Publ. Astron. Obs. Belgrade No. 98 (2018), 121 - 127 *Progress Report*

PROBING THE GALACTIC HABITABILITY TIMESCALES

V. ĐOŠOVIĆ[1], B. VUKOTIĆ[2] and M. M. ĆIRKOVIĆ[2]

[1]*Department of Astronomy, Faculty of Mathematics, University of Belgrade,*
Studentski Trg 16, 11000 Belgrade, Serbia
E–mail: vladimir_djosovic@matf.bg.ac.rs

[2]*Astronomical Observatory, Volgina 7, 11000 Belgrade, Serbia*
E–mail: bvukotic@aob.rs, mcirkovic@aob.rs

Abstract. There has been a surge of interest in numerical modelling of habitability in the last couple of years. Here we implement a probabilistic toy model of the Galactic disk astrobiological history, including colonization of habitable sites by hypothetical extraterrestrial intelligent species. Characteristic times for the emergence of catastrophic and colonization events are varied in the relevant range. The results averaged over three runs show an emerging pattern of astrobiological landscape which can be used to quantify the probability of various models for evolution and expansion of Galactic civilizations. Various approaches to building numerical models of Galactic habitability are briefly compared, and some potentially fruitful direction for the further work outlined.

1. INTRODUCTION

Numerical astrobiology and Search for Extra-terrestrial Intelligence (SETI) studies are still in their infancy and there are many possible approaches to be tested. This particular work is motivated, among other things, by the apparent absence of extraterrestrial life detections within Earth's past light cone, usually labelled as Fermi's Paradox. Developed over the past years, numerous hypotheses for resolution of Fermi's Paradox are summarized in the popular book by Webb (2015) while a robust review and scientific significance are given in Ćirković (2018).

The results of the contemporary space missions make the paradox even more appealing. Despite the abundance of confirmed extrasolar worlds all our SETI efforts did not yield the Detection. The future space missions like Transiting Exoplanet Survey Satellite or James Webb Space Telescope might provide a far better insight into the atmospheres of exoplanets and expand on our modelling of biological signatures (possibly pointing to the existence of simple life forms). The studies that relate the evolution of galactic parameters to habitability, such as metallicity, star formation rate, etc. are becoming numerous (for a review on some of them see e.g. Vukotić 2017). However, all of this might not directly contribute to the resolution of the Fermi's Paradox but rather stimulate and constrain further SETI efforts and rethinking of the existing SETI strategies.

Even with the rapid development of modern astrobiological studies in the last couple of decades neither of the 75 solutions from Webb (2015), or some combination of them, cannot be supported to be far more plausible than the alternatives: the paradox is still undoubtedly unresolved! The primary goal of this pilot study is to establish a fresh angle of view that would hopefully take us a step closer in resolving one of the greatest scientific puzzles of the modern era.

The operational foundation of the approach presented here is probabilistic simulation. A simple, fast running simulation is required to evolve the highest possible number of objects in three independent sets of probabilistic runs. The timescales that are indicative of hindering and degrading the evolution of objects towards the present day (or some fiducial epoch in the future), like the state of Earth's biosphere, as well as the ones that are relevant for spatial spreading via colonization, are varied. In contrast to our previous work (e.g. Vukotić & Ćirković 2007, 2010, 2012), simulation presented here has the most efficient and simplistic implementation that offered the best time resolution we were able to achieve so far, namely by neglecting the spatial aspects of the model. The achieved 10^4 yr simulation time step is comparable to the historical time span of the human civilization and is drastically shorter than the astronomical or evolutionary timescales. This opens several new possibilities. Not only biologicaly relevant timescales (that are usually very long compared to other relevant phenomena) but also a socio-technological ones, indicative of the development of our (or some other similar) civilization, can be discussed and modelled with such simulations, at least in principle.

Next section gives a detailed description of the simulation and model followed by the presentation of results (Section 3). The summary and some guidelines for future work are given in the concluding section 4.

2. MODEL DESCRIPTION

We simulate the evolution of Earth-like life by temporal propagation of simulation entities, for the sake of simplicity dubbed as objects. The state of each object is evolved in time according to the timescales relevant for life on Earth and development of human civilization. Each object can have 4 different discrete states labelled as: **0** – object represents the lifeless planet, **1** – object has a biosphere with simple life, **2** – biosphere has complex organisms, **3** – a technological civilization.

