EXOBIOLOGY

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Introduction

In 1633, the Vatican's Collegio Romano placed Galileo's treatises *Assayer* and *Dialogue* on the Index, a list of heretical works banned from publication. This led to one of mankind's most important scientific paradigm shifts. For centuries the doctrine of geocentricism, the Earth as the center of the universe, had been accepted despite attempts by religious and academic scholars to suggest otherwise. This change to the intellectual milieu seemed to have heightened appreciation of the importance of other planets in the universe. However, it was not until 1960 that Lederberg coined the term *exobiology* to describe the search for life beyond Earth [1]. From the very outset it was clear that studies of Earth's own prebiotic evolution and exobiology were intimately linked. By understanding more of our own prebiotic to biotic evolution, further light could be shed upon the possibility of extraterrestrial life.

Exobiology

Much of exobiology's theories are based on studies of Earth's biota. How life started on Earth is uncertain. Evidence favors that the prebiotic atmosphere was a reducing one (methane and nitrogen, ammonia and water vapor or carbon dioxide, nitrogen and hydrogen), but even this is by no means certain. In their comprehensive review of this subject, Lazcano and Miller discussed the vast number of possible scenarios that could lead to life, and the paucity of hard evidence to really support or refute each one [2]. All current theories of the origins of life—the Standard Model (Oparin-Haldane), in which production of organic molecules on early Earth over 3.8 giga years ago, followed by a fast increasing complexity phase, leads to life; the Panspermia Model, in which life is carried to Earth

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from another planet; or the Inorganic Model (Clay-Lattice), in which the initial energy source is chemical energy or sunlight—require liquid water [3]. Irrespective of theory, it appears that the accumulation of biological precursors in the prebiotic soup may have been the rate-limiting step to the emergence of life. The Warawoona microfossils provide good evidence for cyanobacteria-like communities on Earth 3.5 billion years ago, and recently, paleontologists have focused on silicified coastal sediments where these complex microbial communities, fueled by photoautotrophy, may have existed. Hydrothermal systems also could have been favorable areas for local emergence of life, as redox reactions between water and certain minerals would establish a potential for organic synthesis in and around such vents [4, 5]. As yet, however, no studies of this hypothesis have been carried out.

The uncertainty over the modus operandi of biotic development on Earth has been a mixed blessing to exobiological studies: while it has allowed the generation of numerous theories, it has been very difficult to establish what significance should be attached to each one. However, exobiology initially began with far greater aspirations than the identification of extraterrestrial microbes—it originated in the search for extraterrestrial intelligence (SETI). An intellectual fascination with extraterrestrial life flourished faster than the technology was available to search for direct evidence, thereby fueling Earth-based searches.

When NASA launched its High-Resolution Microwave Survey (HRMS) to identify main sequence stars within 50 light years that could have Earth-like planets, it was laying the foundations for the targeted search survey (TSS) for intelligent extraterrestrial life. Project Phoenix, using just such a TSS, exists to find evidence of cosmic radio messages by looking at a huge number of frequencies, as well as by using logical guesses of probable frequencies that an intelligent civilization would use to communicate e.g. that of positronium 1(3S1)→1(3S0) transition. The foundations for TSS were laid in 1960 by Frank Drake, who launched Project Ozma. Using a one-channel receiver tuned to 1420 MHz (21cm), the resonant frequency of neutral hydrogen, Drake observed the two solar-type stars, Tau Ceti (11.9 light years away) and Epsilon Eridani (10.7 light years) for signs of intelligent life. His work, as well as that of Cocconi-Morrison, set the stage for the SETI project.

The SETI project uses the imposing Drake's formulae to calculate the probability of extant extraterrestrial technical civilizations. Drake's formula for "galactic organisms with distinct intelligence" is given by

$$N = R^* \times F_p \times n_e \times f_l \times f_i \times f_c \times L$$

where **N** is the number of extant technical civilizations; **R*** the average rate of star formation over the life time of the galaxy; $\mathbf{F_p}$ the fraction of stars with planetary systems; $\mathbf{n_e}$ the number of planets per star with ecologically suitable environments; $\mathbf{f_l}$ the fraction of planets (n_e) on which life arises; $\mathbf{f_i}$ the fraction of planets (F_l) on which intelligence develops; $\mathbf{f_c}$ the fraction of planets (f_i) on which technical civilizations develop; and **L** the lifetime of the technical civilization.

