A trampoline effect occurring in the stages of planetary reseeding

Ian von Hegner
Aarhus University

Abstract Impactors have hit the Earth ever since its formation and have continued to be infrequent guests throughout the Earth's history. Although the early part of the Earth's history was marked by these violent events, it is known that life was present early, possibly existing already in the Hadean Eon. It is possible that life can be, and still is, transported between the worlds of the solar system due to impacts leading material away from the impact region. In addition to this lithopanspermia theory, it has been suggested that ejected material can also return to its home planet and 'reseed' life after the world has recovered after a global impactor, thus restarting evolution, the so-called 'refugium hypothesis'. Next to such impactors more frequent impacts from smaller non-sterilizing impactors existed during the Heavy Bombardment epoch, feeding material potentially harboring viable organisms into near Earth space. During the three stages of planetary reseeding the encapsulated bacterial population will experience abiotic stressors, specifically they will experience pressure and heat shock twice, in stage 1 and after a recovery phase in stage 2, again in stage 3. While many circumstances have played a role in life’s endurance in the early history of the Earth, a particular biological effect could potentially be conferred on a bacterial population in this scenario. Thus, the surviving population will not only experience an increase in the frequency of robust genotypes, but it can also be expected that their stress tolerance is enhanced compared to non-stressed organisms of the same species. Hence, the trampoline effect means that the mean robustness of the bacterial population towards these stressors is higher in stage 3, than at stage 1. In principle, the time between the impactor and the reimpactor need not be long before this trampoline effect appears. Experiments simulating stage 1 have to take this effect into consideration when attempting to estimate the survival probabilities of a population of organisms in worlds such as the past Earth. Thus, the stages in planetary reseeding can themselves be considered facilitators for a process that enhances the stress capacity of the collected bacteria and thus their survival capacity. This process may have played a role in the survival of life through these violent periods of Earth's history, and thus may have an impact on inhabited worlds in general.

Keywords: astrobiology; evolution; late heavy bombardment; lithopanspermia.

Introduction

Impactors have hit the Earth ever since its formation via accretion from the solar nebula approximately 4.5 billion years ago. They have continued to be infrequent guests throughout the history of the Earth, although their frequency and size have declined since the late heavy bombardment epoch [Reyes-Ruiza et al., 2012]. The Late Heavy Bombardment occurred approximately 4 billion years ago and usually dates to end 3.8 billion years ago, although evidence indicates that terrestrial impacts did not cease here, but rather waned gradually until approximately 3.0 Ga ago [Lowe et al., 2014]. While the Earth is still affected by impactors from time to time, kilometer-scale asteroidal or cometary impactors are now a rare, though still a potential event, estimated to occur at millions of year’s intervals [Chapman and Morrison, 1994].

Although the early part of the Earth's history was characterized by these violent events, it is known that life already existed at this time, and evolution thus was active even then. Thus, while the details are still under debate and much remains to be elucidated, it is clear that the first fully autonomous cell with a high certainty existed 3.5 billion years ago [Schopf et al., 2007], thus existing in the Archean Eon which is usually been dated to between 3.8 and 2.5 billion years ago [Coenraads and Koivula, 2007]. The prebiotic processes that led to this cell were probably not a single event but instead the transition from chemistry to biology was a gradual series of steps of increasing complexity, possibly taking place in a ‘great prebiotic spot’ on the planet [von Hegner, 2019]. Thus, several lines of evidence point to the emergence of life on Earth between 4.1 to 3.5 billion years ago [Bell et al., 2015], thus, taking place in the Hadean Eon, which usually dates from the end of the Earth's accretion until 3.8 billion years ago [Coenraads and Koivula, 2007].
With these two facts in place, impactors and the presence of life, it is possible that life can be, and still is, being transported between the worlds of the solar system, as such impacts can lead to material accelerated away from the impact region. Thus, depending on the impactor energy, such ejected material can reach velocities higher than a world's planetary escape velocity, permitting meteorites from e.g. Mars to reach Earth and vice versa [Brennecka et al., 2014]. Thus, lithopanspermia is a seasoned theory that proposes the natural exchange of organisms between solar system bodies due to asteroidal or cometary impactors.