Objects are activated and assigned a state 0 in the probabilistic manner. For this purpose, we used random sampling from the probability density function. This function is derived from the Earth-like planet formation rate over cosmological timescales. For better compatibility with our previous works we used the rates from Lineweaver (2001), although more recent estimates are available (e.g. see Zackrisson et al. 2016).

Unlike the activation probability described above, the probability of changing the state is calculated for each object using the cumulative density function (CDF) derived by integrating the Epanechnikov (1969) kernel function:

$$p(u) = \frac{3}{4}(1 - u^2), \quad |u| \leq 1, \tag{1}$$

where argument u is calculated as:

$$u = \frac{t - \tau}{\sigma}. \tag{2}$$

Table 1: Simulated transitions and parameters of the corresponding probability functions with mean τ and standard deviation σ_τ. The entries under numbers 4, 5 and 6 are varied in the given interval on the logarithmic scale with a step of 0.2. While almost all of the transitions are towards states designated with higher numbers, the transition #4 represents the degradation of the achieved complexity possibly caused by the following or any other reason: local (e.g. asteroid impact), self-induced (e.g. nuclear armageddon), global factors that are related to galactic parameters (a nearby supernova explosion, stellar collison, etc.).

#	transition	τ[yr]	σ_τ [yr]	cause
1	$0 \to 1$	5×10^8	1×10^8	evolution
2	$1 \to 2$	1×10^9	3×10^8	evolution
3	$2 \to 3$	6×10^8	1×10^8	evolution
4	$3 \to 2$	$[10^4, 10^{10}]$	0.1τ	catastrophism
5	$2 \to 3$	$[10^4, 10^{10}]$	0.1τ	colonization
6	$1 \to 3$	$[10^4, 10^{10}]$	0.1τ	colonization

Here, t is the time that object have spent in current state, τ is the length of the relevant timescale and σ controls the kernel width. The derived CDF has the form:

$$0.25(-u^3 + 3.0u + 2.0), \quad |u| \leq 1. \tag{3}$$

This is a parabolic function and has a higher computation efficiency when compared to more commonly used kernels (such as the error function derived from integration of a Gaussian kernel, or the uniform kernel). Parameters of the used CDFs for all simulated change of object states are given in Table 1.

During the activation of the objects each object is assigned a set of 6 random numbers (one for every allowed transition). In each step of the simulation the number for the relevant transition is compared against the probability derived from the CDF as described above. After activation, objects in state 0 are examined for transition to state 1. Objects in states 1 and 2 are first examined for colonization induced transitions to state 3 (transitions induced when other objects in state 3 colonize objects in question that are in state 1 or 2, see transitions 5 and 6 in Table 1).

To calculate if a given object in state 1 or 2 is colonized to state 3 by other objects that are already in state 3, the CDF argument u depends on the average time that objects spent in state 3 in the current instant of the simulation (t_{av3}), current number of objects in state 3 (n_3), total number of simulated objects n_{tot} and $\sigma_{\tau_{\mathrm{col}}}$ as:

$$u = \frac{n_3}{n_{\mathrm{tot}}} \frac{t_{\mathrm{av3}} - \tau_{\mathrm{col}}}{\sigma_{\tau_{\mathrm{col}}}}. \tag{4}$$

Fr the sake of simplicity, our model implements only time variable while colonization also has a spatial character. Since the distances between objects in our simulation are not considered we use time averages of colonization relevant quantities (Equation 4), to make the overall estimate of colonization activity. Unlike Equation 2, where variable u is calculated for each object in each time step, variable u in Equation 4 is calculated only once per time step and is the same for all objects at the given time step since it depends on average values. The further treatment of this variable for calculating transition probabilities using CDF is the same as in the case of Equation 2. The difference between these two cases stems from the fact that a colonization of an object does not depend on that object evolution (except the condition that it should be in state 1 or higher), but on the evolution of colonization conducting objects.

3. MODEL PARAMETERS

In each run of the simulation we have evolved 500 objects and the simulation output is averaged over 3 runs for each set of input timescales. At the beginning of the 10 Gyr simulated time span there are no active objects.

