

On the origin and evolution of life in the Galaxy

Michael McCabe and Holly Lucas

*Department of Mathematics, University of Portsmouth, Lion Terrace, Portsmouth, Hants P041 3HF, UK
e-mail: michael.mccabe@port.ac.uk*

Abstract: A simple stochastic model for evolution, based upon the need to pass a sequence of n critical steps is applied to both terrestrial and extraterrestrial origins of life. In the former case, the time at which humans have emerged during the habitable period of Earth suggests a value of $n=4$. Progressively adding earlier evolutionary transitions gives an optimum fit when $n=5$, implying either that their initial transitions are not critical or that habitability began around 6 Ga ago. The origin of life on Mars or elsewhere within the Solar System is excluded by the latter case and the simple anthropic argument is that extraterrestrial life is scarce in the Universe because it does not have time to evolve. Alternatively, the timescale can be extended if the migration of basic progenotic material to Earth is possible. If extra transitions are included in the model to allow for Earth migration, then the start of habitability needs to be even earlier than 6 Ga ago. Our present understanding of Galactic habitability and dynamics does not exclude this possibility. We conclude that Galactic punctuated equilibrium, proposed as a way round the anthropic problem, is not the only way of making life more common in the Galaxy.

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Introduction

It is usually accepted that our atomic origins are extraterrestrial and that physics is universal. The chemical elements required for life were not created on Earth, but through nucleosynthesis during the Big Bang (H, He, Li), inside the cores of stars (He, C, N, O ...) and within supernovae (Ca, P, S, Na, K, Cl ...). The origin of terrestrial molecules required for life, notably water, is less certain, but comets and meteorites impacting the young Earth must have made a significant contribution and extraterrestrial origins are certainly not excluded. Water ice and organic material has recently been detected on a main belt asteroid (Rivkin & Emery 2010) increasing their possible role in delivering molecules required for life. Chemistry is regarded as universal and our molecular origins are accepted as being both terrestrial and extraterrestrial. Biology is not generally regarded as universal and the question of whether our biological origins are terrestrial or extraterrestrial is highly controversial (Table 1).

Standard evolutionary biology adopts a time on Earth between 3.5 and 4 Ga ago as its starting point with deep ocean hydrothermal vents as one possible location (Martin *et al.* 2008) and recognizes that the rapid emergence of life is a puzzle. Maynard Smith & Szathmary (1995) have suggested eight steps on Earth leading from replicating molecules to mankind, of which seven are regarded as critical. Table 1

includes the critical transitions (1) to (7), but omits the faster transition expected from solitary individuals to colonies between (6) and (7).

A simple stochastic model, first proposed by Carter (1983) and discussed by Barrow & Tipler (1986), Hanson (1998) and Flambaum (2003), assumes that evolution is governed by a series of critical transitions or bottlenecks, which must be passed to advance from basic molecules to simple, complex and then intelligent life. The anthropic model allowed the derivation of a probability density function and expectation time for the final step, based upon the habitable lifetime of the planet. Watson (2008) has further analysed the model to derive probability density functions and expectation times for every step. He identifies seven critical transitions in biological evolution from amongst the eight proposed by Maynard Smith & Szathmary (1995) and compares their probabilities with their estimated times of occurrence. He also discusses geochemical transitions relevant to biology, although they do not form part of the strictly biological evolutionary sequence based upon information.

Critical step model for evolution

The critical step model assumes that there is an ordered sequence of transitions that govern the pace of evolution. Any intermediate steps or stages are assumed to occur rapidly without increasing the time between steps. The critical steps

