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Five- or six-step scenario for evolution?

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Abstract: The prediction that (due to the limited amount of hydrogen available as fuel in the Sun) the future duration of our favourable terrestrial environment will be short (compared with the present age of the Earth) has been interpreted as evidence for a hard-step scenario. This means that some of the essential steps (such as the development of eukaryotes) in the evolution process leading to the ultimate emergence of intelligent life would have been hard, in the sense of being against the odds in the available time, so that they are unlikely to have been achieved in most of the earth-like planets that may one day be discovered in nearby extrasolar systems. It was originally estimated that only one or two of the essential evolutionary steps had to have been hard in this sense, but it has become apparent that this figure may need upward revision, because recent studies of climatic instability suggest that the possible future duration of our biologically favourable environment may be shorter than had been supposed, being only about 1 Gyr rather than 5 Gyr. On the basis of the statistical requirement of roughly equal spacing between hard steps, it is argued that the best fit with the fossil record is now obtainable by postulating the number of hard steps to be five, if our evolution was exclusively terrestrial, or six, if, as now seems very plausible, the first step occurred on Mars.

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1. Introduction

It is generally recognized that the Darwinian process leading to the evolution of what we recognize as intelligent life must have passed through a number of essential steps, starting of course with the origin – called biogenesis – of life itself in the form of self-reproducing organisms. Another obviously important step, at a much later stage, is what might be called combigenesis, meaning the origin of sexual recombination, whereby the reproduction of genes ceases to be simply amalgamated with reproduction of the host organisms, so that evolution (in large populations) can proceed much faster. What opinions differ about, however, is the extent to which such essential steps were easy, in the sense of being destined to occur automatically, given a favourable planetary environment. The aim of the present discussion is to clarify the problem of identifying which of the essential steps may have been hard in the sense Carter (1983) of depending on the fortuitous occurrence of some combination of random events that would automatically happen sooner or later if unlimited time were available, but that would be improbable within the time actually available.

According to the line of opinion that Davies (2003) has referred to as hypothesis B, the emergence of even the most primitive life would (due to the intricacy and complexity of biological mechanisms involved) have depended on transitions that were hard in this sense. According to the alternative hypothesis A, primitive life will emerge (and perhaps be detectable Leger *et al.* (1996) on extrasolar planets) by spontaneous generation or perhaps by panspermia wherever possible. However, holders of this latter opinion are still divided about what follows. According to what is classifiable as hypothesis A-minus, after the easy establishment of primitive life, one or several hard steps must be achieved before the possible emergence of intelligent life, which will thus be very rare, even where conditions are favourable. In contrast, according to the more extreme alternative opinion classifiable as hypothesis A-plus, not just primitive life, but even intelligent life, will occur (and perhaps be detectable Tarter (2001) by the SETI program) wherever possible.

It was pointed out a quarter of a century ago Carter (1983) that evidence against the last of these three alternatives, hypothesis A-plus (and thus against the likelihood of success for the SETI program), is provided by the astrophysical consideration that the possible future duration of the favourable terrestrial environment provided by our host star, the Sun, is comparatively limited. The underlying reason for this limitation is that the hydrogen still available for thermonuclear burning is sufficient for a time estimated to be only of the same order as the time that has already elapsed since the Earth was formed a little less that 5 Gyr ago. The severity of this already highly significant limitation has been reinforced by more recent work Caldiera & Kasting (1992) according to which – due to destabilization of the climate by the rise in stellar temperature in the later part of the hydrogen burning phase – the environmentally favourable period still available is reduced to the order of perhaps only 1 Gyr.

The narrowness of the margin by which we emerged on Earth so near the end of the time window of biological opportunity was puzzling on the basis of the traditional way of thinking about our Darwinian evolution just as a causal process within the limited framework of our own past planetary environment. However, it can be given a reasonable interpretation – as evidence for a hard-step scenario Carter (1983) – within the broader framework invoked by the anthropic principle, according to which we should think of ourselves as a randomly selected sample within the category of comparable intelligent observers at other places and other times in the history of the universe.