We use biological timescales inferred from Earth's Fossil Record. After the formation of Earth, 4.556 billion years ago, it took the next several 10^8 yr for the appearance of the earliest single-celled life (cf., Dodd et al. 2017). Complex metazoan lifeforms took very long time (about 3.5×10^9 yr, Maloof et al. 2010) to appear and take hold in the so-called Cambrian Explosion. This left cca. 5×10^8 yr until present (Maloof et al. 2010) and the appearance of a technological civilization on Earth. Our ignorance of extraterrestrial civilizations limits our knowledge about civilizations in general. From the fossil record we can argue about the beginnings of the civilized era on Earth, but it is much more complicated to predict if or when such a civilization might experience an extinction, possibly in a self-destruction (for analyses of such scenarios see Bostrom & Ćirković 2012). Also, there is an uncertainty about the time scale for such a civilization to develop a potential for colonizing the other worlds. In our model we are probing different values for the timescales indicative of colonization, as well as hazardous events that might degrade the state of simulated objects (see Table 1 for the coverage of the parameter space).

In Table 1, the entries in rows 1-3 are representative of the timescales inferred from the Earth's fossil and historical records and should be understood as the fiducial values (Copernicanism suggests that we should regard ourselves as typical, i.e. close to mean values of whatever is the underlying distribution). Timescale from row 4 (τ_{cat}) is varied independently of transitions from rows 5 and 6 which are varied together as they both represent the colonization phenomena and since they are varied in the same manner the related timescale is labelled as τ_{col} in the further text.

The upper limit for the time intervals of transitions 4-6 (Table 1) is the time span of our simulation which corresponds to the present age of the Galaxy. The lower limit for the same transitions is the best achieved time resolution of our simulations which is realistic in terms of our current understanding of interstellar travel and Earth civilization time scales. It is important to emphasize how the drastic difference between civilization-related and astrophysical timescales erases any specific uncertainty as too the numerical values of the former (e.g. Lipunov 1997).

4. RESULTS AND ANALYSIS

For each set of input timescales given in Table 1 we made 3 runs of the simulation. While this is obviously not enough for obtaining statistically valid conclusions, the purpose of this exercise has been primarily to test the general soundness of the procedure and obtain an estimate of the computational load. The averaged results are given in Figures 1 and 2.

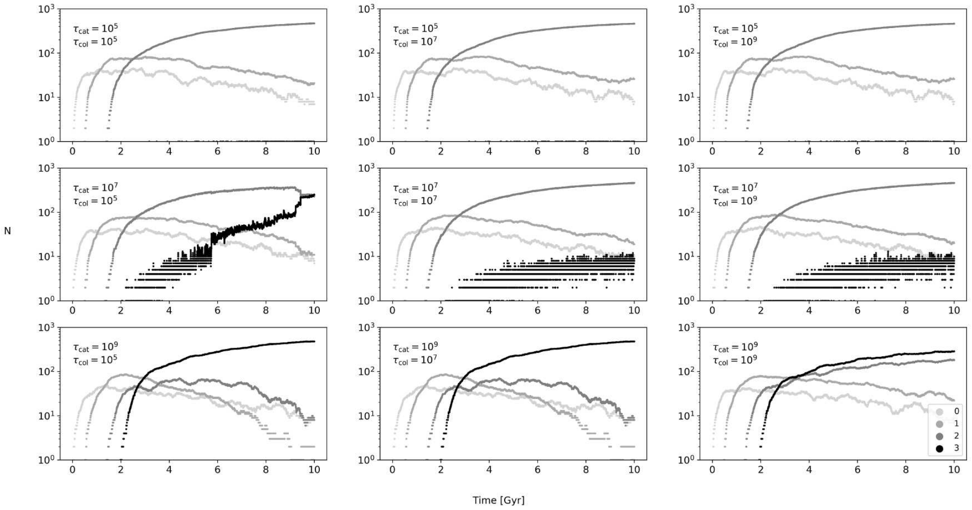

Figure 1: Number of objects in a given state (N, vertical axes of panel plots) at each time step (horizontal axes). Legend in the lower right panel is applicable to all panels. It indicates the gray- scale coding of the object's state. Each panel gives a different combination of τ_{cat} and τ_{col}, the values indicated on the panels are given in years. Results are averaged over 3 runs.

