Hypothesis Article

Galactic Punctuated Equilibrium: How to Undermine Carter's Anthropic Argument in Astrobiology

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Abstract

A new strategy by which to defeat Carter's "anthropic" argument against extraterrestrial life and intelligence is presented. Our approach is based on relaxing hidden uniformitarian assumptions and considering instead a dynamical succession of evolutionary regimes governed by both global (Galaxy-wide) and local (planet- or planetary system–limited) regulation mechanisms. Notably, our increased understanding of the nature of supernovae, gamma-ray bursts, and strong coupling between the Solar System and the Galaxy, and the theories of "punctuated equilibria" and "macroevolutionary regimes" are in full accordance with the regulation-mechanism picture. The application of this particular strategy highlights the limits of application of Carter's argument and indicates that, in the real universe, its applicability conditions are not satisfied. We conclude that drawing far-reaching conclusions about the scarcity of extraterrestrial intelligence and the prospects of our efforts to detect it on the basis of this argument is unwarranted. Key Words: Astrobiology—Extraterrestrial intelligence—Galaxy: evolution—History and philosophy of science. Astrobiology 9, 491–501.

An unflinching determination to take the whole evidence into account is the only method of preservation against the fluctuating extremes of fashionable opinion.

Alfred North Whitehead, *Science and the Modern World* (1929), p 268.

Thunderbolt steers all things.

Heraclitus of Ephesus, *On Nature*, fragment B64.

1. Introduction: Carter's Argument

THE WELL-KNOWN ARGUMENT against the existence of extraterrestrial intelligence, (ETI) attributed to the astrophysicist Brandon Carter (1983) and developed by various authors (*e.g.,* Barrow and Tipler, 1986), can be characterized as follows:

If astrophysical (t_*) and biological (t_b) timescales are truly uncorrelated, life in general and intelligent life in particular form at random epochs with respect to the characteristic timescale of the astrophysical environment (notably, the Main-Sequence lifetime of the considered star). In the Solar System, $t_* \approx t_b$, within a factor of two. However, in general, it should be either $t_b \gg t_*$ or $t_b \sim t_*$ or $t_* \gg t_b$. The second case is much less probable *a priori* in light of the independent nature of these quantities. Carter also dismisses the third option, since in that case it is difficult to understand why the only planetary system known to be inhabited (that is, the Solar System) exhibits $t_* \approx t_b$ behavior. On the contrary, one would then expect that life (and intelligence) arose on Earth, and predict that it arose at other places in the Solar System, much earlier than they in fact did. This provides a weak probabilistic reason to believe that $t_b \gg t_*$ (in which case the observation selection effect explains very well why we do perceive the $t_* \approx t_b$ case in the Solar System). Thus, extraterrestrial life and intelligence have to be very rare, which is the reason why neither has been observed to date, in spite of the

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conjecture that favorable conditions for them exist at many places throughout the Galaxy.[1]

Carter's argument (CA) has been given a great deal of attention in discourses related to astrobiology and the Search for Extraterrestrial Intelligence (SETI). It has been assessed favorably in the monograph of Barrow and Tipler (1986). Authors as diverse as Maddox (1984), Bostrom (2002), Barrow (2002), Lineweaver and Davis (2003), Davies (2003), and Duric and Field (2003) hold CA in high regard. Astrobiologists McKay (1996) and Livio (1999) regard CA as an all-important constraint on astrobiological theories (though Livio presents an empirical counter-argument, he does not challenge the validity of the reasoning behind it). SETI skeptics, such as Tipler (1988, 2004), use CA to support the claim that we are alone in the Galaxy. Lineweaver and Davis (2003) mention CA approvingly and note that (i) it applies to the origin of intelligence rather than to biogenesis (origin of life) and (ii) any finding suggestive of long future duration of the biosphere will undermine it.

However, CA has also been criticized. Two most pertinent criticisms are those of Wilson (1994) and Livio (1999), the former mainly from the logico-methodological point of view, the latter the physical point of view. We use elements of their criticisms here, but the bulk of the present remarks have not been presented, to date, in the literature.[2] Wilson's criticism is mostly methodological; he argues that Carter is wrong in restricting the range of possible relations of t_b and t_* to the three cases listed above and that the fact that we appeared on Earth significantly before the end of the Sun's main-sequence lifetime decreases our confidence in CA. In addition, Wilson points out that the role of anthropic reasoning in CA is very minor, almost trivial. In several places, Wilson vaguely alludes to some of the empirical inadequacies of CA (see below) but refrains from investigating them further. In the next sections, we present such an investigation.

The crucial assumption of CA is that there is no *a priori* reason for correlation between t_* and t_b. Livio (1999) pointed out that this is the main weakness of this argument; processes that *induce* correlations between the two timescales, like the oxygenation of the atmosphere on terrestrial planets, undermine the argument. Notably, if stellar UV radiation prevents the appearance of land life due to high absorption by nucleic acids and proteins, then it is critical that a sufficient ozone layer occur before land life can appear. This, in turn, might induce a correlation between the astrophysical and biological timescales, since various stellar masses (and thus various lifetimes) will generate different amounts of UV radiation and dictate various rates of oxygenization of the atmospheres of hypothetical planets in their respective habitable zones. With elimination of this essential assumption of independence of two timescales, CA is significantly undermined.

Here, we question the basic premises of Carter's argument in an attempt to show that the reasoning behind the argu-

ment is inherently flawed. Carter's argument relies on the assumption that there are fixed (or at least well-defined) and roughly known timescales for astrophysical processes. In addition, it is assumed that the relevant biological timescale is well defined, albeit unknown, as well. We reject these assumptions and show below that there is sufficient physical justification to propose alternatives. These alternatives are more complicated than those basic principles that comprise Carter's argument, but this is in keeping with the many achievements of modern astrophysics and astrobiology in recent years. (In addition, Carter requires that the relevant timescales are independent, but this was criticized by Livio and others and is only a part of our argument here.) The alternatives encompass (i) external physical forcings acting on local biospheres throughout the Galaxy and (ii) elements of complex evolution, namely quasi-periodicity, stochasticity, change of macroevolutionary regimes, and secular evolution with cosmological time. In other words, the core element of CA, the belief that "the probability of intelligence increases *monotonically* with time" (Barrow and Tipler, 1986; see Section 3 below), is a case of special pleading and likely inaccurate on empirical grounds.

