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ARE WE FROM OUTER SPACE?

A Critical Review of the Panspermia Hypothesis

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1. Introduction¹

Aspects of “astrobiological” research, such as searching for exoplanets, characterizing extremophilic microbes, and searching for biosignatures of ancient life undoubtedly offer important insights into the origin and evolution of life on Earth. Because of the important implications of such work, it is hardly surprising that claims of important breakthroughs often inspire heated debate – one famous example was the claim that the Martian meteorite ALH84001 contained fossilized life (McKay et al., 1996). This claim required researchers to critically assess fossil and geochemical evidence with a new level of scrutiny, and it has been suggested that despite the consensus that this claim has been refuted, the academic debate has better prepared scientists to assess future evidence for ET (extraterrestrial) life (Dick and Strick, 2004). While this may be true in a situation where conclusions can be subject to rigorous independent analysis, the field of astrobiology also includes speculative research that is at present difficult, if not impossible, to independently test in the manner of the Martian meteorite (Rinaldi, 2007).

Taken in this context, the hypothesis known as *panspermia* that posits life on Earth was introduced from elsewhere may indeed spur innovative research through healthy debate, but it is equally clear that inconclusive evidence is currently cited by some authors as strong evidence of the panspermia hypothesis (Wickramasinghe et al., 2003).

The concept of panspermia can be traced back to a number of different historical origins, from ancient societies that believed in the universality of life to the musings of the early astronomers (Temple, 2007; Crowe, 2008). Fred Hoyle and Chandra Wickramasinghe are commonly associated with the modern

¹Abbreviations: ET, extraterrestrial; GC/MS, Gas chromatography/mass spectrometry; LR, labeled release; LUCA, last universal common ancestor; PAHs, polycyclic aromatic hydrocarbons.

incarnation of panspermia, apparently being convinced of the truth of panspermia after the widespread nature of organic compounds in interstellar space was discovered (Hoyle and Wickramasinghe, 1996). Aside from Crick and Orgel's (Crick and Orgel, 1973) discussions of "directed panspermia" (intentional seeding by intelligent beings, proposed earlier: "J.B.S. Haldane... expressed a belief, in 1954 (Haldane, 1954), that life may have... been launched into space by intelligent beings" (Bernal, 1962)), few other authors have developed a hypothesis as extensive in detail as Hoyle and Wickramasinghe (Wickramasinghe, 2010). These authors suggest that microbial life is ubiquitous and persistent in the cosmos and serves as a constant source of inoculum and genetic material for new planets, contributing to evolutionary trends on each world. We use the structure of their hypothesis to inform discussion on the following questions about panspermia:

1. What, if any, evidence is there for life outside Earth?
2. Is it conceivable that life as we know it could be viably transferred through space to other habitats?
3. How likely is it that transferred life would become established and go on to seed neighboring systems, thus amplifying the process?
4. Can panspermia influence evolutionary progress or affect the origin of life debate?

2. Question 1: Is There Any Compelling Evidence for Life Outside Planet Earth?

2.1. MARS AND THE VIKING EXPERIMENTS

Mars is a planet that has long inspired speculation about extraterrestrial life (Pickering, 1921), and the Viking Mars landers used some of the most sophisticated life-detecting instrumentation yet deployed anywhere outside the Earth to probe Martian soils for signs of microbial life. Three of the four experiments designed to test for the presence of life gave negative or ambiguous results (GC/MS, gas exchange, and pyrolytic release experiments), but one final test, the labeled release (LR) experiment, offered a striking positive response. This test, which aimed to detect the respiration of radioactively labeled organic compounds by microorganisms, yielded a strong positive result, with control experiments offering negative responses. The LR experiment was extensively field-tested on Earth and was found to be sensitive to extremely small quantities of viable cells in extreme Earth environments, the closest we have to a Martian analogue. However, after the fact, this evidence was discounted in favor of an inorganic explanation that theorized that UV-produced peroxides in the Martian soil were responsible for the oxidation (Quinn and Zent, 1999), despite the validity of these theories remaining questioned by the inventor of the apparatus, Gilbert Levin (Levin, 1981, 2007).

Levin's case has been bolstered by a recent investigation that suggested that the GC/MS experiment aboard the Viking would have been insensitive to the

organic constituents of Antarctic soils, which are by no means devoid of life (Navarro-González et al., 2006). In addition to this, recent evidence of water ice under the Martian surface (Boynton et al., 2002), in its atmosphere (Pearl et al., 2001), as well as the discovery of seasonal methane emissions (Krashnopolsky et al., 2004) has led Levin to opine: “What would be truly extraordinary in the light of present knowledge would be finding Mars to be sterile” (Levin, 2007). Despite this evidence, recent information obtained from Martian landers suggests an arid, acidic, and oxidizing early Mars (Squyres and Knoll, 2005), and the recent unexpected discovery of perchlorate salts in the Martian soil (Hecht et al., 2009), gives evidence for the presence of an oxidant that may yet convincingly explain the results of the LR experiments as abiotic. Future robotic missions that are slated for the current decade aim to clarify some of these questions by sampling up to 2 m below the Martian surface and may yet offer generally accepted signs of life on Mars (Rinaldi, 2007). Other authors have described instruments that may overcome the limitations of the Viking GC/MS experiments by detecting PAHs (polycyclic aromatic hydrocarbons) with higher sensitivity and distinguishing between enantiomers of amino acids (Bada, 2001), though final confirmation may have to await proposed sample return missions (Schulze-Makuch and Irwin, 2002).