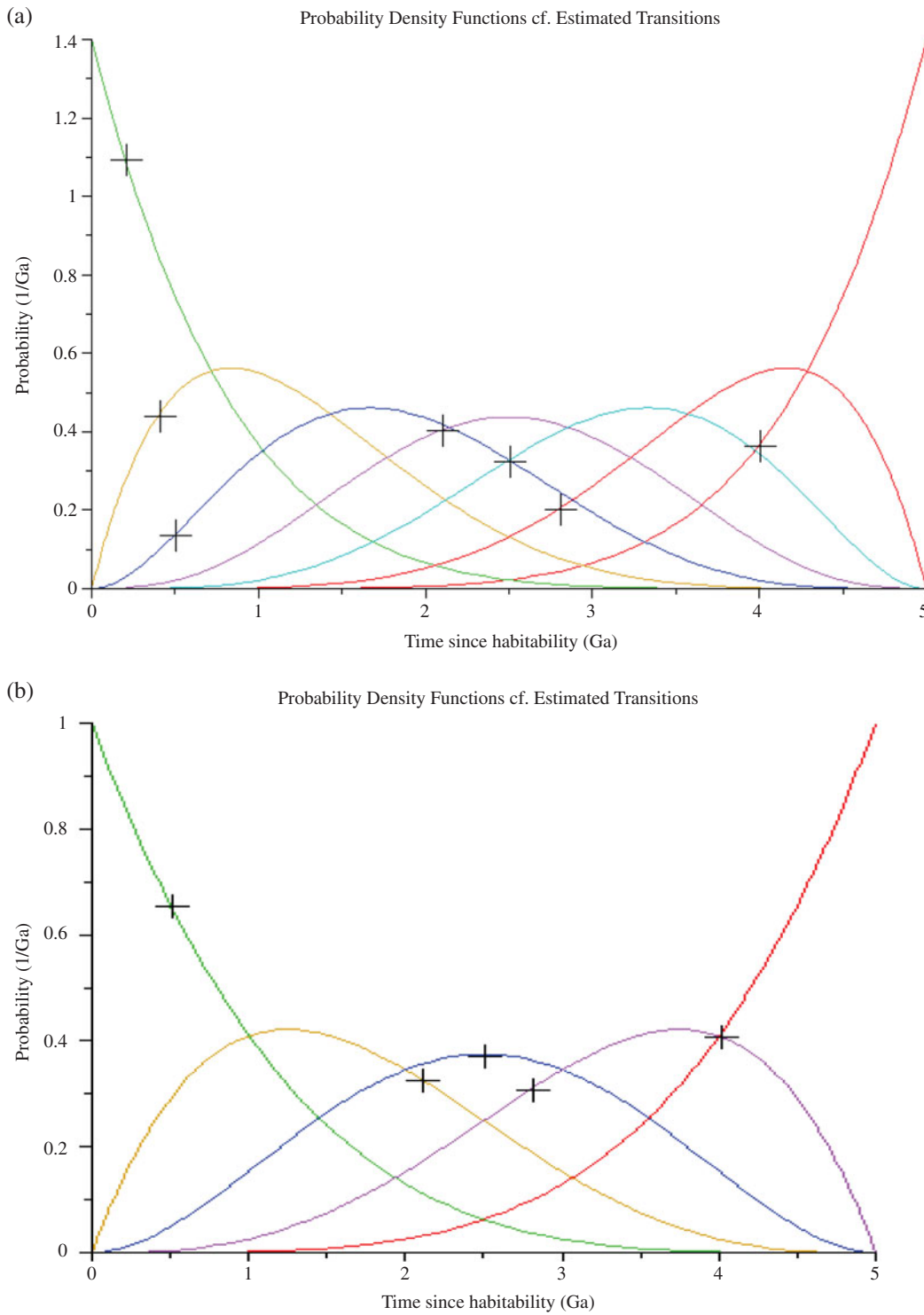


Fig. 1. Critical transition models for (a) seven steps and (b) five steps compared with estimated transition times (start of habitability = 4 Ga ago).

are assumed to occur stochastically with uniform, small, but unequal probabilities, $\lambda_1 \dots \lambda_n$, where $\lambda_n \ll 1/t_h$, where t_h is the habitable lifetime of the planet. One alternative would be a ‘long, slow fuse’ model, which allows for a much larger sequence of more likely events.

The probability density for the m th critical step in an n critical step model is

$$P_{m/n}(t) = \frac{n!}{(n-m)!(m-1)!} \frac{t^{m-1}(t_h-t)^{n-m}}{t_h^n} \tag{1}$$

Table 1. *Extraterrestrial origins and transitions required for human life to emerge*

Entity	Modern examples	ET origin	Transition
Small atoms	H to He	Big Bang	Nucleosynthesis
Medium atoms	Li to Fe	Stellar cores	Nucleosynthesis
Large atoms	Above Fe	Supernovae	Nucleosynthesis
Smaller molecules	H ₂ O	ISM, comets	Chemical reaction
Larger molecules	Glycine	ISM, meteorites	Chemical reaction
Replicating molecules	Lipids	Comets/meteorites	Chemical reaction
Protocells	Bilayer vesicles	Least unlikely	Self organization (1)
Chromosomes	Retrovirus (RNA)	Less unlikely	Synthesis (2)
Prokaryotes	Bacteria	Unlikely	RNA to DNA (3)
Eukaryotes	Algae	More unlikely	Endosymbiosis (4)
Protists	Protozoa	Most unlikely	Asexual to sexual (5)
Animals/plants/fungi	Primates	Science fiction	Cell differentiation (6)
Humans	Authors MM/HL	Science fiction	Language (7)

RNA: ribonucleic acid; ISM: interstellar medium; DNA: deoxyribonucleic acid.

Table 2. *Probability density functions for one- to five-step models (habitability lifetime $t_h = 5$ Ga)*

$P_{m/n}(t)$	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$
$n=1$	$\frac{1}{5}$				
$n=2$	$\frac{2}{5} - \frac{2}{25}t$	$\frac{2}{25}t$			
$n=3$	$\frac{3}{125}(5-t)^2$	$\frac{6}{125}t(5-t)$	$\frac{3}{125}t^2$		
$n=4$	$\frac{4}{625}(5-t)^3$	$\frac{12}{625}t(5-t)^2$	$\frac{12}{625}t^2(5-t)$	$\frac{4}{625}t^3$	
$n=5$	$\frac{1}{625}(5-t)^4$	$\frac{4}{625}t(5-t)^3$	$\frac{6}{625}t^2(5-t)^2$	$\frac{4}{625}t^3(5-t)$	$\frac{1}{625}t^4$

The expectation time for the m th critical step in an n critical step model is

$$\langle t_{m/n} \rangle = \frac{m}{n+1} t_n, \tag{2}$$

i.e. the spacing of the steps will therefore tend to be even throughout the habitability period, although they will be subject to statistical variation.