Since billions of rocks were launched during this early violent time of the solar system [Sleep and Zahnle, 1998], and e.g. Mileikowsky et al. (2000) estimated that a fraction of a Bacillus subtilis spore population ($10^6$) would in fact survive cosmic radiation in space for approximately 1 Ma if protected by 1 m of meteorite material (assuming the rock initially harbored about $10^3$ spores/g) and 25 Ma if protected by 2 to 3 m of meteorite material, the lithopanspermia hypothesis seems to have some justification.

Thus, the transport of life from Earth may have reached Venus and even the moons of Jupiter and Saturn. Indeed, it has been suggested that life first appeared on Mars and subsequently transported to Earth [Davies, 2003]. Lithopanspermia is characterized by three distinct stages in which the transmission of life takes place from a donor world to an acceptor world: (1) Planetary ejection - organisms need to survive ejection from a planet; (2) Interplanetary transit - organisms need to survive the transmission through space; and (3) Planetary entry - organisms need to survive entry from space onto a word [von Hegner, 2019].

In addition to this interesting exchange between solar system bodies, another scenario exists where ejected material may instead return to its home planet and 'reseed' life after the world has recovered after the sterilizing effect of a global impactor, which would be for decades Mars, millennia for Earth, thus restarting evolution on a world. This is the so-called ‘refugium hypothesis’ [Sleep and Zahnle, 1998].

Thus, it has been calculated by Wells et al. (2003) if an impactor ~300 km in diameter with a relative velocity of 30 km s$^{-1}$ hit the Earth and ejected material into space, a substantial amount of this terrestrial ejecta would in fact return within a time scale of less than 3000-5000 years. Furthermore, if microorganisms had been launched as well in this sterilizing global impact, protected within the ejected material, then an initial population of order $10^3$-$10^5$ organisms kg$^{-1}$ is estimated to be sufficient for one single organism to endure the refugium and return back home to a recovered Earth within this time frame [Wells et al., 2003].

The stages of lithopanspermia are similar in many ways to what goes on in this scenario, since a viable return to the home planet and a viable transfer to a nearby rocky planet possess comparable probabilities in terms of the material ejected from a world [Sleep and Zahnle, 1998]. Thus, as for lithopanspermia, 3 stages of planetary reseeding can be defined: (1) Planetary ejection - organisms need to survive ejection from the planet; (2) Planetary proximity refugium - organisms need to survive the stay in space; and (3) Planetary entry - organisms need to survive entry from space onto the world. Thus, early terrestrial life could have survived e.g. the Late Heavy Bombardment through a temporary shelter in a meteorite in space, and subsequently reseeded Earth after an otherwise lethal impact had occurred on the planet.

More local impactors that do not jeopardize the global distribution of life also exist. In fact, a greater frequency of rocks in transit due to smaller non-sterilizing impacts is the common scenario, whereas large sterilizing impacts are rare [Sleep and Zahnle, 1998]. Thus, studies have estimated that if an arbitrary impactor size of 1 km diameter was chosen, then the current impact rate at that size would be approximately one every 600,000 yrs, an impact rate that would probably have been 100 times higher in the ancient history of the solar system. Hence, a < 6 kyr interval for such impactors would have been the case, each 1 km impactor capable of ejecting order 1 billion rocks with mean sizes of order a decimeter [Miliékowa et. al., 2000; Gladman et al., 2005]. Thus, during the Heavy Bombardment epoch near Earth space was almost continuously being feed by terrestrial material due to the frequent impacts of such smaller impactors which nonetheless could eject material potentially harboring viable organisms [Gladman et al., 2005].

The transmission of organisms in stage 2 of lithopanspermia usually requires millions of years, a period that can present significant challenges to the survival of the organisms involved. Indeed, planetary reseeding may thus have a greater probability of organism survival because an important difference that will be addressed in this article is that although organisms must also survive their stay in stage 2, the time for this stage may be briefer. Thus, Gladman et al. (2005) estimated that approximately 1% of the mass ejected by an impactor with velocity 30 km/s will return to the Earth within 30,000 years. It was also calculated that for impactors with ejection velocities between 1 and 2 km/s a fraction of the ejected mass would return after roughly 5000 years. In fact, material ejected with $V_\infty = 2$ km/s makes up approximately half the mass that
returns to Earth, and this independent of the impactor speed [Gladman et al., 2005]. In a study by Reyes-Ruiza et al. (2012) it was concluded that particles launched with only 1% above Earth's escape velocity 11.22 km/s overall would remain in orbits close to that of the planet, and within 30,000 years approximately 5% of these particles - 7783 out of 163,842 in their simulation - would fall back to Earth, in fact, would potentially be returning in less than 5,000 years.

