



Reconfiguring SETI in the microbial context: Panspermia as a solution to Fermi's paradox

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ABSTRACT

All SETI (Search for Extraterrestrial Intelligence) programmes that were conceived and put into practice since the 1960s have been based on anthropocentric ideas concerning the definition of intelligence on a cosmic-wide scale. Brain-based neuronal intelligence, augmented by AI, are currently thought of as being the only form of intelligence that can engage in SETI-type interactions, and this assumption is likely to be connected with the dilemma of the famous Fermi paradox. We argue that high levels of intelligence and cognition inherent in ensembles of bacteria are much more likely to be the dominant form of cosmic intelligence, and the transfer of such intelligence is enabled by the processes of panspermia. We outline the main principles of bacterial intelligence, and how this intelligence may be used by the planetary-scale bacterial system, or the bacteriosphere, through processes of biological tropism, to connect to any extra-terrestrial microbial forms, independently of human interference.

We can learn more about life from terrestrial forms than we can from hypothetical extraterrestrial forms.

George Gaylord Simpson (1964).

1. Introduction

The key biological concept – Darwinian evolution by natural selection – was conceived and developed based on what was known in the mid 19th century about animal and plant breeding, as well as human behaviour (Herbert Spencer's influence) (Darwin 1861). One century later, Woese's classification of lifeforms into three domains, Bacteria, Archaea, and Eukaryota (Woese et al., 1990), suggests that Darwin and his contemporaries based evolutionary deliberations on only a fraction of the Eukaryota domain. The historic ignorance of microscopic lifeforms (microbes in the rest of the text) – bacteria and archaea, as well as protists, microbial fungi, and viruses – had profound consequences on some areas of biology. These include symbiosis research until Lynn Margulis' seminal paper (as Sagan 1967), and applied disciplines, such as the SETI (Search for Extra Terrestrial Intelligence) programme

(Sharov and Gordon, 2013). All the SETI programmes, thus far, have conspicuously ignored panspermia – microbes might exist throughout the cosmos – as a potential form of non-human SETI (see for example Sharov and Gordon 2013; 2017; Temple and Wickramasinghe, 2019; Slijepcevic 2020; Wickramasinghe et al., 2021).

Recent empirical demonstration that microbes can (i) survive cosmic-like conditions for several years (Kawaguchi et al., 2020) and (ii) be revived after spending 100 million years in a dormant state (Morono et al., 2020), coupled with various versions of panspermia hypotheses including cometary panspermia (Hoyle and Wickramasinghe, 1982; Wickramasinghe 2010), lithopanspermia (Melosh 1998; Worth et al., 2013), transpermia (Davies 2003) and directed panspermia (Crick and Orgel, 1973) (for details see section 3), allow us to argue that the classical version of SETI should be modified to take account of new evidence. Furthermore, astonishing geo-engineering and biogeochemical capacities of microbes (Sonea 1988; Mathieu and Sonea, 1996; Sonea and Mathieu 2001; Shapiro 2007), and their evolutionary precedence and dominance over other forms of life (Hug et al., 2016), argue in favor of a microbial form of SETI (see sections 5 and 6).

The classical version of SETI emerged in 1959, as the brainchild of

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astrophysicists (Cocconi and Morrison, 1959). The key assumption was that “a newly evolved [extraterrestrial] society” should possess human-like capacities in the domain of intelligence capable or desirous communication. This intelligence was interpreted as the technological advancement of a human-type civilisation to the point of the facility in radio-communication, with similarly advanced humanoid civilisations (Simpson 1964), located somewhere else in the universe, within its communication reach (Drake 1961). The SETI programme continued to be developed along the lines of promoting the idea of human intelligence as being the only form of terrestrial intelligence capable of extra-terrestrial communication until the present day (for reviews see Tarter 2001; Tarter et al., 2010; Vakoch 2011; Smart 2012; Almar 2014; Margot et al., 2019).

However, research carried out during the past few decades challenges the validity of the argument that humans are the *only* intelligent species on Earth. In the most striking challenge to the zoo-centrism of Modern Synthesis (Huneman and Walsh, 2017) an alternative picture of the biological world is emerging – a picture dominated by microbes (Shapiro 1988, 1998; Mathieu and Sonea, 1996; Sonea 1988; Sonea and Mathieu, 2001; McFall-Ngai et al., 2013). For example, the most abundant lifeform in the present-day biosphere are indeed bacteria (Hug et al., 2016), while viruses are the most numerous biogenic structures on Earth (Moelling and Brocker, 2019). Animals can be viewed as nothing more than “co-evolved microbial communities that must undergo sexual cycles of fusion (fertilization) and restoration of the haploid (by meiotic reduction)” (Margulis 1990). The reason animals have brains and nervous systems is mainly to cope with the challenges of motility: the requirement to constantly assess ever-changing organism-environment interactions (Musall et al., 2019). Consequently, the lack of brains does not necessarily mean a lack of intelligence. Indeed, several biologists argued that plants and microbes possess a form of intelligence not inferior to human intelligence (see for example Trewavas and Baluška, 2011; Trewavas 2017; Calvo et al., 2020; Lyon 2015; 2017). In line with this possibility, one prominent microbiologist argued “that bacteria are far more sophisticated than human beings at controlling complex operations.” (Shapiro 2007; see below for explanation).

This paper aims to re-examine SETI from an angle that is not anthropocentric. The critique we want to present may be characterised as the “instrumentalist” form of SETI scepticism (Čirković 2013). In brief, this type of scepticism is not against the SETI programme itself but argues that SETI’s potential has not been realized, or that it has not been formulated precisely enough. Our angle is panspermia (Hoyle and Wickramasinghe, 2000; Wickramasinghe 2010) as a potential solution to Fermi’s paradox. While the focus of Fermi’s arguments, thus far, was exclusively human or humanoid type intelligence as a way of communication (Brin 1983), we shall argue that microbial forms of cosmic communication could be far superior to the humanoid equivalents. Our arguments are centered on two key assumptions: (i) the biological tropism as a form of cosmic communication independent of human intelligence (Louie 2010; Slijepcevic 2020) and (ii) intelligence of microbial lifeforms, so far largely ignored by mainstream biology (Shapiro 2007; Lyon 2015, 2017; Slijepcevic 2019). In section 2 we shall outline peculiarities of the microbial world including its communication potential and intelligence. In sections 3 and 4, we will focus on Fermi’s paradox, panspermia, and survivability of microbes in space. In sections 5 and 6, we will present a tentative form of microbial SETI. In section 7, we will argue that the concept of intelligence, in a general sense, requires a radical reassessment along the lines of de-anthropocentrism.

2. Peculiarities of the microbial world

The standard interpretation of bacteria is predicated on the assumption that these microbes are single-cell organisms (see for example Richard et al., 2019). Shapiro (1988; 1998) argued that the notion of bacteria as single-cell organisms is a consequence of medical microbiology practices – bacteria being seen primarily as

disease-causing organisms. To identify a disease-causing bacterium, single cells are artificially isolated from human pathological samples and grown in laboratory conditions, until a pure bacterial culture is established (Davey 2011).

