Astrobiology Perspectives on Life of the Universe

PLANET FORMATION AND PANSPERMIA

New Prospects for the Movement of Life through Space

Edited by
Branislav Vukotić
Joseph Seckbach
Richard Gordon

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Planet Formation and Panspermia

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Astrobiology Perspectives on Life of the Universe

Series Editors: Richard Gordon and Joseph Seckbach

In his 1687 book *Principia*, Isaac Newton showed how a body launched atop a tall mountain parallel to the ground would circle the Earth. Many of us are old enough to have witnessed the realization of this dream in the launch of Sputnik in 1957. Since then our ability to enter, view and understand the Universe has increased dramatically. A great race is on to discover real extraterrestrial life, and to understand our origins, whether on Earth or elsewhere. We take part of the title for this new series of books from the pioneering thoughts of Svante Arrhenius, who reviewed this quest in his 1909 book *The Life of the Universe as Conceived by Man from the Earliest Ages to the Present Time*. The volumes in ***Astrobiology Perspectives on Life of the Universe*** will each delve into an aspect of this adventure, with chapters by those who are involved in it, as well as careful observers and assessors of our progress. Guest editors are invited from time to time, and all chapters are peer-reviewed.

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Preface

The panspermia hypothesis dates back to the works of ancient philosophers. In the 1800s, organics in meteorites were considered by the Swedish chemist Jacob Berzelius [1.3] [1.4] and later German physician Hermann E. Richter [1.15] speculated on the possibility of life transport by meteors. Lord Kelvin [1.9], discussed the possibility of panspermia in his Presidential Address to the British Association for the Advancement of Science. At the beginning of the next century, Swedish physicist/chemist Svante August Arrhenius (1908) presented his book on the panspermia theory [1.2]. There is a long history from before this time through the last century of claims of finding life in meteorites [1.6]. Astronomical sciences also developed significantly during this period to the point where we can observe gravitational waves from merging black holes, which was hardly imaginable just a few decades ago, and visualize black holes. With the discovery of many exoplanets astrobiology has matured as a scientific discipline. A tentative discovery of the intergalactic meteor particle in 2007 [1.1] and recent discoveries of an anomalous object "Oumuamua [1.11] and comet 2I/Borisov [1.8], that appear to have visited us from outside the Solar system, point out that our planet and its host star may not be an isolated island, in an otherwise lifeless universe. They are likely to exchange matter with the other stars from their vicinity as probably is the case with other stellar systems too, perhaps containing life. There is currently a bias that any such panspermia, if they exist, are prokaryotes [1.13] [1.16] or rugged, microscopic Eukaryotes [1.14].

In addition to transporting the physical bodies of microorganisms, another important aspect is the transport of biological information about these living systems. After all, the evolution of life on Earth is about altering the genetic code, either by natural or artificial means. Given that the organic matter, the building blocks for living organisms, is omnipresent in the universe, the aforementioned information might in some way be considered as the essence of life, at least in our current genocentric view of life [1.5]. The aspect of sending just the information signal in order to spread life is investigated in the visionary sci-fi novel “His Master’s Voice” by Polish writer Stanislaw Lem, first published in 1968 [1.10]. Contemporary with the beginning radio SETI searches [1.18], this offered a convergence point between sending and receiving SETI signals and the panspermia hypothesis. Information panspermia was later born in 2005 with the work of Vahe Gurzadyan [1.7].

In times when a number of exciting new discoveries are made and the new ones seem to be just around the corner, the millenia old panspermia hypothesis has not yet matured into a full fledged theory and some of its aspects might still not have been envisioned. Along the lines of scientific falsificationism, we can consider that no evidence against panspermia are found to date and that much of the controversy still remains [1.12]. The search is even more active in the opposite direction but still there is an evident lack of convincingly non-terrestrial microorganisms on Solar system bodies other than Earth. The recent experiments with micro-organisms exposed to space conditions at the International Space Station offer accumulating evidence that these organisms can withstand the harsh conditions of open space for long periods of time while preserving their biological potential. Even more, there are mounting concerns that human made space vehicles can spread life from our biosphere to other bodies of the Solar system, the most recent one being that the Israeli space mission that transported tardigrades to the Moon [1.17].

While panspermia is related to microorganisms and small scale processes on one end, on the other end, the transport of material depends on environmental conditions in galaxies. The evolution of galaxies depends on the interaction of galaxies within galaxy clusters and the overall evolution of matter in the universe. The galaxies are the main building blocks of our universe, analogous to cells in a human body. The stars and their planets are condensed from the clouds of galactic gas and dust that are rich in organics. The process of planetary formation is at the middle among the above stated scales that are relevant for panspermia. Starting from planetary formation, studies can go in either direction, to larger or smaller scales, to investigate phenomena that could spread life.