2.2. FOSSIL EVIDENCE?

The ALH84001 Martian meteorite caused an intense media stir when it was claimed that it contained proof of past biogenic activity, which spurred then US President Bill Clinton to address the nation on the significance of the finding (Dick and Strick, 2004). Several lines of evidence were used to reach this conclusion, including the presence of PAHs, magnetite and sulfide minerals, and carbonate globules that resembled bacteria, though an order of magnitude smaller than any known Earth cell (McKay et al., 1996). The initial enthusiasm for this claim has largely subsided, based on the fact that the biological production of any one of the lines of evidence used by the authors to argue for this is no more compelling than the argument for a “null” abiotic origin. J. William Schopf addressed some of the limitations of their finding (Dick and Strick, 2004) relating to the “micro-fossils” discovered within the meteorite:

Even though they showed multiple examples of the microbe-like objects in question, their suggestion failed because the putative fossils lack cell lumina, carbonaceous cell walls, taphonomically credible variable preservation, and plausible biological size ranges. (Schopf et al., 2005)

Other authors suggested that the geology of the meteorite was inconsistent with a life-supporting environment (Golden et al., 2004; Min and Reiners, 2007; Barrat and Bollinger, 2010) or proposed plausible mechanisms for the abiotic synthesis of organics and magnetite crystals (McCollom, 2003). Despite these criticisms, arguments are still made that some of the magnetite crystals contained

in the meteorite represent what “In a terrestrial context...would be interpreted as a biosignature indicative of the presence of past metabolic activity by magnetotactic bacteria” (Thomas-Keprta et al., 2002).

This fierce debate was echoed several years later when the ALH84001 skeptic Schopf found himself on the defensive as Oxford’s Martin Brasier raised doubts about the biogenicity and phylogeny of the 3.5-billion-year-old terrestrial Apex chert microfossils, long thought to be conclusive evidence of Archean life (Dalton, 2002). These microscopic fossils, which were originally characterized tentatively as cyanobacteria existing in a shallow sea bottom, were criticized based on their visual appearance as well as their geological context (Brasier et al., 2002). Brasier *et al.* claimed that the fossils had morphology inconsistent with cyanobacteria and that they were in fact carbonaceous artifacts produced in a hydrothermal environment. This debate resulted in many follow-up publications by both Brasier and Schopf describing techniques for testing evidence, such as confirmation of three-dimensional morphology (Schopf and Kudryavtsev, 2005), as well as a number of arguments about the placement of these fossils in a more robust geological context (Brasier et al., 2005).

Although heated at times (Dalton, 2002), the debate served the purpose of clarifying the provenance of some of the oldest microfossils on Earth. Publications by Schopf and colleagues offer evidence to support the biogenicity of these fossils through more in-depth examinations of both morphology as well as the organic constituents of the microfossils (Schopf et al., 2005, 2007; Schopf, 2006). This debate is still far from over – new data suggests the structures are not in fact microfossils, though still indicative of microbial life (Marshall et al., 2011). However, Brasier’s most significant achievement has been the reframing of the world where these ancient organisms existed, as well as their phylogenetic affinities – no longer do paleontologists believe that these organisms were undoubtedly cyanobacteria existing in a temperate “early Eden” (Brasier et al., 2004); rather, they appear to have existed in a geologically active hydrothermal environment. This example is a cautionary tale – if Schopf’s picture of the early Earth as enshrined in textbooks can be so easily challenged, inferences made about life outside of Earth (that we have even less ability to directly study) may be overturned just as quickly. Purported ET (extraterrestrial) microfossils must be similarly examined with extreme caution with every attempt to confirm the null hypothesis, before claims can be made that they represent unambiguous signs of life.

Another similar debate occurred with the discovery of “nanobacteria,” with extraordinary initial claims of an undiscovered type of life ultimately yielding to an abiotic explanation (Cisar et al., 2000; Raoult et al., 2008; Young and Martel, 2010). Despite this, proponents of panspermia have seized on these claims, suggesting a “cosmic prevalence of nanobacteria” (Wickramasinghe and Wickramasinghe, 2008) and detecting their fossils (McKay et al., 1996; Rozanov et al., 2001; Folk and Taylor, 2002; Hoover et al., 2004).

The debate over life in meteorites is a long, repeated, and substantial one, which we delve into in a separate chapter (Gordon and McNichol, 2012).

2.3. BACTERIA FROM SPACE?

As these other investigations are proceeding, Wickramasinghe and colleagues have taken a different tack, collaborating with the India Space Research Organization (ISRO) to conduct a series of experiments that seek direct evidence for the panspermia hypothesis. The ISRO has used balloons to sample the upper stratosphere, with the goal of intercepting extraterrestrial microbes filtering down from space (Narlikar et al., 2003; Wainwright et al., 2004). This research has had an unsurprisingly controversial air, with a first experiment isolating several organisms from the upper atmosphere (Wainwright et al., 2003), though a collaborating group disavowed themselves of the results (Willerslev et al., 2003). The organisms that were isolated are common to the terrestrial environment and almost genetically identical, based on 18S rRNA sequences.

Newer work with the same methodology by independent laboratories has isolated new strains from the stratosphere, some of which have been described as new species based on genetic and chemotaxonomic characteristics (Shivaji et al., 2006, 2009; Yang et al., 2009, 2010). Whether or not these species are extraterrestrial in nature is still unproven (see Vaidya, 2009 for some discussion points) since not all possible methods of transfer to the stratosphere from the lower Earth can be discounted – it has been suggested that small particles captured represent Earthly contamination, whereas the larger particles represent incoming biological material (Wainwright et al., 2006), although it should be noted that even small spiders balloon to the upper stratosphere (Filmer, 1991). Supporting an Earthly origin, bacteria and other biological materials are common components of cloud condensation nuclei (Christner et al., 2008), and there have been several mechanisms suggested for the transfer of particles to the upper atmosphere (Rohatschek, 1996; Fromm, 2004; Damoah et al., 2006; Dehel, 2006).

