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ON THE TIMESCALE FORCING IN ASTROBIOLOGY

B. Vukotić[1] and M. M. Ćirković

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia

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SUMMARY: We investigate the effects of correlated global regulation mechanisms, especially Galactic gamma-ray bursts (GRBs), on the temporal distribution of hypothetical inhabited planets, using simple Monte Carlo numerical experiments. Starting with recently obtained models of planetary ages in the Galactic Habitable Zone (GHZ), we obtain that the times required for biological evolution on habitable planets of the Milky Way are highly correlated. These results run contrary to the famous anti-SETI anthropic argument of Carter, and give tentative support to the ongoing and future SETI observation projects.

Key words. Astrobiology – Methods: numerical – Galaxy: evolution – Extraterrestrial intelligence

1. INTRODUCTION

Recent astrobiological developments have helped elaborate the concept of the Galactic Habitable Zone (henceforth GHZ), as the region of the Galaxy containing habitable planets. The exact boundaries of GHZ are still uncertain, although the basic physical processes determining it are clear: build-up of metallicity through the Galactic chemical evolution, frequency of close stellar encounters and supernovae, and, possibly, the cosmogonical effects of environmental UV irradiation. In general, GHZ has the form of an annular ring, several kpc wide, and comprising the Solar circle at galactocentric distance of 8.5 kpc. A great leap forward occurred with the work of Lineweaver and his collaborators (Lineweaver 2001, Lineweaver, Fenner and Gibson 2004) on the age distribution of planets in GHZ. One of the most interesting consequences of that study is that the median age of terrestrial planets in the Milky Way is 1.8 ± 0.9 Gyr greater than the age of the Earth (a finding making the classical Fermi paradox even more disturbing![2]). In the meantime, advances in evolutionary biology and paleontology have recently reaffirmed the decisive role of mass extinction episodes in determining the outcome of evolution of the biosphere on Earth. This offers a useful framework to try to access how likely the completion of biological evolution (in the sense of Carter's 1983 paper; see below) is in the wider context of GHZ. It is our contention that the best approach to this problem lies with large-scale numerical simulations which could be updated with every improvement in our understanding of the underlying astrophysical and astrochemical mechanisms. In a way, this is analogous to using Monte Carlo simulations in other branches of physics where the detailed knowledge of individual subsystems' history and properties is unobtainable or undesirable, and only the global outcome subject to specific boundary conditions is of interest (e.g. percolation or diffusion models).

[1]Corresponding author: bvukotic@aob.bg.ac.yu.

[2]For fine reviews see Brin (1983), Duric and Field (2003).

2. A SIMPLE MODEL

An important paper of Annis (1999) opened a new vista by introducing (though not quite explicitly) the notion of global regulation mechanism, that is, a dynamical process preventing or impeding uniform emergence and development of life all over the Galaxy. In Annis' model, which he dubbed the phase-transition 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. GRBs observed since 1950s have been known for more than a decade to be of cosmological origin. Astrobiological and ecological consequences of GRBs and related phenomena have been investigated recently in several studies (Thorsett 1995, Dar 1997, Scalo and Wheeler 2002, Thomas et al. 2005). To give just a flavor of the results, let us mention that Dar (1997) has calculated that the terminal collapse of the famous supermassive object Eta Carinae could deposit in the upper atmosphere of Earth the energy equivalent to the simultaneous explosions of 1 kiloton nuclear bomb per km^2 all over the hemisphere facing the hypernova! According to the calculations of Scalo and Wheeler (2002), a Galactic GRB can be lethal for eukaryotes up to the huge distance of 14 kpc. Thus, this "zone of lethality" for advanced lifeforms is bound to comprise the entire GHZ whenever a GRB occurs within inner 10 kpc of the Galaxy. Annis suggested that GRBs could cause mass extinctions of life all over the Galaxy (or GHZ), preventing or arresting the emergence of complex life forms. Thus, there is only a very small probability that a particular planetary biosphere could evolve intelligent beings in our past. However, since the regulation mechanism exhibits secular evolution, with the rate of catastrophic events decreasing with time, at some point the astrobiological 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 can arise in the interval between the two extinctions and make themselves immune (presumably through technological means) to further extinctions.

It is important to understand that the GRB-mechanism is just one of possible physical processes for "resetting astrobiological clocks". Any catastrophical mechanism operating (1) on sufficiently large scales, and (2) exhibiting secular evolution can play a similar role. There is no dearth of such mechanisms; some of the bolder ideas proposed in 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). Moreover, all these 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, than their distribution function will dominate the global risk function and force the phase transition.) GRB 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. In fact, 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, cca. 440 Myr before present), corresponds to a Galactic GRB event.

