Fermi Paradox and the Replication Limit

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Abstract. A well-known paradox in astrobiology has been discussed at length by the research and general community. In this work we offer a novel perspective associated with the relationship of timescales of development and response of natural learning systems. It is shown that a balance that could lead to a long-term stable development of such systems can be highly unstable and the development trajectory is predisposed to one of the two main tracks: gradual decline in a harsh environment; or exponential expansion driven by replication, with resulting depletion of the environment. Thus, the possibility of a stable balanced development beyond planetary level can be strongly suppressed for such systems that can explain observed absence of advanced intelligent species at the solar system and higher levels of development.

Keywords: biological systems, replicating systems, astrobiology, Fermi paradox, Drake equation

1 Introduction

In this work we consider replication-based biological systems. Replication is a highly effective adaptive mechanism that ensures stability and propagation of natural living systems in complex and changing environments. A great majority of species on Earth use this strategy.

Replication is a complex and volatile process [1,2] that strongly depends on abundance of required resources and favorable configurations of specific conditions [3]. The opposite is true as well: deficit or insufficiency of resources can result in decline of replication ability and eventually, general decline.

Thus, one can distinguish two principal types of development trajectories of replicating systems: facilitated replication, associated with favorable environment and abundance of resources; and replicatory and / or general decline, where the environment is harsh and the resources available from the environment are not sufficient for stable and reliable replication.

2 Replicating Systems

First, we will examine more closely replicating systems in a favorable environment. With facilitated replication, two consequences occur naturally: population growth and as a result, increase in resilience of the system as a whole; and specialization and diversification, caused by differentiated environment and specifics of adaptation in the population groups. That, in turn brings about the effect of competition, with groups developing superior replication abilities coming to dominate and becoming the new baseline for the next phase of development, resulting in continuing improvement in replication ability as long as positive resource environment remains in place.

It needs to be stressed here that replication in general can mean more and considerably more than physical replication of an individual organisms. It can mean as well:

- replication of the immediate environments;
- of multiple dependent resources;
- of the means and methods of producing those;
- of any other objects, materials or information, beneficial for individuals or socially;
- and eventually, of models of the environment.

In the course of evolution, organisms and species came up with numerous and diverse replication strategies.

2.1 Replication Timescale Law

We would like to examine two statements related to facilitated development of a replicating system. The first one is that the timeframe of replication monotonously diminishes, while the impact or outcome, measured in some units of replicated entity, increases exponentially.

The second statement is that exponential increase in the impact of a replicating system is associated with an exponential increase in consumption of energy from the environment.

Let us consider first the effect of competitive development mentioned earlier and its impact on characteristic timescale of replication. For an example, let us consider two groups of population with different replication strategies. If the difference is in physical replication of individuals, for a number of possible reasons, it can be expected that in several generations the population of the group with superior replication strategy would grow significantly higher than that of the other group and it would come to dominate.

Secondly, consider an example of the first group obtaining superior method of production of life necessities. Clearly in the course of a single generation, or less it could acquire significantly more resources than the other group and would be able to dominate economically, through acquisition of property and resources.

Lastly, we will consider a case of replication of information. Information trends, such as popular ideas, music, personalities and so on, can propagate in the modern social environments almost instantly creating a world-wide wave of replication of the entity of interest.

What can be seen in these examples is steadily diminishing replication timescale τ_R, in physical time necessary to propagate the replicated entity through the same element of the environment. One can suggest an approximate law of the form:

$$\tau_R \to \frac{\tau_R}{n} \tag{1}$$

within the same unit of physical time, *t* and as long as the conditions of favorable development are satisfied. As is straightforward to see, it results in an exponential law of production of replicated entity:

$$r \propto e^{\beta t} \tag{2}$$

where *r* is the rate of replication.

The condition (2) can be supported with the following simple yet realistic model. Suppose there is *K* independently developing groups of population, producing incremental improvement in replication rate α with probability *p* over a unit of time. The resulting change in the replication rate *r* over time *t* can be estimated from Bernoulli distribution as:

$$dr \sim \alpha\,(1-(1-p)^K)\,r \sim \alpha\, p\, K\, r = \beta\, r \tag{3}$$

producing an exponential law (2) for *r(t)*.