The defining feature of a hard-step scenario is that one or more of the essential steps (such as combigenesis) in the chain leading to the evolution of intelligent observers is hard in the sense (as recalled above) of being against the odds within the allowed time. (For example, with an ordinary dice, getting two successive sixes would be easy if hundreds of throws were allowed, but if there were time for only a dozen throws it would count as a hard step.) Hard-step scenarios can be compatible with opinions of the types listed above as hypothesis B or hypothesis A-minus, but evidently not with hypothesis A-plus. The purpose of the present article is to update the evaluation of the number of essential steps in our evolution that would have been hard in this sense, and to consider what those hard steps may have been, giving particular attention to the question of whether they could have included biogenesis itself, as hypothesis B would have it.

2. Two-step versions of the hard-step scenario

In simple hard-step models, according to the mathematical analysis recapitulated in the next section, the expected interval between the time of completion of the chain of hard steps and the end of the time available has the same magnitude as the expected time interval between the hard steps, of which the last is presumably identifiable as the development of the large brain needed for intelligent observation. On the basis of this equal spacing property, when the use of such a hard-step scenario was originally suggested, the supposition that the remaining available time interval is comparable to the age of the Earth implied Carter (1983) and Maddox (1984) that the total number of hard steps would only have been one or two. Of these, the other earlier one – if any – then seemed to be plausibly identifiable with biogenesis itself.

With respect to the equal spacing property, the identification of biogenesis as the first of just two hard steps would have made sense if (as was supposed when its name was chosen) the onset of the Proterozoic eon – when the age of the Earth was a little over 2 Gyr – really had been the time of biogenesis. However the (unexpected) discovery Schopf (1993) of what are apparently (although not quite certainly Brasier, Green & McLoughlin (2004)) the remains of photosynthesizing bacteria from long before the beginning of the so-called Proterozoic can be considered Catling *et al.* (2005) as rather strong evidence against this particular kind of two-step scenario.

A two-step scenario of a more viable kind can, however, be obtained on the supposition that the first of the two hard steps was the emergence of eukaryotic organisms (with cell nuclei) at a time that now seems to fit reasonably well with the beginning of the Proterozoic, when the Earth was about half its present age. This revised two-step scenario is incompatible with hypothesis B, but it is consistent with hypothesis A-minus, which means that it would be favoured if future observations Leger *et al.* (1996), Arnold *et al.* (2002), Kiang *et al.* (2007) of extrasolar planets reveal the widespread presence of primitive photosynthesizing life systems.

The information available at present would, however, appear to be weighted (albeit not overwhelmingly) against any scenario with only two hard steps, because of the increasing (but not yet absolutely conclusive) amount of evidence Caldiera & Kasting (1992) to the effect that, as remarked above, the environmentally favourable period still available may only be of the order of 1 Gyr, not of 5 Gyr as originally supposed, so that (as was suspected Carter (1983), Barrow & Tipler (1986) from the outset) the likely number n of hard steps is correspondingly larger than one or two, most probably in the range $4 \lesssim n \lesssim 8$

3. Mathematical statistics of hard-step scenarios

The basic principle of a hard-step scenario is that, within the relevant environmentally favorable timescale, τ_e say, a number, n say, of essential but random processes in the evolutionary chain leading to the outcome in question (for our purpose that of intelligent life) are hard in the sense of having random occurrence rates λ_i ($i = 1, \ldots ,n$) so low that the corresponding characteristic timescales $\tau_i = 1/\lambda_i$ are long compared with what is available, $\tau_i \gg \tau_e$. This means that, unlike other essential but easy steps, such hard steps will in most cases never be achieved at all, with the implication that the outcome in question will be rare, even in favourable environments (something that may become observationally verifiable when capabilities for observation Leger *et al.* (1996), Arnold *et al.* (2002), Kiang *et al.* (2007) of extrasolar planets are sufficiently improved).