Watson (2008) adopted 4 Ga ago as the start of habitability, corresponding roughly to the period of late, heavy bombardment. The end of habitability is taken as 1 Ga in the future, corresponding to the time when solar luminosity and atmospheric models predict an extreme temperature rise resulting from faster weathering of rocks to carbonates and subsequent CO₂ loss. The probability density functions for the n -step models with $n=1,2, \dots, 5$ are the polynomials shown in Table 2.

The fit between the probability density distributions in the seven-step model and the estimated times at which the critical steps actually occurred is poor. The main cause of the discrepancy is that prokaryotic life emerged relatively soon after habitability. The first three steps are much more closely spaced than the subsequent steps, in disagreement with the expectation of closer spacing predicted by the model. Watson (2008) shows that the fit can be significantly improved by

Table 3. *Expectation time for transitions, $\langle t_{m/n} \rangle$ in Ga (habitability lifetime $t_h = 5$ Ga)*

$\langle t_{m/n} \rangle$	$m=1$	$m=2$	$m=3$	$m=4$	$m=5$
$n=1$	5/2				
$n=2$	5/3	10/3			
$n=3$	5/4	10/4	15/4		
$n=4$	1	2	3	4	
$n=5$	5/6	10/6	15/6	20/6	25/6

assuming that prokaryotic life only required a single step in a five-step model.

Considering the final transition alone, the emergence of humans after 4 Ga of a 5 Ga habitable lifetime on Earth implies that the n th out of n transitions occurred after 4 Ga. Table 3 shows the expectation times derived from Eq. (2) and indicates that this is most likely for $n=4$, since $m=n=4$ gives $\langle t_{4/4} \rangle = 4$ Ga. An alternative to a single step leading to prokaryotes is the suggestion that the timescale for evolution might be extended back by starting evolution earlier (Carter 2008; Watson 2008). Evidence of water on Earth 4.3 Ga (Valley *et al.* 2002) ago could signify the start of habitability.

Table 4. *Astrobiological timings*

Time in past (Ga)	Time since habitability on Earth (Ga)	Critical event/transition	Type
13.7		Big Bang	C
13.7–		Nucleosynthesis of H/He after ~100s	C
13.7–		Atoms formed after 0.3 My (CMBR)	C
13.6		First stars expected	C
13.2 ¹		First (halo) stars in Galaxy observed	A C
[13.5] 8.5 [3.5] ²		Existence of Galactic Habitable Zone	A
[6.5] 8.3 [11.1] ³		Galactic thin disc formed	A
4.57		Formation of Sun	A E
4.55		Formation of Earth	E
[4.4] 4.3⁴		Liquid water on Earth	E
[4.1] 4.0 [3.8] ⁵	0.0	Late heavy bombardment (Earth habitability)	L
	0.2	Proto-cells (molecules in compartments)	B (1)
	0.4	Chromosomes (RNA)	B (2)
[3.85] 3.5–3.0 [2.6]	0.5	Emergence of prokaryotes (life)	B (3)
[3.2] 2.8–2.6		Oxygen photosynthesis	E
2.2–2.0		Atmosphere becomes oxidizing	E
[2.7] 1.9–1.2 [0.8]	2.1	Prokaryotes to eukaryotes	B (4)
	2.5	Asexual to sexual populations	B (5)
[1.9] 1.2–0.6	2.8	Protists to animals/plants/fungi (cell differentiation)	B (6)
0.55		Microscopic to macroscopic life (Cambrian)	E
0.0001–0.0002	4.0	Primates to man	B (7)
(1.0) in future	5.0	Predicted CO ₂ loss (inhabitability)	B

C: Cosmology; A: Astronomy/Galaxy; E: Earth Science/Geology; L: Lunar Science; B: Biological Information; (n) Critical Evolutionary Transitions [extreme estimates] **best estimates**; CMBR: cosmic microwave background radiation; RNA: ribonucleic acid. (1) to (7) represent the critical evolutionary transitions (Maynard Smith and Szathmary 1995; Watson 2008).

¹Frebel (2007); ²See preceding text; ³Del Pelosa (2005); ⁴Valley *et al.* (2002); ⁵Cohen *et al.* (2000).

Meteorites from Mars suggest that life might have originated there and migrated to Earth (Treman *et al.* 2000). If the origin of life occurred elsewhere in the Solar System, it must have been within the past 4.6 Ga. This extension of 0.6 Ga to the time over which life evolved helps to resolve the discrepancy between the model and the estimated transition times but it does not alter the conclusion that the optimum number of critical transitions is less than seven. Carter (2008) suggests an optimum of six transitions if early evolution began on Mars, but stops short of proposing any earlier steps towards life.

Origins within our Galaxy

Our Galaxy appears to be almost as old as the Universe itself, since the oldest known halo star is estimated at 13.2 Ga old (Frebel 2007). This ancient star is metal poor and lacking in the heavy elements needed for planetary formation. The oldest brown dwarfs, intermediates between stars and planets, are estimated to be 10 Ga old (Schilbach *et al.* 2009). The Galactic thin disc, where conditions are more favourable for life, is estimated to be between 6.5 and 11.1 Ga old (Del Peloso 2005).