It is intuitively clear that such correlated behavior undermines Carter's argument. With a set of modest additional assumptions it is possible to show it quantitatively. For instance, in Figs. 1-4 we show results of simple numerical experiments performed in order to see how timescale forcing arises in simplified evolving systems. This presents a simple realization of the astrobiological regulation model of Annis (1999). GRBs are taken to be random events occuring with exponentially decreasing frequency

$$\nu(t) = \nu_0 \exp\left(-\frac{t}{t_\gamma}\right), \qquad (1)$$

with the fixed characteristic timescale (Gyr) in accordance with the cosmological observations (e.g. Bromm and Loeb 2002), and biological timescales for noogenesis (emergence of intelligent observers) are random sample from a uniform distribution between 10^8 (minimum suggested by McKay 1996) and 10^{16} yrs (the total lifetime of the Galaxy as a well defined entity, Adams and Laughlin 1997). It has been assumed that the ages of planets are distributed according to the Lineweaver (2001) age-distribution for terrestrial planets and that the GRBs occur along the whole timespan considered in Lineweaver (2001). It is taken that the chain of events leading to life and intelligence can be cut by a sufficiently strong environmental perturbation at any planet in our toy-model Galaxy with probability Q and its astrobiological

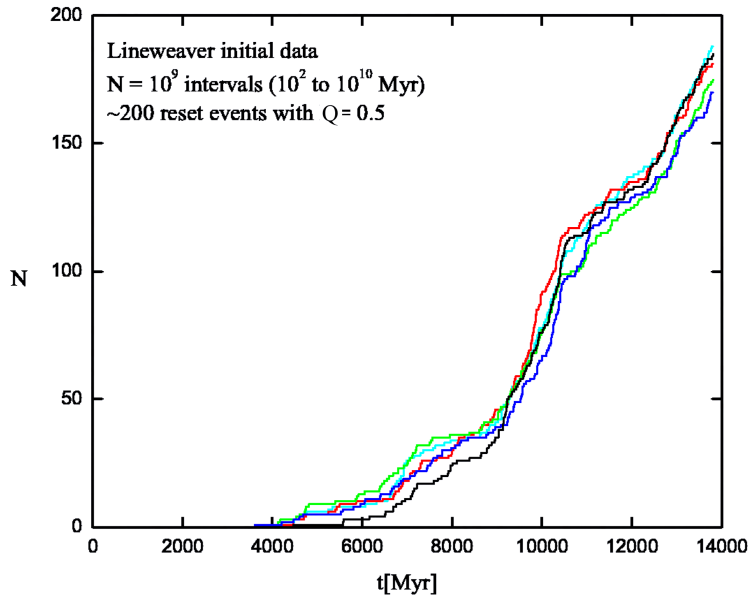

Fig. 1. *Five runs of the simplest model with exponentially distributed GRBs, Lineweaver age distribution, and probability of sufficiently strong perturbation equal to* $Q = 0.5$.

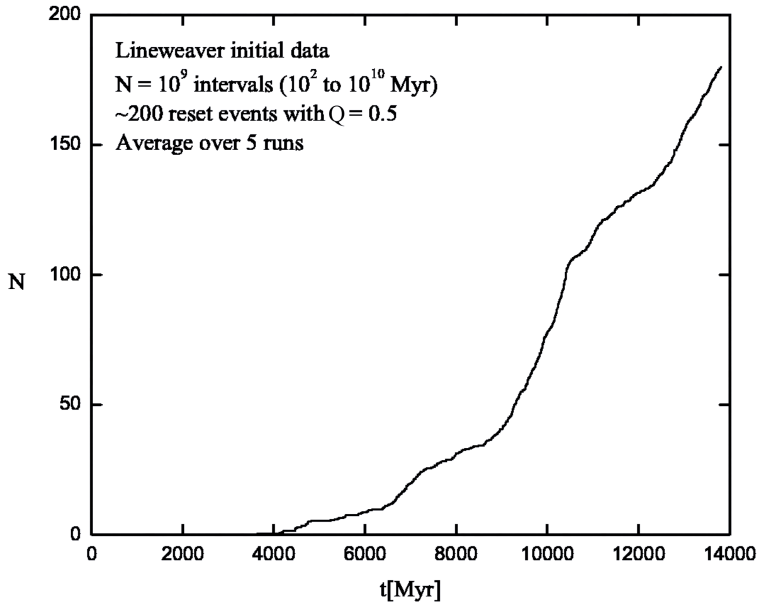

Fig. 2. *The mean value of runs shown in the previous figure for* $Q = 0.5$.