It should also be noted that the discovery of new microbial species is not surprising in itself, and a tolerance to ionizing radiation does not necessarily indicate that these isolates are space-faring – they are by no means extremophiles, growing best under mild conditions (10–30°C). It may be that infrequent events cause bacteria to be transferred to the stratosphere, with only the UV-resistant cells remaining viable for recovery in these microbiological experiments. Alternatively, it may be that the process of transport to the upper atmosphere and consequent return to the surface is enough to select for organisms resistant to ionizing radiation, similar to the argument of Pavlov et al. (2006).

Criticisms aside, these experiments are a realistic method of testing the panspermia hypothesis – as Wainwright (2003) notes. Unless we disavow the methodology completely, one needs to explain the presence of viable bacteria at this height. Even if these isolates can be proven to represent surface life in an extreme environment, it extends the definite reach of microbial life to the upper atmosphere. Such evidence may be strengthened by using culture-independent methods of identifying microbes at this height (Wainwright et al., 2004) or investigating the isotopic composition of any purportedly extraterrestrial biomass and comparing it to known signatures found in cosmic dust (Busemann et al., 2006).

2.4. EVIDENCE FOR LIFE IN INTERSTELLAR SPACE

It is now known that molecules essential to life such as water, ammonia (Decin et al., 2010), and carbon compounds (Smolders et al., 2010) are commonly generated in stars and transported to the interstellar medium. The precise identity of this carbonaceous mixture has been variously suggested to be a material similar to kerogen (Papoular, 2001), buckyballs (Chen et al., 2008), or similar compounds formed under conditions common in the circumstellar envelope of certain stars (Kwok, 2004). Certain proponents of panspermia take this ever-increasing inventory of organic molecules as evidence of the ubiquity of life, disputing the previously mentioned processes:

In view of the impossibility of producing cosmically, by non-biological means, organic material from inorganics like water, carbon monoxide and nitrogen gas, it is clear that the immense amount of interstellar organics must be biological in origin. (Hoyle and Wickramasinghe, 1996)

Recent claims that biological breakdown products are responsible for the signal of organic carbon in the interstellar medium echo this opinion (Rauf and Wickramasinghe, 2010).

While it may indeed turn out that we will discover interstellar carbon-based compounds that are in fact “postbiotic,” it is fundamentally difficult to distinguish abiotic from biotic carbon based on spectra alone – more complex direct tests are clearly required as applied to meteoric PAHs (Naraoka et al., 2000) or as have been applied to verify the biogenicity of petroleum reserves on Earth (Glasby, 2006). Equally important to consider is the consistent argument by the proponents of this hypothesis that biological materials more exactly duplicate the emission/absorption spectra collected and therefore should be considered correct (Wickramasinghe, 2011). Few would likely dispute that biological extracts as suggested by these authors create a more complex absorption/emission profile that in some cases may better approximate astronomical data. However, it will be also clear to observers that nonbiological models produce a less complex spectrum because they are a simplification in attempt to explain the data (Horneck, 1995).

Recent investigations of carbonaceous meteorites have discovered many complex organic compounds not of Earthly origin, including several nucleotide bases (Martins et al., 2008). This data has also been claimed as the breakdown products of living organisms, but we do well to caution that simple processes such as UV irradiation of PAHs can produce compounds such as alcohols and quinones (Bernstein et al., 1999), and innumerable papers on the origin of life have demonstrated the abiotic synthesis of compounds such as nucleotides and sugars from precursors present in space (Orgel, 2004; Kim and Benner, 2010; Lambert et al., 2010a, b). While it is not possible to completely discount the possibility of life producing some of these signatures, it strains one’s credulity less to explain this evidence in terms of abiotic processes that currently have the balance of evidence in their favor.

2.5. EVIDENCE OF OTHER GAIAS? PLANETARY SPECTRAL SIGNATURES

Indirect evidence for extraterrestrial life may soon come from the analysis of exoplanet atmospheres – the identification of certain nonequilibrium gases such as oxygen would strongly argue for life as the most plausible explanation. The detection of seasonal plumes of methane in Mars' atmosphere has ignited debate on the possibility of chemoautotrophic methanogens surviving there (Krashnopolsky et al., 2004), perhaps in habitats similar to those discovered in the high Arctic (Grasby and Londry, 2007). This interpretation is not without controversy, as there are differing theories for the methane's origin (Fiebig et al., 2007). In a similar vein, infrared spectroscopy has also been suggested to identify characteristic chemical bonds in the European ice sheets that may indicate biological activity (Dalton et al., 2003).

Outside of our solar system, the ambitious *Darwin Project* aims to track the presence of gases such as CO₂, H₂O, CH₄, and O₂ in exoplanets (Cockell et al., 2009). The analysis of the spectrum of a newly discovered exoplanet, a so-called hot Jupiter, has revealed the presence of all the previously mentioned gases in its atmosphere, with the exception of oxygen (Swain et al., 2009). While the presence of methane in large gas giants is not regarded as evidence of life in our own solar system or elsewhere, the recent discovery of several rocky planets dubbed “super Earths” (Charbonneau et al., 2009) gives hope that we will soon discover a rocky planet with an atmosphere indicative of active biology.

Currently, no one line of evidence has offered conclusive proof of extraterrestrial life, let alone panspermia, with controversies that have erupted over fossil evidence exposing our relative lack of understanding about these topics. Clearly, there is mounting evidence that life may survive in the far reaches of space, but the strategy of many proponents of panspermia to make sweeping conclusions from ambiguous evidence is untenable. More cautious authors note that evidence for life such as geochemical biosignatures may well be cryptic (Cockell et al., 2009), perhaps not as clear-cut as on our planet, which has taken many billions of years to reach this level of obvious biological activity.

