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RESEARCH ARTICLE

Abiogenesis: the Carter argument reconsidered

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Abstract

The observation of life on Earth is commonly believed to be uninformative regarding the probability of abiogenesis on other Earth-like planets. This belief is based on the selection effect of our existence. We necessarily had to find ourselves on a planet where abiogenesis occurred, thus nothing can be inferred about the probability of abiogenesis from this observation alone. This argument was first formalized in a Bayesian framework by Brandon Carter. Though we definitely had to find ourselves on a planet where abiogenesis occurred, I argue here that (1) the Carter conclusion is based on what is known as the 'Old Evidence Problem' in Bayesian Confirmation Theory and that (2) taking this into account, the observation of life on Earth is not neutral but evidence that abiogenesis on Earth-like planets is *relatively* easy. I then give an independent timescale argument that quantifies the prior probabilities, leading to the inference that the timescale for abiogenesis is less than the planetary habitability timescale and therefore the occurrence of abiogenesis on Earth-like planets is not rare.

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Introduction

Current theories of abiogenesis (AB) vary in extremes from it being thermodynamically favoured (England 2013) and therefore presumably nearly automatic given the same chemical and environmental conditions as existed on early Earth, to an occurrence of less than once in the history of the observable universe (Totani 2020). Historically, the Principle of Mediocrity (along with evidence that life on Earth appeared relatively early) was used to argue that AB is likely given similar chemical and environmental conditions as early-Earth (e.g. Shklovskii and Sagan 1966). Subsequently, with the publication of Carter's anthropic selection principle (Carter 1974) and its importance in evolutionary biology (Carter 1983; see also Crick 1981) it was realized that the assumption that Earth is a random member of the reference class of all early-Earth-like planets was not justified, by virtue of our existence. We necessarily had to find ourselves on a planet where AB occurred. It is a fact that we (and life on Earth) exist regardless of whether AB is easy or hard or something in between. If there were only a single example of life in the universe then it would necessarily be Earth. The Principle of Mediocrity is still useful but should be applied only after all relevant anthropic selection effects are taken into account (Whitmire 2020). For example, Earth is not a typical planet even in our own Solar System, but may be typical of planets that host intelligent observers.

Besides the selection effect of our existence, the occurrence of relatively early AB on Earth might be a selection effect due to the long evolutionary time required for an intelligent species to evolve after AB has occurred (Lineweaver and Davis 2003). A Bayesian analysis of whether early AB on Earth is evidence of AB being easy in general on other early-Earth-like planets has been addressed by Spiegel and Turner (2012; see also Kipping 2020). Their analysis specifically takes into account the time required for the evolution of intelligent observers. They conclude that although there is some evidence in favour of easy AB it is not significant and that the posterior probability for easy AB depends almost entirely on the assumed prior; and that it is not possible to reject the hypothesis that Earth is the only location of intelligent life in the universe.

The Carter argument

Independent of the non-significant early AB evidence (which the Carter argument doesn't address), we can reproduce the Carter conclusion that the posterior probability of the hypothesis that AB is easy depends entirely on the assumed prior probability. For the simple binary case of interest here Bayes' theorem is:

$$P(H|E) = \frac{P(E|H)P(H)}{P(E|H)P(H) + P(E|\bar{H})P(\bar{H})}, \tag{1}$$

where $P(H|E)$ is the posterior probability of hypothesis H, E is the evidence used to update the prior probability $P(H)$ of the hypothesis, and $\bar{H}$ = not-H is the mutually exclusive alternative binary hypothesis. In this case $P(H) + P(\bar{H}) = 1$.

Let hypothesis H = 'AB is easy', $\bar{H}$ = 'AB is hard' and let the evidence E = 'LoE exists', where LoE = Life on Earth. Bayes' theorem for the posterior probability then gives:

$$P(\text{AB easy}|\text{LoE}) = \frac{\text{P(LoE}|\text{AB easy)P(AB easy)}}{\text{P(LoE}|\text{AB easy)P(AB easy)} + \text{P(LoE}|\text{AB hard)P(AB hard)}} \tag{2}$$

where P(AB easy) is the prior probability that AB is easy in general before taking into account the evidence of LoE and P(AB hard) is the prior probability that AB is in general hard before taking into account that LoE exists. Binarity of hypotheses is not a necessary assumption but sufficient to make the argument. Now, LoE exists regardless of whether AB is easy or hard, consequently the likelihoods P(LoE|AB easy) = P(LoE|AB hard) = 1. Inserting this into equation (2) and noting that P(AB hard) + P(AB easy) = 1, gives

$$P(\text{AB easy}|\text{LoE}) = \frac{\text{P(AB easy)}}{\text{P(AB easy)} + \text{P(AB hard)}} = \text{P(AB easy)}, \tag{3}$$

or the posterior probability that AB is easy given LoE = prior probability that AB is easy. Therefore the observation of LoE is not evidence that AB is easy or hard (i.e. the evidence of LoE doesn't update the prior). This is the Carter AB argument, which has been generally accepted explicitly (e.g. Crick 1981; Bostrom 2002a; Spiegel and Turner 2012) or implicitly (e.g. Mash 1993; Kukla 2010; Waltham 2014).