The second statement is based on the assumption of energy parity per replicated unit of information. For example, one can compare the energy cost of replication of a cellular unit of information, an amino acid to that of a digital unit of information, a bit in modern communications systems: $U_{cell} \sim 10^{-19} - 10^{-18}$ J; $U_{inf} \sim 10^{-5} - 10^{-4}$ J [4-6]. Table 1 shows the estimate of replication energy balance over the course of Earth evolution.

Table 1. Energy cost of replication over time, Earth system.

Epoch	Duration, BY	Characteristic	Replication energy, GJ
Hadean	0.5	early amino acids?	vanishing
Precambrian	4	early life	small
Mesozoic	0.5	pre-human life	to be estimated
Preindustrial	0.06	human pre-industrial	10^{11} (1)
Industrial	3×10^{-7}	industrial	to be estimated
Post-industrial	3×10^{-8}	post-industrial	$> 2 \times 10^{11}$ (2)

(1) Based on rubisco – amino acid cellular replication energy estimate, Appendix A.1.

(2) Based on digital replication energy estimate, Appendix A.2.

As can be concluded from these estimates, the energy cost of replication of the Earth system is showing exponential-type trend, in agreement with the arguments presented earlier in this section.

2.2 Response Timeframe and "Narrow Window" Trend

Response of a replicating system to changes in the natural environment, including those caused by itself, is based on its perception and forecasting of the trend of change. It can be argued that the trend is linear based on the points in its experience and memory.

For example, an organism can attempt to forecast a trend based on several recent time points in its memory. An elder of a prehistoric settlement will have an active lifespan of approximately a generation to estimate the trend.

Modern governments have even shorter decision timeframes, a fraction of the generation span as a reference time scale. As a result, the system will produce a "narrow window" estimate or forecast of the trend as a linear approximation over the interval of reference recorded in its memory.

2.3 Replication Gap

The replication gap is the gap between the actual development curve of a replicating system in a favorable environment and the trend that can be expected or forecasted by it as discussed in the preceding section, as illustrated in Fig.1.

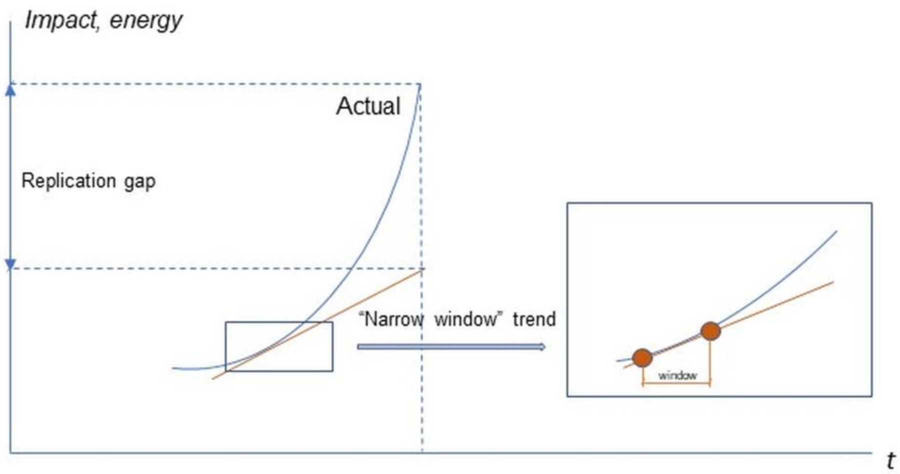

Fig.1 Actual replication curve vs. "Narrow window" trend

As a result, a developing replicating system always underestimates the change in the environment with continuously growing gap between anticipated and actual effect. The exponentially growing gap is dictated by the principles of the evolution of a replicating system and it has no capacities or means to correct and balance it.