The concept of a Galactic Habitable Zone (GHZ), a region within the Galaxy favourable for the development of life, was first introduced by Gonzalez (2001) and expanded upon in Gonzalez (2005). Lineweaver *et al.* (2004) identified the present GHZ as an annular region between 7 and 9 kpc, which has moved outwards from the Galactic centre and is composed of stars that formed between 4 and 8 Ga ago. Their

model of Galactic evolution and habitability considered the need for adequate star formation, heavy elements for planets to form and time for life to evolve, together with an absence of supernovae. Prantzos (2008) concludes that that habitability is far less clear-cut, because the factors involved are poorly understood. In particular, the effect of heavy metals on planet formation, hot Jupiters on terrestrial planet survival and supernovae radiation on life are extremely uncertain. His own model predicts a narrow annulus for Galactic habitability starting at 3 kpc around 13 Ga ago, which then expands as it moves outwards, until it eventually encompasses the whole Galaxy within the lifetime of the Solar System and has a peak probability of Earth-like planets with life approaching 0.1 at 10 kpc from the Galactic centre today. More recent work (Mattson 2009) has modelled the build-up of carbon in the Galaxy, predicting a peak at ~5.5 kpc around 8 Ga ago and at the solar distance ~9 kpc around 5 Ga ago, close to the time when Earth formed.

Some of the necessary ingredients and conditions for life may have existed within the Galaxy, albeit at different locations, for many billions of years before the formation of Earth. Based upon current understanding, it is reasonable to consider the possibility of life originating elsewhere in the Galaxy before it began on Earth. Proponents of the Rare Earth Hypothesis (Ward & Brownlee 2000) may place many further conditions upon the emergence of complex life, but we are concerned with the earliest, simple stages.

Table 4 summarizes some of the timings for key events and transitions through the history of the Universe and Earth. Although many may be regarded as controversial, they are

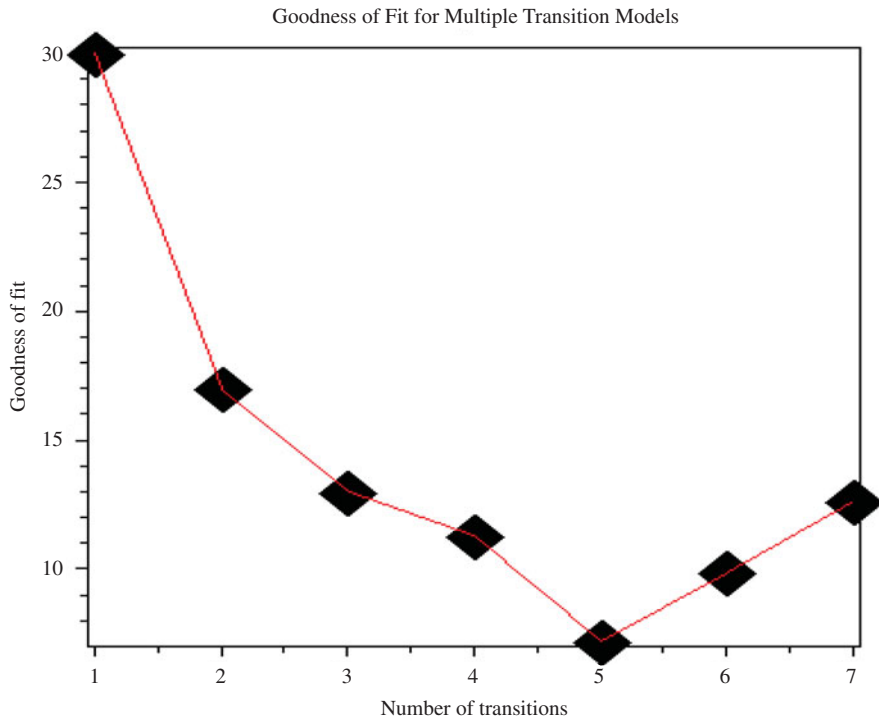


Fig. 2. Optimization of the number of transitions in the critical step model.