In a very limited form, this central argument has been sketched in Dragićević and Ćirković (2003). In brief, we believe that CA violates the second part of this important methodological guideline by failing to take into account timescale correlations induced by both secular evolution of the Galaxy and sudden catastrophic events. In addition, the issues CA touches upon constitute a microcosm of several traditional issues in philosophy of science in general and philosophy of biology in particular: issues of inevitability vs. contingence, gradualism vs. catastrophism, local vs. global influences on the biosphere, position of intelligent observers on the "tree of life," etc., all of which recur in the study of CA and related topics.

It is sometimes stated that CA offers an example of the scientific nature of anthropic reasoning by virtue of its falsifiability; it offers a prediction that our current astrobiological and SETI efforts will fail and that we will not discover extraterrestrial intelligent beings in the Milky Way. Formally speaking, this does indeed make the hypothesis scientific, but it can be argued that in this case the meaning of falsifiability is stretched beyond its reasonable usage. For instance, the statement "There are no intelligent alien species in the Galaxy" presumes our capacity to discriminate between intelligent and non-intelligent aliens with certainty, which can hardly be taken for granted (*cf.* Raup, 1992; Lem, 1987). Even if it were, the timescales for this kind of falsification are outstanding; in fact, they are *at least* equal to the often-cited Fermi-Hart timescale for visiting (or colonizing) all stars in the Milky Way.[3] Even the most ardent Popperian should pause when faced with such a remote prospect of falsification, especially when it is not necessary to doubt the anthropic reasoning itself in order to contest a specific argument with use of many auxiliary assumptions.

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[1]Strictly speaking, this is just half of Carter's argument in his fascinating 1983 paper. The rest concerns the issue of the number of "crucial" (or "critical") steps in emergence of intelligent observers on Earth and possibly elsewhere. Although later commentators, like Barrow and Tipler (1986) or Wilson (1994), devoted much attention to this "anthropic" prediction, it lies outside of the scope of the present paper.

[2]A companion paper (Ćirković and Vukotić, 2008) deals with Fermi's Paradox from a similar viewpoint.

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[3]The qualification is necessary given our inability to determine decisively, for example, the degree of intelligence and consciousness of some of the species we share our planet with, namely marine mammals (*e.g.*, Browne, 2004). Since it is easier to make oneself known than to establish or refute intelligence on an alien planet with certainty, the expected timescale can only be larger than the Fermi-Hart limit (*cf.* Ćirković and Bradbury, 2006).

It is important to emphasize that we do not intend to make a case for the existence of ETIs in the Milky Way. That is a quite distinct (and, arguably, much more formidable) task. Our aim is to show how a particular anti-ETI argument—strengthened, unfortunately, by endless uncritical repetitions in both research and popular literature—can be undermined. It can be said, only insofar as our lack of credence in the existence of ETI within the relevant part of the Galaxy is based on CA, that our study offers an indirect support for ETI plausibility. There are, however, other anti-ETI arguments—notably the Tsiolkovsky-Fermi-Viewing-Hart-Tipler argument, usually known simply as Fermi's paradox (Brin, 1983; Webb, 2002)—which are beyond the scope of the present study and could, in principle, support ETI skepticism even if CA is dismantled.

2. Are There Well-Defined Timescales?

There are many cases in everyday life, as well as in science, where apparently independent quantities are of similar or even the same order of magnitude. Even if there is no causal link between t_b and t_*, it would be erroneous to reject the $t_b \sim t_*$ case as Carter does. How many orders of magnitude does this region possess? Are there different *external* constraints on the timescales, precluding them having values in the entire $(0, +\infty)$ range? We shall argue now that, due to the oversimplification, there are additional timescales, which make $t_b \sim t_*$ the most interesting case. Then it becomes an additional benefit that such choice would make Earth truly unexceptional; thus, it is in good agreement with the Copernican principle.

We will first redefine the astrophysical timescale t_* as the timescale of *continuous habitability* of a terrestrial planet in the Milky Way galaxy. The difference may sound pedantic, but it is in fact crucial when we recognize that (astro)physical processes other than the evolution of its parent star can influence the habitability of a planet. In particular, the need to abandon the "closed box" astrobiological picture of Earth (and terrestrial planets in general) is emphasized in a number of recent studies from different points of view. Most pertinently, Lineweaver *et al.* (2004) investigated the concept of the Galactic Habitable Zone (GHZ), introduced by Gonzalez *et al.* (2001), which is comprised of the stars in the Milky Way that potentially possess habitable planets with complex life [for a fine review, see Gonzalez (2005)].[4] The GHZ constitutes an annular ring several kpc wide, comprising the solar circle at a galactocentric distance of 8.5 kpc; and, though its definition does not mention intelligent beings, it should clearly be the main target of SETI studies. In both astrobiology and Earth sciences, a paradigm shift toward an interconnected, complex view of our planet has already been in place for quite some time in both empirical and theoretical work (*e.g.,* Clube and Napier, 1990; Cockell, 1998; Burgess and Zuber, 2000; Lenton and von Bloh, 2001; Franck *et al.,* 2000; Iyudin, 2002; Gies and Helsel, 2005).