Thus, if the conjecture is granted that life can indeed remain viable in all three stages of this planetary reseeding scenario, then it is not only a topic of planetary science but also a biological topic which necessitates a framework that combines the physical dynamics of the stages with the dynamics of evolutionary processes. This will be explored in this article.

Discussion

In the following, the focus will be mainly on the more modest impactor/launchers that affect a restricted region of a world and which have probably belonged to the dominant scenario in the history of the Earth.

This entire scenario of local bombardments can be symbolically illustrated as a flat surface, a trampoline. This flat surface gets hit by millions of drops of matter spread over time and distance. Each time an impactor hits the trampoline, a drop of matter containing bacteria is sent high above the ground before the drop returns as a reimpactor on the trampoline.

This trampoline or bouncing ball analogy can be important, because while many processes and circumstances have played a role in life’s endurance and evolution in the early history for a world like the Earth, a particular biological effect could potentially be conferred on a bacterial population in this scenario.

In the traditional discussion of lithopanspermia and planetary reseeding, life is usually treated as a passive cargo that becomes enclosed and protected until it arrives in a world and is released again. But life is not passive however. It reacts back against environmental stressors. Thus, evolution outline that a competition for survival between individual organisms within any given species takes place. Furthermore, organisms not only compete against each other, organisms also adapt to a changing environment. Thus, in evolutionary theory, it can be predicted that robustness, that is, a capacity to survive adverse environmental conditions caused by e.g. heat stress or cold stress in a given species can be a trait that the species gradually adapts to in response to a harsh environment [Lenz et al., 2018].

The three stages of planetary reseeding represent a changed environment for organisms, and the environmental stressors encountered therein will thus provoke evolutionary responses. The hypothesis can be put forward, which states that robustness or stress tolerance can also be acquired during an invasion process involving members of one species being transported from one region to another over a certain period of time [Lenz et al., 2018]. Here, mortality during transport due to stress will increase the mean tolerance to the same type of stress in the group of transported organisms due to an increase in the frequency of robust genotypes [Sakai et al., 2001]. In other words, mortality rates are lower among survivors of a preceding stress event than among non-stressed organisms of the same species [Gavan et al., 2016; Lenz et al., 2018].

A study by von Hegner (2020) showed that although the transport of life in lithopanspermia is most likely to occur in a dormant state, the scenario in which life remains active during transmission exist. Here, evolutionary processes will thus play a role, which can give life a stress tolerance different from what one would expect if analyzed only from the dynamics of planetary science. The framework developed therein can also be applied to this similar yet different scenario here. Thus, in this paper, the following assumptions will be made:

(i) The trampoline effect is a prevalent effect among bacteria, meaning that the mean robustness of bacteria towards a stressor is higher at the end of the planetary proximity refugium than at the beginning.
(ii) The bacterial population can remain active in stage 2.

Throughout approximately the first 2 billion years of life's history on this planet, life consisted of single-celled organisms, and so only these will be addressed.
The trampoline effect

The three stages of planetary reseeding are conjectured to be capable of storing a bacterial (or archeal) population for a period of time. This storage will expose the encapsulated bacteria to stressful abiotic conditions. Thus, since organisms possess the potential to modify their stress tolerance, the question then arises what potential processes can occur in the three stages of planetary reseeding?

Stages 1 and 3

In planetary reseeding, impactors will hit the ground in stage 1 and send up matter containing a bacterial population, after which a reimpactor will return and deliver them to another location on the world in stage 3. After some stressful abiotic conditions, the bacterial population will experience pressure shock as well as heat shock.