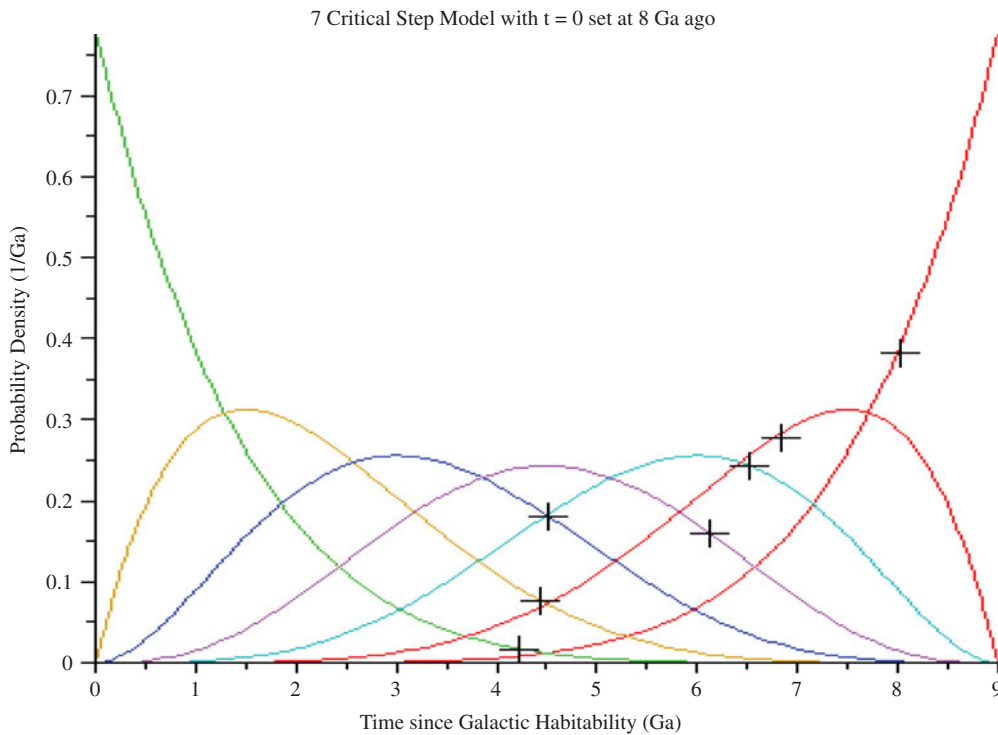


Fig. 3. Critical transition models for seven steps compared with estimated transition times (start of habitability = 8 Ga ago).

used as best estimates in subsequent calculations. The origin of life in the Galaxy, or more specifically the start of habitability, is taken to have occurred 8.5 ± 5 Ga ago, where the central value of 8.5 Ga reflects the work of Lineweaver *et al.*

(2004), Prantzos (2008) and Mattson (2009) and the range of uncertainty allows for the most extreme conceivable values from the first stars in the Universe to the origin of life on Earth.