However, while medical microbiology interprets bacteria as undesirable single-cell pathogenic entities, the natural state of the biosphere suggests that without the vast global bacterial community life on Earth would not be even possible (Sonea 1988; Mathieu and Sonea, 1996; Sonea and Mathieu 2001). Bacteria maintain biogeochemical cycles of organic elements, including nitrogen, carbon, and sulphur cycles. It has been argued that life, in the present form, would be difficult to maintain without bacteria and archaea (Gilbert and Neufeld, 2014).

More importantly, it should be noted that naturalists often interpret bacteria not as single-cell microbes, but rather as loosely organised multicellular organisms – microbial communities that are structurally and functionally interconnected into the global bacterial supersystem or the bacteriosphere (Sonea and Panisset, 1983; Sonea 1988; Mathieu and Sonea, 1996; Sonea and Mathieu, 2001). In the planetary-scale bacterial community, also dubbed the world-wide-web of genetic information (Sonea and Mathieu, 2001), no Darwinian rules apply. Instead, bacteria seemingly opted for a global communication system that favoured minimal genomes in the constituent members of microbial communities, thus resulting in a global genome at the level of the bacteriosphere (Sonea and Panisset, 1983; Mathieu and Sonea, 1996; Sonea and Mathieu, 2001). The existence of the global bacteriosphere genome precludes the operation of normal Darwinian rules. For this reason, Sonea and Mathieu (2001) argued that there are no species in prokaryotes, such as bacteria and archaea.

The concept of species applies only to plants and animals, organisms that are reproductively isolated by virtue of the vertical gene transfer (Wilkins 2006). By contrast, the global bacterial community is not reproductively isolated and it is characterised by the widespread horizontal gene transfer that occurs in the genomes without chromosomes. Instead of chromosomes, which exist only in eukaryotic organisms (Margulis et al., 2000; Margulis 2004; Villasante et al., 2007; Slijepcevic 2018a), bacterial cells contain large replicons called genophores, and small replicons in the form of plasmids and phages (bacterial viruses) (Sonea and Panisset, 1983; Sonea and Mathieu, 2001). This allows (i) survival of microbial communities that occupy specific ecological niches and share the specific genomic content and (ii) maintenance of the biosphere homeorhesis through sharing bioenergetic and functional capabilities of the global genome of the bacteriosphere.¹

Because of the specific organisation of microbial communities and their global domination relative to eukaryotic organisms (Sonea and Panisset, 1983; Sonea and Mathieu, 2001), it is important to understand microbial social organisation including communication and intelligence capabilities. It has been known for several decades that bacteria use a sophisticated communication system based on exchanging chemical messages (Shapiro 1988; Bassler 2002). This communication process has been likened to the human language (Ben Jacob et al., 2004). For example, the use of chemical messages by bacteria leads to the emergence of syntax (meaning independent lexicon) and semantics and pragmatics (messages convey meaning) (Ben Jacob et al., 2004; Slijepcevic 2018b). Furthermore, the transmission of meaningful messages is integrated with genome plasticity (Ben-Jacob 2009). The final results of the sophisticated communication process that combines chemical messaging with genome plasticity is the emergence of colonial identity, intentional behavior, and collective decision-making (Ben-Jacob, 1998, 2009; Slijepcevic 2019). Ben-Jacob et al. (2004) argued that by using linguistic-like communication bacteria show behavior consistent with

¹ The concept of homeorhesis represents the regulation of the biosphere in the form of a steady flow. The regulatory points are dynamic and moving, in contrast to a steady-state of homeostasis. Homeorhesis is the key element of the Gaia hypothesis.

social intelligence.

The processes of information detection, transmission, and interpretation, which lead to decision making at the level of the bacterial colony (social intelligence), are cognitive processes (Lyon 2105; 2017) that may be interpreted as a form of intelligence not requiring a nervous system (Slijepcevic 2020). In line with this possibility, Ben Jacob (2009) argued:

“They [bacteria] know how to collectively glean information from the environment, “talk” with each other, distribute tasks, generate collective memory, and turn their colony into a “cybernetic system”— a massive “brain” that can perform natural distributed information processing, learn from past experience, and possibly alter the genome organization or even create new genes to better cope with novel challenges.”

Furthermore, Shapiro (2007; 2014; 2016 a, b) argued that bacteria alter their genomes in the massive acts of natural genetic engineering, a process he termed “read-write genomes”. The key argument proposed by Shapiro is that the genome is not a passive information depository that exists in the “read-only memory” state. Instead, the genome of the bacteriosphere may be interpreted as a fluid planetary-scale system, coupled with the bacterial chemical communication system, that regulates life processes on the planetary scale. This regulation, fundamental to the biosphere homeorhesis, significantly exceeds the capacities of human technologies:

“In addition, bacteria display astonishing versatility in managing the biosphere’s geochemical and thermodynamic transformations: processes more complex than the largest human-engineered systems. This mastery over the biosphere indicates that we have a great deal to learn about chemistry, physics and evolution from our small, but very intelligent, prokaryotic relatives.” (Shapiro 2007).

Specific types of bacterial intelligence developed in one cosmic habitat may well be transferable to others if entire ecologies can be transported via a suitable panspermic process. We shall return to this in a later section, but note here that entities such as the Kordylewski Dust Clouds at the Lagrange libration points of the Earth-Moon system, may well serve as transferable repositories of local microbial intelligence (Temple and Wickramasinghe, 2019). Another way in which microbial colonies may serve a SETI project is through their potential for storing information in their non-coding silent DNA. Although this might sound far-fetched at present it remains a logical possibility that an “advanced” civilisation might possibly use it to replace the rather crude “message in a bottle” technique that has been used by humans thus far. The presumption here is that an advanced human-type civilisation in the galaxy might have acquired the capacity to insert “redundant” DNA segments into cultures of microorganisms, carrying vast amounts of decodable digital information and using panspermia as the way to broadcast this information on a galaxy-wide scale (Wickramasinghe et al., 2021).

3. SETI in the microbial context – panspermia and Fermi’s paradox

The arguments presented in section 2, in particular concerning a planetary scale bacterial intelligence, undermine the SETI assumption that the *only* true intelligence on Earth belongs to the human technological civilisation. For example, the Drake equation, one of the essential tools in the SETI repertoire, makes a distinction, in one of its variables, between intelligent life (human civilisation) and all other forms of life taken to be either non-intelligent or not intelligent enough to facilitate cosmic communication (Drake 1961). However, if we acknowledge the existence of bacterial intelligence, the term “intelligent life” becomes a tautology, because bacteria are the first forms of life. Assuming that all other lifeforms are derived from the first lifeforms, it follows that (i) the process of life is inherently intelligent, and (ii) SETI cannot be a human cultural phenomenon, but it is biological imperative *par excellence* (see

below). Thus, the orthodox SETI programme which relies on human intelligence requires fundamental revision.

