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Re-evaluating the probability of the emergence of intelligence using suitable terrestrial data

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Abstract

Bayesian models have been used to infer the prevalence of life and intelligence elsewhere in the universe for several decades. In most, the emergence of intelligent life is judged against the time it took to emerge following the emergence of life as whole. However, such approaches are flawed in that they do not relate the emergence of "intelligent traits" to the absolute requirement for high rates of metabolism to support high levels of cognitive activity. They also make temporal assumptions that are based on fossil evidence, which is incomplete, particularly when one goes back to the Archaean. Instead, we provide a series of analyses, using simple Bayesian modelling to investigate the probability of two processes arising on Earth: endothermy and intelligent behaviours, the latter referred to as abstraction. The emergence of these traits is judged against known prior events, such as the origin of life (OoL); the Great Oxidation Event (GOE) and the Neoproterozoic Oxygenation Event (NOE). Likewise, we evaluate different plausible requirements for the emergence of abstract behaviours. The models show that there is a marginal preference for the requirement of oxygenation at the NOE over other events for the evolution of endothermy. However, such models are not fully able to distinguish preferences for the emergence of abstract behaviours. Finally, using the same approaches, we show that the emergence of Apes from other Primate lineages has a lower than expected probability.

Introduction

Numerous authors have used statistical methods to infer the likelihood of intelligent life in the cosmos, using our singular, example as a basis for further inference (for example, Carter, 1983; Wilson, 1994; Livio, 1999; Lineweaver and Davis, 2002; Bettini, 2004; Ćirković et al., 2009; Spiegel and Turner, 2012; Loeb et al., 2016; Kipping, 2020; Snyder-Beattie et al., 2021; Song and Gao, 2022). In the original work, Brandon Carter (1983) laid out a simple thought experiment in which, with some assumptions, concluded that intelligent life in the cosmos could be rare. It should be clear that Carter (1983) laid out his thought experiment

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with many important caveats and the manuscript was designed to provoke further discussion and analysis; along with comments on the term “anthropic principle” (Carter, 1983)

Of these statistical approaches, Bayesian modelling is by far the most commonly applied, often concluding that intelligent life must be rare (Spiegel and Turner, 2012; Chen and Kipping, 2018; Kipping, 2020; Snyder-Beattie et al., 2021). However, quite aside from having the Earth as “N = 1” for such models, the question posed by Wilson (1994) is whether we can extrapolate to other worlds using the Earth as a typical example (Loeb et al., 2016).

For example, multicellularity has evolved in all branches of life, more than once (King, 2004). Subsequently, since the Neoproterozoic Oxygenation Event (hereafter, NOE), viviparity has emerged over 100 times (Helmstetter et al., 2016: Recknagel, et al., 2021); and endothermy more than 14 times (below). Catling et al (2005) proposed that the time it takes a planet to develop an oxidizing atmosphere is a critical period that affects the subsequent evolution of life (Lenton et al., 2014; Eden et al., 2022). The term, “Time Since Oxygenation” (TSO) defines the interval between the NOE and a particular evolutionary event (Catling et al., 2005).

Here, we produce a series of related models, which employ observed rates of emergence of traits (as *a priori* information), but with differing modelled timelines (*a posteriori* models). In doing so we wish to explore the likely dependency of trait emergence on the geological evolution of the planet and the probability of the emergence of intelligent behaviours on the emergence of these other traits. To reduce the complexity and the number of these models, we choose two biological events that one can reasonably argue are essential for, or evidence of, intelligence on Earth: the emergence of endothermy; and (as a descriptor) the emergence of language as “abstract” storage/transmission of information. For our purposes, we assume, firstly, that intelligence is dependent on the formation of complex multicellular, differentiated organisms. Secondly, that oxygen is required to provide a suitable redox potential to provide sufficient Work needed to sustain the high levels of cognitive activity associated with intelligence. Endothermy, the propensity to produce or retain sufficient warmth as to have a near-constant internal temperature, is typically regarded as unique to mammals, birds (and some dinosaurs, Wiemann et al., 2022). However, endothermy is widespread in animals and has arisen multiple, independent times since the Permian-Triassic boundary (Crompton et al., 1978; Robertshaw, 1984; Gavrilov, 2013; Polymeropoulos et al., 2018; Legendre and Davesne, 2020; Araújo; et al., 2022). The first conclusive evidence for endothermy is seen

233 million years ago in the Triassic, although it is suggested that it arose earlier in the Permian (Bajdek et al., 2015). Variants of the vertebrate processes are also common in insects, such as bees (Ono et al., 1987; Bernd, 1993). These diverged from vertebrates prior to the Cambrian (Simakov et al., 2020). One could argue that even if warmth is required for the development of intelligence, that organisms living in warm aquatic or marine environments could become intelligent: cephalopods are a good case in point. However, we would contend that irrespective of the intelligence of such life, it could never become technologically-advanced as it lives in an environment that precludes the development of said technologies. Metallurgy, for example, is not feasible in a wet and (relatively) low oxygen environment.

We are largely ignoring the occurrence of endothermy in insects, for the reason of simplicity, as there is sufficient evidence of multiple emergences of endothermy in vertebrates to meet the demands of the article. However, we note that the invertebrate lineages, which gave rise to insects, diverged from the pre-vertebrate lineage around the time of the NOE (Simakov et al., 2020).

The paper is subdivided into hierarchical sections. In the first (model, method and parameters) we consider how to disentangle various “issues” with interpretation of Bayesian outputs, from the usefulness of the methodology. In the second section, we describe how we scrutinize a perfectly logical model (Spiegel and Turner, 2012) by applying two groups of data (endothermy and abstraction); before analysing the outputs.

Prior Data and Related Considerations

To construct a Bayesian framework, we identify suitable priors and define, clearly, the reasoning for the selection of relevant time points. The following sub-sections provide this information.

The Origin of Life

The exact point at which life emerges is unclear and may well be a gradual emergence of life processes (Harrison et al., 2023) rather than a hard-point in time. Previous works use the geological record, either as a direct appearance of microscopic fossils (Nutman et al., 2016) or isotopic evidence for processes such as photosynthesis (Mojzsis et al., 1996; Bell et al., 2015). These give an origin of life at approximately 4.1-3.85 Gya. However, it is apparent from phylogenetics that the origin of life increasingly approaches the origin of the Earth or at least the origin of its oceans (Mahendrarajah et al., 2023; Moody et al., 2022; Moody et al., 2024). Rather than being concordant with carbon-13 excursions at 3.85 GYa (Mojzsis et al., 1996), LUCA appears to have been present in a biological community by 4.2 GYa (Moody et al., 2024). Therefore, life likely emerged as early as 4.4-4.3 GYa. That places life's emergence within the first 150-250 million years of the formation of stable crust (Korenaga 2017). Consequently, we take a fairly conservative Origin of Life timepoint at 4.3 GYa.

Oxygenation

Both the GOE and NOE are well constrained by various biogeochemical proxies, such as $\delta^{13}C$ excursions and formation of banded iron formations (Lyons et al., 2014). For our purposes we note that the NOE is delineated by $\delta^{13}C$ excursions beginning around 800 Mya, but accelerating at 580 Mya and culminating at 550 Mya (Och and Shields-Zhou, 2012). For the purposes of this analysis, we will use the time of "completion" at 550 Mya, which brings the oxygen levels to 0.5 PAL. This concentration supports further evolutionary transitions and forms a sensible time point for further discussion. Likewise, the GOE appears to be similarly broad (Lyons et al., 2014) with oxygenic photosynthesis beginning around 3.0 GYa (Sánchez-Baracaldo, Hayes, Blank, 2005; Fischer, Hemp and Johnson, 2016; Fournier et al., 2021; Stevenson, 2022). However, for the purposes of our analyses, we pick a time of 2.45 GYa (the GOE), which is demarcated in the geological record by the rapid deposition of Banded Iron Formations (BIF) and other isotopic excursions (Frei et al., 2009).