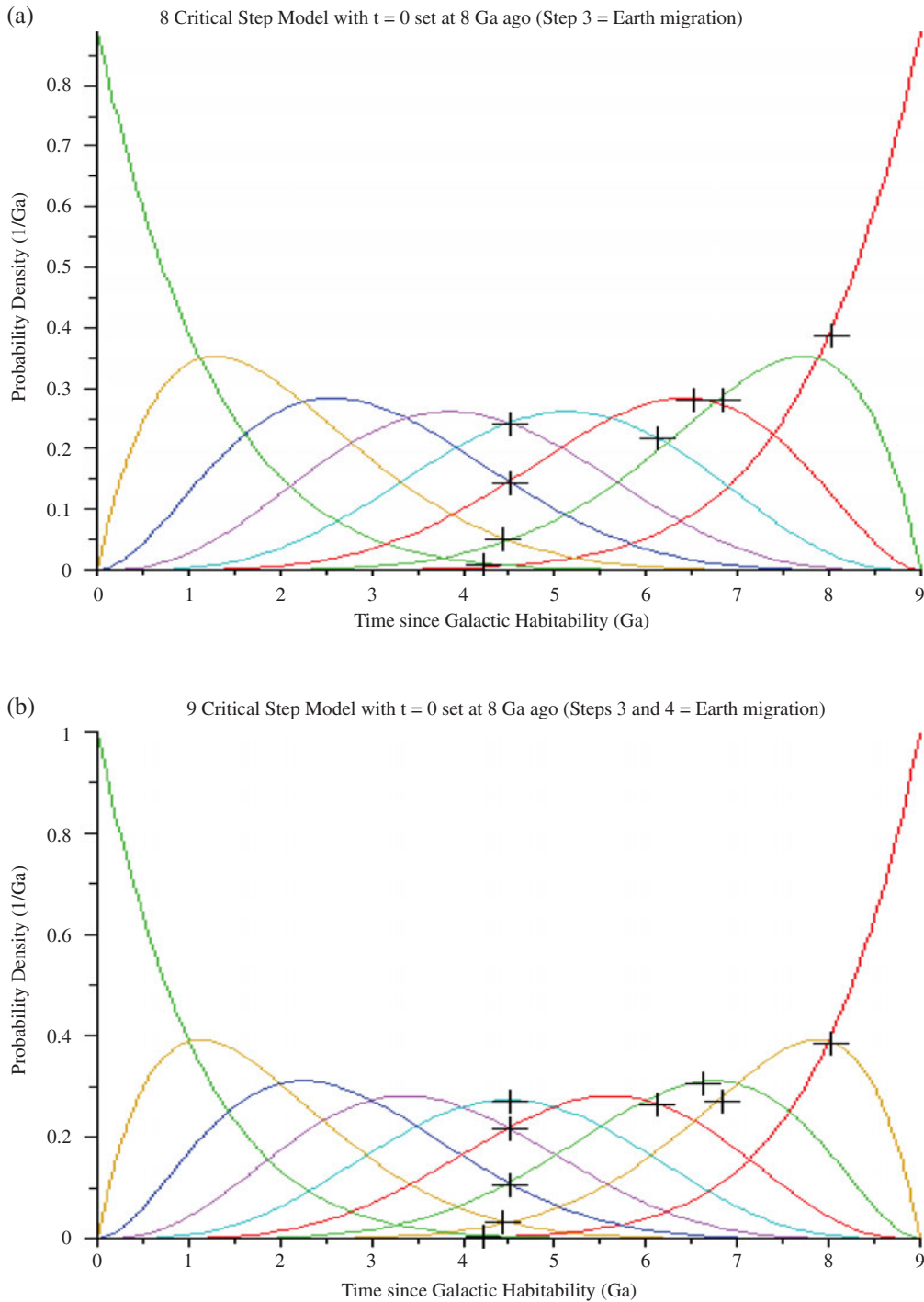


Fig. 4. Critical transition models for (a) eight steps and (b) nine steps compared with estimated transition times (start of habitability = 8 Ga ago).

Extending the timescale in the critical transition model

Calculations of the critical transition model have been carried out using the Maple computer algebra system. Maple was used to plot and integrate the probability density distributions defined by Eq. (1) and hence determine the probability that a transition would occur before its estimated time. Since

the distributions are polynomial functions, no numerical techniques have been required to perform the integrations. Figure 1 shows the probability density distributions for the seven-step and five-step models with the best estimates for the actual transition times marked on each curve by a cross. For the intermediate curves a cross towards the peak of the distribution suggests a good fit. The integrated area below the probability density curve to the left of the cross provides a

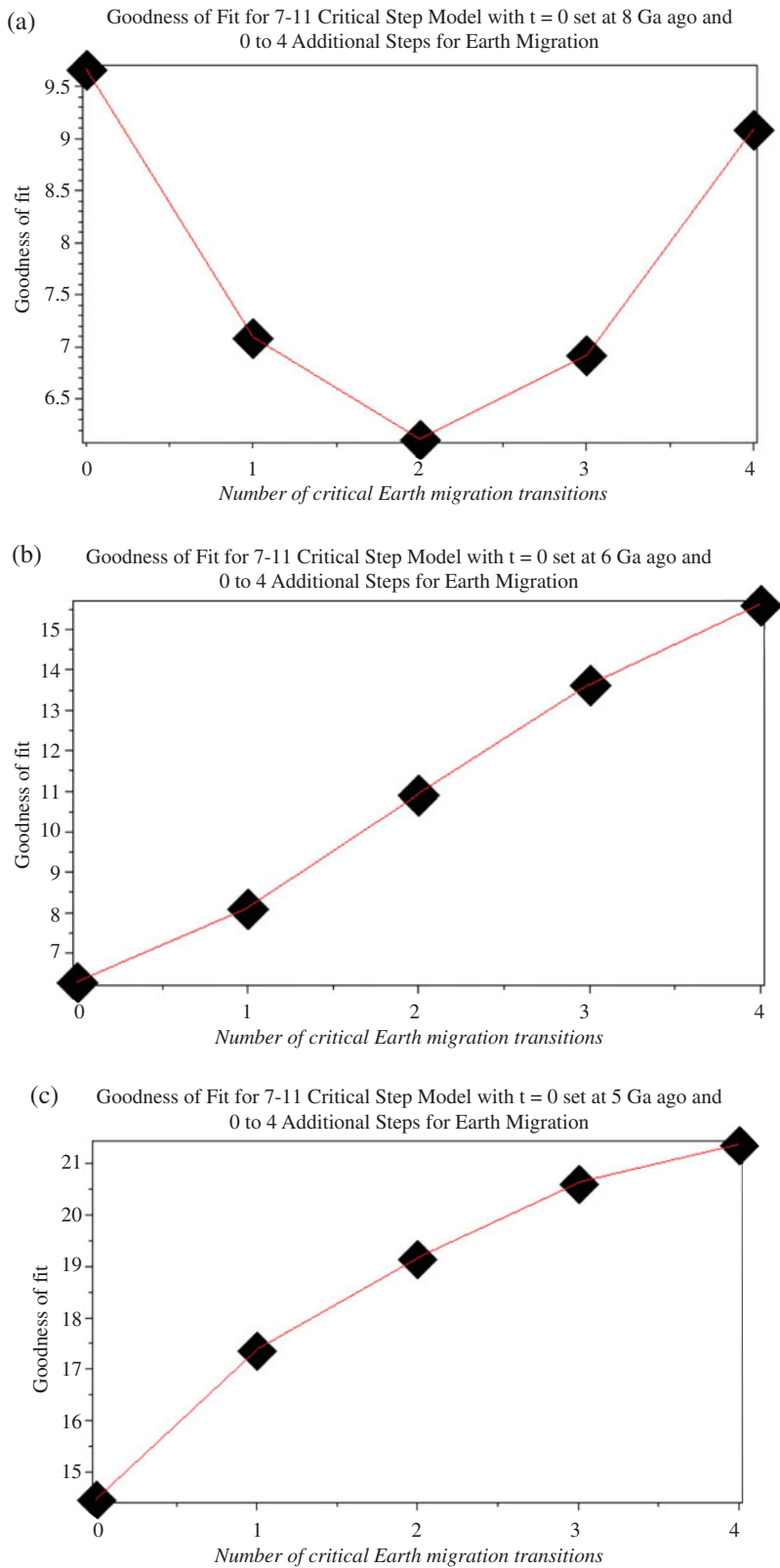


Fig. 5. Model dependence upon the number of earth migration transitions of habitability at (a) 8 Ga. (b) 6 Ga. and (c) 5 Ga.