The revision of orthodox SETI may be initiated by relying on the three classical arguments against SETI: contingency argument (Simpson 1964), anthropic argument (Carter 1983), and Fermi’s paradox (Brin 1983; Ćirković 2009). We will ignore the first two arguments in this study and focus on Fermi’s paradox. In brief, Fermi’s paradox may be stated as follows. Enrico Fermi argued that, given the astrophysical reality based on the size and age of our galaxy, human-like civilisations capable of cosmic travel and communications must exist, and yet there is no contact with them. The conclusion drawn from this argument is that we are faced with deathly cosmic silence in the quest for our “replicas” elsewhere in the universe (Brin 1983; Ćirković 2009). Several solutions for Fermi’s paradox have been proposed (reviewed in Ćirković 2009). We would like to propose a new one that relies on microbial intelligence and the panspermia hypothesis.

If we take into account the arguments for bacterial intelligence (section 2), and place the bacteriosphere as a planetary-scale structure into the wider cosmic context, including the panspermia hypothesis according to which microbial life is a cosmic phenomenon (Wickramasinghe 2010), Fermi’s paradox loses its validity and it may no longer be considered a paradox at all (see below).

There are several versions of the panspermia hypothesis including cometary panspermia (Hoyle and Wickramasinghe, 1982; Wickramasinghe 2010), lithopanspermia (Melosh 1998; Worth et al., 2013), transpermia (Davies 2003), and directed panspermia (Crick and Orgel, 1973). According to cometary panspermia, life does not arise through abiogenesis (Earth-based origin of life), but instead, it has the cosmic origin (Hoyle and Wickramasinghe, 1982; Wickramasinghe 2010). Transpermia and lithopanspermia argue that life arises through abiogenesis, for example on a planet like Mars, and it is transported through planetary ejecta onto neighbouring planets like Earth (Melosh 1998; Davies 2003; Worth et al., 2013). The concept of directed panspermia suggests that life may be intentionally seeded on selected planets by technologically superior civilisations (Crick and Orgel 1973).

In addition to rocks carrying random collections of microbiota from one life-laden planet in the galaxy to another, the genetic products of evolved life could also be disseminated on a galaxy-wide scale. Such ideas have been extensively discussed elsewhere (Napier 2004; Wallis and Wickramasinghe, 2004; Wickramasinghe and Napier, 2008). Our present-day solar system is surrounded by an extended halo of some 100 billion comets (the Oort Cloud) and this entire system orbits the centre of the galaxy with a period of 240 My. On average, once every 40 My the Oort cloud of comets becomes gravitationally perturbed by a close encounter with a molecular cloud such as the Orion Nebula. The result is that cometary bodies in the Oort cloud are thrown into the inner solar system, some to collide with the Earth. Such a process could hold a clue to understanding episodes of mass extinction that have punctuated the history of the evolution of life on the Earth. When a major impact, such as the one that led to the extinction of the dinosaurs 65 My ago occurs, vast amounts of debris can be shown to survive shock-heating and become expelled from the Earth and eventually from the entire solar system (Wallis and Wickramasinghe, 2004). This expelled material would not only contain random collections of surviving microorganisms but also entire microbial ecologies as well. Such microbial ecologies could well be imbued with an internally defined intelligence that would be transferable to another distant planetary system, the transfer taking place within a few hundred million years of the impact ejection event.

4. Survivability under space conditions

Irrespective of potential merits or failures of various panspermia hypotheses, the major initial obstacle to accepting them as scientifically valid, was the criticism that microbes would not be able to survive travel from one planet to another, let alone the intergalactic travel, because of harsh space conditions not hospitable to life (Becquerel 1924). However,

these criticisms have been dealt with in the formulation of the theory of cometary panspermia where replication of cosmic microbiota occurs within radioactively heated, liquid domains of comets within which microbial survival will not be a problem (Hoyle and Wickramasinghe, 1982, 1985). Such liquid conditions can be shown to persist for cosmologically relevant timescales.

Further, the extensive studies carried out on the survival of bacteria under the most hostile conditions mimicking those of space give added credence to their survivability under cosmic conditions. Recently, a group of Japanese scientists has conducted experiments with bacteria (*Deinococcus radiodurans*) placed on the exterior of the International Space Station and shown that clumps of such bacteria can survive for at least 3 years, possibly more (Kawaguchi et al., 2020). Another group of Japanese scientists has revived microbes that were in a dormant state for more than 100 million years in the South Pacific seabed – in sediment that is poor in nutrients but has enough oxygen to allow them to live (Morono et al., 2020).

Moreover, it should be stressed that the exposure to potentially damaging radiation in microbes transiting between planetary systems takes place over a limited timescale of a few million years. A large fraction might lose viability, but a small fraction *always* survives. The picture is similar to the sowing of seeds in the wind. Few are destined to survive, but so many are the seeds that some among them inevitably take root. The requirement for panspermia to operate is that a fraction of $\sim 10^{-24}$ survives during interstellar transits, and this requirement is difficult if not impossible to violate (Hoyle and Wickramasinghe, 2000). This cosmic replication cycle is depicted in Fig. 1. At least a hundred billion circuits in this loop have been completed in our galaxy alone, one for every sun-like star. Comets in this model serve not only as amplifiers of cosmic microbiota but also as their distributors, as well as the long-term storage sites in the universe.

A recent paper has reported that carbonaceous (C-type) asteroids, which circulate within our solar system, are highly porous and hence riddled with cavities that were probably once filled with water (Okada et al., 2020). This conclusion was based on thermographic images of the C-type asteroid 162173 Ryugu generated by the thermal infrared imager onboard the spacecraft Hayabusa 2 (Kitazato et al., 2021). What was discovered was declared by the investigators as surprising:

“Contrary to predictions that the surface consists of regolith and dense boulders, the boulders are more porous than typical carbonaceous chondrites and their surroundings are covered with porous

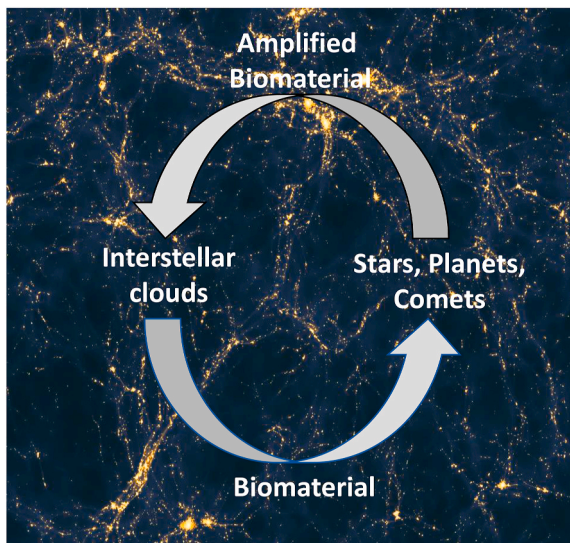


Fig. 1. Bacteria and viruses expelled from a planetary/cometary system are amplified in the warm radioactively heated interiors of comets and thrown back into interstellar space. Background picture: mapping light in the cosmos.

fragments more than 10 cm in diameter This high-porosity asteroid may link cosmic fluffy dust to dense celestial bodies.” (Okada et al., 2020)

It is obvious that such carbonaceous asteroids of high porosity have the potential to transport not just dust but also microbiota – entire colonies of microorganisms – around the solar system and beyond on the galactic scale. Recently a model of panspermia developed by Ginsburg et al. (2018) confirms that transference of microbiota is not confined to solar-system scales, but it can occur on galactic scales.