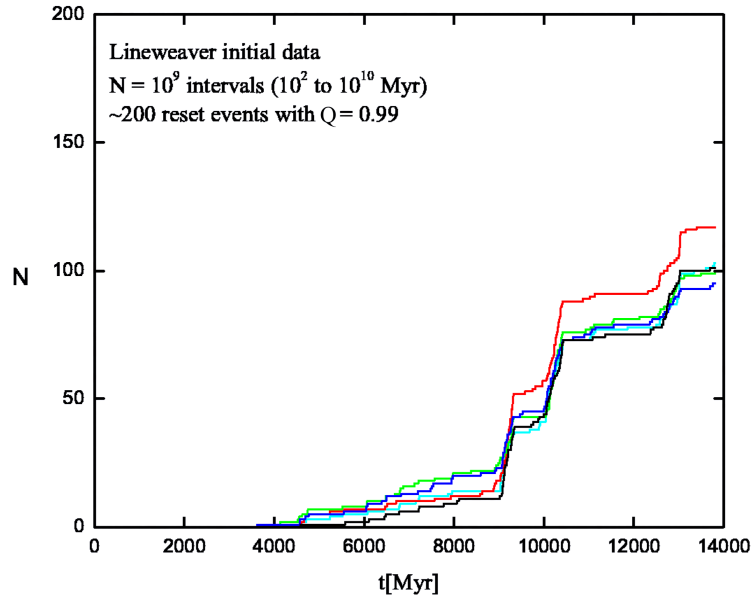

Fig. 3. *Five runs of the simplest model with exponentially distributed GRBs, Lineweaver age distribution, and probability of sufficiently strong perturbation equal to* $Q = 0.99$.

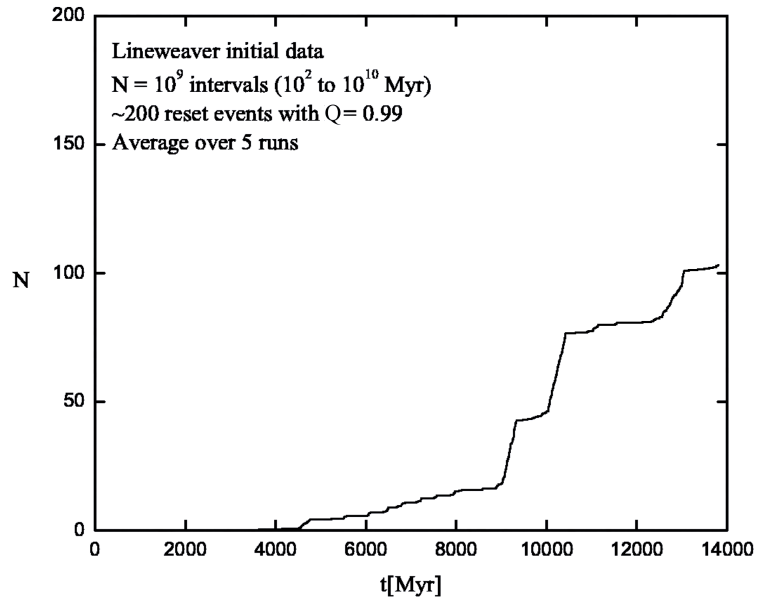

Fig. 4. *The mean value of runs shown in the previous figure for* $Q = 0.99$.

clock reset; this includes cases in which the destruction of local biospheres is not complete, but the outcome is sufficiently deflected from the pathways leading to noogenesis that the "new" timescale shoots out of our temporal window. If the "new" timescale falls within the temporal window (corresponding to more than a single noogenesis per planet) it is counted. Thus, the toy model counts only planets achieving noogenesis at least once and it does not take into account any subsequent destructive processes, either natural or intelligence-caused (like nuclear or biotech self-destruction). Probability Q can be regarded as both (1) a geometrical probability of an average habitable planet being in the "lethal zone" of a GRB, and (2) probability describing more complex effects dealing with the physics and ecology of the extinction mechanism. It is important to keep in mind that both these effects can be subsumed into a single quantity in simple models, but more sophisticated future work will include two probability parameters.