In a hard-step scenario of the kind specified in this way, the (very small) probability, $\mathcal{P}$ say, of ever completing the evolutionary chain – leading in the case of interest to the emergence of intelligent observers at a particular site – will be given as a product of contributions from the n steps of the chain by

$$\mathcal{P} \propto \prod_i \mathcal{P}_i, \qquad \mathcal{P}_i = \frac{\tau_e}{\tau_i} \ll 1, \tag{1}$$

while the chance of completing the chain within some given time t (which must necessarily be less than the maximum available time τ_e) will be given by $\mathcal{P}\{t\} \propto t^n \prod_i \lambda_i$ with a proportionality factor of the order of unity whose exact numerical value depends on whether or not the steps have to be taken in a particular order. Independently of that, and independently of the values of the long timescales τ_i, the expected arrival time $\bar{t}$ (in the small fraction of cases for which the

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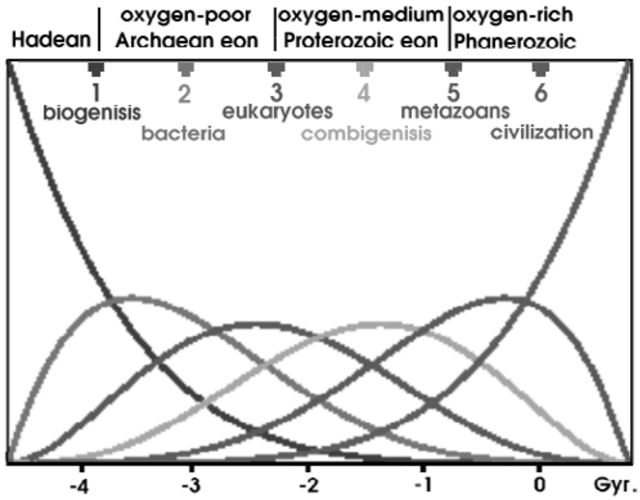

Fig. 1. Conditional probability distributions with corresponding (numbered) expectation values and suggested interpretations, for a chain with $n=6$ hard steps within an allowed time range that (in the chronological scale underneath) has been taken to be nearly 6 Gyr, so as to get the best fit to our own terrestrial case.

chain is completed) will be given by

$$\frac{\bar{t}}{\tau_e}=\frac{n}{n+1}. \quad (2)$$

On the basis of the plausible assumption that the hard steps actually do have to be carried out in a well-defined order, it can easily be seen that, subject to the restriction that the chain be completed within the allowed interval τ_e, the conditional probability for the time $t\{r\}$ of occurrence of the rth step will have a distribution, $\dot{P}\{r\}=\mathrm{d}P/dt\{r\}$, given by

$$\dot{P}\{r\}=\frac{n!t^{r-1}(t-\tau_e)^{n-r}}{(r-1)!(n-r)!\tau_e^n}, \quad (3)$$

as shown, for the case $n=6$ in Fig. 1. It is evident that the maximum of the distribution for the rth hard step will occur when $t/\tau_e=(r-1)/(n-1)$. This means that the maxima are uniformly spaced, all with the same separation $\tau_e/(n-1)$. For practical purposes it is more important to know the corresponding mean expectation values $\bar{t}\{r\}$, which are given by the formula

$$\frac{\bar{t}\{r\}}{\tau_e}=\frac{r}{n+1} \quad (4)$$

(of which (2) is the special case for $r=n$), from which it can be seen that (like the maxima) these averaged times of occurrence will also be evenly spaced, with separation

$$\Delta\bar{t}=\frac{\tau_e}{n+1}. \quad (5)$$

Although it is highly simplified, this kind of hard-step description is rather robust. One might seek higher accuracy by allowing for time variation of the rates λ_i, but as these rates cancel out in the observationally relevant formula (4), and as the random scatter is characterized by standard deviations of at least the same order as the mean separation (5), the statistical significance of improvement obtainable by such elaboration would hardly be enough to be worth the trouble.

