability of a successful abiogenesis event and the total probability of successful and unsuccessful events must equal 1, we can convince ourselves that,

$$p(t_1|\lambda_L) = e^{-\lambda_L t_1} \tag{5}$$

and,

$$p(t_2|\lambda_L) = 1 - e^{-\lambda_L t_2} \tag{6}$$

where equation 3 and 6 are the same, t_1 is 2 Gyr and t_2 is 5 Gyr.

In plotting the posterior for this second observation Figure 7 (right), we notice a peak for lambda at approximately 0.25, which means there is likely a successful abiogenesis event around every 4 billion years.

Once more, this makes sense. Although knowledge is still limited, Baye's theorem tells us that if there was no life at 2 billion years, but there was life at 5 billion years, life most probably appeared a billion years before the second visit and 2 billion years after the first visit. We can easily convince ourselves that we do expect a peak in this range.

Finally, if observations were recorded once every billion years, with no life in the range of 1-4 billion years and life in the range of 5-10 billion years, one would expect a peak for λ_L between 0.2 and 0.25, as shown in Figure 8 (red posterior). This is exactly what we observe, with a peak at around 0.23. All of the posteriors are plotted to show how our knowledge of λ_L changes as more measurements are taken. At this point, Bayes' theorem is telling us that we have narrowed down our appearance of life to one successful abiogenesis event every 4.35 billion years, approximately.

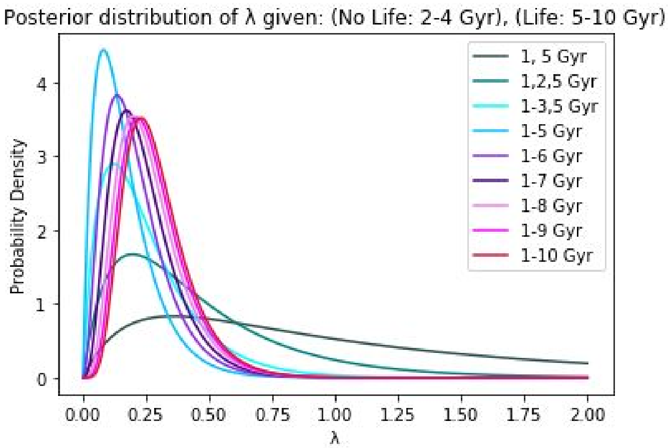


Figure 8: The probability of a successful abiogenesis event with increasing observations of life present or not present at a given time

The reason that measurements from after the discovery of life were still recorded and included, is because the measurements are assumed to be independent. Let's say we were trying to determine the average height of males. It is obvious that the height of one individual is unrelated to the height of another. If a few really short men are measured, it would probably be best if we continue to take samples.

The same logic can be applied here. It might be easier to think that perhaps, a few groups of independent observers have pooled their data together.

It can also be observed that there might not be a peak in between 0.2 and 0.25 if, for example, we have only 4 measurements at 1,2,3 and 5 billion years. In this case, we assume no life at 1,2 and 3 billion years, and then we observe life at 5 billion years. It can be seen in Figure 9 that we still observe a peak, however, the peak is to the left of our lower limit of 0.2. Therefore, we are forced to pick the most probable λ_L in our range of 0.2 and 0.25. In this case, 0.2 is the most likely.

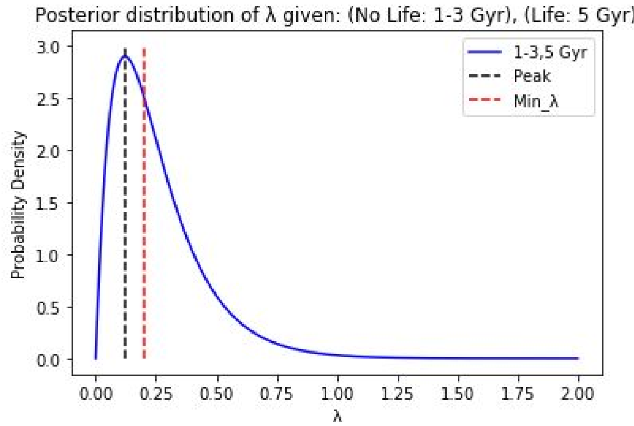


Figure 9: The probability of a successful abiogenesis event with observations of no life present at 1-3 Gyr and life present at 5 Gyr

3.3. *Gaussian Prior*

We also experimented with a gaussian prior as shown in Figure 10. It can be observed that this prior does produce a well defined peak, which seems promising, but is actually misleading.

