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ARE BIOLOGICAL AND ASTROPHYSICAL TIMESCALES TRULY UNCORRELATED?

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Abstract. A well-known argument due to Brandon Carter suggests that intelligent life in the Galaxy is much rarer than a conventional probabilistic reasoning would suggest. A crucial assumption in that application of the anthropic reasoning is that the biological timescales for the development of life and intelligence are entirely independent ("uncorrelated") of astrophysical timescales for habitability of planetary ecospheres around Main Sequence stars. This assumption may be too naive extrapolation from our state of relative ignorance. We discuss the impact of several plausible mechanisms inducing a correlation between the two timescales, some of them of fairly recent origin, such as the impact of local ("galactic") gamma-ray bursts. Although the results are still far from conclusive, due mainly to our poor understanding of biogenesis and noogenesis, we hope to set up a long-term research programme aimed at addressing these uncertainties in a quantitative manner.

Explosive development of astrobiology (e.g. Darling 2001) coincided with the recent resurgent interest in catastrophism in terrestrial and life sciences (e.g. Clube & Napier 1990; Clube 1995; Raup 1999). Hereby, we discuss an important link between the two: correlation introduced by catastrophes of cosmic origin between the astrophysical and biological timescales. Why is this important for an astrobiologist? There are several relevant reasons, but the one we wish to concentrate here on pertains to the role of such correlations in probabilistic arguments attempting to answer the question about the frequency of (higher forms of) life and intelligence in our Galaxy.

The well-known argument due to Carter (1983), and developed by various authors (e.g. Barrow and Tipler 1986), goes as follows. If astrophysical (τ_*) and biological (τ_l) 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, $\tau_* \approx \tau_l$, within the factor of two. However, in general, it should be either $\tau_l >> \tau_*$ or $\tau_* >> \tau_l$. In the latter case, however, it is difficult to understand why the very first inhabited planetary system (that is, the Solar System) exhibits $\tau_* \approx \tau_l$ behaviour, since 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 $\tau_l >> \tau_*$ (in which case the anthropic selection effects explains very well why we do perceive the $\tau_* \approx \tau_l$ 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.

Now, the crucial assumption here is that there is no *a priori* reason for correlation between τ_* and τ_l. Livio (1999) has pointed out that this is the main assumption of this argument; processes which **induce** correlations between the two timescales, like the oxygenization of the atmosphere on terrestrial planets, undermine the argument. Interestingly enough, it seems that the growing awareness of the planetary catastrophes caused by cosmic (i.e. astrophysical) agencies, undermines Carter's argument. The situation is ironic, since those very destructive occurences might, in fact, be construed to help our astrobiological efforts, by bringing our attention to weaknesses in the purportive argument supporting the idea of scarcity of life, which is antithetical to the substance of the astrobiological endeavor.

Not any relationship linking biological and astrophysical timescales can be construed as a counter-argument to Carter's reasoning. For instance, it seems obvious that both biological and astrophysical timescales are bounded from above by the timescale of predicted proton decay (e.g. Adams & Laughlin 1997), so that any integral over probability densities intended to yield true probabilities must count with this high-end cut-off. Obviously, this is irrelevant from the point of view of the present problem. But this should prompt us to try to define what conditions should any link between the two (classes of) timescales satisfy in order to qualify for what we shall call "spoiling correlation"—that is, a relationship which forbids us to treat $\tau_*$and τ_l as a random numbers drawn from a prescribed set.

Generally speaking, correlation between these two timescales could be found concerning three major problems in biology: (1) origin of life; (2) evolution of life; (3) extinctions and mass extinctions. As long term processes (on biological timescale), all of these three are closely related to changes of physical conditions on the Earth and these changes are frequently dependent on astrophysical environment. Rates of radiation, flux of light, temperature changes, duration of day, land/sea ratio, magnetic field changes and many other physical factors affect biological processes and are certainly connected with astrophysical environment.

Astrophysical phenomena are usually accompanied with high-energy radiation and both mutagenic and destroying effects of ionizing radiation on living beings and biomolecules are well known. Therefore, such a radiation could have played an important role in processes of origin and evolution of life on Earth. According to the synthetic theory of evolution, spontaneous mutations, i.e. mutations with unknown cause, are one of the essential mechanisms of biological evolution. Their cause and rate could be related to nonlethal cosmic rays or γ-ray bursts. Rates of speciation and extinction also are, among other factors, dependent on the mutation rate.