However, many scientists reject the very basis of SETI, arguing that intelligent life is a unique product of this planet. These scientists argue that if we were to re-run biotic evolution on Earth, intelligence would be unlikely to appear a second time. This difference of opinion differentiates SETI from exobiology. The latter's intention is not to develop a case for extraterrestrial intelligence, but rather to generate hypotheses and collect evidence for the means by which life could arise and spread from its source-planet. This data could also be used in an attempt to define the parameters within which life has a high probability of emerging. This fundamental point needs to be emphasized: too often exobiology is equated with SETI—something which it is not. As DeVincenzi put it so well, the aim of the "Exobiology Program is to understand the origin, evolution and distribution of life and life-related molecules, on Earth and throughout the universe" [6].

However, some aspects of the SETI project have useful in formulating a conceptual framework for exobiology. If we look closer at Drake's formula, a simplified version can be used to give some idea of the probability of the existence of any type of exobiological organism:

$$N_{exbio} = F_p \times n_e \times f_l$$

This solution to exobiological probability certainly conforms to the principle of Occam's razor, i.e., it is the solution with the fewest assumptions. But its numerical value is difficult to ascertain because of the scarcity of information regarding the three variables. Various estimates have been made about the possible number of biological planets, ranging from a hundred million to a hundred billion, depending on the stringency of the stellar constants used. In Drake's original formula where intelligent life is concerned for this particular time frame, N may well equal 1 ($N \leq 1$); however, the probability that ($N > 1$) when set against all types of biological life—be it intelligent or non-intelligent—is much higher.

Unfortunately, if it is evidence of only non-intelligent life that we are seeking then this may be far more difficult to accomplish. Unlike SETI, the technology is only just emerging to search within our solar system for evidence of exobiology. There certainly appear to be prebiotic Earth templates within our solar system. Titan has an equivalent atmospheric pressure to Earth, being composed mainly of nitrogen. Although its temperature is low (72 to 180 K), liquid water may be present due to tectonic activity and/or comet/meteorite strikes [7]. Oxygen has been detected on the Galilean moons Europa, Ganymede, Callista, and now Rhea and Dione [8, 9]. Ozone is also abundant, due to the activity of UV or charged particle radiation on atmospheric oxygen [10]. The recently launched Cassini Mission will be able to study at firsthand complex extraterrestrial organic chemistry in the atmospheric phase [11]. As Earth has a number of anerobic chemolithoautotrophic hyperthermophiles, it is tempting to speculate that any planet or moon which is tectonically active and contains liquid water may also harbor such life forms [12]. However, as we shall discuss later, attempting to compare Earth biota with any non-terrestrial forms of life is unwise. It would make the search too narrow, missing as it would certain forms of life unique to the particular extraterrestrial environment. There is still, however, a deeply held belief that certainly within our solar system similar Earth-like microbial life may have existed in the past (e.g., on Mars), and may even now exist (e.g., on Europa).

In March 1998, a conference convened in Houston, Texas, to discuss a controversial piece of evidence that could indicate past life on Mars. The 4.5-billion-year-old meteorite Allan Hills (ALH) 84001 is of Martian origin, and it is certainly old enough to have experienced the ancient warm, wet early Martian climate. But what certain investigators found was evidence of bacterial nanofossils associated with various organic molecules, such as carbonate globules and polycyclic aromatic hydrocarbons [13]. However, as other contributors at this conference pointed out, these rock anomalies may have been the result of geochemical/mineralogical forces, and not Martian bacteria [14]. What is certain is that this meteorite contains abundant polycyclic aromatic hydrocarbons which may be indicative of a fossilized past Martian biota [13]. Mars emerged from heavy asteroid bombardment some 3.8 Gyr ago with surface water. However, under climatic conditions today (140 to 295 K surface temperature) any remaining water will only be trapped under the permanent polar permafrost. Furthermore, there is likely to be little groundwater because of the lack of tectonic activity [3]. A similar environment exists on Earth. In the vast, almost waterless deserts of the Antarctic, within porous sandstone rocks, live cryptoendolithic microorganisms. These conditions may be similar to Mars, but the chances of successfully sampling Martian microorganisms by present missions is very small [15].