This collection of chapters incorporates studies from biology, astronomy and geology that investigate the possibility of panspermia, with most of them directly investigating phenomena related to the process of planetary formation. The processes described in these chapters permit the panspermia hypothesis, but empirical confirmation is still lacking at the level of our current knowledge. The basic aim of this book is to provoke readers to contemplate their respective research fields that are related to panspermia. For that matter it presents the basics of panspermia but also the advanced studies in the research fields presented. The chapters are comprehensible on a student level but at the same time they might be very interesting to experienced researchers. Possibly, some of them are already working on current and future space missions that may offer an empirical vindication of extra-terrestrial life transfer through the vastness of space.

Branislav Vukotić
Richard Gordon
Joseph Seckbach
September 1, 2021

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Part I

PHILOSOPHICAL ASPECTS OF PANSPERMIA

1

"On the Origin of Life"

By Lord Kelvin (William Thomson)

Excerpt. From the Presidential Address to the British Association for the Advancement of Science; held at Edinburgh in August, 1871 Reprinted in Kelvin's ***Popular Lectures and Addresses***, p. 132-205. (Bracketed additions are from reprint.)
[p. 197.]

> Think now of the admirable simplicity with which Tait's beautiful "sea-bird analogy," as it has been called, can explain all [?] these phenomena.

The essence of science, as is well illustrated by astronomy and cosmical physics, consists in inferring antecedent conditions, and anticipating future evolutions, from phenomena which have actually come under observation. In biology the difficulties of successfully acting up to this ideal are prodigious. The earnest naturalists of the present day are, however, not appalled or paralysed by them, and are struggling boldly and laboriously to pass out of the mere "Natural History stage" of their study, and bring zoology within the range of Natural Philosophy. A very ancient speculation, still clung to by many naturalists (so much so that I have a choice of modern terms to quote in expressing it) supposes that, under meteorological conditions very different from the present, dead matter may have run together or crystallised or fermented into "germs of life," or "organic cells," or "protoplasm." But science brings a vast mass of inductive evidence against this hypothesis of spontaneous generation, as you have heard from my predecessor in the Presidential chair. Careful enough scrutiny has, in every case up to the present day, discovered life as antecedent to life. Dead matter cannot become living without coming under the influence of matter previously alive. This seems to me as sure a teaching of science as the law of gravitation. I utterly repudiate, as opposed to all philosophical uniformitarianism, the assumption of "different meteorological conditions"—that is to say, somewhat different vicissitudes of temperature, pressure, moisture, gaseous atmosphere—to produce or to permit that to take place by force or

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motion of dead matter alone, which is a direct contravention of what seems to us biological law. I am prepared for the answer, "Our code of biological law is an expression of our ignorance as well as of our knowledge." And I say yes: search for spontaneous generation out of inorganic materials; let any one not satisfied with the purely negative testimony of which we have now so much against it, throw himself into the inquiry. Such investigations as those of Pasteur, Pouchet, and Bastian are among the most interesting and momentous in the whole range of Natural History, and their results, whether positive or negative, must richly reward the most careful and laborious experimenting. I confess to being deeply impressed by the evidence put before us by Professor Huxley, and I am ready to adopt, as an article of scientific faith, true through all space and through all time, that life proceeds from life, and from nothing but life.

How, then, did life originate on the Earth? Tracing the physical history of the Earth backwards, on strict dynamical principles, we are brought to a red-hot melted globe on which no life could exist. Hence when the Earth was first fit for life, there was no living thing on it. There were rocks solid and disintegrated, water, air all round, warmed and illuminated by a brilliant Sun, ready to become a garden. Did grass and trees and flowers spring into existence, in all the fulness of ripe beauty, by a fiat of Creative Power? or did vegetation, growing up from seed sown, spread and multiply over the whole Earth? Science is bound by the everlasting law of honour, to face fearlessly every problem which can fairly be presented to it. If a probable solution, consistent with the ordinary course of nature, can be found, we must not invoke an abnormal act of Creative Power. When a lava stream flows down the sides of Vesuvius or Etna it quickly cools and becomes solid; and after a few weeks or years it teems with vegetable and animal life; which, for it, originated by the transport of seed and ova and by the migration of individual living creatures. When a volcanic island springs up from the sea, and after a few years is found clothed with vegetation, we do not hesitate to assume that seed has been wafted to it through the air, or floated to it on rafts. Is it not possible, and if possible, is it not probable, that the beginning of vegetable life on the Earth is to be similarly explained? Every year thousands, probably millions, of fragments of solid matter fall upon the Earth—whence came these fragments? What is the previous history of any one of them? Was it created in the beginning of time an amorphous mass? This idea is so unacceptable that, tacitly or explicitly, all men discard it. It is often assumed that all, and it is certain that some, meteoric stones are fragments which had been broken off from greater masses and launched free into space. It is as sure that collisions must occur between great masses moving through space as it is that ships, steered without intelligence directed to prevent collision, could not cross and recross the Atlantic for thousands of years with immunity from collisions. When two great masses come into collision in space it is certain that a large part of each is melted; but it seems also quite certain that in many cases a large quantity of debris must be shot forth in all directions, much of which may have experienced no greater violence than individual pieces of rock experience in a land-slip or in blasting by gunpowder. Should the time when this Earth comes into collision with another body, comparable in dimensions to itself, be when it is still clothed as at present with vegetation, many great and small fragments carrying seed and living plants and animals would undoubtedly be scattered through space. Hence and because we all confidently believe that there are at present, and have been from time immemorial, many worlds of life besides our own, we must regard it as probable in the highest degree that there are countless seed-bearing meteoric stones moving about through space. If at the present instant no life existed upon this Earth, one such stone falling upon it might, by what we blindly call *natural* causes, lead to its becoming covered with vegetation. I am fully conscious of the many scientific objections which may be urged against this hypothesis, but I believe them to be all answerable. I have already taxed your patience too severely to allow me to think of discussing any of them on the present occasion. The hypothesis that [some] life [has actually] originated on this Earth through moss-grown fragments from the ruins of another world may seem wild and visionary; all I maintain is that it is not unscientific, [and cannot rightly be said to be improbable.]