From a first consideration, the few surviving bacteria that could cope with the impactor/launcher in stage 1 could also be expected to have an opportunity to survive the reimpactor in stage 3, because robustness towards e.g. heat stress or cold stress in a species can be an inherent trait that has gradually evolved in response to a harsh environment. Here, life is merely a passive cargo being shipped, stored, and returned by a meteorite [von Hegner, 2020]. However, the situation can be more complex than just this existing option. An interesting biological effect is responsible for the fact that the bacterial population can actually achieve greater robustness than what this scenario can offer.

When the impactor hits and ejects material from a world, stage 1 of planetary reseeding will lead from a temperate to a briefly elevated temperature. Hence, during a temperate transportation of bacteria that starts and ends with a briefly increased temperature event, all bacteria within the ejected material will experience temperature changes.

Thus, during stage 1, temperatures will be reached that constitute heat shock for the bacterial population and this heat shock can lead to a decrease in quantity, that is, to partial mortality among the collected bacterial population, which can select for those bacterial genotypes initially expressing the greatest tolerance towards heat shock. Hence, the quality of the bacteria should increase afterwards, that is, the frequency of heat shock tolerant genotypes in the bacterial population will increase during stage 2. Interestingly enough, however, their stress tolerance to the second stress event of the same kind will be higher than would be expected based on robust genotypes alone, see figure 1.

We have the bacterial population in A and B that undergoes the traditional stages of planetary reseeding. This population of bacteria experiences pressure and heat stress twice, in stage 1 and after a recovery phase in stage 2, during which the pressure fades and the heat decreases, again experiences pressure and heat stress in stage 3.

Then we have a hypothetical bacterial population in C of the same species that experiences pressure and heat stress only once, in stage 3. These two bacterial populations spend the same amount of time in each meteorite in stage 2 and experience the same conditions.

It can be expected that the stress the bacterial population in A and B experienced through stage 1 caused major mortality in the population. It is now the case that the surviving individuals experience a second stress event of the same child in stage 3, and their survival is then compared to the robustness of the bacterial population in C who had not experienced these elevated pressure and heat shocks before until stage 3.

It can then be expected that stress tolerance in survivors of the population in A and B is enhanced by the previous pressure and heat stress compared to the stress tolerance the population in C. Hence, the robustness the bacterial population in A and B have towards these pressure and heat stressors should be higher at the end of their refugium, in stage 3, than at the beginning at stage 1.

Thus, in stage 1, the impactor/launcher will initiate a natural selection of initially pressure and heat tolerant bacteria, and this reduction in quantity, that is, the stress-induced mortality among them, will increase the quality of the surviving bacterial population, that is, the average robustness towards pressure and heat stress, in stage 3, as a consequence of having previously experienced these stressors.

Experiments supporting such a prediction have been done. Gavan et al. (2016) studied the stress resistance of a small fraction of severely heat stressed E. coli. The surviving E. coli were initially only slightly more
sensitive to a second heat treatment, instead being more resistant to a second shock against another stressor such as high hydrostatic pressure (HHP) shock compared to their unstressed control *E. coli* counterparts. However, it was observed that as the resuscitation phase continued the initial HHP resistance of the initially sublethally injured *E. coli* faded out, while their heat resistance increased and eventually surpassed the initial heat resistance of the unstressed *E. coli* counterparts [Gavan et al., 2016].

Figure 1. (a) The classic scenario of the bacterial population being transmitted, and after a period of time returning to the home world again by an asteroid (the asteroid is not to scale). (b) The bacterial population experiencing pressure and heat shock in Stage 1, and after a period in stage 2 returns to the home world, demonstrating an increased tolerance to a stress event of the same kind in stage 3. (c) The control group of bacteria experiencing pressure and heat shock only once. Credits: artistic image of Ancient Mars by Detlev Van Ravenswaay; bacteria adapted from Mirumur, 2011.

Lenz et al. (2018) made a study that mimicked the heat stress experienced by mussels during a transoceanic voyage. In this study, groups of individual mussels, which are often hitch hiking as hull fouling or in ballast water tanks in ships, were exposed to thermal stress causing 60–83% mortality in the groups. The surviving mussels were later exposed to a second heat stress event. The results were that two mussel species demonstrated an increased resistance to heat stress when they had survived a previous heat stress event [Lenz et al., 2018].