Panspermia

If nonterrestrial life indeed exists, then evidence of it may have reached Earth. The most sophisticated version of this theory suggests that the start of life on Earth was dependent on just such nonterrestrial "seeding." It remains an intriguing prospect that comets and other interstellar bodies may carry fossilized evidence of exobiology. Interestingly, it is now apparent that comets may also harbor biological precursors. The comet C/1996 B2 Hyakutake is just such an example, as hydrogen isocyanide, ethane, methane, carbon monoxide, and water have been detected within its ice core [16]. Although 80 percent of the comet is water, acetylene has also been discovered, which was probably picked up from ice-covered interstellar silica grains [17]. Catastrophic comet or meteorite impacts on target planets could deliver viable biological entities, although this is a controversial hypothesis [18].

Over 30 years ago, Francis Crick, disillusioned with the theory that life began on Earth, declared that life had originated elsewhere in the universe and had arrived as a type of ultra-resistant space spore [19]. Both Hoyle and Arrhenius added their support to the theory that life on Earth began as a result of the "seeding" of prebiotic terrestrial milieu by just such interstellar borne biological particles—a theory that became known as the Panspermia Model. However, for this theory to have worked in practice, a number of events—each of low probability—need to have happened. Life needed to exist at another source (i.e., another planet), and it needed to escape the source, survive the hazards of interstellar travel, and finally arrive at a primed, prebiotic Earth. These various stages are discussed in greater detail below.

LIFE EXISTING AT SOURCE

Although there is no agreement on numbers, many cosmologists accept that there must be other planets that at one time or another have developed a biota. Evidence from the study of stars with protoplanetary discs suggests that circumstellar discs commonly give rise to planetary systems [20]. Furthermore, from our current knowledge of terrestrial development, planets with an oxygen atmosphere within habitable zones of the parent star will, in all probability, be in a prebiotic or biotic state [21].

SOURCE BOMBARDED WITH STELLAR DEBRIS WITH SUFFICIENT FORCE TO ALLOW BIOACTIVE MATERIAL TO REACH PLANETARY ESCAPE VELOCITY WITHOUT ITS DESTRUCTION

Critical biomass is only likely to be achieved with meteorite bombardment. However, it has been shown in stratospheric dust that hydrated layer-lattices (clays) are present which can act as important biogenic catalysts (Clay-Lattice theory of biotic generation). Biogenesis is probably a combination of the achievement of (1) critical biogenic mass, (2) catalysts, and (3) suitable host macroenvironment. Catalysts are especially important when considering the explanations for the relatively short jump from prebiotic to biotic phases that Earth has experienced. We therefore have a situation where an unstable prebiotic phase, through increasing complexity, would "jump" to a relatively stable biotic phase.

BIOACTIVE MATERIAL EVADES THE HAZARDS OF INTERSTELLAR TRAVEL

Such interstellar hazards are (1) high vacuum of 10^{-14} Pa leading to dehydration; (2) intense particle radiation, i.e., protons, electrons, α-particles, and heavy ions, which can all cause irreversible degradation and damage to organic molecules; (3) electro-magnetic radiation, composed of infra-red, visible, and UV spectrum, again leading to organic damage and degradation; and (4) periods of extreme temperature (> 4000 K). If viable organisms are unable to survive the interstellar journey, then what may be delivered to a suitable target planet are the organic remains. It is known that star outflows of polycyclic aromatic hydrocarbons, fullerenes, and unsaturated hydrocarbon chains can undergo polymerization to complex structures in the presence of UV photolysis and/or thermal polymerisation [22]. Interstellar biotic remains may contribute to these organic precursors.

TARGET PLANET EXISTS IN PREBIOTIC STATE

The Oparin-Haldane model, put forward in 1928, has been the gold standard as far as attempts to recreate prebiotic conditions have been concerned. But there are many problems, not least the uncertainty about initial biotic conditions. The energy sources used in modern research are at the very best an approximation of what the initial abiotic/biotic interface was exposed to. Attempts to recreate enormous geological periods of time (> 100 million years), using increased energy input to prebiotic mixtures over a short period of time (< 1 year), may be insufficient to recreate the primordial environment. Further attempts to overcome time problems with Earth-based experiments have been made by increasing UV-radiation dosage. However, this does not equate with cumulative exposure.

