Plant Science 175 (2008) 756–760

Contents lists available at ScienceDirect

Plant Science

journal homepage: www.elsevier.com/locate/plantsci

Review

The origin of life, panspermia and a proposal to seed the Universe

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ARTICLE INFO

Article history:
Received 27 June 2008
Received in revised form 25 August 2008
Accepted 25 August 2008
Available online 4 September 2008

Keywords:
Flavonoid
Plant seed
UV resistance
Origin of life
Exospermia
Panspermia

ABSTRACT

Although the origin of life is experimentally elusive, the commonality of the genetic code is well established, as is the presence of life on Earth early in the planet's history. Spontaneous generation of life has not been documented, but life's ability to travel through space (at least for short distances) is clear from human exploration of the solar system, which has carried men to Earth's moon and microbial stowaways to exoenvironments, such as Mars. Direct evidence for panspermia (the universality of life) is thus limited to exospermia (the exportation of life from Earth). The hypothesis of general panspermia as the source of life on Earth is difficult to test, but microbes appeared during the first billion years of Earth's existence, and all species investigated so far use a similar genetic code, indicating a common origin. General panspermia requires that life survive transfer through the space. Thus, the plausibility of panserpmia can be evaluated by examining life forms on Earth for their capacity to survive in space. This approach has mostly concentrated on bacterial spores. In this essay, plant seeds are proposed as model panspermia vehicles, and directed exospermia (the deliberate dispersal of life away from the Earth) is suggested, using plant seeds and bundled, endophytic microorganisms.

Contents

1. The origin of life: spontaneous generation or panspermia?

The Earth formed approximately 4.5 billion years ago. Zircon minerals from about 4.4 billion years ago bear chemical signatures for the presence of liquid water at the time of their formation [1,2]. Fossils found in rocks from 3.4 billion years ago are thought to represent microbial biofilms and mats [3,4]. It is remarkable that fully formed microbial cells were probably present so early in the history of the Earth.

All forms of life tested so far use DNA to store genetic information, and they rely on a similar genetic code [5]. Thus, the life forms we know most likely came from the same source. Two explanations for the origin of life on Earth are currently in vogue: either it formed spontaneously from chemical precursors, or it came from elsewhere in the form of a microbial organism, probably equipped with our current genetic code or a similar precursor.

These alternative theories, ancient spontaneous generation and panspermia, are not easy to test. Attempts to generate life have produced molecules, such as amino acids, from constituents typical of the universal chemistry found in interstellar dust and meteorites [6], but nothing approaching life is on the experimental horizon (although efforts are being made to synthesize a minimal bacterial genome). The second speculation, panspermia, is at least as ancient as written history. The concept of panspermia sidesteps the question of the origin of life, proposing that life is universal, and that life on Earth came from outside the biosphere, possibly carried by meteorites or comets [7–14]. The theory of spontaneous generation would be supported (but of course not proven) by a laboratory reenactment of the spontaneous formation of a

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doi:10.1016/j.plantsci.2008.08.007

membrane-bound, self-replicating, evolving chemical system, similar to a living organism. Panspermia would be confirmed if organisms based on DNA, and using the same genetic code, were found outside our biosphere, *e.g.*, on Mars, which is thought by many to be a probable source of life on Earth.

Humans have sent numerous objects to Mars, beginning with a Soviet probe in 1971 (Mars 2). The first soft landing probes (Viking 1 and 2) produced controversial evidence for the presence of life [15]. While the Viking probes were heat treated, other space probes are contaminated by bacterial spores [16]—up to 300,000 per spacecraft, according to guidelines [17], but this figure refers to contamination detected by growth on bacterial culture media. Only a few percent of the bacteria on Earth can be cultured, so the spacecraft spore count is probably higher. Thus, seekers of evidence for the panspermia hypothesis will thus have to search for life that is genetically similar to ours on a virgin planet or moon, using equipment that does not carry contaminants from Earth. Chances of finding true exoorganisms on Mars will further decrease with the arrival of manned missions scheduled by the Russians and the Americans within the next 20 years. (A gram of human feces contains about 10^{12} bacteria; thus an fatal accident or a waste storage problem on Mars would release vast numbers of bacteria.) Proving that life came to Earth via panspermia could thus be just as difficult as showing spontaneous generation. But there is one clear fact in the murky question of life's origin: contemporary life can travel through space.

Man's recent space explorations show that humans can disperse life (both intentionally and unintentionally) within the solar system and well beyond. Voyager 1 (launched in 1977) is currently at about 103.6 AU (15.6 billion km) from the Sun. In November 2005, it was traveling at 61,920 km/h. In 40,000 years, Voyager 1 will be within 1.7 light years of the star AC+793888 in the Camelopardis constellation. Voyager 1 and 2 carry a golden record on which pictures and sounds of the Earth are encoded, as well as symbolic directions for playing the record and data detailing the location of Earth. The Voyager probes are almost certainly contaminated with bacteria, but given the radiation doses accumulated over the time necessary to reach other stars, their survival would seem unlikely [18,19].