Thus, in a favorable environment a developing replicating system always moves in the direction of exponentially accelerated replication (2) associated with maximum consumption of resources and ultimately, energy from the environment.

2.4 Replication Limit

As a result of the effect of exponential expansion and replication gap, a replicating system in a favorable environment is bound to reach the boundary of its "livable" space defined by the limits of resources and energy that can be obtained from the surrounding environment.

A replicating system has a strong dependence on sufficiency or abundance of necessary resources. In an environment where resources are not sufficient to sustain replication, the system would entire the trajectory of decline.

Thus, the evolution of a replicating system near the environmental boundary can be described by an oscillation around it (Fig.2). Expansion past the boundary would cause depletion of resources and a switch to a decline trajectory. At some point below the boundary, under favorable conditions, accelerating replication can reignite, and the cycle can continue for a number of iterations.

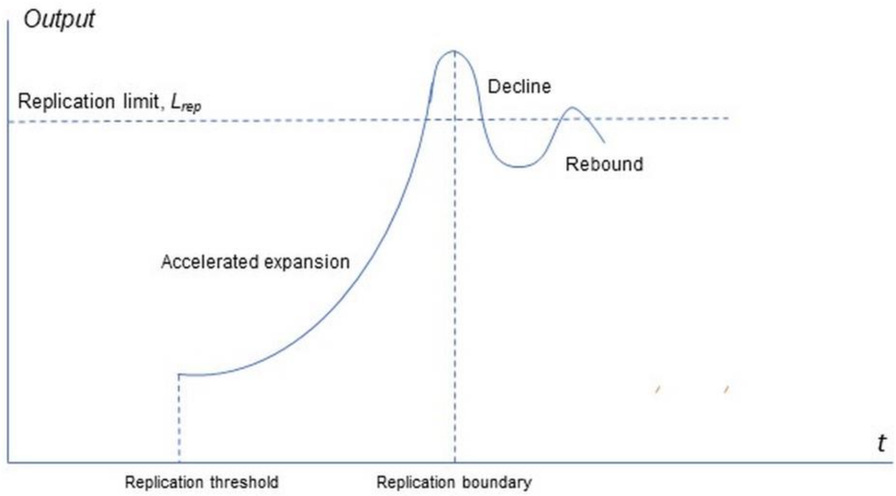

Fig.2 Trajectory near the replication limit

Even if a balance can be achieved at a certain point of the trajectory, a minimal change in the environment could tip it to accelerating expansion or decline, being an unstable temporary state between the stable configurations of accelerating expansion and decline (two valley landscape).

This qualitative analysis suggests that there is a natural limit of evolution: replication limit, that cannot be passed in by a standard, main sequence system ("fish below the ice" analogy).

In the described picture, a replication limit is specific for each combination of replication system and its immediate environment. One can also define a more general "planetary-type" replication limit, that however is not limited to planetary systems, as the maximum limit of expansion in a connected environment of a similar character.

Such environments can be planets and planetary systems; nebulas; stars; and other specific regions of space with consistent composition.

Quantitatively, replication limit can be expressed as a fraction of the energy flow through the environment of the system as defined earlier that is utilized by the replicating system:

$$L_{rep} = \frac{e_{util}}{e_{tot}} \quad (4)$$

where e_{tot}: total energy flow through the environment; e_{util}: utilized fraction thereof. Note that definition (4) is a naturally dimensionless number, $0 < L_{rep} < 1$. Specific value of L_{rep} at which the effects discussed in this section could be observed can be determined from quantitative models.

3 Replication Limit and Drake Equation

The well-known and often quoted in the context Drake equation [7] estimates probability of emergence of advanced intelligent species and civilizations beyond planetary level. It has several challenges that have been discussed widely, including: some of the probabilities are difficult to estimate without representative samples of the distributions; the other is that it reflects to a large extent, an Earth-based planetary human technological civilization, and therefore can be interpreted as Earth-centric and anthropocentric model that may not be sufficiently general to account for civilizations significantly different from ours.