Experiments testing the survival of organisms during pressure shocks simulating stage 1 have also been performed. Horneck et al. (2008) conducted shock recovery experiments on, among others, the endolithic cyanobacterium *Chroococcidiopsis*, which survived shock pressures up to 10 GPa (survival rate nearly 10⁻³) before reaching survival below the threshold of detection [Horneck et al., 2008].

These experiments did not test whether the surviving bacteria could show increased robustness to a second pressure shock event compared to a control group that has only experienced this pressure shock event once, and the number of survivors in stage 1 of these pressure shock experiments was not necessarily due to random survival among the cyanobacteria. Instead, the experiments could select for those individual genotypes that have a pre-adapted tolerance to pressure shock, allowing the bacteria with the greatest genetically adapted robustness to survive longer. However, the trampoline effect is apparently not due to preadapted mutants, since as found by Gavan et al. (2016), the majority of heat stressed *E. coli* survivors did not consist of heat resistant mutants displaying a significantly increased robustness toward stress. Hence, it has instead been suggested that the heat shock triggered either a translation independent response or conferred an as yet poorly understood physiological state upon the surviving bacteria that will mitigate the effects of the second stress event [Gavan et al., 2016].
Thus, it is possible that bacteria may also exhibit a increased pressure stress robustness to a second stress event of the same kind in stage 3 [von Hegner, 2020]. Hence, it can be expected in the stages of planetary reseeding that a reduction in quantity among the bacterial population will increase the quality in the surviving population by not only increasing the frequency of robust genotypes, but also conferring a physiological state upon the surviving bacteria that will mitigate the effects of pressure and heat stress in stage 3.

In this scenario, the bacterial population is not merely a passive cargo stored in the meteorite before a reimpact on the planet. Life responds to the environment and can thus affect the outcome of the storage itself as well as a successful resettlement on the planet. Thus, the first stage can in itself be considered as a facilitator of a process that enhances the ability of the collected organisms to survive stage 3.

**Stage 2**

In order for the trampoline effect to occur, it is necessary that the meteorite has been able to protect the bacteria in the planetary proximity refugium in stage 2 long enough in order for them to have a recovery phase and thus have been able to actively maintain their most basic functions. The big difference between lithopanspermia and planetary reseeding emerge here, rather than in the difference between the two worlds and one world scenarios.

In lithopanspermia, stage 2 acts as a transport and protection of the organisms from a donor world to an acceptor world. In planetary reseeding, it's a different situation. Here, the planetary proximity refugium acts as a kind of natural microbial bank, almost analogous to an artificial seed bank, although the organisms are not dormant here.

The possibility of planetary proximity refugium and reseeding appears to be higher than for lithopanspermia. First, this is due to the fact that the transmission time in stage 2 of lithopanspermia can be long, lasting an average of millions of years, thus reducing the probability of bacterial survival, while the time of planetary proximity refugium can be significantly shorter. Second, the transmitted material with organisms has a higher probability of arriving in a potentially habitable world, returning to its home world, than it has in arriving in another alien and potentially world.

Thus, for example, Wells et al. (2003), as mentioned, calculated that it would be possible for a transmitted meteorite to return to Earth 3000-5000 years later. This was for a global event, but here we have restricted ourselves to discussing local non-sterilizing events. During the Heavy Bombardment epoch smaller impactors would be dominant. Thus, it has been estimated that if arbitrary impactors with size of 1 km diameter were the case, then these would be continuously feeding near Earth space by each launching of order 1 billion viable rocks [Gladman et al., 2005]. It has been estimated that impactors with velocities greater than 2 \( V_{esc} \) will allow a significant amount of terrestrial material to return in less than 5,000 years [Reyes-Ruiza et al., 2012].

Thus, for planetary reseeding, the time in stage 2 is generally given by:

\[
0 < \text{refugium} \leq 5000 \text{ yrs}
\]  

(1)

where 5000 years is the estimate given by Wells et al. (2003). The authors argued that in the general hostile conditions of the space environment, e.g. exposure to radiation, biological material would be rendered nonviable after a few thousand years. However, it is important here to distinguish between life existing in the refugium period in dormant form, or existing in it in active form, since its resistance to stressors then differs. Thus, what is required in stage 2 is that the meteorite can provide an internal protected environment in which the bacterial population can remain active. Many factors play into that possibility. One of them is the meteorite itself, where it protects the encapsulated organisms. Another is that the shorter the time spent in space, the greater the possibility of staying active. A third additional factor comes from the bacterial population itself.