5. Microbial panspermia

We next discuss the hypothesis that panspermia – the transport of microbial colonies - is a solution to Fermi’s paradox. If the entire domain of life on Earth is represented in the form of the bell shape curve (normal Gaussian distribution), the typicality of lifeforms can be judged by the 3-sigma rule or 68-95-99.7 rule² (Graferend 2006, Fig. 2). When we try to allocate the space for “intelligent life” – that is the human intelligence and its technologies – the result is a non-typicality beyond 3-sigmas (Fig. 2). Assuming that life on Earth is at least 3.8 billion years old and that human intelligent technologies emerged in the last 400 years starting with the industrial revolution, the point occupied by “intelligent life” on the curve is 0.00001% (Fig. 2). This is outside the last sigma of 99.7%. Therefore, what is called “intelligent life”, is within the atypical territory on the distribution curve of terrestrial lifeforms.

This possibility is in line with the Fermi paradox. If the distribution curve (Fig. 2) is used as a model to search for extraterrestrial life, the conclusion is straightforward: “intelligent life” is unlikely to be found anywhere else in the universe where life may exist. A recent study by

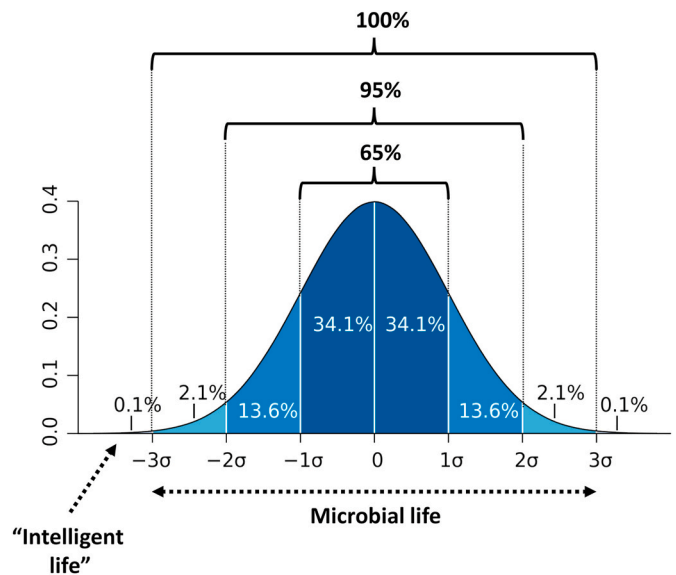


Fig. 2. Lifeforms are represented in the form of the normal Gaussian distribution and the three-sigma rule. According to the three-sigma rule of thumb, almost all values within three standard deviations of the mean, or 99.7%, in the case of normal distribution, are taken to be equal to 100% (the 99.7% probability is an empirical certainty). Thus, any value located beyond 3 sigmas, must be discarded as a non-representative outlier. The basic graph courtesy of Wikimedia commons.

² The three-sigma rule is a heuristic in empirical sciences that all values lie within three standard deviations of the mean, in the case of normal distribution. This means that the 99.7% probability is almost a certainty (see Fig. 2).

Snyder-Beatti et al. (2021) confirms this using a different approach.

However, if we replace the narrow version of intelligence confined to human technological civilisation, with the much wider form of intelligence that typifies the planetary-scale bacterial system (see section 2) and combine it with the panspermia hypothesis and the inevitability of microbial spread, Fermi's paradox is resolved. By using the above distribution curve (Fig. 2), typicalities of lifeforms can be estimated for any species. The most typical lifeforms on Earth are those forms that cover the territory of 3-sigmas. The lifeforms that cover this territory are microbes: bacteria, archaea, and viruses (Fig. 2) because they exist in continuity since the inception of life on Earth 3.8–4.2 billion years ago.

Current estimates suggest that the most abundant lifeform in the Earth's biosphere is in the form of bacteria (Hug et al., 2016). The most numerous biogenic forms on Earth are viruses (Moelling and Broecker, 2019). According to some biologists, viruses do not qualify as lifeforms because they are parasites (Lopez-Garcia 2012). However, other biologists view life as the co-evolution between hosts (three domains of life: bacteria, archaea, and eukaryotes) and parasites (viruses), with parasites acting as drivers of evolution (Koonin and Starokadomskyy, 2016). If we accept this latter view the search for life in space must include bacteria, archaea, and viruses, as the most typical biogenic forms in the Earth's biosphere (Fig. 2).

Given that one of the problems of Fermi's paradox is the discrepancy between the Fermi-Hart timescale (time required to colonize the galaxy by the intelligent human-like civilisation) taken to be 10^6 – 10^8 years (see Ćirković 2009), and the age of Earth which is 4.46×10^9 years, this discrepancy is resolved by the timescale of microbial life on Earth (3.8×10^9 – 4.2×10^9 ; see also Fig. 2) which is not much distant from Earth's age. Furthermore, the concept of "intelligent life" in Fermi's paradox is too narrow, as we argued in Section 2. In conclusion, Fermi's paradox is resolved on two levels: the timescale discrepancy and the concept of bacterial intelligence.

6. Tentative form of microbial SETI

This section aims to describe a version of SETI that is framed exclusively in the microbial context. The justification for this endeavour is the argument presented in sections 4 and 5, namely that (i) the search for extraterrestrial life should be modelled on the lifeforms that cover the territories of 3 sigmas (Fig. 2) and (ii) panspermia is a solution to Fermi's paradox.

The human SETI has three components. These include capacities to (i) collect cosmic-scale information, (ii) process collected information using the appropriate exploratory apparatus (a techno-science like method), and (iii) direct the reaction on the cosmic scale with the hope of establishing contacts with similar non-local civilisations within a communicable range (Ćirković and Vukotić, 2013). These capacities are replicated by the planetary-scale microbial system, such as the bacteriosphere (Slijepcevic 2020). The bacteriosphere can (i) read the portion of the electromagnetic spectrum emitted from space (visible light coming from the Sun), (ii) process the collected information and turn it into the energy-producing system (photosynthesis as a form of biotechnology), and (iii) use biological tropism to establish contacts with biogenic structures that have a cosmic origin (Slijepcevic 2020) (Fig. 3).