(It is important to understand here that the very talk about habitable zones makes the assumption of independent events suspicious, at best. Habitable zones are *defined* as spatio-temporal regions where conditions for life arise due to *correlated* processes. As far as prospects for SETI are concerned, the relevant region is the GHZ, which occurs as a consequence of roughly understood processes of chemo-dynamical evolution of the Milky Way and its stellar populations. Even more telling is the concept of the Cosmic Habitable Age, as introduced by Gonzalez (2005). Insofar as habitable zones are an unavoidable part of the modern astrobiological discourse, any argument based on the independent development of biospheres automatically loses force.)[5]

Before we analyze the particulars of these external influences and consequent timescale forcing, we wish to emphasize that the very idea that main-sequence stellar lifetimes are the only relevant (astro)physical timescales is already a dangerous simplification. For instance, the "Snowball Earth" episodes that occurred at least twice in the geological past (Hoffman *et al.,* 1998; Kirschvink *et al.,* 2000) represent global catastrophes that may have annihilated all life except for the small habitats around marine volcanoes and hydrothermal vents. It is entirely plausible that similar episodes of severe global glaciation could have annihilated all life at Earth analogues elsewhere, so that the "astrobiological clock" gets a complete reset, possibly even without any external causative agent but due to an unfortunate combination of plate movement and Milankovich cycles.[6] Similarly, it seems clear that geophysical processes governing the carbon-silicate cycle are sustainable for a time shorter than the main-sequence timescales in at least a fraction of potentially inhabitable terrestrial planets in the Milky Way (*e.g.,* Lindsay and Brasier, 2002; Ward and Brownlee, 2002; Gerstell and Yung, 2003). This was not known at the time of Carter's 1983 article. Any such large-scale trends make CA *a posteriori* less appealing, since they induce further correlations and have their own quasi-deterministic timescales, which thus undermine the independence assumption.

This is related to the important issue of biotic feedback. Another consequence of discoveries in Earth sciences and astrobiology in the last decade or so is that the existence of life on Earth tends to make it more habitable both complexity-wise and time-wise. Simple life-forms induce changes in the environment conducive to the appearance of more complex life-forms; and, even more pertinently from the present point of view, the existence of both simple and complex life tends to increase the time span of habitable Earth beyond the bounds set by the main-sequence evolution of the Sun (Lenton and von Bloh, 2001). This shows that the probability of observing an inhabited planet within a given planetary sample at a particular time is not a linear function of the probability of biogenesis, as one would naively expect. This does not represent an argument against CA yet, since the latter takes the total lifetime of a star on the main sequence as the ultimate limit on the time span of the biosphere, which remains true irrespective of the feedback. However, this conclusion

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[4]As kindly pointed out to us by Professor David Grinspoon, the first suggestion of anything even remotely similar to the GHZ was given by the great author and philosopher Stanislaw Lem (1986). Lem foreshadowed and inspired much of the contemporary research in astrobiology, including the present study (especially Lem, 1987).

[5]A minor additional argument to the same effect may come from the panspermia hypotheses, which, although quite speculative, have experienced recent resurgence. Thus, Napier (2004), as well as Wallis and Wickramasinghe (2004), have constructed working panspermia models.

[6]However, for a view ascribing even the "Snowball" glaciations to our astrophysical environment, see Pavlov *et al.* (2005).

indirectly weakens CA, since it shows that the probability of finding life at a particular place cannot be a linear function of time *ceteris paribus*.

We do not need to emphasize that the biological timescales are still very poorly understood. Russell (1983, 1995) claimed that the appearance of intelligent beings occurs on the average about 3 billion years after the initial stages of planetary formation. Much shorter timescales have been proposed: McKay (1996) argued that plate tectonics actually *delayed* the appearance of complex life-forms on Earth by keeping the level of oxygen low for a long time. According to that idea, the duration of environmental conditions such as those that were experienced during the Precambrian could be as low as 10^8 years on planets without plate tectonics, such as Mars. This would, in turn, significantly accelerate the emergence of sufficient complexity as a precondition for intelligence.

It is in this astrobiological key that we can reiterate part of Wilson's (1994) criticism of CA contained in the following passage:

> At first glance, the claim that t_e should not differ from a given value of $\bar{t}$ seems to be equivalent to the claim that $\bar{t}$ should not differ from a given value of t_e. But these claims are fundamentally different. The reason the latter one is invalid is that $\bar{t}$, insofar as it represents the time that evolution is intrinsically most likely to require, is a probabilistic or statistical quantity. Our knowledge of the value of such quantity cannot be significantly enhanced by the evidence of a single case, especially the nonrandomly chosen one of our own evolution. Only if we were to become aware of a large number of actual cases of extraterrestrial evolution and their corresponding timescales, or if we were to advance our knowledge of the timescales governing var-

ious evolutionary mechanisms, could we provide a reasonable estimate of $\bar{t}$, and perhaps eliminate values of $\bar{t}$ much less than τ_0. But given only $t_e \sim \tau_0$, we cannot on the basis of this single evidential sample conclude much at all about $\bar{t}$. We certainly cannot eliminate, as Carter thinks we can, the possibility that $\bar{t} \ll \tau_0$.

3. Hidden Gradualism

Consider the different situations described in Fig. 1. With obvious simplification, we imagine extinction probability of life-forms as generally very low, except for short "spikes" that may correspond either to recurring (similar to mass extinction episodes in Earth's history) or single adversary events (for instance, the end of stellar evolution), *i.e.,* everything which is subsumed in Carter's astrophysical timescale t_*. If there is a well-defined biological timescale, CA can be represented as choosing between the cases shown in (a) and (b). CA suggests that we should accept case (a), in which the probability of appearance of life on an average terrestrial planet in the Galaxy is minuscule. However, what about cases (c) and (d)? It is clear that in these cases the governing timescale is the one associated with the increase or decrease in frequency of the extinction spikes. It follows that

(1) "Carter's criterion" of the relationship between the biological and astrophysical timescales is time dependent and not universal; and

(2) we may need additional timescales, linked to all astrophysical processes that can cut or impede biological evolution.