BIOACTIVE MATERIAL HAS FAVORABLE INTERACTION WITH TARGET PREBIOTIC MILIEU TO FACILITATE OR ACTIVATE THE PROCESS OF LIFE

We know that important prebiotic compounds are HCN, H_2CO, C_2H_2, HC_2CN, and CH_3C_2H. These are all found within stellar clouds. Studies have also revealed that CH_2/CH_3 functional groups and Si-O are abundant throughout our galaxy, probably as grains with silicate cores and organic mantles [23]. In 1952 Stanley Miller synthesized 17 amino acids in reducing conditions, as well as purines, pyrimidines, and lipid precursors. However, if primitive Earth's atmosphere is found to be nonreducing, then the probability of panspermia playing a significant role in Earth's biological development is much greater. Furthermore, there is good evidence that meteorites have delivered extraterrestrial compounds to Earth. The Sudbury meteorite was found to contain nonterran helium trapped within fullerenes ($C_{60/70}$) [24]. Even more intriguing is the case of the Murchison meteorite, in which amino acids have been discovered in L-enantiomeric excess [25]. Examination of the individual amino acid residues have confirmed that they are of extraterrestrial origin and may predate the origin of life on Earth [26]. At some point in Earth's biotic evolution, L-enantiomers were chosen over D. Why this occurred remains a mystery, but we do know that chirality extends beyond the confines of Earth [27]. With the evidence from the Murchison meteorite there is the intriguing possibility that meteorite strikes during Earth's prebiotic phase could have contributed in some way to the L-enantiomeric biota. This is a view that has received widespread scientific support, not least of which from those concerned with natural history [28]. However, this theory is by no means without its detractors, who argue that there would not have been sufficient extraterrestrial bombardment to account for the L-enantiomeric biota on Earth [29]. Furthermore, as Chris Chyba argues, an enantiomeric preference may have arisen during either prebiotic or biotic development. Chiral choices could have been made: for example, an achiral peptide nucleic acid strand (a potential precursor of DNA) could have been chirally fixed by the addition of a terminal L- or D-lysine residue [30].

What then is the relevance of all this to the development of life on Earth? Well, we know that the efficiency of synthesis of organic compounds is critically dependent on oxidative state. If the Earth's—or any other planet or moon's—prebiotic atmosphere was nonreducing, then external delivery of the required biotic materials is probably the only way a biota would develop. For Earth, at least, an equivalent biomass could have been delivered in 10 Myr if the interplanetary dust grain and micro-meteorite bombardment was as high as 5×10^7 Kg.yr^{-1}, with a primitive dense atmosphere of $\sim$10 bar [31]. However, the simplest solution to the question of our own origins is the Standard Model—this does not negate against exobiological entities, but it does make them more unlikely. In 2004, the Cassini-Huygens mission will reach the Saturn system and begin to send back data on the organic composition of one of its moons, Titan [32]. This mission may well result in new evidence to support exobiological theories. If it is shown by current research that the weight of probability is against terrestrial-only genesis, then we may have to consider an essential exobiological element. Not only would this be proof for the existence of extraterrestrial biota, but it would further underline the unremarkable nature of life on this planet.

REFERENCES

1. Lederberg, J. Exobiology: Approaches to life beyond the Earth. *Science* 132:393, 1960.
2. Lazcano, A., and Miller, S. L. The origin and early evolution of life: Prebiotic chemistry, the pre-RNA world, and time. *Cell* 85:793–98, 1996.
3. Carr, M. H. Water on early Mars. *Ciba. Found. Symp.* 202:249–65, 1996.