It is well-known that bacteria have a life cycle much faster than multi-cellular organisms. Thus, the doubling time of different bacteria can be from 9.8 minutes to several hours [Eagon, 1962; Gibson et al., 2018]. The recovery or resuscitation time in bacteria after sublethal injury is typically within 2 hours,
regaining metabolic functions and the ability to divide [Ray, 1986; Kang and Siragusa, 1999]. However, Gavan et al. (2016) reported that the growth of *E. coli* survivors only became evident approximately 5 h after a heat shock.

In the scenario discussed here, the planetary proximity refugium in stage 2, recovery simply means that the effect of pressure and heat shock on the bacteria decreases so that they can resume their functions, thus demonstrating an increased robustness towards a second stress challenge of the same kind in stage 3. The survivors from the impactor do not necessarily have to suffer any injury. Thus, if we assume this 5 h observation (the effect of pressure shock is not included), then we have that the time for the occurrence of the trampoline effect is given by:

\[
5 \text{ h} \leq T_{\text{effect}}
\]  

(2)

This means that, in principle, the refugium period need only be within 5 hours in order for the bacterial population to achieve an enhanced tolerance towards stage 3.

The launch and return times for the impactor/launcher I and reimpactor R in this specific scenario are given by:

\[
0 < I < R \leq T_{\text{effect}}
\]  

(3)

Thus, in principle, the meteorite need not be sent far away from a world before the trampoline effect appears. In many ways we thus have the opposite situation in relation to lithopanspermia. Here, the interest is focused on how far away an impact can launch material. But here there is only 5 h between the impactor and the reimpactor. The material may not even need to be ejected with an escape velocity greater than that of the planet.

This short period of time is not an issue for another reason. Firstly, we are not dealing with a situation where life can only return once a world has recovered from a global impactor. Because while a local impactor/launcher has sterilized the affected area, the local reimpactor probably won't hit the same spot as the impactor/launcher. Instead, it will hit another location on the planet where life or the possibility for life can exist. Of course, when the reimpactor hits it can also sterilize the area. But firstly, the surrounding area can still remain fertile, or the reimpactor can break up and spread over a larger area, thus not doing much damage when the transported life arrived. Secondly, the main point discussed here was that the returning organisms have a greater tolerance for a stress event of the same kind in stage 3 than they had when they were ejected in stage 1. Thus, they can actually demonstrate higher tolerance towards pressure and heat shock than before.

Thus, the first and second stages of planetary reseeding can in themselves be considered as facilitators of a process that enhances the stress capacity of the collected bacteria and thus their survival probability.

*The stages of planetary reseeding: biological processes*

There has been a focus here on local events, rather than global sterilizing events, although the trampoline effect may also have an impact on such planet wide impactor/launchers. However, such local events have been among the dominant scenarios, being produced with greater frequency, although global events may have occurred during the early history of the Earth.

Such repetitive local impacts may also have had implications other than the global impactors/launchers. Thus, repetitive local impacts may have played a further role than simply having the sole effect of reseeding life after a single large global impact, because repeated inputs of organisms with different tolerances may have significance in evolution. Darwinian evolution is after all based on a competition for survival between individual organisms within any given species - or more fundamentally, a competition between genes within gene pools. Thus, optimal trait values change continuously and natural selection results in the gradual evolution of more fitting organisms, hence removing suboptimal forms that hitherto were well adapted to a given environment [Simons, 2011].

Repeated local reimpactors delivering inputs of organisms with not only enhanced stress tolerance, but also different genotypes will therefore be able to give the organisms a better chance of surviving in the violent period of a world than if a uniform population of organisms arrived at once after a global impactor.
Thus, if the time between local impactor and local reimpactor is measured in years, or local impactor and local reimpactor arrive at widely different places on a world, then this has an impact on genetic diversity, with the arriving bacteria placed among bacteria that remained on the planet, thus being different from them, and a competition between the fittest therefore takes place.