2

Why We Should Take Interstellar Panspermia Seriously

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Abstract
After a long period of neglect, the hypothesis of interstellar panspermia has gained new consideration in recent years, due to a series of theoretical and observational developments. In this chapter, I briefly outline why this possibility should not be dismissed, especially in regions of the Galaxy with higher stellar density than average. Furthermore, I give some motivations for taking the mechanism into account when developing theoretical models of the distribution of life in the Galaxy (such as in studies of the galactic habitable zone) and in drawing implications from the results of future searches for biosignatures in exoplanets. This theoretical work should be complemented by experimental studies, in order to assess the concrete feasibility of panspermia with higher confidence.

***Keywords*:** Astrobiology, extraterrestrial life, galactic habitabile zone, biosignatures, interstellar panspermia

2.1 Introduction

The idea that biological material—and even living organisms—can be exchanged between planetary systems is more than one century old, but it has not been part of the mainstream discussion in astrobiology for long [2.28, 2.43]. Historically, skepticism on the early proposals of panspermia, put forward at the beginning of the 20th century [2.3], was at least in part motivated by an incorrect understanding of planetary formation

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mechanisms, which was dominated by the "catastrophic" theories of Buffon, Chamberlin, Moulton, and Jeans [2.9]. However, even many decades after such theories were abandoned, panspermia failed to regain a place in the scientific discourse.

This has changed recently, at least in the version of panspermia—more appropriately called "lithopanspermia"—which posits that life can travel across space carried by meteoroids and other minor bodies. There is now well-established evidence that rock fragments have indeed been exchanged between nearby planets in the Solar System, such as Mars and the Earth [2.32]. Available data on the survivability of radio-tolerant organisms in deep space, as well as experimental tests on hypervelocity impacts, make it conceivable that extremophiles trapped in rocks can be expelled by an inhabited planet and reach other locations unharmed [2.18, 2.19, 2.33]. This has led to speculation that nearby planets in the Solar System could have cross-contaminated in the past [2.30] and that other, more densely packed planetary systems, such as the one around TRAPPIST-1, might be even more conducive to the accidental spreading of life from one habitable location to another [2.20, 2.23]. The possible occurrence of panspermia within the Solar System would have obvious direct consequences for the problem of the origin of life on Earth.

Enlarging the scope to galactic scale, the observation of the first interstellar asteroid visiting the Solar System [2.27] has confirmed that the exchange of material between stellar systems is feasible. In light of this, the idea that life can be disseminated by natural processes over interstellar distances cannot be dismissed. In this short chapter, I will argue that the mere possibility of interstellar panspermia should be given careful consideration, as it would have relevant consequences on the assessment of galactic habitability and on the interpretation of future exoplanet observations.

2.2 The Case for Interstellar Panspermia

The possibility that panspermia could act over interstellar distances has been debated for at least two decades. Initial estimates of the probability that a rock ejected from Earth could be captured by another terrestrial planet in a different stellar system in the solar neighborhood were deemed too small to be relevant as a life-spreading mechanism [2.29]. Thus, interstellar panspermia was also dismissed as implausible. However, subsequent studies argued that such a conclusion was probably too pessimistic [2.45, 2.13, 2.46]. In fact, it was shown that the capture probability could increase in crowded environments, such as in star-forming clusters [2.2, 2.7], and can be significantly enhanced by interactions with binary systems [2.24].