To accept a picture like (c) or (d) we need to abandon one of the most cherished prejudices of the 19th and most of the
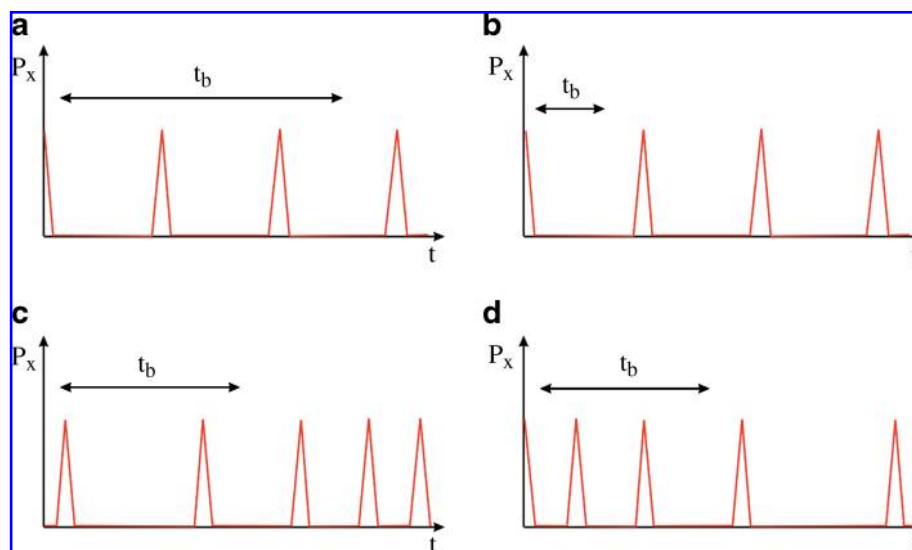

FIG. 1. Schematic presentation of possible relationship of two independent timescales. With t_b we denote the median of biological timescales on different planets of the GHZ. We may assume that P_X corresponds to some measure of the extinction probability in the most general sense. While (**a**) and (**b**) correspond to the situation envisaged by Carter's rendition of the anthropic reasoning [in particular, case (a) is the situation encapsulated by CA], we argue that these situations are unjustified simplifications. Physical reality corresponds to cases *at least* as complex as cases (**c**) and (**d**), where we have the environment monotonously becoming either more hostile or friendlier to life. In these cases, we need to take into account another timescale, which describes the rate of increase or decrease of the extinction events. Color images available online at www.liebertonline.com/ast.

20th century, which is uniformitarianism of rate (or gradualism). It is not only that the habitability of an astrobiological site is not constant in time but also that the frequency of important events ("extinction spikes") is changing with the evolution of the galactic system. We shall argue below that the situation shown in Fig. 1d is the best model for astrobiology, and in such a framework CA fails. As we have said, there are a host of recent indications that the Solar System is in fact an open system, strongly interacting with its galactic environment (*e.g.,* Rampino, 1997; Leitch and Vasisht, 1998; Shaviv, 2002; Melott *et al.,* 2004; Pavlov *et al.,* 2005; Gies and Helsel, 2005). Interactions induce correlations; correlations ruin arguments based on independence assumptions and coincidences. Why is that simple fact so widely shunned in favor of a prejudice representing essentially a return to the outdated 19th-century Lyellian gradualism?

Barrow and Tipler (1986) succinctly stated this critical uniformitarian assumption for which we need a specific label:

> **THESIS (*)**: "the probability of intelligence *increases monotonically* with time" (p 559, our emphasis).

We deny this assumption for reasons to be discussed below. It is important to understand that (*) is the central plank of CA—with it gone, the whole edifice crumbles.

First, (*) encapsulates an anthropocentrism unwarranted even in the simplest local case of the biological evolution on Earth. It is by no means clear (and many evolutionary biologists have denied it) that the history of the terrestrial biosphere represents anything even remotely describable as a "monotonical" approach to intelligence. Even if we take the broadest interpretation of "monotonically," which allows for paleontological stasis, there is simply no indication in the history of life that intelligence is inherently more probable today than, say, in the middle of the Cretaceous or in 10^8 years from now. [Quite contrary to the seeming intention of Barrow and Tipler, it is anthropic reasoning which tells us that we should *not* invoke our presence to argue for the thesis (*)—it is a trivial observation that our discussing the subject matter shows that intelligence exists now, while it does not tell us anything about its intrinsic probability. Moreover, the same fact suggests that the intelligence posing these questions is not very old, at least compared to geological or astrophysical timescales, since it is hardly conceivable that any significantly older intelligent species would not have much better insight into the nature of intelligence.]

Second, the problem is not that the probability of intelligence increases with time *ceteris paribus.* It is quite clear that the probability of observing any particular physically possible phenomenon at least once increases with cosmic time; the very statistical nature of our world ensures that. Of course, we need to take into account our cosmological knowledge: if the lifetime of our universe is finite—as was believed in the now mostly discredited recollapsing "Big Crunch" models—then most physically allowed configurations of matter will simply have no time to arise accidentally due to statistical fluctuations. Contrariwise, if the time is infinite and the world is finite and stationary on large scales (as was commonly thought in the time of the Boltzmann/Zermelo debate), then any configuration of matter in accordance with the general conservation laws will be achieved countless times, no matter how *a priori* improbable.

But this is entirely different from the claim that we have a monotonic "ascent" toward intelligence under very specific (and in the cosmological context very atypical) conditions required for biogenesis and evolution. Such a monotonic approach entails some specific causal reason, since both the spatial and temporal timescales we are considering here are many hundreds of orders of magnitude smaller than those required for the random assembly of even the simplest living systems. In Stephen Jay Gould's (1984) words: "the failure to find a clear 'vector of progress' in life's history … [is] the most puzzling fact of the fossil record." And if that is true for a single, by astrobiological measure, physically stable and uniform terrestrial biosphere, we have grounds for accepting it *a fortiori* for the set of (actual or potential) biospheres comprising the GHZ.