When the hard-step picture encapsulated in (1) and (2) was originally put forward Carter (1983), its implementation was based on the identification of τ_e (the duration of the window of biological opportunity) with the theoretically predicted main sequence (hydrogen burning) lifetime $\tau_\odot$ of our Sun, which is of the order of 10 Gyr, as well as on the identification of $\bar{t}$ with the present age of the Earth, which is nearly 5 Gyr. The revised implementation here will be based on the attribution of a shorter value, only about 6 Gyr, to τ_e, in accordance with the estimate Caldiera & Kasting (1992) that we have already used up about five-sixths of the originally available time before the aging Sun makes the Earth too hot. On this revised basis it can be seen that reasonable conformity with the formula (2) is obtained by supposing n to be in the range $4\lesssim n\lesssim 8$, with the best fit given perhaps by $n=6$.

4. The six-step scenario

If, as before, one starts by supposing that the first hard step is biogenesis itself (including the origin of the genetic code) then, as the final step will in any case be our own recent emergence as very large brained animals, it remains to identify just four other intermediate hard steps if we wish to complete a scenario in which the total hard-step number is $n=6$.

In view of the lack of precision of the estimate Caldiera & Kasting (1992) for τ_e, as well as the statistical scatter of the distributions (3), whose standard deviations are at least of the same order as the mean separation (5), the optimization of the matching of the formula (2) within the range $4\lesssim n\lesssim 8$, should not in itself be taken too seriously.

It has, however, been pointed out by Hanson (1998) that if we want to match not just the final arrival formula (2) but also the formula (4) for the evenly distributed expected time of completion of the intermediate steps, then – according to the new interpretation advocated by Schopf (1999) – the fossil record provides supplementary evidence in favour of a scenario with just four intermediate hard steps, and therefore with total number $n=6$. Subsequent to a first step consisting of biogenesis at a date too early to be evaluated today, Schopf identifies four successive transitions that are undoubtedly of cardinal importance, and that are plausible candidates for the status of steps that are hard in the technical sense used here, meaning that their occurrence within the available time $\tau_e\approx 6$ Gyr was against the odds *a priori*. These steps are separated by time intervals that fluctuate from about 0.6 Gyr to about 1.3 Gyr, with a mean interval $\Delta\bar{t}$ of about 0.8 Gyr.

The four intermediate steps of the Schopf list are as follows. To start with, the candidate for the status of the second hard step is the emergence of procaryote (simple celled) cyanobacteria about 3.5 Gyr ago; the candidate for the status of the third hard step is the emergence of eukaryotes (with cell nuclei) which were certainly present 1.8 Gyr ago, and for which there is evidence Brocks *et al.* (1999) dating back to late Archaean times, roughly 2.5 Gyr ago; the candidate for the status of the fourth hard step is what can be called combigenesis, meaning the introduction of sexual gene propagation, about 1.2 Gyr ago; and finally the candidate for the status of the fifth hard step is what can be called macromorphogenesis, meaning the emergence of metazoans (large multicellular animals) about 0.6 Gyr ago. On this basis, the emergence of our own anthropic civilization now would count as the sixth hard step.

5. Hard steps as transitions between eons

The description of the geological history of the Earth is facilitated by its convenient step-like structure, characterized by comparatively rapid transitions between periods during which conditions were fairly stable, with a hierarchical structure whereby periods are grouped into longer units known as eras, and these are grouped into the longest units of all which are known as eons. The classification used in Darwin's time recognized only two eons: the recent relatively short Phanerozoic eon, to which the entire macroscopic fossil record is limited, and the enormous pre-Cambrian super-eon, which included everything older than about half a Gyr, but about which very little was known until relatively recently.

In the more modern classification commonly used today, the 4 Gyr pre-Cambrian super-eon has been subdivided into three parts. This makes a total of four eons, which group into two pairs each comprising about half of terrestrial history. It used to be thought that life was present only in the second half, in which the Phanerozoic eon was preceded by the much longer Proterozoic eon, during which only relatively simple, mainly single celled, organisms were present. The first half started with the relatively brief the Hadean eon, during which conditions are thought to have been too extreme for survival of any life on Earth. This was followed by the much longer and more favorable Archaean eon, which was originally thought to have been sterile, but during which it is now thought Schopf (1993) that the Earth was host to a thriving population of photosynthesizing cyanobacteria. It now seems reasonable to associate the transition from the Archaean to the Proterozoic era with the development of eukaryotic life, in which the cells have an elaborate structure with chromosomes contained in nuclei.