more precise measure for establishing the goodness of fit. The adoption of the values in Table 4, which differ within reasonable limits from those adopted by Watson (2008), yields different probabilities that a step occurred at or before

the observed time, but confirms his conclusions. A seven-step model fits poorly (probabilities of 25%, 10%, 3%, 33%, 23%, 11% and 21%, respectively), where values closer to 50% imply a more acceptable model. While a five-step

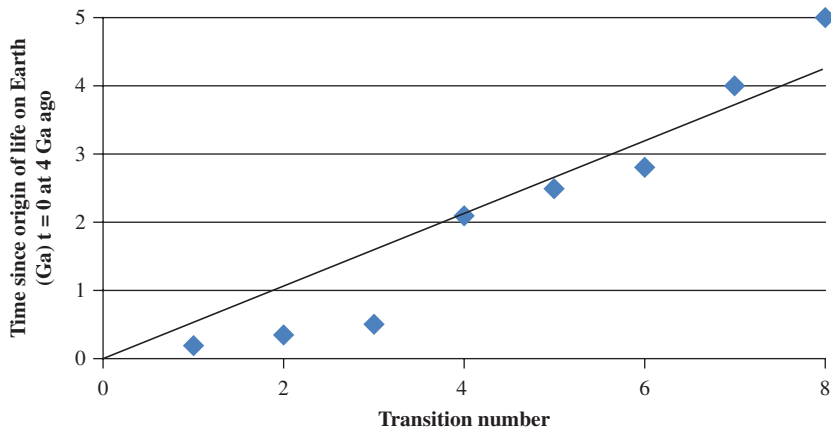


Fig. 6. The enforcement of critical spacing in a seven-step evolutionary model.

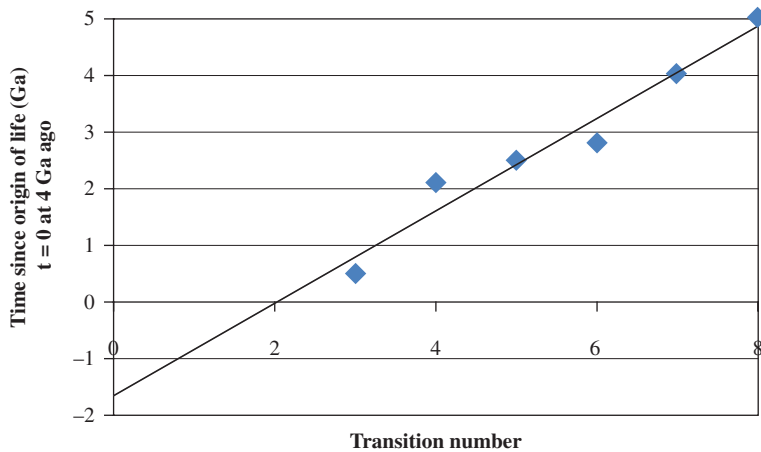


Fig. 7. The enforcement of critical spacing in a five-step evolutionary model.

model fits much better (probabilities of 41%, 70%, 50%, 27% and 33%, respectively). The essential distinguishing factor between the models is the rapid emergence of life, which is allowed for in the five-step model by combining the first three transitions of the seven-step into one.

An alternative explanation is that the earlier transitions have occurred elsewhere in the Solar System or beyond. By considering the goodness of fit,

$$F = \frac{\sum_{i=1}^n \sqrt{(P_i - 50)^2}}{n}, \quad (3)$$

where P_i is the probability of the i th step occurring before its actual estimated time (%) and n is the total number of steps, we have examined how the model performs when different numbers of steps and earlier transitions on extraterrestrial locations are allowed. If all the probabilities were 50%, giving $F=0$, the fit would be regarded as ideal. Figure 2 shows that F is minimized for $n=5$ and that the five-step model does indeed fit the data best for purely Earth-based evolution.

If these earlier transitions have taken place ‘off-site’ they can be re-incorporated into the model by extending the timescale. Given that this needs to be longer than the age of

the Solar System to make any significant difference to the model, a time of 8 Ga ago, corresponding to the estimated age of the thin disc and start of Galactic habitability according to the Lineweaver *et al.* (2004) model, is adopted. The probability density distributions and estimated transition times are shown in Figure 3, where the probabilities for the five terrestrial transitions become 77%, 84%, 70%, 46% and 44%. The first two extraterrestrial transitions need to be excluded from the goodness of fit, since there is no sensible estimate for their times.