3. CARTER'S ARGUMENT

The well-known argument against the existence of extraterrestrial intelligence (henceforth ETI) due to the astrophysicist Brandon Carter (1983), and developed by various authors (e.g. Barrow and Tipler 1986), goes as follows. If astrophysical (t_*) and biological (t_b) timescales are truly uncorrelated, life in general, and intelligent life in particular, forms at random epoch with respect to the characteristic timescale of its astrophysical environment (notably, the Main-Sequence lifetime of the considered star). In the Solar system, $t_* \simeq t_b$, within the factor of two. However, in general, it should be either $t_b >> t_*$ or $t_b \simeq t_*$ or $t_* >> t_b$. The second case is much less probable a priori in light of independent nature of these quantities. Carter dismisses the third option either, since in that case it is difficult to understand why the very first inhabited planetary system (that is, the Solar System) exhibits $t_* \simeq t_b$ behaviour. On the contrary, we would then expect that life (and intelligence) arose on Earth, and probably at other places in the Solar System, much earlier than they in fact did. This gives us probabilistic reason to believe that $t_b >> t_*$ (in which case the observation selection effect explains very well why we do perceive the $t_* \simeq t_b$ case in the Solar System). Thus, the extraterrestrial life and intelligence have to be very rare, which is the reason why we have not observed them so far, in spite of the conjecture that favorable conditions for it exist at many places throughout the Galaxy.

It is clear that the conclusion of Carter's argument depends on the validity of the independence assumption. In the first place, it is the independence of biological and astrophysical processes, but the two are linked through further assumption of the independence of individual sites of biogenesis and noogenesis (namely, individual planetary systems containing Earth-like planets). We can clearly undermine this assumption by showing that the catastrophic events, like GRBs, which influence a large part or all of GHZ *induce temporal correlations* between astrobiological histories of these sites.

The conclusions one can draw from our simple models is that, for sufficiently destructive regulation events in general and GRBs in particular, the timescale forcing occurs in the system, and the assumption of independence fails. This effect is particularly visible in the Fig. 4, where long plateaux (incidentally, one including the measured age of the Solar System!) are clearly visible, i.e. a significant number of habitable planets have their timescales correlated in this manner. This significantly reduces the rationale behind Carter's argument.

4. DISCUSSION AND FUTURE PLANS

In the work of Livio (Livio 1999, and references therein), the author implies that the independence assumption can be undermined by noticing that circumstellar habitable zones exist only around stars in the spectral range of about F5 to mid-K and that the build-up of oxygen in planetary atmospheres and the ozone layer formation provide a mechanism for linking astrophysical properties with the timescales for biological evolution. Livio's model has the lower limit for t_* of approximately 3 Gyr (the main sequence lifetime of F5 stars). However, it has significant limitations; notably, it takes into account only biospheres very similar to Earth's and neglects, for instance, possibility of habitable moons around Jovian planets (e.g. Williams, Kasting and Wade 1997). In general, though, our simple model is in rough agreement with Livios findings. According to our results it is to be expected that in the "near" future even larger values of t_b fall through the temporal window.

We conclude that even the simplest preliminary models show it is too early to draw sceptical 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 mechanism(s) reset local astrobiological clocks (which, consequently, tick rather unevenly) offers a way to reconcile both our astrophysical knowledge and the idea about multiple habitats of life and intelligence in the Galaxy. However, they are very unevenly distributed in the course of GHZ history. 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 epoch*, at stages of evolution of their biospheres similar to the one reached at Earth, or at least differing for a time factor much less than the Gyr-scale one obtained by straightforward projecting Lineweaver's distribution. Unsupported assumption of gradualism is identified as the main source of confusion and unwarranted SETI skepticism (for a related discussion in the context of the Drake equation see Cirkovic 2004). In particular, we expect that future more detailed models will be able to refine these results, to show relative importance of various local and global effects in the resulting noogenesis timescales, and to point a way toward better understanding the observed "Great Silence" and the likely SETI targets.

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О ПРИНУДНИМ КОРЕЛАЦИЈАМА ВРЕМЕНСКЕ СКАЛЕ У АСТРОБИОЛОГИЈИ

B. Vukotić[1] and M. M. Ćirković

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia

УДК 52–37

Претходно саопштење

Истражујемо ефекте корелисаних глобалних механизама регулације, посебно Галактичких гама бљескова (ГБ), на временску расподелу хипотетичких насељених планета, употребљавајући једноставне Монте Карло нумеричке експерименте. Полазећи од недавно добијених модела старости планета у Галактичкој Настањивој Зони (ГНЗ), добијамо да су времена неопходна за биолошку еволуцију на настањивим планетама Млечног Пута високо корелисана. Ови резултати иду супротно познатом анти-СЕТИ антропичком аргументу Картера, и дају подршку за тренутне и будуће пројекте СЕТИ посматрања.

[1]Преписка: bvukotic@aob.bg.ac.yu.