Intentional dispersal of life through the universe was foreseen by Crick and Orgel [20], and called "directed panspermia." They proposed that a life form elsewhere in the Universe deliberately dispersed the life we find on Earth. There is no doubt that we are engaged in directed panspermia, but it is exospermia with the Earth as the source [21–23], not the introspermia with the Earth as the recipient, which was originally envisaged.

At least two conclusions concerning panspermia can thus be drawn: from the commonality of the genetic code, it seems likely that life on Earth came from a single source, and it is clear from Man's space explorations that life can be transferred through space. In addition, some of the meteorites found on Earth originated on Mars, and some show no signs of excessive heating [10,24]. This suggests the possibility of interplanetary transfer of life via ejection caused by impacts. Furthermore, bacteria have survived the ejection and landing forces associated with interplanetary transfer caused by impact [25,26].

Even if the fundamental question of life's origin is currently irresolvable, it is possible to test the feasibility of panspermia by screening organisms on Earth for the capacity to resist the conditions found in space (vacuum, temperature extremes, UV and cosmic radiation). Unicellular organisms are obvious models, since the fossil record clearly shows that they were present before multicellular organisms. Bacteria and their spores have thus received particular attention [7,10,16,27–29]. Experiments have included exposure of bacteria to simulated space conditions on Earth and exposure in space by attaching samples to the exterior of a satellite [30]. Other organisms have also been experimentally exposed to these extreme conditions, including lichens [31] and plant seeds (see below). UV light is a major liability for bacteria [32]. Some spores are resistant [16], but not to the UV fluxes encountered in interplanetary space travel. They would still require shielding, *i.e.* by being embedded in rock [30,33–36].

Microbes morphologically similar to contemporary bacteria can be found in early rocks, but this says nothing about the nature of the hypothetical panspermia space traveler. Perhaps the founding organism was multicellular, serving as a vector for an endophytic microbe? Were nucleated, eucaryotic, unicellular cells present from the beginning, derived from a multicellular founder [22,37]? What current multicellular life forms could do this? How about higher plants? Collectively, they have several promising properties: they are multicellular, eucaryotic, photosynthetic organisms with redundant genomes and plastic development, and they carry photosynthetic endosymbionts (chloroplasts). Most of all, some plants produce seeds that appear unusually resistant to the conditions found in space [38–40]. The following attempts to cast plants in the role of a panspermia vehicle [22].

2. Plant biology and the hypothetical panspermia vehicle

If life arrives in a sterile exoenvironment, *e.g.*, after surviving transfer through space, it will have to cope with hostile conditions, but it will not have to compete with indigenous life. Even a degraded organism will not be scavenged by resident species, as it is on Earth. A friendly exoenvironment might thus resemble a tissue culture medium and a biochemical reaction buffer. Water is common in the Universe. Much of the water on Earth probably came from collisions with asteroids and comets [41], which might have also carried life [42]. Water and dissolved minerals are a medium for plant growth and the growth of plant organs or cells, assuming an energy source such as photosynthesis. Plant cells and organs are thus capable of growth in a sterile aqueous environment, rich in minerals and flooded with light, and in many cases plant cells and organs are capable of regenerating whole plants. Survival of an incoming plant-like organism would thus not be an "all or none" affair, but one of degree [22]. Damaged parts could liberate cells or at least the components of cells, including organelles and the chemical components of life (*e.g.* enzymes, nucleic acids, ribosomes, amino acids, lipids, cofactors) (Fig. 1). Thus, even if plants only partially survive transfer through space, the pieces of a damaged plant might reconstitute life in a sterile environment [22]. A precedent is seen in the reconstruction of cells, then plants, from cytoplasm released from damaged algae [43,44].

Survival in an exoenvironment will depend on genome integrity. Plants have complex genomes, compared to bacteria, built up through polyploidy, retrotransposon replication, duplication and through inputs from foreign genomes, such as the chromosomes of the endosymbiont chloroplasts and mitochondria or through hybridization with other plant species [45]. Plant genomes are therefore redundant, so a loss of information during space travel could be compensated by other copies of similar information. Plant genes are implanted in a voluminous background of non-coding DNA. Essential genes are thus diluted targets for degradation, suggesting adaptive significance for non-coding, genomic DNA.