Eukaryogenesis

That there is only evidence for one instance of eukaryogenesis argues that this event is improbable. However, that conclusion rests on a poor understanding of both the process, itself, and our incomplete understanding of the microbial world.

Until recently, it was suggested that LECA existed after 1.6 GYa (Mills et al., 2022). However, that (relatively) late emergence is challenged by two findings. Firstly, fossilized evidence of multicellular eukaryotes has been found, which is dated at 1.63 GYa (Miao et al., 2024). The presence of multicellular eukaryotes implies that eukaryogenesis likely occurred closer to Lomagundi-Jatuli Event (hereafter, LJE), when oxygen levels peaked after the GOE (Prave et al., 2020; Schavemaker and Muñoz-Gómezm 2022). Likewise, two studies, which examined the phylogeny of eukaryotes (and other species) suggested that both the mitochondrial ancestor and the Archaeal ancestor of eukaryotes emerged at around 2.5 GYa (Mahendrarajah et al., 2023; Moody et al., 2024), with eukaryotes emerging at approximately 2.3-2.0 GYa (Moody et al., 2024) and diverging at around 1.3 GYa (Moody et al., 2024).

These concordant dates are significantly earlier than previous studies, but they agree with the identification of multicellular eukaryotes prior to 1.6 GYa (Miao et al., 2024).

While the focus of this work is on complex, multicellular eukaryotes, we note that active, multicellular prokaryotes, whether bacteria (Jahan et al., 2021; Lyons and Kolter, 2015; Muñoz-Dorado et al., 2016; Hammerschmidt et al., 2020; Stoy and Ratcliffe, 2024, Schaible et al., 2024) or Archaea (Chimileski et al., 2014) can also prosper under aerobic conditions. The presence of multicellular life-styles across the three domains of life on Earth signifies the importance of environmental permissivity: i.e., in this instance, the requirement that the environment is able to support the evolutionary transition to multicellularity (King 2004).

Animalia

Phylogenetics places the likely divergence of animals and fungi from their common ancestor at the earliest isotopic excursion NOE at 800 Mya (Fisher, Shik and Boomsma, 2020). Divergence of animalia occurs during the Ediacaran and subsequently (Cole et al., 2020).

Mammals

The ancestral group (Mammaliamorpha) arose in the late Permian, with the first endothermic mammals evolving approximately 40 million years later, in the late Triassic, at around 225 MYa (Araújo et al., 2022).

Endothermy

With the probable and singular exception of cephalopods (Schnell et al., 2021), intelligent behaviours (discussed below) are associated with endothermy. While, generally assumed that endothermy is confined to Birds and Mammals, there are multiple incidences of endothermy in vertebrates and invertebrates (Legendre and Davesne, 2020; Wiemann et al., 2022). Indeed, based on phylogenetic evidence, endothermy repeatedly appears in the vertebrate lineages after 270 million years ago, with several incidences occurring in the last 100 million years. While one may argue that, on the basis that these events occur in vertebrates, these events are not independent of one another, the phylogenetics shows that the majority of incidences do not share a recent common ancestor (birds and mammals are the closest). Therefore, with the exception of the two aforementioned clades, it is reasonable to assume that emergence events occurred independently.

Likewise, if one wishes to include endothermy in the invertebrates (not considered further, in this work), then the most recent common ancestor of the vertebrate and invertebrate endotherms approximates with the NOE (Wagner, Amemiya, and Ruddle,2003; Simakov et al., 2020). Therefore, while available evidence suggests that endothermy is confined to Animalia, the multiple emergences of the trait in the Kingdom appear unrelated to one another other than it is a trait of animals. Moreover, within the Kingdom the manner in which endothermy manifests varies. There is little or no direct evolutionary relationship between the mechanisms of endothermy in neighbouring lineages (Polymeropoulos et al., 2018; Legendre and Davesne, 2020).

Therefore, we assume: that excluding invertebrates, there are 14 instances of endothermy in animals (Wong, 2019; Wong, 2020). Seven of these involve "non-shivering endothermy", which means maintenance of above-ambient internal temperature involves mechanisms other than shivering (Legendre and Davesne, 2020).

Cephalopods

The Cephalopods are likely intelligent and ectothermic (Schnell et al., 2021). Able to perform complex problem solving and simple tool-use, at face-value, cephalopods would refute our suggestion that intelligence requires endothermy. However, there are two countering arguments. Firstly, Cephalopods, primarily, live in warm water, where the oceans buffer internal temperature changes and maintain it at a relatively high level. Secondly, the environment in which these animals live is fairly constant and it is clearly not conducive to technological development, beyond simple tool use. Therefore, with regard to technological development, for multiple reasons (relatively low oxygen; an inability to produce metals from ores; relatively fixed environmental stimuli), we do not consider marine (or aquatic) life as likely to progress intellectually or technologically.

Primates

We argue that the evolution of the Primate lineage (rather than Hominids per se) was critical on Earth to the development of intelligent, tool-using, language-bearing life. While many non-Primate organisms, notably the Corvids, use tools (Rutz et a., 2016; Bayern et al., 2018), tool-use is endemic in the Primates, with at least 32 species seen using them (Bentley-Condit and Smith, 2010; Haslam, 2013; Proffitt et al., 2016; Falótico et al., 2019; Agnolín and Agnolín, 2023). There are also at least three Primate species able to use spoken languages (Girard-Buttoz et al., 2022). While Humans, obviously, have the most complex languages, our anthropocentric bent is increasingly challenged by observations of Gorillas, Chimpanzees and Bonobos (Girard-Buttoz et al., 2022). However, while we are happy to conclude that spoken language may not be unique to Humanity, based on phylogeny, it is not reasonable to conclude that such instances of spoken language in Primates are independent from one another. Therefore, in the Apes, we assume that spoken language has emerged once.

Redefining Intelligence

The word “intelligence” carries a lot of anthropocentric baggage (Schneider, 2011). For example, we could regard tool-use as intelligent (Bentley-Condit and Smith, 2010; Haslam, 2013). In the past the use of tools was regarded as intelligent, principally, one suspects because we were viewed as the only species using tools. However, birds and a wide-variety of other species use tools (Rutz et a., 2016; Bayern et al., 2018), such as fish and cephalopods, as well as a wide range of primates (Haslam, 2013).

Later the emergence of language was regarded as intelligent behaviour – again because we were the species that appeared uniquely to engage in this behaviour. However, when one dissects what language is, in terms of communicating information, bird song is as rich as spoken word in humans (Fletcher, 2009), with Whale song comparable, as well (Lawson, 2023). Therefore, we take a different approach to the definition of this variable. Rather than consider “intelligence” as a monolithic block, we can sub-divide it into behaviours that are not directly encoded in the genome. These are: tool-use, which we redefine as “industry”; and language, written, spoken or otherwise expressed, as “abstraction”. Tool-use as industry, then includes the Primates (Morgan et al., 2015), Cephalopods (Schnell et al., 2021), Corvids (Rutz et a., 2016) and some insects (Maák et al., 2016; Soley and Herberstein, 2023). There are probably other species engaging in tool-use, of which we are unaware.

Given that we may find species in the future (on Earth or wider-afield) that use mechanisms of communication we do not, we use the term *abstraction* to mean the transfer of information through non-genetic or epigenetic means. Abstraction is defined as any conveyance of information between individuals and across generations, through any means not directly encoded in the genome. This definition excludes the use of chemoattractants and VOCs (Mattingly et al., 2021); as well as encoded sonic languages, such as those used by insects (Fletcher, 2009). Abstraction includes: spoken language (sonic abstraction); artistic expression, whether musical or through an expressive Art, such as painting; written languages and mathematics (literary abstraction). For the purposes of this work, we regard written language and mathematics as extensions of Art, whereby symbols are used to convey information, as a minimum describing the environment. We use this definition as we need to consider that any non-terrestrial species may exhibit intelligent behaviours that we do not recognize directly in ours. The definition of abstraction allows “intelligence” to be defined based on non-encoded transfer of information (and Work). Tool-use is also a transfer of information and Work, but is easier to identify as a behaviour.