It is important to explain the concept of biological tropism on the cosmic scale. Tropism is usually described as either movement or locomotion of organisms, or direction of biological growth, in response to a stimulus (Cassab et al., 2013). It is an essential feature of all living organisms. Types of tropism include phototropism, chemotropism, gravitropism, hydrotropism, etc. Tropism is easy to observe in bacteria and viruses (McCall, 2021).

The origin of cosmic tropism can be traced to the proponent of the school of relational biology, Robert Rosen. Rosen interpreted organisms as anticipatory systems (Rosen 1985) causally entailed in the form of epistemological relationship between themselves and their ambience (Rosen 1991; reviewed in Slijepcevic 2020). When biological structure

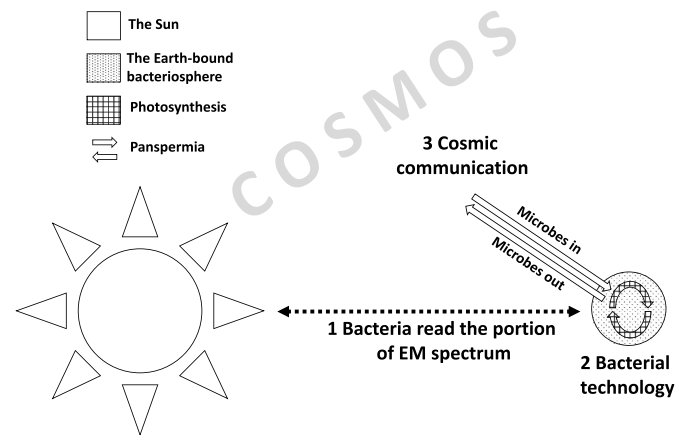


Fig. 3. A tentative form of microbial SETI. 1. Bacteria read the portion of the electromagnetic spectrum (EM), in the form of visible light, as a result of phototropism or heliotropism. 2. This leads to the emergence of photosynthesis as a form of energy production by cyanobacteria, which also become part of plants through the process of endosymbiosis (Slijepcevic 2021). 3. The bacterial planetary supersystem (bacteriosphere) can attract microbes coming from space (panspermia) or eject microbes into space, leading to a form of microbial communication through biological tropism (Louie 2010; also see text) without the human input.

and function are introduced into Rosen's model, they become causally linked. Biological structure, as a form of natural measurements carried out by the sensorium of each species, is causally entailed by the natural process of epistemological search for the biological function (Kineman 2007). The final result is that all organisms, from bacteria to mammals, are anticipatory systems that possess internal predictive models of themselves and their environments (Rosen 1985, 1991).

One of Rosen's collaborators, Aloisius H. Louie, argued that biological tropism also represents the capacity of organisms, or biological systems, to produce predictive models of themselves and their environments in the manner of Rosen's anticipatory systems (Louie 2010). In the context of the planetary-scale biogenic system (the bacteriosphere; see section 2) and the potential existence of microbial lifeforms throughout the cosmos (panspermia hypothesis; see sections 3 and 4) biological tropism acquires a cosmic form. The planetary-scale biosystem, such as the bacteriosphere, is capable of self-producing the predictive model of its cosmic environment through "advertising itself to the cosmos-wide flow of biogenic particles", which may range from viruses to bacteria or archaea (Slijepcevic 2020). Provided these microbes survive galactic or intergalactic cosmic travel, as predicted by the panspermia hypothesis (Hoyle and Wickramasinghe, 2000; Wickramasinghe 2010; Kawaguchi et al., 2020), from its original cosmic source to the Earth-bound bacteriosphere, the final result will be the contact between terrestrial and extraterrestrial lifeforms (Fig. 3). Ensembles of microbiota arriving at the Earth, e.g. in cometary bolides, may also be repositories of extraterrestrial intelligence provided coded messages can be deciphered (Wickramasinghe et al., 2021).

It is important to stress that the version of cosmic tropism discussed above is essential for microbial SETI and it is an integral part of the solution to Fermi's paradox (see sections 3-5; Fig. 3). What follows clearly from microbial SETI is that some elements of orthodox SETI require re-evaluation. For example, the likelihood of identifying technological signatures in the form of Dyson spheres (Bradbury et al., 2011), as signs of technological civilisations, is possibly very small (Snyder-Beatti et al., 2021, Fig. 2). However, the concept of looking for a technological signature acquires a different meaning in the context of microbial SETI. The technological signature that is to be looked for, becomes the bio-signature (Fig. 3). Any form of life on a habitable planet, which becomes established over the cosmic temporal scale, is likely to produce an altered planetary atmosphere that exists in dynamic

disequilibrium, detectable spectroscopically, as argued by James Lovelock (1972; 1995).

With this in mind, we can conclude that the only planet in the solar system that harbours life as the planetary phenomenon is probably Earth. Other planets in the solar system, given that they possess only inert forms of atmospheres may (i) not have any microbial lifeforms, with Venus being a possible exception (Wickramasinghe and Slijepcevic, 2020); (ii) have only sporadic microbial lifeforms incapable of turning inert atmospheres into dynamic version altered by microbial metabolic activities and (iii) had planetary-scale life in the past but these become extinct.

7. What is intelligence?

The final section aims to argue that the concept of intelligence, as understood in the present form, requires a revision, given the reasons presented in section 2. Intelligence as a biological trait is almost exclusively interpreted as the human-only capacity to understand the world through consciousness-based cognition, which can be further enhanced through merging human bodies with AI technologies (Kurzweil 1990; Bostrom 2014; Price 2016). The bias towards the brain, neural intelligence, and its derivative, AI, dubbed by a prominent botanist 'brain chauvinism' (Trewavas 2017), is apparent in orthodox SETI (see, for example, Drake's equation mentioned above). However, evidence from different disciplines of biology, including relational biology, biosemiotics, evolutionary epistemology, and the system's view of life, supports non-neural forms of intelligence that may not be inferior to human intelligence (reviewed in Slijepcevic 2020).

The central problem of any attempt at revision of the definition of intelligence is how to integrate intelligence in the anthropocentric form, into a wider evolutionary picture. This problem becomes acute in the case of two research programmes shaped by the anthropocentric interpretation of intelligence, AI (Alexander 2019) and SETI (e.g. the debate between Carl Sagan and Ernst Mayr about the validity of SETI; cited in Lineweaver 2007). Some AI-based predictions clash with the predictions stemming from the concept of bacterial intelligence (section 2). A typical example is a prediction of an influential futurist, Ray Kurzweil, according to which the planet Earth will become a gigantic AI-based computer by the year 2099 (Kurzweil 2010). This, according to Kurzweil, is the logical consequence of the emergence of technological singularity, or AI-based superintelligence, which is predicted to occur roughly by the mid 21st century. However, Kurzweil's prediction completely ignores the fact that natural computation on the planetary scale has existed for billions of years in the form of bacterial regulation of biogeochemical cycles of organic elements (Margulis 1999; Sonea and Matheiu 2001).