Therefore, the thesis (*) represents a particularly illuminating example of what biologists came to call a chain-of-being fallacy: the quasi-Victorian idea that the evolution of biosphere is a steady, linear progression through more and more complex forms culminating in the elite, well-to-do of the time). As shown by Gould in the very first chapter of *Wonderful Life,* this iconography has been conventionally employed in support of various scientifically wrong, but socially comforting, ideological issues (Gould 1989). Although fierce debates on the issue of "progress"—or large-scale evolutionary trends in general—continue to this day (*e.g.,* Dawkins, 1989; Dennett, 1995; Gould, 1996, 2002; Shanahan, 1999, 2001; Carroll, 2001), both sides do agree that the chain-of-being picture is untenable. Thus, (*) is ideologically loaded: it supports the idea that intelligence is fundamentally different from other biological traits and that the bearers of intelligence are entitled to a higher and more important place in the natural order of things.

Ironically, distinguished biologists who have opposed SETI, such as Mayr (1993) and Simpson (1964), devoted a large part of their professional careers to debunking the chain-of-being fallacy. Notably, the adaptationist paradigm of which Mayr (1942) is one of the founding fathers even hesitates to ascribe any particular importance to intelligence or to proclaim it different from any other trait. Within the framework of adaptationism, there is no *a priori* difference between intelligence and, say, the spiral form of the shell of the nautilus. Now, just imagine rephrasing (*) in the following form:

> **THESIS (*″)**: "the probability of a spiral shell with a pitch angle between $23°$ and $25°$ increases monotonically with time."

In our view, (*″) is almost obvious nonsense; why should we then—if we discard sentimentality, anthropocentrism, and possible extrascientific agendas—give better treatment to (*)? If, to use Stephen Jay Gould's famous metaphor, "the tape was rewound" to the time of the Cambrian Explosion, it would be highly unlikely for humans to reappear after sufficient time had elapsed (Gould, 1989). Gould forcefully argued in several books and papers (Gould, 1985, 1987, 1989, 1996) that the very notion of "progress" of the terrestrial biosphere is highly suspicious, culture-laden, and has very slim empirical support (if at all). How much more pretentious and vacuous does it sound when applied to the immense diversity that other galactic environments may present? If the thesis (*) is an interpretation of "progress" or "ascent," the same classical criticisms apply. For example, if humans were to go extinct

soon (perhaps as a result of runaway climatic catastrophe, nuclear winter, or a misuse of biotechnology or nanotechnology), all traces of human civilization would be obliterated in a few million years (except for the satellites in stable orbits and a couple of long-range space probes). Would the next intelligent species, if it ever arose subsequently, have the same cultural predilection for (*) as we have?

If we conclude that (*) is unjustified for the simplest local model of biological evolution on a single planet, how likely is that (*) will apply to a large set of habitable planets that comprise the GHZ? Even if the planets were isolated, "closedbox" idealizations, the uniform behavior implied by (*) is as probable as sudden motion of molecules of homogeneous air in a room into a $1\,m^3$ volume in a corner. As Boltzmann, Zermelo, Culverwell, and others already knew in the 19th century, such conspiratorial behavior is highly unlikely on statistical grounds without going into detailed physics of thermodynamical systems (*e.g.,* Steckline, 1983). By analogy, without knowing any details on a particular astrobiological development in each habitat, we might argue that uniformity of evolution expressed by (*) is improbable. Of course, our discussion here and elsewhere pertains only to the evolution of hypothetical biospheres in the GHZ, which are of interest to SETI studies; if we take into account other galaxies, clusters, etc., the situation may be both quantitatively and qualitatively different.

When we reject hidden uniformitarianism, even the $t_b \ll t_*$ case of Carter's dilemma is not to be rejected so lightly. An obvious counterexample in this respect is the much-debated "impact frustration" of early life-forms (Raup and Valentine, 1983; Maher and Stevenson, 1988; Oberbeck and Fogleman, 1989). It is conceivable that early terrestrial life appeared independently several times, only to be destroyed by catastrophic impacts during the epoch of the so-called Late Heavy Bombardment. Only when the frequency of impacts decreased sufficiently were early life-forms capable of spreading, diversifying, and evolving in such a way as to produce a rich and complex terrestrial biosphere. If this were so, $t'_b \simeq 10^7$ to 10^8 years $\ll t_*$ where with t'_b we denote the timescale for biogenesis. While we cannot still infer anything about "true" t_b (*i.e.,* the timescale for the development of intelligence), if for any reason there were an upper limit to t'_b (related perhaps to the chemical evolution of Earth's atmosphere or surface and the increase of solar radiation flux), it could be perfectly conceivable that life could entirely miss the temporal window of opportunity due to the impact interruptions. This scenario is instructive, since it shows (A) strong coupling between lifeforms and physical environment and (B) timescale forcing through which a physical timescale (the interval between major impacts) actually becomes the relevant quantity. Inferring trends from values obtained by slow averaging procedures tends to be uncertain at best (as illustrated schematically in Fig. 2).

FIG. 2. In the context of CA we can regard the origination of intelligence as an extremely slow type of physical "measurement"—it took 3.8 billion years on Earth. It is likely that the physical conditions throughout the GHZ vary substantially on shorter timescales, which precludes getting information on the basis of a single astrophysical timescale.