A case in point is the recent suggestion that fungi have a language consisting of as many as 60 words (Adamatzky, 2022); while plants appear to communicate with infrasound (Khait et al., 2019). Use of the broad term, abstraction, could, therefore, allow us to identify completely alien systems of communication as intelligent, even if they are unfamiliar on our world. Much of the language of "evolutionary progress" is tightly framed around human evolution (McShea, 1991; McShea and Simpson, 2011), rather than *process evolution,* and we need to be cautious when applying our human experience to evolutionary innovations that may occur elsewhere in the cosmos.

Whale song is likely sonic abstraction as it appears to be inventive, rather than solely encoded (Lawson, 2023). Likewise, Bird song has features of abstract behaviour, such as mimicry of human spoken language and other noises (Fletcher et al., 2009), or the ability of Corvids to count through squawks (Liao et al., 2024). Therefore, bird song is likely sonic abstraction, as is whale and other Cetacean song or chatter. While we admit that inclusion of birds and Cetaceans as "abstract" (intelligent) may be controversial, it is reasonable based on our definition of intelligence.

For the purposes of this analysis, we will use the presence of Art to delineate the emergence of "abstraction" in our ancestors. The genus *Homo erectus* is the first to convincingly produce Art as we would recognize it (Bednarik, 2003; Joordens, et al., 2015); and is coincidentally the first to have physiological evidence and cultural evidence of spoken language (Morgan et al., 2015). While there are indications that other Great Apes also use spoken language (Girard-Buttoz et al., 2022), none show Art or written language, independent of human intervention. *Homo erectus* emerged 2 Mya, with the first convincing artistic endeavours dated to approximately 0.5 Mya (Bednarik, 2003; Joordens et al., 2015).

As abstraction could be limited to our singular example, determining the rate (λ) for this evolutionary event (and for other uncommon events, such as mass transport) could be questioned if only based on the fossil and phylogenetic record. Therefore, for the purposes of this work we follow two linked methodologies. In the first we assume that the observed rate is a genuine reflection of its likelihood. That data gives a value for λ as 1.81 per billion years, if the NOE is taken as the point from which the emergence of the process is assessed. When assessed from the GOE, when oxygenation of the biosphere became widespread, that rate decreases to 0.4 Gy^{-1}; and 0.25 Gy^{-1} if assessed from the origin of life (table 2). We may then use this information as our prior.

Timeline of Events

Tables 1 summarises the geological times that are used in this work. Table 1 provides an overview of the emergence of various evolutionary events and their geological framework.

Event	Time from Origin of Life ca 4.3 GYa/ Gy	Time from GOE/ Gy	Time from NOE/ Gy
Emergence of oxygenic photosynthesis	1.3	-	-
Formation continental crust	0.0 – 1.0	-	-
Emergence bulk continental crust from oceans	1.1 – 1.8	-	-
Multicellularity	1.8	-	-
Sexual reproduction/eukaryogenesis	≥ 2.3	≥ 0.5	-
Time to 0.5 PAL O_2	3.8	1.9	-
Mass transport	3.8	1.9	0.05
Viviparity	4.0	2.1	0.30
Endothermy	4.0	2.2	0.32
Industry	4.0	2.2	0.30
Literary Abstraction	4.3	2.45	ca. 0.55

Table 1: The relative timings of events used in subsequent analysis. Times are in GYa. Formation of continental crust overlaps the origin of life and is likely protracted. Multicellularity is taken from the divergence of cyanobacteria, which exhibit the trait, but it could be older.

The NOE is taken as completing at 550 MYa. Continental formation is contentious, with some models positing the majority of crust is formed by 4.0 GYa, while others have continued formation until the Proterozoic, albeit at a diminishing rate (Korenaga, 2017; Korenaga, 2021). However, the progressive emergence of continental from the oceans is increasingly well constrained to the interval 3.2 – 2.5 GYa, based on strontium isotopic and other evidence (Johnson et al., 2021).

Mass transport is seen only in the kingdoms, plantae and animalia. The first multicellular plants appear at ca. 1.0 GYa (Tang et al., 2020). Animals diverge from fungi by 800 MYa. Mass transport appears to emerge synchronously across the NOE in animals, but emerging in plants in the Cambrian-Ordovician, approximately 100 My later, as plants evolved on-land (Li et al., 2010; Stigall, 2017; Servais et al., 2019).

The radiation of mammals is taken as the KT event at 66 MYa. The fossil record identifies the first primate fossils at around 55 Mya (Franzen et al., 2009), with an earlier divergence time for the lineage at 81 MYa (Tavaré et al., 2002). Perhaps, unsurprisingly then, the divergence of the family which gives rise to Literary Abstraction is synonymous with the radiation of mammalian species. Therefore, we take the T_{min} for this event as the KT extinction event from ca. 66 MYa.

Prior and Posterior Models

In each instance we choose the simplest possible model with the fewest considerations based on terrestrial observation. A Poisson Distribution assumes that there is no bias in the timing of events and that each event is independent of every other event. The sections above support or refute the likely independence of events as are relevant to further analysis.

Frequencies

We could assume that our observations are atypical of the universe at large and select values for λ over a suitable range as in other studies (e.g., Spiegel and Turner, 2012; Snyder-Beattie et al., 2021). What constitutes a suitable range? Traditional approaches select values that extend over several orders of magnitude in the hope of capturing a "true value". While such a blind approach should (one would hope) encompass a realistic value, it does not directly relate the circumstances in which it arose to our emergence. Therefore, an alternative approach is to calculate the probability of the emergence of abstraction as a fraction of the total number of (eukaryote) species that have emerged on Earth since the beginning of the Phanerozoic. However, we also determine a more optimistic value as abstraction as the fraction of the number of NST mammalian species that have emerged since the KT boundary. These values are used as alternative prior probabilities (P(H)).

For the purpose of determining priors based on Eukaryogenesis and the number of mammals, we use an older method to estimate numbers of species. From this we determine the frequency of relevant events. As we cannot be certain of the number of species, S, that have existed since the NOE (approximating the beginning of the Phanerozoic), a reasonable approach is provided by Sepkoski (1994) and Raup and Sepkoski (1982). In Seposki's analysis, the number of potentially fossilisable species alive today is taken and divided by their approximate longevity in the record. That figure is then multiplied by the proportion of time (in Sepkoski's case 65 My; but 550 My for the period from the NOE). The product is then multiplied by the assumed rate of increase in species number over that interval: equation

1a. In our instance we take the value of the number of eukaryote species (8.7 million, Mora et al., 2011), rather than the 100,775 fossilisable species used in Sepkoski (1994).

$$X_s = \left(\frac{T}{\bar{t}}\right) r.S \tag{1a}$$

Where S is the total number of eukaryote species present now (the species richness); *T* is the time interval; *t* is the mean time over which any one species exists; and *r* is the observed (or chosen) rate of increase.

$$S = \left(\frac{550}{6.5}\right)\left[\left(\frac{0.2 + 1.0}{2}\right)\right] 8.7 million \tag{1b}$$

The change in species richness during the Phanerozoic is likely a significant overestimate (Close et al., 2020), with a reasonable rate of increase in the Cenozoic (post-KT extinction) likely about two thirds that implied from the fossil record. Therefore, these values set an upper bound. Substituting our values for species number and time into 1b gives 4.42 x 10^8 species, which is a reasonable upper limit for eukaryote species numbers during the period after the NOE. We accept that the determined value is effectively *abstract* as some of the eukaryotes that we are familiar with only arose in the last 140 million years or so. However, it is a useful upper bound.