The atmosphere of the primeval Earth at the time of the origin of life was, as it is believed today, either reducing or neutral and molecular nitrogen and other components of the atmosphere could be affected by high-energy radiation, such as cosmic rays and γ-rays. Products of chemical reactions could be various nitric oxides (in the atmosphere and under the sea) and ammonia (at the bottom of the sea, near volcanic active places, at high temperatures and in the presence of ferrous compounds), the latter being a source of organic nitrogen, necessary for amino acid synthesis. Concentration of organic compounds in ancient ocean, where life originated according to

Table 1: Possible catastrophic occurences of cosmic origin, shown at various spatial scales. The references for the least well-known ones are: 1.b.: Hut & Rees (1983); Jaffe et al. (2000); 1.c.: Adams & Laughlin (1999); Ćirković & Bostrom (2000); 2.a.: Clark (1981); LaViolette (1987).

#	**Catastrophic event type**	**Time-scale (yrs)**	**Comment**
1.	**Cosmological**		
	1.a. Recollapse of the closed universe	$> 10^{11}$	**very** unlikely
	1.b. Vacuum phase transition	???	possibly technologically triggered
	1.c. Horizon formation & heat death	10^{10-15}	likely in view of new cosmological data
2.	**Galactic**		
	2.a. Recurrent nuclear activity	10^{7-8}	highly controversial
	2.b. γ-ray bursts	10^{7-8}	strongly epoch & location dependent
3.	**Galactic disk/local ISM**		
	3.a. Supernovae	10^{8-9}	strongly location dependent
	3.b. Encounters with stars or GMCs	10^{7-9}	stochastic
4.	**Solar system**		
	4.a. End of Sun's life	6×10^9	MS lifetimes anthropically tuned (Dicke 1961)
	4.b. Cometary/asteroidal bombardment	3×10^7	periodicity controversial
	4.c. Secular changes in luminosity	1.1×10^9	(for the Sun at present)
	4.d. Long-term changes of orbits	10^8 (?)	highly uncertain
5.	**Planetary**		
	5.a. Moon-related (tides, sea level)	???	Benn (2001)
	5.b. Atmosphere formation/changes	10^9	Livio (1999)
	5.c. Geophysical effects (volcanism, tectonic effects, etc.)	???	no quantitative data so far

the prevailing opinion, needed for macromolecule synthesis could be reached by tidal movements. Low tide could have left behind little, shallow ponds, rich in "molecules of life", on dry land made of hard, volcanic rock, rich in minerals. Anaerobic, single-celled life could be originated in a number of little ponds like this. The influence of Moon-related events, such as strong tides (significantly stronger in the past, due to the closer proximity of the Moon), can also be recognized in so called tidal biorhythms (reproduction of some plankton organisms, some hormonal cycles, etc.) in various living organisms. Concerning these examples it is very probable that astrophysical phenomena and biological processes, especially evolution of thermodynamically open, living systems, are related, as well as their timescales.

The most interesting source of correlation recently investigated are γ-ray bursts (Thorsett 1995; Scalo & Wheeler 2002). Their catastrophical impact consists in following mechanism. The atmosphere is opaque to high-energy γ-rays and cosmic ray nuclei, and protects life on Earth from their incoming constant flux. Collisions in the upper atmosphere, however, produce a flux of energetic muons which reach the sea level. Normal flux is about 10^{-2} muons s^{-1} cm^{-2}, and the deposited ionization in biological materials is ~ 2.4 MeV g^{-1}. But, if very large fluxes of γ-rays and/or cosmic ray nuclei suddenly impinge on the atmosphere, they can have a devastating effect on life on Earth. Sources of such flux could be γ-ray bursters, for which we now have good evidence to be at cosmological distances, which makes them the most energetic events in the universe. It has been argued that, if a γ-ray burst occurs in the Milky Way, it can produce lethal fluxes of atmospheric muons at sea level, underground and underwater, destroy the ozone layer, and radioactivate the environment. Thus, some of them could have caused some of the mass extinction during the Phanerozoic era. It has also been argued (Annis 1999) that this may account for the absence of detectable extraterrestrial intelligent activity ("Fermi's paradox", "Great Silence," or "astrosociological paradox"; the best review is Brin 1983).

$\gamma-$ray bursts are particularly interesting from the present point of view, since their origination in either neutron star mergers, or in particular type of supernovae, as well as the wealth of observational data, enables tracking of their distribution function in both spatial and redshift space (e.g. Schmidt 2001; Bromm & Loeb 2002). From this distribution function it is possible, in principle, to deduce the approximate timescale for any given location within the Galaxy. Thus, we get an additional **constraint** for any astrobiological theory. We postpone the elaboration of this method for a subsequent work (Dragićević & Ćirković, in preparation).

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