4. A Plausible Alternative: Global Extinction Mechanisms

If we accept that CA is at least severely limited by the nonuniformitarian history of life, it is natural to ask for more details about the major non-uniformities that impede its "monotonic" progress.[7] Fortunately, modern astrophysical research offers much in this respect. An important paper of Annis (1999) opened a new vista by introducing (though not quite explicitly) the notion of a *global regulation mechanism*, that is, a dynamical process that prevents or impedes uniform emergence and development of life all over the Galaxy.[8] In Annis' model, which he dubbed the phasetransition model for reasons to be explained shortly, the role of such global galactic regulation is played by gamma-ray bursts (henceforth GRBs), colossal explosions caused either by terminal collapse of supermassive objects ("hypernovae"), or mergers of binary neutron stars. Astrobiological and ecological consequences of GRBs and related phenomena have been investigated recently in several studies (Thorsett, 1995; Dar, 1997; Scalo and Wheeler, 2002; Smith *et al.,* 2004; Thomas *et al.,* 2005). To quote some of the results, note that Dar (1997) calculated that the terminal collapse of the famous supermassive object η Carinae could deposit, in the upper atmosphere of Earth, energy equivalent to the simultaneous explosion of the equivalent of 1 kiloton nuclear bombs per km^2 over the surface of the hemisphere facing the hypernova. According to the calculations of Scalo and Wheeler (2002), a galactic GRB can be lethal for eukaryotes up to a distance of 14 kpc. Thus, this "zone of lethality" for advanced life-forms is bound to comprise the entire GHZ whenever a GRB occurs within the inner 10 kpc of the Galaxy. Of course, this is biased toward land-evolving life-forms, since marine life is significantly less likely to be influenced by radiation of cosmic origin; this is partially offset by the estimate of SETI researchers (*e.g.,* Sagan and Shklovskii, 1966) that landbased ETI are likelier to develop technological civilization, thus becoming relevant SETI targets. Since the regulation mechanism exhibits secular evolution, with the rate of catastrophic events decreasing with time, at some point the as-

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[7]We do not presume any special understanding of evolutionary biology here; the formulation is applicable to a case of stable, only very slowly changing biological environment—a single macroevolutionary regime in terms of Jablonski (1986, 1989)—in which Barrow and Tipler's metaphor of "monotonic approach to intelligence" might perhaps work. Such a world is not the real world, but its juxtaposition with the real world can teach us some important lessons.
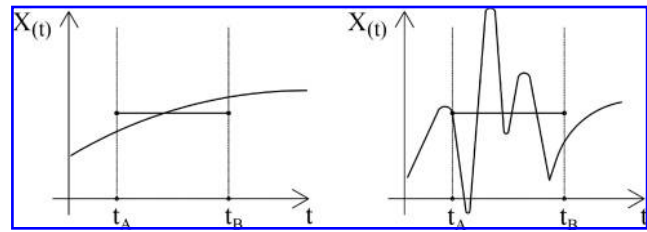
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[8]A similar suggestion had been made earlier by Clarke (1981), although his model was entirely qualitative and incorrectly incorporated a physical mechanism (galactic core outbursts) for global regulation.

trobiological evolution of the Galaxy will experience a change of regime. When the rate of catastrophic events is high, there is a sort of quasi-equilibrium state between the natural tendency of life to spread, diversify, and complexify, and the rate of destruction and extinctions. When the rate becomes lower than some threshold value, intelligent and space-faring species could arise in the interval between the two extinctions and make themselves immune (presumably through space-faring technology) to further extinctions.

It is important to understand that the GRB mechanism is just one of several possible physical processes hypothesized for "resetting astrobiological clocks." Any catastrophic mechanism that operates (1) on sufficiently large scales and (2) exhibits secular evolution can play a similar role. There is no dearth of such mechanisms; some of the bolder ideas proposed in the literature are cometary impact-causing "galactic tides" (Asher *et al.*, 1994; Rampino, 1997), neutrino irradiation (Collar, 1996), clumpy cold dark matter (Abbas and Abbas, 1998), or climate changes induced by spiral-arm crossings (Leitch and Vasisht, 1998; Shaviv, 2002). All such effects are cumulative: the total risk function of the global regulation is the sum of all risk functions of individual catastrophic mechanisms. The secular evolution of all these determine collectively whether and when conditions for the astrobiological phase transition of the Galaxy will be satisfied. Of course, if GRBs are the most important physical mechanism of extinction, as Annis suggested, then their distribution function will dominate the global risk function and force the phase transition.

Gamma-ray burst regulation has an important correlation property: the rhythm of biological extinctions should be synchronized (up to the timescales of transport times $\sim 10^4$ yrs for γ-rays and high-energy cosmic rays) in at least part of the histories of all potentially habitable planets. A bold hypothesis has been put forward recently by Melott *et al.* (2004) that a known terrestrial mass-extinction episode, one of the "Big Five" (the late Ordovician extinction, *ca.* 440 Ma), corresponds to a galactic GRB event.

Such an extinction, if correlated to a galactic GRB event, would undermine Carter's argument. With a set of modest additional assumptions, it is possible to show it quantitatively. For instance, in Fig. 3 we show results of a toy numerical experiment, which was designed as a simple realization of the astrobiological regulation model of Annis (1999) and performed to determine how timescale forcing arises in simplified evolving systems. GRBs are taken to be random events that occur with exponentially decreasing frequency

$$v(t) = v_0 \exp\left(-\frac{t}{t_\gamma}\right),$$

with the fixed characteristic timescale $t_\gamma = 5$ billion years in accordance with the cosmological observations (*e.g.,* Bromm and Loeb, 2002). Biological timescales for the origin of intelligence are randomly sampled from a log-uniform distribution between 10^8 [the minimum suggested by McKay (1996)] and 10^{16} years [the total lifetime of the Galaxy as a well-defined entity (Adams and Laughlin, 1997)]. For simplicity, it has been assumed that the age of the Galaxy is exactly 12 billion years and that all planets are of the same age. It is taken that the chain of events that lead to life and intelligence can be cut by a catastrophic event at any planet

in our toy-model Galaxy with probability Q, and its astrobiological clock reset. The toy model counts only planets that achieve intelligence at least once, and it does not take into account any subsequent destructive processes, either natural or intelligence caused (like nuclear or biotechnological self-destruction). Probability Q can, in the first approximation, be regarded as a geometrical probability of an average habitable planet being in the "lethal zone" of a GRB, and more complex effects dealing with the physics and ecology of the extinction mechanism can be subsumed in it.