If, for example, we once again observe life at 5 billion years, we might be tempted to put a gaussian prior, centered at $0.2Gyr^{-1}$. This is wrong because we are essentially assuming that life must've appeared in recent history. It is neglecting the possibility that life was present long before anyone ever got there.

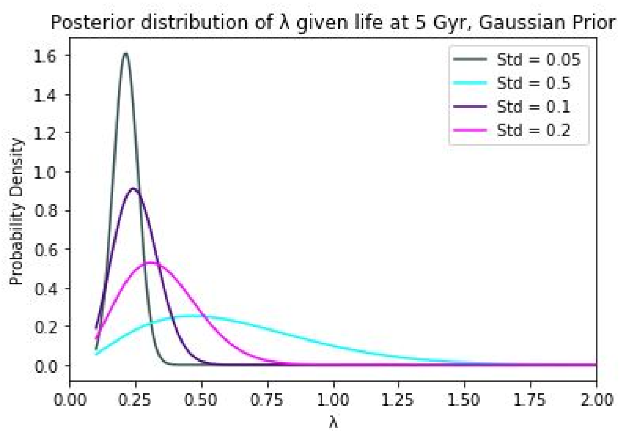


Figure 10: The probability of a successful abiogenesis event given a gaussian prior

For all we know, it is highly possible that life appeared at 1 billion years. The Gaussian prior eliminates the possibility of recovering that truth.

This is not to say that a Gaussian prior should never be used. If we can really narrow down the range for which life appeared and we can recover some important knowledge, perhaps through carbon dating for example, it might be appropriate to use a Gaussian since our prior knowledge is very strong..

We tested the prior with a few different standard deviations. The sensitivity depends on what we know about its habitability. A small standard deviation means that we are certain of the different parameters, and how they compare to Earth.

For example, if we are certain that an exoplanet meets the conditions of Earth and has life at time t, then we say that we are very certain that it has the max rate of 2.

But if we find a planet where life appears after a certain amount of time, but aren't certain about the different parameters, then the standard deviation will be larger. We are therefore less sure what the rate of abiogenesis is.

4. CONCLUSION

In summary, this paper aimed to provide a potential method for inferring the probability of life existing on Europa. We developed a model that takes in empirical evidence of what we know about the three parameters, and plot the probability of a successful abiogenesis event over time. Furthermore, the model can be extended to any exoplanet, assuming we know the water volume, biogenic element mass and amount of free energy. As these measurements improve, so does our knowledge of the rate of abiogenesis.

There are a few significant drawbacks to this oversimplified model. The most notable being that life is much more complex and more factors must be taken into account and in the right ratio. The parameters are much more nuanced than a simple value of 1.26. We simply assumed that Earth had a rate of 2, but this might not be the truth.

There is a degeneracy associated with this model as well. For example, if we have a given value for water and free energy, taking half the water and double the free energy would yield the exact same λ_L. This is not realistic because it doesn't account for the potential ratios required between the factors.

The models we chose to represent the information about the three factors might also lead to a few issues. Namely, life might not follow a step function, linear or quadratic relation, though future studies can confirm this. Furthermore, the rate of abiogenesis on a different planet may be totally unrelated to that of Earth and it is in fact not the maximum value.

We have also assumed that life requires water, biogenic elements and free energy. For all we know it may not require one or all of those factors. Our model is based on life as we know it to be on Earth and is biased to this single data point.

In the second section, we inferred λ_L based on knowledge attained from travelling to the planet and recording whether or not life is present.

An obvious drawback to this is that we can't observe a planet over its entire life. While it was an interesting exercise to infer the rate, it is not a realistic one. The first example, where life is detected once at 5 billion is the most realistic. Unfortunately, this example can only offer us a lower bound on the rate parameter.

Based on our results, if our model is consistent with reality, than there is the potential for life on Europa. While we are fairly certain that Europa meets two out of the three conditions of Earth, further investigation into these three parameters would give us a better estimate for λ_L. Even if life isn't currently on Europa, there is still time for it to develop.

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