Similarly, SETI assumes that the only form of intelligence that could exist outside the planet Earth is either the humanity-type intelligence or a higher form of intelligence resulting from the post-biological evolution, e.g. some form of machinocene (Price 2016). However, both these options ignore the possibility that the planetary-scale structures, such as the bacteriosphere, can communicate with the biogenic structures potentially existing elsewhere in the cosmos through the process of biological tropism (see section 6) and that they are overwhelmingly more abundant. It is important to stress, in this context, that biological tropism is not a passive trait. In line with the four disciplines of biology mentioned above, the bacteriosphere may be capable of actively anticipating the virosphere, through modelling relations (relational biology), sign interpretation (biosemiotics), natural learning (evolutionary epistemology), and autopoiesis (system's view of life) (see Slijepcevic 2020 for review; see also Section 6).

The problem of integrating anthropic intelligence with the wider natural intelligence is further exacerbated by the additional two factors. First, even in the fields of human cognition and AI, the concept of intelligence lacks a unified theoretical basis. For example, at least 70 different definitions of intelligence exist in the literature (Legg and

Hutter, 2007). Second, some proponents of plant intelligence interpret it almost like a metaphysical concept that may not be testable by experimental research at present (Chamovitz 2018).

A necessary step in eliminating anthropic bias when it comes to interpreting the concept of intelligence is to recognise that intelligence is not associated exclusively with the human-type cognitive process. The evidence from the four disciplines of biology, mentioned above, is overwhelming: human-type intelligence is only a fragment in the spectrum of natural intelligence (Slijepcevic 2020). However, given existing controversies associated with interpreting human-type intelligence and how AI, as a derivative of this type of intelligence, is integrated with it, a cautious approach is required to fully grasp intelligence as a biological trait. Even though several biologists proposed definitions of intelligence in an evolutionary context, ranging from integrated problem solving (Trewavas and Balaška, 2011), evolutionary fitness (Trewavas 2017; Calvo et al., 2020), information processing as a form of adaptation (Slijepcevic 2018, 2019), etc., these attempts, irrespective of their validity in narrow scientific or philosophical disciplines, cannot be used yet as the basis for any generalised concept of natural intelligence. This is because of a conflict between investigative disciplines with vested interests, resulting in a lack of consensus in any theoretical sense. To resolve this issue we advocate a pragmatic approach initiating a wide-ranging discussion between various interested parties. These include proponents of microbial and plant intelligence, the AI community and its critics, SETI researchers and proponents of panspermia, astrophysicists and astrobiologists, cognitive scientists, information theorists, and evolutionary biologists. The goal should be to establish a coherent theoretical and experimental platform for the study of intelligence in the biological and evolutionary sense. A memorable debate between Carl Sagan and Ernst Mayr (cited in Lineweaver 2007) that took place more than twenty years ago is a good example of a constructive presentation of different views, which resulted in a more mature interpretation of SETI.

Declaration of competing interest

We declare no conflict of interest

References

- Alexander, V.N., 2019. AI, stereotyping on steroids and alan turing's biological turn. In: Sudmann, A. (Ed.), *Democratization of Artificial Intelligence: Net Politics in the Era of Learning Algorithms*. Transcript, Bielefeld, Germany, pp. 43–54.
- Almár, I., 2014. Old and New from SETI: a Review. *Frontier Research in Astrophysics* 26–31 May, 2014. Mondello (Palermo), Italy.
- Bassler, B.L., 2002. Small talk: cell-to-cell communication in bacteria. *Cell* 109, 421–424.
- Bequerel, P., 1924. La vie terrestre provient-elle d'un autre monde? *L'Astronomie* 38, 393–417.
- Ben-Jacob, E., 1998. Bacterial wisdom, Gödel's theorem and creative genomic webs. *Physica A* 248, 57–76.
- Ben-Jacob, E., Becker, I., Shapira, Y., Levine, H., 2004. Bacterial linguistic communication and social intelligence. *Trends Microbiol.* 12, 366–372.
- Ben-Jacob, E., 2009. Learning from bacteria about natural information processing. *Ann. N. Y. Acad. Sci.* 1178, 78–90.
- Bostrom, N., 2014. *Superintelligence: Paths, Dangers, Strategies*. Oxford University Press, Oxford.
- Brin, G.D., 1983. The 'great silence': the controversy concerning extraterrestrial intelligence. *Q.J. R. Astr. Soc.* 24, 283–309.
- Bradbury, R.J., Čirković, M.M., Dvorsky, G., 2011. Dysonian approach to SETI: a fruitful middle ground? *J. Br. Interplanet. Soc. (JBIS)* 64, 156–165.
- Cassab, G.I., Delfeena, E., Campos, M.E., 2013. "Root hydrotropism: an update". *Am. J. Bot.* 100 (1), 14–24.
- Calvo, P., Gagliano, M., Souza, G.M., Trewavas, A., 2020. Plants are intelligent, here's how. *Ann. Bot.* 125, 11–28.
- Carter, B., 1983. The anthropic principle and its implications for biological evolution. *Phil. Trans. R.Soc. A* 310, 347–363.
- Chamovitz, D.A., 2018. Plants are intelligent; now what? *Native Plants* 4, 622–623.
- Cocconi, G., Morrison, P., 1959. Searching for interstellar communications. *Nature* 184, 844–846.
- Crick, F.H.C., Orgel, L.E., 1973. Directed panspermia. *Icarus* 19, 341–346.
- Čirković, M.M., 2009. Fermi's paradox – the last challenge for copernicanism? *Serbian Astron. J.* 178 1–20.
- Čirković, M.M., 2013. Who are the SETI sceptics? *Acta Astronaut.* 89, 38–45.