While we present more-detailed analysis and interpretation of these and similar numerical experiments in separate studies (Vukotić and Ćirković, 2007, 2008), some conclusions invariably support our criticism of CA and are worth mentioning here. The system exhibits a systematic shift of behavior as we move from small values of Q (gradualism) to large values (catastrophism). At large Q, we have a step-like succession of astrobiological regimes, governed by external timescale forcing. In each regime, it is obvious that the ages of inhabited planets are not independent and uncorrelated, just the contrary, as expected from the considerations above.

In other words, neocatastrophism removes, ironically enough, the basic tacit assumption of CA. If the agents of extinction are correlated over the spatial scale of the GHZ, timescale forcing undermines Carter's reasoning in a natural way. As Heraclitus fancied 25 centuries ago, (astrophysical) *thunderbolt* may indeed *steer all things* (astrobiological).

(It is important to emphasize that in the simulation above we have neglected all sources of correlations between the life-bearing sites barring GRB regulation. Some processes— like panspermia, either natural or directed—certainly deserve to be taken into account, and we shall discuss them in detail in a forthcoming study. All these will only strengthen the correlations, thus decreasing our confidence in CA.)

6. Conclusions

We conclude that it is too early to draw skeptical conclusions about the abundance of extraterrestrial life and intelligence from our single data point via the "anthropic" argument of Carter (1983). In addition to other deficiencies of the argument pointed out in the literature, we emphasize that a picture in which regulation mechanisms reset local astrobiological clocks (which, consequently, tick rather unevenly) offers a way to reconcile our astrophysical knowledge with the idea of multiple habitats of life and intelligence in the Galaxy. In other words, Earth may be rare in time, not in space. Quite contrary to the conventional wisdom, we should not be surprised if we encounter many "Earths" throughout the Galaxy at this particular moment in time, at stages of evolution of their biospheres similar to the one reached at Earth. The unsupported assumption of gradualism is identified as the main source of confusion and unwarranted SETI skepticism. This pertains to the Milky Way galaxy, where communication times are short enough to make the effort worthwhile (and to bring other factors, such as Fermi's paradox, into play). If we take into account progressively larger ensembles, it will be possible sooner or later to find the monotonic behavior criticized above, but this is largely formal and irrelevant for practical SETI.

The astrobiological picture presented here can be understood by means of loose analogy with the much-discussed
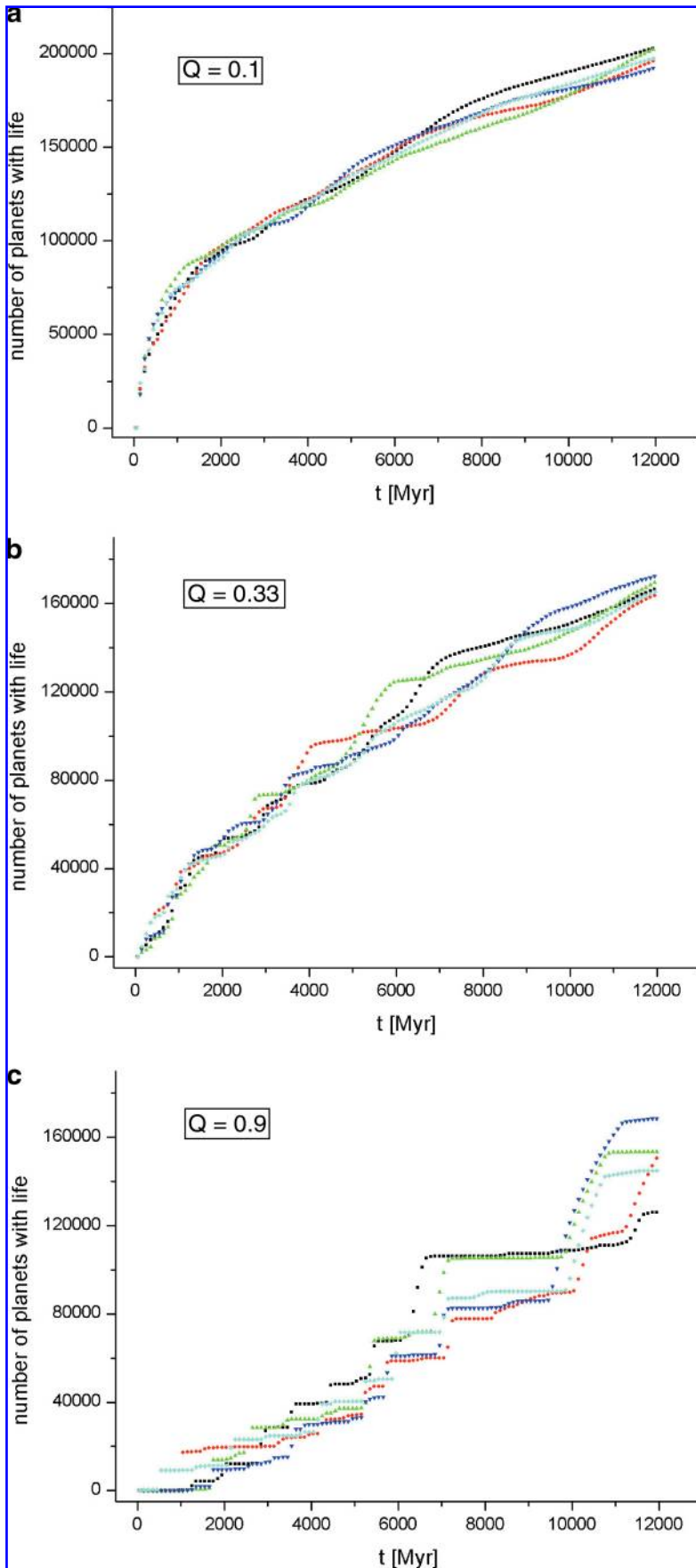
FIG. 3. Results of a simple Monte Carlo simulation demonstrating timescale forcing in the toy model of a galaxy with $N = 10^6$ habitable planets. Three cases of different average extinction probability Q are given (with five color-coded runs for each case), where small Q represents an approximation to the classical uniformitarian case, while $Q \rightarrow 1$ corresponds to catastrophe-driven evolution. Color images available online at www.liebertonline.com/ast.