3. Question 2: Is It Conceivable that Life as We Know It Could Be Viable Transferred to Other Habitats?

The existence of numerous lunar and Martian meteorites identified by their unique geology gives strong proof that there is an exchange of material between planets within our solar system. The possibility that these objects could carry viable life has led many to revisit the possibility of panspermia. This topic was ably reviewed by Horneck and Brack (1992), who point out several mechanisms for particles to reach space, including volcanic eruptions, flyby meteorites, and direct meteorite

impacts. In these cases, both large pieces of rock as well as smaller particles would reach escape velocity. Large particles may travel to another planet by random chance (lithopanspermia), and smaller particles may be accelerated outwards from their parent star by radiation pressure or carried by interstellar particle clouds (radiopanspermia) (Horneck, 1995). Aside from impacts, small particles may also be directly transported to space (Dehel, 2006) or created through subsequent impacts with other objects (Napier, 2004). In this manner, we can imagine a small number of large meteorites and a larger number of smaller particles exiting a planet's surface, all with the potential to carry resistant forms of life.

A clear barrier to transfer is the sudden shock of temperature and pressure that will occur on both exit and atmospheric reentry. Despite these harsh conditions, simulations indicate that many resistant forms of life such as bacterial endospores can survive (Mastrapa et al., 2001; Stofferl et al., 2007), although there appears to be a critical size below which a meteorite would not be suitable for transfer (Parnell et al., 2008; Foucher et al., 2010) due to heat sterilization at depths of 2–5 cm. This implies that any lithopanspermia event will filter out organisms such as phototrophs that do not exist deep within rocks (Cockell, 2008). While bacteria have been found living in the interior of many substrates (Takai et al., 2001; Wainwright et al., 2009), indicating a random impact will eject organisms to space, the small amount of biological material contained within may reduce the probability of a successful transfer (Clark, 2001).

Noting that many organisms, including some animals (Jonsson et al., 2008), can survive extreme cold and desiccation and remain viable, the largest obstacles to panspermia are the time scale of transfer and the deleterious effect of radiation. Known Martian meteorites took from between $\sim 6.0 \times 10^5$ and up to ~ 14 million years to arrive on Earth (Eugster et al., 1997), and radiopanspermia has been suggested to take a minimum of 10^6 years to reach a new planetary system although considerably less within a solar system (Secker et al., 1996). While bacterial life has been claimed to be potentially viable for possibly up to millions of years (Vreeland et al., 2000), this has been criticized on the basis that DNA is not thermodynamically stable enough to remain intact for this long (Graur and Pupko, 2001) and that there is possibility of contamination during sampling procedures that purport to isolate ancient life (Willerslev et al., 2004; Willerslev and Hebsgaard, 2005). Even if contamination is ruled out, the thermodynamic argument remains strong since DNA is inherently unstable – experiments examining dormant bacteria trapped in Antarctic ice corroborate this line of reasoning (Bidle et al., 2007), showing decreased viability of cells with an increased period of dormancy. In addition, the ability for DNA to remain viable may vary with phylogeny, with calculations suggesting that mesophiles are least likely to retain viable DNA over long periods, while thermophiles have a much better chance (Nicholson, 2003).

Radiation damage will inevitably accelerate this process and, combined with the factors of low temperature and vacuum, may act synergistically to destroy DNA (Fekete et al., 2005), although it has been also suggested that extreme cold

tends to retard the destruction of DNA (Demidov et al., 1995). Radiation shielding is plausible with lithopanspermia events, but the small particle sizes necessary for radiopanspermia decrease radiation shielding greatly, although it has been suggested that a thin film of carbon may be sufficient to shelter organisms from inactivating UV radiation (Wickramasinghe et al., 2009).

The radiation environment in which these transfers might take place may also vary – for example, the interior of our galaxy likely experiences higher background radiation from supernovae because the density of stars is greater. The radiation from a supernova may offer a dose sufficient to sterilize particles of the size necessary for radiopanspermia or even small rocks. As Andrew Karam (Karam, 2002) notes, “...radiation may place constraints on the ability of living organisms to be transferred between planets or stellar systems because the mean interval between ‘sterilizing’ doses is less than the expected transit time.” In addition to harmful radiation from an initial blast, supernovae remnants may also make transfer more difficult by increasing the background radiation in interstellar space (Grzedzielski et al., 2010).

Given this, it appears that radiopanspermia transfer events to another solar system will only be possible in certain circumstances. One proposed scenario is during the red giant phase of a star’s life where sterilizing UV radiation would be less of an issue (Secker et al., 1996). Experiments involving life exposed to space for nearly 3 years have been proposed (Warmflash et al., 2007), which would further our knowledge about life’s resistance to the rigors of space.

Estimates of the probability of successful lithopanspermia events indicate that material potentially containing viable microbes likely was exchanged between Earth, Mars, and Venus in the past, perhaps affecting the early development of the biosphere (Mileikowsky et al., 2000a, b; Schulze-Makuch et al., 2005a, b). In addition, transfer between bodies in a common stellar “nursery” may be likely (Adams and Spiegel, 2005), supported by data that “... imply that a substantial fraction of the Oort cloud comets, perhaps exceeding 90%, are from the protoplanetary disks of other stars” (Levison et al., 2010). This is corroborated by the recent understanding gained from the NASA Stardust experiment that material in comets was created from the “mixing on a grand scale” of the original constituents of our solar system (McKeegan et al., 2006; Vaidya, 2009).