- Ćirković, M.M., Vukotić, B., 2013. Astrobiological landscape: a platform for the neo-Copernican synthesis? *Int. J. Astrobiol.* 12, 87–93.
- Darwin, C., 1861. *On the Origin of Species by the Means of Natural Selection*. D. Appleton and Company, New York (A New Edition, Revised and Augmented by the Author).
- Davey, H.M., 2011. Life, death, and in-between: meanings and methods in microbiology. *Appl. Environ. Microbiol.* 77, 5571–5576.
- Davies, P.C.W., 2003. How bio-friendly is the universe? *Int. J. Astrobiol.* 2, 115–120.
- Drake, F.D., 1961. US Academy of Sciences Conference on "extraterrestrial Intelligent Life" (Green Bank: West Virginia).
- Gilbert, J.A., Neufeld, J.D., 2014. Life in a world without microbes. *PLoS Biol.* 12, e1002020.
- Ginsburg, I., Lingam, M., Loeb, A., 2018. Galactic panspermia. *Astrophys. J. Lett.* 869, L12.
- Grafarend, E.W., 2006. *Linear and Nonlinear Models: Fixed Effects, Random Effects, and Mixed Models*. Walter de Gruyter, Berlin, New York.
- Hoyle, F., Wickramasinghe, N.C., 1982. Comets: a vehicle for panspermia. In: Ponnamperna, C. (Ed.), *Comets and the Origin of Life*. D. Reidel, Dordrecht, pp. 227–239.
- Hoyle, F., Wickramasinghe, N.C., 1985. *Living Comets*. Cardiff Press, University College.
- Hoyle, F., Wickramasinghe, N.C., 2000. *Astronomical Origins of Life. Steps towards Panspermia*. Kluwer, Dordrecht.
- Huneman, P., Walsh, D.M., 2017. *Challenging the Modern Synthesis: Adaptation, Development, and Inheritance*. Oxford University Press, Oxford.
- Hug, L.A., Baker, B.J., Anantharaman, K., Brown, C.T., Probst, A.J., Castelle, C.J., Butterfield, C.N., Hershendorf, A.W., Amano, Y., Ise, K., Suzuki, Y., Dudek, N., Relman, D.A., Finstad, K.M., Amundson, R., Thomas, B.C., Banfield, J.F., 2016. A new view of the tree of life. *Nature Microbiology* 1, 16048.
- Kawaguchi, Y., Shibuya, M., Kinoshita, I., Yatabe, J., Narumi, I., Shibata, H., Hayashi, R., Fujiwara, D., Murano, Y., Hashimoto, H., Imai, E., Kodaira, S., Uchihori, Y., Nakagawa, K., Mita, H., Yokobori, S., Yamagishi, A., 2020. DNA damage and survival time course of deinococcal cell pellets during 3 Years of exposure to outer space. *Front. Microbiol.* 11, 2050.
- Kineman, J.J., 2007. Modeling relations in nature and eco-informatics: a practical application of rosennean complexity. *Chem. Biodivers.* 4, 2436–2457.
- Kitazato, K., Miliken, R.E., Tsuda, Y., 2021. Thermally altered subsurface material of asteroid(162173) Ryugu. *Nature Astronomy*. <https://doi.org/10.1038/s41550-020-01271-2>.
- Koonin, E.V., Starokadomsky, P., 2016. Are viruses alive? The replicator paradigm sheds decisive light on an old but misguided question. *Stud. Hist. Philos. Biol. Biomed. Sci.* 59, 125–134.
- Kurzweil, R., 1990. *The Age of Intelligent Machines*. MIT Press, Cambridge, MA.
- Kurzweil, R., 2010. *How My Predictions Are Faring?* <https://www.kurzweilai.net/images/How-My-Predictions-Are-Faring.pdf>.
- Legg, S., Hutter, M., 2007. A collection of definitions of intelligence. In: Goertzel, B., Wang, P. (Eds.), *Advances in Artificial General Intelligence: Concepts, Architecture and Algorithms*. IOS Press, pp. 17–24.
- Lineweaver, C.H., 2007. In: Seckbach, J., Walsh, M. (Eds.), *From Fossils to Astrobiology. Cellular Origin, Life in Extreme Habitats and Astrobiology*, vol. 12. Springer, Dordrecht, pp. 353–368.
- Lopez-Garcia, P., 2012. The place of viruses in biology in light of the metabolism-versus-replication-first debate. *Hist. Philos. Life Sci.* 34, 391–406.
- Louie, A.H., 2010. Robert Rosen's anticipatory systems. *Foresight* 12, 18–29.
- Lovelock, J., 1972. Gaia as seen through the atmosphere. *Atmos. Environ.* 6, 579–580.
- Lovelock, J., 1995. *The Ages of Gaia: A Biography of Our Living Earth*. Oxford University Press.
- Lyon, P., 2015. The cognitive cell: bacterial behavior reconsidered. *Front. Microbiol.* 6, 264.
- Lyon, P., 2017. Environmental complexity, adaptability and bacterial cognition: godfrey-Smith's hypothesis under the microscope. *Biol. Philos.* 32, 443–465.
- Margulis, L., 1990. Kingdom Animalia: The Zoological Malaise from a Microbial Perspective. *Amer. Zool.* 30, 861–875.
- Margulis, L., 1999. *The Symbiotic Planet: A New Look at Evolution* (Phoenix).
- Margulis, L., Dolan, M.F., Guerrero, R., 2000. The chimeric eukaryote: origin of the nucleus from the karyomastigote in amitochondriate protists. *Proc. Natl. Acad. Sci. U. S. A.* 97, 6954–6959.
- Margulis, L., 2004. Serial endosymbiotic theory (SET) and composite individuality: transition from bacterial to eukaryotic genomes. *Microbiol. Today* 31, 172–174.
- Margot, J.-L., Croft, S., Lazio, T.J.W., Tarter, J., Korpela, E.J., 2019. The radio search for technosignatures in the decade 2020-2030. [arXiv:1903.05544](https://arxiv.org/abs/1903.05544).
- Mathieu, L.G., Sonea, S., 1996. Review of the unique mode of evolution of bacteria: an opinion. *Symbiosis* 21, 199–207.
- McCall, L.-I., 2021. Quo vadis? Central rules of pathogen and disease tropism. *Front. Cell. Infect. Microbiol.* 11, 640987.
- McFall-Ngai, M., Hadfield, M.G., Bosch, T.C.G., Carey, H. V., Domazet-Lošo, T., Douglas, A.E., Dubilier, N., Eberl, G., Fukami, T., Gilbert, S.F., Hentschel, U., King, N., Kjelleberg, S., Knoll, A.H., Kremer, N., Mazmanian, S.K., Metcalf, J.L., Nealon, K., Pierce, N.E., Rawls, J.F., Reid, A., Ruby, E.G., Rumpho, M., Sanders, J. G., Tautz, D., Wernegreen, J.J., 2013. Animals in a bacterial world, a new imperative for the life sciences. *Proc. Natl. Acad. Sci. U.S.A.* 110, 3229–3236.
- Melosh, H.J., 1988. The rocky road to panspermia. *Nature* 332, 687–688.
- Moelling, K., Broecker, F., 2019. Viruses and evolution - viruses first? A personal perspective. *Front. Microbiol.* 10, 523.
- Morono, Y., Ito, M., Hoshino, T., Terada, T., Hori, T., Ikehara, M., D'Hondt, S., Inagaki, F., 2020. Aerobic microbial life persists in oxic marine sediment as old as 101.5 million years. *Nat. Commun.* 11, 3626.