Although Carter first presented the argument in a Bayesian framework (Carter 1983), Francis Crick had previously emphasized the same concept (1981), as acknowledged by Carter. Crick had suggested calling the old (misapplied) principle of mediocrity argument the 'statistical fallacy' as he was apparently unfamiliar with the Anthropic Principle terminology at the time. Carter also presented a separate argument in the same paper (1983) which concluded that the mean timescale for the evolution of intelligent observers is much greater than the solar lifetime. That argument is not directly relevant to his AB argument addressed here, though it will be discussed separately below in connection with the priors P(AB easy) and P(AB hard).

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The Carter AB argument encapsulates two concepts: (1) The selection effect of our existence on a planet where AB necessarily occurred and (2) the inference from this fact that (therefore) nothing can be concluded about the probability of AB in general on Earth-like planets. It is this second part of the argument that I question here. My approach is based on the 'problem of old evidence' in Baysian Confirmation Theory.

Even though the Carter AB argument has not been refuted and there is no other significant counter evidence, surprisingly there seems to be a scientific optimism that AB is likely given the conditions present on early Earth. This attitude may be due to the counter intuitive conclusion of the Carter argument, in spite of its seemingly logical appeal.

The problem of old evidence

In spite of its common acceptance, the Carter argument appears to be vulnerable to what in Bayesian Confirmation Theory is called the 'Old Evidence Problem' (Glymour 1980). Bayes' formula is used to update a theory or an hypothesis H when new evidence E is taken into account. If the evidence is not new but already exists then the probability of the evidence is $P(E) = 1$ and the posterior probability $P(H|E) =$ prior probability $P(H)$, as in the Carter argument, independent of the hypothesis. Glymour (1980) gives the following kind of trivial example to illustrate the point. A coin is tossed three times and lands heads up each time. Applying Bayes' formula to determine the probability of the hypothesis that the coin is fair we get,

$$P(\text{fair}|3\text{ heads}) = \frac{\text{P(3 heads| fair)}P(\text{fair})}{\text{P(3 heads| fair)}P(\text{fair}) + \text{P(3 heads)|not fair)}P(\text{not fair})} \tag{4}$$

Using the existing (old) evidence of 3 heads then $P(3\text{ heads}|\text{fair}) = P(3\text{ heads}|\text{not fair}) = 1$ and $P(\text{fair}|3\text{ heads}) = P(\text{fair})$, or the posterior probability of 3 heads = prior probability of 3 heads. Thus the existing (old) evidence did not update or affect the prior probability, as in the Carter argument. But this is clearly not correct. The probability of any existing evidence is always 1, regardless of the hypothesis. The correct analysis uses the prior conditional probability (or prior likelihood) *before* the coin is flipped to calculate $P(3\text{ heads}|\text{fair}) = 1/8$, and $P(3\text{ heads}|\text{unfair}) = 1$, if for example the coin was heads on both sides. Assuming equal priors the result is $P(\text{fair}|3\text{ heads}) = 1/9$, which is approximately what one would expect intuitively. In the case of old evidence (Glymour 1980) recommends applying Bayes' theorem counterfactually or 'historically' before the evidence is known.

Another example is the following (Bostrom 2002b). There are two urns, A and B. One urn contains 10 balls numbered 1–10 and the other contains one million balls numbered 1 to 1 000 000. A coin is flipped to determine the urn from which a ball will be selected and it's urn A. The selected ball is labelled #7. What is the probability that urn A is the urn which contains 10 balls? Intuitively, an appeal to the principle of mediocrity strongly suggests that urn A is the one that contains 10 balls since then #7 would be typical of the balls in urn A. Applying Bayes' theorem for the hypothesis = urn A contains 10 balls, gives

$$P(\text{urn A}|\#7) = \frac{\text{P(\#7|urn A)}P(\text{urn A})}{\text{P(\#7|urn A)}P(\text{urn A}) + \text{P(\#7|urn B)}P(\text{urn B})} \tag{5}$$

If we use the old evidence = #7 then both likelihoods = 1 and the posterior probability = prior probability = 1/2. As in the coin flip example, the correct analysis is to evaluate the likelihood of obtaining the evidence #7 under each hypothesis before the evidence #7 is known. Assuming the hypothesis that urn A is the one containing 10 balls, the probability that #7 is drawn from urn A is 1/10 while the probability that #7 is drawn from urn B is 1/1 000 000. This gives a posterior probability $P(\text{urn A}|\#7)$ that the ball came from urn A = 0.999.