Using the value of 4.42 x 10^8 multicellular eukaryotes, the frequency of humans is 2.26 x 10^{-9} in the last 0.55 Gy.

Similarly, we use equation 1a to compute the approximate numbers of mammalian species that have existed since the KT boundary. Assuming approximately 6,500 mammalian species (Burgin et al., 2018), currently, that approximates 3.9 x 10^4 mammalian species since the KT. Again, this value could be an over-estimate, if the rate of change is significantly less than estimated (Peters and Foote, 2001; Close et al., 2020), or the current estimate of mammalian species is too low (Burgin et al., 2018).

Assuming that humans emerge randomly from mammals, using a value of 3.9 x 10^4 mammalian species, we have a frequency of literary abstraction of 2.56 x 10^{-5} on Earth in the last 0.065 Gy (post-KT). Obviously, we could extrapolate back to the first emergence of endothermic lineages, 233 million years ago, which would decrease the frequency.

In terms of the time of emergence, the interval from the emergence of animals to endothermy and endothermy to abstract behaviour is comparable with time from the origin of the Earth to the origin of life. That is, approximately, 100-300 million years.

Table 2 provides the numbers and frequencies of events used in further analysis.

Event	**Number of independent events since NOE**	**Frequency (λ) / yr^{-1}**		
		NOE	**GOE**	**OoL**
Mass transport	2	$3.63\mathrm{x}10^{-9}$	$8.20\mathrm{x}10^{-10}$	$4.65\mathrm{x}10^{-10}$
Endothermy (NST)	7	$1.27\mathrm{x}10^{-8}$	$2.86\mathrm{x}10^{-9}$	$1.63\mathrm{x}10^{-9}$
Endothermy (all)	14	$2.54\mathrm{x}10^{-8}$	$5.76\mathrm{x}10^{-9}$	$3.26\mathrm{x}10^{-9}$
Industry	4	$7.27\mathrm{x}10^{-9}$	$1.63\mathrm{x}10^{-9}$	$9.3\mathrm{x}10^{-10}$
Abstraction	1	$1.81\mathrm{x}10^{-9}$	$4.08\mathrm{x}10^{-10}$	$2.33\mathrm{x}10^{-10}$

Table 2: Illustration of the relative frequency of evolutionary events that contribute to the development of intelligent behaviours (Industry and Abstraction) on Earth. Endothermy is present in 14 families. NST – non-shivering-thermogenesis, excludes insects. Mass transport is present in two kingdoms and is essential for the functioning of large, multicellular organisms. Industry is present in four separate classes of animal. Abstraction (with the restrictive definition of intelligence used here) is present in three families, but Written (Literary) Abstraction is present in one (the Primates).

Prior – A Poisson Distribution

To estimate an *a priori* probability, *H*, we follow the methodology of Valentine, Ort and Cortés (2021). For a discrete random variable X, which follows a Poisson distribution, the probability of having *k* events, with an average frequency of events λ (events/ time) is equal to:

$$P(H, X = k) = \frac{e^{-\lambda t}(\lambda t)^{k}}{k!} \tag{2}$$

where λt is the expected number of occurrences in the given time t.

For endothermy there are 14 events 550 million years or $\lambda = 2.54 \mathrm{~x~} 10^{-7}\mathrm{yr}^{-1}$. We assume that there are 4 independent emergences of tool-use (Industry; Birds, Cetaceans, Cephalopod and

Primates) and three emergences of Verbal Abstraction (Spoken Languages; Birds, Cetaceans and Primates). There is one instance of Literary Abstraction (Humans/Primates).

Equations 1a and 1b are used to determine the frequency of emergence of mammals and abstract behaviour in eukaryotes. For the purposes of the final model, we use the emergence of Art in *Homo erectus* as a defining point in the creation of written abstraction at 0.5 Mya (Bednarik, 2003; Joordens et al., 2015). For each example of Abstraction, we accept that our definition may not please everyone, but that these are at least supportable as working definitions for this exploration of intelligence.

Table 3 summarises the frequencies and corresponding a priori probabilities used in the remainder of this work. Note, that the number of prokaryote species (Archaea and Bacteria) is controversial but likely approximates the number of eukaryote species (Mora et al., 2011; Louca et al., 2019). Therefore, the effect on frequency of processes against all life on Earth is not substantially different to that for eukaryotes.

Event per Interval	**Frequency (λ) yr^{-1}**
NOE to Endothermy	2.55E-08
GOE to Endothermy	5.71E-09
OoL to Endothermy	3.26E-09
Eukaryogenesis to Abstraction	4.080E-10
NOE to Abstraction	1.82E-09
Endothermy to Abstraction	4.29E-09
Mammals to Abstraction	4.44E-09
Primates to Abstraction	1.23E-08
Primate to Apes	3.85E-08

Table 3: Summary of the frequencies and corresponding *a priori* probabilities for the events discussed in this work. Abstraction is taken as Literary Abstraction (1 event in Primates), rather than sonic abstraction (three independent events in endotherms). Methodologies are discussed in the text.

Posterior Model

We reapply the model of Speigel and Turner (2012) simply because it has the fewest assumptions. Their likelihood function was based solely on the observed timing of events and did not assume that one event is more likely than another or dependent on other events. While there are other models (e.g. Kipping, 2020), the simplicity of this model, in our opinion, satisfies Occam's Razor. Table 4 summarises the definitions used in this work and the original ST (2012) work.

Event	Original ST Definition	Revised Definition
T_{min}:	The minimum age the Earth could have for life to emerge (0.5 Gy)	The minimum permissive time between the NOE to the origin of endothermy (0.10 Gy)
T_{max}:	The maximum time the biosphere can persist and life can emerge from the origin of the Earth (10 Gy).	The maximum time the biosphere can persist and endothermy (or other trait) can emerge from the NOE (ca. 1.5 Gy).
T_{emerge}	The age of the Earth from when the earliest extant evidence of life remains (0.3-0.7 Gy)	The time from the NOE when the earliest extant evidence of an evolutionary innovation is determined by the fossil and phylogenetic record (0.32 Gy)
T_{evolve}	The minimum amount of time required after the emergence of life for cosmologically curious creatures to evolve (ca. 3.8Gy)	The minimum amount of time required since the evolution of endothermy for abstract creatures to evolve (ca. 0.07 Gy)
$T_{required}$	The maximum age that the Earth could have had at the origin of life in order for humanity to have a chance of showing up by the present (?)	The maximum interval between the NOE and endothermy so that abstract creatures have a chance of showing up by the present (0.48 Gy)

Table 4: Terminology used in subsequent analysis for NOE model. The ST definitions in the left column are from Spiegel and Turner (2012), while the right column has intervals relative to NOE, rather than the origin of the Earth in giga-years. T_{max} is set to +1 GY from present (ca. 1.5 GY from NOE), rather than maximum biosphere age (10 Gy) in Spiegel and Turner (2012). T_{min} in Spiegel and Turner (2012) is the minimum time to the origin of life, whereas here, times are relative to the NOE, as we are concerned with innovations that occurred after biosphere oxygenation. T_{emerge} is the time from the NOE to the first fossil evidence for endothermy at 0.233 GYa. T_{evolve} is taken as the time from the first fossil evidence of endothermy at 0.233 GYa to the present. Likewise, $T_{required}$ is taken as the time from the first chordate evolution of endothermy and the

demise of the dinosaurs – so that humanity could emerge. The choice of this interval would equate to the time to the death of the dinosaurs, when modern mammalian lineages radiated – 0.48GY.