The bottom row of panels in figure 1, gives the highest number of objects in state 3 which is expected since the τ_{cat} is long. Interesting case of $\tau_{\text{cat}} = \tau_{\text{col}} = 1$ Gyr gives the lowest number of objects in state 3 (for the bottom row of panels) since it has the least efficient colonization which results in higher number of objects in state 2. The upper panel row gives almost none objects in state 3 due to low value for τ_{cat} that degrades objects from state 3 to state 2. The results are similar for all panels in this row even when scales are comparable $\tau_{\text{cat}} = \tau_{\text{col}} = 10^5$ yr. The results from bottom and upper rows indicate that in the current simulation the hazardous events are somewhat more dominant at $\tau_{\text{cat}} = 10^5$ yr over colonization than vice versa for the $\tau_{\text{col}} = 1$ Gyr case. This might be even more appealing since the colonization is implemented via two transitions while the catastrophic events are only in one ($3 \rightarrow 2$) transition.

However, the most interesting from the standpoint of resolving the Fermi's paradox might be the middle row of panels. When $\tau_{\text{cat}} = \tau_{\text{col}} = 10^7$ yr apparently does not differ from $\tau_{\text{cat}} = 10^7$ yr and $\tau_{\text{col}} = 1$ Gyr. Even such a small number of objects in state 3 might point towards the regime that should be investigated for the purpose of resolving the Fermi's paradox. In addition, this regime shows rapid relative oscillations in the number of objects in state 3, when that number is small. This produces parallel horizontal black lines, since the N scale is logaritmic and N is an integer variable. The much higher number of state 3 objects for $\tau_{\text{cat}} = 10^7$ yr and $\tau_{\text{col}} = 10^5$ yr case implies that colonization might just have an upper hand over catastrophic events, unlike the catastrophic regimes from upper and bottom rows.

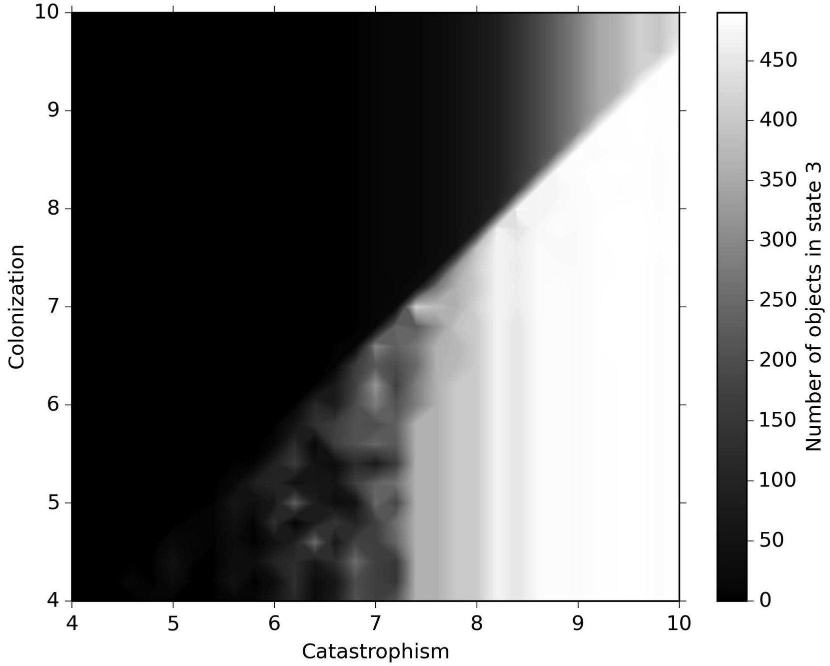

Figure 2: Gray-scale coded averaged number of objects in state 3 at the end of the simulation for all simulated combinations of τ_{cat}, axis labelled "Catastrophism and τ_{col}, axis labelled "Colonization".