During the habitability period, the first two transitions would have taken place on an extraterrestrial location and the final five on Earth, where we assume that the migration to Earth is not a critical step. However, we can consider the consequences if the physical transfer to Earth is regarded as a critical step, resulting from an unlikely event over a long timescale. For example, a randomly occurring collision of a suitable comet or meteorite with Earth might be necessary. Alternatively, one collision or event might be required to initiate a transfer from one location and another to complete it by collision with Earth. Lithopanspermia, an idea first suggested by Lord Kelvin in 1871, has been well discussed in subsequent years. Some calculations have suggested that

interstellar panspermia is unlikely (Melosh 2003), but viable mechanisms have subsequently been suggested (Napier 2004; Wallis & Wickramasinghe 2004). The effect of adding one or two critical transitions to the model is shown in Fig. 4.

The best fit is obtained with the nine-step model, i.e. by having two Earth migration transitions (Fig. 5(a)). By reducing the start of habitability to 6 Ga ago, a similar goodness of fit can be achieved without any Earth migration transitions (Fig. 5(b)). Any further reduction in the start of habitability towards the age of the Solar System (Mars) decreases the goodness of fit (Fig. 5(c)).

Discussion

The equal spacing property of the critical transition model can be used to explain what is happening. If transitions 1–7 are equally spaced upon the x -axis, together with 0 = start of Earth habitability and 8 = end of Earth habitability, and the estimated times from Table 4 are plotted, then a best fit line through the origin can be used for comparison (Fig. 6). The fit is poor because of the rapid early transitions.

If the first two transitions are removed and the best fit line is no longer required to pass through the origin, the y -intercept of -1.6 Ga gives an estimate for the origin of life, i.e. around 5.6 Ga ago (Fig. 7). This corresponds to the value of 6 Ga identified for the start of habitability when there were no Earth migration transitions. If additional transitions are introduced for Earth migration, then the y -intercept will decrease and life emerges further back in the past.

Lépine *et al.* (2003) have shown that resonance with the spiral gravitation field can cause stars to move radially through the Galaxy over distances of 2–3 kpc in significantly less than 1 Ga. Roškar *et al.* (2008) have modelled this stellar migration and considered its astrophysical implications. A serious possibility is that it could account for the migration of simple life from closer to the Galactic centre. Haywood (2009) has analysed solar neighbourhood stars, showing that around 50% have come from elsewhere, primarily by migration from the inner disc, where Galactic habitability was greater at an earlier time. Not only does the GHZ move radially outwards from the Galactic centre according to most models (Lineweaver *et al.* 2004; Prantzos 2008), but so do a significant number of stars. Thus from both a dynamic and chemical perspective, it may be possible for simple life to migrate from the inner disc of the Galaxy on realistic timescales and hence be included within the critical transition model. Wesson (2010) argues that, despite viable mechanisms for distributing organic material throughout the Galaxy, life could not survive the UV and cosmic ray bombardment. He does though suggest that necropanspermia, the transfer of information via damaged biological molecules, is feasible.

Conclusions

A simple stochastic model for evolution, based upon the need to pass a sequence of n critical steps (Carter 1983; Watson

2008), has been applied to both terrestrial and extraterrestrial origins of life. In the former case, the time at which humans have emerged during the habitable period of Earth suggests a value of $n=4$. Progressively adding earlier evolutionary transitions (Maynard Smith & Szathmary 1995) gives an optimum fit when $n=5$, implying either that the initial transitions are not critical or that habitability began around 6 Ga ago. The origin of life on Mars or elsewhere within the Solar System is excluded by the latter case. Carter (2008), in reviewing his original work, argues for a five-step model for terrestrial evolution and a six-step model if Mars evolution is included. If extra transitions are included to allow for Earth migration by simple life, the start of habitability needs to be at an even earlier time. Our present understanding of Galactic habitability and dynamics does not exclude this possibility. Each additional migration transition pushes back the start of habitability by around 1 Ga.

The Drake equation has long been used as a touchstone for astrobiology. Its mix of astrophysical, biological and social science, with an increasing level of uncertainty, continues to provoke discussion (Burchell 2006). The critical transition model addresses an issue for any Drake-type equation, e.g. the Rare Earth equation (Ward & Brownlee 2000). If any one of the factors is zero, then the result is zero. The critical transition model breaks down the crucial biological steps, typically only represented by one or two factors, and introduces time dependence. In particular, it provides a reasonable fit to the timescales for the emergence of life on Earth. Furthermore, if the possibility of life originating beyond Earth is considered, it can provide useful clues as to the time that life might have emerged.

Whether the assumptions of the model and the identification of the transitions are reasonable is open to debate (e.g. Cirkovic *et al.* 2009). For example, the likelihood of critical transitions could be governed by causal links between astrophysical and biological events.

Transitions might occur relatively quickly with a high probability if life emerges through stages of Galactic punctuated equilibrium separated by irregular catastrophic (catalytic?) events in the Galaxy such as gamma ray bursts or supernovae as suggested by Cirkovic *et al.* (2009). The Earth is certainly not a closed system, being exposed to electromagnetic radiation, neutrinos and cosmic rays from beyond the Solar System and material from within it. The extent to which the Earth is an open system and the degree of correlation between astrophysics and biology are key issues, which ‘grand’ astrobiological models can help to resolve. Critical transition models, incorporating both biological and astrophysical concepts, provide a standard against which other models can be judged.

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