4. Knoll, A. H., and Walter, M. R. The limits of palaeontological knowledge: Finding the gold among the dross. *Ciba. Found. Symp.* 202:198–209, 1996.
5. Shock, E. L. Hydrothermal systems as environments for the emergence of life. *Ciba. Found. Symp.* 202:40–52, 1996.
6. DeVincenzi, D. L. NASA's Exobiology Program. *Orig. Life* 14:793–99, 1984.
7. Clarke, D. W., and Ferris, J. P. Chemical evolution on Titan: Comparisons to the prebiotic earth. *Orig. Life Evol. Biosph.* 27:225–48, 1997.
8. Hall, D. T., Strobel, D. F., Feldman, P. D., et al. Detection of an oxygen atmosphere on Jupiter's moon Europa. *Nature* 373:677–81, 1995.
9. Vidal, R. A., Bahr, D., Baragiola, R. A., et al. Oxygen on Ganymede: Laboratory studies. *Science* 276:1839–42, 1997.
10. Noll, K. S., Roush, T. L., Cruikshank, D. P., et al. Detection of ozone on Saturn's satellites Rhea and Dione. *Nature* 388:45–47, 1997.
11. Raulin, F., Gautier, D., and Ip, W. H. Exobiology and the solar system: The Cassini mission to Titan. *Orig. Life* 14:817–24, 1984.
12. Stetter, K. O. Hyperthermophiles in the history of life. *Ciba. Found. Symp.* 202: 1–10, 1996.
13. McKay, D. S., Gibson, E. K., Jr., Thomas Keprta, K. L., et al. Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. *Science* 273:924–30, 1996.
14. Arrhenius, G., and Mojzsis, S. Extraterrestrial life: Life on Mars—then and now. *Curr. Biol.* 6:1213–16, 1996.
15. Friedmann, E. I., and Ocampo Friedmann, R. The Antarctic cryptoendolithic ecosystem: Relevance to exobiology. *Orig. Life* 14:771–76, 1984.
16. Mumma, M. J., Disanti, M. A., Dello Russo, N., et al. Detection of abundant ethane and methane, along with carbon monoxide and water, in comet C/1996 B2 Hyakutake: Evidence for interstellar origin. *Science* 272:1310–14, 1996.
17. Brooke, T. Y., Tokunaga, A. T., Weaver, H. A., et al. Detection of acetylene in the infrared spectrum of comet Hyakutake. *Nature* 383:606–8, 1996.
18. Davies, P. C. The transfer of viable microorganisms between planets. *Ciba. Found. Symp.* 202:304–14, 1996.
19. Hoch, J. A., and Losick, R. Panspermia, spores and the Bacillus subtilis genome. *Nature* 390:237–38, 1997.
20. Koerner, D. W. Analogs of the early solar system. *Orig. Life Evol. Biosph.* 27:157–84, 1997.
21. Kasting, J. F. Habitable zones around low mass stars and the search for extraterrestrial life. *Orig. Life Evol. Biosph.* 27:291–307, 1997.
22. Tielens, A. G., and Charnley, S. B. Circumstellar and interstellar synthesis of organic molecules. *Orig. Life Evol. Biosph.* 27:23–51, 1997.
23. Pendleton, Y. J. Detection of organic matter in interstellar grains. *Orig. Life Evol. Biosph.* 27:53–78, 1997.
24. Becker, L., Poreda, R. J., and Bada, J. L. Extraterrestrial helium trapped in fullerenes in the Sudbury impact structure. *Science* 272:249–52, 1996.
25. Cronin, J. R., and Pizzarello, S. Enantiomeric excesses in meteoritic amino acids. *Science* 275:951–55, 1997.
26. Engel, M. H., and Macko, S. A. Isotopic evidence for extraterrestrial non-racemic amino acids in the Murchison meteorite. *Nature* 389:265–68, 1997.
27. Thiemann, W. Life and chirality beyond the earth. *Orig. Life* 6:475–81, 1975.
28. Fortey, R. *Life: An Unauthorised Biography*. London: Flamingo, HarperCollins, 1998.
29. Cronin, J. R., and Chang, S. *The Chemistry of Life's Origins*. Amsterdam: Kluwer Academic, 1988.
30. Chyba, C. F. Origins of life: A left-handed solar system? *Nature* 389:234–35, 1997.

31. Whittet, D. C. Is extraterrestrial organic matter relevant to the origin of life on Earth? *Orig. Life Evol. Biosph.* 27:249–62, 1997.
32. Raulin, F., Coll, P., Coscia, D., et al. An exobiological view of Titan and the Cassini-Huygens mission. *Adv. Space Med.* 22:353–62, 1998.