Although in these two cases the issue of old evidence is easily resolved, the problem of old evidence in general is more complicated and controversial philosophically because in several well-known special

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cases old evidence has been considered as being on an equal footing with new evidence. Most notably, the precession of the perihelion of Mercury, which was known for 50 years prior to the publication of Einstein's General Theory of Relativity, was universally considered strong evidence supporting Einstein's theory. Newton's law of gravity explained Kepler's laws of planetary motion which had been well-known old evidence for over 50 years. From a non-philosophical physics perspective these cases might be justified by the fact that the theories were not developed specifically to explain that data. These, in general unresolved, philosophical complications are not important in the above examples or in the AB case of interest discussed below.

From the above old evidence considerations alone it can be seen that the Carter argument fails since the (counterfactual) likelihoods P(LoE prior to LoE|AB easy) and P(LoE prior to LoE|AB hard) are not both equal to 1 but instead P(LoE prior to LoE|AB easy) > P(LoE prior to LoE|AB hard). Below I give an argument that further quantifies the posterior probability P(AB easy|LoE)

The conception analogy

An analogy closely related to the AB case of interest here and the old evidence issue is the following. The conception (origin) of me could have occurred if my parents used contraception (conception hard = CH) or if they did not use contraception (conception easy = CE). What is the probability of the hypothesis H = CE, given the evidence that I exist? Bayes' formula for this posterior probability is

$$P(\mathrm{CE}|\mathrm{I\ exist}) = \frac{\mathrm{P(I\ exist|CE)}P(\mathrm{CE})}{\mathrm{P(I\ exist|CE)}P(\mathrm{CE}) + \mathrm{P(I\ exist|CH)}P(\mathrm{CH})}. \tag{6}$$

As in the Carter argument, I could say that I exist regardless of whether conception was easy or hard so P(I exist|CE) = P(I exist|CH) = 1, and then P(CE|I exist) = P(CE), or the posterior probability = prior probability and thus the evidence = 'I exist' doesn't alter the prior. But, as in the case of the coin flips and urns, this is not the correct analysis. It's not the old evidence of my existence that's important but rather the prior conditional likelihoods P(I *will* exist prior to my conception|CE) and P(I *will* exist prior to my conception|CH). For example, assume that without contraception the mean probability of conception is 0.85 per year = P(I will exist prior to my conception|CE) and that with contraception the mean probability is 0.01 per year = P(I will exist prior to my conception|CH). Assuming equal priors, this gives the posterior probability P(CE|I exist) = 0.99. Assuming more realistic priors (the statistics of the general use of contraception) might change the posterior probability somewhat. Note that this approximate result seems intuitive. In the Conception analogy I make myself the observer, rather than some random person, since this better corresponds to the AB case of interest where there is only one Earth which is not chosen randomly.

Abiogenesis

As in the Conception analogy, we consider two binary options, AB is easy and AB is hard, and assume (only) that the likelihood probabilities P(LoE prior to LoE|AB easy) > P(LoE prior to LoE|AB hard).

Setting hypothesis H = 'AB is easy' in general on Earth-like planets and evidence = LoE, Bayes' formula is

$$P(\mathrm{AB\ easy}|\mathrm{LoE}) = \frac{P(\mathrm{LoE\ prior\ to\ LoE}|\mathrm{AB\ easy})P(\mathrm{AB\ easy})}{P(\mathrm{LoE\ prior\ to\ LoE}|\mathrm{AB\ easy})P(\mathrm{AB\ easy}) + P(\mathrm{LoE\ prior\ to\ LoE}|\mathrm{AB\ hard})P(\mathrm{AB\ hard})}. \tag{7}$$

The following timescale argument can be used to determine the priors P(AB easy) and P(AB hard) = 1–P(AB easy). The argument parallels one that was crucial to Carter's conclusion that the timescale for the evolution of intelligent life τ_i is much greater than the solar timescale/lifetime, $\tau_{\odot}$ (Carter 1983).