Plants carry obligate endosymbionts derived from free-living bacteria. Chloroplasts are the probable descendants of the cyanobacteria-like organisms that are found in ancient fossils and thought to be responsible for the accumulation of oxygen in the atmosphere [46]. They are no longer capable of independent existence, but plants carry other commensal microorganisms in

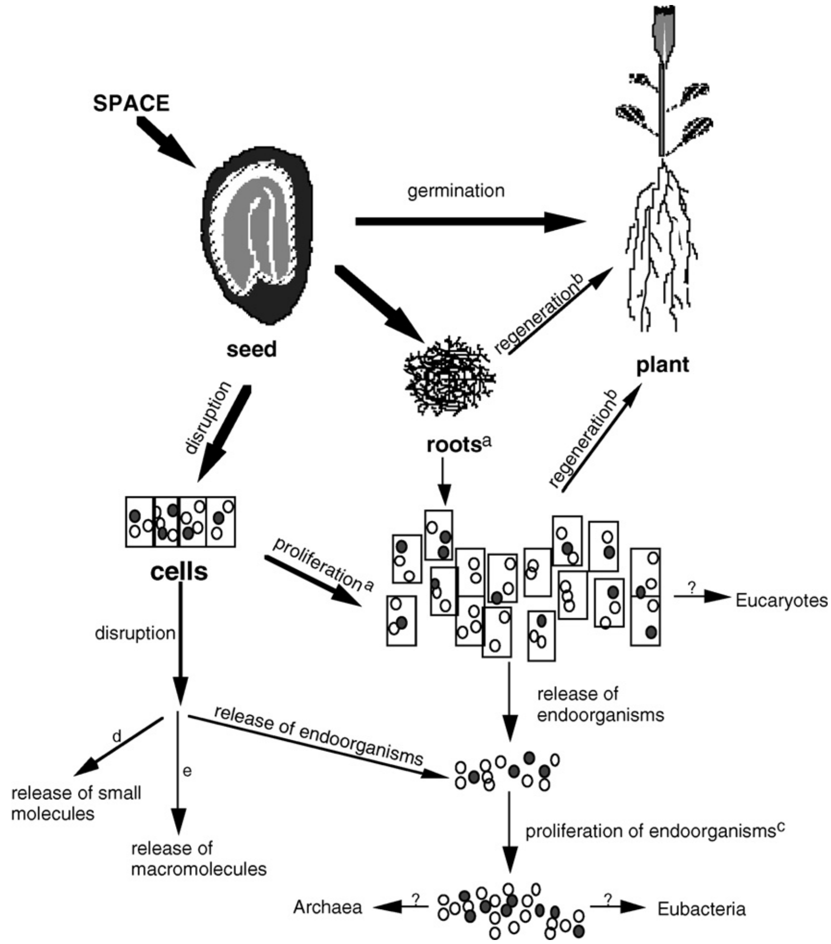

Fig. 1. Degrees of survival. (a) Some plant cells and organs (*e.g.*, roots) grow autonomously in chemically defined media consisting of minerals, vitamins and a carbon source, which can be photosynthesis. (b) Many plant cells and roots can regenerate into a whole plant. (c) Eucaryotic cells within seeds contain endosymbionts (mitochondria and chloroplasts), ancient bacteria no longer capable of living free of the host cell. Seeds also sometimes contain endophytic bacteria and fungi, capable of living outside the host. They will be released upon disruption of the seed. (d) Disruption of cells will release small molecules: *e.g.*, nucleotides, amino acids, lipids, co-factors, etc. that could provide the chemical basis for life. (e) Cell breakage will also release macromolecules: *e.g.* DNA, RNA, proteins (including enzymes and enzyme complexes with nucleic acids), complex polymers (including cellulose and lignin), as well as membranes, cell walls, ribosomes, chromatin, viruses, viroids, etc. These could provide the structural basis for a reorganization of life.

their tissues, such as the endomycorrhizal fungi and various bacteria. Introduction of a plant into an exoenvironment could thus also deliver microorganisms, protected by the plant.

A proper space traveler will have to maintain a dormant state for long periods. Dormancy in plants is achieved by several strategies, including the production of seeds. Seeds are suited for long periods of exposure to the harsh conditions of space. They are dehydrated, with metabolism essentially stopped. The lack of water would reduce the formation of free radicals by UV and cosmic radiation. They carry a preformed plant in the form of an embryo, and they respond to the presence of water by germinating and initiating embryo growth, using nutritional reserves accumulated during seed maturation on the mother plant. Seeds resist extreme cold, vacuum and some seeds resist exposure to temperatures of 150 °C [47]. Lotus seeds have germinated after 1200 years in the soil [48].