- Musall, S., Kaufman, M.T., Juavinett, A.L., Gluf, S., Churchland, A.K., 2019. Single-trial neural dynamics are dominated by richly varied movements. *Nat. Neurosci.* 22, 1677–1686.
- Napier, W.M., 2004. A mechanism for interstellar panspermia. *Mon. Not. R. Astron. Soc.* 348, 46–51.
- Okada, T., Fukuhara, T., Tanaka, S., et al., 2020. Highly porous nature of a primitive asteroid revealed by thermal imaging. *Nature* 579, 518–522.
- Price, H., 2016. *Now It's Time to Prepare for the Machinocene*. <https://aeon.co/ideas/now-it-s-time-to-prepare-for-the-machinocene>. (Accessed 11 March 2021).
- Richards, T.A., Massana, R., Pagliara, S., Hall, N., 2019. Single cell ecology. *Phil. Trans. R. Soc. B* 374, 20190076.
- Rosen, R., 1985. *Anticipatory Systems: Philosophical, Mathematical, and Methodological Foundations*. Pergamon Press, Oxford.
- Rosen, R., 1991. *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*. Columbia University Press, New York.
- Sagan, L., 1967. On the origin of mitosing cells. *J. Theor. Biol.* 3, 225–274.
- Shapiro, J.A., 1988. Bacteria as multicellular organisms. *Scientific American* 82–89 (June).
- Shapiro, J.A., 1998. Thinking about bacterial populations as multicellular organisms. *Annu. Rev. Microbiol.* 52, 81–104.
- Shapiro, J.A., 2007. Bacteria are small but not stupid: cognition, natural genetic engineering and socio-bacteriology. *Stud. Hist. Philos. Biol. Biomed. Sci.* 38, 807–819.
- Shapiro, J.A., 2014. Physiology of the read-write genome. *J. Physiol.* 11, 2319–2341.
- Shapiro, J.A., 2016a. Nothing in evolution makes sense except in the light of genomics: read-write genome evolution as an active biological process. *Biology* 5, 27.
- Shapiro, J.A., 2016b. The basic concept of the read-write genome: Mini-review on cell-mediated DNA modification 140, 35–37.
- Sharov, A.A., Gordon, R., 2013. *Life before Earth*. <http://arxiv.org/abs/1304.3381>. (Accessed 1 June 2020).
- Sharov, A.A., Gordon, R., 2017. Life before earth. In: Gordon, R., Sharov, A.A. (Eds.), *Habitability of the Universe before Earth*. Elsevier B.V., Amsterdam, pp. 265–297.
- Simpson, G.G., 1964. The nonprevalence of humanoid. *Science* 143, 769–775.
- Snyder-Beattie, A.E., Sandberg, A., Drexler, K.E., Bonsall, M.B., 2021. The timing of evolutionary transitions suggests intelligent life is rare. *Astrobiology* 21, 2149.
- Slijepcevic, P., 2018a. Genome dynamics over evolutionary time: "C-value enigma" in light of chromosome structure. *Mutat. Res.* 836, 22–27.
- Slijepcevic, P., 2018b. Evolutionary epistemology: reviewing and reviving with new data the research programme for distributed biological intelligence. *Biosystems* 163, 23–35.
- Slijepcevic, P., 2019. Principles of information processing and natural learning in biological systems. *J. Gen. Philos. Sci.* <https://doi.org/10.1007/s10838-019-09471-9>.
- Slijepcevic, P., 2020. Natural intelligence and anthropic reasoning. *Biosemiotics* 13, 285–307.
- Slijepcevic, P., 2021. Serial Endosymbiosis Theory: from biology to astronomy and back to the origin of life. *Biosystems* 202, 104353.
- Smart, J.M., 2012. The transension hypothesis: sufficiently advanced civilizations invariably leave our universe, and implications for METI and SETI. *Acta Astronaut.* 78, 55–68.
- Sonea, S., Panisset, M., 1983. *A New Bacteriology*. Jones and Bartlett Publishers, Sudbury.
- Sonea, S., 1988. A bacterial way of life. *Nature* 331, 216.
- Sonea, S., Mathieu, L.G., 2001. Evolution of the genomic systems of prokaryotes and its momentous consequences. *Int. Microbiol.* 4, 67–71.
- Tarter, J., 2001. The search for extraterrestrial intelligence (SETI). *Annu. Rev. Astron. Astrophys.* 39 511–548.
- Tarter, J.C., Agrawal, A., Ackermann, R., Backus, P., Blair, S.K., Bradford, M.T., Harp, G. R., Jordan, J., Kilsdonk, T., Smolek, K.E., Richards, J., Ross, J., Shostak, G.S., Vakoch, D., 2010. SETI turns 50: five decades of progress in the search for extraterrestrial intelligence. In: Hoover, Richard B., Levin, Gilbert V., Rozanov, Alexei Yu, Davies, Paul C.W. (Eds.), *Instruments, Methods, and Missions for Astrobiology XIII*, vol. 7819. Proc. of SPIE, p. 781902.
- Temple, R., Wickramasinghe, N.C., 2019. Kardylewski dust clouds: could they Be cosmic "superbrains"? *Ad Astra* 4, 44001.
- Trewavas, A., 2017. The foundations of plant intelligence. *Interface focus* 7, 20160098.
- Trewavas, A., Baluška, F., 2011. The ubiquity of consciousness. *EMBO Rep.* 12, 1221–1225.
- Vakoch, D.A., 2011. Responsibility, capability, and Active SETI: policy, law, ethics, and communication with extraterrestrial intelligence. *Astra Astronautica* 68, 512–519.
- Villasante, A., Abad, J.P., Méndez-Lago, M., 2007. Centromeres were derived from telomeres during the evolution of the eukaryotic chromosome. *Proc. Natl. Acad. Sci. U. S. A.* 104, 10542–10547.
- Wallis, M.K., Wickramasinghe, N.C., 2004. Interstellar transfer of planetary microbiota. *Mon. Not. R. Astron. Soc.* 348, 52–61.
- Wickramasinghe, J.T., Napier, W.M., 2008. Impact cratering and the Oort cloud. *Mon. Not. R. Astron. Soc.* 387, 153–157.
- Wickramasinghe, N.C., 2010. The astrobiological case for our cosmic ancestry. *Int. J. Astrobiol.* 9, 119e129.
- Wickramasinghe, C., Slijepcevic, P., 2020. Microbial transfers from Venus to earth. In: Steele, Edward J., Wickramasinghe, N. Chandra (Eds.), *Advances in Genetics*, vol. 106. Academic Press, pp. 123–132.
- Wickramasinghe, C., Tokoro, G., Temple, R., 2021. *Ad. Ap.*, in Press.

Wilkins, J.S., 2006. The concept and causes of microbial species. *Hist. Philos. Life Sci.* 28, 329–348.

Woese, C.R., Kandler, O., Wheelis, M.L., 1990. Towards a natural system of organisms: proposal for the domains Archaea, Bacteria, and Eucarya. *Proc. Natl. Acad. Sci. U.S.A.* 87, 4576–4579.

Worth, R.J., Sigurdsson, S., House, C.H., 2013. Seeding life on the moons of the outer planets via lithopanspermia. *Astrobiology* 13, 1155–1165.