The likelihood function compares the time an event took to occur compared with the time in which it could have occurred: i.e., how quickly an event occurred after it was possible. We assume that events occur at a constant rate, λ, after conditions become conducive.

$$\mathrm{P(E|H)} = \frac{1 - exp\left[-\lambda\left(t_{emerge} - t_{min}\right)\right]}{1 - exp\left[-\lambda\left(t_{required} - t_{min}\right)\right]} \tag{3}$$

Where λ is much less than 1 then P(E|H) approximates $(t_{emerge}-t_{min})/(t_{required}-t_{min})$.:

$$\mathrm{P(E|H)} \approx \frac{t_{emerge} - t_{min}}{t_{required} - t_{min}} \tag{4}$$

The time periods used in these calculations come from Tables 1 and 2 and are summarized in Table 5. As λ is always much less than 1, we use equation 4 in further analysis.

Model	**T_{min}/yr**	**T_{emerge}/yr**	**$T_{required}$/yr**
Endothermy-NOE	1.00×10^8	3.17×10^8	4.80×10^8
Endothermy-GOE	1.00×10^8	2.22×10^9	2.38×10^9
Endothermy-OoL	1.00×10^8	4.10×10^9	4.23×10^9
Eukaryogenesis (LJE)-Abstraction	1.93×10^9	1.99950×10^9	1.99985×10^9
NOE-Abstraction	4.80×10^8	5.495×10^8	5.499×10^8
Endothermy-Abstraction	1.52×10^8	2.3250×10^8	2.3285×10^8
Mammals-Abstraction	9.50×10^7	2.245×10^8	2.2485×10^8
Primates-Abstraction	1.50×10^7	8.05×10^7	8.085×10^7
Primate clade	1.50×10^7	2.60×10^7	6.10×10^7

Table 5: Summary of time periods chosen in each of the subsequent analyses. LJE is Longman-Julian Event at ca 2.0 GYa, approximating eukaryogenesis from phylogenetic modelling. T_{min} is set to a default value of 100 million years after the chosen event, for the three endothermy models. T_{min} in the abstraction models are based on the distance between the founding event (e.g. NOE or Endothermy) and the earliest time at which abstraction could occur: the KT event (NOE-Abstraction); the phylogenetic emergence of Primates (Endothermy and Mammalian-Abstraction); the interval between phylogenetic and fossil evidence for Primates (Primate-Abstraction and Primate Clade models). NOE – Neoproterozoic Event (0.55GYa); GOE – Great Oxygenation Event (2.45 GYa); Abstraction – development of artistic presentation of learnt information (0.0005 GYa).

Figures 1 (Endothermy) and 2 (Literary Abstraction) illustrate the models summarized in table 5.

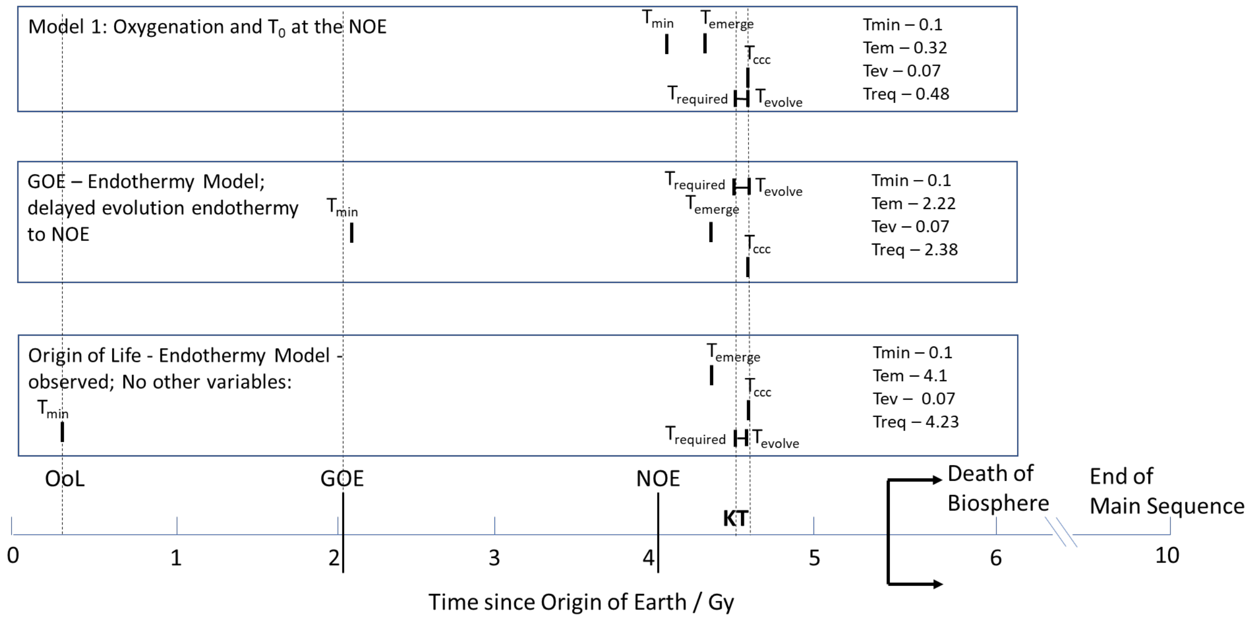

Figure 1: Illustration of parameters used in the NST-Endothermy models.

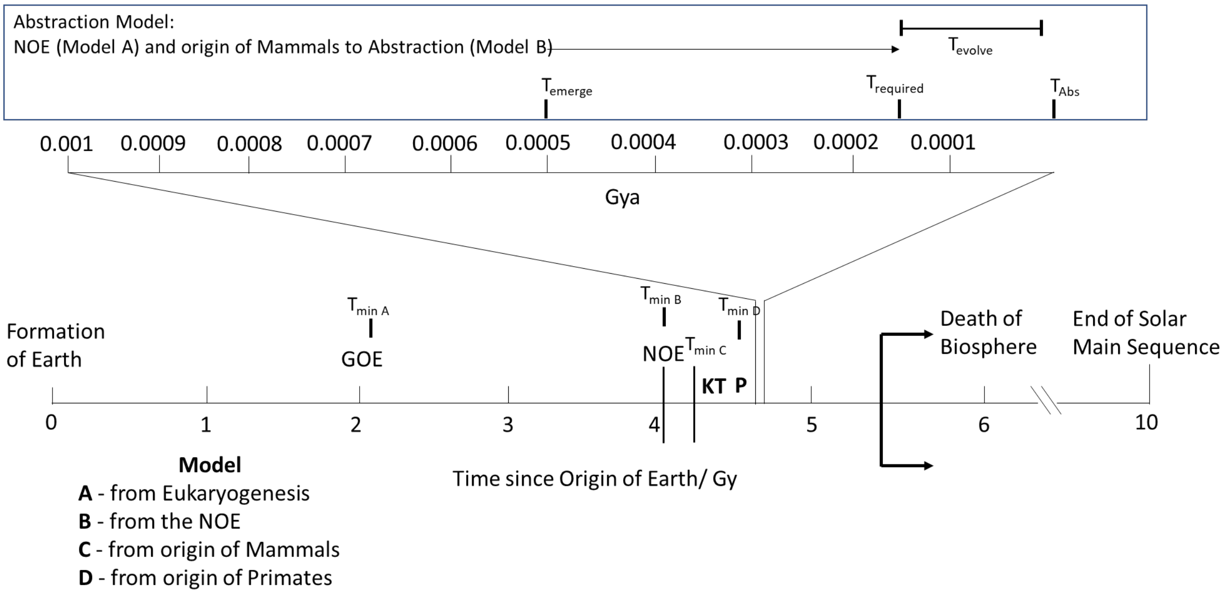

Figure 2: Illustration of the parameters used in the evolution of abstraction model. The Primate Clade model is not shown for reasons of clarity but is described in the text.