However, this still assumes that the organisms arrive at an environment that is sufficiently similar to the environment from which they came, so that they can survive the initial encounter there. If it is too different, then their chances of survival will diminish, even if it is a habitable environment [von Hegner, 2019].

Of course, the stress tolerance or robustness achieved is only against the stress the bacterial population experienced through these stages. It will not necessarily give tolerance to all the other types of environmental stressors that have been present on a world like the early Earth and which the bacteria will encounter upon their return. However, if the meteorite protects them well enough for them to be active and they have sufficient time, then they can also develop stress hardening [Lou and Yousef, 1996] and also cross tolerance [Johnson, 2002]. This can indeed give them a robustness towards many different stressors.

However, organisms living on the planet may also develop stress hardening and cross tolerance to the environmental stressors they live among, and thus there will not necessarily be a competitive advantage for the arriving bacteria therein. So we cannot say in advance whether the arriving bacteria will gain benefits than the organisms that remained on the planet cannot also achieve.

If the bacteria can remain active after their recovery, having sufficient nutrients and enjoying protection in the meteorite for 3000 to 5000 years before their return, then another scenario will emerge. Their number is not increased in the scenario discussed so far, but if the bacterial population can remain active in the meteorite for say, 3000 years, then their number will increase again, and evolution will thus be in effect. Thus, on one hand, the quantity of the bacterial population could initially decrease through stage 1 of planetary reseeding, but the quantity could subsequently increase again through stage 2, in effect distributing quality along the way, meaning that the quality of the population will increase. In addition, the bacterial population could potentially achieve even greater survival capacity before entering stage 3, since natural selection among the organisms in the meteorite environment could evolve new traits they did not previously possess.

Furthermore, since it is life, or more precisely, survival, that is the primary topic of interest here, rather than the physical dynamics of impactors/launchers and reimpactors, it can be then be stated that a meteorite that successfully ejects, stores and returns life, itself can be considered a physical invariant.

Thus, the stages in planetary reseeding can themselves be considered facilitators for a process that enhances the biological survival capacity of the collected organisms.

**Conclusion**

The overall situation discussed in this article is that ejected material can return to Earth again after 3000 to 5000 years. This is short from an astronomical point of view, but from a biological point of view long. Conversely, there is the situation that surviving bacteria can recover from stress after 2 to 5 hours. This duration is barely noticeable from an astronomical point of view, but from a biological point of view much can happen during this time.

The overall situation discussed is that stress-induced mortality in stage 1 can potentially increase quality or population robustness toward a second stress challenge of the same kind in stage 3 of planetary reseeding. This has been illustrated as a trampoline effect. The participating bacteria on the trampoline will be better to endure the reimpactor than when they were first ejected by the impactor. Thus, while it is possible to make estimates of the survival probability of bacteria based on e.g. pressure shock experiments simulating stage 1, the next stages will give a probability of survival higher than otherwise expected from this type of experiment, which is an fact that needs to be taken into consideration when attempting to estimate the survival probabilities of a population of organisms in worlds such as the past Earth.

Of course, this trampoline effect does not represent an adaptive perpetuum mobile. A repeated series of transmission and return of the same bacterial population cannot be expected to lead to a population of ‘super’ organisms capable of withstanding any and all degrees of environmental stress. Evolutionary adaptation will be needed to truly evolve the organisms even further. However, it is not yet known from the few experiments
that have so far been done, how far such a repeated series can go, which would certainly be interesting to know here.

Whether this impact of drops by local impactor/launchers and reimpactor collectively has had a bearing on driving the survival of life on the flat surface is an open question. This is still a specific adaptive scenario among other scenarios. What is known is that besides the infrequent bombardment itself, the Hadean and Archean environment on Earth was in many ways a harsher and stressful environment than today's Earth. Upon launch, the bacterial population would not only ensure the continuation of life after a potential sterilizing event, but upon return, the bacterial population would possess a greater tolerance to pressure and heat stress than when ejected, increasing their survival capacity at the same time. Thus, this process may have played a role in the survival of life through these violent periods of Earth's history. We cannot yet say how important this effect has played for life's early history. But its existence seems to be clear. It may thus have an impact on inhabited worlds in general.

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