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This statistical argument (separate from his AB argument) is based on the assumption that if two timescales are independent, i.e. they depend on different physics (in this case nuclear physics/gravity versus biology) then there is no *a priori* reason why they should be comparable. Therefore we expect one to be either much greater than or much less than the other. In Carter's case the expectation is that $\tau_i \ll \tau_\odot$ or $\tau_i \gg \tau_\odot$. He argues that since the former inequality is inconsistent with the only observation we have, the latter inequality is the correct one, as it is consistent with our existence and also with our being relatively near the end of Earth's habitable period.

In the present case the two relevant timescales are the AB timescale τ_{AB} and the habitability timescale τ_{Hab}. The former timescale depends primarily on pre-biotic chemistry/geology and the latter timescale depends primarily on the sun and thus nuclear physics/gravity. Since there is no *a priori* reason to believe these two timescales should be comparable we assume that either $\tau_{\mathrm{AB}} \ll \tau_{Hab}$ or $\tau_{\mathrm{AB}} \gg \tau_{Hab}$. I adopt these two inequalities as the natural definitions of the priors for easy and hard AB since these are the (unconditional) expectations prior to the occurrence of LoE. It might be tempting to conclude that $\tau_{\mathrm{AB}} \ll \tau_{Hab}$ is the correct inequality since $\tau_{\mathrm{AB}} \gg \tau_{Hab}$ is inconsistent with observation, by analogy with the Carter τ_i argument. However, the latter inequality can't be rejected due to the anthropic selection effect of our existence. It's possible that $\tau_{\mathrm{AB}} \gg \tau_{Hab}$ could be correct but nonetheless, on Earth, AB necessarily had to happen early in order that there be ample time for intelligent life to evolve. These timescale definitions for the easy and hard priors are equivalent to $P(\text{AB easy}) \sim 1$ during the habitability period and $P(\text{AB hard}) = \epsilon$, where $\epsilon \ll 1$. Inserting these priors into equation (7) gives

$$P(\text{AB easy}|\text{LoE}) = \frac{P(\text{LoE prior to LoE}|\text{AB easy})(1)}{P(\text{LoE prior to LoE}|\text{AB easy})(1) + P(\text{LoE prior to LoE}|\text{AB hard})(\epsilon)} = \frac{1}{1+\frac{\epsilon}{R}} \sim 1 \tag{8}$$

where R is the ratio of the likelihoods = $P(\text{LoE prior to LoE}|\text{AB easy})/P(\text{LoE prior to LoE}|\text{AB hard}) > 1$. The uncertainty in this result is incorporated in the order of magnitude symbols '$\sim$' and '$\ll$' used in the specification of the priors.

In contrast to the previous studies of Spiegel and Turner (2012) and Kipping (2020), whose Bayesian analyses were based on the (assumed new) evidence of the timing of the first appearance of life and of intelligent life, our result, which is based on the (old) evidence of our existence and a separate timescale argument, excludes the possibility that AB could be extremely rare on Earth-like planets.

In terms of the Conception analogy τ_{Hab} corresponds to the fertility timescale $\tau_F \approx 30$ years and τ_{AB} corresponds to the conception timescale τ_C. Like the AB case, we assume that we have no information about the prior likelihoods other than $P(\text{I exist}|\text{CE}) > P(\text{I exist}|\text{CH})$. The natural timescale for defining easy and hard conception would be the fertility period. Thus easy conception would be defined as $\tau_C \ll 30$ years and hard conception as $\tau_C \gg 30$ years. This is consistent with our previous (known) values of $1/0.85/\text{year} = 1.2$years and $1/0.01/\text{year} = 100$years, given that the timescale for 'conception hard' could be greater than 100 years, for example the timescale assuming abstinence. Although the analogy is consistent, the rationale for the priors has to be postulated since τ_C and τ_F both depend on biology and therefore they are not necessarily independent.

The result equation (8) strictly applies to exact Earth-twins (which statistically wouldn't exist in our own bubble universe) though we make the common assumption that it also applies to the vaguer notion of Earth-like planets which have similar macroscopic chemical, thermodynamic and geological conditions as Earth.

Conclusion

Notwithstanding the fact that we necessarily had to find ourselves on a planet where AB occurred, I have argued that this datum is nonetheless not neutral, as the Carter argument concludes, but rather it implies that the probability of AB sometime during the habitable lifetime of an Earth-like planet is ~ 1. This conclusion is based on (1) the fact that life on Earth constitutes old evidence and it should be evaluated in that context, and (2) the application of an independent time-scale argument to determine the Bayesian prior probabilities.

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Conflict of interest. None.

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