The recognition of these four rather clearly distinct eons might be considered as *prima facie* evidence in favour of a hard-step model with $n=4$. However, such an interpretation is disfavoured by the observation that the durations of these eons differ considerably, whereas it is to be recalled that the hard-step model predicts that the durations will on average be equal, with deviations that will not be very large compared with their mean. The fact that two of the eons – namely the Archaean and the Proterozoic – have roughly double the length of the other two suggests that if the short eons – namely the Hadean and the Phanerozoic – are each associated with a single hard step, then the long eons should each be associated with a pair of hard steps, so that one finally obtains a total of six hard steps, as proposed in the preceding section, see Fig. 1.

6. Oxygen: a convenient byproduct of combigenesis

A crucial issue in the interpretation of the fossil record concerns the question (raised by Darwin himself) of why the penultimate step, namely the emergence of metazoans, occurred at such a relatively late time. In reply to this question, one of the key points emphasized by Schopf and many others Catling *et al.* (2005) is that large multicellular organisms need an oxygen-rich environment which was not available on Earth until about the last gigayear. It has been suggested that this requirement should be interpreted as an astrophysical restriction, reducing the past time duration of what should be considered as an anthropically favourable environment from nearly 5 to less than 1 Gyr. Taken by itself Livio & Kopelman (1990), this interpretation would have reduced the estimated value of n to zero (with the implication Livio (1999) that intelligent life could be very common) but in conjunction with the future limitation Caldiera & Kasting (1992) of the same order, namely about 1 Gyr, it would mean simply that τ_e should be interpreted as having a smaller value, of order $\tau_{\odot}/5$ which would merely restore the original Carter (1983) estimate $1 \leqslant n \lesssim 2$.

It is, however, rather difficult Catling *et al.* (2005) to explain the – comparatively recent – time of oxygen enrichment of the atmosphere on an essentially astrophysical basis. A more plausible alternative is to follow Schopf (1999) in construing the oxygen enrichment as part of the biological evolution of the environment. Postulating the oxygen enhancement to actually be itself – or to be an immediate consequence of – one of the hard steps in the chain suffices to restore the viability of the picture proposed above, in which the total available time, τ_e, is taken to be between 5 and 6 Gyr, and the average time $\Delta\bar{t}$ between steps is given by the estimated time Caldiera & Kasting (1992) remaining available in the future, which is of the order of 1 Gyr, with the implication that the hard-step number n is likely to be in the range $4 \lesssim n \lesssim 8$ which includes the particular suggested value $n=6$.

The doctrine advocated by the Schopf school is effectively as follows. It has long been consensually accepted that during most of terrestrial history the source of atmospheric oxygen (originally at a level far too dilute for metazoans) has been photosynthesis by the cyanobacteria whose emergence is one of the most obvious hard-step candidates Barrow & Tipler (1986), counting as the second in the chain of six steps listed above, and as the first of the pair of hard steps to be associated with the long Archaean eon (the other – signalling the completion of the Archaean – being the arrival of the eukaryotes).

The ensuing concentration of oxygen would have depended on the balance of this photosynthetic production against oxygen absorbtion by various sink mechanisms (including combination with iron during the Archaean eon, prior to what is listed above as the third step) of which it seems likely that the most important was – and remains – combination with carbon to form carbon dioxide and carbonates such as chalk. According to an interpretation of the kind proposed by Schopf (1999), the emergence of successively more advanced life forms would have increased the effectiveness of inhumation processes whereby some of the carbon was taken out of atmospheric circulation in unoxidized form. The most important example of this in recent terrestrial history is the conversion of buried vegetable residues to coal.

Schopf has suggested that the augmentation of the proportion of oxygen to carbon dioxide in the atmosphere by such inhumation processes would have become particularly important as a convenient byproduct of combigenesis (the development of sex), counted as the fourth in the chain of six steps listed above, and as the first of the pair of hard steps to be associated with the long Proterozoic eon (the other – signalling the completion of the Proterozoic – being the arrival of the metazoans). The efficient propagation of genetical material made possible by this innovation would (as described elsewhere Carter (1983)) have greatly increased the potential rapidity of evolution, thereby enabling occupation of new ecological niches by many specialized life forms of unprecedented diversity. The presumption is that these would have included kinds whose life style would posthumously produce substantial carbon inhumation and ensuing oil production.