In contrast, transfer between stellar systems by lithopanspermia is thought to be extremely unlikely due to the astronomically small probabilities of interstellar meteorites falling on another small planetary body (Melosh, 2003). Some have suggested that panspermia was more likely at the time of our planet’s formation since there was a higher number of suitable planets from which an inoculum could arrive (Von Bloh et al., 2003; Franck et al., 2007) or because transfer events would have been more likely due to a larger number of impacts (Mileikowsky et al., 2000a, b). Lineweaver’s analysis (Lineweaver, 2001) suggests that most extant terrestrial planets are older than Earth, further supporting the assertion that panspermia may have been more common in the past.

Other, more esoteric mechanisms include the transfer of biological particles from the upper atmosphere to space (Wickramasinghe and Wickramasinghe, 2008), or the ejection of entire “embryonic” planets from solar nebulae, which could go on to support and possibly spread life (Stevenson, 1999). Transfers between galaxies in the same cluster may also be possible when there are ejected jets of material that contain life-supporting material (Gordon and Hoover, 2007).

Nicholson (2009) treats the sequence of probabilities necessary for a successful transfer event in a similar manner to the famous Drake equation, which reminds us that while there may be situations in which viable transfer is possible, we are largely ignorant of the numerous variables that challenge the spread of life. However, even if life was not viably transferred, these events may have an impact – DNA or other prebiotic chemicals could conceivably offer a “kick-start” for the origin of life on sterile planets (Secker et al., 1996).

4. Question 3: How Likely Is It That This Transferred Life Would Become Established and Go on to Seed Neighboring Systems, Thus Amplifying the Process?

Discussions of panspermia tend to focus on the mechanistic aspects of viable transfer, but equally important to constraining the probability of successful transfer is the ability of organisms to persist in a new environment. At this time, arguments that life is likely to be based on organic carbon polymers and existing in liquid water (the so-called *carbaquist* perspective (Fry, 2000)) constrain the type of environments where life may exist. Liquid water may exist well below 0°C in some cases (Rothschild and Mancinelli, 2001), and it may be possible for some organisms to have metabolic activity even below this level (Rivkina et al., 2000). With this evidence in mind, Pace (2001) suggests a temperature range from –50°C to 200°C for the existence of life and less stringent requirements on pressure – an interesting experiment has recently demonstrated metabolic activity at gigapascal pressures (Sharma et al., 2002). As evidence begins to accumulate for exoplanets that resemble Earth, Pace (2001) notes that an equally important question becomes the metabolic strategies organisms can potentially exploit to survive in extraterrestrial environments – all organisms, no matter the diversity of their metabolic strategies, require an influx of energy and a means of removing waste products.

If we consider a putative space-faring organism colonizing a lifeless world, it would be a fair assumption that conditions may resemble the early Earth – that is, either with a neutral or partially reducing atmosphere and with a potential influx of organic compounds from comets and interstellar space (Horneck, 1995). If we also assume some form of active geology, as well as light at a wavelength appropriate for photosynthesis, a high diversity of anaerobic strategies may succeed in these environments.

Among the most adaptable microbes thus far discovered are chemosynthetic. These organisms, also known as chemoautotrophs, are able to fix carbon wholly

from inorganic chemicals in a process completely independent of photosynthesis. Chemosynthetic organisms exist in the most extreme and poorly understood regions of the Earth, including deep-sea vents where the oxidation of hydrogen sulfide is coupled to carbon fixation (Jannasch, 1985), or deep crustal environments where hydrogen-based, hyperthermophilic subsurface lithoautotrophic microbial ecosystems (“HyperSLiMEs”) exist completely independent of the surface biosphere (Takai et al., 2004). Chemoautotrophs appear to be highly diverse (Nakagawa and Takai, 2008), and iron-oxidizing bacteria can apparently survive on unsupplemented extracts of iron meteorites (González-Toril et al., 2005). Speculation about extant life on Mars naturally tends to favor these ecosystems (Nealson et al., 2005) since they do not require a reduced carbon source and can thrive on common inorganic compounds. From the perspective of panspermia, this type of metabolism may be preferentially transferred by meteorite impacts since these organisms are most likely to be living within the interior of rocks.

In contrast to chemoautotrophs, photosynthetic organisms can take advantage of a much more reliable source of energy and thus are able to thrive in a huge diversity of environments on Earth – from Antarctic ice (Fritsen and Priscu, 1998; Thomas, 2005) to the hyperarid deserts of the Atacama (Wierzchos et al., 2006), where cyanobacteria associated with heterotrophic bacteria colonize halite deposits in rocks. While there may be a selective pressure preventing the dispersal of cyanobacteria and other phototrophs (Cockell, 2008), they are interesting to astrobiology for a number of reasons, including high radiation tolerance due to UV-absorbing compounds (Sinha and Hader, 2008) that are increasingly synthesized when exposed to stress such as desiccation (Fleming and Castenholz, 2007). Many cyanobacteria remain viable after long periods of time in dark permafrost soils (Vishnivetskaya et al., 2003), although it appears that the resistant cells, known as akinetes, have limited resistance to the rigors of space unless shielded from radiation (Olsson-Francis et al., 2009). These organisms can survive at extremely low irradiances and extremes of pH and temperature and can switch their photosynthetic metabolism from oxygenic to anoxygenic under differing conditions (Garcia-Pichel and Castenholz, 1990).

Other photosynthetic microbes include strictly anoxygenic phototrophic bacteria, which also thrive under extreme conditions, and may represent the earliest phototrophic life on Earth (Madigan, 2003). These organisms have unique metabolic pathways of carbon fixation (Berg et al., 2007) and may not require solar radiation for photosynthesis – a new strain of green sulfur bacteria has been discovered that exists as an obligate phototroph at hydrothermal vents, relying on purely geothermal radiation to photosynthesize (Beatty et al., 2005). With this knowledge in mind, Cockell and Raven (2004) have concluded that the lack of a UV-absorbing atmosphere would not preclude the colonization of anoxic extra-solar planets by photosynthetic life.