theory of punctuated equilibrium in evolutionary biology. Seeking to explain the evident stop-start nature of the fossil record, Eldredge and Gould (1972) proposed the theory of punctuated equilibria (for the detailed elaboration and synthetic view see Gould, 2002). According to this theory, species tend to remain stable for long periods of time ("stasis"). The equilibrium is punctuated by abrupt changes in which existing species are suddenly (on geological timescale) replaced. The astrobiological analogy of paleontological stasis can be found in Fig. 3c, where we perceive long periods (of ~ 1 billion year duration) with the same number of inhabited planets before a sudden change. This feature is in itself antithetical to the spirit of CA; as emphasized by Gould (1989):

> Hence, a good deal more than half the history of life is a story of prokaryotic cells alone, and only the last one-sixth of life's time on earth has included multicellular animals. Such delays and long lead times strongly suggest contingency and a vast realm of unrealized possibilities. If prokaryotes had to advance toward eukaryotic complexity, they certainly took their time about it.

This is directly opposite to the thesis (*) and its monotonic ascent toward a (perceived) noble goal.

This is intimately linked to the issue of existence or otherwise of a well-defined biological timescale, universal for all habitable planets in the Milky Way. Obviously, in order to discuss this issue we have first to establish to which degree observed timescales on Earth (the one for appearance of life, the one for rise of complex metazoans, or the one for emergence of intelligent species) are a consequence of deterministic or just contingent processes and how big a role chance has played in their values (Carroll, 2001). Gould's (1985) "paradox of the first tier" points in the same direction: "mass extinctions are sufficiently frequent, intense, and different in impact to undo and reset any pattern that might accumulate during normal times." Here we add another aspect to this "enlightened" view of catastrophes: not only do they provide the pump of evolution by enabling innovative overthrows of entire faunas, but—in the astrobiological context—they provide correlations on the basis of which we could meaningfully consider astrobiological evolution of the Galaxy; indirectly, they offer weak support for our current and future SETI efforts.

This undermining of CA accords with the well-known tendency in the history of science and human culture in general: overcoming of the sense of privilege surrounding the Solar System, Earth, terrestrial life, and humanity. This "Copernican" tendency comes as a *consequence* of the astrophysical discourse, not as a sacred dogma to be preserved at all costs. A natural generalization of the history of the terrestrial biosphere to the case of the Milky Way from the astrobiological point of view entails the acceptance of a sort of galactic neocatastrophism (or a galactic punctuated equilibrium). It immediately undermines CA, since there is no fixed, unique, reified timescale in the core of the argument.

There are several reasons of a partly nonscientific nature for the strong impression of CA's hypothesis. As we have seen, it is tempting to subsume all complicated astrophysics and planetary science into a single timescale, though this degree of simplification is, in fact, unwarranted. This applies to biology even more forcefully. There is an unfortunate tendency in the philosophy of science to downplay radical

scientific theories and underestimate our present level of understanding; sometimes this tendency is motivated by healthy reasons of skepticism, but often—Mach's fierce "philosophical" opposition to Boltzmann's atomism comes to mind—it actually represents a conservative backlash, impeding recognition of new ideas. In addition, the textbook account of the defeat of catastrophism and the misleading philosophical legacy imparted to it in the mid-19th century lead all too often to half-conscious neglect of any temporal markers in investigation of natural phenomena other than the beginning and the end. Finally, CA offers an emotionally satisfying, but nevertheless false, sense of "strength in numbers."

A particularly dangerous form of "quick and dirty" generalization is embodied in the thesis (*) of monotonical ascent toward intelligence criticized above. Naive chain-of-being anthropocentrism (or intelligence-centrism) that surrounds the reasoning of CA proponents is starkly manifested here. In our view, there is no physical basis (gradualism of environmental conditions) for it, nor is there clear biological justification (since the adaptive value of intelligence is still an unknown quantity). Thus, CA more represents wishful thinking coupled with intellectual inertia when faced with abandoning gradualism and the closed-box assumption, than a serious scientific argument.

The tremendous progress in astrobiology (Chyba and Hand, 2005) clearly demonstrates that the oversimplifications inherent in CA are no longer tenable. To retain them means to reject all we have achieved in the last couple of decades on establishing concrete physical and chemical conditions for emergence of life in the cosmic context. If CA is largely, as Carter himself admitted, an argument from ignorance, then any decrease in our ignorance ought to prompt its reassessment and reevaluation. We are fortunate enough to live in the epoch of truly wonderful results in this field, from cosmology and orbital observatories down to biochemical labs and paleontology museums. That it is also the epoch in which CA can be effectively undermined is by no means a coincidence.

All in all, we have no *a priori* (or even anthropic-based) reason to reject the existence of extraterrestrial intelligence in the Milky Way. Geocentrism stays defeated, and the road for serious SETI studies is as open as ever.

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Abbreviations

CA, Carter's argument; ETI, extraterrestrial intelligence; GHZ, Galactic Habitable Zone; GRBs, gamma-ray bursts; SETI, the Search for Extraterrestrial Intelligence.

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