It is to be remarked that an inconvenient Gore (2006) byproduct of the rise of civilization, counted as the sixth step in the chain, is the reversal of this process, by conversion of coal and oil back to carbon dioxide.

7. The puzzle of the first hard step

An important question in this more definitive implementation of the hard-step picture, as in its original application Carter (1983), is whether the first difficult step was the original development – presumably by establishing the genetic code – of the most primitive forms of what we recognize as life itself. However, according to (4) as remarked above Hanson (1998), it is a generic feature of hard-step scenarios that the intervals between the various hard steps can all be expected to have the same order of magnitude, $\Delta\bar{t}$ meaning, in this case, a substantial fraction of a gigayear (the remaining time available in the future). On the basis of this consideration, the increasing amount of evidence Line (2002) suggesting that the time gap between the establishment of favorable conditions and the appearance of primitive life on Earth may have been much shorter that 1 Gyr has been interpreted Lineweaver & Davis (2002) as implying that this was not a hard step, but should be counted as easy, with the implication that life (but not intelligent life) in the universe may be fairly common. In the five-step scenario obtained in this way, the Hadean eon would not be counted as part of the environmentally favourable window, so the picture in Fig. 1 would have to be truncated by removal of the first zone on the left.

Although it seems compelling at first sight, the conclusion that the emergence of primitive life should be relegated to the status of an easy step has recently been shown to be on a shakier footing than at first appeared. It has been pointed out by Davies (2003) that there are strong reasons for believing that the relevant arena consists not of the single planet Earth, but of the neighbouring pair constituted by Earth with Mars. The idea is that primitive life in the solar system emerged first on Mars, where conditions would have been more favourable during an initial Hadean period lasting a substantial fraction of a gigayear – in other words, long enough to be comparable with the average hard-step separation $\Delta\bar{t}\approx 0.8$ Gyr. It would have been only toward the end of this Martian phase – about the beginning of the Archaean eon – that conditions would have become relatively favourable on Earth, to which primitive life could have been transferred quite rapidly via meteorites. According to this rather plausible picture, the transfer would have counted as an easy step (due to the high rates of asteroid collisions at that early epoch) but the origin of the primitive life itself (such as that of the oxygen photosynthesizers and carbon buriers later on) could indeed have been one – presumably the first – of the hard steps, in which case (as supposed by hypothesis B) all kinds of life (not just intelligent life) in the universe would be very rare.

8. Conclusion: six hard steps or only five?

The claim Caldiera & Kasting (1992) that the remaining time before destabilization of the terrestrial climate by the aging Sun is only about 1 Gyr favours a six-step or five-step scenario, but if it were found to be 2 Gyr or more then a two-step alternative would be a better bet. Although significant, such evidence by itself cannot be overwhelming, as the corresponding probability distributions (see Fig. 1) are rather broad (with standard deviations of 0.5 Gyr or more for a six-step scenario and three times larger for a two-step scenario). However, further evidence reinforcing the hypothesis of a six- or five-step scenario (and thus tending to confirm the 1 Gyr estimate for the remaining available time) is provided Hanson (1998) by the fossil record, in which it transpires that the transitions between geological eons match reasonably well with estimated times of occurrence of hard-step candidates.

In the most plausible variant of the two-step scenario, the first hard step does not occur until after the installation of photosynthesizing bacteria, which would therefore occur commonly at favourable sites in extrasolar planetary systems, where their effects could Leger *et al.* (1996), Arnold *et al.* (2002), Kiang *et al.* (2007) become observationally detectable. Such a detection might provide a rather decisive falsification of the six-step and five-step scenarios, but the latter, for the time being, seems to be most likely on the basis of the limited evidence already available.