Organisms that are reliant on external sources of reduced carbon are the final category, which can be either aerobic or anaerobic – although it is assumed that when considering the evolution of primitive ecosystems, only organisms

that are obligate or facultative anaerobes would be relevant. To produce the reduced compounds necessary for their growth, we can imagine a variety of organic compounds being synthesized through UV irradiation of carbonaceous building blocks in space (Bernstein et al., 1999), and we do know organisms that can survive on completely inorganic compounds such as buckminsterfullerene (Wainwright, 2003) and hydrocarbons such as toluene and naphthalene (Fredrickson et al., 1991). In addition to organisms that survive on simple organic compounds, some are metabolically versatile such as the magnetotactic bacteria that can grow as chemoorganoheterotrophs or chemolithoautotrophs (Thomas-Keprta et al., 2002). Nonetheless, heterotrophic organisms are probably less likely to survive independently on a new planet because they require a constant supply of an external carbon source – something that may be unlikely given the ability of geochemical processes to oxidize organic matter on a relatively short timescale.

4.1. CONSTRAINTS ON ALL METABOLIC STRATEGIES

As already mentioned, even with organisms that do not rely on sunlight or reduced organic compounds, there needs to be a constant source of reductant and inorganic carbon; otherwise, their metabolism will grind to a halt (Wilkinson, 2003). Aside from the geochemical processes we are familiar with from Earth, it has been suggested that radiation photolysis of water to H_2 may provide this energy in Europa-like systems (Chyba, 2000), and geologically active bodies with sufficient iron may support abiotic H_2 production through a process known as serpentinization (Oze and Sharma, 2007).

All life, including photosynthetic organisms, produces waste products that must be removed. In an Earthly context, most organisms do not exist in isolation for this simple reason – syntrophic organisms provide mutually beneficial “services” (see, e.g., Kotsyurbenko, 2005; Guerrero et al., 2002), casting doubt on the possibility of a single strain seeding a new planet. Indeed, theoretical analysis of the supposed “last universal common ancestor” (LUCA) on Earth has suggested that “[the] LUCA does not appear to have been a simple, primitive, hyperthermophilic prokaryote but rather a complex community of protoeukaryotes with RNA genomes, adapted to a broad range of moderate temperatures, genetically redundant, morphologically and metabolically diverse” (Glansdorff et al., 2008). Nonetheless, it may, however, be possible for certain organisms to accomplish multiple ecological functions – see, for example, a recent report of a single-species ecosystem discovered deep in the Earth’s crust (Chivian et al., 2008). Wilkinson (2003) has considered this topic in depth and suggests that diverse metabolic strategies are necessary to maintain an active biosphere. This implies that either multiple organisms with different metabolic strategies or one highly adaptable organism would be needed to seed a new world.

Very little is yet known about extrasolar habitats – some guesses have been made regarding a “galactic habitable zone,” but there is not yet enough evidence to make any far-reaching conclusions (see Prantzos, 2008). We may yet discover that systems similar to our own are common (Vázquez et al., 2010), but the vast majority of systems discovered include “hot Jupiters,” large gas giants orbiting extremely close to their sun. This has led to speculation about the possibility of terrestrial planets existing with these large planets as neighbors, with calculations indicating that these large planets will not necessarily suppress rocky planet formation (Raymond et al., 2005), with other estimates suggesting up to one fourth of known extrasolar planetary systems may be habitable (Menou and Tabachnik, 2003). Other authors have suggested that a host star requires a specific metallicity to effectively form rocky planets like our own (Lineweaver, 2001).

On a similar note, the different elemental composition of planets or oxidation state may be important – it is possible that life evolving on one world may find a new environment toxic due to the abundance of an element rare on its home world. On Earth, cyanobacteria are known to have a low threshold for cadmium toxicity, which is explained by the fact that the environment in which they originally evolved contained less free cadmium due to a different oxidation state (Saito et al., 2003). It is also equally possible that life may be metabolically adaptable in ways we have yet to discover – a new report of bacteria that purportedly use arsenate to replace the biological function of phosphate offers support for this notion (Wolfe-Simon et al., 2011a). However, at the time of writing, the methodology of this study has been widely discussed and criticized (Benner, 2011; Borhani, 2011; Cotner and Hall, 2011; Csabai and Szathmari, 2011; Foster, 2011; Oehler, 2011; Redfield, 2011; Rosen et al., 2011; Schoepp-Cothenet et al., 2011), with the report’s claims and response to comments (Wolfe-Simon et al., 2011b) at this point appearing inconclusive at best.

4.2. LOCATIONS FOR AMPLIFICATION

Despite the lack of information about the existence of extrasolar habitats, we can make some guesses about the possibility of panspermia on different bodies as modeled on our own solar system. In the case of icy bodies such as Europa, panspermia may be less likely because ice will be less amenable to transfer or UV shielding. Planets with strictly atmospheric life have been suggested as on a contemporary Venus (Schulze-Makuch and Irwin, 2002), and these could offer an excellent method of transfer since the organisms already inhabit a highly extreme environment that is in close exchange with space (Wickramasinghe and Wickramasinghe, 2008).