Based on the analysis in this work, one can propose a more general theoretical and practical model that allows to make some intuitive qualitative estimates. Based on these considerations, to achieve a stable, sustained survivability on the level above planetary-type as described earlier, a replication-based species would need to penetrate two essential barriers: the replication threshold, and the replication limit.

$$P_{plan} = P_{thr} \times P_{lim} \quad (5)$$

where P_{thr}: probability of crossing replication threshold; P_{lim}: probability of passing the replication limit.

The first term can be strongly suppressed at least in planetary systems due to the fact that it requires environments abundant in specific resources as well as specific conditions for begging of self-replicating reaction. This opinion is supported by theoretical research [2,3] as well as observations in the Solar system that so far have not found traces of replicating systems originating in different planetary environments in our solar system.

The arguments that the latter factor can be strongly suppressed by the principles of development of replicating systems were discussed in the preceding sections, with the conclusion that for a main sequence replicating systems $P_{plan} \ll 1$, consistent with the observation of the paradox.

4 Escaping the Limit: Exceptions and Limitations

As was shown above, a transition of a main sequence replicating system beyond its natural “planetary” (in a broader sense as discussed earlier) environment is strongly suppressed by the factors of replication threshold and replication limit.

A system can escape this scenario by transitioning to another environment such as near outer space (or a sequence of transitions). This option, popular in science fiction can be suppressed as well by the condition of facilitated replication or specificity, that is, an abundance of specific resources under specific conditions. Indeed, a system transitioning into another unfamiliar and potentially hostile environment would require additional resources even to sustain its current replication level. That would require an environment more beneficial than the one it is escaping, with ready abundance of multiple necessary resources and ample energy sources. Such a coincidence could be extremely rare by statistical considerations such as probabilities of simultaneous availability of multiple critical resources and abundance of energy.

Another possible strategy would be to attempt to avoid the consequences of approaching the replication limit and achieve a lasting balance with the environment via imposing self-regulation. We argue that for a system with origins in replication this can be an exceptional scenario. An argument that would need to be substantiated in a more in-depth discussion is that in a stable thermodynamical equilibrium a subsystem must have a constant number of degrees of freedom. Thus, limiting energy consumption of a system in a stable equilibrium with the environment would be equivalent to imposing a strict limit on its independent degrees of freedom. Such a limit would be in a strong contradiction to the character of a replicating system expanding exponentially and thus naturally predisposed to creating new degrees of freedom. This conflict would create a permanent tension with the balancing action, increasing instability and acting in the opposite direction to it.

Moreover, even if such a balancing strategy could succeed, it would likely severely reduce both channels of detection of an advanced intelligent system: modification of the natural environments and communications. This, this both likelihood and interspatial visibility of escape channel can be expected to be suppressed as well.

The final type of exception would be a non-replicating system capable of long-term adaptation, that emerged naturally (mono-organism) or as biological modification of an earlier replication systems (post-replication). Instances of such systems are not known at this time and while they could pose interesting philosophical questions discussed in the literature, much of it could be considered speculation at this time.

5 Observational Results

The approaches outlined here provide a basis for observational studies with the aim of finding developing civilizations approaching the replication limit. As pointed out in Section 2.1, Table 1 to locate a developing replicating civilization one needs to be looking for significant changes in the energy dissipation patterns on the planetary scale, excluding possible natural causes.

5.1 Earth-like Planetary Replicating Systems

Suppose there is a sample of Earth-like planets in the adjacent sector of the galaxy of a compatible age and instruments and methods are available to measure planetary characteristics such as: albedo, spectral emissions, temperature, atmospheric composition and others. Suppose also that based on some framework of theory and observations one can associate instances in the sample with planetary baseline of characteristics at the initial phase of the planetary evolution.

Then, by comparing current observations of planetary characteristics with the baseline and accounting for effect of natural forces, one can estimate the population of candidate replicating systems as the fraction of the sample showing significant change outside of known physical causes (as there is at least one known instance, $P_{thr} > 0$). Achieving certain level of confidence in such observations would allow to establish bounds on the replication threshold for Earth-like planets:

$$P_{thr,e} \sim \frac{N_{rep}}{N_{sam}} \tag{6}$$

where N_{rep}: the population of the candidate replicating sample; N_{sam}: the size of the sample.