Bayes Theorem and Bayes Factor

Bayes Theorem may be written as:

$$\mathrm{P(H|E)} = \frac{\mathrm{P(E|H)P}(H)}{\mathrm{P(E)}} \tag{5}$$

Where,

- P(H|E) is the probability of event H occurring, given event E has already occurred
- P(E|H) is the probability of event E occurring, given event H has occurred (our models, which use known or assumed *a priori* information)
- P(H) is the probability of event H (*a priori* information)
- P(E) is the probability of event E (data)

The Bayes factor allows numerical comparison of different models and the testing of a priori assumptions. Specifically, if two models are compared then a Bayes factor of greater than 10 favors the model in the numerator over the denominator (Spiegel and Turner, 2012). Bayes factor, R, is approximated as follows:

$$R \approx \frac{\Delta T2}{\Delta T1} = \frac{t_{required} - t_{min}}{t_{emerge} - t_{min}} \tag{6}$$

Table 3 lists the definitions of T_{emerge}; T_{min}; $T_{required}$, T_{max} that are used in this work, comparing them with their original definitions, used in Spiegel and Turner (2012). Tables 4 and 5 list the models and time intervals used in subsequent analysis.

Posterior Model Summary

The following models are pursued in this work.

- NOE Model: comparison of emergence times of endothermy with times since the NOE;
- GOE Model: likewise comparative model time to endothermy since the GOE
- Null Model: likewise comparative model time to endothermy since the Origin of Life (OoL)
- Eukaryogenesis-Abstraction: time to Literary Abstraction since the Eukaryogenesis (taken at the LJE)
- NOE-Abstraction: time to Literary Abstraction since the NOE
- Endothermy-Abstraction: time to Literary Abstraction since the advent of endothermy
- Mammals-Abstraction: time to Literary Abstraction since the mammalian emergence (approximating within 50 MYa when endothermy arose)
- Primates-Abstraction: time to Literary Abstraction since origin Primates
- Primate Clade: time to the divergence of Apes from the emergence of Primates

Results

Tables 6a and 6b summarise the outputs of the Bayesian modelling for the models summarized above. Table 6a has the prior as a probability per year, while 6b adjusts all parameters to per hundred million years, bringing the units into line with the numerical values in the posterior model.

Model	P(H) (yr)	P(E|H)	P(H|E)	R
NOE to Endothermy	2.55E-08	0.571	3.39E-08	1.75
GOE to Endothermy	5.71E-09	0.908	5.63E-08	1.10
OoL to Endothermy	3.5E-09	0.969	1.08E-07	1.03
Eukaryogenesis to Abstraction	4.08E-10	0.995	8.10E-08	1.01
NOE to Abstraction	1.82E-09	0.994	3.16E-07	1.01
Endothermy to Abstraction	4.29E-09	0.996	9.87E-07	1.00
Mammals to Abstraction	4.44E-09	0.997	1.64E-06	1.00
Primates to Abstraction	1.23E-08	0.995	2.31E-06	1.01
Primate Clade	3.85E-08	0.239	1.21E-08	4.18

Table 6a: Summary of the outputs of the current analysis. Bayes Factor, generally, indicates no preference for the posterior models employed (R≈1). However, the Primate Clade models (the emergence of Apes and abstraction in this group) favour the numerator (time required for emergence over time to trait emergence) suggesting that a longer interval of time was needed to develop abstraction within this evolutionary branch. Likewise, there is a marginal preference for a longer time for the evolution of endothermy from the GOE. Use of equation 3 rather than 4 makes no measurable difference.

Model	P(H) (adjusted)	P(E|H)	P(H|E)	R
NOE to Endothermy	0.0248	0.571	0.0326	1.75
GOE to Endothermy	0.00570	0.908	0.0046	2.24
OoL to Endothermy	0.00325	0.969	0.0063	1.52
Eukaryogenesis to Abstraction	0.000408	0.995	0.0388	1.01
NOE to Abstraction	0.00181	0.994	0.153	1.01
Endothermy to Abstraction	0.000429	0.996	0.0898	1.00
Mammals to Abstraction	0.000444	0.997	0.141	1.00
Primates to Abstraction	0.359	0.995	0.982	1.01
Primate Clade	0.0820	0.239	0.374	4.18

Table 6b: Identical calculations to those in Table 6a, except that the P(H) and subsequent Bayes calculation is per hundred million years rather than per year. The adjustment brings the values for *a priori* probabilities into line with those for the posterior probabilities, which are per hundred million years.

The outcomes from these analyses are described, below.

Endothermy

There is no evidence for the evolution of endothermy prior to the NOE. All examples emerge after the atmospheric concentration of oxygen approximate PAL. Bayesian modelling also marginally favours the emergence of endothermy after the NOE, compared with the GOE (one order of magnitude) and the Origin of Life (two orders of magnitude). The Bayes Factor, R, indicates minimal preference for the choice of posterior model: i.e. the time at which the process emerged is approximately the same as the time it was “necessary” to evolve so that we could see it. These observations are in keeping with our understanding of the requirement for abundant oxygen to provide suitable energetics for the process.

In terms of probabilities, using values per hundred million years, it is reasonably probable that endothermy emerges on Earth given sufficient oxygen (3.3%). In the absence of abundant oxygen (<1%, which is reasonable for the bulk of the Proterozoic, Prave et al., 2020) the output probabilities since the origin or life or GOE are less than 1%). In everyday terms, 3.3% may seem low. However, considering the number of organisms that have arisen since the NOE (442 million multicellular eukaryotes – see methods), 3.3% is significant, implying that the process is probable on an ecosystem-scale.

Literary Abstraction

Likewise, the emergence time of Literary Abstraction (the fossil evidence for Art, in this case) approximates the time in which it had to appear for us to observe it ($R \approx 1$). That suggests that the emergence time had to be close to the observed time within the intervals considered. In terms of raw probabilities Bayes modelling suggests that endothermy was important ($P(H|E)$ of approximately 9%); with the emergence of Primates critical (98%).

However, we need to consider what these abstraction models are showing. Are the abstraction models really telling us anything we don't already know? The 98% probability is only affirming that *Homo erectus* is an Ape and that we are also descended from another Ape. In effect, it says our ability to determine the origin of Art in *Homo erectus* is related to our ability to carry out similar abstraction because we are related.

Primates

A little more interesting is the Primate clade model, which is the time to the divergence of Apes from the emergence of Primates. This gave a Bayes Factor more than 4, implying that Apes could have emerged earlier but did not. Likewise, the $P(H|E)$ is approximately 37% suggesting that the emergence of Apes, while probable, was not certain. These values may be surprising given the apparent likelihood that endothermy was probable after the NOE and that the emergence of Primates, as a whole, highly probable after the NOE.

Discussion

In this work we investigate the effect of the choice of prior and posterior models on the outcome of Bayesian modelling of the likelihood of endothermy and abstract behaviours arising.

Although our probabilities are higher than many other similar works (Carter, 2008; Snyder-Beattie et al., 2021; Kipping, 2020), it's clear that the modelling is dependent on the choice of variable. While that observation is nothing new in itself, our data clearly suggests that the environmental conditions determine the probability of outcome. Again, nothing new to any biologist, it is an insight that is often lacking when astrobiologists consider probabilities in similar analysis (Snyder-Beattie et al., 2021).

Rather than modelling various processes as a Poisson distribution, Miele, Valli and Maccone (2023) estimate the probability of evolutionary stages occurring as lognormal processes. Interestingly, these lognormal models give fairly high probabilities for the emergence of life in the 100-million-year interval ($p= 0.52$) after the formation of the Earth. Similarly, eukaryogenesis is modelled as $p = 0.54$, with a probability of between 0.01 and 0.02 every 5000 years; while the evolution of land animals with limbs is modelled at probability of between 0.5 and 1 every 500 000 years; and the evolution of intelligence, like that in humans a probability of between 0.005 and 0.01 every 500 000 years. Like our work, the approach of these authors also considers the evolutionary stages occurring in conjunction with changes to the environment which facilitate them.