One of the few types of bodies we can be fairly sure exist throughout the cosmos are comets, and these bodies are an essential part of Hoyle-Wickramasinghe’s version of panspermia, in which comets offer a location for the origin of life as well as a “vehicle” for the transfer of life (Hoyle and

Wickramasinghe, 1999). There does appear to be some evidence that comets and potentially asteroids contained liquid water early in their history from the decay of radioactive aluminum (Wilson et al., 1999; Merk and Prialnik, 2006), with frozen water ice still clearly visible in contemporary comets (Sunshine et al., 2006). Wickramasinghe et al. (2009) have also claimed that comets could allow for liquid water near perihelion based on surface temperatures above 300 K. However, the assertion that life evolved and persists in comets has been roundly criticized (Horneck, 1995). Bar-Nun et al. (1981) also point out that comets may not have the structural integrity necessary to contain liquid water and that any organic compounds produced on the surface through interactions with stellar UV radiation would be sublimated at perihelion. In addition, it has been noted that organisms thus far claimed to be inhabitants of comets show no specific adaptations to that niche (Jalasvuori et al., 2009; Vaidya, 2010).

Many questions about comets will be answered by the ROSETTA probe, which is set to intercept comet 67P/Churyumov-Gerasimenko in 2014. Equipped with devices that can measure the chemical composition of the comet from afar, the probe also includes a lander that will be able to measure biologically important characteristics such as the enantiomeric composition of amino acids in the comet (Thiemann and Meierhenrich, 2001), which may offer insight into both solar system formation as well as any possible biological activity.

As with comets, asteroids may have been more amenable to life early in the solar system's history, based on the possibility of liquid water (Wilson et al., 1999). Nonetheless, it seems unlikely that life could currently persist in asteroids despite the discovery that asteroids still contain water (Campins et al., 2010), simply because the current temperatures would be too low to support life. Nonetheless, extracts of meteorites have been shown to be amenable to algal growth, with dissolved inorganic salts supporting cell division (Mautner, 2002).

Along with the literature on cometary life, suggestions have been raised that diatoms may inhabit these bodies (Hoover et al., 1999). This is unlikely for a number of reasons. Aside from the previously mentioned criticisms of life in comets, eukaryotic cytoskeletons are unlikely to develop normally in microgravity (Papaseit et al., 2000) (a testable proposition: Gordon et al., 2007), and diatoms are also a recent arrival in the geological record (Sims et al., 2006), which makes their appearance in bodies that originated many billions of years previously extremely unlikely. Other published accounts have attempted to draw a connection between "red rain" events and panspermia (Louis and Kumar, 2006), though no evidence to the authors' knowledge was presented to substantiate this claim.

We agree with Bar-Nun et al. (Bar-Nun et al., 1981), who in reference to the theories of the cosmic abundance of life opine that "...we feel that it is not warranted to extrapolate from these observations to the existence of interstellar or cometary life." Citing inexplicable events such as "red rain" or ambiguous data as "proof" of panspermia will likely only be convincing to the ardent supporters of these hypotheses. Similarly, speculation about how extremophile organisms may thrive in extraterrestrial habitats cannot be taken as proof of life's ability to colonize

the universe – there may be unknown factors that prevent life from easily adapting to new environments that we are only just beginning to discover.

5. Question 4: Could Panspermia Influence Evolutionary Progress or Affect the Origin of Life Debate?

5.1. INFLUENCE OF OUTSIDE GENETIC MATERIAL ON EVOLUTION

Aside from an initial “seeding” playing an essential role in the rise of life, a natural corollary is that “cosmic life forms” could have an ongoing influence on the evolution and diversity of life on Earth. Hoyle and Wickramasinghe have championed the highly controversial suggestion that viruses come from space, believing that the often unpredictable pattern of communicable diseases becomes intelligible in the light of inoculation from above. A paper attributing the recent SARS outbreak to this mechanism (Wickramasinghe, 2003) has been roundly criticized for a number of reasons (Willerslev et al., 2003), and more general problems have been raised in regard to the potential role of viruses in ET environments (Jalasvuori et al., 2009).

The exchange of biological particles with Earth is an essential part of Hoyle-Wickramasinghe’s manifestation of the panspermia hypothesis, and they find proof in microbes discovered at high altitudes (see above section):

The fact that these are similar to terrestrial microbes is no problem; it is fully consistent with panspermia theories in which Earth organisms are derived from cometary organisms that transit through the stratosphere. (Wickramasinghe, 2003)

In this case, the null explanation (that these organisms are terrestrial) is indistinguishable from the “predictions” of their hypothesis, so it is no wonder many scientists remain unconvinced.

The notion that genetic information from panspermia could explain innovation in evolution via galactic horizontal gene transfer (Sheldon and Hoover, 2008) ignores more prosaic hypotheses such as duplication and subsequent specialization of gene batteries (Gordon, 1999) or developmental plasticity.

5.2. PANSPERMIA AND THE ORIGIN OF LIFE

Evidence discussed in the previous sections suggests that Earth is unlikely to be uniquely capable of supporting life and therefore may be common throughout the cosmos (Lineweaver and Davis, 2002) – both panspermia and many independent origins of life could produce this inferred pattern. Little is known about the probability of panspermia carrying life over galactic distances, though it has been suggested that:

On the assumption that this ejection mechanism [radiopanspermia] is common in other planetary systems environmentally capable of supporting life, a “chain

reaction” may seed the disc of the Galaxy within a few billion years. In that case it is unlikely that life originated on Earth. (Napier, 2004)

The belief that effective transfer events are inevitable and the a priori probability of life self-organizing is extremely low has led Hoyle and Wickramasinghe to suggest an independent origin is not relevant to the rise of life on Earth (Hoyle and Wickramasinghe, 1996). While some authors have suggested panspermia events were more likely at the time of Earth’s formation (see above sections), the logic that life is an “accident” of prebiotic chemistry and therefore unlikely to have occurred by random chance on Earth has been challenged by other authors (Trevors and Abel, 2004), although considerable uncertainty remains about the probability of an independent origins of life on Earth (Davies, 2003).