It is more challenging to propose approaches to experimental verification of the replication limit P_{lim} as that would require confirmed observations of civilizations that have achieved a level of development beyond planetary.

5.2 Communications Window

There are two main channels in which a developing replicating system approaching planetary replication limit can be detected: modification of its natural environment; and communicating. The analysis in the preceding sections pointed to the conclusion that passing a planetary replication limit for such system can be strongly suppressed and receiving communications from advanced post-planetary civilizations, unlikely.

This leaves only extremely brief, in planetary timescales periods or windows of communications where still developing civilization could have both the incentive and the means to engage into communication attempts on the scale beyond planetary: a replicating system has to be sufficiently close to the replication limit being able to produce and release sufficient amounts of energy; at the same time, in the trajectory phase before transitioning into the decline mode (i.e., before the decline point, Fig.2). In the history of humanity such a window can be expected to last in the order of 10 – 100 years (depending on the measure of planetary optimism at this time), that is, $\sim 2 \times 10^{-8}$ of the planetary timescale. Clearly, a coincidence of two or more communicating civilizations in a close region of space can be estimated to be extremely rare statistically.

From these arguments one can conclude that the probability of detecting communications from either of the sources: advanced post-planetary replicating civilization; and near replication limit planetary civilizations can be strongly suppressed, in agreement with the observations up to date.

5.3 Other Types of Replicating Systems

Evaluating characteristics of non-planet-based replicating systems, such as nebula; stellar; gas giant-based, complex cosmic electromagnetic fields and others, now an exclusive domain of science fiction could be an interesting and challenging direction of future research.

6 Discussion

As follows from the presented arguments, progression of replication-type civilizations past planetary replication limit can be expected to be strongly suppressed by the factors of replication threshold and replication limit ("main replicatory sequence"). These findings are consistent with the statement of Fermi paradox that becomes a corollary of the presented framework of analysis.

Observable exceptions from the main sequence appear to be suppressed as well as discussed in Section 4.

Further progress in the precision and scope of exoplanetary astronomy in the coming decades as discussed in Section 5.2 can offer more experimental insights into the existential question: how likely is the emergence of life in the Universe, if the principles and forces discussed in this work would not put a brake on this line of investigation in a manifestation of some universal irony.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Appendix. Energy Cost of Cellular and Digital Replication

A.1 Cellular Replication

Based on published sources [4,5], the replication cost of a single amino acid ε_{aa} can be estimated in the order of 1 – 10 ATP, equivalent to 10^{-19} – 10^{-18} J. The higher end of the range, 10^{-18} will be taken for the estimate.

Next, based on the estimate of the total planetary mass of a common protein like rubisco [7], the total planetary population of amino acids can be estimated as:

$$N_{aa} = N_{rub} \times \alpha_{rub} \times f_{sc} \sim 5 \times 10^{38}$$

where N_{rub}, the total planetary number of rubisco protein molecules that can be obtained from the estimate in [8]; α_{rub} = 470, amino acids in rubisco; f_{sc}, scale factor to account for other types of proteins, assumed 10^2.

The resulting value for the energy cost of cellular replication can be estimated as:

$$E_{cell} = N_{aa}\, \varepsilon_{aa} \sim 5 \times 10^{11} \text{ GJ} \tag{7}$$

A.2 Digital Replication

A unit of digital information in replication and transmission is one bit. The estimate is based on the estimate of the global data volume by 2025 of 180 zettabyte (1.4×10^{24} bits) [9].

The energy cost of copying and transmitting one bit of information was estimated as 0.1 kWh ~ 0.4 MJ per 1 GB ~ 5×10^{-5} J / bit [6]. The resulting value for the energy cost of digital replication can be estimated as: $E_{dig} \sim 10^{11}$ GJ.

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