There has been a tendency to view a planet as a monolithic block that is non-evolving. Life then evolves on this static object. However, that is not how life evolves. Life evolves, filling the niches that are available to it (e.g. Price et al., 2014; see Cole et al., 2020 for a nuanced discussion). Certain biological events are nigh-on impossible in the absence of conducive environmental priors. Therefore, while the probabilities for the emergence of endothermy since the GOE are comparable with those from the NOE, only the latter is valid. For endothermy, we see that there are no (known) events in the first 3.75 billion years of terrestrial history, when there was an abundance of life for the vast majority of that period. However, that observation does not mean that endothermy is intrinsically improbable, only that the process is unlikely (likely impossible) in the absence of sufficient oxygen. We should also note that events with intrinsically low inherent probabilities are unlikely to ever emerge because of competition from other organisms with more probable and sustainable behaviours and metabolisms.

If we choose the 2 billion year-long period of time between the GOE and the NOE, when there was some oxygen in the atmosphere and oceans, we have no evidence for endothermy arising. Therefore, if we took this information as our prior, we would conclude that endothermy, *as a process*, was extremely improbable. However, that conclusion would be incorrect. Endothermy is dependent on a high partial pressure of oxygen in all terrestrial species that exhibit it. Therefore, we *should* conclude that endothermy will never arise on planets with low partial pressures of oxygen. If we then look at the emergence time after conditions became conducive, we would conclude that the evolution of endothermy was highly probable. The summative conclusion is that endothermy is highly probable in extant life *if* there is a high partial pressure of oxygen in a planet's atmosphere, not that endothermy is particularly likely on habitable planets *per se*. Unfortunately, these rather different conclusions are usually conflated.

That erroneous line of reasoning – that is the conflation of probabilities – leads to the false notion of "hard-steps" in evolution (Carter, 2008; Watson, 2008; Snyder-Beattie et al., 2021), whereby certain "evolutionary transitions" (Ayala, 1974; McShea and Simpson, 2011; West et al., 2015) are perceived as intrinsically more difficult than others. Again, the probability of a particular evolutionary step arising is based on observation of timing of the event, rather than whether that event was even possible until some other circumstance arose. The question should always be framed, if the environment was conducive to the survival of a trait, how quickly is there evidence for that trait arising and persisting?

Therefore, if we find a planet which is both habitable and has an atmosphere with a high partial pressure of oxygen, we should expect that such a planet *could* host multicellular life with mass-transport and endothermy. The environment is dictating whether the evolutionary event is observable – that is to say at some point in future, we can see that it occurred (Helaouet and Beaugrand, 2009; Price et al., 2014; Hagena et al, 2021; Igea and Tanentzap, 2021). An interesting counter-argument might be that endothermy is only present in one lineage (Animalia) that exhibits mass transport and that mass transport is unlikely (two examples in all eukaryotes) – therefore, endothermy must be unlikely. However, while we have not pursued the probability of mass transport through the same Bayesian scheme, one can reasonably conclude that if there is a high partial pressure of oxygen, there is at least the opportunity for larger multicellular organisms to evolve that can utilise the high concentration gradient. As such, these multicellular organisms will require mechanisms to reduce the length of the diffusion pathway from the atmosphere to their intercellular environment. That is to say they must have mass transport systems. Moreover, such mass transport systems in plants and animals require a significant investiture of energy in the form of ATP, therefore, also require aerobic respiration.

Likewise, is the evolution of intelligence (Industry or Abstraction) probable on a planet? Again, in the absence of oxygen at suitable partial pressures, we can conclude that it is highly improbable. Aerobic respiration produces approximately 17-times the number of moles of ATP per glucose respired, as do anaerobic systems. Such high productivity is essential for neurotransmission and computation: the energy cost of transferring one Bit across a synapse and along an axon requires the hydrolysis of 10^4 - 10^7 ATP molecules (Laughlin, van Steveninck and Anderson, 1998). Therefore, one can safely assume that sophisticated computation is not going to be the parlance of anaerobes. To that end, while not examined directly, there are no instances of (evident) intelligent behaviour in terrestrial life prior to the NOE. Indeed, with the exception of cephalopods, there is no evidence of intelligent behaviour in any ectothermic species – and cephalopods have their internal temperature buffered to relatively high (20-30ºC) ambient levels by surrounding seawater. Abstract behaviour is confined to endotherms with mass transport: these processes evolved after the NOE (Ediacaran onwards), when simple diffusion became metabolically-limiting.

The interesting point is that when probabilities are considered as a fraction per hundred million years, abstract behaviour has a reasonable probability in multicellular eukaryotes. That is to say it’s not the kind of vanishingly small percentage one might expect. Likewise, of the analyses presented in this work, the only one that really stands out is the evolution of Apes from pre-existing primate lineages. Given that Primates exhibit extensive tool-use and evidence of “cultures” the relatively long time Apes took to emerge as the Abstract clade implies that their emergence was not “guaranteed” in the interval prior to our observation.

Do these arguments address the probability of intelligent, abstract life in the cosmos? Simply stated, no. None of the arguments presented here favour the emergence of Abstraction. We have only addressed probabilistic arguments for the emergence of endothermy and abstraction given otherwise suitable conditions. The emergence of mammals was largely congruent with the evolution of endothermy in the Permian (Araújo; et al., 2022). The subsequent emergence of Primates was less than 150 million years later, but their diversification was almost certainly dependent on the extinction of the Dinosauria. Here, one could argue that since Dinosaur lineages emerged at approximately the same time as mammalian lineages, a subtle change in circumstances might have led to the earlier emergence of Primates if Dinosaurs were unable to evolve.

In that sense, observation is often more powerful than statistical analysis. We could analyse the data in completely different ways and come up with probable arguments that are in fact completely false. For example, approaching the data, blindly, we could suggest that eukaryogenesis is required for oxygenation to NOE levels. That would be to suggest, while oxygenation (through the evolution of cyanobacteria) has a moderate probability, oxygenation to NOE levels (0.5 PAL) requires eukaryotic life. This argument would propose that since animals and fungi emerged at the start of the NOE (Och and Shields-Zhou, 2012), the subsequent diversification of these eukaryotes caused the completion of the NOE at 550 MYa – which is (almost certainly) false. What we are pointing out, if you wish to use Bayesian analysis, that (NOE) oxygenation is dependent on eukaryogenesis, is not an unreasonable conclusion.

However, while arguing that diversification of eukaryotes caused the NOE is almost certainly putting a large cart before a small horse, it does underscore the limitations of arguments based on probability. We would argue, instead, that when utilizing powerful approaches, such as Bayesian probability, one should be careful of which priors we choose. In itself, that statement is nothing new, but as such the sentiment is not reflected in much of the published analysis. Snyder-Beattie et al (2021) conclude that intelligent life must be inherently rare in the cosmos, based on the kinds of "summative probabilities" we propose are inherently flawed. Critically, the authors presented a number of peculiar and incorrect biological statements. These include, comments on the protein folding "*Given this, it would take* 10^{200} *times the present age of the universe for a particular folding to occur, even assuming a sampling rate of 1 trillion conformational states per molecule per second and a volume of concentrated protein solution the size of Earth's oceans*", which makes no sense. That implies that proteins simply cannot fold – in which case we would not exist; rather than we don't understand the process, fully. Likewise, the statement, "*The transition to eukaryotic life also involves similar* "*chicken and egg" difficulties, with uncertainty on how an archaeon acquired a proto-mitochondrion, since endocytosis requires complex machinery only present in eukaryotes,*" ignores the published information of the Asgard superphylum and the presence of genes encoding said proteins in their genomes (Zaremba-Niedzwiedzka et al., 2017; Spang et al., 2018; Imachi et al., 2020; Liu et al., 2021). Critically, these statements were then used to validate the selection of very low probabilities of particular events.