Clearly, neither explanation can be proven correct at the moment, but it does appear that a minimum number of multiple origins are necessary if we assume a homogenous distribution of life throughout the universe. Gordon and Hoover (2007) have argued based on a calculated “speed of life” (the maximum speed at which panspermia could move with ejecta) that at least 50,000 unique origins would be necessary to explain universal life (which amounts to at least once per 2,000 galaxies). It is also conceivable that the origin of life is much more probable than Hoyle and Wickramasinghe consider – this would be supported if we were able to discover biochemically distinct forms of life on Earth that are the product of a unique origin. Some authors have suggested searching for “...opposite chirality biomarkers, nonracemic mixtures of biological material, or anomalous ratios of stable isotopes that cannot be explained by abiotic or normal biotic processes” (Davies and Lineweaver, 2005). Other evidence may come from investigating phenomena such as “desert varnish” which appear biological but have not been satisfactorily explained (Cleland, 2007; Davies et al., 2009). The discovery of these hypothesized “shadow biospheres” would offer evidence that the origin of life is highly probable given clement conditions. Any such discovery would, in the opinion of some authors, be more significant than evidence for a successful panspermia event since it would inform the probability of life originating not just on Earth, but throughout the universe (Shapiro and Schulze-Makuch, 2009).

While there is still considerable debate on the interpretation of early microfossils (see above sections and Gordon and McNichol, 2012), it is now generally accepted that life appeared on Earth very quickly after conditions of the Hadean era became more hospitable to life. This early appearance of life, combined with evidence suggesting that many complex biochemical processes were present in the LUCA, has led Line (2002) to consider that an extraterrestrial origin of life was necessary to provide sufficient time for these evolutionary innovations to develop. How much time was available for early life to evolve from a “prebiotic” state to life as we know it is still unknown – it has been recently suggested that early “sterilizing impacts” were not sufficient to wipe out thermophiles (Abramov and Mojzsis, 2009) and that Earth could have been reseeded by impact ejecta (Wells et al., 2003), in which case life may have had more time to develop on Earth than previously supposed. Evidence for this period of Earth’s history is missing from

the geological record, though it may be preserved as ejected meteorites on the moon or other bodies (Crawford et al., 2008).

Line (2002) has suggested that we may be able to confirm evidence for the evolution of life on Earth elsewhere in the universe if we were to discover life on Mars or Europa that was genetically related to Earthly life. There are naturally pitfalls in any potential interpretation of such data, and Ebach et al. (2008a) caution us to heed the past failures of biogeography and not seek to draw conclusions where data is scanty or lacking. This viewpoint earned criticism from ardent supporters of panspermia as geocentric (Wallis et al., 2008) though it has been noted that at this point, we cannot help but be “geocentric” (Ebach et al., 2008b). The discovery of biochemically related life would be unlikely to quell this debate since it would undoubtedly be difficult to resolve its provenance (Pace, 2001). Indeed, it is likely that the discovery of ET life would only deepen the mystery of our origins.

6. Conclusions and Future Research Directions

At first glance, the hypothesis of panspermia appears to be supported by the weight of much biological and astronomical research, but despite a few tantalizing hints, it remains currently in the realm of conjecture. Few would likely disagree that imaginative speculation about the fundamental questions of life’s origin has inspired much great research, as it currently inspires research into astrobiology. Unfortunately, science’s power to explain these phenomena is constrained by ambiguous, controversial, or nonexistent data. The study of astrobiology therefore is often significantly influenced by opinion – Sir Francis Younghusband’s musings on this subject remain relevant even today to discussions of panspermia:

The onus of proving that nowhere else throughout the whole mighty universe than on this tiny speck of a planet does life appear rests upon those who deny it. (p. 47 in (Younghusband, 1927))

This argument appears central in the writings of ardent supporters of panspermia but cannot in itself prove anything satisfactorily. While proponents of programs optimistic about the existence of extraterrestrial life likely also dream of a day when we have evidence for life outside of this “tiny speck,” it is equally clear that, at present, no generally accepted evidence exists.

We do not disavow the possibility of panspermia but believe that a credible case has yet to be made for much of the evidence that seeks to prove a cosmic abundance of life. The debates over the ALH84001 meteorite as well as the Apex Chert microfossils were possible because multiple parties could analyze the same samples critically and have done much to give us a clearer picture of the challenges that will undoubtedly face scientists as we gain more information about life in the universe – the same rigorous debate, with falsifiable hypotheses, is essential for any serious discussion of panspermia. Such debate is now going on regarding the possible substitution of arsenic for phosphorus in DNA, another problem put

forward as one of astrobiology (Wolfe-Simon et al., 2011a). Carl Sagan's "Extraordinary claims require extraordinary evidence" (Sagan, 1979), stated in the context of UFOs (unidentified flying objects) has seemed to plague astrobiologists. But in science do we really only require "ordinary" evidence for "ordinary" claims? We suggest not, that is, that all claims in science are open to the same degree of scrutiny. The strongest claims are those that have passed the most scrutiny. The record for panspermia claims in this ordinary science regard is spotty. We are presently faced with the unproven belief that life could be widespread in the universe, fortified by the presence of organic matter in meteorites and elsewhere, contrasted with our certainty that life exists on earth. That should be enough to motivate us to continue the search, with humility:

I find that as beginners in this business most people are brash but after they have stayed in it a while, they tend to become more humble. I am very humble. Harold C. Urey in: (Laurence, 1961)

Current research on the diversity and limits of microbial life, the discovery and investigation of extrasolar planets, and new scientific missions to bodies in our solar system are most likely to offer clear and uncontroversial evidence for astrobiology. It is, however, important to note that even with unambiguous proof of ET life, controversy over its origin is unlikely to be resolved anytime soon. Whether life on Earth began solely here or was transferred from elsewhere, both panspermia and origin of life research will likely have complementary parts to play in probing these mysteries.

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