TOWARDS A GENERAL THEORY OF LITHOPANSPERMIA.

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Introduction: Although the philosophical underpinning of panspermia theory was first established over two millennia ago, several lines of evidence obtained within the past two decades have dramatically refined our views regarding the possibility of interplanetary transfer of life within our solar system [reviewed in 1-3]. As in other astrobiological endeavors, the development of a coherent theory of lithopanspermia requires the incorporation of data from a number of disciplines ranging from cosmology and planetary sciences, through geophysics and classical geology, to molecular microbiology and the microbial ecology of extreme environments, including reliance upon robust mathematical models.

Planetary Science perspective: Currently it is thought that the solar system arose ~5 Ga ago by gravitational condensation from an interstellar gas cloud called the solar nebula. The contracting nebula began to rotate and assumed the shape of a central protostar surrounded by a protoplanetary disk, from which the sun and planets formed by further gravitational collapse. During the final phase of planetary formation, from ~4.5-3.8 Ga ago, the increasing gravity fields of the new growing planets, coupled with migration of planets into their present orbits, swept up local debris and perturbed the orbits of smaller asteroids and comets, thus showering themselves and each other with a cascade of impacting objects during a period known as the Heavy Bombardment. It is thought that during the Heavy Bombardment a significant fraction of Earth's water and critical prebiotic organic compounds may have been delivered from the outer solar system by such impactors, and that there was active exchange of surface rocks among the inner terrestrial planets. Such exchange continues to the present day (albeit at a lower rate), as evidenced by the current collection of relatively young martian meteorites [4].

Geophysical perspective: Petrogaphic examination of their heat-labile carbonates and magnetic signatures indicated that many of the martian meteorites had been boosted into space suffering only rather light shock pressures and heating. Indeed, some martian meteorites apparently were never heated above ~100˚C. Recent advances in the physics of impacts have provided insights into how rocks can be launched into space with relatively little shock damage. A considerable amount of theoretical and experimental support has accumulated favoring a spallation mechanism for impact ejection [5]. In this mechanism, a transient spallation zone forms around an impact site, where the reflected shock wave of the impact is directly translated into acceleration of surface rocks to escape velocity with relatively little shock or heating.

Microbiological perspective: The igneous origin of most martian meteorites argues that putative microbial passengers would be endolithic. Relatively little is known regarding the ecology of endolithic microbes, but estimates of total microbial numbers in basalts and granites range up to 10^7-10^8 total organisms per gram [6]. A fraction of microbes inhabiting the interior of basalt and granite were found to be spores of *Bacillus* spp. Interestingly, these endolithic isolates were very closely related to a restricted number of *Bacillus* spp. previously found to inhabit globally distributed endolithic sites (biodeteriorated murals, stone tombs, underground caverns, and rock concretions) and extreme environments (Antarctic soils, deep sea floor sediments, and spacecraft assembly facilities) [7, 8].

Experimental models: Although spores of *Bacillus subtilis* have been used most extensively as a model organism for lithopanspermia studies [2], the list of microorganisms is growing, including both Gram-positive and –negative species, archaea, cyanobacteria, and even lichens and lower eukaryotes [1]. Some of these organisms have been subjected to both simulated and real impact-mediated launches, exposure to the space environment, and high-speed atmospheric entry from space. In nearly all cases a significant fraction of the starting populations have survived these treatments [1-3]. In addition, an area of active study involves investigation of the ability of various extremophilic terrestrial microbes to survive, grow and evolve in simulations of extraterrestrial environments such as those found on Mars.

Evolution of planets and microbes: Current evidence suggests that in the early days of the solar system, the environments of Venus, Earth, and Mars were much more similar than they are today. Each planet likely possessed a relatively warm environment with abundant liquid water and an atmosphere dominated by CO_2, conducive to the origin of life. Because this period coincided with the latter part of the Heavy Bombardment, it has been postulated that early life-bearing rocks were actively being exchanged throughout the solar system, particularly among the inner rocky planets. However, over the next 4 billion years or so, Venus, Earth, and Mars embarked on divergent evolutionary pathways leading to their present radically different environments. The accumulated evidence leads us to the following scenario, although others are certainly possible. Early in the history of our solar system, somewhere around 4 billion years ago, the early terrestrial planets (Venus, Earth, Mars) were accreting as a result of impact bombardment. During this period water and prebiotic organic compounds were being regularly delivered from the outer solar system by comets and asteroids, but the energy released by their impacts probably kept the planetary surfaces too hot for liquid water to form. Bombardment continued, but eventually the impact rate dropped to the point that each planetary surface cooled to a temperature at which liquid water could exist. On one or more of the terrestrial planets (which one, no one can say), life likely arose in contact with liquid water, heat and nutrients, perhaps in a subterranean or submarine hydrothermal system. Exactly how this may have happened is currently the subject of intense debate (see [9] and references therein). Some scientists think that, during the period when life was gaining a toehold, occasionally the terrestrial planets were struck by leftover impacting objects that were large and energetic enough to actually boil away the oceans again into the atmosphere--these have been called "sterilizing" impacts [10]. After each sterilizing impact, the planet cooled again, and water condensed and rained back into the oceans. Eventually the supply of sterilizing impactors was exhausted.

The molecular phylogenetic tree suggests that the earliest life forms may have been anaerobic thermophilic microorganisms (although this is also the subject of intense debate, [11]), implying that life might have originated in a hot ocean, or in a subterranean or submarine hydrothermal system similar to those found today in "black smokers" on the ocean floor or in deep hot spring systems such as those in Yellowstone National Park. Alternatively, some scientists speculate that these ancient microbial lineages merely represent the survivors of the last sterilizing impact, which were situated in protected refuges, perhaps near hydrothermal vents on the ocean floor or in deep subsurface hydrothermal systems.

An intriguing twist on the theory of lithopanspermia has been suggested as a mechanism for refuge of microorganisms to sterilizing impacts [10]. In this scenario, a sterilizing impactor could have blasted large quantities of microbe-bearing surface rocks into space, and that many of these rocks lacked the velocity to completely escape Earth's gravity. These rocks would enter decaying orbits, eventually showering back onto Earth over decades, hundreds or thousands of years. As the Earth cooled, water condensed, and the oceans reformed in the years following a sterilizing impact, Earth could once again be inoculated by microbe-bearing meteorites, but this time of Earthly origin.

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