This means that if the catastrophic events operate on the scales of tens of millions of years, which is very likely for physical timescales induced from Earth's records (e.g. global climate and magnetic field changes), studies of the Sun and other bodies in the Solar system. The sensitivity of number of state 3 objects to τ_{col} in $\tau_{\mathrm{cat}} = 10^7$ indicate that colonization might be a much harder task than originally thought through by Enrico Fermi during his famous Los Alamos lunch time saying.

Figure 2 is a filled contour plot, gray-scale coded. Location of the turbulent region, that might offer the most fruitful research on resolving the Paradox is clearly seen in Figure 2, $\tau_{\mathrm{cat}} \approx (10^6, 10^7)$ and $\tau_{\mathrm{col}} \approx (10^4, 10^7)$. In addition to findings from Figure 1, Figure 2 implies that for the lower catastrophic timescales lower colonization timescales are in the turbulent regime, but still the diagonal feature on the plot (separating brighter from darker part) is somewhat below the $\tau_{\mathrm{cat}} = \tau_{\mathrm{col}}$ line which supports the findings from Figure 1 that longer colonization times (when compared to catastrophic timescales) are likely for the efficient resolution of the Paradox.

Other features, although less pronounced than the turbulent region, are also evident in Figure 2 and this requires more investigation with simulations of higher resolution. However, the turbulent region is the most interesting part of our investigation, which needs more detailed analyses.

5. CONCLUSION

We made a simplistic simulation calibrated to relevant timescales of evolution of life on Earth. Multiple sets of runs (3 for each point in the relevant parameter space) are performed varying the timescales relevant for colonization and catastrophic events. If confirmed by subsequent detailed implementation in many runs, our results will imply that likely resolution to Fermi's paradox is in the regime where catastrophic events are somewhat more dominant over colonization events. This implies that current absence of detecting other civilizations in the Milky Way might be explained with the fact that colonization and expansion are a really hard to perform tasks, while the amplitude of risk is higher than hitherto assumed. These tentative conclusions are in accordance with the astrobiological phase transition hypothesis (Annis 1999; Ćirković & Vukotić 2008). Also, we have outlined the region of the parameter space that offers the most fruitful direction for future research.

Acknowledgment

The authors acknowledge financial support from the Ministry of Education, Science and Technological Development of the Republic of Serbia through the project #ON176021 "Visible and invisible matter in nearby galaxies: theory and observations".

References

Annis, J.: 1999, *J. Brit. Interpl. Soc.*, **52**, 19.

Bostrom, N., Ćirković, M. M.: 2008, *Global Catastrophic Risks*, Oxford University Press, Oxford.

Ćirković, M. M., Vukotić, B.: 2008, *Orig. Life Evol. Biospheres*, **38**, 535.

Ćirković, M. M.: 2018, *The Great Silence*, Oxford University Press.

Dodd, M. S., Papineau, D., Grenne, T., Slack, J. F., Rittner, M., Pirajno, F., O'Neil, J., Little, C. T. S.: 2017, *Nature*, **543**, 60.

Epanechnikov, V. A.: 1969, *Theory Probab. Appl.*, **14**, 153.

Lineweaver, C. H.: 2001, *Icarus*, **151**, 307.

Lipunov, V. M.: 1997, *Astyrophys. Space Sci.*, **252**, 73-81.

Maloof, A. C., Porter S. M., Moore, J. L., Dudás, F. Ö., Bowring, S. A., Higgins, J. A., Fike, D. A., Eddy, M. P.: 2010, *GSA Bulletin*, **122**, 1731.

Vukotić, B., Ćirković, M. M.: 2007, *Serb. Astron. J.*, **175**, 45.

Vukotić, B., Ćirković, M. M.: 2010, *Publ. Astron. Obs. Belgrade*, **90**, 85.

Vukotić, B., Ćirković, M. M.: 2012, *Orig. Life Evol. Biospheres*, **42**, 347.

Vukotić, B.: 2017, *Habitability of the Universe before Earth, eds. R. Gordon & A. Sharov*, Elsevier.

Webb, S.: 2015, *If the Universe Is Teeming with Aliens ... WHERE IS EVERYBODY?*, Springer International Publishing, Cham Switzerland.

Zackrisson, E., Calissendorff, P., González, J., Benson, A., Johansen, A., Janson, M.: 2016, *ApJ*, **833**, 214.