Because the survivability of microorganisms in deep space depends on the shielding mechanism provided by the rocks, there is probably a minimal mass to life-carrying fragments for panspermia to work at interstellar distances, of order ~1–10 kg. If the typical survival time of microorganisms trapped in the rocks is τ_s, the fraction of surviving microorganisms after a travel time t can be modeled as $P \propto e^{-t/\tau s}$ [2.13]. No exact estimate for τ_s exists, although values of order ~10^5 years or higher seem possible given favourable conditions. In this regard, we note that the assumption that microorganisms can only survive when shielded within rocks is rather conservative: more speculative scenarios can be envisioned, where microorganisms endure the vacuum of space without insolation and atmosphere (powered, for example, by slow chemical reactions or even long-lived radionuclides), leading to much larger values of τ_s. Whichever the case, by adopting this simple survival model and assuming a dynamical mechanism for the transfer of material, one can estimate the rate of life-bearing rocks impacting a terrestrial planet at any location in the Galaxy.

The possibility that interstellar panspermia played a role over the entire disk of the Milky Way is certainly not established conclusively, but it cannot be entirely dismissed either. Because of the different stellar densities at various locations, the effectiveness of the mechanism is not homogeneous over the whole Galaxy, and it might have been more important within specific subvolumes. In [2.5], we argued that the eventuality of lithopanspermia should be given special consideration for planets residing in the galactic bulge, where the high density of stellar systems might make the transfer more likely than in the disk (see also [2.8]). We made an initial estimate of the efficiency of panspermia in the bulge by adopting the model outlined in [2.29, 2.2] for the rate of life-bearing rocks impacting a terrestrial planet in another stellar system

$$\tau = \sigma v n_L \tag{2.1}$$

where v is the relative velocity of rocks with respect to the stars, n_L is the number density of life-bearing rocks, and σ is the impact cross-section. The latter can be computed as the product of the capture cross-section from a stellar system, σ_c, and the probability that a rock impacts a terrestrial planet in the system once is captured, P_{impact}. Plausible values for σ_c are in the range 0.01–0.05 AU^2 [2.29] and are expected to vary based on the average stellar velocity dispersion, orbital configurations and multiplicity of the stellar and planetary systems, ejection velocity, rock size distribution, and so on. In our analysis, we adopted the values $\sigma_c = 0.025$ AU^2 and $P_{impact} = 10^{-4}$ from [2.29]: these are probably conservative in general, and in particular with respect to the conditions in the bulge. In fact, the value adopted for σ_c applies to planetary systems with a Jupiter-type planet in a Jupiter-like orbit. However, only ~10% of all systems meet this criterion. As already mentioned, binary star systems (that make up roughly 40% of all stars) have a much higher cross-section [2.24, 2.13]. Similarly, the capture rate can be enhanced in systems that contain massive hot Jupiters or brown dwarfs, both of which could have habitable exomoons. As an illustration, using the fit for σ_c from [2.2] and assuming a velocity dispersion ~120 km/s for stars in the bulge [2.44] would result in a value $\sigma_c = 0.045$ AU^2.

The number density of life-bearing rocks per year can be assumed to be proportional to the star density, $n_L = \gamma nt$, with γ~15/yr [2.2]. Then, the typical diffusion timescale for life between stellar systems in the galactic bulge can be found by $t = 1/\Gamma$ and is

$$t_D = (\sigma v \gamma n)^{-1/2} \tag{2.2}$$

If indeed life "colonizes" a suitable planet after transport, t_D represents the typical timescale for the evolution of the fraction of inhabited planetary systems in the bulge. Adopting a realistic model for the stellar density n leads one to conclude that, all over the bulge, even a single inhabited planet might in principle spread life to all other suitable stellar systems in a time ~1 Gyr, much smaller than the age of the Galaxy [2.5].

While this is not a full-fledged examination of the problem, it gives some support to the idea that the galactic bulge could be seeded with biological material much more efficiently than the solar neighborhood. A possible hindrance, in this respect, is the effect of the radiation environment, which is certainly harsher near the galactic center than in the disk [2.4, 2.5], as well as the higher risk of potentially sterilizing events such as supernovae or tidal disruption events [2.35]. Even if life is not completely wiped out, ionizing radiation can still influence planetary habitability by enhancing the rate of atmospheric mass loss (see, e.g., [2.34]). Furthermore, it has been argued that a high level of ultraviolet radiation could suppress the formation of terrestrial planets via protoplanetary grain evaporation [2.1]. However, strong ultraviolet doses could also have beneficial effects, for example, by increasing the rate of prebiotic synthesis of biomolecular building blocks [2.25].

It should also be noted that there might be safer routes for microorganisms if the transfer happens indirectly, for example, through cometary

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