A more delicate question is the distinction between the six-step scenario whose viability depends on the interpretation Davies (2003) of the Hadean eon as a Martian phase, and the truncated five-step scenario in which the Hadean is excluded from consideration as part of the environmentally favourable time window. This is an issue that might be settled by future exploration of Mars, but that would be difficult to resolve just by observation of extrasolar planets. The difficulty is that whereas, according to the five-step (which in our case means exclusively terrestrial) scenario, the occurrence of very primitive life would have been widespread, its presence on extrasolar planets would probably have been ephemeral (depending on non-renewable resources) and would usually not have engendered a signature of the easily detectable kind provided, in the two-step scenario, by more advanced photosynthesizing life forms.

References

Carter, B. (1983). The anthropic principle and its implications for biological evolution. *Phil. Trans. Roy. Soc. Lond.* **A310**, 347–363.

Davies, P.C.W. (2003). Does life's rapid appearance imply a Martian origin? *Astrobio.* **3**, 673–679. arXiv:astro-ph/0403049.

Leger, A., Mariotti, J.M., Mennesson, B., Ollivier, M., Puget, J.L., Rouan, D. & Schneider, J. (1996). Could we search for primitive life on extrasolar planets in the near future? *Icarus* **123**, 249–255.

Tarter, J. (2001). The search for extraterrestrial intelligence (SETI). *Ann. Rev. Astron. Astrophys.* **39**, 511–548.

Maddox, J. (1984). New twist for anthropic principle. *Nature* **307**, 403.

Caldiera, K. & Kasting, J.F. (1992). The life span of the biosphere revisited. *Nature* **360**, 721–723.

Schopf, J.W. (1993). Microfossils of the early Archaean Apex chert: new evidence of the antiquity of life. *Science* **260**, 640–646.

Brasier, M.D., Green, O.R. & McLoughlin, N. (2004). Characterization and critical testing of potential microfossils from the early Earth: the Apex 'microfossil debate' and its lessons for Mars sample returns. *Int. J. Astrobio.* **3**, 139–150.

Catling, D.C., Glein, C.R., Zahnle, K.J. & McKay, C.P. (2005). Why O_2 is required by complex life on habitable planets, and the concept of planetary oxygenation time. *Astrobio.* **5**, 415–438.

Arnold, L., Gillet, S., Lardière, O., Riaud, P. & Schneider, J. (2002). A test for the search for life on extrasolar planets. Looking for the terrestrial vegetation signature in the Earthshine spectrum. *Astron. Astroph.* **392**, 231–237 (arXiv:astro-ph/0206314).

Kiang, N.Y., Segura, A., Tinetti, G., Govindjee, Blankenship, R.E., Cohen, M., Seifert, J., Crisp, D. & Medows, V.S. (2007). Spectral signatures of photosynthesis II. Coevolution with other stars and the atmosphere of extrasolar worlds. *Astrobio.* **7**, 252–274 (arXiv:astro-ph/0701391).

Barrow, J.D. & Tipler, F.J. (1986). *The Anthropic Cosmological Principle*, pp. 562–569. Oxford University Press, Oxford.

Hanson, R. (1998). Must early life be easy? The rhythm of major evolutionary transitions. *preprint*, http://hanson.gmu.edu/hardstep.pdf.

Schopf, J.W. (1999). *Cradle of Life*. Princeton University Press, Princeton, NJ.

Brocks, J.J., Logan, G.A., Buick, R. & Summons, R.E. (1999). Archean molecular fossils and the early rise of eukaryotes. *Science* **285**, 1033–1036.

Livio, M. & Kopelman, A. (1990). Life and the Sun's Lifetime. *Nature* **343**, 25.

Livio, M. (1999). How rare are extraterrestrial civilizations, and when did they emerge? *Astroph. J.* **511**, 429–431 (arXiv: astro-ph/9808237).

Gore, A. (2006). *An Inconvenient Truth*. Bloomsbury, London.

Line, M.A. (2002). The enigma of the origin of life and its timing. *Microbiology* **148**, 21–27.

Lineweaver, C.H. & Davis, T.M. (2002). Does the rapid appearance of life on Earth suggest that life is common in the universe? *Astrobio.* **2**, 293–304 (arXiv:astro-ph/0205014).