UV light is a liability for space travelers, unless there is shielding from surrounding matter, *e.g.* a meteorite. Even with shielding during transfer through space, UV poses a dilemma upon the arrival of a photosynthetic space traveler in a new environment. On Earth, life is shielded from UV below 300 nm, but the ozone that provides the filter is the product of oxygen, itself produced by photosynthesis. A newly arrived space traveler in an exoenvironment would thus probably need protection against UV. Plants produce polyphenols, such as flavonoids, which have absorption spectra similar to that of nucleic acids [23]. Seeds carry concentrated flavonoids in their seed coats, and they are particularly resistant to short wavelength UV—at least five orders of magnitude more so than the most resistant bacterial spores [39]. *Arabidopsis* seeds have survived short exposures to space conditions [49–51], and they are currently attached to the outside of the Columbus module of the International Space Station for an 18-month exposure (EXPOSE project, European Space Agency).

While less resistant than their seeds, higher plants respond to UV by producing flavonoids and other UV screens, which could help to protect them in an exoenvironment [23,52,53]. Metabolic engineering could be used to increase the accumulation of small molecules, such as flavonoids, to improve resistance to UV, particularly in the short wavelengths (<300 nm), where DNA absorbs strongly [54]. Free nucleotides can also serve as UV screens, and the UV absorption spectrum of ATP suggests that it would be a particularly effective DNA protector, perhaps explaining its use in the storage and transport of biological energy [52].

It is intriguing that higher plants contain flavonoids having the same short wavelength UV absorption spectrum as DNA [23], because plants evolved well after the accumulation of ozone in the stratosphere, which filters out these wavelengths. Contemporary cyanobacteria use other pigments to protect against UV [55], and these do not appear (according to the absorption spectra) to be as ideal as flavonoids in protecting DNA in the short UV wavelengths that no longer reach the Earth [23]. Perhaps the core polypropanoid pathway was inherited by plants from the original cyanobacterial endosymbiont, retained by plants as a source of UV screens, free radical scavengers and signal molecules, but lost in the meantime by cyanobacteria [23].

3. Exospermia using plant seeds

If humans are intent on colonizing the solar system, it could be a manifestation of the innate behavior of organisms to disperse themselves. But humans are poorly suited for space travel. Small packets of bacteria propelled by solar sails have been proposed to disperse life through space [56,57]. Alternatively, plant seeds could be accelerated towards distant targets [23]. The vehicle would be a space probe of the sort already sent beyond the solar system, but this time containing large numbers of seeds. (A 20-kg payload could deliver one billion *Arabidopsis* seeds.) Acceleration would be via the usual methods, but would be boosted close to the target by a timed explosion, propelling the seeds towards it like shot from a gun. Seeds could be coated with additional shielding against UV, and their flavonoid content could be increased. Their genome could even be modified to include a coded message (for the literary-minded). Seeds could be loaded with microorganisms, like *Dicococus radiodurans*, already adapted to rebuild after genome damage, and endophytic mycorrhizal fungi, necessary for mineral absorption by most land plants. A payload of seeds and selected companion organisms could be dispatched toward exoplanets having a life-friendly profile. Since we are already engaged in self-directed panspermia by propelling ourselves and contaminating microorganisms around the solar system, why not do it better with seeds?

4. Potential conflicts

Fears of science are sometimes expressed through ethics, which we often (justifiably) invoke to control the applications of science. Deliberately seeding the Universe with life from Earth is contrary to the ethic of the preservation of nature. However, if Earth's life is uncommon in the Universe, it should be preserved, and sending life into the Universe would seem less worrisome than controversial Earth-bound, fearsome fruits of science (like atomic energy, transgenic plants and the cloning of animals). The ethics of directed exospermia, like general anti-science sentiment, will thus fuel much discussion – probably with little negative effect, because in the end, humanity has little to lose from sending seeds into distant space, and ethics have rarely hindered the drive to expand – as so many wars have shown.

Perhaps seed exospermia will appeal for its romatic science fiction, despite its high-tech, genetically engineered underpinnings, and exospermia will provide a common goal for truculent humans. (Pursuing exospermia would surely be technically simpler than fixing the problems on Earth.) It could turn out to be the Noah's arc that saves the life we know on Earth.

5. Conclusions

The origin of life will remain unknown for quite some time, but turning the question toward the future logically leads to directed exospermia, a potential boon to plant science. The financial and engineering spin-offs from the space program have done wonders for research in physics, materials science, computer science and electronics. Now is the time for biology and biotechnology to participate. Plant science has much to contribute to the exospermia enterprise. Plants will be as necessary for human existence in space as they are on Earth. The genetic basis for metabolism and development in plants is under intensive study. Plant seeds can be genetically manipulated to improve such things as flavonoid accumulation, which is the basis for their resistance to UV [54,58]. If the interplanetary transfer of life is already taking place, it might be wise to admit that humans, like other species, are obligate self-dispersers, and let them have at it—perhaps with a little help from seeds.

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