By contrast, we take the opposite approach: we relate observed frequencies of biological processes to their environmental circumstances to determine their likelihood. That is to say, while Bayesian analysis of the probabilities of such processes is perfectly reasonable, what you get at the end of the analysis is not necessarily anything more valid than you could have found through observation.

Conclusions

We cannot conclude that intelligent life is probable or improbable in the universe; nor that endothermy is probable or improbable, based on terrestrial observation. However, we can make suitable conclusions based on the dependence of trait evolution and the terrestrial environment.

These conclusions may be summarized as follows:

- NOE Model: Bayesian modelling marginally supports the requirement for oxygenation to PAL in the evolution of endothermy over other models (below);
- Observation and knowledge of the underlying biology allows us to conclude that oxygenation to NOE levels and higher is required for endothermy and abstraction;
- GOE Model: there is less support for oxygenation to pre-NOE levels in the development of endothermy, compared to the NOE-Endothermy model;
- OoL Endothermy Model: this model has the lowest support among the three endothermy models, suggesting that having more time to develop endothermy is not relevant to its development;
- Observation and knowledge of the underlying biology of endothermy and abstract behaviour says that the GOE and the OoL models are invalid;
- Abstraction models: perhaps unsurprisingly, the time taken to develop abstraction was by far the largest part of the period in which it could have formed. T_{emerge} is very much at the eleventh-hour so none of these models support a preference for oxygenation or otherwise. In the employed models, $T_{required}$ can never be significantly different from T_{emerge}. Therefore, all these models show is that abstract behaviours are inherently low probability per year, but not unreasonably so over one hundred million year-intervals. None of the models can determine whether the process is inherently unlikely, *per se*, only that it had a low probability on Earth, with that probability increasing after oxygenation to NOE levels;
- Primate Clade: of the models linked to abstraction, the Primate Clade model is the most interesting. The model does not address abstraction, directly, rather the probability of the emergence of Apes from other Primate groups. This model suggests that the evolution of Apes was less likely than one might suppose, given its emergence time was later than the time in which this evolution could have occurred.

In this work, we show that the use of suitable prior information and posterior models does not overtly predict the likelihood of endothermy or abstract behaviour arising on the Earth. However, observation alone suggests that endothermy is highly unlikely in an environment with low partial pressures of oxygen; a conclusion one could reach merely be investigating the biological requirements for the process (Caitlin, 2005).

Likewise, the probability of emergence of abstract behaviours is low, but we already knew this given observations of terrestrial life. The most useful outcome is then, that given the vast number of species that have evolved on Earth since the inception of life, the probability of an intelligent species arising is non-trivial per hundred million years. However, for biological reasons, this is only likely to the true on planets which have atmospheres rich in molecular oxygen. Moreover, since we already know that a warm internal temperature is essential for abstract behaviour on Earth, those planets on which such behaviours will arise will have constitutively warm environments. There is no evidence to support the emergence of abstract behaviours in any species prior to the NOE. Again, we can conclude this without recourse to statistical analysis: knowledge of biology will suffice.

Consequently, we can conclude that, with regard to the evolution of endothermy and abstraction, the time to oxygenation (Caitling et al., 2005) is the critical feature of any potentially-habitable planet. Planetary mass and composition will determine how quickly the surface environment becomes oxidising. Too soon and biomolecules may not organise into something we regard as living. Too late and the planet may become uninhabitable through stellar evolution.

Similarly, we may suppose, but have no evidence to support the conjecture, that in the absence of endothermy, abstract aliens could evolve on synchronously-rotating worlds with suitable insolation (Stevenson and Wallace, 2021). Likewise, while abstract behaviours could (in principle) arise in aquatic or marine environments (Lingam, Balbi and Mahajan, 2023), organisms would be unable to develop technology because they could not extract metals and develop technologies dependent upon them; something referred to as The Spongebob Effect (Stevenson, 2019). From an ecological perspective, Lingam, Balbi and Mahajan evaluating the number and suitability of niches. In the case of life on synchronously-rotating planets or in the oceans, the environment buffers the temperature of the organism. Buffering facilitates the high levels of metabolism required for abstraction. Figure three illustrates (some of) the dependences of biological events and why assessing summative probabilities of the kind frequently published is inappropriate.

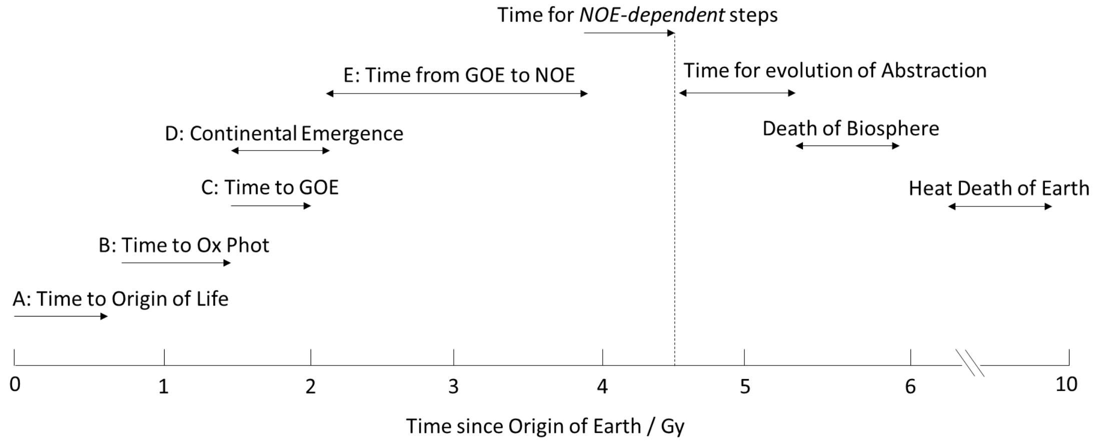

Fig. 3: Some of the variables affecting the evolution of oxygen-dependent endotherms that query life in the universe. Dependence on oxygen requires that a variety of other independent variables are met in the time interval from the origin of the Earth, or other planet. Variable A – the origin of life is likely dependent on the nature of the host planet and the planet's astrochemical environment. Variable B is likely dependent on a variety of subordinate biological variables, such as mutation rate, the nature of the genetic material and environmental chemistry and selection. Variable C likely depends on variables B and D, which provide the genetic material and selection pressures, as well as suitable habitats for oxygenic photosynthetic organisms. Variable D will be dependent on planetary mass and composition as well as stellar irradiation. Finally, variable E is likely dependent on planetary chemistry and mass, affecting how quickly the surface becomes oxidized. Therefore, it is inappropriate to determine the probability of abstract organisms arising, based on the terrestrial timeline.

Consider this: an alien considering the probability of finding intelligent life on Earth might want to include the following variables: planetary composition and mantle degassing (Unterborn et al., 2021); the depth of oceans (Cowan and Abbot, 2011); the rate of formation and emergence of continents (Korenaga, 2021); the landscape diversity of our planet's surface (Walz, 2011; Stevenson and Wallace, 2021); the nature of our genetic material; the presence and partial pressure of oxygen (Caitlin et al., 2005); and whether the activity of transposable elements made their central nervous systems conducive to integrating large and diverse volumes of information (Jönsson et al., 2019).

Summating the probability of all of these variables might sound like something that would cause one to throw in the towel: abstract life must be very rare in the universe. Yet that argument negates the simple observation of our vast biosphere. With over 16 million species and population sizes measured in millions to trillions, those probabilities melt away and the seemingly impossible is not. Perhaps, we should consider the number of suitable niches a planet hosts, as a better measure of whether abstract life is inherently probable.

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